**QUANTIFYING CLIMATE CHANGE DRIVEN
ENVIRONMENTAL LOSSES IN COASTAL AREAS**

A PRACTICAL FRAMEWORK

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SUMMARY

Natural hazards, apart from the economic losses and loss of life, can cause massive damage to the environment and may disrupt or cease the natural services that the environment provides. Coastal hazards, such as flooding and coastal erosion, can result in degradation or even the disappearance of coastal wetlands. Climate Change (CC) impacts (i.e. increase in sea water temperature, sea level rise (SLR), changes in the intensity/frequency of storms, etc.) may exacerbate these environmental damages and elevate the threat level for the coastal wetlands in future. This could result in a decrease in services provided by the wetlands ecosystems such as mangroves, coral reefs, beach and dune systems, seagrass beds, and pelagic systems, which will negatively affect the flow of services that are vital to human wellbeing. Analysis of CC impacts on the coastal wetlands is of great importance, considering that a large proportion of the World's population lives in coastal zones and directly or indirectly benefits from the ecosystem services of these habitats. Understanding the uncertainties associated with the physical CC impacts on coastal wetlands over a long time span (e.g. century), has remained a challenge for both economists and ecologists for decades.

In view of the above, achieving a sound understanding of potential CC driven variation in the health status of coastal wetlands is of great importance. In addition, while a vast majority of available literature has focused on the Present-day Value (PV) of coastal ecosystem services (CES), this strand of literature does not offer a straightforward approach to quantifying the potential magnitude of the climate change impacts on the PV of CES. This knowledge gap is especially prevalent in developing countries that are likely to suffer the most from CC. The local communities residing in regions vulnerable to CC driven hazards in developing countries are often dependent on CES to make ends meet, while their adaptive capacity to CC impacts remains low.

To address the above knowledge gaps, this study presents and formulates a practical framework that offers a novel scenario-based approach to Quantify CC driven Environmental Losses (QuantiCEL) which coherently assesses the likely physical impacts of climate change on CES, and pursues the valuation study with primary data collection. To present a proof of concept, the developed QuantiCEL framework is applied to the coastal areas in three developing countries to quantify potential environmental losses due to relative sea level rise (RSLR)-induced coastal inundation (in Indonesia, and Bangladesh), and SLR and storm-induced coastal recession (in Sri Lanka) in the next 100 years. The framework application is then extended further for quantifying the environmental risk (a very little known topic in the literature) in the Sri Lanka case study.

The QuantiCEL framework links the potential impacts of coastal inundation and erosion on CES with economic concepts used in valuation studies (i.e. consumer and producer surpluses). Within this framework, (1) the present-day value of CES is quantified by using accepted economic valuation techniques; (2) the potential impacts of RSLR-induced inundation (for the year 2100 inundation scenarios), and storm and RSLR-induced coastal

recession (for the year 2110 beach retreat scenario) on ecosystem services provided by mangrove swamps, beach, dune and pelagic systems are identified; and (3) these impacts are monetized by developing a novel scenario-based approach using expert opinion and available secondary data.

The results show that there are considerable variations in the estimates of loss value among the CES considered in the three study sites. Art service is the most sensitive service to the considered CC driven hazards, showing an estimated maximum loss of 90% relative to its PV (extreme scenario). Tourism is the second sensitive service to CC impacts, with an estimated reduction of its PV by nearly 65% for the considered extreme scenario, followed by amenity service with a decrease of upto 50%. The results also indicate that food provision service (fish and marine species) is likely to decrease by a maximum of about 30%. Provision of raw materials, timber and fuelwood, is the service with the lowest percentage loss value, estimated to be about 5% loss of its PV, under a low inundation scenario. In addition, quantification of coastal recession-driven risk associated with the value of tourism service provided by CES of Trincomalee in Sri Lanka, shows a medium risk value, estimated within range of US\$ 0 – 1.10 per m² of beach area.

Applying the QuantiCEL framework to three developing countries (i.e. Indonesia, Bangladesh, and Sri Lanka) generally shows that, where the absolute loss value of CES by the end of the 21st century is concerned, food provision and tourism are the CES with higher loss values. However, art, amenity, and tourism are the highly affected CES where the percentage loss (by the end of the 21st century) relative to the present-day value of CES is concerned. However, more studies of this nature are required to gain more confidence in the generic applicability of these observations.

The QuantiCEL framework presented in this study follows a clear step-wise approach that makes it amenable for use in a wide range of similar applications. This application will provide an estimation of potential CC driven losses in the value of CES. This scenario-based framework is of relevance, especially in data-scarce environments (i.e. developing countries), where it is not possible to apply standard ecological and mathematical simulation methods. However, generalization of the outcomes of this study for the similar applications is not suggested prior to further verification, and hence, for the time being, it is advisable for the framework to be applied case by case. The extension of QuantiCEL framework to quantify the environmental risk value, presents a novel method that can contribute to the development of much needed risk based coastal zone management frameworks for the sustainable management of coastal areas.

SAMENVATTING¹

Over het algemeen kunnen natuurrampen, afgezien van het veroorzaken van economisch verlies en verlies van mensenlevens, enorme schade aanrichten aan het milieu en daarmee de natuurlijke diensten die het milieu aanbiedt verstoren of beëindigen. Kustgevaren, zoals overstromingen en kusterosie, kunnen resulteren in de afbraak van -, of zelfs het verdwijnen van kustwetlands. Invloeden van klimaatverandering (zoals de toename van zeewatertemperatuur, zeespiegelstijging, veranderingen van de intensiteit/frequentie van stormen, etc.) kunnen deze milieuschade verergeren en het dreigingsniveau voor de kustwetlands in de toekomst laten toenemen. Dit kan resulteren in een afname van diensten die door de wetlands ecosystemen worden geleverd, zoals mangroves, koraalrif, strand- en duinsystemen, zeegrasvelden en pelagische systemen, wat de doorstroom van belangrijke diensten voor het menselijke welzijn negatief kan beïnvloeden. Een analyse van de invloeden van klimaatverandering op kustwetlands is van groot belang, gezien het feit dat een groot deel van de wereldpopulatie in kustgebieden woont en direct of indirect profiteert van de ecosysteemdiensten van deze leefgebieden. Het interpreteren en begrijpen van de onzekerheden die geassocieerd worden met de fysieke invloeden van klimaatveranderingen op kustwetlands over een tamelijk lange periode (zoals een eeuw), is decennialang een uitdaging gebleven voor economen en ecologen.

Op grond van het voorgaande is het behalen van een gedegen begrip van potentiële klimaatverandering gedreven variatie in de gezondheidstoestand van kustwetlands van groot belang. Hoewel een meerderheid van de beschikbare literatuur zich focust op de actuele waarde van kustecosysteem-diensten (CES) biedt deze literatuur geen eenvoudige benadering om de potentiële omvang van de invloeden van klimaatverandering op de actuele waarde van kustsysteem-diensten te kwantificeren. Deze kenniskloof heeft voornamelijk de overhand in ontwikkelingslanden die het meest leiden onder klimaatverandering. Lokale gemeenschappen die in bepaalde regio's leven in ontwikkelingslanden, die voornamelijk kwetsbaar zijn voor de klimaatverandering gedreven gevaren, zijn vaak afhankelijk van kustecosysteem-diensten om "de eindjes aan elkaar te kunnen knopen", terwijl hun aanpassingsvermogen tegenover invloeden van klimaatverandering laag blijft.

Om de bovengenoemde kenniskloven aan te pakken haalt dit onderzoek een praktisch kader aan dat een nieuw, op scenario's gebaseerde benadering aanbiedt om klimaatverandering-gedreven milieuschade te bepalen, wat op samenhangende wijze de fysieke invloeden van klimaatverandering op kustecosysteem-diensten beoordeelt, en het waarderingsonderzoek met primaire dataverzameling nastreeft. Om een proefconcept te presenteren is het QuantiCEL kader toegepast in de kustgebieden in drie ontwikkelingslanden om de potentiële milieuschade door relatieve zeespiegelstijging (RSLR)- geïnduceerde kustoverstroming (in Indonesië en Bangladesh), en SLR en storm-geïnduceerde kustrecessie (in Sri-Lanka) voor

¹ This summary is translated to Dutch by Mrs. Bianca Wassenaar, Secretary of Department "Environmental Engineering and Water Technology", IHE Delft.

de komende 100 jaar te bepalen. De toepassing van het kader wordt daarna verder verlengd voor de bepaling van milieurisico's (een onderwerp wat niet erg bekend is in de literatuur) in de case study over Sri Lanka.

Het QuantiCEL kader linkt de potentiële invloeden van kustoverstroming en erosie van kustecosysteem-diensten (CES) met economische concepten die gebruikt worden in waarderingsonderzoeken (zoals consumenten – en producentensurplus). Binnen dit kader wordt (1) de actuele waarde van kustecosysteem-diensten (CES) bepaald door economische waarderings technieken te gebruiken; (2) worden de potentiële invloeden van RSLR-geïnduceerde overstroming (voor het jaar 2100 overstroming scenario's), en storm en RSLR-geïnduceerde kustrecessie (voor het jaar 2110 de scenario omtrent de terugtrekking van het strand) op ecosysteemdiensten die aangeboden worden door mangrove moerasland, strand, duinen en pelagische systemen geïdentificeerd; en (3) deze invloeden worden becijferd door de ontwikkeling van een nieuw, op scenario-gebaseerd kader dat gebruik maakt van deskundig oordeel en beschikbare secundaire data.

De resultaten tonen aan dat er een aanzienlijke variatie bestaat in de schattingen omtrent het waardeverlies rond de kustecosysteem-diensten (CES) dat overwogen werd in de drie onderzoek locaties. De kunstsector is de meest kwetsbare sector voor de desbetreffende klimaatverandering-gedreven rampen, met een aantoonbare schatting van een maximaal verlies van 90% ten opzichte van de sector's actuele waarde (PV) (uitgaande van een extreem scenario). De toeristensector is de op één-na meest kwetsbare sector voor de invloeden van klimaatverandering, gevolgd door de recreatiesector, met een afname van 50%. De resultaten geven ook aan dat de sector omtrent voedselvoorzieningen (vis en zeedieren) hoogstwaarschijnlijk zal afnemen met een maximum van ongeveer 30%. De voorziening van grondstoffen, hout en brandhout, is de sector met het laagste waardeverliespercentage, naar schatting zo'n 5% verlies omtrent de sector's actuele waarde (PV), gebaseerd op een lage inundatiescenario. De kwantificering van kustrecessie-gedreven risico's geassocieerd met de waarde van de toeristensector, aangeleverd door kustecosysteem-diensten (CES) van Trincomalee in Sri Lanka, laat bovendien een medium risicowaarde zien, geschat binnen een scala van US\$ 0-1.10 per m² strandgebied.

Het toepassen van het QuantiCEL kader in drie ontwikkelingslanden (zoals Indonesia, Bangladesh en Sri Lanka) laat over het algemeen het absolute waardeverlies van de kustecosysteem-diensten (CES) aan het einde van de 21^e eeuw zien. Voedselvoorzienings- en de toeristensector zijn de kustecosysteem-diensten (CES) met een hoger waardeverlies. Toch zijn de kunst-, recreatie- en toeristensector de meest aangetaste CES waarbij het gaat om het verliespercentage (aan het einde van de 21^e eeuw) ten opzichte van de actuele waarde van CES. Echter zijn meer van dit soort onderzoeken vereist om meer zekerheid in de generieke toepasbaarheid van deze observaties te winnen.

Het QuantiCEL kader dat gebruikt is in dit onderzoek, volgt een duidelijke stapsgewijze benadering wat het bruikbaar maakt in een breed assortiment van vergelijkbare toepassingen. Deze toepassing zal een schatting van potentiële klimaatverandering-gedreven verliezen verstrekken in de waarde van kustecosysteem-diensten (CES). Dit op scenario-gebaseerde

kader is relevant, voornamelijk in gebieden met geringe data (zoals ontwikkelingslanden), waar het niet mogelijk is om standaard ecologische – en wiskundige simulatiemethoden toe te passen. Echter, generalisatie van de onderzoek resultaten voor vergelijkbare toepassingen wordt niet aanbevolen voorafgaand aan verdere verificatie, en daarom is het voor nu verstandig om het kader per casus toe te passen. De verlenging van het QuantiCEL kader om de milieurisicowaarde te bepalen, presenteert een nieuwe methode dat kan bijdragen aan de ontwikkeling van belangrijke, op risico-gebaseerde kustgebied-managementkaders voor het duurzame beheer van kustgebieden.

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ACRONYMS

AR5	Fifth Assessment Report
BDT	Bangladeshi Taka
CC	Climate Change
CCM	Contingent Choice Method
CES	Coastal Ecosystem Service
CS	Consumer Surplus
CVM	Contingent Valuation Method
DEM	Digital Elevation Map
DIVAA	Dynamic and Interactive Vulnerability Assessment
ER	Environmental Risk
GHG	Greenhouse Gas
GIA	Glacial Isostatic Adjustment
IDR	Indonesia Rupiah
IPCC	Intergovernmental Panel on Climate Change
LB	Literature Based
LKR	Sri Lanka Rupee
MEA	Millennium Ecosystem Assessment
MSL	Mean Sea Level
PCR	Probabilistic Coastal Recession
PS	Producer Surplus
PSMSL	Permanent Service for Mean Sea Level
PV	Present-day Value
RCL	Reference Coastline
RCP	Representative Concentration Pathways
RSLR	Relative Sea Level Rise
SB	Survey Based
SLAMM	Sea Level Affecting Marshes Model
SLR	Sea Level Rise
SMF	Sundarbans Mangrove Forest
SRES	Special Report on Emissions Scenarios
TEV	Total Economic Value
WES	Wetland Ecosystems Service
WTP	Willingness To Pay

CHAPTER 1

Introduction¹

¹ This Chapter is partially based on: Mehvar, S., Filatova, T., Syukri, I., Dastgheib, A., and Ranasinghe, R. (2018b). Developing a framework to quantify potential Sea level rise-driven environmental losses, a case study in Semarang coastal area, Indonesia. *Environmental Science and Policy*, 89, 216-230.

1.1 Background

The increasing popularity of coastal areas for housing and tourism has led to more investment and therefore higher potential for damage due to coastal hazards (e.g. coastal recession, inundation, formation and closure of small tidal inlets). There is now reasonable certainty that the frequency, severity, and consequences of coastal hazards will increase in future with changes in the global climate. For example, Sea Level Rise (SLR) associated with global warming will intensify the impact of coastal hazards, specifically in low lying areas which are substantially susceptible to these hazards. Changes in wave direction may result in closure of tidal inlets. In addition, changes in storm surge characteristics, together with SLR will result in more frequent episodic coastal flooding.

It has become evident in recent years that the environmental impacts of natural hazards can be beneficial or harmful, and that quantifying these benefits and losses present challenges with equal or greater complexity comparing to quantifying economic and life-safety issues (Baecher, 2009). Coastal wetlands (both tidal and non-tidal) are among the most spatio-temporally variable environments threatened by direct drivers (e.g. storm surge, and climate change). It should also be noted that these areas have been already affected by direct human drivers such as dredging, reclamation and land conversion for aquaculture, as well as indirect human drivers such as population growth and economic development.

The issue of environmental losses caused by coastal hazards has always been an important topic (Nicholls et al., 1999; Smith, 2003; Daniel et al., 2009; Sayers et al., 2012; Balica et al., 2012). In recent years, a substantial amount of research has been conducted to evaluate flood hazards and their consequences with the aim of reducing flooding risk and improving risk awareness in coastal areas (McGranahan et al., 2007; Dawson et al., 2009; Kellens et al., 2011; Wang et al., 2012). Generally, the consequences of hazards comprise three aspects (Baecher, 2009):

- Loss of life (also health, welfare, and social disruption)
- Economic losses
- Environmental impacts

The first aspect concerns loss of life and social disruption, which can be very pronounced, especially in developing countries in Asia as being the continent with the highest number of people living in the low-elevation coastal zones exposed to flooding (Neumann et al., 2015). The second aspect concerns direct economic losses to buildings and infrastructure, agricultural land, and other developments. Additionally, there are possible indirect losses caused by disruptions to transportation and mobility.

The third aspect is associated with damages to the environment and ecological systems caused by coastal hazards. Apart from social disruption and economic losses, the coastal environment

will undergo major physical changes triggered by contemporary and climate change (CC) modified coastal hazards (Wong et al., 2014). Any environmental degradation and damage due to this type of hazards such as hurricanes (Figure 1.1), storm surges and flooding should thus be carefully assessed in order to develop approaches to increase resilience and ensure the safety of the vulnerable coastal areas. Such environmental assessments, which is currently an "emerging" science, is of great importance, since the sustainability and socio-economic wellbeing of most coastal communities rely considerably on the services that coastal wetlands provide.

Figure 1.1 Coastal damages caused by Hurricane Sandy along the New Jersey coast (USA) at Lavallette in 2012. Source: Greenpeace/Tim Aubry

CC will most likely exacerbate these environmental damages, threatening coastal areas globally. Importantly, quantitative fine-scale physical and monetary assessments of CC driven losses – including ecosystem losses – form the basis for estimating global CC related damages in Integrated Assessment Models.

Available CC impact assessment studies have mostly explored the first order CC impacts on coastal and marine areas such as changes in sea level, ocean conditions and biogeochemistry, without monetizing these impacts on the services provided by ecosystems (Daw et al., 2009; Cochrane et al., 2009; Mohanty et al., 2010; Sumaila et al., 2011; Cheung et al., 2011). A few studies have performed quantitative analysis of ecological impacts of CC on Coastal Ecosystem Services (CES). For example, Cheung et al. (2011) demonstrated that changes in phytoplankton community structure as well as ocean acidification (i.e. 30% reduction in oxygen demand as the H^+ ion concentration in the ocean doubles) may substantially reduce the maximum fish catch potential by about 20%-30% in the Northeast Atlantic.

Kuhfuss et al. (2016) conducted a valuation of CC-driven changes in CES in France, showing that a 1 m SLR scenario in 2100 helps gain additional territory to the regional coastal wetlands due to the retreat of agricultural and urban areas. In this study, the transformations of ecological habitats, depending on their distance from salt water, were examined by assuming proportionality between the surface area and CES. This scenario-based approach resulted in a projected increase of total CES value (i.e. ecotourism, biodiversity, flood drainage, etc.) between 2.593 million and 8.094 million of 2010 euros, due to 1 m of SLR by 2100 (relative to 2010) depending on different adaptive strategies considered. In a large scale study, Roebeling et al. (2013) projected coastal erosion patterns in Europe for Intergovernmental Panel on Climate Change (IPCC)-Special Report on Emissions Scenarios (SRES) scenarios B1 and A1FI, by using the Dynamic and Interactive Vulnerability Assessment (DIVA) data base, in combination with a benefit transfer approach. According to this study, SLR-induced erosion led to total territory losses between 3700 km² and 5800 km² in different land cover types (coastal wetlands, agricultural areas, forests and semi natural areas) resulting in annual damage (by 2050) of approximately € 2.9 billion to associated CES. However, the outcomes of these studies are very diverse and sometimes conflicting, depending on the perspective of the observer, adding to the uncertainty related to the potential costs of CC impacts on CES.

Despite the few applications mentioned above, there are still two main challenges with respect to quantifying CC impacts on CES; (1) identifying CC driven physical impacts on diverse CES; and (2) monetizing these impacts. While most of the available valuation studies have estimated the Present-day Value (PV) of CES in local study sites, this strand of literature has not explicitly quantified the changes in the value of different CES due to CC impacts (Mehvar et al., 2018a). Such quantifications are especially problematic in developing countries due to: a) a general lack of data even to assess physical impacts and associated losses (Bosello et al., 2012; Farmer et al., 2015; Burke et al., 2016); b) field work can be difficult to arrange and/or is expensive; c) Willingness To Pay (WTP) or willingness to avoid environmental damages (WTA) information is difficult to extract in lower-income countries, especially for assessments of losses for a faraway future, while peoples' current needs are already difficult to meet. Perhaps as a result, most of the reported assessments have been carried out in developed countries, making it difficult to transfer these valuations into the context of developing countries. Yet, it is in fact developing countries that are likely to suffer most, given that local population is often dependent on CES to survive, while adaptive capacity to CC impacts is also low (Duong et al., 2016).

1.2 Research objective

The overarching objective of this study is to develop and demonstrate a framework to quantify the monetary value of future climate change driven environmental losses caused by coastal flooding (including the effects of concurrent coastal erosion) at a range of local scales in coastal areas of developing countries.

1.3 Research questions

To achieve the above objective, this study will seek to answer the following specific research questions (RQ), through developing the QuantiCEL (Quantifying Climate change driven Environmental Losses) Framework:

- **RQ1-** How do the selected study sites compare with each other in terms of the type of coastal wetlands, ecosystem services provided, and governing CC driven hazards?
- **RQ2-** What is the motivation for the development of the QuantiCEL framework, and what methodological steps need to be included in this framework?
- **RQ3-** To what extent can CC driven hazards potentially affect the CES of the study sites?
- **RQ4-** What are the future potential CC driven environmental loss values of CES estimated in each study site? What is the variation of loss values between the CES of the considered study sites?
- **RQ5-** What are the limitations and advantages of QuantiCEL framework, and what are the main uncertainties associated with the results of this study?
- **RQ6-** What other applications of QuantiCEL framework are possible in valuation studies?

1.4 Research approach

This study starts with an extensive literature review on the valuation of CES, to identify the current status of coastal wetlands and to highlight relevant ecological and economic concepts. Herein, frequently considered ecosystems in the available valuation studies, the highest/lowest estimated values of the services, and the commonly used economic techniques in valuing the services are identified. In addition, direct and indirect drivers of changes to coastal wetlands are reviewed to identify common drivers of change in coastal wetlands, and the little known issue of potential climate driven changes on the services provided by the wetland ecosystems is also addressed.

The overall approach used in this study, is to first develop the QuantiCEL framework and its stepwise methodology. This framework relies on using economic valuation techniques (i.e. contingent valuation, market price, net factor income, and hedonic price) combined with developing a novel scenario-based approach grounded in local expert knowledge and in secondary data from literature review. Secondly, the framework developed is applied to different study sites. To this end, the study in Semarang coastal area in Indonesia, is a first demonstration of QuantiCEL framework to quantify changes to the value of the CES due to Relative Sea Level Rise (RSLR)-induced inundation in 2100. The second study in the Bangladesh coastal area presents an application of the QuantiCEL framework for quantifying

losses of Wetland Ecosystem Services (WES) due to RSLR-induced inundation in 2100. Finally, the third study in Sri Lanka's Eastern coast presents an extension of the QuantiCEL framework for quantifying losses of CES due to storm and RSLR-induced recession in 2110, and for quantifying environmental risk.

Two types of primary and secondary data are used in this study. The primary data are obtained to estimate the PV of CES through field observations, participatory discussions, surveys and interviews with a range of stakeholders. These data are used here to quantify potential changes to the ecosystems services due to RSLR-induced hazards (inundation and recession). The secondary data collated for this study include ecological and hazard-related information for each study site. The methodology used in this research is described in detail for each study site in the corresponding chapters.

1.5 Thesis outline

This dissertation is structured in 7 chapters, which are partially based on peer reviewed articles, as indicated in each chapter:

- Chapter 1 constitutes the introduction to the study which presents the research background including different types of consequences of natural hazards, with a focus on environmental degradation, and potential changes to the CES. In addition, a brief description is provided indicating the importance of CC and potential impacts thereof on coastal wetlands as can be gleaned from the limited amount of available literature.
- Chapter 2 provides an overview of coastal wetlands and their ecosystem services, and a review on the fundamental concepts in valuation of CES. This chapter offers a systematic analysis of the best practices in valuation studies by analyzing two global scale and 30 selected local and regional study sites, in which different CES have been valued.
- Chapter 3 describes direct and indirect drivers of changes in coastal wetlands with a focus on climate change driven impacts on the services provided by these ecosystems.
- Chapter 4 develops the coherent three-step QuantiCEL framework, and subsequently demonstrates its application in the coastal area of Semarang in Indonesia to quantify potential RSLR-driven changes in the monetary value of ecosystem services. Within this framework, the following sequential steps are followed: (1) quantify the present-day value of CES by using economic valuation techniques; (2) identify the potential impacts of RSLR-induced inundation on ecosystem services provided by mangrove swamps, beach, dune and pelagic systems (for the year 2100 inundation scenarios); and (3) monetize these impacts by using a novel scenario-based approach.

- Chapter 5 investigates the potential climate change driven losses in the value of wetlands ecosystems services due to RSLR-induced inundation in the Western coastal area of Bangladesh in 2100. To this end, the developed QuantiCEL framework in the previous chapter, is applied to quantify the inundation driven changes to the services provided by the Sundarbans Mangrove Forest (SMF), pelagic system and aquaculture ponds.
- Chapter 6 presents a different application of the QuantiCEL framework, to quantify the value of environmental losses and risk due to storm and RSLR-induced coastal recession (i.e. long term erosion) along the East coast of Sri Lanka in 2110. This quantitative assessment is conducted in the Trincomalee district for the services provided by its coastal wetlands such as mangroves and beaches. In this chapter, the QuantiCEL framework application demonstrates the quantification of Environmental Risk (ER) using estimates of loss values of tourism service. Combining the loss values and exceedance probability of coastal recession derived from the Probabilistic Coastal Recession (PCR) model (Dastgheib et al., 2018), the ER value is quantified, which shows a spatial variation of coastal recession driven risk in the tourism value of coastal wetlands for the three beaches of Trincomalee district (Nilaveli, Alas Garden, and Trincomalee).
- Chapter 7, finally presents the conclusions of this study by answering the research questions posed in Chapter 1, and by providing a summary of the main results. In addition, future research directions are also suggested.

CHAPTER 2

Economic Value of Coastal Ecosystem Services¹

¹ This Chapter is partially based on: Mehvar, S., Filatova, T., Dastgheib, A., De Ruyter Van Steveninck, E. D., and Ranasinghe, R. (2018a). Quantifying Economic Value of Coastal Ecosystem Services, a Review. *Journal of Marine Science and Engineering*, 6(1), 5.

2.1 Introduction

Coastal areas cover only 4% of the earth's total land area and are equivalent to 11% of the world's ocean area (Barbier, 2013). However, they host one third of the world's population and are twice as densely populated as inland areas (MEA, 2005). The population density increases in the coastal zones annually due to migration driven by global demographic and socio-economic changes (Neumann et al., 2015). Growing population and accompanying infrastructure build-up provoke agglomeration economies that attract even more people and capital to the coastal zone, which has resulted in 15 out of the 20 present-day megacities of the World being located in low elevation coastal areas (Bierbaum and Fay, 2010). More than 60% of the total value of the biosphere is attributed to oceans and coastal regions (Costanza et al., 1997; Martinez et al., 2007). An assessment of global ecosystem goods and services by Costanza et al. (1997) indicates that a value of US\$ 24 trillion per year can be attributed to the coastal zone.

Worldwide, the economies of coastal communities and their resilience highly depend on the ecosystem services that the coastal zone provide. Interest in ecosystem services in both research and policy-making communities has grown rapidly (Braat and de Groot, 2012), leading to many studies which have estimated the value of ecosystem services for different wetland types, most of which have been limited to a particular local-scale case study (e.g., Emerton and Kekulandala, 2003; Hussain and Badola, 2008; Lew and Larson, 2014; Castano-Isaza et al., 2015; Vo et al., 2015).

On a larger spatial scale, Chaikumbung et al. (2016) reviewed 1432 valuation studies of wetlands worldwide with the aim of providing a meta-regression analysis of their economic value and factors that influence it. In addition, Rao et al. (2015) estimated the global value of Coastal Ecosystem Services (CES) for specific coastal wetlands, resulting in large range of 0.4–1,998 US\$/ha/year in 2003 corresponding to 0.5–2530 US\$/ha/year in 2013. A more recent study (Costanza et al., 2014) indicated that global land use has changed between 1997 and 2011, resulting in an ecosystem services loss of between US\$ 4 and US\$ 20 trillion per year. However, studies estimating the monetary effects of climate change (CC) impacts on CES are scarce. Such an endeavor often requires a multidisciplinary effort - even more than in traditional ecosystem valuation exercises that do not consider CC effects.

Despite the above mentioned local scale and global studies, a coherent review on the valuation of CES with a systematic description of fundamental concepts and key reported applications, has not been undertaken to date. This chapter takes a step towards addressing this knowledge gap. Specifically, a number of salient questions that one has to consider when seeking to estimate the value of certain coastal wetlands are discussed herein. In particular, (1) What type of wetlands and ecosystems are being assessed? 2) What type of ecosystem services, goods and values need to be considered? (3) Which direct and indirect drivers are the most prominent in affecting these ecosystem services and values? (4) What kind of valuation methods should be

used for valuing a particular ecosystem service? (5) What type of data are required, given the limitations and costly process of its collection? and (6) How have CES been valued in previous global and local case studies, and what are the highest and lowest valued services and the most frequently used valuation methods therein? These questions are sequentially addressed in the subsequent sections of this chapter, following the sequential structure shown in Figure 2.1.

Figure 2.1 Schematic depiction of the sequential structure of this chapter

This chapter first presents a background on types of coastal wetlands, ecosystems and their services/goods (Section 2.2.1), followed by a summary description of the concepts underlying ecosystem services valuation studies, current economic valuation methods and required data for conducting such studies (Section 2.2.2). This is followed by Section 2.3 which presents and analyses 30 selected local and regional-scale valuation studies of CES and two global-scale cases where they are clustered based on type of ecosystem to highlight the current status of valuation studies of CES.

2.2 Background

2.2.1 Coastal Wetlands and Ecosystem Services

- Coastal wetlands

As defined by the Ramsar Convention¹, wetlands are “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tide does not exceed six meters” and “may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands” (Ramsar Convention Secretariat, 2016). The Ramsar Convention Secretariat, in addition to human-made wetlands, recognizes five major natural wetland types: 1) marine, 2) estuarine, 3)

¹ The convention of Ramsar was founded in Iran in 1971 and the main objective of this convention is wetland conservation and wise use of environmental resources. It is the only global intergovernmental convention that addresses the interactions between water and ecosystems.

lacustrine, 4) riverine, and 5) palustrine. The present study deals with selected wetlands from the first two categories, here categorized as coastal wetlands (adapted from de Groot et al., 2018) as follows:

- Estuaries
- Salt marshes
- Mangroves
- Lagoons
- Beach and dune systems
- Seagrass beds
- Coral reefs
- Pelagic systems

Some of these wetlands are shown in Figure 2.2, and are described as follows:

Estuaries

Estuaries and their surrounding wetlands are bodies of water usually found where rivers meet the sea and as such are places of transition from land to sea, and from freshwater to saltwater. Estuaries are home to unique plant and animal communities that have adapted to brackish water—a mixture of fresh water draining from the land and salty seawater. Although influenced by tides, estuaries are generally protected from the full force of ocean waves, winds, and storms by reefs, barrier islands, or strips of land, mud, or sand that surround them. Estuaries serve as natural filters for runoff making them highly productive systems. They provide nursery grounds for many species of birds, fish, and other animals and many animals rely on estuaries for food, places to breed, and migration stopovers. Also people recreate and enjoy nature in estuaries and the wetlands surrounding them (derived from US EPA definition: www.epa.gov).

Salt marshes

Salt marshes are areas of land, covered dominantly by vegetation that are flooded and drained by salt water brought in by the tides. They occur worldwide, particularly in middle to high latitudes, along protected shorelines in estuaries. They also provide essential food, refuge, and nursery habitat for many fisheries species, including crustaceans, shellfish and finfish. By buffering wave action and trapping sediments, salt marshes help protecting shorelines from erosion. They reduce flooding by slowing and absorbing rainwater and protect water quality by filtering runoff, and by metabolizing excess nutrients.

Mangroves

Mangroves with more than 80 different species (Blaber, 2007) can be considered the (sub) tropical counterpart of salt marshes. Mangroves are a taxonomically diverse group consisting of trees and shrubs that live in the coastal intertidal zone in (sub) tropical latitudes (Giri et al., 2011). They grow in areas with low-oxygen soil, where slow-moving waters allow fine

sediments to accumulate. Many mangrove forests can be recognized by their dense tangle of prop roots that make the trees appear to be standing on stilts above the water. This tangle of roots allows the trees to handle the daily rise and fall of tides. The roots also slow the movement of tidal waters, causing sediments to settle out of the water and build up the muddy bottom. Mangrove forests stabilize the coastline, reducing erosion from storm surges, currents, waves, and tides. The intricate root system of mangroves also makes these forests attractive to fish and other organisms seeking food and shelter from predators and mangroves are well-known for their role in providing coastal communities with food and fiber. In spite of this, many mangrove forests are threatened by aquaculture development, overharvesting, land reclamation, etc.

Lagoons

Coastal lagoons are inland water bodies, usually located parallel to the coast, separated from the ocean by a barrier or connected to the ocean by one or more restricted inlets which often remain open and have water depths rarely exceeding a few meters. A lagoon may or may not be subject to tidal mixing, and salinity can vary from that of a coastal fresh-water lake to a saline lagoon, depending on the hydrologic balance. Lagoons are formed as a result of rising sea level, mostly during the Holocene and the building of coastal barriers by marine processes. They are often highly productive and ideal systems for aquaculture projects but are, at the same time, highly stressed by anthropogenic activities (Kjerfve, 1994).

Beach and dune systems

The beach and dune systems can also be defined as ecosystems. Dunes occur along the sandy shores of most continents (Martínez and Psuty, 2008; van Puijenbroek et al., 2017), and including their native vegetation, these ecosystems play a key role in trapping and stabilizing sand on the dune, providing protection against storms and coastline erosion.

Seagrass beds

Except for Antarctica, seagrasses are found in shallow salty and brackish waters around the world, typically along gently sloping, protected coastlines. In particular in tropical regions, they can form dense underwater meadows. Seagrass beds provide spawning, nursery, refuge, and foraging grounds for many animals, including invertebrates, fish, crabs, turtles, marine mammals and birds and in this way support biodiversity and commercial fisheries. By reducing the flow of water and binding sediments with their root system, seagrass beds can stabilize sediments, thus reducing coastal erosion and preventing adjacent coral reefs from becoming buried by sediments. Seagrass beds are capable of improving water quality by absorbing nutrients, while in nutrient poor waters, they can contribute to the redistribution of nutrients from soil to water. They also capture and store carbon from the atmosphere. Seagrasses are vulnerable to natural disturbances (waves, storms, animal activities), and in particular to impacts of human activities. Thus, input of fertilizers (wastewater, agriculture) can cause eutrophication resulting in oxygen depletion. Runoff of sediments from land (agriculture, construction works) or from dredging can block sunlight and smother seagrasses.

Coral reefs

Coral reefs are highly productive and diverse shallow water marine ecosystems (Odum, 1955), which are based on rigid lime skeletons formed through growth, deposition and consolidation of the remaining reef-building corals and coralline algae. Reef building stony corals are limited to tropical waters. They contain symbiotic algae (zooxanthellae) which allow them to deposit limestone in quantities sufficient to form reefs, and therefore need sufficient light (i.e. clear waters) for photosynthesis. There are four types of coral reefs: fringing reefs, patch reefs, barrier reefs and atolls. Coral reefs span about 250,000 km² of the ocean, less than 0.1% of the marine environment (McAllister, 1994). Coral reefs are important habitats for commercial important species, they protect shorelines against waves and storms and are extremely attractive for tourism and recreation. However, they are very sensitive to disturbances like overfishing (including blasting), eutrophication, and impacts of climate change (e.g. ocean acidification, and coral bleaching).

Pelagic systems

The pelagic system comprise of the water column of the open ocean from the surface of the sea to the bottom. This type of coastal wetlands (ecosystems) can also be named as aquatic systems which are divided into different water layers with different depths. The pelagic life among the marine species, decreases with increasing water depth due to the reduction of light, and is affected by other factors such as temperature, oxygen amount and nutrients supply.

Figure 2.2 Different types of coastal wetlands; a) collection of coral reefs at Palmyra atoll national wildlife refuge (Jim Maragos/U.S. Fish and Wildlife Service); b) mangroves in the Salinas estuary, Puerto Rico (Boricuaeddie); c) beach dune Renesse Holland dune (Dronepicr); d) Pelagic zone at Königswinter (Akshath Rajan); e) A seagrass meadow, Florida keys national marine sanctuary (NOAA photo library-Heather Dine); f) Marshland near Blythburgh, view over the tidal river Blyth (Eileen Henderson). Source: all pictures from Wikimedia Commons.

- Ecosystem Services

According to de Groot et al. (2018), it might not be possible to agree on one classification that captures the myriad of ways in which ecosystems support human life and contribute to human well-being. In general, ecosystem services are defined as the immaterial benefits to humans with a monetary value generated (Leemans and de Groot, 2003). Thus, ecosystem services are the benefits (sometimes referred to as flows of the benefits) that people obtain from ecosystems, while ecosystem goods consist of food provision (such as fish, fiber), and raw materials (such as wood), sometimes also called stocks of natural ecosystems.

Tinch and Mathieu (2011) stated that the ecosystem services framework focuses on the flows of valuable goods and services that are provided by the stock of natural resources. Accordingly, these two terms should be differentiated since flow values are the ones that can be derived over a defined time interval, while stock values are the net Present-day Value (PV) sum of all flow

values that may be derived from an ecosystem over a future period. A variety of benefits can be explicitly classified as ecosystem services such as use and non-use values including existence and bequest values (MEA, 2005; Barbier et al., 1997; Cesar, 2000). Table 2.1 indicates the classification of the main coastal and marine ecosystem services modified from Barbier et al. (1997); and Cesar (2000). It should be noted that these services result from ecosystem processes and functions (Mace et al., 2012). For the present study this means that any impact on the biophysical structure or process of an ecosystem could result in a change in the dependent ecosystem service(s) and, ultimately, in the quality of human wellbeing.

Table 2.1 Values provided by coastal and marine ecosystem services, modified from Barbier et al. (1997); and Cesar (2000)

Use Values		Non-Use Values
Direct Values	Indirect Values	Existence and Bequest Values
Food, fiber and raw materials provision	Flood control	Cultural heritage and spiritual benefits
Transport	Storm protection, wave attenuation	Resources for future generations
Water supply	CC impacts mitigation	Biodiversity
Recreation and tourism	Contaminant storage, detoxification	
Wild resources	Shoreline stabilization/erosion control	
Genetic material	Nursery and habitat for fishes and other marine species	
Educational opportunity	Nutrient retention and cycling	
Aesthetic	Regulation of water flow, water filtration	
Art	Source of food for sea organisms	
	Climate regulation, primary productivity as Oxygen production and CO ₂ absorption, Carbon sequestration etc.	

Direct use values refer to the ecosystem services that can be directly used and associated with human well-being. Indirect use values include services that provide benefits outside the ecosystem. These latter values refer to ecosystem services with values that can be only measured indirectly, since they are only derived from supporting and protecting activities that have directly measurable values (Barbier, 2011). It should be noted that some of the cultural services (referred to as non-use values in Table 2.1) can also be included in other typologies of ecosystem services (Dluzewska, 2016). For example, recreation and tourism services offer non-consumptive values such as the enjoyment of recreational and cultural amenities (e.g., wildlife, bird watching and water sports) (Chen et al., 2009). Recreational services can also be classified as a direct use value (Hein et al., 2006), which is how they are considered in this review (see Table 2.1).

Non-use or passive use values represent the value of ecosystem services which exist even if they are not used. These include existence and bequest values which refer to the public

awareness of ecosystem services that exist and will persist for future generations to enjoy. Table 2.2 provides an overview of some of the coastal wetlands and their attributed use-value services modified from MEA (2005).

Table 2.2 Overview of some of the coastal wetlands and their attributed use-value services (modified from MEA, 2005)

Coastal Wetlands	Direct Use Value	Indirect Use Value
Mangrove forests	Raw material (wood production), aesthetic, educational opportunities, artistic value	CC impact mitigation, storm protection and wave attenuation, shoreline stabilization and erosion control, flood control, nursery and habitat for fishes and other marine species, regulation of water flow and filtration, carbon sequestration, oxygen production and CO ₂ absorption, contaminant storage and detoxification
Coral reefs	Aesthetic, recreation and tourism (snorkeling), educational opportunities, artistic value, raw material for building, jewelry and aquarium trade	Nursery and habitat for fishes and other marine species, wave attenuation and shoreline stabilization, nitrogen fixation
Seagrass beds	Aesthetic, contribution to recreation and tourism (snorkeling)	Nursery and habitat for fishes and other marine species, source of food for sea organisms, shoreline stabilization and erosion control, primary productivity as oxygen production and CO ₂ absorption, water filtration
Beach and dune systems	Recreation and tourism, fiber and raw material (wood source) provided by the dune vegetation, aesthetic value, artistic value	Flood control, erosion control, nursery for some marine species (turtles)
Pelagic systems	Food source, aesthetic value, tourism services, artistic value	Source of food for sea organisms, nursery and habitat for fishes and other marine species

2.2.2 Valuation of Ecosystem Services and Goods

In principle, economic valuation of ecosystem services is based on “people preference” and their choices. Therefore, it is quantified by the highest monetary value that a person is willing to pay in order to obtain the benefit of that particular service. The “willingness to pay” approach determines how much someone is willing to give up for a change in obtaining a certain ecosystem good or service (MEA, 2005). Thus, the key outcome of valuation studies is to illustrate the importance of a healthy ecosystem for socio-economic prosperity and to monetize the gains that one may achieve or lose due to a change in ecosystem services Sukhdev et al., 2014).

The value of ecosystem services can be measured in three different ways (Tinch and Mathieu, 2011): (1) Total economic value (TEV) that refers to the value of a particular ecosystem service

over the entire area covered by an ecosystem during a defined time period; (2) average value of an ecosystem service per unit, which is often indicated for a unit of area or time; (3) marginal value which is the additional value gained or lost by an incremental change in a provision of a particular service.

The valuation starts from estimating a TEV of an ecosystem, which is in fact a sum of Consumer Surplus (CS) and Producer Surplus (PS). This is done by applying different valuation techniques. By definition, CS is the difference between the actual market price of the product and the maximum amount that people are willing to pay, while PS refers to the benefit that the producer earns when the market price is higher than the costs of production (also called net income). For example, in the case of tourism, PS is the direct or indirect benefit from the local ecosystems for the tourism sector by considering the revenue made from tourists minus the costs of providing these services to them (van Beukering et al., 2007). In addition, CS conveys the maximum amount that tourists are willing to pay for visiting the specific recreational area.

Value of nature depends on the perspective of various stakeholders such as local residents, visitors, policy makers, etc. The key factor of valuation studies is to show how a healthy ecosystem is important for socio-economic prosperity (Sukhdev et al., 2014). The usefulness of economic valuation of the environment is essentially dependent on scientific assessment, individual awareness, and the ways in which the valuation may affect personal welfare (Bateman et al., 2011). Figure 2.3 illustrates the conceptual model of interaction between drivers of ecosystem loss, changes in environmental services and goods, economic valuation process and the outcomes used for policy and decision makers, all contributing to human well-being.

Figure 2.3 Conceptual model of interaction between the ecosystem services and human well-being (adapted from MEA, 2005)

2.2.2.1 Valuation Methods

There are different ways of classifying economic methods used for valuing ecosystem services and goods. These techniques consist of revealed preference methods, stated preference methods, market price, and benefit transfer method. Table 2.3 shows an overview of these techniques including their attributed CES and goods following Costanza et al. (1997); King and Mazzotta (2000); Barbier et al. (2011); Barbier (2013); Bateman et al. (2011); and Russi et al. (2013).

Table 2.3 Overview of the valuation methods and their attributed coastal ecosystem services and goods

Valuation Method		Description	Coastal Ecosystem Services and Goods
Revealed preference methods (use-value)	Production-based (net factor income)	Often used to value the ecosystem services that contribute to the production of commercially marketed goods	Regulating services such as oxygen production, CO ₂ absorption, nitrogen fixation and carbon storage, providing fish nurseries, water purification, coastal protection

	Hedonic pricing	Commonly used to value the environmental services contributing to amenities. Property's price often represents the amenity value of ecosystems	Tourism and recreation, aesthetic, improving air quality
	Travel cost	Basically considers the travel costs paid by tourists and visitors to the environmental value of a recreation site	Tourism and recreation, recreational fishery and water sports
	Damage avoided cost, replacement cost	Based on either the cost that people are willing to pay to avoid damages or lost services, the cost of replacing services or the cost paid for substitute services providing the same functions and benefits	Buffering CC impacts such as wave attenuation, providing coastal protection against storms and erosion, flood impact reduction, water purification, carbon storage
Stated preference methods (both use and non-use value)	Contingent valuation (CVM)	The most applied method for both use and non-use values, based on surveys asking people their WTP to obtain an ecosystem service	Tourism and recreation, recreational fishery and water sports, aesthetic value, cultural and spiritual value, art value, educational value
	Contingent choice (CCM)	WTP is stated based on choices between different hypothetical scenarios of ecosystem conditions	
Market price	Often used for the ecosystem products that are explicitly traded in the market		Fiber, wood and sea food provision, raw material
Benefit transfer	It transfers available data from previous valuation studies for a similar application		Mostly applied for gross value of coastal wetlands associated with recreation

The valuation methods of ecosystem services shown in Table 2.3 are described below in more detail:

Production-based (net factor income)

The production-based method, also known as the 'net factor income', is often used to value an ecosystem service that contributes to the production of commercially marketed goods. For instance, increasing water quality is one of the ecosystem services contributing directly to productivity of irrigated agricultural crops or purifying drinking water. Therefore, the production rate of crops represents an indication of the value of the service (providing high water quality) contributed to that particular ecosystem. Similarly, this method can be used to value ecosystem services contributing to fisheries, since fish are commercially sold in the market and any services contributing to their health, affect the production rate. In addition, the production-based method is also used to quantify the difference in the value of productive output of an ecosystem before and after they are degraded or lost due to a hazard. For example, coral mining and coral bleaching are common threats to coral reefs leading to fewer number of tourists and fish production. This method can be used to measure the decreased revenue of reef services due to such destructive events.

Hedonic Pricing Method

The perception of valuing environmental services and goods is often based on "beauty" as a very subjective criteria. Picturesque sceneries of coastal and marine ecosystems such as coral reefs, sandy beaches and coastal and marine species deserve high monetary value (Boero and Briand, 2008). Thus, the hedonic pricing method is commonly used to value the environmental services contributing to amenities. One of the most common applications of this method is when the value of a beach is quantified by considering the price of residential properties nearby. The difference between the properties price having a sea/beach view compared to those that don't, is indicative of the beach's amenity value in monetary terms.

Travel Cost Method

The travel cost method is used to quantify the value of recreational sites and touristic areas where visitors spend money to travel and visit these areas. This method basically considers the travel costs to quantify the value of the recreational site. The reason to categorise this method under the revealed preference methods is that it reflects actual behavior and choices among the visitors. This implies that visitors' preferences are revealed by their choices in terms of type of accommodation, transportation, and other expenses they pay for visiting a lake, beach, estuary, etc. Notably, the method has an advantage which is based on actual actions and not WTP. Also, this method is rather inexpensive to apply and the results are easily interpreted.

Damage Avoided Cost and Replacement Cost

These methods are based on either the cost that people are willing to pay to avoid having damage or loss of services. The replacement cost method refers to the cost of replacing services or the cost paid for substitute services providing the same functions and benefits as the target ecosystem. These methods are often used to value the flood protection services provided by dune beaches, marshes, coral reefs and other ecosystem services associated with coastal protection against flooding and storm surges. For example, valuing erosion protection service of a dune beach can be quantified by the cost of removing eroded sediment. In other words, the investment amount to control coastal erosion by constructing revetments and breakwaters is a proxy of the protection service provided by reefs or marshes in the study site. Similarly, the water purification service of marshes can be valued by the cost of filtering and other treatment plans. The advantage of these methods is that they are less resource and data intensive, and it is easier to estimate the cost of producing benefits than measuring the benefits themselves.

Contingent Valuation Method (CVM)

The most applied method for economic valuation of ecosystem services is the Contingent Valuation Method (CVM), which is suitable for estimating both use and non-use values. This method is based on conducting a survey which directly asks people how much they are willing to pay to obtain a specific ecosystem service by stating their preference. This is the reason why it is called "contingent", since the method is applied contingently on a particular hypothetical

scenario. Notably, the result of survey is considerably sensitive to what people believe and understand about the service and nature of the ecosystem change.

Contingent Choice Method (CCM)

To estimate non-use as well as use values, another stated preference method called Contingent Choice Method (CCM) can be applied similar to the CVM method. CCM was first applied to environmental management problems by Louviere and Williams in 1994. In this method, people state their preferences based on the choices they are given to make priorities between different hypothetical scenarios. It is not a revealed preference approach, because the direct monetary value of the services is not explicitly revealed. This method is remarkably appropriate for decision makers to value the environmental services of different scenarios with distinguished environmental conditions in terms of benefits or losses referred to people. The CCM method consists of three phases; design of survey, choice experiment and procedure of data collection (van de Kerkhof et al., 2014). The advantage of this method over CVM is that it allows estimation of the ecosystem services from more than one attribute, presenting a wider range of environmental scenarios with different quality through behavioural actions and choices (Hanley et al., 1998).

Market Price Method

Some ecosystem products are explicitly traded in the market for a certain amount of money. Their value can be quantified using the market price method based on the price that they are bought for. The value of these goods, such as fish and wood, can be estimated by measuring consumer and producer surplus. In fact, the market price method uses standard economic techniques for measuring the direct benefits earned from marketed goods depending on the number of people purchase these goods at different prices. This method has the advantage of including the direct reflection of individual WTP. Also, the required data is relatively easy to obtain in this method.

Benefit Transfer Method

Benefit transfer method is another technique to quantify the economic value of CES by transferring available data from previous studies for a similar application. This method is often used for most of the cases with time and budget limitation to conduct an original valuation. The benefit transfer method could be a reliable method when the similarity of two cases in population, ecosystem quality, location and environmental change is considerable. One of the advantages of this technique is that it can be quickly conducted. Typically, the gross value of recreational sites can be quantified using this method, since there is likely to be similar areas with the same conditions close to the study site. Richardson et al. (2015) described a coherent analysis of the benefit transfer method summarizing advancements, databases and analysis tools provided to simplify the application of this method.

2.2.2.2 Required Data

The data required for valuation of ecosystem services are collected in different ways. Primary data is obtained via field observations, surveys, participatory approaches and stakeholder involvement which is often in the form of presenting questionnaires and doing interviews. This way of collecting data is costly and time consuming, but the flexibility of the approach allows researchers to collect data on specific averting behaviors, attitudes, perceptions, and on the prices of averting behaviors stated by people (Champ et al., 2017). This type of data is mostly obtained when using stated preference methods. For example, for valuation of recreation service, information is obtained from beach visitors stating their WTP to obtain the benefit of recreational services of coastal wetlands.

In absence of such primary data, one may use secondary data that is obtained from existing sources, such as global and national databases or available literature. Using secondary data is becoming more common due to time and budget constraints involved in most studies/projects. A widely used method in valuation studies relying on secondary data is the benefit transfer method, which derives information and estimates of values from previous studies (Champ et al., 2017).

2.3 Analysis of available valuation studies - Selected sample

Valuation of CES can be done at different spatial scales, ranging from local and regional to global scale. In general, the spatial variability of ecological services might be of importance, affecting the net ecological benefits that they provide (Aburto-Oropeza et al., 2008; Barbier et al., 2008; Koch et al., 2009). For example, Barbier et al. (2008) showed that the magnitude of wave attenuation by coral reefs, salt marshes, seagrass beds, and sand dunes varies spatially across ecosystems. This geographical influence was also observed by de Groot et al. (2012).

2.3.1 Local and regional scale applications

In this review, 30 local and regional valuation studies have been selected to represent a sample of current valuation studies. This sample has been chosen by searching the scientific database of google scholar considering applications in which the value of CES has been estimated and reported. These selected references have been considered in such a way to be able to distinguish them based on specific characteristics such as ecosystems and services considered, valuation methods used and estimated value. Here, they have been clustered based on the type of coastal wetlands that have been valued. Tables 2.4 to 2.7 show the ecosystem services provided, valuation methods used, and estimated CES values for each case.

Table 2.4 *Selected applications of valuation of coral reef ecosystem services*

Reference	Valuation Method/s	Ecosystem Service/Good	Estimated Value
Mathieu et al., 2003	Stated preference	Tourism and recreation (marine national park in Seychelles)	US\$ 88,000 (whole area)
Wilkinson et al., 1999	Hedonic price	Aesthetic (Indian ocean)	US\$ 174 (per hectare)
Seenprachawong, 2016	Travel cost, stated preference	Recreation (Andaman sea of Thailand)	US\$ 205.41 million (per year)
Van Beukering et al., 2007	Production-based, avoided damage cost, travel cost, stated preference	Fishery, tourism, biodiversity, amenity, coastal protection (Guam)	US\$ 141 million (per year)
Schep et al., 2013	Market price, net factor income, stated preference	Recreational and commercial fishing (Caribbean Netherlands, Bonaire)	US\$ 400,000 and US\$ 700,000 (per year)
Berg et al., 1998	Avoided damage cost	Protection to coastal erosion (Sri Lanka)	US\$ 160–172,000 (per km of reef, per year)
Schep et al., 2013	Avoided damage cost	Habitat support for fisheries (Caribbean sea)	US\$ 95–140 million (projected by 2015)
Burke and Maidens, 2004	Avoided damage cost	Tourism (Caribbean sea)	US\$ 300 million (projected by 2015)
Van Zanten and van Beukering, 2012	Avoided damage cost	Coastal protection by wave dissipation (Bonaire Island, Caribbean, Netherlands)	US\$ 33,000–70,000 (within 10 years–beyond 10 years)
Burke et al., 2008	Avoided damage cost	Coastal protection (Tobago, St. Lucia, (Caribbean)	US\$ 18–33 million, US\$ 28–50 million (annual values)
Burke et al., 2004	Replacement, substitute cost	Coastal protection in Caribbean coastline	US\$ 750 million–2.2 billion (annually)

The economic value of ecosystem services provided by coral reefs

Table 2.4 shows studies in which coral reef services have been valued at local and regional spatial scales. These services vary from recreational and tourism services to fishery, erosion control and coastal protection services. Depending on the service, different valuation methods have been used. Geographically, the selected study sites are mostly located in the Caribbean region highlighting this area as one of the important and large habitats of coral reefs. According to Table 2.4, coral reef services are valued at different estimations ranging from US\$ 33,000–70,000 (van Zanten and van Beukering, 2012) to a very high value between US\$ 750 million and US\$ 2.2 billion (Burke and Maidens, 2004). This Table also shows that compared to other services, the coastal protection service provided by coral reefs is the highest value estimated for this type of ecosystems.

Table 2.5 *Selected applications of valuation of mangrove ecosystem services*

Reference	Valuation Methods	Ecosystem Service/Good	Estimated Value
Vo et al., 2015	Market price, replacement cost	Fishery, timber, carbon sequestration and storm protection (Vietnam)	US\$ 3000 (per hectare, per year)
Barbier, 2007	Avoided damage cost	Coastal protection, wood, habitat support for fishery (Thailand)	US\$ 10,158–12,392 (per hectare)
Das and Crépin, 2013	Avoided damage cost	Storm (wind) protection (Odisha region, India)	US\$ 177 (per hectare) (1999 price level)
Brander et al., 2012	Benefit transfer (from 48 selected studies)	Fisheries, fuel wood, coastal protection, water quality (Southeast Asia)	(mean) US\$ 4185 (per hectare, per year) (2007 price level)
Hussain and Badola, 2008	Replacement cost	Nutrient retention value (India)	US\$ 232 (per hectare)

The economic value of ecosystem services provided by mangroves

Table 2.5 shows selected applications of CES valuations for mangroves, indicating a range of estimations which is mostly considered per hectare of the study area. According to Table 2.5, fishery and storm protection are among the most frequently valued services reflecting the importance of these two services provided by mangroves. With respect to the estimated values, depending on the number of services considered, low values of US\$ 177/ha (Das and Crépin, 2013) and US\$ 232/ha (Hussain and Badola, 2008) were estimated in the coastal area in India, while higher values between US\$ 10,158/ha and US\$ 12,392/ha were estimated in Thailand (Barbier, 2007).

The economic value of other coastal wetlands

Table 2.6 shows 7 selected study sites in which the value of other coastal wetlands such as marshes, beaches and pelagic systems have been estimated using a variety of methods. These studies highlight the difference between types of values affecting estimated results. For example, Emerton and Kekulandala (2003) estimated the total value of flood control services provided by marshes in Sri Lanka at US\$ 5 million per year, while Bell (1997) estimated average values of US\$ 6471 and US\$ 981 respectively with respect to habitat support for fishery provided per acre of marsh on the East and West coasts of Florida in 1984 dollars. Among these selected applications, a high value of US\$ 23–44 billion was estimated by Molnar et al. (2012) for food provision service of the marine area (referred to as pelagic system in this review) in British Colombia in 2004.

Table 2.6 *Selected applications of valuations of other coastal wetlands*

Reference	Wetland	Valuation Methods	Ecosystem Service/Good	Estimated Value
Emerton and Kekulandala, 2003	Marsh	Avoided damage cost	Flood attenuation (Colombo, Sri Lanka)	US\$ 5 million (per year)
Bell, 1997	Marsh	Production-based	Habitat support for fisheries (Florida coast)	a. US\$ 6471 (East) b. US\$ 981 (West) (per acre)
Castaña-Isaza et al., 2015	Beach and dune system	Stated preference	Tourism (San Andres Island, Colombia)	US\$ 997,468 (annual consumer surplus)
Boero and Briand, 2008	Pelagic system	Avoided damage cost, market price	Food provision (fish) (UK)	£ 513 million (in 2004)
Molnar et al., 2012	Pelagic system	Benefit transfer (literature data)	Aesthetic and recreation (British Colombia)	US\$ 23-44 billion (per year)
Czajkowski et al., 2015	Pelagic system	Travel cost	Recreation (Baltic Sea)	€15 billion (total annual)
Lew and Larson, 2014	Pelagic system	Stated preference	Food provision (fish) (coast of Southeast Alaska)	US\$ 248–313 Mean value for single-day private boat fishing trips

The economic value of combined coastal wetlands

There are some valuation studies in which coastal wetlands have been valued as a holistic system. These cases, which are shown in Table 2.7, indicate that one may value a combination of services (Cooper et al., 2009) and goods, grouped as coastal nature or a combination of two ecosystems such as coral reefs and mangroves as presented by Cooper et al. (2009), and van Beukering and Wolfs (2012). Most of the selected cases in Table 2.7 were derived from studies that approximated the value of coastal nature in Caribbean Islands.

Among the used methods, the net factor income has been applied for estimating research and artistic value of coastal nature as presented by van Beukering and Wolfs (2012). Selected applications show that direct-use value of the coastal environment was mostly considered in these studies, indicating the highest value for providing erosion protection service at US\$ 231–347 million in Belize in 2007 (Cooper et al., 2009). In contrast, art value of the coastal environment was estimated at a relatively low annual value of US\$ 290,000 in Bonaire Island (van Beukering and Wolfs, 2012). Notably, all estimated values of services provided by the coastal environment are presented as an annual value.

Table 2.7 Selected applications of valuation of combined coastal wetlands

Reference	Wetland	Valuation Methods	Ecosystem Service/Good	Estimated Value
Van Beukering and Wolfs, 2012	Coastal nature	Net factor income	Research opportunity (Bonaire Island, Caribbean)	US\$ 1,240,000–1,485,000 (in 2011)
Van Beukering and Wolfs, 2012	Coastal nature	Net factor income	Pharmaceutic (Bonaire Island, Caribbean)	US\$ 688,788 (annual)
Van Beukering and Wolfs, 2012	Coastal nature	Net factor income	Art (Bonaire Island, Caribbean)	US\$ 460,000 (annual)
Schep et al., 2013	Coastal nature	Stated preference	Tourism (Bonaire Island, Caribbean)	US\$ 50 million (annual)
Gibbons et al., 2014	Coastal nature	Hedonic price	Amenity (analysis of 1 million housing transactions) from 1996 to 2008 (UK)	£ 3700 (moving the bottom 1% postcode to the best 1% postcode (per year))
Cooper et al., 2009	Coral reef and mangrove	Net factor income, avoided damage cost	a. Tourism b. Fisheries c. Erosion protection (Belize, Caribbean)	a. US\$ 150–196 mil. b. US\$ 14–16 mil. c. US\$ 231–347 mil. (in 2007)
Van Beukering and Wolfs, 2012	Coral reef and mangrove	Market price	Carbon sequestration (Bonaire Island, Caribbean)	US\$ 290,000 (annual)

2.3.2 Global scale applications

The few reported global scale ecosystem service valuation studies have used the benefit transfer method, where global assessments have been derived based on the results of different local and regional study sites. For example, Costanza et al. (2014) estimated the value of global ecosystem services at US\$ 125 trillion per year (assuming updated unit values and changes to the biomes) and US\$ 145 trillion per year (assuming only unit values changed) both in US\$ 2007.

In contrast, the global valuation of coastal wetlands reported by de Groot et al. (2012) estimated the total monetary value of a bundle of ecosystem services. Table 2.8 indicates the results of this study in standardized units (Int. \$/ha/yr - 2007 price level) for the coastal area categorized as open ocean, coral reefs, coastal systems and coastal wetlands. According to de Groot et al. (2012), the open ocean (referred to as *pelagic system* in this review) represents the largest area of the marine ecosystem including deep sea (water and sea floor below 200m). The coastal systems studies include several distinct ecosystems such as seagrass fields, shallow seas of continental shelves, rocky shores and beaches, which are found in the terrestrial near-shore as well as the intertidal zones - i.e., until the 200 m depth contour. Moreover, de Groot et al. (2012) separately studied coral reefs and coastal wetlands (mangroves and tidal marshes) because of the important and unique ecosystem services that these systems provide.

Table 2.8 Global valuation of coastal ecosystem services (total monetary value per biome)
Source: de Groot et al. (2012) (values in Int. \$/ha/year, 2007 price level)

Coastal Wetlands / Ecosystems	No. of Estimates	Total of Service Mean Value	Total of Median Value	Total of Minimum Value	Total of Maximum Value
Open ocean	14	491	135	85	1,664
Coastal systems	28	28,917	26,760	26,167	42,063
Coastal wetlands	139	193,845	12,163	300	887,828
Coral reefs	94	352,915	197,900	36,794	2,129,122

2.4 Discussion

The local and regional applications reviewed in this chapter indicate that *tourism and recreation* as well as *storm protection* services are the most commonly valued ecosystem services. This is in agreement with the conclusions made by Castaño-Isaza et al. (2015); Seenprachawong (2016); and van Zanten and van Beukering (2012). In addition, these two types of services are often valued higher than other ecosystem services. For example, Cooper et al. (2009) conducted a valuation study in which tourism and erosion protection services of coral reefs and mangroves were valued at US\$ 150–196 million and US\$ 231–347 million, respectively, while providing fishery habitat value was estimated much lower at US\$ 14–16 million. In contrast, very little appears to be known about the value of cultural services of coastal wetlands such as aesthetic and artistic values. Van Beukering and Wolfs (2012) presented one of the few examples of valuing these less considered services in Caribbean Islands with an associated call for conducting similar studies in other coastal areas.

With respect to valuation methods used in the selected applications, avoided damage, replacement, and substitute cost methods are the most frequently used techniques for valuing storm/flood protection service provided by mangroves. Stated preference and production-based methods (net factor income) are the second and third commonly used methods for the valuation of services, respectively.

The selected 30 studies also highlight one of the main limitations in valuation of CES, i.e. they all provide incomplete estimation of the total value of all ecosystem services. The reason for this incomplete estimation might be the complexity of covering and valuing all the services provided by ecosystems in a particular area. Therefore, services are often missing in the valuation studies. Data scarcity in some coastal areas together with the time consuming and high cost associated with data collection are also other important factors that discourage investigators from considering and valuing all services provided by a particular coastal wetland.

Tables 2.4 to 2.7 also illustrate that the range of estimated values quantitatively vary due to the many inconsistencies and irregularities in their characteristics. These discrepancies might be

due to the temporal scale of studies, the way that data have been collected, the number of services valued, the type of the estimated values, the location of the study sites, the probability of the hazard occurrence, and the importance of the hinterlands (relevant for the replacement, substitute and avoided damage cost method), and other factors that make the estimated results not easily comparable. For instance, the high estimated value for the food provision service provided by marine areas in the study of Molnar et al. (2012) may not be directly comparable with the results of Boero and Briand (2008) for the same coastal wetland because the location, the type of valuation method, and the services considered are different in these two studies. Also, in some of the selected applications, estimated values are presented per year (total value), while in some others (e.g., Burke and Maidens, 2004), marginal values have been projected for the future.

Apart from the above mentioned irregularities, in some methods such as stated preference, socio-demographic data such as age, level of education, mean salary etc. may affect the WTP stated by the visitors. This can affect the estimated value and consequently result in a rather different estimation for a certain CES.

The aforementioned factors, discrepancies and inconsistencies render the inter-comparison of the results of different valuation studies a difficult challenge to overcome.

2.5 Concluding remarks

This chapter provides a coherent review on the valuation of CES by systematically describing the main definitions, and concepts in valuation of CES. To achieve this objective, firstly a summary of coastal wetlands, ecosystems and their ecological services they provide, as well as valuation methods, and required data for performing valuation studies was provided.

Secondly, two global scale and 30 local and regional scale study sites of coastal wetland valuation were analysed. This analysis has resulted in the following main conclusions:

- Valuation studies reviewed in this study indicate coral reefs and mangroves as the most frequent coastal wetland considered, while seagrass beds are the least investigated one in terms of the monetary value provided by their services.
- With respect to ecosystem services provided, tourism and recreation as well as storm protection are the most common CES that have been monetized. These two services are often valued higher than other services provided by coastal wetlands. In contrast, cultural services such as aesthetic and artistic values have been hardly valued so far, indicating the necessity for further research regarding these services.
- With respect to the valuation methods, avoided damage, replacement and substitute cost methods are the most commonly used techniques for valuing storm or flood protection

services. In addition, stated preference and production-based methods (net factor income) are also frequently used for valuation of many different ecosystem services.

- The most common limitation of the reviewed studies is the incomplete measure of ecosystem value they provided. The reason for this incomplete estimation can be associated with the complexity of considering and valuing all the services provided by ecosystems as well as data scarcity in the study areas.

CHAPTER 3

Climate Change driven Losses on Coastal Ecosystem Services¹

¹ This Chapter is partially based on: Mehvar, S., Filatova, T., Dastgheib, A., De Ruyter Van Steveninck, E. D., and Ranasinghe, R. (2018a). Quantifying Economic Value of Coastal Ecosystem Services, a Review. *Journal of Marine Science and Engineering*, 6(1), 5.

3.1 Introduction

There is ample evidence indicating that a considerable proportion of coastal wetlands is intensively under degradation, with 50% of marshes, 35% of mangroves, 30% of coral reefs and 29% of the known global coverage of seagrasses either lost or degraded already (FAO, 2007). According to MEA (2005), mangroves have been lost mostly because of aquaculture development, deforestation and fresh water diversion. Similarly, coral reefs have been lost in the last decades due to overexploitation, destructive fishing practice, pollution, siltation, and climate change (CC) impacts. The drivers of change of coastal wetlands and their associated ecosystems are divided into direct and indirect drivers as follows:

3.1.1 Direct drivers

Most of the drivers of ecosystem change are direct drivers, affecting the coastal wetlands directly. These drivers include natural forcing factors such as CC, storm surges, and coastal erosion. Human induced factors such as land-based resource uses including agriculture, aquaculture, deforestation, damming and irrigation are also direct drivers of ecosystem changes. These anthropogenic factors can include infrastructure developments such as dikes, levees as well as water withdrawal, diversion of fresh water flows (mostly in estuaries), land conversion, dredging and overexploitation. The most dominant direct drivers of coastal wetlands loss constitute of coastal hazards, CC impacts, overfishing, coastal development, land conversion, transportation, tourism, and mining activities. In this chapter, a brief overview of *coastal hazards* and *CC impacts*, within the context of drivers of ecosystems change, is presented, since these two factors are the focus of this study.

- Coastal hazards

Natural hazards including storm surge, hurricanes, tsunamis, coastal erosion and river flooding belong to the most devastating natural phenomena. Apart from human fatalities and economic losses, environmental damages caused by these natural hazards represent the most destructive (direct) driver of the environmental loss. The impacts of these phenomena are intensified by other direct factors such as CC impacts and anthropogenic impacts. Coastal hazards resulting in environmental damage are essentially coastal erosion (chronic and episodic) and coastal inundation (permanent and episodic), coastal floods (Spalding et al., 2014), which are driven by SLR, storm wave conditions, storm surges, mean wave conditions, storm frequency etc. As CC is expected to affect some or all of these drivers, these coastal hazards are likely to be exacerbated due to CC (Ranasinghe, 2016).

- Climate change impacts

CC impacts could impose substantial change on coastal wetlands, including oceans, intertidal estuaries, salt marshes and coral reefs. For example, temperature rise and eutrophication, two of the likely CC impacts, will result in increasing nutrient fluxes.

According to IPCC (2013), the gradual increase of average global temperature over the 20th century has already resulted in a number of impacts to the hydrological cycle, including changes in precipitation.

Ocean acidification is also one of the impacts of CC which has been threatening coastal and marine ecosystems globally. Increasing carbon dioxide emissions are gradually leading the World's oceans to become more acidic, resulting in lower coral growth rates (Mollica et al., 2018). CC may also play a role in degradation of ecosystems by increasing algal cover, leading to a reduction in species diversity and fish abundance. Ocean warming is another CC impact that is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010 (IPCC, 2013). Coral bleaching that was observed in the Great Barrier Reef, off the coast of Queensland in North-Eastern Australia (Marshall and Baird, 2000), is a good indication that coral reefs are among the most sensitive ecosystems to CC.

With regards to potential SLR impacts, salt water marshes, coral reefs and river deltas are among the most vulnerable habitats, which are particularly at risk of SLR. According to IPCC (2013), over the period 1901-2010, global Mean Sea Level (MSL) rose by 0.19 m. Global mean SLR projections in 2081-2100 relative to 1986-2005 will likely be in the ranges of 0.26-0.55 m for the climate scenario of RCP2.6 (Representative Concentration Pathways), 0.32-0.63 m for RCP4.5, 0.33-0.63 m for RCP6.0, and 0.45-0.82 m for RCP8.5 (medium confidence). For RCP8.5, the rise by the year 2100 is projected from 0.52 to 0.98 m, with a rate of 8-16 mm per year (medium confidence) during 2081 to 2100. These ranges are derived from CMIP5 climate projections in combination with process-based models and literature assessment of glacier and ice sheet contributions (IPCC, 2013). The impacts of SLR can be directly seen on the coastal habitats in the form of coastal erosion, coastal inundation, aquifer and agricultural soils contamination, loss of fish and birds habitats, etc.

3.1.2 Indirect drivers

The popularity of coastal areas has led to a continuous migration of people to live close to beaches. As a result of urban and suburban expansion caused by population growth, many coastal wetlands have been converted into settlements in the last few decades. This migration has indirectly increased the economic and environmental losses in coastal areas. In addition to population growth, economic development in the coastal zone has become an indirect driver of ecosystem degradation as well.

3.2 Coastal wetlands vs climate change impacts

The consequences of coastal hazards as direct drivers of change, not only affect the inhabitants of the coastal areas, but also pose a considerable threat to the coastal environment. CC is likely to have a significant impact on the threat levels faced by Coastal Ecosystem Services (CES) in future. The World's coastlines are shaped by MSL, wave conditions, storm surge, and river flows, while CC driven variations in these forcing factors will affect the coastal areas (Ranasinghe, 2016). As a result, CC will significantly affect the direct or indirect benefits that

humans obtain from these ecosystems (Grimm et al., 2016). Thus, CC will substantially alter or eliminate certain ecosystem services in the future. To better understand the impacts of CC on CES and to develop effective adaptation measures where possible, it is essential to improve our knowledge on the links between CC and ecosystem services and the corresponding economic impacts (Shaw et al., 2011).

Academic literature discusses two types of links between CC and CES; climate regulation service provided by CES and CC impacts on CES (see Figure 3.1).

Figure 3.1 Links between CC, coastal ecosystem services (CES) and their valuation. SCC: Social Costs of Carbon

3.2.1 CC link with climate regulation service

Coastal wetlands provide many services as indicated in Table 2.1; one of them being climate regulation through their ability to absorb CO₂ (right hand side of Figure 3.1). Blue carbon (CO₂) sequestered by mangroves, seagrass beds, tidal marshes and vegetation present in other coastal wetlands (Vierros, 2017) attracts considerable attention in CC mitigation discussions. For example, Jerath et al. (2016) performed a valuation study of regulatory climate service of mangrove forests of the Everglades National Park in Florida, USA.

In valuation studies, the benefits of this regulatory service are usually compared with the average abatement costs of carbon that the mangroves provide. The valuation exercise of the regulatory climate service in this case is rather simple. Since CC mostly has adverse effects globally, the common practice is to apply the value transfer method based on the social costs of carbon (SCC) to derive a single value per ton of carbon absorbed. SCC indicates the marginal damage costs of 1 ton of CO₂ emitted, based on the global estimates of damages caused by CC (Pachauri et al., 2014).

Global CC induced damage in general, comprises the monetary assessments of climate-induced damage to various economic sectors, health and human lives as well as ecosystems across the entire planet using global Integrated Assessment Models (Greenstone et al., 2013). However, the monetary damage to various ecosystems including coastal are very rudimental (Hallegatte and Mach, 2016; Burke et al., 2016). In the Florida study, Jerath et al. (2016) used the IPCC value of SCC equal to \$36/tCO₂ in US\$ 2007 price level, which translated into US\$ 2015 per ton of carbon amounts to \$167/tC. Furthermore, the total carbon absorption of coastal mangroves was potentially estimated and multiplied on this monetization rate. While this connection between CES and CC is an important research direction, it is the other link between CC and CES that is most relevant to this research study.

3.2.2 CC driven changes on CES

CC will result in changes in temperature and hydrology, which will alter ecosystems. As coastal wetlands evolve under CC, the benefits that they provide in the form of ecosystem services are likely to decline (Grimm et al., 2016) and therefore, impact the socio-economic wellbeing of people. Any attempt to monetize CC driven variations in CES (left hand side of Figure 3.1) should necessarily follow a number of steps, as summarized below.

First, the results of global climate models have to be downscaled to a study site area to identify likely changes in climate variables and resulting physical changes in the coastal environment under different CC scenarios. Potentially, different CC mitigation (Lane et al., 2015; Turner et al., 2016) or adaptation (Kuhfuss et al., 2016) scenarios can be considered. When exploring CC impacts on the East coast of England, Turner et al. (2016) used 17 climate model projections till 2080 and a range of local weather data to estimate the key climate variables for coastal wetlands. They included increases in average monthly and average monthly maximum temperatures, changes in monthly precipitation patterns, SLR and changes in extreme events. CC-driven changes in temperature significantly influence coastal and marine areas as they alter ocean conditions such as water temperature and biogeochemistry (Daw et al., 2009; Cochrane et al., 2009; Sumaila et al., 2011). As a result, oceans become warmer and more stratified. In addition, higher levels of CO₂ lead to higher acidity of oceans (Mohanty et al., 2010). Both will influence ocean flora and fauna. Increase in precipitation may cause growing nutrient fluxes due to heavy runoff from land leading to eutrophication risks in coastal waters (Sumaila et al., 2011).

Potential CC physical impacts on coasts - SLR and extreme wave/surge events - in particular, lead to episodic coastal inundation and permanent submersion of low lying land, episodic storm erosion of beaches and dunes, episodic formation and closure of small tidal inlets, and/or chronic coastal recession (Ranasinghe, 2016). Coastal recession will result in less opportunity for beach recreational use. In general, less attractive beaches for recreation might result from any of the CC driven impacts on sandy coasts listed in Ranasinghe (2016).

Secondly, these CC driven physical impacts need to be linked to specific ecosystem services that are currently provided by coastal wetlands in a particular location. This should ideally start with a qualitative assessment of changes in the provision of CES. In particular, it is necessary to assess whether changes in temperature, precipitation and other climatic variables will affect different use and non-use values of services provided by coastal wetlands. Each of these two groups of CES should be specified and translated into measurable physical units. For instance, CC driven changes in temperature may be linked to changes in regulation services (categorized as indirect use value in this study) measured through eutrophication, changes to food provision services measured in fishing stock, and changes to cultural and recreational ecosystem services measured through impacts on tourism and visitor numbers (Turner et al., 2016). Similarly, SLR can be linked to regulation services measured through a need for flood protection to avoid land inundation (Kuhfuss et al., 2016) or to food provision services measured through increasing salinity of coastal soils (Turner et al., 2016).

Sumaila et al. (2011) discussed the potential CC driven changes on food (fish) provision aspect of CES through change in fish productivity (MAB, 2009) caused by changes in physiology (Portner and Knust, 2007). These CC driven changes on fish production affect economics of fisheries through a change in fishing costs due to adaptation to CC, a change in the relation between fish supply and ex-vessel revenue ultimately leading to changes in the price of fish and gross revenue. CC may also alter fish abundance by shifting their habitat and spatial distribution through changes in salinity, food web, water temperature, vertical mixing rate (stratification effect), wind driven circulation, etc. (Cochrane et al., 2009).

It should also be noted that the impacts of CC might alter CES differently depending on the ecosystem type and provided services. For example, changes in sea temperature may not always negatively affect the health condition of mangroves (McLeod and Salm, 2006), since mangrove swamps can expand due to increases in temperature. Thus, it is important to note that ecosystems are not always damaged due to CC impacts, and in fact these ecosystems can extend under a warmer climate. Changes in precipitation patterns caused by CC may also positively affect the growth of mangroves and their areal extent (Field, 1995; Snedaker, 1995). However, decreases in the value of some CES may have a positive impact on other ecosystem services such as educational and research value, where damage due to CC impacts on coastal wetlands and their ecosystems might attract scientists and researchers to allocate higher academic budgets for undertaking research into these destructive impacts.

It should be noted that in quantification of CC-driven ecosystem changes, adaptation of some ecosystems to the physical changes can positively affect the services they provide. Moreover, it is very important to consider whether there is room for coastal wetlands to migrate inland (mostly applicable for mangroves). For example, if SLR-induced inundation causes inland salt intrusion, and if a landward migration is possible, then a favored habitat could be created for mangroves farther inland, resulting in inland expansion of such ecosystems. Therefore, these

CC-driven changes can result in providing more mangrove services, and adding value rather than losing value.

Thirdly, the qualitative trends in CES provision need to be specified in quantitative terms. This often involves domain-specific modelling and data, for example, on fisheries or on land submersion. While research on the previous two steps is rather extensive, only a few studies have performed detailed quantitative analysis of physical impacts of CC on CES. One exception is the work of Cheung et al. (2011) who estimated that ocean acidification in the North Atlantic will result in the reduction of fish growth, leading to a 20–30% decrease in harvests.

Finally, the CC driven variations in CES have to be monetized. Until recently, monetary valuation of potential losses of ecosystem services under different CC scenarios (left hand side of Figure 3.1) have been scarce, leading to rudimental assessments of CC damages to ecosystems (Burke et al., 2016), which are part of global SCC (right hand side of Figure 3.1). Currently there is a fast growing body of literature with individual case study as well as attempts for large-scale valuations. As the first estimate of the potential cost of adapting the World's fishing sector to CC, Sumaila and Cheung (2010) estimated that globally, the fishing sector may suffer from a \$17 to \$41 billion annual loss in landed value (gross revenue). Kragt et al. (2009) presented another example in the Great Barrier Reef Marine Park in Australia, where reef trips by divers and snorkelers could decrease by 80% given a hypothetical decrease in coral and fish biodiversity, corresponding to a loss of AU\$ 103 million per year in tourism revenues.

Kuhfuss et al. (2016) presented an example of a thorough valuation of CC driven changes in CES in coastal wetlands in France. Given a 1 m SLR scenario by 2100, regional coastal wetlands are expected to gain additional territory due to the retreat of agricultural and urban areas, and thus result in an overall increase in the total value of wetland ecosystem services, ranging between 2.593 million and 8.094 million of 2010 euros. Large-scale valuations have also indicated that annual damage to CES in Europe due to CC driven SLR could be about €2.9 billion by 2050 (Roebeling et al., 2013).

CHAPTER 4

Developing a Framework for Quantifying potential Climate Change driven Environmental Losses (QuantiCEL), and its demonstration at Semarang Coastal Area, Indonesia¹

¹ This Chapter is partially based on: Mehvar, S., Filatova, T., Syukri, I., Dastgheib, A., and Ranasinghe, R. (2018b). Developing a framework to quantify potential Sea level rise-driven environmental losses, a case study in Semarang coastal area, Indonesia. *Environmental Science and Policy*, 89, 216-230.

4.1 Introduction

Semarang with a population of about 1.57 million people and an area of 374 km² (BPS, 2014) is the capital of Central Java Province in Indonesia. The coastal area of Semarang, which is already suffering from coastal inundation and climate change (CC) impacts (KPP Nasional, 2014), constitutes of 4,575 Ha (DKP, 2008) which provides diverse Coastal Ecosystem Services (CES) and large nursery habitat for coastal flora and fauna. While existing structural measures are not sufficiently developed to effectively protect affected areas (Marfai and King, 2008), CC impacts have been intensifying inundation in Semarang through rising sea level, changes in rainfall and increase of extreme weather events (KPP Nasional, 2014).

This chapter presents the development of a framework to Quantify potential CC driven Environmental Losses (QuantiCEL), representing a new methodology compared to previous studies by presenting a link between potential impacts of RSLR-induced inundation and CES associated attributes. The QuantiCEL framework links the potential impacts of inundation on CES with economic concepts (consumer and producer surpluses), providing a straightforward method that can be applied in situations where ecological and economic model simulations may not be possible due to data scarcity or other limitations. The application of this framework is then demonstrated in the coastal areas of Semarang, Indonesia. To this end, the following specific questions are addressed in this chapter: (1) what is the present monetary value of CES in Semarang?; (2) to what extent can CC impacts, represented here only by RSLR [summation of mean SLR and land subsidence rate]-induced inundation, affect the services provided by coastal wetlands of Semarang in the year 2100?; and (3) how can the identified impacts be monetized?

The QuantiCEL framework used in this study, comprise three consecutive steps. Firstly, using economic valuation methods, the present monetary value of CES, currently provided by mangrove swamps, beach, dune and pelagic systems, is estimated. Secondly, by considering a “what if scenario” approach, the potential impacts of RSLR-induced inundation on the (pre-valued) ecosystem services for various year 2100 inundation scenarios are identified. Thirdly, these changes in CES - which could be losses or gains - are monetized using the pre-estimated values in step 1.

4.2 Methods

4.2.1 Study area

Marina and Maron beaches, comprising about 33 Ha in total, and Plumbon estuary with an approximate area of 23 Ha, located in the lowland of Tugu and Semarang Barat districts, were selected as the study sites for this part of the study (Figure 4.1). The coast of Semarang mainly comprises volcanic terrain (Datema, 1989), and the soil types are generally alluvial due to fluvial sedimentation (Rahmawati et al., 2013).

There are different types of CES in the study area. Mangrove swamps mostly cover the Tugu district where the Plumbon estuary is located, while beach and dune systems are the dominant ecosystems in Maron and Marina areas. In addition, Java Sea represents another ecosystem constituting a pelagic system.

Figure 4.1 Location of Semarang showing the study sites highlighted by red circles

4.2.2 Methodology

To estimate the value of potential changes to CES, here, the QuantiCEL framework is developed consisting of three methodological steps (Figure 4.2). Using this framework, firstly, assessing the value of ecological services provided by coastal wetlands is focused (hazard impact to urban developments and infrastructure is excluded). For doing this, the available economic valuation methods are applied to estimate the present-day monetary value of CES. Secondly, the potential impacts of RSLR-induced inundation on CES in 2100 are identified. Therefore, a particular scenario-based approach is used which is grounded in expert knowledge and in secondary data from literature review. Finally, the resulting losses and/or gains to CES are quantified for the year 2100 inundation scenarios by combining the pre-estimated monetary values with anticipated changes in quantity and quality of CES.

Figure 4.2 The QuantiCEL framework comprising three methodological steps

4.2.2.1 Step 1: Valuation of CES (current status)

In the first step of this study, three standard economic methods are applied (i.e. contingent valuation, net factor income and hedonic price), to estimate the Present-day Value (PV) of CES in Semarang. Semarang coastal wetlands offer a variety of direct and indirect services such as provision of fibre and raw materials, educational opportunities, storm protection and wave attenuation, shoreline stabilization and erosion control as well as climate regulation services. In this study, four services that provide direct use values are considered; recreation or tourism and fishery - the dominant sources of income in Semarang, together with art and amenity value - the less investigated services in current valuation studies, which are nevertheless beneficial to human well-being. Valuation of other CES is beyond the scope of this study due to the limited time and/or resources for data collection (e.g. wood production provided by mangroves) and/or because of extensive modelling and experimental requirements (e.g. wave attenuation service). However, excluding these services in this study does not necessarily mean that they do not provide any significant CES in the Semarang area.

Monetary values of the four considered CES are estimated by using different valuation methods: net factor income and contingent valuation (for the recreation, and fishery values), net factor income (for the art value), and hedonic price method (for the amenity value). Table 4.1 summarizes the coastal wetlands and ecosystem services considered and the methods used for valuing these services in this study.

Table 4.1 Coastal wetlands and services considered and the methods used for economic valuation in this study

Coastal wetlands	Ecosystem service (direct use value)	Economic valuation method
Mangrove swamps, Beach and dune systems, Pelagic Systems	Tourism, Fishery	Contingent valuation, Net factor income
	Art	Net factor income
	Amenity	Hedonic price

Using the net factor income method, the revenue earned through recreational activities of tourists in Semarang, which directly or indirectly depend on the status of coastal wetlands, is taken to represent the total tourism value of coastal wetlands. Similarly, the net revenue earned from selling fish and other marine species in the market is taken to represent the total value of the fisheries service. Using this method, art value of coastal wetlands is also estimated by considering the annual earnings from selling art works that either directly or indirectly captured the scenery associated with coastal wetlands of Semarang coastal area.

In addition, the contingent valuation technique, being the most commonly applied method for both use and non-use CES values, is used to quantify the value of tourism and fishery services by eliciting visitors and local community's WTP, respectively for benefiting from tourism-related attributes and for each kilo of fish or other marine species traded in the market.

The hedonic price technique is also used here, to capture the hedonic value of coastal nature in Semarang which is reflected by property prices. Conducting surveys among several local real estate agents, here information on property prices in Semarang is obtained and analyzed as a function of distance to the sea to estimate the amenity value of coastal wetlands. Valuation of these CES and the estimates for each service are presented below in detail.

4.2.2.2 Step 2: Identifying potential impacts of RSLR-induced inundation on CES

In the second step of this study, the hazard, its causes and affected area along the coast of Semarang are identified. After identifying the hazard, the associated impacts of identified hazard that can potentially affect the target CES are analysed. Semarang has long been suffering from coastal inundation and CC impacts (KPP Nasional, 2014), mainly due to land subsidence and high tidal levels. Land subsidence in Semarang is primarily due to groundwater extraction (Marfai et al., 2008; Rahmawati, 2010; Kuehn et al., 2010; Soedarsono, 2011).

- Hazard identification

Since the hazard history in Semarang shows the frequent occurrence of coastal inundation and the high importance of SLR impacts on the coastal area of Semarang, here, inundation due to

SLR was considered as the primary CC induced hazard in this application of the QuantiCEL framework. However, other CC-induced hazards such as coastal erosion also can result changes to the CES of Semarang, the evaluation of which is beyond the scope of this study.

SLR can substantially change the extent and nature of coastal wetlands and the important ecosystem services they provide (Kassakian et al., 2017). In the study area, SLR and land subsidence can potentially alter the CES provided by the Maron and Marina beaches, Java Sea and mangrove swamps in Plumbon estuary. For example, SLR driven beach loss and degradation of the mangrove swamps would result in changing CES such as recreation, fishery and amenity.

Here, secondary data from literature were used to determine the rate of land subsidence and SLR. These two quantities were then summed to obtain an estimate of RSLR. Different rates of land subsidence have been reported for the study area. Abidin et al. (2013) found that given temporal and spatial variations, this rate varies between 6-7 cm/year with a maximum of 14-19 cm/year at some locations in the Eastern part of Semarang. This high rate of land subsidence in the Eastern part has been also reported by Murdohardono et al. (2009), and Kuehn et al. (2009). In this study, the land subsidence data reported by Abidin et al. (2013) was used for the Western part of Semarang with an average level of 4 cm/year based on the subsidence rates derived from GPS measurements in the period 2010-2011. For SLR in Semarang, the 7.8 mm/year projection given by ISET (2010) was considered. Thus, a RSLR of 4 m by 2100 (relative to present) was adopted for Semarang area in this study.

- Developing Scenarios and determining the resulting inundation areas

In order to determine the area that will be inundated by the projected RSLR, two scenarios in relation to the identified hazard were developed. In scenario A, the area that will be inundated by the projected 4 m of RSLR was determined using a bath tub approach in which a 30 m resolution Digital Elevation Map (DEM) (<https://earthexplorer.usgs.gov>) was used (Figure 4.3-a). Thus, Scenario A presents a situation where all of the mangrove swamps, beach and dune systems including their flora and fauna are fully inundated. Scenario B represents a situation where the above inundation area is halved due to a RSLR of 1.10 m by 2100 (Figure 4.3-b). Scenario B could arise due to many reasons such as SLR projection, a decreasing rate of land subsidence over time, or any adaptation measures that may increase the resilience of area, making it less exposed to inundation.

Figure 4.3 Inundation areas (in dark blue) due to 4 m RSLR by 2100 (relative to present) for the scenario A (a), and due to 1.10 m RSLR by 2100 for the scenario B (b), showing that the three selected study sites will be completely (a) and 50% (b) inundated in 2100

- Potential impacts of RSLR induced inundation on CES

To identify the potential impacts of inundation on CES, the ecosystem-related attributes are defined and the potential impacts of RSLR-induced inundation are analyzed on each of these attributes. For this purpose, depending on the scenario and attributes, the impacts are quantified by assigning a percentage range of change for each attribute, resulting in changes in CES value for scenarios A and B. These quantitative ranges are indicated by positive or negative impact indications (+ or – sign) representing a 20% increase or decrease for each positive or negative sign, respectively. This implies four ranges of 20% - 40%, 41% - 60%, 61% - 80% and 81% -

100% corresponding to the assigned impact indications from one (+/-) to four signs (++++/- - - -), respectively.

Assignment of these impact indications is based on consultation with local experts and a ‘‘what if scenario’’ approach depending on the individual CES, its attributes and the 2100 inundation scenario considered. This implies that for two of the services (fishery and art), the local fishermen and experts who deal with art works are interviewed to elicit their points of view regarding the likely future changes of these two services. For the two other services (tourism and amenity) a ‘‘what if scenario’’ approach is used, in which it is assumed that the full inundated area will result in potential losses of tourism and amenity value in the ranges of 81-100% and 41-60% for scenario A, and 41-60% and 20-40% for scenario B with 50% inundated area. Due to unavailability of literature nor similar application in Indonesia, in this study, the temporal rate of degradation, and landward migration (providing lateral accommodation space) for the considered ecosystems are not considered.

It should be noted that in this study, similar to other applications (i.e. Payo et al., 2016), it was assumed that the MSL (as zero elevation reference) is the lowest elevation upto which coastal wetlands such as mangrove swamps of Plumbon estuary can develop and provide services. Therefore, no future expansion and recovery is considered for the submerged ecosystems below MSL. This assumption is necessary as it is at present impossible to predict the resilience of the coastal wetlands in Semarang to RSLR and their resulting potential future ecological behavior due to data/knowledge scarcity. Potential impacts of RSLR-induced inundation on CES in Semarang are described below in detail for each ecosystem service considered.

Impacts on recreation/tourism service

Changes in the value of recreation or tourism service are estimated by assessing the potential impacts of RSLR-induced inundation on consumer and producer surplus values¹. The impacts on CS of visitors are determined through the direct answers that interviewees provided for the damage-related questions in the custom-designed questionnaire developed for this study. Here, respondents to the interviews are asked to state their WTP to avoid losing 100% and 50% of the recreational attributes related to coastal wetlands of Semarang. Selection of these attributes is based on the visitors’ preferences derived from the interviews, showing that tranquility, shore water quality and diversity of birds and coastal species are the most important recreational factors that draw tourists to the Semarang coast. Thus, the questionnaire elicits variations in WTP due to potential future changes in such attributes, resulting in different values of CS for the two considered inundation scenarios.

To identify impacts on the PS of the local providers of recreational services for tourists (accommodation, boats, food), visitors are asked to indicate an approximate contribution level

¹ Total tourism value is calculated by summing the CS referring to the WTP to obtain a recreational benefit stated by the visitors and the PS representing the net revenue generated by the visitors.

of their expenditures for the pre-stated recreational attributes which draw them to the study area. Then by using scenarios of likely inundation impacts, loss percentages of 81-100% and 41-60% are respectively assigned to the three considered attributes, when the entire area (scenario A) and 50% of it (scenario B) is considered to be inundated. The hypothetical assignation of the impact indication here, is due to the unavailability of data or a sound approach/application for quantifying inundation driven losses of such attributes. Therefore, the assessment as done here, could be considered as being scenario based.

Impacts on fishery service

To quantify how fishery could be affected by inundation, secondary data from the literature are used. This literature provides the basis for identifying different fishery-related variables, which can be potentially affected by CC impacts and RSLR-induced inundation. These variables comprise changes in marine fishery-related variables (i.e. primary and secondary fish production, distribution or migration pattern, food web, fish abundance, size of nursery area, health conditions of species) and land-based fishery (i.e. changes in fish pond structures and fishery facilities).

Selection and analysis of these variables are based on fishermen's opinions and using the available literature in which CC impacts (i.e. ocean acidification, increase in water temperature, extreme flood events, etc.) have been analyzed on fishery industry. For example, Portner and Knust (2007), Sumaila et al. (2011) and Mohanty et al. (2010) showed that CC may potentially affect distribution pattern, species abundance and pose damages to fish habitats. These studies conducted an economic assessment of CC impacts on fishery, suggesting that (for example) damages to fish habitat due to flooding are likely to decrease catch potential, resulting in an increase of both fish market price, and fishing/adaptation costs. In addition, Williams and Rota (2011) and MAB (2009) reported that flooding of low lying areas due to SLR may create ideal conditions for fish farmers due to expansion of salt water areas (if the negative impacts such as flooding related damages to aquaculture ponds were to be excluded).

CC impacts on fish communities can also be grouped into changes in phenology (Cochrane et al., 2009), which is excluded from this analysis due to the consideration of inundation impacts on coastal wetlands over a long time span, thus no cyclic phenomena (seasonal change) are considered in this analysis. Reviewing the study conducted by Cochrane et al. (2009), potential RSLR-induced inundation impacts are assessed on other fish/fishery related variables such as fish productivity, abundance and food web, for which changes in vertical mixing and nutrient supply may be relevant.

Notably, the literature used here mostly present analysis of CC impacts on fishery and do not specifically assess the likely impacts of SLR-induced inundation on fishery. For this reason, this secondary data was used and adapted to the Semarang study site by developing the analysis on inundation-related fishery variables. This consideration led to add other inundation-related

variables such as ‘‘health status’’ and the physical structure of ‘‘fish ponds’’. However, changes in some variables due to inundation (such as distribution pattern of species) was found to be difficult to analyze, because of interaction among different factors such as temperature, salinity and wind driven circulation.

Ultimately, the potential impacts were determined by combining the knowledge gleaned from the aforementioned literature with fishermen’s opinions elicited from the interviews with a group of 20 local fishermen. For example, interviews with fishermen highlighted damages to fish ponds as a serious effect of inundation on fishery compared to other variables such as reduction of health condition of species due to higher probability of having diseases caused by inundation. Thus, assignation of the potential impacts and the role of these variables in consumer and producer surplus values are qualitatively assessed employing both secondary data and experts opinions aforementioned. Subsequently, the quantitative impacts of future inundation on these attributes and the value of fishery service (also refers to as food provision service in this dissertation) are assessed, which will ultimately change the fishery value provided by the Java Sea in Semarang.

Impacts on amenity service

Amenity value of coastal wetlands in developing countries has been poorly studied and thus little is known about this service. Using the aforementioned impact indications, the impact of inundation on the visual amenity of the beaches and ocean view is determined by assigning a range of negative impacts on the current amenity value. This impact identification is dependent on the average property prices as well as the considered inundation scenarios. This assignation is scenario based, since amenity value is subjective and there is no accepted principle for a definitive quantitative assessment of this impact.

Impacts on art service

To quantify changes in the art value of CES due to inundation, first the art-related attributes affecting the art value of coastal wetlands are determined. These attributes include marine and coastal landscape, and coastal flora and fauna. Further, a range of scenarios of negative impacts¹ of inundation is presented (with the ranges defined before) to experts who deal with art work (paintings, photos, books, etc.). Through this scenario-based approach - e.g. considering whether the whole area (scenario A) or 50% of it (scenario B) is inundated – the expert opinion on likely quantitative changes in art-related attributes of CES is elicited, and further the impact indications for each attribute are assigned.

¹ This hypothetical assumption (i.e. the current landscape is aesthetically more attractive than the future inundated landscape) had to be inevitably used here due to two reasons; (1) the data for such potential losses are currently unavailable; (2) landscape evolution of coastal environment due to RSLR-induced inundation can occur in a multitude of ways, and several stages may be recognizable in formation of a new environmental landscape, as reported by Razjigaeva et al. (2018).

4.2.2.3 Step 3: Quantifying monetary value of the identified changes to CES

After the potential impacts are identified, the corresponding loss or gain in ecosystem services value is estimated by incorporating the pre-estimated monetary value of ecosystem services and the identified impacts.

4.3 Results

The results of this study are presented below as distinct parts: (1) monetary value of CES in their present state; and (2) changes in these values due to losses or gains in CES resulting from RSLR-induced inundation by the year 2100.

4.3.1 Present-day value of CES in Semarang

To quantify the monetary value of selected CES, primary and secondary data is used. The secondary data, including ecological and hazard-related data, were collected via a literature review (Durand and Petit, 1995; Marfai, 2011; Rahmawati et al., 2013). The primary data were obtained to estimate the Present-day Value (PV) of CES of the Semarang study area through field observations, participatory discussions, surveys and interviews with a range of stakeholders. This field data were collected in July-August 2015 by interviewing tourists, artists, fishermen, and people who work in the real estate sector. Figures 4.4a and 4.4b show selected pictures taken from the surveyed study sites during the interviews and data collection phase.

Figure 4.4a Selected photos taken during the data collection process, showing the study sites

Figure 4.4b Selected photos taken during the interviews with different stakeholders

Depending on the type of ecosystem services and target stakeholders, different questionnaires (eliciting environmental and socio-economic data) were designed. All interactions with local population were performed through a native language interviewer. Subsequently different valuation methods that are most suitable to assess the value of a particular CES were used (Table 4.1). In what follows, details of each data collection phase for each CES are provided.

Recreation/tourism value

Contingent valuation and net factor income methods were used to estimate the value of recreation and tourism services provided by coastal wetlands. Tourism value is estimated as a sum of consumer and producer surpluses based on the similar approach used by Van de Kerkhof et al. (2014b). Consumer surplus is estimated using the CVM. Following a scoping exercise, a questionnaire was designed to elicit the recreation value of beaches and dunes. In total 210 visitors on selected beaches and estuary were interviewed. Through this survey, recreational attributes such as beach tranquillity (in terms of storminess), shore water quality and diversity of birds and coastal species were determined. The questions aimed to elicit visitors' WTP assuming they fully benefit from the present conditions of these attributes with no environmental loss considered. The total WTP (consumer surplus) is finally estimated by averaging the WTP stated by the respondents multiplied by the number of total visitors in 2014.

PS is estimated by using net factor income method. It considers the net income earned by the recreational activities dependent on coastal wetlands. The resulting income include total direct and indirect average expenditures spent by the visitors in the selected sites. Direct expenditures are the values that are spent in recreational areas where coastal wetlands provide direct benefits to visitors. These values are directly dependent on the quality and health conditions of coastal and marine ecosystems. On the contrary, indirect expenditures are the visitors' expenses for food, transportation, accommodation, entrance tickets, equipment rental etc., which are indirectly dependent on the status of the coastal wetlands. Because of the data scarcity on the cost structure of the tourism industry in Semarang, it was assumed that 25% of the average expenditure reflects the added value to the tourism industry (adapted from Schep et al., 2013). Also, the dependency level of the recreational activities on coastal wetlands was assumed to be 25% and 60% for direct and indirect values, respectively (adapted from Van de Kerkhof et al., 2014b).

To estimate the net revenue generated by the visitors, direct and indirect average expenditures (per day) were summed and multiplied with the added value and the factor of ecosystem dependency. The total net revenue (PS here) was finally estimated by multiplying the resulted value with the number of total visitors recorded in 2014 (252,840 and 13200 visitors for the selected beaches and estuary, respectively) and the average duration of stay of 1.4 days per visit per person (only considered for the beach area)¹. It should be noted that CS captures the value that people receive from enjoying the natural benefits that the coast provides, while the

¹ Tourist data is based on the tourist statistics 2014: "Badan Pusat Statistik (BPS) Kota Semarang".

PS indicates the net recreational revenue generated by visitors. Thus, in using CVM, the questionnaire was designed carefully to avoid double counting of the same recreational aspects.

Fishery value

Fishing is an important source of income and livelihood in Semarang coastal and marine area creating the welfare basis for local coastal communities. Similar to the recreation service, the total value of commercial¹ fishery is estimated by adding up the consumer and producer surpluses as done by Schep et al. (2012). Using the net factor income, the PS was estimated to represent the net revenue generated by the ecosystem-related fishery. The revenue is the difference between gross revenue generated in the market and the production and maintenance fishing costs. These secondary data were collected from BPS (2014). The calculated value was then multiplied by the ecosystem dependency factor which was approximated based on a group discussion with local fishermen which indicated that fishery is approximately 40% dependent on the coastal wetlands in Semarang. Using the CVM, CS was obtained by asking the local community (20 respondents in this survey) the maximum amount they are willing to pay for each kilogram of fish. This WTP was then subtracted from what they actually pay in the market. Then by multiplying the obtained value with the total production in 2014, the annual CS was estimated.

Art value

Ecosystems provide art value through picturesque landscapes and artistic views captured in art works. The net factor income method was used to estimate the art value of coastal wetlands in Semarang. To this end, an art-related survey was conducted with a specifically-designed questionnaire among 8 book stores, 4 painting and 8 photo shops. This survey was conducted to assess how coastal nature in Semarang is represented in the art works and in the annual earnings from selling art works that either directly or indirectly captured the scenery associated with coastal wetlands in Semarang. The final annual value was estimated by summing the total revenue earned from all the art works sold in these shops in 2014. Since art-related shops were few in Semarang, it was assumed that the 20 surveyed stores provided a reasonable representation of the art value of coastal wetlands in Semarang. This approach was adapted from Van Beukering and Wolfs (2012) who presented a similar valuation study in Caribbean Islands.

Amenity value

The amenity value of Semarang coastal wetlands for local residents was estimated by using the hedonic price method that traditionally aims to capture the hedonic value of coastal nature by considering property prices. The proximity of properties to the Java Sea is likely to capture the influence of ocean views on local properties prices, which indirectly represents the amenity

¹ Recreational fishery is excluded in this study because of little importance for local population leading to data limitations.

value of coastal wetlands. Following Fraser and Spencer (1998), the hedonic value of coastal amenity, primarily the ocean view was estimated by using a scoring system and a proportional change in the sale price of residential property. To this end, a survey was conducted among several local real estate agents to collect information on property prices. In total 35 properties (at different distances from the sea) were assessed. While this small sample does not allow a full scale hedonic analysis, the aforementioned scoring system, which identifies the proportional change in the sale prices, serves as a suitable alternative in such data-scarce environments. Thus, following this survey, the property prices were categorized in different groups based on proximity to the coast and assigned proportional percentages of the sea view/accessibility to each group. Subsequently, this assigned proportion (as a percentage) was multiplied with the corresponding mean sale price to estimate the final amenity value of coastal wetlands for each distance-from-sea property category.

4.3.1.1 Results of valuation study

Fishery value

This section presents the valuation results of the fishery service provided by the Java Sea and mangrove swamps in Semarang by estimating the consumer (Table 4.2) and producer surpluses (Table 4.3). Results show that the total value of fishery is primarily formed by the PS, constituting 22,486 million Indonesian Rupiah (IDR) versus only 845 million IDR of CS. Therefore, the value of fishery service is dominated by the market price and fishing costs that affect the PS. The much lower value estimated for CS (3.75% of the PS) is due to the fact that local people are not willing to pay much higher than the market price for each kilogram of fish. By summing the two, the value of fishery provided by the Semarang coastal wetlands was estimated at 23,331 million IDR, which is equivalent to approximately US\$ 1,750,000 annually, given the 2015 prices and the exchange rate at 15.07.2015 (note: these conversions were used consistently in this chapter).

Table 4.2 Consumer surplus of fishery value. Source: Survey Based (SB), Literature Based (LB)

No.	Fish type	Market price/kg (IDR) [SB]	Average WTP/kg (IDR) [SB]	Annual production in kg [LB]	Consumer surplus (mln. IDR)
1	Manyung	30,000	31,700	8781	14,9
2	Bawal Putih	20,000	29,600	4316	41,4
3	Belanak	23,000	24,600	3869	6,2
4	Beloso	15,000	25,500	1042	10,9
5	Cumi-cumi	40,000	29,300	31551	-337,6
6	Peperek	28,000	3100	72925	218,7
7	Tongkol Krai	25,000	44,600	893	17,5
8	Kembung	27,000	29,100	38695	81,2
9	Layur	15,000	22,600	43606	331,4
10	Rajungan	35,000	38,600	24854	89,4

11	Selar	23,000	24,800	7441	13,4
12	Tembang	25,000	25,600	82747	49,6
13	Tengiri	32,000	46,500	1935	28
14	Teri	45,000	49,600	101573	467,2
15	Udang Putih	60,000	51,600	22175	-186,2
Total					845

Table 4.3 Producer surplus of fishery value. Source: Survey Based (SB), Literature Based (LB)

No.	Fishing net method	No. of fishing gear/yr [LB]	Cost/unit (mln. IDR) [LB]	Gross revenue/unit (mln. IDR) [LB]	Net revenue/unit (mln. IDR)	Ecosystem related factor [SB]	Producer surplus (mln. IDR)
1	Payang seine	20	106,9	311,8	204,9	0.4	1639
2	Danish seine	16	114,5	379,7	265,2	0.4	1696
3	Beach seine	60	58,6	112,4	53,8	0.4	1291
4	Set gill	40	10,3	18,8	8,5	0.4	136
5	Trammel	36	265,5	1432	1166	0.4	16790
6	Boat/raft	12	17,7	108,9	91,2	0.4	438
7	Portable trap	17	20,7	93,8	73,1	0.4	496
Total							22,486

Art value

Table 4.4 shows revenue generated by selling art works related to Semarang coastal wetlands. The survey also revealed that 44% of art works depict coastal landscape, 38% depict coastal fauna, and 18% include coastal flora and marine area. Total annual art value of coastal wetlands is estimated at 213 million IDR (US\$ 16,000).

Table 4.4 Total annual art value of coastal wetlands in Semarang. Source: Survey Based (SB)

Category	No. of sold pieces in 2014 [SB]	Annual revenue (mln. IDR)
Painting	411	129
Photo	184	3
Book /Journal/Poster	1462	81
Total		213

Recreation/tourism value

The tourist Information Centre of Central Java Province states that foreign visitors do not often visit the coastal area due to the lower quality and popularity of these environments compared to other coastal areas in the country. Interviews during this study confirmed this, revealing that half of the visitors to the area originate from the suburban area, and the rest from other cities in Indonesia. Thus, the recreational value of coastal wetlands in Semarang is primarily formed by the stated WTP (consumer surplus) and resulting net ecosystem benefit (PS) of Indonesian visitors.

Table 4.5 shows the results of calculation of CS (estuary and beaches) based on the interviewees stated WTP for fully enjoying the present benefits of three considered ecosystem-related recreational attributes (with no loss considered). The results show a higher WTP for the Plumbon estuary compared to the beaches for the two attributes of shore water quality and diversity of birds and coastal species.

Table 4.5 *Consumer surplus for estimating the recreation value of coastal wetlands in Semarang.*
Source: Survey Based (SB)

Ecosystem-related attributes	Average WTP (mln. IDR) [SB]	
	Beaches	Estuary
Tranquility (in terms of storminess)	0.0025	0.0023
Shore water quality	0.0016	0.0116
Diversity of birds and coastal species	0.0037	0.0103
Total/person/day	0.0078	0.0242
Total *	1,970	320

* Annual value calculated based on the total number of visitors in 2014.

Table 4.6 shows the estimated PS and total net ecosystem-related benefits generated from tourism in Semarang. Accordingly, "boat rental" is the only source of income indicated for the direct value generated in the selected beaches of Semarang, since there is no diving, snorkelling or other marine-based recreational activities (swimming does not provide any monetary benefit). However, the net benefit obtained from the boat tours are not fully dependent on the ecosystems and could still be earned even if the shore water quality is not high (here a 25% dependency level is considered). The final estimated value for the annual PS is 17,000 million IDR for the beaches and 83 million IDR for the estuary (US\$ 1,275,000 and US\$ 6,200, respectively).

Table 4.6 Producer surplus for estimating the recreation/tourism value of coastal wetlands in Semarang. Source: Survey Based. B: Beach. E: Estuary

Values	Added value	Average expenditure /day (IDR)		Added value (IDR)		Factor Ecosystem dependency	Net ecosystem benefit (mln. IDR)	
		B	E	B	E		B	E
Direct values								
Boat rental	25%	4167	-	1041	-	25%	0.0002	-
Indirect values								
Entrance ticket	25%	4415	-	1103	-	60%	0.0006	-
Food/beverage	25%	42713	25600	10678	6400	60%	0.0064	0.0038
Transportation	25%	29979	17000	7494	4250	60%	0.0045	0.0025
Accommodation	25%	235833	-	58958	-	60%	0.0353	-
Buoys rental	25%	4375	-	1093	-	60%	0.0006	-
Mats rental	25%	2552	-	638	-	60%	0.0004	-
Total/day/ person		324034	-	81005	-		0.048	0.0063
Total *							17,000	83

*Annual value is calculated based on the total number of visitors in 2014.

Amenity value

Following hedonic analysis literature, here it is assumed that people attached hedonic value to coastal amenities which will be reflected in property prices. Property prices in the coastal area are influenced by the presence of coastal wetlands and more importantly, the visual amenity of ocean views. According to the collected data, properties in the area are private dwellings with rather similar structural characteristics such as size and year of construction. A weighted average price is considered by dividing the results into 7 price categories as a function of distance of the property from the sea.

Figure 4.5 illustrates these results showing an overall decrease when moving farther inland, but a considerable jump in the distance of 25-30 km from the sea, which may be due to the close proximity at that location to shopping, educational and welfare facilities.

Figure 4.5 Average price of the selected properties as a function of distance to the sea (km)

To put a monetary value on the amenity value of the CES (mainly provided by the aesthetic value afforded the Java Sea), it was necessary to rely on the provided small sample of housing price estimates and otherwise poor data available for the Semarang housing market. The amenity value captured in property prices was therefore estimated by considering a proportional percentage of the mean sale price starting from 25% for the closest distance range from the sea (within 0 - 5 km) decreasing to zero for the farthest distance range (30 - 35 km), (adapted from Fraser and Spencer, 1998). Table 4.7 shows that the largest share of 122 million IDR (US\$ 9,150) is captured in properties that are the closest to the sea (0 - 5 km).

Table 4.7 Amenity value of coastal wetlands in Semarang, based on mean property prices. Source: Survey Based

Distance range to the sea (km)	Mean sale price * (mln. IDR)	Proportion of mean sale price (%) **	Amenity value (mln. IDR)
0 - 5	490	25	122
5 - 10	467	20,8	97
10 - 15	444	16,6	73
15 - 20	421	12,5	52
20 - 25	398	8,3	33
25 - 30	375	4,1	15
30 - 35	352	0	0

* Derived from the regression line (Figure 4.5)

** Adapted with modification from Fraser and Spencer (1998)

Table 4.8 summarizes the results of valuation of different CES in Semarang. The total value per hectare is presented in IDR as well as US\$. Notably, the estimated value per hectare is based on the area size for which the services have been considered. Thus, except the recreation value which is estimated specifically for the two selected beaches and estuary, and amenity value which is computed for the coastal area upto a 5 km landward distance from the shoreline, all other values are estimated per hectare of the whole coastal area of Semarang. This consideration is due to the fact that the fishery value is mostly provided by the pelagic system (Java Sea) and no clear boundary can be defined for the marine area associated with pelagic system. Similarly, art works (books, photos, etc.) including picturesque scenery of coastal wetlands in Semarang cannot be explicitly distinguished in terms of representing a specific coastal area. Therefore, the value of art and fishery services is consistently considered for the entire coastal area of the Semarang. With respect to the period in which the valuation is done, all the values are estimated in the year 2015 with a resulting annual value given in 2015 prices.

Table 4.8 Summary of the present-day value estimated for the CES of Semarang

Ecosystem service	Economic valuation method	Area considered (Ha)	Estimated value (mln. IDR)	Estimated value (mln. IDR)/Ha	Estimated value * (US\$)/Ha
Art	Net factor income	4575	213	0.046	3.5
Fishery	Contingent valuation & net factor income	4575	23,331	5.1	380
Recreation/ tourism (beaches)	Contingent valuation & net factor income	33	19,000	575	43,000
Recreation/ tourism (estuary)	Contingent valuation & net factor income	23	400	17	1,300
Amenity **	Hedonic price	-	122	-	-

* Exchange rate of US\$/IDR = 0.000075

** Total value is estimated for CES upto 5 km landward distance from the shoreline.

4.3.2 Changes in the value of CES due to climate-driven RSLR-induced inundation

4.3.2.1 Change in the fishery value

Table 4.9 shows the potential impacts of RSLR-induced inundation on fish and fishery in Semarang for scenarios A and B. The magnitude of likely impacts was assigned for each selected fish/fishery related variable (derived from the literature mentioned in section 4.2.2.2) by interviewing a group of 20 local fishermen and eliciting their opinions regarding the likely impacts of RSLR-induced inundation on each variable (as an average magnitude, rounded off to the impact indication ranges here). Interviews with fishermen highlighted damages to the fish ponds as the most serious threat to fishery with a likely impact stated in the range of 81-

100%, and 41-60% for the two inundation scenarios A and B, respectively. In addition, for the ‘‘health status’’, the negative impact was estimated in likely ranges of 41-60% and 20-40% for Scenarios A and B respectively, since the interviews showed that inundation may result in higher probability of having disease for species with low tolerance to the turbidity caused by inundation. This may cause some species to disappear altogether, leading to a reduction of total catch volume.

For other variables such as primary and secondary production, abundance, food web, and nursery habitat, the interviewees stated an approximate positive impacts of 41-60% and 20-40% for scenarios A and B, respectively. The main reasons of having such positive impacts (Table 4.9, ‘‘Remark’’ column) are the likely increase in provision of nutrient supply and the formation of larger water bodies and nursery areas due to RSLR-induced inundation.

Table 4.9 Different fish/fishery-related variables potentially affected by RSLR-induced inundation in the two inundation scenarios A and B. NK: Not known, NE: No effect. Source: Literature Based; Expert opinion

Fish/fishery related variable	Potential impact of RSLR-induced inundation *		Remark
	Scen. A	Scen. B	
Primary & secondary production	++	+	Vertical mixing is increased leading to more nutrient supply. Larger nursery area is provided for breeding and oviposition.
Distribution/migration pattern	NK	NK	Unknown due to interaction of diverse variables such as water temperature, salinity, vertical mixing rates and wind driven circulation.
Abundance	++	+	Larger water body and nursery area are provided causing more nutrient supply.
Phenology	NE	NE	No phenological and seasonal change due to projected RSLR-induced inundation.
Health status	--	-	Increased turbidity, higher probability of having diseases for species.
Food web	++	+	Increased zooplanktons and nutrients supply.
Nursery habitat	++	+	Providing larger (natural) water bodies.
Fish ponds	----	--	Highly important variable for Semarang's fishery Industry. Probability of considerable damage to the fish ponds when inundation occurs.

* Each (+) and (-) represents a quantitative impact as defined in section 4.2.2.2.

In order to estimate the quantitative change in fishery value, the impacts of inundation are related to its monetary value by analyzing the role of each assumed impact on the consumer and producer surpluses. Thus, changes in each variable are analyzed (identified in Table 4.9), that potentially may alter the catch volume, market price as well as fishing and adaptation costs. By identifying these changes and considering the PS (net revenue) and CS (difference between market price and WTP), the changes in the value of fishery service is estimated. Importantly,

WTP is assumed to be constant with no change over time. This assumption is a necessity, since there is no data about how inundation may affect people's WTP. For example, increase of the primary and secondary fish production results in more catch volume and lower market price that would lead to an increase in CS. However, PS is expected to remain constant, because of the reverse effect of gross revenue and costs which will neutralize each other. Thus the net revenue is likely to not be affected (see Table 4.10).

Table 4.10 shows the final results indicating how fishery value in Semarang is potentially affected by the positive and negative impacts of RSLR-induced inundation in 2100. In consultations with local fishermen, a constant contribution level of 10% is assigned for most of the fishery related attributes, while nursery habitat and fish ponds are weighted higher (25%) than other attributes, and therefore contribute more to the affected value¹. Change in the fishery value is finally calculated for each variable by applying 'potential impact indications' derived from Table 4.9, multiplied with 'contribution to the affected value (%)' and changes of the 'affected value' (whether it is consumer or producer surplus, or both). The results show a losses of 5492– 6954 million IDR (US\$ 412,000 – 520,000) and 2764 – 4250 million IDR (US\$ 207,000 – 318,000) for scenarios A and B, respectively.

Table 4.10 Changes in the fishery value of CES of Semarang for the two 2100 RSLR-induced inundation scenarios. CS: consumer surplus, PS: producer surplus, F: Fishing, A: Adaptation, NK: Not known, NE: No effect. Source: Literature Based

Fish/fishery related variables	Catch volume	Market price	Cost		Affected value		Contribution to the affected value	Change in fishery value (mln. IDR)	
			F	A	CS	PS		Scen. A	Scen. B
Primary & secondary production	↑	↓	↓	↑	↑	NE	10%	+ (34 – 50)	+ (17 – 33)
Distribution/migration	NK	NK	NK	NK	NK	NK	10%	NK	NK
Abundance	↑	↓	↓	↑	↑	NE	10%	+ (34 – 50)	+ (17 – 33)
Phenology	NE	NE	NE	NE	NE	NE	NE	NE	NE
Health status	↓	↑	↑	↑	↓	↓	10%	- (956 – 1398)	- (466 – 933)
Food web	↑	↓	↓	↑	↑	NE	10%	+ (34 – 50)	+ (17 – 33)
Nursery habitat	↑	↓	↓	↑	↑	NE	25%	+ (86 – 126)	+ (42 – 84)
Fish ponds	↓	↑	↑	↑	↓	↓	25%	- (4724 – 5832)	- (2391 – 3500)

¹ This contribution level for fish ponds can be less than that considered here for other applications where the fishery industry is not as aquaculture-dependent as it is in Semarang.

Total gain	188 – 276	93 – 183
Total loss	5680 – 7230	2857 – 4433
Net change	- (5492 – 6954)	- (2764 – 4250)

4.3.2.2 Change in the recreation/tourism value

Table 4.11 shows analysis of the potential inundation impacts on recreation value for the two inundation scenarios. Here, depending on the scenario, different impact percentages (similar to the fishery value analysis) are assigned to the tourism-related attributes. These impact indications are related to the attributes, for which the visitors in the interviews stated their WTP for enjoying 100% and 50% of such recreational attributes.

Table 4.11 Different tourism/recreational attributes potentially affected by RSLR-induced inundation, for different potential impacts for inundation scenarios A and B in Semarang. Source: Survey Based

Tourism/ recreational attributes	Potential impact of RSLR-induced inundation *		Remark
	Scen. A	Scen. B	
Tranquility (in terms of storminess)	- - - -	- -	Visiting the beach or estuary is less pleasant if tranquility is affected by inundation. Less impact is expected when the area is less inundated.
Shore water quality	- - - -	- -	Turbidity caused by inundation affects the shore water quality. Less impact is expected when the area is less inundated.
Diversity of birds and coastal species	- - - -	- -	Considerable impact on the diversity of species expected while inundation occurs. Less destructive impact is expected when the area is less inundated.

* Each (+) and (-) represents a quantitative impact as defined in section 4.2.2.2.

Similar to the previous section, to quantify the changes in tourism value, the assumed impacts of inundation are related to the consumer and producer surpluses and then its influence on these values is analyzed. For the analysis of CS (WTP), the results of interviews are directly used. It is found that when a larger area is inundated, CS increases correspondingly, since the respondents stated higher WTP to avoid having higher percentage of loss for the recreational attributes considered in this survey (see Table 4.12). The total stated WTP is divided by the number of respondents (giving the average WTP per visitor) and multiplied by the annual number of visitors¹ to obtain the total annual value of this attribute corresponding to scenarios A and B, respectively.

¹ According to “Badan Pusat Statistik (BPS) Kota Semarang 2014” 252,840 and 13,200 visitors were recorded in 2014 for the selected beaches and estuary, respectively.

However, PS is expected to decrease, since the hypothesis is that when the entire beach area is inundated, tourism will severely be affected due to the fact that there would not be any opportunity for visitors to visit the beaches and enjoy the tranquility, water sports, and watching birds or other coastal species. This would result in much fewer number of visitors and lower revenue. However, the inundated area might still provide recreational value even after inundation occurred, which is not known for certain. Therefore, as shown in Table 4.11, a conservative scenario of upto 81-100% loss in the tourism value was considered for the worst case scenario of full inundation (scenario A), and a relatively lower loss (41-80%) when half of the area is inundated (scenario B). Presenting losses in a range of 20% is due to uncertainty of potential losses, justifying the hypothesis used in this study.

To establish the link between PS and recreational attributes that are likely to be affected by inundation, the stated importance of each attribute as reported by the respondents in the survey is considered. This importance is represented by ranking the most enjoyed recreational aspects while visiting the beaches and estuary. According to the interviews, tranquility of the beaches and estuary is the most important attribute (stated to be 60% in the survey, thus contributing to 60% of the total PS) followed by the shore water quality (20%) and the diversity of flora and fauna (20%). Changes in the PS is calculated by multiplying ‘potential impact indications’ (derived from Table 4.11) with ‘contribution of changes to the PS (%)’ and ‘PS’ estimated before.

Total change in the tourism value is estimated by summing the changes in CS and PS (Table 4.12). While summing the values, it should be noted that for all the recreational attributes, inundation increases the CS (as higher WTP is indicated in the interviews), whereas the PS is expected to decrease. The final results indicated a total annual losses of 11,550 – 14,800 million IDR (US\$ 866,000 – 1,110,000) and 5,790 – 9,040 million IDR (US\$ 434,000 – 678,000) for inundation scenarios A and B, respectively.

Table 4.12 Changes in the recreation value of CES of Semarang for the two year 2100 RSLR-induced inundation scenarios A and B

Tourism / recreational attributes	Affected value		Average WTP * stated for the loss percentage (mln. IDR)		Contribution to the PS	Change in annual tourism / recreation value (mln. IDR)	
	CS	PS	100%	50%		Scen. A	Scen. B
Tranquility (in terms of storminess)	↑	↓	660	317	60%	- (7642 – 9590)	- (3885 – 5832)
Shore water quality	↑	↓	557	289	20 %	- (2210 – 2860)	- (1111 – 1761)
Diversity of flora and fauna	↑	↓	1070	603	20 %	- (1697 – 2346)	- (797 – 1446)

Total gain	0
Total change	- (11,550 – 14,800) - (5,790 – 9,040)

* Calculated for the total number of visitors in 2014.

4.3.2.3 Change in the art and amenity values

As described in section 4.2.2.2, potential impacts of RSLR induced inundation on art related attributes are quantified by eliciting expert opinions on likely changes to art related attributes of CES due to pre-developed inundation scenarios of A and B. Therefore, in the survey conducted in 20 art-related shops, (photo, book, and painting shops) more than 30 people (who deal with art works) were interviewed and asked to indicate their opinions for likely inundation-induced changes to coastal and marine landscape, and to the coastal flora and fauna of Semarang. Moreover, a range of potential changes in five different classes of 1 (0-20%), 2 (21-40%), 3 (41-60%), 4 (61-80%), and 5 (81-100%) was presented to the respondents, and depending on whether the entire coastal area or 50% of it is inundated, an approximated impact was identified by the interviewees for each inundation scenario. According to the results, the respondents stated that average losses in art value of CES in Semarang are likely to be similar for the two related attributes (landscape, flora and fauna) in classes of 5 (81-100%), and 3 (41-60%) for inundation scenarios A and B, respectively.

Table 4.13-a shows the total loss value calculated by multiplying the loss percentage derived from the survey with the estimated current value, and summing up the resulting loss value of two attributes. The results indicate that RSLR-induced inundation will lead to an annual potential losses of the art value of CES equivalent to 172 – 213 million IDR (US\$ 13,000 – 16,000) and 87 – 128 million IDR (US\$ 6,500 – 9,600) for scenarios A and B, respectively.

With respect to the change in amenity value, Semarang coastal area is expected to lose its visual amenity depending on the extent of the inundated area. While the property price in Semarang correlates with the coastal amenities level, proximity to the coast also increases the risk of inundation, leading to high uncertainty when determining losses or gains in amenity value. Similar to the tourism service, a ‘what if scenario’ approach is considered here, assuming that although the area will be fully inundated, the new landscape and the Sea view may still provide a picturesque scenery affecting the price of properties along the coast. Thus a conservative loss value in the range of 41-60% is assigned for scenario A with full inundation, while a lower range of 20-40% loss is assigned for scenario B when half of the area is inundated. Compared to the obviously large impact of inundation on tourism value, here, a lower impact range for the amenity value was assumed with the hypothesis that amenity provided by the Sea view is likely to be less affected by inundation.

The important point considered here is that the impacts on the amenity value were only considered for the closest distance range of 0-5 km from the coast, where the value (most likely) will decrease due to the reduction of property price affected by inundation. The reason for

excluding the impact quantification for greater distances from the coast is mainly due to the uncertainties associated with future SLR and consequently with inundation/erosion impacts on property prices that may or may not result in a reduction of property value at some location. This is however impossible to ascertain without a detailed numerical modelling study that is able to provide robust estimates of the likelihood of coastal inundation and recession in future, inclusive of uncertain quantifications (see for e.g. Ranasinghe et al., 2012; Jongejan et al., 2016).

The results show total losses of 50 – 73 million IDR (US\$ 3,700 – 5,400) and 24 – 49 million IDR (US\$ 1,800 – 3,600) of the amenity value for scenarios A and B, respectively. This low estimation is due to the relatively low property price in the coastal area of Semarang.

Table 4.13 Changes in the art (a) and amenity value (b) of CES of Semarang for the two year 2100 RSLR-induced inundation scenarios A and B

a)						
Art related attributes	Estimated value (mln. IDR)	Potential impact of RSLR-induced Inundation		Change in art value (mln. IDR)		Remark
		Scen. A	Scen. B	Scen. A	Scen. B	
landscape	115	- - - -	- -	- (93 – 115)	- (47 – 69)	Destructive impact is expected to increases when the coastal area is inundated.
Flora & fauna	98	- - - -	- -	- (79 – 98)	- (40 – 59)	
Total gain				0		
Total change				- (172 – 213)	- (87 – 128)	
b)						
Amenity	Estimated value * (mln. IDR)	Potential impact of RSLR-induced Inundation		Change in amenity value (mln. IDR)		Remark
		Scen. A	Scen. B	Scen. A	Scen. B	
Based on property price	122	- -	-	- (50 – 73)	- (24 – 49)	Aesthetic pleasure is expected to decrease in coastal area, depending on the extent of the inundated area.
Total gain				0		
Total change				- (50 – 73)	- (24 – 49)	

* Considered for upto 5 km landward distance from the shoreline.

4.3.2.4 Overview of the changes in the value of CES in Semarang

Table 4.14 summarizes the estimated changes in the value of CES in Semarang coastal area for the two year 2100 RSLR-induced inundation scenarios A and B. It should be noted however that a number of factors such as development of coastal protection structures, changes in WTP on both consumer and producer surpluses, changes in elasticity, and even in social norms will be likely occurred by 2100, affecting the values estimated here. Consequently, the results presented here should be considered as being indicative of potential losses of CES due to RSLR-induced inundation assuming a constant WTP.

Table 4.14 Changes in the value of CES of Semarang coastal area for the two year 2100 RSLR-induced inundation scenarios A and B

Ecosystem service	Estimated change in the value of CES (mln. IDR)		Estimated change in the value of CES (US\$)/Ha *		Median change relative to present-day value	
	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B
Art	- (172 – 213)	- (87 – 128)	- (2.8 – 3.5)	- (1.4 – 2.1)	-90%	-50%
Fishery	- (5,492 – 6,954)	- (2,764 – 4,250)	- (90 – 113)	- (45 – 70)	-25%	-15%
Recreation**	- (11,550 – 14,800)	- (5,790 – 9,040)	- (15,460 – 19,820)	- (7,750 – 12,100)	-70%	-40%
Amenity***	- (50 – 73)	- (24 – 49)	- (3,700 – 5,400)	- (1,800 – 3,600)	-50%	-30%

* Exchange rate of US\$/IDR = 0.000075

** The total value estimated for the selected beaches and estuary.

*** The total value estimated for upto 5 km landward distance from the shoreline.

4.4 Conclusion

This study presented the newly developed QuantiCEL framework, and demonstrated its application to quantify the environmental losses due to the potential impacts of climate-driven changes, here represented by RSLR-induced inundation by the year 2100, in the Semarang coastal area in Indonesia. Changes in the monetary value of CES (recreation, art, amenity and fishery) provided by mangrove swamps, beach, dune and pelagic systems were estimated using standard economic valuation techniques and a ‘‘what if scenario’’ approach. This presents an opportunity to better understand and to improve quantitative assessment of the SLR-driven impacts on CES, evidence for which is scarce in the current literature, especially in developing countries.

The results of extensive field work conducted in this study, show that complete inundation of the beach area due to 4 m of RSLR in 2100 (scenario A) will considerably decrease the recreational service of coastal wetlands by upto 70% of the current value, equating to US\$ 15,460 – 19,820 per hectare of the selected sites in Semarang (Marina and Maron beaches and Plumbon estuary). For this inundation scenario, considerable losses are also shown in the value of art and fishery services (per hectare) with estimated decreases of 90% (US\$ 2.8 – 3.5) and

25% (US\$ 90 – 113), respectively, by 2100 relative to the present. The amenity service is expected to lose 50% (US\$ 3,700 – 5,400) of its current value. For scenario B, where 50% of the coastal area is considered to be inundated (due to 1.1 m of RSLR in 2100), these changes are relatively lower with estimated losses of 40%, 50%, 15%, and 30% for recreation, art, fishery, and amenity values, respectively (about 40% of the corresponding losses estimated for Scenario A).

It should be noted that the results of this study provide an approximation of the losses of CES as a value range, and not as single deterministic values of such ecological degradations. Thus, the approach used here should be conservatively considered given the inherent uncertainties of CC impacts and likely ecological responses. The framework presented in this study can be used for a wide range of applications providing an approximate estimation of RSLR-driven impacts on CES value, especially in data-scarce environments such as developing countries for which it is not feasible to apply standard ecological and economic simulation methods. Outcomes of this study can also be useful for assessments of environmental risk which is an important topical area for researchers and policy makers.

CHAPTER 5

Application of QuantiCEL framework for a case study in the Sundarbans Region, Western Coast of Bangladesh¹

¹ This Chapter is partially based on: Mehvar, S., Filatova, T., Sarker, M. H., Dastgheib, A., and Ranasinghe, R. (2018c). Climate change driven Losses in Ecosystem Services of Coastal Wetlands, a case study in the West Coast of Bangladesh. Ocean & Coastal Management (accepted for publication).

5.1 Introduction

In this chapter, the QuantiCEL framework developed and demonstrated in Chapter 4, is applied to a different study site located on the Western coast of Bangladesh to quantify the inundation driven changes to the services provided by the Sundarbans Mangrove Forest (SMF), pelagic system and aquaculture ponds.

The coastal area of Bangladesh is threatened by climate change (CC) impacts such as increasing frequency and intensity of cyclones, erosion, SLR, salt water intrusion and inundation (Loucks et al., 2010; Minar et al., 2013; Payo et al., 2016; Dasgupta et al., 2017). The low-lying geography of the area, combined with a very high population density, lack of efficient infrastructural and institutional capacity predefines the high vulnerability therein (Denissen, 2012). In addition, Bangladesh is known as the 3rd most susceptible country to SLR in the World in terms of the number of people potentially affected (Minar et al., 2013).

The Western coastal area of Bangladesh contains the Sundarbans swamps, which is recognized as the richest natural forest and most economically valuable coastal wetlands in Bangladesh (Mondal and Debnath, 2017). More than 3 million people living in Bangladesh benefit from the Wetland Ecosystem Services (WES) provided by the West coast of Bangladesh and, especially those provided by the Sundarbans swamps (Giri et al., 2007).

This region is focused due to its high importance in providing ecosystem services, and vulnerability of the coastal area to the CC impacts. In this study, the RSLR-induced inundation is focused as the sole hazard. The term RSLR here, refers to the sum of mean SLR and the rate of local land subsidence. The study area covers two wetlands: (1) an estuary containing the Sundarbans Mangrove Forest adjacent to the marine area representing mangrove swamps and pelagic ecosystems, and (2) the aquaculture lands located mostly in the Northern part of the SMF. Compared to the demonstration case of the Semarang coastal area in the previous chapter, here the main ecosystem focused on is the dense and large area of the Sundarbans mangrove forest. In addition, here, the services obtained from the rather large areas of aquaculture lands in the Northern Sundarbans (referred to as man-made wetlands), are also considered.

Using the QuantiCEL framework, firstly, the present monetary value of four WES (food provision, provision of raw materials, art and tourism) are estimated which are currently being provided by the SMF, marine area and aquaculture lands. Secondly, by using a ‘‘what if scenario’’ approach, the likely impacts of RSLR-induced inundation on WES are identified by 2100 under three IPCC scenarios of RCP2.6 (with 0.25 m of RSLR), RCP6.0 (with 1.18 m of RSLR), and RCP8.5 (with 1.77 m of RSLR). Finally, the potential changes in the value of WES of the West coast of Bangladesh are quantified by combining the results of previous two steps, linking the identified likely impacts of RSLR-induced inundation on WES with economic concepts.

5.2 Methods

5.2.1 Study area

The study area with a total extent of 13,000 km² is situated in the Western coastal area of Bangladesh in the three districts of Khulna, Satkira and Bagerhat, containing the Sundarbans forest adjacent to the Bay of Bengal in the South. Figure 5.1 shows the land use map of the study area representing estuarine river and aquaculture lands as the two dominant wetlands containing the SMF and pelagic system which are the coastal wetlands considered in this study.

Figure 5.1 Study area showing the land use information, and the boundary of data collection sites in yellow. Source: CEGIS

The Sundarbans were discovered about 200 years ago with an extent of 16,700 km² (Mahadevia and Vikas, 2012; Mondal and Debnath, 2017), that has now dwindled to approximately one third of its original size due to coastal hazards. The SMF is widely accepted to be the largest single patch of mangrove forest in the World (Das and Siddiqi, 1985; Ali, 1994; Iftekhar, 1999;

Rahman, 2003; Biswas et al., 2007; Roy et al., 2013; Uddin et al., 2013; Payo et al., 2016). The part of this forest located in Bangladesh is about 6000 km² (Uddin et al., 2013; Hossain et al., 2018), comprising of 4,143 km² of land area and 1,874 km² of water area (Dasgupta et al., 2018). Tidal creeks and mud flats are the main characteristics of the Sundarbans (Hazra et al., 2016). A majority of this region lies at elevations between 0.9 m and 2.1 m above MSL (Iftekhhar and Islam, 2004; Hazra et al., 2016).

The interior parts of the intertidal zone and mudflats govern the morphology of the SMF, which serves as a desirable habitat for about 300 species of flora and 425 species of fauna, some of which are being threatened and endangered (Biswas et al., 2007). The Sundarbans region is known for its unique biodiversity (Dasgupta et al., 2018), providing a large nursery area for birds and numerous species of small fishes, crabs, shrimps, reptiles, and mammals such as tigers.

This natural environment contributes considerably to fishery (fishing and aquaculture) which is one of the major livelihoods in Bangladesh being threatened by CC impacts such as SLR and saline water inundation (Chand et al., 2012). Notably, the threat of SLR to the SMF is still unclear (Payo et al., 2016) and the potential resilience capacity of the Sundarbans swamps to a certain inundation regime (as referred to ‘‘elevation capital’’ by Lovelock et al., 2015) is highly uncertain. The inundation tolerance capacity which varies remarkably among mangrove species (Yang et al., 2013) depends on the tidal range, positive effects of sediment supply and mangroves response to the increase in water salinity. On the other hand, these impacts of CC on fishery, and - in particular, on aquaculture, are also now being increasingly observed. Aquaculture with an impressive growth rate of about 9% per year plays an important role in the fishery sector in Bangladesh, compared to capture fisheries with its 4% growth rate (DOF, 2010; Belton and Azad, 2012). Figure 5.2 shows the Sundarbans area contributing to fishery and tourism industries in Bangladesh.

Apart from providing habitat for flora and fauna, the SMF also contributes to the wood-based industry in Bangladesh by providing raw materials such as timber, fuelwood and thatching. Tourism as a cultural service is another service provided by the SMF (Hazra et al., 2016) through the aesthetic and recreational value of its scenic landscapes for local and foreign visitors. The tourism industry has been improving over the years in the West coast of Bangladesh as a result of an increase in organized recreational tours and improved tourism facilities (Uddin et al., 2013).

Figure 5.2 The Sundarbans region, showing the mangroves forest, fishing and tourist boats. Photos by Hiroki Ogawa (top left), Samim Akhter (top right), Joiseyshowaa (down left), and Juggadery (down right). Source: Wikimedia Commons

5.2.2 Methodology

To quantify potential CC driven damages to the WES in the West coast of Bangladesh, here the QuantiCEL framework is applied. First, by employing standard economic valuation techniques, the present monetary value of WES is estimated using the original field work undertaken for this study. Secondly, using a scenario-based approach grounded in expert knowledge and secondary data from a thorough literature review, the potential impacts of RSLR-induced inundation on the pre-valued WES are identified for the year 2100 under three IPCC scenarios (RCPs 2.6, 6.0 and 8.5). Finally, the RSLR induced losses in WES are quantified by combining the results of previous two steps.

5.2.2.1 Step 1 - Current Status: Valuation of WES

In the first step of this study, standard economic techniques are applied for estimating the Present-day Value (PV) of WES currently provided by the SMF, pelagic system and aquaculture lands. In this study, aquaculture lands together with two natural ecosystems (mangrove forest and pelagic system) are considered as one consistent system named *wetland ecosystems*. From a variety of services which are provided by wetland ecosystems in Bangladesh (e.g. flood control, erosion stabilization, climate regulation service such as carbon sequestration, etc.), here four WES are considered. The assessment of other important services are excluded due to limitation in data and resources.

Figure 5.3 shows a schematic of the coastal wetlands, ecosystems and services considered in this study. Accordingly, four wetland ecosystems services (WES) are considered in this study providing direct use values, comprising recreation or tourism, food provision, art and provision of raw materials. Depending on the type of services, three valuation techniques are used: contingent valuation, net factor income and market price method (see Table 5.1).

Figure 5.3 Schematic representation of coastal wetlands, ecosystems and services considered in this study

Table 5.1 Economic valuation methods corresponding to the services used in this study

Wetland ecosystems service (direct use value)	Economic valuation method
Recreation/tourism	Contingent valuation
Food provision (fish and marine species)	Net factor income
Art	Net factor income
Provision of raw materials (timber and fuelwood)	Market price

• Data collection

For the valuation of WES in this study, a well-structured primary data collection was implemented with the help of CEGIS (Centre for Environmental and Geographic Information Services) in Dhaka, Bangladesh. This was done through field observations, participatory discussions, surveys and interviews with different stakeholder groups such as tourists, fishermen, local communities and artists/art dealers. Different questionnaires were designed depending on the type of WES and target stakeholders to elicit the environmental and socio-economic data. All interactions with local community were undertaken by native language interviewers.

To collect the required data from the study area, eighty (80) locations along the SMF were identified and selected, considering the importance of the study area in terms of natural resources and rich habitats provided by the wetland ecosystems. A complete listing of data collection locations spanning the districts of Khulna, Bagerhat and Satkhira was provided in Table 5.2. For this study, a dedicated 9-day field work campaign was executed by three research teams to collect the primary data during the period 3-11 June 2017. In addition to the primary data, secondary data were collated from available literature and data sources of CEGIS, as required for this study.

Table 5.2 Field data collection sites

District	Sub-district (Upazila)	Union	Village (Mouza)	No. of sites
Khulna	Koyra	South Bedkashi	Gharilal	2
			Golkhali	2
			Angtihara	2
		North Bedkashi	North Bedkashi	3
		Moharajpur	Mathbari	3
		Moheswaripur	Tenturtolar Char	2
			Banikhali	3
			Hadda	3
	Dacope	Sutarkhali	Nalian	3
			Sutarkhali	4
		Kailashganj	Dhopadihi	1

Bagerhat	Mongla		Kailashganj	3
		Banishanta	Banishanta	3
		Chila	Joymonigol	3
			Badyamari Bazar	3
			Holdibunia	2
		Sundarbans	Karma/Jiudhara	4
	Bajikar Kanda		2	
	Shoronkhola	Dhansagar	Dhansagar	3
			Rajapur	2
		Rayenda	South Rajapur	1
		Southkhali	Sonatola	3
			Sharankhola	4
Satkhira	Shyamnagar	Ranijannagar	Kalinchi	1
			Betkhali	2
		Munshiganj	Harinagar	2
			Munshiganj	5
		Burigoalini	Burigoalini	3
			Purakatta	2
		Gabura	Dumuria	2
			Parshemari	2
Total				80

The valuation of each WES as conducted in this study is described below:

- Recreation/tourism value

Contingent valuation and net factor income methods are used to estimate the value of recreation or tourism service provided by the wetland ecosystems in the Western coastal area of Bangladesh. Tourism value is quantified by summing the producer and CS, which is the approach used by van de Kerkhof et al. (2014b). To achieve this, a questionnaire was designed and presented to visitors asking them their average expenditure per day which directly or indirectly depends on the status of the wetland ecosystems (considered in this study as the combination of SMF, pelagic system and aquaculture ponds). Therefore, on-site interviews with 50 local visitors (there were no foreign tourists present at the sites during the interviews) were conducted for collecting this data as well as collecting socio-demographic information.

Direct expenditure is the amount that is spent where the wetland ecosystems provide recreational benefits to the visitors such as water sports and sightseeing of the mangrove forest (group tours). These values are directly dependent on the quality and health condition of the mangroves. On the other hand, indirect expenditures are the visitors' expenses for food, transportation, accommodation, entrance tickets, etc., which are for the purpose of visiting the touristic area, but are indirectly dependent on the status of the wetland ecosystems.

By using the CVM, it was aimed to estimate the CS as another factor contributing to the total recreation value, but since most of the visitors stated no WTP for preserving the current status

of wetland ecosystems, this value has been excluded in this valuation study. Therefore, here, the recreation value is estimated purely based on the PS and revenue generated from the visitors according to their expenditure for visiting the study area.

- Food provision value (fish and marine species)

The large amount of fishing undertaken along the Western coast of Bangladesh, and in particular, in the Sundarbans region contributes to the food provision service provided by the estuarine river, marine area (pelagic system) and the SMF. Apart from the marine and estuarine river fishing, aquaculture is another important source of fish and other marine species, contributing to the fishery industry in Bangladesh.

Similar to the recreation service, the total value of commercial fishery service (recreational fishery is excluded in this study due to data scarcity) is estimated by summing the consumer and producer surpluses, similar to the approach used by Schep et al. (2012a). To collect the fishery-related data for this study, 80 fishermen were interviewed at different sites in the study area and more than 20 different species including fish, shrimps and crabs were identified in this survey. Figure 5.4 shows two selected pictures taken during the survey and interviews with fishermen.

Figure 5.4 Selected photos taken during the interviews with fishermen

Using the net factor income method, PS was considered to represent the net revenue generated by the ecosystem-related fishery (here is dominantly dependent on the status of the SMF and aquaculture ponds). This value is then multiplied by 40% which is assumed to be the ecosystem dependency factor, meaning that fishery is approximately 40% dependent on the status of the ecosystems (no secondary data is available to explicitly quantify the dependency level of fishery on the wetland ecosystems in Bangladesh). Furthermore, the CVM method is used to calculate the consumer surplus value (i.e. the difference between market price and WTP for

each kilogram of fish and other marine species), but most of the interviewees stated no WTP and thus, the food provision value of coastal wetlands computed here is only based on the PS and net revenue earned in the fish market.

- **Art value**

The Western coast of Bangladesh provides art value through scenic landscapes and artistic views captured in art works. Here, the net factor income method is used to estimate this value that inspire the artists and encourage art dealers/financiers. Therefore, an art-related survey was conducted with a specifically designed questionnaire, which was presented to the painting and photography shops (no book stores were found in the study area). The aim was to assess how the natural landscape of the wetland ecosystems (mostly provided by the SMF and marine area) is represented in the art works and how much is annually earned by selling the art pieces that either directly or indirectly capture the art value of the wetland ecosystem in the study area. The total annual value was estimated by summing the total revenue earned from selling the art works in these shops during 2016-2017. This method has been adapted from Van Beukering and Wolfs (2012) who conducted a similar valuation study in Caribbean Islands.

- **Raw materials value (timber and fuelwood)**

The Sundarbans mangrove swamps are important sources of timber for the paper industry as well as fuelwood for the locals and market. Here the market price method is used in a survey to estimate the value of timber and fuelwood as the raw materials provided by the SMF in the study area. The information regarding the wood price per m³ was collected from the timber merchants for 23 wood types harvested in the Sundarbans forest. The total value of the raw materials is estimated by summing the timber prices per m³ and fuelwood per mound.

5.2.2.2 Step 2 - Physical Impacts: Identifying potential impacts of RSLR-induced inundation on WES by 2100

In this step, first the RSLR scenarios are developed for the coastal area of Bangladesh. To do this, the local spatial variations in RSLR in Bangladesh by 2100 are determined. Secondly, the RSLR-induced inundation scenarios are developed and the inundated area are determined for each inundation scenario. After identifying the extent of inundated areas for each scenario, potential impacts of inundation on WES are identified by 2100. These steps are described as follows:

- **Development of RSLR Scenario**

Developing RSLR scenarios is based on different CC scenarios for the Central Coast of Bangladesh. Developing RSLR scenarios constitute two main sections: a) Determining the current trends in local RSLR (Baseline); b) Developing the scenarios for local RSLR by the year 2100.

- **Development of RSLR-induced inundation scenarios**

In this step, the extent of inundation areas due to the RSLR scenarios are determined along the coast of Bangladesh derived from the previous step. These inundation scenarios are developed for the three IPCC RCPs (i.e. RCP2.6, RCP6.0 and RCP8.5).

- **Potential impacts of RSLR-induced inundation on WES in 2100**

SLR can physically affect the coastal area by flooding and submerging ecosystems as an immediate effect, as well as erosion as a longer term effect (Nicholls and Cazenave, 2010). In this study, the impacts of inundation due to RSLR on WES are focused, implying that increasing water salinity as a side effect of inundation is also considered as a threat to the WES.

To identify the potential impact of RSLR-induced inundation on WES, here a “what if scenario” approach was used combined with secondary data from the literature. In this approach, related attributes for each WES are analysed to explore how inundation can potentially affect each of these attributes. For this analysis, depending on each service, its attributes and the 2100 inundation scenario, the impacts are quantified by assigning a range of change for each attribute, resulting in changes of WES value for the three RCPs. Therefore, by considering an *impact indication*, a 10% increase or decrease in the value of attributes is represented for each + or - sign, respectively. This implies different ranges of change as 0% - 10%, 11% - 20%, 21% - 30%, 31% - 40%, corresponding to the assigned *impact indications* from one to four +/- signs.

For two services (food provision, and art), local fishermen and experts who deal with art works were interviewed to elicit their opinions regarding the likely future changes of wetland ecosystems due to inundation. For the two other services (provision of raw materials, and tourism), a “what if scenario” is considered by which potential losses of these two services are hypothetically assumed, depending on the extent of inundated area in each scenario. It should be emphasized that, in this study the wetland ecosystems are considered as one system. Therefore, the impacts of RSLR-induced inundation on each of the SMF, aquaculture ponds, and marine area are not separately assessed, since the limited available data did not allow the evaluation of these impacts on the share of services provided by each wetland ecosystem. This qualitative assessment is described in detail for each service as follows:

- *Impacts on food provision service (fish and marine species)*

CC can potentially affect the fishery industry and the lives of fishing communities by increasing the frequency of storm events (Minar et al., 2013), and by SLR causing the wetland submergence and salt intrusion. These impacts result in changing the food provision service provided by the pelagic system (Bay of Bengal) and the SMF (i.e. two coastal wetlands considered), and aquaculture fish ponds (i.e. man-made coastal wetland), which are situated in the North West of the SMF.

Here, the following literature is reviewed for the basis of analysing the primary CC impacts on fishery: Harley et al. (2006); Portner and Knust (2007); MAB (2009); Cochrane et al. (2009); Mohanty et al. (2010); Sumaila et al. (2011); Williams and Rota (2011); and Mahadevia and Vikas (2012). Following this literature, different fishery related variables, which can potentially be affected by RSLR-induced inundation are identified. For example, distribution pattern and fish abundance can potentially be altered due to CC impacts such as water temperature rise, changes to the ocean chemistry, ocean acidification, expansion of oxygen minimum zones, and climate-induced changes in hydrography (Portner and Knust, 2007; Mohanty et al., 2010; Sumaila et al., 2011). In addition, flooding of low lying areas due to SLR may provide an ideal habitat for the fish community due to the occurrence of salt water (MAB, 2009; Williams and Rota, 2011). Since the literature mentioned above do not specifically assess the inundation impacts on fishery due to SLR, here it is used as a basis to further develop the scenario-based approach used in this study, by considering a number of fishery-related variables that are very likely to be affected by inundation.

After identifying the variables, the likely impacts of inundation on these variables are identified by eliciting local fishermen's opinions, derived from the interviews (with 80 fishermen in this study). To this end, a qualitative assessment is conducted and *impact indications* are assigned to each variable, depending on the interview results and the extent of inundated area. The role of these impacts is linked to the PS value of the food provision service, and the potential change in the value is ultimately quantified by summing the loss values estimated for each fishery-related variable.

- *Impacts on recreation/tourism service*

Changes in the value of recreation or tourism service, provided mainly by the SMF and marine area, and to a less extent by the aquaculture lands, are estimated by assessing the potential impacts of RSLR-induced inundation on the PS value of this service. To this end, different tourism-related attributes are considered (as stated by the visitor interviews) in a custom-designed questionnaire, in which the visitors are asked to rank their preferred aspects (among the attributes) for which they visit the study area. Consequently, the results represent each attribute with a weighted contribution level (as a percentage) to the total pre-estimated PS value.

The total RSLR-induced inundation impact on recreation value is ultimately identified by assigning the quantitative *impact indication* (as defined before) to each (weighted) recreational attribute which varies for each inundation scenario. The hypothetical assignation of *impact indications* to the recreation service is necessary due to the scarcity of data and the lack of a similar application/methodology for conducting quantitative assessments.

- *Impacts on art service*

To estimate the changes to art service provided by the SMF, marine area and aquaculture lands, first the art-related attributes are determined including coastal landscape as well as flora and fauna. Further, a range of scenarios of negative impacts¹ of inundation (by assigning the pre-defined *impact indications*) are presented to experts who deal with the art works (paintings, photos, etc.). Through this scenario-based approach, the ultimate negative impact is identified by eliciting expert opinions on changes in art related attributes which is different for each inundation scenario.

- *Impacts on provision of raw materials service (timber and fuelwood)*

Submergence of mangroves below MSL together with the impacts of soil and river salinity are the main factors that govern the loss of merchantable wood volume (adapted from Chaffey et al., 1985; Minar et al., 2013). Similar to the art value assessment, there is no established approach to quantify the inundation driven losses of the wood sources provided by the SMF. Therefore, here, a scenario-based approach is used, in which, depending on the extent of inundated area and lost mangrove area, different negative *impact indications* are considered on the wood market value. Notably, due to existence of the embankments which are partially located along the Northern boundary of the SMF, here, a moderate level of landward migration of mangrove swamps is considered, implying that more space is accommodated for this ecosystem to migrate while inundation occurs. This would imply consideration of more conservative *impact indications* for quantifying potential changes in the value of raw materials provided by the SMF due to likely effects of RSLR-induced inundation by 2100.

5.2.2.3 Step 3 - Monetizing Climate Change Impacts: Quantifying the monetary changes in the WES value

In the third and final step of the methodology used here, the environmental losses for each RCP are quantified by using the results of environmental impact identification (section 5.2.2.2), combined with the present monetary value of WES estimated in section 5.2.2.1. The final loss values are estimated in terms of PV of money (in 2017 price) implying that the discounting rate² is assumed to be zero, meaning that the current value of money is assumed to be the same as that in future.

- **Sensitivity analysis of discounting values**

Discounting the distant future is used in valuation of the consequences of CC (Newell and Pizer, 2003). In some economic analyses of global warming, discounting the future value has been performed at rates as high as 6% (IPCC, 1995; Voinov and Farley, 2007). The unresolved

¹ The data for such losses are currently unavailable. Thus, these assessments of the share of losses on art-related attributes could be considered as scenarios.

² In economic analysis, discounting a value refers to an estimate of the current value of future sum of money which decreases over time by using a discount rate.

debate on the choice of an appropriate discounting factor (Arrow et al., 1996; Halsnæs et al., 2007; Quiggin, 2008; Garnaut, 2008; Dasgupta, 2008; Tol and Yohe, 2009; Weitzman, 2009; Millner, 2013; Keighley et al., 2018) demands at minimum a sensitivity analysis of any long-term valuation studies on the discounting rate.

Hence, a sensitivity analysis is performed here for discounting factors with different rates of change to see how varying discounting rates will affect the final loss value of the WES estimated in this study. In doing this, the *PV* of losses for the food provision value is re-calculated by using exponential and hyperbolic discount factors. Equation 1 indicates how to calculate *PV* of losses by using an exponential discount factor FD_{exp} (Eq. 2), where a_t is the estimated loss value at time t , and k is the discount rate by which the loss value will be discounted from time 0 to time n (Beaves, 1993).

$$PV = \sum_{t=0}^n (a_t) (FD_{exp}) \quad (1)$$

$$FD_{exp} = \frac{1}{(1+k)^t} \quad (2)$$

Besides using the exponential discount factor FD_{exp} (Eq. 2), the *PV* of losses is also calculated by using hyperbolic discount factor which is suggested as an alternative to the classical discounting (exponential) for sustainability projects (Voinov and Farley, 2007; Saez and Requena, 2007). Thus, in hyperbolic discounting, the *PV* of losses is calculated as it is for equation 1, but by replacing FD_{exp} with FD_{hyp} defined in Equation 3 (Saez and Requena, 2007):

$$FD_{hyp} = \frac{1}{(1+at)^{b/a}}; \quad a, b > 0; a=b=2k \quad (3)$$

To address the uncertainty related to discounting mentioned above, the loss values of Sundarbans' WES estimated in 2100 are used, and re-calculated by considering five discounting options including two hyperbolic and exponential discount factors, and three discount rates of 0% (base case with zero-discounting); 3.4% (World Bank interest rate for Bangladesh, derived from <https://data.worldbank.org/indicator/FR.INR.RINR?view=map>); and 7% (current Bangladesh interest rate, derived from <https://tradingeconomics.com>).

Thus, five options are considered as follows; (D1) base case with $k=0$; (D2) exponential discounting with $k=0.034$; (D3) exponential discounting with $k=0.07$; (D4) hyperbolic discounting with $k=0.034$; and (D5) hyperbolic discounting with $k=0.07$.

5.3 Results

The results are presented below in two parts; (1) Present monetary value of WES; and (2) Potential impacts of RSLR-induced inundation on WES, and resulting losses in the value of WES, estimated for the three considered RCPs in 2100.

5.3.1 Present monetary value of WES

- *Food provision value (fish and marine species)*

The total food provision value of the wetland ecosystems in the Western coast of Bangladesh is quantified by using the net factor income method in which the PS value is estimated. Table 5.3 shows the valuation results in which the PS has been estimated by calculating the net revenue generated in the market. This value was estimated first by calculating the annual gross revenue earned for each type of species (i.e. the annual production multiplied by the average market price).

With respect to the market price obtained, ‘‘Awaous grammepomus’’ and ‘‘Chello’’ are the two fish species with the lowest market price at 45 BDT (Bangladeshi Taka) per kilogram, while ‘‘Boma’’ is the highest priced at 1500 BDT per kilogram. Among the prawn species, ‘‘Gusha’’ and ‘‘Macrobrachium rosenbergii’’ have the lowest and highest prices at 80 BDT and 950 BDT per kilogram, respectively. The lowest and highest prices for the crab species are 300 BDT and 1100 BDT per kilogram of ‘‘Chapa’’ and ‘‘Pachygrapsus marmoratus’’, respectively.

Total gross revenue was obtained by summing the gross revenue of all types of species. Having computed the annual gross revenue, the annual net revenue was then estimated by multiplying the gross revenue by the fishing costs. Since the primary data was not completely available for the fishing costs including operation and maintenance costs, here, the approximate fishing cost in Bangladesh was considered reported by Ahmed et al. (2011) at about 40% of the gross revenue.

Finally, the PS was calculated by multiplying the annual net revenue (for each type of species) with the ecosystem dependency factor which is assumed to be 40% (adapted from Schep et al., 2012a). By summing the PS estimated for each type of species, the total food provision value is estimated at about 9250 million BDT, which is equivalent to approximately US\$ 112 million annually. In these computations, the 2017 prices and the December 2017 exchange rate (1 BDT = 0.0121 US\$) was used throughout.

Table 5.3 Calculation of producer surplus for estimating food provision value of the wetland ecosystems in the West coast of Bangladesh. Producer Surplus (PS). Source: Survey Based (SB), Literature Based (LB)

Type of species	Market price range (BDT/kg) [SB]	Annual production (MT) [SB]	Annual gross revenue (mln. BDT)	Fishing cost [LB]	Annual net revenue (mln. BDT)	Ecosystem dependency factor [LB]	PS (mln. BDT)
Fish	45 -1,500	38,555	6,888	40 %	4,133	0.4	1,653
Shrimp/ Prawn	80 - 950	6,812	4,887	40 %	2,933	0.4	1,173
Crab	300 – 1,100	28,079	26,751	40 %	16,051	0.4	6,420
Total		73,446	38,526		23,117		9,250

- *Recreation / tourism value*

Collected information in the survey shows that the visitors are young people (mostly men) in the age range between 20 and 30 years who were originally from the Bangladesh (see Figure 5.5).

Figure 5.5 Socio-demographic information of the visitors (interviewed in June 2017) of the wetland ecosystems in the Sundarbans region

Table 5.4 shows the calculation of the recreation value represented here by estimating the PS which is the net revenue generated by the visitors derived from their direct and indirect expenditures during their visit. Thus, the net recreational benefit for the study area was calculated by multiplying average expenditure per day by the added value and the factor of ecosystem dependency. Because of data scarcity on the cost structure of the tourism industry, here it is assumed that 40% of the average expenditure reflects the added value to the tourism (adapted from Schep et al., 2013). Also, the dependency level of recreational activities on the wetland ecosystems of the study area is assumed to be 80% and 50% for direct and indirect values, respectively (adapted from van de Kerkhof et al., 2014b).

Total net revenue is finally estimated by considering the total number of 230,000 visitors in the study area recorded in 2016-2017 (Molla, 2017), and the average duration of stay of 1.4 day

per visit (derived from the survey). This calculation resulted in an estimated annual value of about 120 million BDT which is equivalent to an annual value of approximately US\$ 1.5 million.

Table 5.4 Calculation of producer surplus for estimating recreation/tourism value of the wetland ecosystems in the West coast of Bangladesh. Source: Survey Based (SB), Literature Based (LB)

Values	Added value [LB]	Average expenditure /day (BDT) [SB]	Added value	Factor ecosystem dependency [LB]	Producer surplus (BDT)
Direct values					
Visits to mangrove swamps, river cruising, wildlife watching, etc.	40%	332	33	80%	106
Indirect values					
Transportation, accommodation, food	40%	1,326	30	50%	265
Total/person/day		1,658	63		371
Total					120,000,000

- *Art value*

The survey results revealed that 75% of the art works contain the natural landscape of the SMF, marine area, aquaculture ponds as well as the flora and fauna, reflecting a unique artistic characteristic of the study area. Table 5.5 shows the results of revenue generated through selling paintings and photos as sold in the art shops.

The total amount represents an approximation of the art value of scenic landscape and artistic view of the wetland ecosystems captured in art works. The total art value was thus estimated at about 623,000 BDT which is equivalent to an annual rate of approximately US\$ 7,550.

Table 5.5 Calculation of the art value of the wetland ecosystems in the West coast of Bangladesh. Source: Survey Based (SB)

Category	No. of sold pieces in 2016-2017 [SB]	Annual revenue (BDT) [SB]	Ecosystem related factor [SB]	Estimated art value (BDT)
Painting	285	331,000	75%	248,000
Photo	200	500,000	75%	375,000
Total	485	831,000		623,000

- *Raw materials value (timber and fuelwood)*

The SMF is the habitat of about 69 species of flora with a dominant type as Sundari (*Heritiera fomes*) (Minar et al., 2013). In this study, twenty three (23) different types of species were identified in the survey results. Table 5.6 shows the estimated value of raw materials provided by these species in the study area. The mean value was estimated by averaging the entire market price of timber per m³ and fuelwood per mound, resulting in total mean value of about 240,000 BDT per m³ (each fuelwood mound is assumed to occupy 1 m³).

Total annual value was then calculated by multiplying the estimated mean value with the annual amount of timber harvested in the Sundarbans which is 3567 m³ as reported by Uddin et al. (2013). This results in a total value of about 856 million BDT which is equivalent to approximately US\$ 10 million per year.

Table 5.6 Value of raw materials provided by the SMF. Source: Survey Based (SB)

Type of species [SB]	Timber value (BDT/m ³) [SB]	Fuelwood value (BDT/mound) [SB]
Koloi	0	100
Goran	10,600	3,970
Khalshi	31,802	1,560
Vola	0	265
Singara	0	440
Dundole	113,074	150
Hethal	0	165
Amur	10,600	670
Bola	0	450
Choila	0	100
Lakri	0	150
<i>Heritiera fomes</i>	1,466,784	3,800
<i>Xylocarpus mekongensis</i>	1,725,265	2,580
<i>Xylocarpus granatum</i>	91,872	720
<i>Bruguiera gymnorrhiza</i>	399,293	3,635
<i>Avicennia officinalis</i>	764,134	5,440
<i>Excoecaria agallocha</i>	193,109	5,290
<i>Ceriops decandra</i>	28,268	940
Kholisa	21,201	130
<i>Sonneratia apetala</i>	423,321	4,770
Boloi	0	200
<i>Nypa fruticans</i>	132,508	11,510
<i>Sonneratia caseolaris</i>	40,636	520
Mean value	240,000	
Total	856,000,000	

- *Summary of the valuation results (present-day value)*

Table 5.7 shows a summary of the present WES value of the Western coast of Bangladesh, which is estimated in million (mln) BDT and US Dollars per hectare¹ (with the exchange rate of December 2017). According to the results, food provision (in terms of fish and marine species) represents the highest WES value estimated at 135 US\$/Ha. Provision of raw materials represents the second most valuable WES at 27 US\$ per hectare of the mangrove area of the Sundarbans, followed by recreation service (1.7 US\$/Ha), while art value represents only 0.01 US\$/Ha in the study area.

Table 5.7 Summary of the present-day value of WES in the Western coast of Bangladesh

WES	Estimated value (mln. BDT)	Estimated value (BDT/Ha)	Estimated value (US\$/Ha)
Food provision (fish and marine species)	9,250	11,150	135
Raw materials (timber and fuelwood)	856	2,265	27
Recreation / tourism	120	145	1.7
Art	0.62	0.75	0.01

5.3.2 Potential impacts of RSLR-induced inundation on WES by 2100, and resulting losses in the value of WES in 2100

5.3.2.1 Development of RSLR Scenario

In this section, first the current trends in local RSLR are determined as the baseline, and secondly the scenarios for local RSLR in 2100 were developed, by using the global mean SLR and regional SLR for the coast of Bangladesh. The Ganges–Brahmaputra–Meghna Delta area (GBMD) is focused, which is located in the central part of Bangladesh coastal area between the latitudes of 21.65°–22.90° North and between the longitudes 89° – 91.50° East. Its coastline is bounded by the Bay of Bengal to the South.

¹ The estimation of raw materials value (timber and fuelwood) is considered only for the mangroves area of the Sundarbans with extent of 3,778 km², according to Payo et al. (2016), while the value of other three services are estimated per hectare of the whole wetland ecosystems considered as the SMF, pelagic system and aquaculture lands with total size of 8,300 km².

- **Current trends of local RSLR**

To determine the current trends in local RSLR (i.e. baseline) for the coast of Bangladesh, first, all available data from different sources were collected. These data were then analyzed to determine the current trends in local RSLR.

The main source of data and information for local sea level is tide gauge records. The major global data source for tide gauge records is the Permanent Service for Mean Sea Level (PSMSL). Instrumental records of sea-level rise measured with tide gauges are available both locally and globally. This database is up-to-date and in addition to new measurements, long-term historic measurements are on occasion added to the archive (Douglas, 1997; Haigh et al., 2009; Woodworth et al., 2009). Other sources of sea-level data such as the World Ocean Circulation Experiment (WOCE) may also offer suitable data, while national and port authorities can be consulted for data as well. In this study, data were obtained from the above-mentioned global data bases. Based on the length and the quality of data, the PSMSL recorded data were deemed to be the best source of tide gauge data for this study. Figure 5.6 shows the location of stations (white marks) where the data is derived in the study area.

Figure 5.6 Location of tide gauge stations (white marks) in the coast of Bangladesh. From left to right: Hiron Point, Khepupara, Charchanga, and Chittagong

Figures 5.7 and 5.8 show the available data at CHARCHANGA and CHITTAGONG stations, which span 21 and 7 years, respectively. In addition to these two stations, two other stations (KHEPUPARA) and (HIRON POINT), with data spanning 23 years, were also considered. The RSLR trends for these 2 stations are shown in Figures 5.9 and 5.10. The obtained RSLR trends for all the four stations are summarized in Table 5.8, showing the spatially variable rate of SLR along the coast of Bangladesh.

Figure 5.7 Monthly and annual mean sea level data and corresponding SLR trends at CHARCHANGA station

Figure 5.8 Monthly and annual mean sea level and corresponding SLR trends at CHITTAGONG station

Figure 5.9 Monthly and annual mean sea level and corresponding SLR trends at KHEPUPARA Station

Figure 5.10 Monthly and annual mean sea level and corresponding SLR trends at HIRON POINT Station

Table 5.8 Current local trends of RSLR in Bangladesh coastal area, based on available data

Name	Years of data used	RSLR based on monthly data (mm/ year)	+/- 95% CI	RSLR based on Annual data (mm/ year)	+/- 95% CI
CHITTAGONG	7	-1.25	25.98	3.17	14.67
CHARCHANGA	21	8.82	7.18	8.15	5.5
KHEPUPARA	23	14.84	5.31	19.15	4.62
HIRON POINT	23	4.62	5.27	3.55	4.42

• Developing local RSLR scenarios by 2100

To determine local RSLR by 2100 in the coastal area of Bangladesh, IPCC guidelines prescribed by Nicholls et al. (2011) are used, in which three different options are given based on data availability. Here, the ‘intermediate’ option is used together with the most recent CC projections reported by the Fifth Assessment Report (AR5) of IPCC for developing local RSLR scenarios. The most recent CC projections used here are the RCPs, describing four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. Compared to the previous projections (i.e. SRES), the RCPs cover a wider range, as they also represent scenarios with climate policy. In terms of overall forcing, RCP8.5 is broadly comparable to the SRES A2/A1FI scenario, RCP6.0 to B2 and RCP4.5 to B1. For RCP2.6, there is no equivalent scenario in SRES (Pachauri et al., 2014).

RSLR projections for a specific location should take into account the different contributions from the components at the global, regional and local scales, as relevant to the study area. These can be integrated for a given site (here, for the Bangladesh coastal area) using following equation: (Nicholls et al. (2011))

$$\Delta RSL = \Delta SL_G + \Delta SL_{RM} + \Delta SL_{RG} + \Delta SL_{VLM} \quad (4)$$

where:

- ΔRSL is the change in relative sea level
- ΔSL_G is the change in global MSL
- ΔSL_{RM} is the regional variation in sea level due to meteo-oceanographic factors
- ΔSL_{RG} is the regional variation in sea level due to changes in the earth’s gravitational field
- ΔSL_{VLM} is the regional variation in sea level due to vertical land movement

According to the equation 4, developing local RSLR scenarios is based on the summation of two major components; (1) **global MSL change (ΔSL_G)**; and (2) **regional spatial variations in sea level ($\Delta SL_{RM} + \Delta SL_{RG} + \Delta SL_{VLM}$)**. These two components are described as follows:

1. Global MSL change

The global MSL change results from the change in the volume of the global ocean. This is mainly due to: i) thermal expansion of the ocean as it warms; ii) melting of glaciers and ice caps due to global warming (Bindoff et al., 2007; Meehl et al., 2007); and, iii) changes in the mass balance of the Greenland and Antarctic ice sheets, which is less certain (Shepherd and Wingham, 2007). The Synthesis report of International Panel on Climate Change (IPCC) in 2014 reports that the global MSL rose by 0.19 m [0.17 to 0.21 m] with an average rate of 1.7 mm/year in the 20th Century (Bindoff et al., 2007). The IPCC's AR5, 2013 (Church et al., 2013) indicates a transition in the late 19th century to the early 20th century from relatively low mean rates of rise over the previous two millennia to higher rates of rise (high confidence). From 1961 to 2003, the average rate of SLR was 1.8 ± 0.5 mm/yr, while between 1993 and 2010 the rate was very likely higher at 3.2 mm/yr [2.8 to 3.6 mm/yr]; similarly high rates likely occurred between 1920 and 1950.

Derivation of global mean sea level rise from IPCC's AR5

Global mean SLR projections are obtained here, by using the projections given in IPCC's AR5, considering the 'intermediate' option prescribed by Nicholls et al. (2011). Following the graphs of SLR given in AR5, the SLR estimates presented here are from 2008 to 2100, with a global mean SLR of 40 mm by 2008 relative to 1986-2005. To represent the time variation of the global mean SLR, the curves presented in AR5 (Figure 13.11 in Church et al., 2013) for the four RCPs are reproduced here by deriving the coefficients of Nicholls's method as follows:

$$\Delta SL_G = a_1 t + a_2 t^2 \quad (5)$$

where:

- ΔSL_G is the change in global mean sea level
- t is the number of years starting from 2008
- a_1 is the rate of sea level change (per year)
- a_2 is the change in the rate of sea level change (per year)

Table 5.9 indicates the calculated coefficients for each scenario. Figure 5.11 shows the resulting SLR curves that are generated via Equation 4 for the four RCPs; (estimated upper and lower limits are based on the 5th and 95th percentile reported).

Table 5.9 The rate of global sea level rise and acceleration of this rise for the four IPCC RCPs

Name	Bound	a ₁ (m/year)	a ₂ (m/year ²)	Name	Bound	a ₁ (m/year)	a ₂ (m/year ²)
RCP 2.6	Upper	0.004934	1.206 e-5	RCP 4.5	Upper	0.004570	2.589 e-5
	Middle	0.004426	-1.220 e-6		Middle	0.003953	1.366 e-5
	Lower	0.003400	-6.940 e-6		Lower	0.002977	6.939 e-6
RCP 6.0	Upper	0.004544	2.820 e-5	RCP 8.5	Upper	0.003349	6.451 e-5
	Middle	0.003965	1.486 e-5		Middle	0.003279	4.131 e-5
	Lower	0.003010	7.776 e-6		Lower	0.002675	2.598 e-5

Figure 5.11 The range of possible global average sea level rise during the 21st Century using Equation 4, based on estimates reported in Church et al. (2013) - Table 13.11. The upper and lower limits refer to the 5th and 95th percentiles of the sea level distribution; which is assumed to be Gaussian (Reproduced here based on the methodology of Nicholls et al., 2011)

2. Regional spatial variations in sea level change

Over the next decades, regional RSLR in most parts of the World are likely to be dominated by dynamical changes, resulting from natural variability, although exceptions are possible near rapidly melting ice sheets where static effects could become large (Church et al., 2013). Figure 5.12 shows ensemble mean regional relative sea level change between 1986-2005 and 2081-2100 for RCPs 2.6, 4.5, 6.0 and 8.5 (these values include the global MSL change as well as regional variations). It is very likely that in about 95% of the World Oceans, regional RSLR will be positive, while most regions with estimated sea level fall are located near contemporary and former glaciers and ice sheets. It should be noted that the effect of vertical land movement, consisting of 'tectonic uplift' (except Glacial Isostatic Adjustment 'GIA' factor) and land subsidence is not included in estimates of regional RSLR shown in Figure 5.12.

Figure 5.12 Ensemble mean regional relative sea level change (m) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0, and (d) 8.5 between 1986-2005 and 2081-2100. Each map includes effects of atmospheric loading, land ice, glacial isostatic adjustment (GIA), and terrestrial water sources (Source: Church et al., 2013)

Regional spatial variations in sea level change are mainly due to the different factors. Following Nicholls et al. (2007), here, these factors for the coastal area of Bangladesh are described and computed as follows:

a. Meteo-oceanographic factors (ΔSL_{RM}), including differences in the rates of oceanic thermal expansion, changes in long-term wind and atmospheric pressure, and changes in ocean circulation (such as the Gulf Stream - e.g. Lowe and Gregory, 2006 and in the Indian Ocean - Han et al., 2010). The contributions from these phenomena could be significant, causing large

regional departures of up to 50-100% from the global average value of SLR. However, coupled atmosphere-ocean climate models of these effects under global warming are inconsistent on the location of such larger-than-average changes (Meehl et al., 2007; Pardaens et al., 2011). In previous IPCC reports, this component was presented as a separate map (Figure 10.32 in Meehl et al., 2007), while AR5 presents maps that combine the global mean SLR and the ΔSL_{RM} component, as shown in Figure 5.12. Therefore ΔSL_{RM} is computed (see Table 5.10) for the year 2100, by calculating the difference between the values shown in Figure 5.12 and the 2100 global mean SLR values for each RCP as indicated in Table 5.9. It should be noted that, the temporal variation in ΔSL_{RM} is assumed to be linear from 2008 to 2100.

Table 5.10 Difference between Regional RSLR (m) and Global mean SLR (m) for the coast of Bangladesh due to meteo-oceanographic factors in 2100

Parameter	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Regional RSLR (Fig. 5.10)	0.4	0.49	0.5	0.65
Global mean SLR	0.38	0.46	0.47	0.62
Regional Variation (ΔSL_{RM})	0.02	0.03	0.03	0.03

b. Changes in the regional gravity field of the Earth (ΔSL_{RG}), which is due to ice melting (caused by redistribution of mass away from Greenland, Antarctica as well as glaciers). The global SLR caused by melting of an ice sheet will not be evenly distributed as a single “global eustatic” or global mean value (see Section 5.5.4.4 in Bindoff et al., 2007). If a polar ice sheet melts, then the volume of water in the oceans increases, but at the same time, the gravitational pull from the ice sheet on the oceans close to the ice sheet falls. The net effect of these processes is that SLR occurs faster in areas farther away from the source of the melting. For example, in the case of melting Greenland ice, there would be less SLR than the global average in the North Atlantic, near Greenland, while an enhanced SLR (compared to the global eustatic value) will occur at low latitudes and in the Southern oceans (Plag, 2006). Each potential mass source or sink (Greenland ice sheet, Antarctic ice sheet, glaciers, water storage on land) will produce its own pattern or “fingerprint” of sea level change measured at the coast (e.g. Mitrovica et al., 2001). A few studies are now starting to develop scenarios of future sea level that recognize changes in the global and regional gravity field associated with mass exchange with the ocean. However, due to the unavailability of reliable projections of the potential RSLR change due to this phenomenon at present, this effect is not taken into account in this study.

c. Vertical land movements (uplift and subsidence) (ΔSL_{VLM}), which is due to various natural and human-induced geological processes (Emery and Aubrey, 1991; Peltier, 2004; Ericson et al., 2006; Christensen et al., 2007; Syvitski, 2008). Apart from land subsidence phenomena which could significantly affect local RSLR, tectonic uplift may also affect RSLR which is caused by other natural factors including: i) neotectonics, ii) glacio-isostatic adjustment (GIA), and iii) sediment compaction/consolidation. These changes can be regional, slow and steady,

as in the case of GIA, but can also be localized, large and abrupt, for example due to earthquakes.

Here, *tectonic uplift* is only considered as the component of land movement. Here, the land subsidence factor is excluded in computation of RSLR scenarios, since there is a significant spatial variation of local land subsidence, and as a result, this component cannot be directly incorporated in the regional scale projections of RSLR along the coast of Bangladesh. In addition, other components causing vertical movement such as GIA are already included in the regional RSLR projected by IPCC (Figure 5.12). To obtain the value of *tectonic uplift* in the study area, the dataset¹ presented by Prof. Richard Peltier at the University of Toronto was used, using the ICE-5G (VM2 L90) model, estimated that the mean uplift at the Bangladesh delta area is 0.35mm/year, corresponding to 0.032 m in 2100 ($0.35 \times (2100-2008)$). Combining the above values, the regional variations in sea level change (including tectonic uplift, but excluding land subsidence) are finally estimated in 2100. Table 5.11 shows the results, reflecting the influence of tectonic uplift on the regional variations of SLR.

Table 5.11 Effects of tectonic uplift factor on regional variation of RSLR (m) in the coast of Bangladesh in 2100

Parameter	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Regional variation (ΔSL_{RM})	0.02	0.03	0.03	0.03
Tectonic uplift (ΔSL_{VLM})	-0.032	-0.032	-0.032	-0.032
$\Delta SL_{RM} + \Delta SL_{VLM}$	-0.012	-0.002	-0.002	-0.002

Table 5.12 indicates the final value of local RSLR projected for the coastal area of Bangladesh, by summing the two major components described above (Equation 4). Accordingly, the lowest and highest projected values of local RSLR for 2100, relative to 2008, are 0.256 m and 0.961 m, for the RCP2.6 and RCP8.5, respectively.

¹ Source: http://www.atmos.physics.utoronto.ca/~peltier/datasets/Ice6G_C_VM5a_O512.

Table 5.12 Estimation of the RSLR (m) in Central coast of Bangladesh (excluding Land Subsidence) based on different Scenarios projected by 2100 (relative to 2008)

Year	Bound	Climate Change Scenarios			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5
2025	lower	0.074	0.075	0.076	0.078
	upper	0.123	0.124	0.125	0.127
2050	lower	0.144	0.167	0.168	0.192
	upper	0.265	0.288	0.289	0.318
2075	lower	0.205	0.256	0.263	0.338
	upper	0.422	0.478	0.489	0.599
2100	lower	0.256	0.360	0.372	0.517
	upper	0.594	0.704	0.724	0.961

Figure 5.13 shows the resulting composite RSLR values projected above, taking into account the global mean SLR and regional variations of SLR due to the effects of tectonic uplift and meteo-oceanographic factors ($\Delta SL_{RM} + \Delta SL_{VLM}$) projected from 2008 to 2100. It should be noted that, in developing the RSLR scenarios in this study, one extra scenario could have been also developed based on the extrapolation of historical rate of RSLR derived from tide gauges (Table 5.8), but since the observed trends cannot be correctly assumed to continue linearly into the future, this extrapolation was not undertaken here.

Figure 5.13 RSLR including the effects of global mean SLR (blue), tectonic uplift and meteorological factor (Red) for the coast of Bangladesh from 2008 to 2100 - No land subsidence included. Upper and lower limits (dashed lines) indicate the 5th and 95th percentiles of distribution, which is assumed to be Gaussian

5.3.2.2 Development of RSLR-induced inundation scenarios

In this step, first the extent of the inundated area due to RSLR in 2100 (relative to 2008) is determined along the West coast of Bangladesh for the three newly developed IPCC scenarios of RCP2.6, RCP6.0 and RCP8.5. These RSLR scenarios, which are based on the projected RSLR derived from the previous step (Table 5.12), include a local land subsidence rate of 8.8 mm/year (81 cm by 2100) for the Western coast, derived from Brown and Nicholls (2015); Roy et al. (2017).

Table 5.13 shows the calculated RSLR by 2100 including and excluding land subsidence for each RCP. Notably, in order to encapsulate the largest possible difference in the extent of inundated area, here, the maximum variation of RSLR is used by considering lower and upper projections for the scenarios RCP 2.6, RCP 6.0 and RCP 8.5 while selectively including or excluding the land subsidence (since the future land subsidence rates are uncertain over the time scale of this study). This resulted in the development of three scenarios A, B, and C, representing each RCP indicated in Table 5.13.

Table 5.13 Estimation of RSLR (m) and corresponding inundated area (Ha) by 2100 for the three RCPs considered in this study

Parameter	Scenarios		
	RCP 2.6 (A)*	RCP 6.0 (B)**	RCP 8.5 (C)***
RSLR (m) - from Table 5.12	0.25	0.37	0.96
Land subsidence (m)	-	0.81	0.81
RSLR (m)	0.25	1.18	1.77
Inundated area (Ha)	16,000	61,200	80,500

* Low scenario - Low SLR projection, no land subsidence

** Moderate scenario - Low SLR projection, including land subsidence

*** Worst case scenario - High SLR projection, including land subsidence

After developing the RSLR scenarios, corresponding inundated area is determined by using the most recent open-source DEM of Bangladesh coastal area, which is available with a spatial resolution of 30 m (<https://earthexplorer.usgs.gov>). Figure 5.14 shows the inundation area determined by using ArcGIS and a bath tub approach corresponding to the three developed RSLR scenarios A, B, and C.

Figure 5.14 Extent of the inundation area in blue for each scenario in 2100; (a) Scenario A with 0.25 m of RSLR; (b) Scenario B with 1.18 m of RSLR; (c) Scenario C with 1.77 m of RSLR

5.3.2.3 Potential impacts of RSLR-induced inundation on WES, and resulting losses in the value of WES in 2100

- Changes in the food provision value (fish and marine species)

Table 5.14 shows the identification of potential impacts of inundation on fishery industry for each considered RSLR scenario, leading to changes in the value of food provision service provided by the wetland ecosystems in the study area. As described in section 5.2.2.2, *impact indications* are assigned to each fish or fishery related variable, based on the elicitation of fishermens' opinions regarding the likely impacts of inundation on each variable (as an average magnitude, rounded off to the *impact indication* ranges). Expected inundation impacts are justified for each variable as indicated in Table 5.14 (adapted from Mehvar et al., 2018b).

Table 5.14 Different fish/fishery-related variables potentially affected by RSLR-induced inundation for the three scenarios considered in this study. Each + or - indicates a 10% increase or decrease in the characteristics of variables compared to present. NK: Not known

Fish / fishery related variable	Potential impact of RSLR-induced inundation			Expected inundation effect
	Scen. A	Scen. B	Scen. C	
Primary & secondary production	+	++	+++	Due to the increase of vertical mixing, more nutrients are likely to be supplied. Ideal situation is created for breeding and oviposition, as larger nursery area is developed.
Distribution / migration pattern	NK	NK	NK	Unknown due to interaction of diverse variables such as water temperature, salinity, vertical mixing rates and wind driven circulation.
Abundance	+	++	+++	Larger water body and nursery area will provide more nutrients.
Health status	-	--	---	Increased turbidity, probability of having diseases for species.
Food web	+	++	+++	Increased zooplanktons and nutrients supply.
Nursery habitat	+	++	+++	Due to the creation of larger (natural) water bodies.
Fish ponds & fishing community	-	----	-----	Due to probability of considerable damage to the fish ponds while inundation occurs.

Quantitative changes in the food provision value of WES in the West coast of Bangladesh are estimated by relating the identified inundation impacts to fishery through analysing how the affected variables (as shown in Table 5.14) can potentially change the present-day PS. Since the PS represents the net revenue (gross revenue subtracted by the costs) generated by the fishery industry, in this analysis, the likely inundation impacts on catch volume, market price and fishing and adaptation costs are considered. By identifying these impacts, resulting changes in the food provision service are quantified (see Table 5.15). For example, inundation increases the extent of natural nursery habitat for fishes, resulting in a likely increase in catch volume, and hence lower market price. Therefore, PS is expected to remain constant, due to the opposite

effects of gross revenue and costs which will neutralize each other. As indicated in Table 5.15, a constant contribution level of 10% is assigned for most of the fishery related variables, while nursery habitat and fish ponds are weighted higher (25%) than other attributes, and therefore contribute more to the PS value¹. This would represent the weight of each fishery-related variable as a percentage of the total value of PS. These percentages are approximate indications (adapted from Mehvar et al., 2018b), since there is no concrete evidence available yet to enable quantitative estimation of CC driven changes (in particular, RSLR-induced inundation) to the fishery related variables over a long time span.

Changes in the food provision value due to RSLR-induced inundation is ultimately calculated as a range for each variable by using potential *impact indications* (Table 5.14), when the appropriate ‘contribution to the PS value (%)’ is multiplied by the pre-estimated (present-day) PS value. The total change is finally calculated by summing the changes of PS associated with each variable, resulting in losses of 0 – 323 million BDT (US\$ 0 – 3,800,000), 818 – 1,110 million BDT (US\$ 9,800,000 – 13,300,000), and 1,374 – 1,664 million BDT (US\$ 16,500,000 – 20,000,000) for scenarios A, B, and C, respectively.

Table 5.15 Changes in the food provision value due to RSLR-induced inundation by 2100 for the three scenarios considered (in 2017 BDT, discounting rate $k=0$). PS: producer surplus, F: Fishing, A: Adaptation, NK: Not known, NE: No effect. Negative values indicate a loss compared to the present-day

Fish / fishery related variable	Catch volume	Market price	Cost		Effect on producer surplus (PS)	Contr. to the PS value	Change in the food provision value (mln. BDT)		
			F	A			Scen. A	Scen. B	Scen. C
Primary & secondary production	↑	↓	↓	↑	NE	10%	NE	NE	NE
Distribution / migration	NK	NK	NK	NK	NK	10%	NK	NK	NK
Abundance	↑	↓	↓	↑	NE	10%	NE	NE	NE
Health Status	↓	↑	↑	↑	↓	10%	- (0-92)	- (101-185)	- (194-277)
Food web	↑	↓	↓	↑	NE	10%	NE	NE	NE
Nursery habitat	↑	↓	↓	↑	NE	25%	NE	NE	NE
Fish ponds & fishing community	↓	↑	↑	↑	↓	25%	- (0-231)	- (717-925)	- (1,180-1,387)
Total change							- (0 – 323)	- (818 – 1,110)	- (1,374 – 1,664)

¹ Such a higher contribution level for fish ponds and fishing community may not be justifiable at locations where the fishery industry is not as aquaculture-dependent as it is in the Sundarbans region.

- Changes in the recreation/tourism value

As described in section 5.2.2.2, eight tourism-related attributes (e.g. tranquillity, natural landscape, bird watching, etc.) are ranked based on the visitors' preferences expressed for visiting the Sundarbans region. Figure 5.15 shows this ranking, indicating that natural landscape and climate are selected respectively as the most and least favoured attributes. This ranking indicated by percentage is then taken to be representative of the contribution level of each attribute to the total pre-estimated present-day recreation value.

Table 5.16 presents the analysis of RSLR-induced inundation impacts on recreation value indicating that inundation may potentially affect some of the recreational attributes (e.g. natural landscape, welfare facility for visitors), while it may impose no impact on some others (e.g. climatic condition). However, the small inundated area in the Sundarbans region, especially in the Scenario A, has led us to consider a conservative range of change (0-10%) in the recreation value of the SMF, and the marine area. This change is likely to increase for the other two Scenarios B, and C (upto the range of 21-30%) in which a larger extent of inundation in the Sundarbans may result in much fewer number of visitors and lower revenue.

The potential future change in the value of each attribute is calculated by multiplying potential *impact indications* assigned in Table 5.16 with the 'contribution to the total value' derived from Figure 5.15 and the pre-estimated PS value. Total change is calculated by summing the changes of PS associated with each attribute, resulting in estimated losses of 0 – 8.2 million BDT (US\$ 0 – 98,400), 8.9 – 16.4 million BDT (US\$ 106,800 – 196,800), and 17.2 – 24.7 million BDT (US\$ 206,000 – 296,000) for scenarios A, B, and C, respectively.

Figure 5.15 Contribution of each recreational attribute to the total tourism value as indicated by visitors through ranking of their preferred attributes

Table 5.16 Changes in the recreation value due to RSLR-induced inundation by 2100 for the three scenarios considered (in 2017 BDT, discounting rate $k=0$). Each - indicates a 10% decrease in the characteristics of the attributes compared to present. Negative values indicate a loss compared to the present-day. NE: No effect

Tourism/ recreational attributes	Potential impact of inundation			Contrib. to the PS value	Change in the recreation value (mln. BDT)		
	Scen. A	Scen. B	Scen. C		Scen. A	Scen. B	Scen. C
Tranquility	-	--	---	24%	-(0-2.9)	-(3.1-5.7)	-(6-8.6)
Natural landscape	-	--	---	26.7%	-(0-3.2)	-(3.5-6.4)	-(6.7-9.6)
Friendly local people	NE	NE	NE	21%	NE	NE	NE
Safety	NE	NE	NE	8%	NE	NE	NE
Welfare facility for visitors	-	--	---	8%	-(0-0.96)	-(1-1.9)	-(2-2.9)
Watching bird/live species	-	--	---	10%	-(0-1.2)	-(1.32-2.4)	-(2.52-3.6)
Enjoying the beach area	NE	NE	NE	2%	NE	NE	NE
Climate	NE	NE	NE	0.3%	NE	NE	NE
Total change					-(0 – 8.2)	-(8.9 – 16.4)	-(17.2 – 24.7)

- Changes in the art value

Table 5.17 shows the estimation of changes in the art value of the wetland ecosystems. Changes to each art-related attribute are identified based on the stated opinions of experts who deal with art works, and by eliciting their thoughts on the likely changes of future inundation driven changes to the considered attributes. This analysis resulted in assigning low ranges of change to both attributes in Scenario A (0-10%), increasing to higher losses ranging between 21-30% for Scenario C in which a larger inundated area is considered.

The total loss value is calculated by multiplying the *potential impact indications* assigned in Table 5.17 with the estimated PV, and summing the resulting loss values of the two attributes (assuming equal contribution to the total value) for each RSLR scenario. The results indicate losses of 0 – 0.12 million BDT (US\$ 0 – 1,450), 0.13 – 0.25 million BDT (US\$ 1,550 – 3000), and 0.26 – 0.37 million BDT (US\$ 3,100 – 4,400) for scenarios A, B, and C, respectively.

Table 5.17 Changes in the art value due to RSLR-induced inundation by 2100 for the three scenarios (in 2017 BDT, discounting rate $k=0$). Each - indicates a 10% decrease in the characteristics of the attributes compared to present. Negative values indicate a loss compared to the present-day

Art related attribute	Potential impact of inundation			Change in the art value (mln. BDT)		
	Scen. A	Scen. B	Scen. C	Scen. A	Scen. B	Scen. C
Marine and coastal landscape	-	--	---	-(0-0.062)	-(0.068-0.124)	-(0.13-0.187)
Flora & fauna	-	--	---	-(0-0.062)	-(0.068-0.124)	-(0.13-0.187)
Total change				-(0 – 0.12)	-(0.13 – 0.25)	-(0.26 – 0.37)

- Changes in the value of raw materials (timber and fuelwood)

As described in section 5.2.2.2, the negative impacts of inundation on the value of timber and fuelwood provided by the Sundarbans forest, directly depend on the extent of inundated area and the level of soil and river salinity for each scenario. Because of data scarcity in terms of the severity of salinity intrusion to the soil and mangrove roots, and the tolerance capacity of the SMF to this threat, the likely salinity impacts are considered as a hypothetical scenario that potentially change the wood production service provided by the SMF by 2100.

Table 5.18 shows the results indicating a conservative scenario of 0 – 10% reduction in this value for both Scenarios B and C, while no potential loss is considered for Scenario A, in which the SMF is not exposed to inundation due to 25 cm of RSLR by 2100 (see Figure 5.14). The total loss value is calculated by multiplying the potential *impact indications* assigned in Table 5.18 with the estimated PV for each Scenario. The results indicate potential losses in the range of 0 – 85 million BDT (US\$ 0 – 1,000,000) for both scenarios B and C, and no expected loss for Scenario A.

Table 5.18 Changes in the value of raw materials of the SMF due to RSLR-induced inundation by 2100 for the three scenarios considered (in 2017 BDT, discounting rate $k=0$). Each - indicates a 10% decrease in the value of timber and fuelwood. NE: No effect. Negative values indicate a loss compared to the present-day

Raw materials value of the SMF (timber and fuelwood)	Potential impact of inundation			Change in timber & fuelwood value (mln. BDT)		
	Scen. A	Scen. B	Scen. C	Scen. A	Scen. B	Scen. C
Based on market price of timber & fuelwood	NE	-	-	NE	-(0-85)	-(0-85)
Total change				0	-(0 – 85)	-(0 – 85)

- Summary of results

Estimated changes in the value of four WES of the West coast of Bangladesh due to RSLR-induced inundation in the year 2100 indicate (maximum) total potential losses in the range of mln. US\$ 16.5-20, and mln. US\$ 0-1 for the services of food provision (fish and marine species), and provision of raw materials (timber and fuelwood), respectively. The estimated (maximum) losses for tourism and art services are lower in the range of US\$ 206,000-296,000 and US\$ 3,100-4,400, respectively. These maximum estimates represent the changes under the worst case Scenario C (with 1.77 m of RSLR). Table 5.19 provides an overview of the losses, estimated in 2017 prices, in BDT/Ha and US\$/Ha for the three considered inundation scenarios in 2100.

Table 5.19 Summary of losses in the present-day value of WES due to RSLR-induced inundation by 2100 in the Western coast of Bangladesh, for the three scenarios considered in this study (in 2017 price, discounting rate $k=0$)

WES	Estimated losses in the value (BDT/Ha)			Estimated losses in the value (US\$/Ha)		
	Scen. A	Scen. B	Scen. C	Scen. A	Scen. B	Scen. C
Food provision (fish and marine species)	0 – 390	985 – 1,337	1655 – 2,000	0 – 4.7	11.8 – 16	20 – 24
Raw materials (timber and fuelwood)	0	0 – 225	0 – 225	0	0 – 2.7	0 – 2.7
Recreation / Tourism	0 – 9	10.7 – 19.5	20.7 – 30	0 – 0.11	0.12 – 0.23	0.25 – 0.36
Art	0 – 0.14	0.15 – 0.3	0.31 – 0.44	0 – 0.001	0.001 – 0.003	0.003 – 0.005

- Sensitivity analysis of discounting values

Given the 2100 time horizon, here a zero-discounting rate is used for all estimates, since this rate is widely accepted as a good option for long term (more than 30 years) projects with intergeneration consequences and sustainability view of the World (Voinov and Farley, 2007). However, to address the uncertainty related to discounting, a sensitivity analysis was done for the loss values of Sundarbans' WES in 2100 with four non-zero discounting factors. The results of this analysis are in line with the discourse on the discounting rates in CC and sustainability literature, showing that the valuation outcomes are sensitive to the choice of a discounting rate.

Table 5.20 shows the results of the sensitivity analysis of different discounting factors/rates for the estimated loss in food provision value by 2100 for Scenario C (with 1.77 m of RSLR), showing loss reduction (for example) by a factor of 7 between the base case D1 (zero-discounting) and D4 (hyperbolic discounting with the rate of 3.4%).

Table 5.20 Sensitivity analysis of discounting values for the estimated losses in food provision value in 2100 for Scenario C (The results of this study presented in this chapter are estimated with zero-discounting; base case D1)

Case – Discounting factor	Discounting rate (k)	Change in food provision value in 2100 (US\$/Ha)
		Scen. C
D1 – Base	0.0%	- (20 – 24)
D2 – exp.	3.4%	- (1.25 – 1.5)
D3 – exp.	7.0%	- (0.07 – 0.09)
D4 – hyp.	3.4%	- (3.01 – 3.61)
D5 – hyp.	7.0%	- (1.58 – 1.90)

5.4 Discussion

- Application of the QuantiCEL framework in this study

The QuantiCEL framework developed and demonstrated in the chapter 4 was applied in this chapter to a different site in Western coastal area of Bangladesh. The methodological steps used in this study, follow the step-wise approach presented by this framework, starting with estimation of the present-day value of WES, followed by identifying the inundation impacts on WES, and concluding with the estimation of the changes to the value of WES due to three future inundation scenarios in 2100, based on IPCC projections.

- Comparison with available CC-related literature in Bangladesh coastal area

The few available study sites have quantified potential changes in the value of WES due to CC impacts by using the biochemical modelling (Barange et al., 2017), and mathematical models such as Sea Level Affecting Marshes Model (SLAMM) (Yoskowitz et al., 2017), and DIVA (Roebeling et al., 2013). However, here, an alternative and straight forward approach is proposed, adapted from Mehvar et al. (2018b), which is grounded in primary and secondary data, as well as expert opinions to estimate the likely changes of WES due to different RSLR-induced inundation in the West coast of Bangladesh in 2100.

Existing literature on the coastal area of Bangladesh (mostly related to the SMF) provide a few differing assessments of physical CC impacts. For example, Loucks et al. (2010) reported that 28 cm of SLR would result in a great loss of the SMF and degradation of more than 95% of the tiger habitat, while Colette (2007) suggested that global SLR of 45 cm will cause 75% degradation in the area of the SMF by 2100. However, more recent studies present a different picture in which small inundation areas are attributed to projections of different SLR scenarios in Bangladesh. For example, Dasgupta et al. (2018) found that a 1.2 m SLR by 2100 will not inundate the core region of the Sundarbans, showing that even under the worst case SLR scenario, the Sundarbans will remain above the MSL. In addition, Payo et al. (2016) showed that less than 10% of the present SMF area is likely to be lost as a result of different RSLR scenarios of 46cm, 75 cm and 1.48 m by 2100 (considering combined effects of erosion and

inundation). Similarly, Lovelock et al. (2015) suggested that the Sundarbans will persist beyond the year 2100 even under the most severe SLR scenario of 1.4 m by 2100.

The main reason for the differing assessments in the above mentioned literature, is the usage of different DEM files, leading to different projections of inundation in the Bangladesh coastal area. In some studies, such as Payo et al. (2016) and Dasgupta et al. (2018), the DEM file was created by using the elevation data collected by FINNMAP (a Finish consultancy firm) in 1991 for the Sundarbans, while Hazra et al. (2016) used a DEM file created from the elevation data collected by the Survey of Bangladesh (SOB), Institute of Water Modelling (IWM) and CEGIS.

In this study, the most recent open-source DEM file is used, provided by <https://earthexplorer.usgs.gov> with a spatial resolution of 30 m and elevation accuracy of 1m. The small inundated area estimated for the three scenarios considered here, is due to the relatively high elevation of the study area (especially in the SMF) which is nearly 2 m (and higher) above the MSL. This is in agreement with the average elevation data used in other studies such as Iftekhar and Islam (2004), Payo et al. (2016), and Hazra et al. (2016). However, a finer resolution (both vertical and spatial) DEM will provide better insights on the topography of the Western coast of Bangladesh.

The small inundated area of SMF in this study is in line with the findings of Lovelock et al. (2015), who suggests that mangrove forests are likely to persist at sites with high tidal range (here is about 4m), even with a high rate of RSLR and low level of sediment availability. Notably, the small inundation area in this study would limit landward migration of the SMF. This natural response of mangroves to inundation, can play a vital role in preserving the mangrove forests, preventing losses in the services provided by this ecosystem. It should be emphasized that the MSL (as zero elevation reference) is assumed to be the lowest elevation, at which mangroves can provide services, thus no expansion and recovery is considered for the submerged mangroves.

- Resulted low-medium loss values of WES

The low-medium CC driven changes to the value of WES estimated in this study should be considered a lower bound due to different reasons: (1) the small inundated area for all the three inundation scenarios for the year 2100; (2) expert views regarding the likely RSLR-induced inundation impacts on each WES attribute; (3) the fact that here, RSLR (including a uniform land subsidence) is only considered. Therefore, other CC impacts such as erosion, alteration in precipitation patterns, changes in frequency and intensity of coastal storms and cyclones as well as non-CC driven changes such as anthropogenic factors are excluded in this quantitative assessment; (4) this study is limited only to a subset of four WES mentioned above, and thus analysis of CC impact on other important WES are excluded (e.g. flood control, and climate regulation services); and (5) low affordability level of the stakeholders to obtain the four WES considered, affecting the estimated value in step 1 (e.g. tourism-related expenditures, fish

market price, wood market price, and artwork related expenses). For example, the results of the field survey show a monthly average of income stated by the fishermen in the range of BDT 8,500 – 10,500, which is lower than the reported monthly income (BDT 13,258) in Bangladesh in 2017 (<https://tradingeconomics.com>). This has been similarly seen in the tourism related survey, in which the visitors mostly appeared to have low paying jobs (i.e students, service providers, etc.).

- RSLR impact assignation

Quantitative assessment of the RSLR-induced inundation impacts on WES is done by using the QuantiCEL framework which is grounded in primary and secondary data supported by expert opinions. This approach is considered in relation to the inundated area implying that the more the area is inundated, the higher the potential impacts will be. Notably, *impact indications* are applied in a range with 10% variability rather than affecting the services with a single deterministic value, which is due to the very uncertain change in future climate. For example, a conservative impact range was considered for the provision of raw materials service of the SMF for the Scenario B and C (Table 5.18). Assignment of this low impact range (0-10%) is driven by two reasons: (1) low projection of inundation shown in Figure 5.14 conveys that only small parts of the SMF (about 5%), which are adjacent to the river will be inundated, and therefore the study area is expected to be less affected by the water salinity; and (2) the Sundarbans as a multispecies forest is likely to be more resilient to SLR, due to interspecific facilitation (Huxham et al., 2010; Ward et al., 2016).

With respect to the food provision service (Table 5.14), the *impact indications* on different fish/fishery related variables, depend on whether the variables contribute to the fresh water or aquaculture-related fishery. Since it is shown (Figure 5.14) that the inundation will mostly occur in the Northern part of the Sundarbans where the aquaculture-ponds are dominantly located, a higher *impact indication* is therefore assigned (upto 51% - 60% for Scenario C). This is because the physical variable of fish ponds area is expected to be severely damaged and affected by the interference of salt water (Minar et al., 2013). However, for other variables, given the small inundation area, lower impact of 21% - 30% is assigned for Scenario C. To quantify potential inundation impacts on tourism service, a constant *impact indication* is assigned (e.g. 21% - 30% of the estimated value in Scenario C) for the recreation-related attributes, depending on the extent of inundated area. This approach could be also considered as a scenario, since no data could be collected and used for such quantitative assessment.

- Exclusion of estimating consumer surplus in quantifying present-day tourism value

To estimate the PV of tourism service, it is aimed to use the CVM to calculate the CS value. In order to do so, visitors' WTP is intended to be elicited for conserving the coastal environment of Western Bangladesh, and to not lose the recreational attributes associated with its ecosystems. However, the respondents stated that they cannot afford any monetary contribution, and even if it is affordable, they are not willing to pay, since they believe that

they are not responsible for the damages to the coastal wetlands and associated ecosystems in Western Bangladesh. Because of this reluctance observed in the interviews, calculation of CS value is excluded from the valuation study (step 1), and tourism value of wetland ecosystems is therefore based on the net revenue generated by the visitors (PS).

- The likely factors affecting the results

Apart from the likely changes of future climate and its impacts on coastal wetlands, many factors such as changes in tourist expenditure, sample size, market price of fish or timber, types of mangrove species, income and its distribution, expert opinions, ecological responses, and even social norms will likely change these estimates by the year 2100. The sensitivity analysis indicates that the discounting rate remarkably affects the results in the expected direction. Given the long-term horizon for this WES valuation, to avoid placing less importance on the future RSLR-induced inundation in Bangladesh, zero-discounting rate was used as the base case for reporting the results. This is in line with the statement of Voinov and Farley (2007), conveying that catastrophic events occurring far enough in the future (e.g. global warming) can be treated as essentially irrelevant today, (even) if a very low discounting rate is considered.

5.5 Conclusion

In this chapter, potential changes in the value of ecosystem services due to RSLR-induced inundation were estimated for three scenarios by 2100 in the wetlands along the Western coastal area of Bangladesh. To this end, the QuantiCEL framework presented in Chapter 4 is used, in which economic valuation techniques are combined with a scenario-based approach. This approach is applied here to quantify potential losses in the value of four WES; food provision (fish and marine species), tourism, art and provision of raw materials (timber and fuelwood) which are provided by the SMF, aquaculture lands, and pelagic system (Bay of Bengal). The monetization of WES is done by using a combination of contingent valuation, market price and net factor income techniques, based on the original field work undertaken in this study in 2017 in Western Bangladesh.

The results reveal low to medium changes in the value of services provided by the wetland ecosystems for all the three considered inundation scenarios; Scenario A with 0.25 m of RSLR, Scenario B with 1.18 m of RSLR, and Scenario C with 1.77 m of RSLR. The results represent maximum potential losses of 5%, 16% and 17% of the PV of raw materials, food provision and recreation services respectively, for the worst case inundation scenario (C). Notably, the results show that, the loss associated with art value is likely to be higher at 40% of its PV for the same scenario. The outcomes of this study provide a better insight to the little known issue of quantifying CC driven changes to the coastal WES, evidence for which is scarce in the current literature. Such quantitative assessment is of high importance, especially in Bangladesh and other developing countries where flood resilience capacity is insufficient to properly cope with the rapid pace of increasing CC impacts on the coastal wetland ecosystems.

CHAPTER 6

Extension of the QuantiCEL framework for estimation of the environmental risk due to coastal recession: East Coast of Sri Lanka¹

¹ This Chapter is partially based on: Mehvar, S., Dastgheib, A., Bamunawala, J., Wickramanayake, M., and Ranasinghe, R. Quantitative assessment of the environmental risk due to climate change-driven coastline recession, a case study in Trincomalee coastal area, Sri Lanka. Climate Risk Management, (Under review).

6.1 Introduction

Relative to Chapters 4 and 5, which focussed exclusively on inundation related environmental losses, this chapter represents a further extension of the QuantiCEL approach in which environmental risk posed by climate change driven coastal recession is quantified. Here the QuantiCEL framework is adapted and applied on the East coast of Sri Lanka at which diverse coastal wetlands are present. This chapter provides estimates of coastline recession-driven environmental losses, and quantifies the resulting environmental risk (ER) over a 100 year time scale along the coasts of Trincomalee district. In doing this, Trincomalee beaches, mangrove swamps, and marine areas (referred to as pelagic system), providing recreation (tourism), food provision (fish and marine species), and amenity value are selected as the wetlands and associated ecosystem services considered.

Sri Lanka is an island nation with a coastline that stretches 1600 km and is located in the Indian Ocean. Sea level is predicted to rise in this region by 0.5 m over the next two decades with severe consequences anticipated for the coastal area of Sri Lanka (Ahmed and Suphachalasai, 2014; Buultjens et al., 2017; Bakker, 2018). Coastal erosion has been identified as a long standing problem in Sri Lanka (Figure 6.1) (Lakmali, et al., 2017). The low lying areas of coastal zone in Sri Lanka with elevation of less than 1 m in most places upto a distance of 1-2 km inland, result in high vulnerability of these areas to storm erosion and chronic coastline recession (Dastgheib et al., 2018). This high vulnerability of the coastal area to the natural hazards is especially seen in the eastern coast as it is exposed to cyclones, beach recession, storms, and tsunamis. For example, the inundation due to the massive tsunami of 26 December 2004 destroyed 100% of the coastal lagoons, 43% of mangroves and 38% of sand dunes along the East coast (GTC, 2015).

Figure 6.1 Coastal erosion along the South of Sri Lanka - Unawatuna beach - December 2016

The coastal areas of Sri Lanka contribute 80% of the total annual fish production, and also host a large number of archaeological, historical, religious, cultural, scenic and recreational sites (IUCN, 2007). With respect to coastal landforms, Sri Lanka constitutes of mangroves, beaches, estuaries, rocky shores, lagoons, sand dunes, and salt marshes (Dahdouh-Guebas and Jayatissa, 2009; Satyanarayana et al., 2017). Mangroves are among the most important coastal wetlands in Sri Lanka, providing great economic value through the environmental, commercial, recreational, and aesthetic services (Mamiit and Wijayaweera, 2006). The extent of mangroves in Sri Lanka supports 23 true mangrove plant species (Amarasinghe and Perera, 2017).

The Eastern province of Sri Lanka with an extent of about 10,000 km², covers 15% of the total land area of the country, consisting of three districts; Trincomalee, Ampara and Batticaloa (GTC, 2015). These three districts host the majority of communities and developments along the east coast which are densely populated within the coastal belt. The dominant coastal wetlands in this province mostly comprise sand dunes, beaches, mangroves and coral reefs (in the bays), providing important services to human well-being. Apart from agricultural activities such as paddy (rice) cultivation, the eastern province plays an important role in fishery and tourism industries. In particular, Trincomalee district has a large population of fishermen, with around 22% of the residents depending on fishing as their livelihood (GTC, 2015). In addition, the Trincomalee district is known for its world renowned coasts and popular tourist destinations, which is another important economic activity (Resource profile, 2016).

6.2 Study area

The Trincomalee District (Figure 6.2) located in the Eastern Province of Sri Lanka, is selected as the study area. The District is divided into 11 Divisional Secretary's Division (DS Divisions), covering an area of 2,727 km² (Resource profile, 2016). There are three main bays in the area; Back Bay to the North of Fort Frederick; Dutch Bay to the East of the town; and the Inner Harbor to the West. The Inner Harbor is the main deep-water port, but all three are used for fishing and sailing activities (Resource profile, 2016).

Figure 6.2 Trincomalee district located in the Eastern coast of Sri Lanka

Sea and lagoon fishing are among the key elements of the economic base of the area. Tourism, poultry industry, coconut plantation are identified as the other economic activities. Figure 6.3 shows the selected photos of Marble beach, taken during the site survey in this study, showing a typical beach area in the Trincomalee district.

Figure 6.3 Selected photos of Trincomalee coastal area taken during the site survey

6.3 Methodology

Quantification of the environmental losses and risks in this study is presented in two parts.

Firstly, to quantify environmental losses due to coastal recession, the QuantiCEL framework is used, in which the effects of coastal recession on Coastal Ecosystem Services (CES) are quantitatively assessed along the Trincomalee coast for the year 2110. In this two-step approach, (1) the Present-day Value (PV) of CES is quantified through applying economic valuation techniques; and (2) the potential changes in ecosystem services by 2110 are identified, which is due to coastal recession projected by Dastgheib et al. (2018), and these changes are translated to quantitative monetary values. **Secondly**, the application of QuantiCEL framework is extended to quantify the environmental risk value along the coasts of Trincomalee by considering the general concept of risk, which is based on the probability of hazard (considered here as SLR and storm-induced erosion by 2110) and its consequences (losses of CES value, quantified in the previous part). This quantitative assessment is done by multiplying the loss value of tourism service (distributed along the Trincomalee's coast) by the exceedance probabilities of coastal recession in 2110 derived from Dastgheib et al. (2018). Notably, to better represent the variation of risk along the coast, in this second part of the analysis, tourism value of the ecosystems is considered which is mostly provided by the beach area). This is because coastal recession directly threatens the extent of the beach area, and therefore affects the tourism service, compared to smaller potential effect on the two other services considered (i.e. amenity and food provision).

6.3.1 Part 1 - Quantifying environmental losses due to coastal recession in 2110

(a) Valuation of CES (current status)

In the first step of this part of the analysis, the available economic methods are used to estimate the PV of CES in Trincomalee district. Table 6.1 summarizes the ecosystems and services considered as well as the methods that are used for valuing the services.

Table 6.1 Coastal wetlands, ecosystem services and methods considered and used in this study

Coastal wetland	Ecosystem service (direct use value)	Economic valuation method
Trincomalee beaches and dunes, mangrove swamp, pelagic system	Recreation/tourism	Contingent valuation,
	Fishery	Net factor income
	Amenity	Hedonic price

According to Table 6.1, three coastal wetlands are considered: mangrove swamp, beach and dune system, and pelagic system. These ecosystems provide direct use values including recreation or tourism, fishery, and amenity values. Depending on the type of ecosystem services, three valuation methods are used: contingent valuation, net factor income and hedonic price method. Valuation of the three services are briefly described as follows:

Recreation/tourism value

Trincomalee coastal area comprising sandy beaches, bays, mangroves, and picturesque marine landscape, provides an ideal touristic destination for visitors. Uppuveli and Nilaveli located 6 km and 16 km away from the town area, are two of the finest beaches in the Eastern coast of Sri Lanka with shallow waters, extending tens of meters into the sea (Resource profile, 2016). Alas Garden and Marble beaches are other popular beaches for the visitors, providing scenic landscapes and ample opportunities for relaxation and water-based recreational activities. In addition, activities such as snorkeling, scuba diving, surfing, and whale watching are popular among the visitors to the Trincomalee coastal area.

Using the contingent valuation and net factor income methods, recreation/tourism value provided by the beach areas, mangroves and marine area was quantified. For this purpose, an on-site survey was conducted by the Coastal Conservation Department (CCD) of Sri Lanka, in the period of December 2016 – February 2017, by using a pre-designed questionnaire and doing on-site interviews with 70 visitors. Notably, here the description of quantifying producer surplus value is excluded, since the approach used here is similar to that applied in the Chapters 4 and 5.

By using the contingent valuation method, it was aimed to estimate the consumer surplus as another factor contributing to the total recreation value of CES, but since most of the interviewees stated no contribution and WTP to avoid ecosystem degradation, this factor was excluded in the valuation study. Table 6.2 indicates information about surveyed beaches, sample size, mean duration of tourist stays and their origins. Total recreation/tourism value is equal to the PS value estimated here, which is derived from the ecosystem-related tourists' expenditures (no estimation is resulted for the CS value).

Table 6.2 *Summary of the beach survey data*

Surveyed beaches	Sample size	Mean duration of stay (days)	Percent	Tourists' origin
Trincomalee	17	2.5	24%	Sri Lanka, Norway, New
Nilaveli	23	2.3	33%	Zealand , Korea, Malaysia,
Alas garden	7	2	10%	Thailand, England, Germany,
Kuchchaveli	8	2.2	11%	USA, France, India, Australia,
Marble	15	2	22%	Belgium, Denmark, Indonesia,
Total	70	2.2	100%	Japan, Taiwan, South Africa, Netherlands, Sweden, Finland

Figure 6.4 shows selected photos taken during the data collection period, showing the interviews with tourists in Nilaveli beach.

Figure 6.4 Interviews with tourists in Nilaveli beach

Fishery value

The fishery industry contributes about 2% of Sri Lanka's national income with an annual production of 250,000 ton of fish (ITDG, 2005; FAO, 2007a; Venkatachalam et al., 2010). Fishery provides a major source of livelihood and food subsistence for about 170,000 inhabitants along the Northern and Southwestern coasts of Sri Lanka (Mamiit and Wijayaweera, 2006). Supplying 65% of the animal protein consumed by Sri Lankans, fishery plays an important role in the food chain of consumers in Sri Lanka (ITDG 2005), which considerably relies on lagoon fisheries (Ellepola and Ranawana, 2016).

The Trincomalee coastal area hosts many fishermen engaged in commercial fishing, contributing to the food provision service provided by the Indian Ocean. In this study (similar to the recreation service) the total value of the commercial fishery service provided by marine area of Kinniya division (recreational fishery is excluded from this study due to data scarcity) is estimated by summing the consumer and producer surplus values. Using the net factor income, PS was considered to represent the net revenue generated by the ecosystem-related fishery. This value was then multiplied by 40% which is considered as the ecosystem dependency factor stated in the interviews with fishermen (i.e. fishery is approximately 40% dependent on the coastal wetlands in Kinniya). Then, by using the CVM, CS was obtained by asking the local community of Kinniya and surrounding area (45 respondents in this survey) the maximum amount that they are willing to pay (WTP) per kilogram of fish. This WTP was then subtracted from what they actually pay in the market, providing an estimate of the CS value. Figure 6.5 shows the fishermen and their fishing boats on Trincomalee beach.

Figure 6.5 Fishermen pulling in their catch in Trincomalee (top) (Photo by Pierre Andre Leclercq). Source: Wikimedia Comments; Fishing boats on the beach (down-left); and two fishermen with their catches (down-right) (Source: site survey)

Figure 6.6 Interviews with local community of Kinniya division

Amenity value

The Trincomalee coastal area presents scenic views of the Indian Ocean and beaches for visitors and inhabitants. The amenity value of the considered ecosystems in Trincomalee was estimated by using the hedonic price method. To this end, a survey was undertaken among the real estates and property prices were collected for 60 properties located at different distances from the sea. The approach used is similar to that described in Chapters 4, in which a method of quantifying residential land amenity of the ocean view was presented by using a scoring system and proportional change of sale prices. With some modifications, here proportional percentages of the sea view/accessibility as a function of distance to the sea were assigned, and its contribution to the property price was estimated for each considered distance category.

(b) Identifying potential impacts of coastal recession on CES in 2110, and quantifying monetary value of the identified changes

In the second step of this analysis, the potential impacts of storm induced - coastal erosion on the considered CES are identified for the year 2110, and the resulting losses in the value of CES are quantified by using the approach presented by Mehvar et al. (2018b).

- **SLR and Storm-induced coastal erosion in Trincomalee coastal area**

In this step, the results of the study conducted by Dastgheib et al. (2018) are used, in which probabilistic retreat of the Eastern coast of Sri Lanka due to SLR and storm events is obtained in the year 2110. Accordingly, the Probabilistic Coastal Recession (PCR) model (Ranasinghe et al., 2012), and Joint Probability Method (JPM) are used, considering series of storm events (Callaghan et al., 2008, 2009) modeled along the coast of Trincomalee. The PCR framework was designed to calculate a large number of long, realistic sequences of beach erosion and recovery, enabling the statistical analysis of these events. The model

inputs comprise statistical parameters representing the wave climate, water levels (inclusive of SLR), and gaps between storms for randomly generating model forcing conditions. This model calculates erosion during the storm using a profile model, and also compute subsequent recovery during the inter-storm periods¹.

The model output comprises a time series of coastline location. With a repetition of about 100,000 times, a dataset required for statistical analysis is obtained. Notably, the value of coastline retreat can be defined when it is benchmarked to a Reference Coastline (RCL). Thus, the results of PCR model are used here presenting the distance of new coastline (after SLR and storm induced erosion) from the RCL. Here, the RCL is defined as the location of 1% exceedance probability of run-up in the period of 1979-2009. Table 6.3 indicates Dastgheib et al.'s (2018) projections of coastal retreat for the year 2050 and 2110 for a selected coastal profile T18 (see Figure 6.7). In this chapter, the results for the year 2110 is exclusively used. To encapsulate the maximum likely coastal retreat, the affected area is considered from the present day coastline to projected 1% exceedance probability recession in 2110 (i.e red line in Figure 6.7).

Table 6.3 Coastal recession magnitudes (m) associated with different exceedance probabilities in 2110 at selected profiles along the Trincomalee coast (all values from Dastgheib et al., 2018)

Profile	Probability of exceedance by 2050			Probability of exceedance by 2110		
	1%	10%	50%	1%	10%	50%
T-18	54	42	29	72	60	47

¹ More information about the PCR model can be found in Ranasinghe et al. (2012).

Figure 6.7 Example of computed 1% (red) and 50% (orange) exceedance probability coastal recession contours in Trincomalee. (Source: Dastgheib et al., 2018). These projections indicate that there is more than 50% probability of the entire sandy beach area along this stretch of the coast being permanently eroded by 2110

- Identifying potential impacts of coastal erosion on the considered CES

The major consequence of coastal erosion is beach retreat, resulting in loss of/damage to the coastal environments and properties. Coastal erosion can affect ecosystems and the services they provide due to the landward migration of wetlands (Runting et al., 2017). Since there is little known about how coastal recession will quantitatively affect the monetary value of CES, here, the approach presented by Mehvar et al. (2018b) is used, considering a ‘‘what if scenario’’ approach to cope with such uncertainty. In doing this, key ecosystem-related attributes are defined and the potential impacts of coastal recession and beach loss are identified on each of these attributes. A total beach loss is considered here, as the projected coastal recession for Trincomalee indicates that all along this coast, there is more than 50% probability of the entire

sandy beach area being permanently eroded by 2110. Following Mehvar et al. (2018b), the impacts (i.e. changes) are quantified by assigning a percentage range of change for each attribute, resulting in changes in CES value. These quantitative ranges are indicated by positive or negative impact indications (+ or – sign) representing a 20% increase or decrease for each positive or negative sign, respectively. This implies four ranges of 20% - 40%, 41% - 60%, 61% - 80% and 81% - 100% corresponding to the assigned impact indications from one (+/–) to four signs (++++/– – – –), respectively.

Assignment of these impact indications is based on secondary data and consultation with local experts (for the fishery service) and a ‘‘what if scenario’’ approach (for the tourism and amenity services), depending on the individual service, its attributes and the 2110 coastal recession considered (a more detailed description of the way in which potential impacts on each considered service was identified is given in section 4.2.2.2 of this thesis). However, here coastal recession is the driver of complete loss of beach area as opposed to inundation chapters 4 and 5, resulting in some differences in the changes identified for the services considered in this study.

- Quantifying monetary value of the identified changes in CES

After identifying how a complete loss in the extent of beach area of Trincomalee may affect the considered CES, these changes are then translated into quantitative monetary values by using the results of valuation study conducted in step (a).

6.3.2 Part 2 - Quantifying environmental risk due to coastal recession in 2110

6.3.2.1 Background

By definition, the word "risk" has a broad meaning, ranging from economic, environmental to social risk, representing their own concepts. One can define "risk" as a hazard or danger manifesting an exposure to a mischance, or in a narrower context, as a probability of suffering a hazard consequence. In this latter definition, "risk" results in degradations and losses depending on the severity of the consequences. According to Smith (2003), hazard severity can be ranked, hence the probability of an event may be defined theoretically from zero to certainty (1). The overall degree of risk can be determined by the relationship between a hazard and its probability of occurrence.

Risk is widely considered as a combination of the hazard occurrence, the exposure and vulnerability of people, properties and the environment to those hazards (see Figure 6.8) (Smith, 2003; Rotmans, 1998; Jones, 2001; Ness et al., 2007; Covello and Merkhoher, 2013). Exposure represents the extent of the hazard, threatening the environment, people and their assets, while the vulnerability is defined as the susceptibility of a community system or asset to the damaging hazard effects. This concept has been presented by Topuz et al. (2011); Enzenhoefer et al. (2012); Tartakovsky (2013); and Teodosiu et al. (2015), defining the ER as a function of the environmental impact (EI), and its probability of occurrence (P), as presented in Equation 6.1:

$$ER = EI \times P \quad (6.1)$$

Figure 6.8 Framework for environmental risk, combining hazard, exposure and vulnerability
(Source: Spalding et al., 2014)

In recent decades, risk assessments have become a priority for authorities and stakeholders in the countries with low lying areas prone to the coastal hazards. Many studies have been conducted to evaluate flood hazards and their consequences, and to develop ER assessment/risk management frameworks with the aim of reducing flooding risk and improving risk awareness (McGranahan et al., 2007; Dawson et al., 2009; Kellens et al., 2011; Wang et al., 2012).

6.3.2.2 Methodology

The ER considered in this study is due to coastal recession-driven losses in the monetary value of tourism service for the selected beaches of Trincomalee coastal area in 2110. To assess this ER, equation 6.1 is used, considering: (1) the loss value estimated for the tourism service of CES due to coastal recession by 2110, which is derived from the previous section (6.3.1-b); and (2) probability of the coastal recession (due to SLR and storm induced erosion) by 2110, derived from Dastgheib et al. (2018). Three beaches are considered along the coasts of Trincomalee district: Nilavelli beach, Trincomalee beach, and Alas Garden beach. Altogether, the total beach area considered is approximately 2 km². These beaches are among the most touristic beaches of the Eastern coast of Sri Lanka, while they are also vulnerable to coastal erosion.

The **first step** in quantifying the ER is to distribute the computed loss value along the three considered beaches. This is necessary because the total loss value of tourism service estimated in the previous section is computed per m² of the entire beach areas of Trincomalee district. Therefore, the variation of the total loss along the three considered beaches is determined by distributing this value, considering the extent of beach area on each individual beach, and the number of tourism-related venues therein. These recreational venues include hotels, restaurants, resorts, parks, tourist centers, water parks, and centers for water sports and marine recreational activities (surfing, snorkeling, whale watching, scuba diving, etc.). These data were collated using beach surveys (conducted by CCD) together with satellite maps (Google Earth), resulting in total number of 187 venues along the considered beaches. The upper and lower boundary of the considered beach area is aligned with the cross shore sections positioned by Dastgheib et al. (2018), considering from transaction T-15 (beginning of the Nilavelli beach from the North) to T-34 (end of the Trincomalee beach to the South).

For distributing the total loss value along the considered beaches, the study area is divided into six separate beach zones which are delineated based on the number of tourism-related venues identified in each zone. The total loss value for each zone is calculated by multiplying a *weightage factor* by the *total loss value range (min-max)* estimated for the three considered beaches with total extent of 1.63 km². The *weightage factor* is calculated for each beach zone by dividing the number of recreational venues in each zone (the area perpendicular to the shoreline and between the northernmost and southernmost transects in that zone) by the total number of recreational venues along the entire considered beach area (T15-T27, and T29-T34). The *total loss value range* is calculated by multiplying the loss value that was uniformly

estimated per m² of the total Trincomalee beaches (US\$ 0.5 – 0.6, derived from Table 6.10) by the total extent of the three considered beaches¹. The distribution of loss values is presented in detail in Appendix - Table A1. Figure 6.9 shows the three beach areas, the extent of coastal erosion (with exceedance probability of 1% by 2110), and the cross shore transects considered in the risk quantification undertaken here.

Figure 6.9 Study area showing the three beaches (Nilaveli, Trincomalee, and Alas Garden) considered for quantifying the value of coastal recession driven risk for tourism service of ecosystems, showing the cross-shore transects (T15 – T34), and the extent of beach erosion (in white) with 1% exceedance probability by 2110 (a). Zoom in of T29-T34 (b)

¹ For example, to compute the loss for zone 1, first the total loss value per m² of the entire beach area of Trincomalee district, derived from Table 6.10 (US\$ 0.5 – 0.6) is multiplied by the total area of the considered three beaches (1.63 km²), resulting in the total loss value of the considered beaches (US\$ 815,000 – 978,000). This value range is then multiplied by the corresponding weightage factor ($10/187 = 0.053$) for zone 1, resulting in the loss value of the tourism service for this specific zone (US\$ 43,583 – 52,300).

In the **second step**, the exceedance probabilities of coastal recession in 2110 are combined with the loss values as determined for each beach stretch in the previous step. In doing this, the recession probabilities are derived from Dastgheib et al. (2018), and multiplied by the corresponding loss value for a specific location/transect along the coast. The risk value thus computed varies in the cross shore (due to the cross-shore variation in recession exceedance probability from 1% to 100%), as well as alongshore (due to the alongshore variation in the tourism loss value).

To integrate the results from all cross-shore transects, while taking into account the alongshore distance between transects, the following approach is used: using the Delft3D software (Quick-in Menu), a fine curvilinear grid with a resolution of less than 50 cm is constructed and overlaid on the considered beach areas. Interpolating all the exceedance probabilities of coastal recession within the grid, and combining with the loss value per m² of each classified beach stretch (corresponding to the interpolated recession probabilities), the risk value per m² is calculated. Since the loss values are computed as a range, the resulting risk values are also computed as a range.

6.4 Results

The results of this study are presented in three parts; (1) present monetary value of CES; (2) potential loss value of CES due to coastal recession in 2110; and (3) ER value due to coastal recession in 2110.

6.4.1 Present-day value of CES

Food provision value (fish and marine species)

As described in section 6.3.1 (a), by using the net factor income method, the total food provision value of CES in Kinniya division, is calculated in Sri Lankan Rupees (LKR), by summing the consumer surplus (Table 6.4) and producer (Table 6.5) surplus. Table 6.4 indicates that all interviewees stated a lower WTP than the fish market price, resulting in no surplus in both fishing and non-fishing seasons, and therefore CS is estimated to be zero, and excluded from this valuation.

Table 6.4 Calculation of the consumer surplus for estimating food provision value of CES in Kinniya division (2016 prices), resulting in zero consumer surplus (per kilogram of fish). Fishing season (FS)

Fish type	Ave. WTP/kg (LKR)		Market price/kg (LKR)		Difference (LKR)	
	FS	Non FS	FS	Non FS	FS	Non FS
Auxis Thazard/ Frigate Tuna	155	231	300	500	-145	-269
Amblygaster sirm/ clupeidae	120	177	200	300	-80	-123
Trichiuridae/ Ribbon fish	202	273	225	300	-23	-27
Carangidae/ Atule mate	205	289	300	350	-95	-61
Lutjanidae	130	216	300	400	-170	-184
Clupeldai	68	105	250	300	-182	-195
Sardinella albella	60	97	600	750	-540	-653
Engraulidae	254	328	300	500	-46	-172
Cuttle fish	267	335	300	600	-33	-265
Prawn	366	455	600	1,000	-234	-545
Crab	253	352	300	500	-47	-148
Total					-1,595	-2,642
Total CS					0	0

Table 6.5 Calculation of the producer surplus for estimating food provision value of the CES in Kinniya division (2016 prices)

No. of operational crafts *	No. of active fishermen	Total annual production (kg)	Net revenue generated /month (mil. LKR)	Ecosystem related factor	PS (mil. LKR /month)	PS ** (mil. US\$)
550	5,579	214,800	270	0.4	108	9

* Including traditional boats, Vallam, beach seine and Mathal Padu.

** Annual estimation of producer surplus with exchange rate in 2016 (US\$/LKR = 145)

Recreation/tourism value

Recreation or tourism value is estimated by calculating the PS value¹. As indicated in Table 6.2, to estimate the recreation value of CES considered at the selected beaches of Trincomalee coastal area, 70 visitors were interviewed in this study. To calculate the PS (see Table 6.6), net revenue generated by the visitors is estimated by summing direct and indirect ecosystem-related expenditures incurred. Here, the net recreational benefit for the selected beaches are calculated by multiplying average expenditure per day (derived from the interviews) with added value of the considered ecosystems and the factor of ecosystem dependency. Because of

¹ Calculation of CS has been excluded in this valuation, due to the fact that most of the interviewees stated no WTP to avoid ecosystem degradation and losing its recreational value.

data scarcity on the cost structure of the tourism industry in Trincomalee, here, it is assumed that 25% of the average expenditure reflects the ecosystem's added value to the tourism industry. Also, the dependency level of recreational activities on coastal wetlands is taken as 80 % and 60 % for direct and indirect values, respectively.

Total net revenue is then estimated by considering total number of visitors to Trincomalee district recorded in 2015-2016 (110,442 visitors as reported by the divisional secretariats of Trincomalee) and the average duration of stay of 2.2 days per person per visit. Tourism value is finally estimated for the entire Trincomalee district coast with a total beach area of 30 km² (estimated from the google satellite images), resulting in total annual recreation value of US\$ 28 million, equal to approximately 1 US\$ per m² of beach.

Table 6.6 Calculation of producer surplus for estimating recreation/tourism value of Trincomalee beaches

Values	Added value	Average expenditure /day (US\$)	Added value (US\$)	Factor Ecosystem dependency	Producer surplus (US\$)
Direct values					
Surfing, scuba diving, snorkeling, whale watching, beach visits	25%	144	36	80%	29
Indirect values					
Flight ticket, transportation, accommodation, food, etc.	25%	578	144	60%	87
Total/day/person		722	180		116
Total (2015)					28,000,000

Amenity value

Using the hedonic price method, it was assumed that the amenity value of coastal wetlands in Trincomalee district is represented by property prices, which is influenced by the presence of coastal wetlands such as mangroves, beaches and dunes, and more importantly, the visual amenity of coastal views. The property prices per m² were collected by coastal conservation department (CCD) for 60 properties in Trincomalee for properties located at different distances

from the sea¹. The properties considered mostly comprise recreational properties such as hotels with rather similar structural characteristics. Here, the weighted average price is considered by dividing the results into 8 price categories as a function of distance from the sea. Figure 6.10 illustrates these results, showing a relative decrease in the property prices with increasing distance from the sea (except some increases that might be because of proximity to shopping, educational and welfare facilities or other non-environmental and independent variables).

Figure 6.10 Average price of the selected properties in SLR/m² as a function of distance from the sea (m)

To estimate the amenity value, the same approach as used in chapter 4 is applied here by assuming a proportional change in the visual amenity of CES, which is represented by the sea view, depending on the property's prices and distance and accessibility to the sea. Using this approach, different amenity value per m² of beach area for each distance category is calculated, resulting in total estimate as indicated in Table 6.7.

Table 6.7 Estimation of the amenity value of CES in Trincomalee district, based on mean property prices (2016 prices)

Distance range to the sea (m)	Mean sale price* (SLR/m ²)	Proportion of mean sale price (%)**	Amenity value (SLR/m ²)	Amenity value (US\$/m ²)	Total amenity value (US\$)
0 - 50	28,780	25	7,195	50	2500
51 - 100	24,940	21.42	5,342	37	1850
101 - 150	21,110	17.85	3,768	26	1300
151 - 200	17,270	14.28	2,466	17	850
201 - 250	13,430	10.71	1,438	10	500

¹ There is no structured, and open access database available for the property prices in Trincomalee. So, the analysis here is limited to the databases provided by the local real estate agents.

251 - 300	9,592	7.14	684	4	200
301 - 350	3,754	3.57	134	1	50
351 - 400	1,916	0	0	0	0

* Derived from the regression line in Figure 6.10

** Adapted and modified from Fraser and Spencer (1998)

6.4.2 Changes in the value of CES due to coastal recession in 2110

6.4.2.1 Changes in the food provision value

Following the description given in section 6.3.1 (b), the results of quantifying changes in the value of food provision service of coastal wetlands in Kinniya are presented here. Table 6.8 shows the potential impacts of coastal recession on fish/fishery related variables, considering that the whole beach area will be lost by 2110 as shown in Figure 6.9.

Table 6.8 Potential impacts of coastal recession by 2110 on fishery related variables in Kinniya. NK: Not known. Source: Literature Based; Expert opinion

Fish / fishery related variable	Potential impact of coastal recession*	Remark
Primary & secondary production	+	Positively affected due to larger nursery area provided for breeding and oviposition.
Distribution/ migration pattern	NK	Unknown due to interaction of diverse variables such as water temperature, salinity, vertical mixing rates and wind driven circulation.
Abundance	+	Positively affected due to larger water body and nursery area provided, resulting in more nutrient supply.
Health status	NK	Unknown.
Food web	+	Positively affected due to larger water body and more nutrients supply provided.
Nursery habitat	+	Positively affected due to larger (natural) water body provided.
Fish ponds & fishing community	----	Highly important variable for Kinniya division. Considerable loss of the fish ponds due to complete beach recession. Shoreline changes and landward migration will significantly affect livelihood patterns leading to displacement of fishing community and their boats.

* Each (+) and (-) represents a quantitative impact as defined in section 6.3.1 (b).

After identifying the potential recession impacts on fish/fishery related variables (Table 6.8), effect of changes in these variables are analysed on the catch volume, market price, and fishing and adaptation costs. By considering these changes together with the PS (net revenue), change in the food provision value is quantified (see Table 6.9). As an example, the complete beach loss considered here may result in replacement of fishermen, their boats and fishing equipment, since there will be no beach area to use as a landing area for their boats. This will lead to a decrease in catch volume in the area resulting in a higher market price, while the fishing and adaptation costs to these changes would also rise consequently. These changes will ultimately decrease the net revenue and PS. For the contribution level of each fishery-related variable to the total value, the same assumption in Mehvar et al. (2018b) is used here. Change in the food provision value is ultimately calculated by summing the estimated value range of each variable, which is calculated by multiplying 'potential impact indications' (as defined in section 6.3.1-b) by 'contribution to the value (%)', and the PS estimated before.

Table 6.9 Change in food provision value of CES in Kinniya division due to coastal recession by 2110. PS: producer surplus, NK: Not known, NE: No effect. F: Fishing, A: Adaptation, Source: Literature Based. Negative values indicate a loss compared to the present-day

Fish / fishery related variable	Catch volume	Market price	Cost		Effect on producer surplus (PS)	Contr. to the value	Change in the food provision value (mil. US\$)
			F	A			
Primary & secondary production	↑	↓	↓	↑	NE	10%	NE
Distribution / migration	NK	NK	NK	NK	NK	10%	NK
Abundance	↑	↓	↓	↑	NE	10%	NE
Health Status	NK	NK	NK	NK	NK	10%	NK
Food web	↑	↓	↓	↑	NE	10%	NE
Nursery habitat	↑	↓	↓	↑	NE	25%	NE
Fish ponds & fishing community	↓	↑	↑	↑	↓	25%	- (1.8 – 2.25)
Total change							- (1.8 – 2.25)

6.4.2.2 Changes in the recreation/tourism value

Table 6.10 shows analysis of the coastal recession impacts on the recreation value of CES at Trincomalee beaches. Here, different impact indications (similar to the food provision value analysis) are assigned to the various tourist related attributes, which vary due to the expected

recession impact on each attribute (scenario-based). Each attribute has a contribution to the total tourism value, represented by the PS estimated in Table 6.6. This weighted contribution (in percentage) was derived from on-site interviews, in which the visitors were asked to rank their favourite activities (recreational aspect) at Trincomalee beaches. Based on this ranking, 13 recreational attributes are identified and linearly scored from highest to the lowest value. According to the respondents, natural landscape is the most favourable aspect that visitors enjoy the most.

Change in tourist value is ultimately calculated for each attribute, by multiplying together 'potential impact indications' (as defined in section 6.3.1-b), 'contribution to the total value' and PS (US\$ 28 million - from Table 6.6). The total change is quantified by summing the changes for each attribute. Table 6.10 also indicates an approximation of the loss value in the tourism service per m² loss of the beach area, by dividing the total loss value to the total beach area in Trincomalee (30 km²). It should be noted that, the loss of the entire beach area as considered in this study, does not necessarily lead to a decrease in the value of all recreation attributes. According to Table 6.10, coastal recession (complete beach loss as considered here) will considerably affect some of the attributes such as relaxation on the beach, and landscape, while having a smaller impact on others such as weather or water sports. Such impact assignation can be justified by the fact that a reduced number of visitors is very likely to come to a certain area when the entire beach is lost.

For example, beach facilities and centres for water sports such as snorkelling or whale watching are mostly located in the beach area of Trincomalee. Thus, loss of beaches due to coastal recession will decrease the revenue earned by facilitating/servicing these activities. However, water sports such as scuba diving or snorkelling can still generate revenue from the visitors who book the tours beforehand, or visit centres which are not located in the beach areas. This would result in a middle-range quantitative impact (41% - 60%) assigned for these two attributes as indicated in Table 6.10.

Table 6.10 Potential change in the tourism value of coastal wetlands in Trincomalee due to coastal recession by 2110. Source: Survey-based. Negative values indicate a loss compared to the present-day. NE: No effect

Tourism/ recreational attribute	Potential impact of coastal recession	Contribution to the total value	Change in the tourism value (mil. US\$)
Snorkeling	--	7 %	-(0.80 – 1.18)
Beach area for relaxation	----	7 %	-(1.58 – 1.96)
Shore water quality	NE	9 %	NE
Hiking	----	9 %	-(2.04 – 2.52)
Diving	--	8 %	-(0.92 – 1.34)
Beach tranquility	----	6 %	-(1.36 – 1.68)
Friendly local people	NE	8 %	NE
Natural landscape	---	10 %	-(1.70 – 2.24)
Recreational beach facility	----	6 %	-(1.36 – 1.68)
Safety	----	8 %	-(1.81 – 2.24)
Recreational fishery	--	7 %	-(0.80 – 1.18)
Bird watching	----	7%	-(1.58 – 1.96)
Weather	NE	8 %	NE
Total change			-(14 – 18)
Total change / m2			-(0.5 – 0.6) e-6

6.4.2.3 Changes in the amenity value

Changes in the amenity value of coastal wetlands is mostly dependent on the existence of the beach area and coastal wetlands such as mangroves with aesthetic attributes. These factors encourage people to buy properties with higher prices close to the beach. However, since estimation of the amenity value is based on the hedonic price method and the property price, coastal recession will decrease the value of properties located very close to the beach, causing a considerable decrease in the total amenity value. In order to quantify changes in the amenity value of coastal wetlands in Trincomalee beaches, since amenity is subjective, a conservative assumption of 41-60 % reduction in visual amenity value of coastal wetlands is considered, if the entire beach area is lost. Considering this impact range follows the logical reasoning that, even if the entire beach area is lost by 2110, the ocean view will still provide aesthetic value for those who live in properties located close to the sea (see Table 6.11).

Table 6.11 Potential change in the amenity value of coastal wetlands in Trincomalee due to coastal recession by 2110

Amenity value	Estimated present- day value* (US\$)	Potential impact of recession by 2110	Maximum change in amenity value (US\$) by 2110
Based on Property's price	2500	--	-(1000 – 1500)
Total change			-(1000 – 1500)

* Total value is estimated for CES upto 50 m landward distance from the shoreline.

Table 6.12 summarizes estimated losses in the value of CES in Trincomalee district due to coastal recession by 2110.

Table 6.12 Summary of estimated losses in the value of CES in Trincomalee district due to coastal recession by 2110

Estimated change in total tourism value of coastal wetlands of Trincomalee (million US\$)	Estimated (maximum) change in total amenity value of coastal wetlands of Trincomalee (million US\$)	Estimated (annual) change in the total food provision value of coastal wetlands of Kinniya division (million US\$)
- (14 – 18)	- (0.001 – 0.0015)	- (1.8 – 2.25)

6.4.3 Environmental risk value due to coastal recession in 2110

In this section, the results of quantifying coastal recession-driven risk associated with only the tourism service of considered beach areas (Trincomalee, Alas garden, and Nilaveli) are presented for the year 2110. Table 6.13 indicates the results of the first step, representing the distribution of loss values (min – max) for the six classified zones (beach stretches), as described in Section 6.3.2.

Table 6.13 Estimates of the loss value of tourism service due to coastal recession in 2110, distributed among the six classified zones (beach stretches) to be used in risk quantification at the three considered beaches of Trincomalee, Alas Garden, and Nilaveli

Zone	Transect	No. of tourism related venues	Weightage factor	Total loss value (US\$)	
				Min	Max
1	T15 – T17	10	5.3%	43,583	52,300
2	T18 – T19	15	8%	65,374	78,450
3	T20 – T22	36	19%	156,898	188,278
4	T23 – T27	20	10.7%	87,166	104,560
5	T29	67	36%	292,005	350,406
6	T30 – T34	39	21%	169,973	203,968

Since the loss value of tourism service estimated for each zone is given as a range, two risk maps are provided, comprising minimum and maximum risk values, which are shown in Figure 6.11 for the three considered beach areas (divided into 6 beach stretches). The results show a range of risk value from zero per m² (rounded value for the beach area farthest from the sea with 1% exceedance probability of coastal erosion) upto US\$ 1.10 per m² as the maximum risk value on the coastline with 100% exceedance probability of coastal erosion. As shown in Figure 6.11 (pages 140-142), the maximum risk value is for the Alas Garden beach (T29), which is in fact the most touristic beach of Trincomalee with more than 60 recreational venues

and facilities for tourists, leading to a higher number of visits, and consequently higher tourism revenue earned.

Figure 6.11 Minimum and maximum risk value of ecosystem related-tourism service, due to SLR and storm induced coastal recession in the year 2110, estimated for the three considered beaches in Trincomalee district. The maps show that complete loss of the three considered beaches (Nilaveli, Alas garden, and Trincomalee) due to coastal erosion with 1% exceedance probability by 2110, results in a risk value of tourism service upto US\$ 1.10 per m^2 of the beach area

6.5 Discussion and conclusion

In this chapter, the application of QuantiCEL framework is extended to quantify coastline recession-driven environmental losses and risk along the coast of Trincomalee for the year 2110. Trincomalee beaches, mangrove areas, and pelagic system (Indian Ocean) are the ecosystems considered, providing recreation (tourism), food provision (fish and marine species), and amenity values as CES. Consideration of other services such as storm protection, climate regulation, erosion stabilization, etc. is outside the scope of this study, due to data scarcity and time limitation.

In the first step of this part of the study, the present-day value of CES was quantified, showing that both tourism and food provision services are only based on estimates of the net revenue generated by tourism and fishery, since no consumer surplus is considered in the valuation of these two services. This resulted in a reduction in total PV estimated for these services (US\$ 28 million and US\$ 9 million for tourism and food provision service, respectively). This reduction in estimated total PV is rooted in the reluctance presented by the visitors to contribute to the environmental preservation and maintenance plans, as well as lower WTP for fish and marine species stated in the interviews, compared to the current market price. With respect to the amenity service, a value up to US\$ 50 is quantified as the total PV estimated for the entire beach area for the 0-50 m landward distance to the sea, decreasing farther landward. This estimation is based on the proportional change in the property prices as a function of distance to the sea, which is due to presence of the coastal wetlands (beach and marine area) and its associated amenity value (Fraser and Spencer, 1998).

The second step of this study shows different magnitude of losses estimated for the three considered ecosystem services. These estimates include a potential loss in the total amenity value, which is approximated upto US\$ 20 – 30 (within the distance range of 0-50 m to the sea). The tourism value is likely to decrease between US\$ 0.5 – 0.6 per m² of the total beach area in Trincomalee's district. The estimated loss of US\$ 1.8 – 2.25 million in the food provision service provided by coastal wetlands of Kinniya division is affected by the potential positive impact of coastal recession considered on this service. Potential recession driven impacts identified for the fish/fishery related variables (Table 6.8) indicate a positive impact on most of the variables such as primary and secondary production, abundance, and the extent of nursery habitats. Because of the uncertainty associated with the magnitude of these impacts, a conservative positive impact (21- 40%) is considered in this quantitative assessment. This positive impact results in an increase of catch volume, leading to a likely decrease in market price which would neutralize each other's effects, and thus no loss is considered associated with this variables.

Quantifying coastal recession-driven risk associated with the value of the tourism service provided by CES of Trincomalee, shows a medium risk value ranging between US\$ 0 – 1.10 per m², implying that SLR and storm induced erosion in 2110 is not likely to considerably

decrease the value of tourism service that is provided by the beach areas and pelagic system (Indian Ocean). This can be justified by the relatively medium magnitude of the estimated loss in tourism value of the beach area. Notably, it is assumed that even with a total beach loss, coastal wetlands such as the pelagic system may still provide tourism services and thus generate revenues by providing opportunities for water sports and marine related recreational activities. Another reason for having such medium risk value here, can be due to the fact that this assessment relies on the present-day estimated value (with a rather med range magnitude) in the first step of this study, which is only based on the ecosystem-related revenue generated from the tourism in Trincomalee (producer surplus).

It should be noted that there are many uncertainties associated with the risk quantification presented here. These factors mainly include: (1) the methods that determine recession exceedance probabilities, and (2) the methods by which loss values are estimated per m² of the beach area. In addition, other factors that can affect the results of this study include the presence of storm protection structures, and wave attenuation - erosion stabilization services, which can be provided by mangroves swamps, seagrass beds, coral reefs, and beach vegetation. All these factors may have an effect on the exceedance probability of coastal erosion, and therefore affect the present-value of CES estimated over long time span.

CHAPTER 7

Conclusions¹

¹ This Chapter is partially based on: Mehvar, S., Dastgheib, A., Filatova, T., and Ranasinghe, R. A practical framework of Quantifying Climate Change-driven Environmental Losses (QuantiCEL) in coastal areas of developing countries. Environmental Science and Policy, (Under review).

7.1 Introduction

The preceding chapters provided quantitative estimations of future climate change (CC) driven environmental losses caused by coastal inundation and erosion. In doing this, first the QuantiCEL framework has been developed and subsequently applied in three data poor developing countries (i.e. Indonesia, Bangladesh and Sri Lanka). In this chapter, the conclusions of this study are presented by first addressing the research questions and the objective of this study, including the main findings and contribution of this study for other research areas. This is followed by highlighting the limitations and uncertainties associated with this study and the QuantiCEL framework, suggesting further developments required for future research and advancement of this topical area.

7.2 Answers to Research Questions

RQ1- How do the selected study sites compare with each other in terms of the type of coastal wetlands, ecosystem services provided, and governing CC driven hazards?

Comparing the 3 different study sites shows that there are similarities and discrepancies between the coastal wetlands, ecosystem services and hazards considered. In terms of the coastal wetlands, beach and dune systems, pelagic system (marine area), and mangrove swamps are present in all three study sites. With respect to CES, tourism (recreation), art, and food provision (fish and marine species) are the prominent services at all three study sites. In addition, the amenity service was included in the valuation studies of Indonesia and Sri Lanka coastal areas, while provision of raw materials (timber and fuel wood) was considered only in the Bangladesh study.

The coastal hazards considered in this study comprise inundation due to RSLR (in Indonesia and Bangladesh), and coastal erosion due to SLR and storms (in Sri Lanka). The choice of study sites was driven by three main factors; (1) high importance of the coastal area in terms of the existing ecosystems and corresponding services provided (e.g. the SMF which is known as the richest natural forest and most economically valuable coastal wetland in Bangladesh); (2) high vulnerability of the coastal area to the CC driven hazards (e.g. low lying coastal regions with high rate of future RSLR in Semarang); and (3) feasibility of data collection procedure (e.g. collecting the data by help of local professional teams as CEGIS in Bangladesh, and CCD in Sri Lanka).

RQ2- What is the motivation for the development of the QuantiCEL framework, and what methodological steps need to be included in this framework?

According to the literature reviewed in this study, available CC impact assessment studies have mostly been carried out with a focus on the first order CC impacts on coastal and marine areas (i.e. changes in sea level, ocean conditions and biogeochemistry), while a few quantitative assessments have investigated the physical impacts on the ecosystems and services provided. The outcomes of these studies are very diverse and sometimes conflicting, adding to the uncertainty related to the potential costs of adverse CC impacts on CES. In addition, most of

available valuation studies have estimated the Present-day Value (PV) of Coastal Ecosystem Services (CES) in local study sites, and have been mostly carried out in developed countries making it difficult (or impossible) to transfer these valuations into the context of data poor developing countries. These knowledge gaps constitute the main driver for developing the practical QuantiCEL framework to quantify the monetary value of future climate driven environmental losses, that can be especially applicable in data-scarce environments such as developing countries which likely to suffer most from the CC impacts.

The QuantiCEL framework presented in this study, comprises a coherent three-step methodological approach as follows: (1) quantifying the PV of CES using well accepted economic valuation techniques; (2) identifying the potential impacts of CC driven hazards (RSLR-induced inundation; SLR and storm-induced erosion) on ecosystem services (provided by mangrove swamps, beach, dune and pelagic systems (for the year 2100); and (3) monetizing these impacts by using the results of previous steps, and by applying a novel scenario-based approach, grounded in local expert opinions and secondary data.

RQ3- To what extent can CC driven hazards potentially affect the CES of the study sites?

Identification of the potential CC driven hazards on CES considered in this study, shows positive/negative/neutral impacts on different ecosystem related attributes/variables. The potential losses of CES depend on different factors such as the type of ecosystem related attributes, the extent of hazard exposure (scenarios considered in each study site), local expert opinions and secondary data used.

For two of the services (i.e. food provision and art), the impact identification was based on local fishermen and expert opinions, as well as secondary data derived from the literature (e.g. Portner and Knust, 2007; MAB, 2009; Cochrane et al., 2009; Mohanty et al., 2010; Sumaila et al., 2011; Williams and Rota, 2011). For the food provision service, results showed that RSLR-induced inundation, and SLR and storm-induced erosion can potentially affect the fish-fishery related variables in different ways. For example, primary and secondary production, abundance, food web, and the extent of nursery habitat are likely to be positively affected by inundation (e.g. in a range of 21%-60% in the Indonesia study site), while the impacts on species distribution/migration pattern is unknown. In the Bangladesh study site, these positive impacts were less prominent (from 10% to 40%) due to the very low extent of inundation, and lower expectation of local fishermen of a considerable impact. In the Sri Lanka study site, the positive impact of (complete) coastal retreat on the fish-fishery related variables resulted in a range of 20%-40%, representing a relatively less positive impact of coastal erosion, compared to inundation impacts at the other two study sites. The results also showed that health status and fish ponds can be considerably threatened by the impacts of inundation (e.g. 81%-100% damage in the extent of fish ponds due to full inundation scenario in the Indonesia study site).

For the art service, the negative impacts of inundation were estimated as 41%-100% in the Indonesia study site. A lower impact on Art value was computed (31%-40%) for the Bangladesh coastal area. This is mainly due to the reduced inundation area, and lower

expectation of the local experts for a severe impact of inundation on art value of CES in Sundarbans.

For the three other services (i.e. tourism, amenity, provision of raw materials), the ‘what if scenario’ approach used in this study showed a potentially medium-high range of negative impacts. For example, for the tourism service, the negative impact of inundation was estimated to be between 41% and 100% for the Indonesia study site. However, this negative impact on tourism service, was lower (31%-40%) in the Bangladesh study site, due to the very low extent of projected inundation area. In the Sri Lanka study site, the impact of complete erosion-induced beach retreat, results in an expected negative impact of 41%-100% for varied tourism related variables.

In terms of the amenity service, a medium negative impact (41%-60%) was computed for the complete inundation scenario (in the Indonesia study site), and the complete beach recession scenario (in the Sri Lanka study site). With respect to the provision of raw materials service (timber and fuel wood) in the SMF in Bangladesh, a very low negative impact of inundation is computed, mainly as a result of the small projected inundated area (about 5% of the SMF), and also due to the higher resilience of the forest to SLR which is expected as a result of interspecific facilitation.

RQ4- What are the future potential CC driven environmental loss values of CES estimated in each study site? What is the variation of loss values between the CES of the considered study sites?

In response to this question, Figure 7.1 shows a summary of the estimates of CES loss values, and the percentage of losses (median value) relative to the present-day value of CES, in the three study sites. This summary is followed by the corresponding schematic representations of the absolute loss value (presented in million US\$ in logarithmic scale – see Figure 7.2a), and percentage of CES loss value relative to the present-day value (presented in linear scale for the worst case hazard scenarios in the three study sites – see Figure 7.2b). According to the Figure 7.2b, art value is likely to have the highest decrease to 90% of its present-day value (Indonesia study site), while provision of raw materials (Bangladesh study site) is likely to have very low reduction relative to its present-day value.

In general, application of this framework for the selected case studies showed that, where the absolute loss value of CES by the end of the 21st century is concerned, food provision and tourism are the CES with higher loss values. However, art, amenity, and tourism are the highly affected CES where the percentage loss (by the end of the 21st century) relative to the present-day value of CES is concerned. However, more studies of this nature are required to gain more confidence in the generic applicability of these observations.

Figure 7.1 Overview of the estimates of CES loss values (million US\$), and the corresponding median percentage of losses relative to the present-day value for the three study sites

Figure 7.2 Schematic representation of the absolute loss value of CES in logarithmic scale, in million US\$ (a), and percentage of CES loss value relative to the PV in linear scale (b). Green [low value (a)/impact (b)]; yellow [medium value (a)/impact (b)]; orange [high value (a)/impact (b)]; dark red [extreme value (a)/impact (b)]. Both figures represent the worst case hazard scenarios in the three study sites

RQ5- What are the limitations and advantages of QuantiCEL framework, and what are the main uncertainties associated with the results of this study?

The outcomes of this study showed that there are some limitations in using the QuantiCEL framework. One of the largest uncertainties stem from the large CC related uncertainties, which add complexity to the quantitative assessment of CC driven environmental losses. The main limitation in valuation of CES is the incomplete estimation of values for only one or a few selected CES, which is often due to time limitation, complexity of translating the services to the monetary values, and costly process of data collection in a particular study site (especially in data-scarce environments). The findings of this study also showed that valuation techniques may not be completely applicable for valuation of CES in a developing country context. For example, the concept of WTP was not well accepted in both Sri Lanka and Bangladesh study sites, because local communities were not willing to pay to conserve ecosystems, or to not lose the services provided by these habitats. This would imply that there might be other factors (i.e. cultural issues, political issues, educational background, socio demographic factors, etc) affecting the WTP stated by the interviewees. Apart from the valuation itself, uncertainties associated with assessing the physical CC impacts on coastal wetlands over a very long time span present another challenging issue.

The main factors that add uncertainty to the estimation of CC driven environmental losses over a very long time span are: (1) diverse expert opinions and their expectations of CC driven impacts on CES; (2) presence or future implementation of coastal protection structures; (3) discount rates; (4) land subsidence rate which is relatively high and uncertain in developing countries; (5) changes in tourist expenditure (associated with valuation of tourism service); (6) sample size; (7) market price of goods (associated with fish and marine species, and raw materials); and (8) social norms. In this study, the limitations and uncertainties mentioned above resulted in estimating the losses of CES as a value range, and not as single deterministic values. Thus, the approach used here should be conservatively considered.

RQ6- What other applications of QuantiCEL framework are possible in valuation studies?

The QuantiCEL framework is presented in this study as a practical framework to quantify the CC driven changes to the value of CES. Apart from this main utility, it can be also used to quantify the environmental risk due to CC driven hazards, which is a poorly addressed issue in current literature. An example of this application has been presented in Chapter 7, showing how the quantitative results of CC driven environmental losses estimated by using this framework, can be further combined with the exceedance probability of occurrence of a CC driven hazard, enabling a quantitative risk assessment.

7.3 Implication of this study and future research

The development and applications of the QuantiCEL framework presented in this study is a practical method to quantify potential CC driven environmental losses in the coastal areas in developing countries. The applications of the framework at three different study sites have illustrated its versatility in terms of its ability to be applied in each study site with a variety of CES, and two different CC driven hazards. This coherent and straightforward framework can be used for a wide range of applications providing an approximate estimation of CC driven impacts on CES value, especially in data scarce developing countries in which it is not feasible to apply standard ecological and economic simulation methods. The new approach developed in this study is based on both secondary data from the available CC related literature, and experts' opinions (i.e. fishermen, artists/art dealers, real estate's experts), together with presenting a linkage between the potential CC driven changes to ecosystem related attributes, and economic concepts of valuation studies.

Findings of this study show that ecosystem services of coastal areas are not likely to be similarly affected by CC induced hazards (i.e. inundation and erosion). While, the general expectation is that climate change will exacerbate losses of services provided by coastal wetlands, this study shows that at some locations (i.e. Bangladesh study site) other factors (i.e. topography of the coastal area) can potentially decelerate degradation of wetlands ecosystems, and minimize the CC driven losses of services provided by these habitats.

It is essential to apply this framework at more study sites containing different types of coastal wetlands (services). This will provide better insight and more convincing results on whether the framework can be generically used for quantifying losses of other types of coastal ecosystem services. Applying this framework for the coastal areas in developed countries is also recommended, in order to explore whether the results (i.e. PV, loss and risk values of CES, and WTP) are comparable with the results of study sites in developing countries. In addition, further research is required into the possible approaches to minimize the effect of CC related uncertainties on the quantification of associated the environmental losses.

The outcomes of this study are expected to aid international research efforts on mapping monetary valuations of CES and CC driven physical impacts on CES through the quantitative assessment of a number of ecosystem services it provides. The results provide better insight into the little known issue of quantifying CC driven changes to the CES, evidence for which is scarce in current literature. Such quantitative assessment is of high importance for the proper management of coastal zones, especially in developing countries where the flood/erosion resilience is not sufficient to properly cope with the rapid pace of CC impacts on the coastal wetlands. In addition, outcomes of this study can also be useful for assessments of environmental risk which is an emerging important topical area for researchers and policy makers.

APPENDIX

Table A1. Distribution of loss values along the three selected beaches in Trincomalee coastal areas, to quantify the recession driven environmental risk value associated with tourism service. Source: CCD Colombo, Satellite image data (Google Earth)

Class/Zone	Class 1	Class 2
Name of the beach	Nilaveli	Nilaveli
Transect No.	T15-T16-T17	T18-T19
Hotel / Restaurant	Hotel Sadham, Serendib Hotel Nilaveli, Eastwest Restaurant, Spicy Way Restaurant	Serendib Hotel Nilaveli, Nilaveli Beach Hotel, Organic Farm of Nilaveli Beach Hotel, Nilaveli Crystal Blue Hotel, Shajana Hotel, Samurdihi
	Nilaveli Ayurveda Resort, Pigeon Island Beach Resort, Nilaveli Palm House, Irakkandi Bridge, Victory Life Church, Dilaxshan Store	Pigeon Island Beach Resort, Nilaveli Ayurveda Resort, Nagenahira Beach villas, Nilaveli Beach, Anilana Nilaveli (statue) Seadoo rental, Pigeon Island tour, Boat Service
	Other tourism related places (National park/ Resort / Church / Tourist Centre)	
	No. of places	10
	Weighted factor	0.05
Total loss value (US\$)	43583 - 52300	65374 - 78450
Area (m²)	263000	139000
Loss value/m² (US\$)	0.166 - 0.199	0.470 - 0.564

Class/Zone	Class 3	Class 4
Name of the beach	Nilaveli	Nilaveli
Transect No.	T20-T21-T22	T23-T24-T25-T26-T27
Hotel / Restaurant	Cafe Nilaveli, Nilaveli Hybrid Holiday Hotel, Pearl Inn Green Nilaveli, Gopalapuram Guest House, Seaway Hotel, Luma Beach Hotel, Shahrira Hotel Nilaveli, Nilaveli Star View Hotel, Sea Zone Hotel Nilaveli, Vibushan Guest House, white house accommodation, Galaxy Beach Hotel, Shan Guest Nilaveli, Hotel StayGo Nilaveli, Mitty's Round House , Nilaveli Ocean Condos, Ocean Hotel, Cardamon Hotel, Nilaveli Sea Food Restaurant, Front Condominiums Nilaveli, Sea Food Restaurant, Nilaveli Moon Restaurant, Home Food Center Nilaveli, Crab Restaurant Nilaveli, Umami Restaurant , Thirumalai restaurant , Siva Restaurant, Sea View Beach Hotel	Blue Whale Nilaveli , Nilaveli Beach Hostel, Hotel Coral Bay, Walrus Beach Nilaveli, Ocean Way Nilaveli, Restaurant & Beach Cabanas , Leo's café , NN Beach Hotel, New Retreat Guesthouse, Nilaveli Gates Restaurant, Nilaveli Seafood Restaurant
	Brindhavan Cottage, Thirumalai park rooms & restaurant , pranu house statue, Crescent Sea Resort, Poseidon boat Diving Centre Trincomalee, Oceanic White House, St. Joseph's Church Nilaveli, Divisional Hospital Nilaveli, Palm Resort Nilaveli	Nilaveli Diving Centre, AquaCreded Scuba , Public Playgroud, Catamaran Beach Tour, Veloor Thirumurugan Temple, Umair Food Centre, Bella Nilaveli Beach, Periyakulam, lake H.A.M Stores
No. of places	36	20
Weighted factor	0.19	0.10
Total loss value (US\$)	156898 - 188278	87166 - 104600
Area (m ²)	366000	232000
Loss value/m ² (US\$)	0.429 - 0.514	0.376 - 0.451

Class/Zone	Class 5
Name of the beach	Alas garden
Transect No.	T29
<p>Hotel / Restaurant</p>	<p>Trinco Blu by Cinnamon, The Secret Garden Guest House, Summer Guest House, Golden Beach Cottages (PVT) Ltd, Anantammaa Hotel, Hotel Silver Beach, Trinco Beach Resort, Amaranthé Bay Resort & Spa, Hotel Alas Garden, SO J Beach Villa, Sea Lagoon Beach Hotel, Aqua Hotel Trincomalee, Fernando's Bar, Sasvi Cabana, French Garden Regish Guest House, Scuba Lanka, Silaa Cabana, AA Inn Guest, 7 To 11 Restaurant, SO J Beach Villa, Neem Beach House, Eagle Wings Inn, Hotel Sea Shadow, Eastern Lanka Seafood Restaurant, Hotel Gowri, Sun way holiday inn, Athena Guest Inn, Nero Kitchen, Theepam - Rooms and Hall, Koshe Guest, Sunn Top Cabana, Natraj hotel, The Stupa House, Golden Beach Cottages, Hotel Angel Inn Beach, Government Circuit Bungalow, Uppuveli Beach House, Queen's Hotel, SRI star salon, Oyestern Indian Restaurant, Gaga Seafood Restaurant, Rice 'n' Curry Restaurant, N Joy Restaurant, Ceylon Seafood Cafe, Thoru Thoru Restaurant, Be Cool Juice Bar, Messi Bamboo, Hotel Lucky 7, Chill N Grill Restaurant N Bar, Crab Seafood Restaurant, Angel Inn Beach Sea Food Restaurant</p>
	<p>Sea Lotus Park - Beach Resort, Palm Beach Resort, Bluewater Beach Resort, French Garden Resort, The White House, Coconut Beach Lodge, Sarvodaya Trincomalee Center, St. Anthony The Hermit Church, Angel Diving, Weligama Bay Dive Center, Trinco Watersport & Rooms, Nero Adventures, Sarvodaya Trincomalee District Center, Club Dive Paradise French Garden, Ishla Water Park, Sri Lanka diving tours</p>
	67
	0.36
	292005 - 350406
Total loss value (US\$)	323000
Area (m²)	
Loss value/m² (US\$)	0.904 - 1.085

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About the author

Seyedabdolhossein (Abdi) Mehvar was born in Tehran, Iran. He obtained his Bachelor's degree in '*Civil Engineering*' from Iran in 2007. After a short stint at an engineering consultancy company, he moved to the Netherlands and joined the double degree program of Saxion University of Applied Sciences in Enschede and obtained a second Bachelor's degree in '*Civil Engineering*' in 2011. Following his professional interest, Abdi then joined IHE Delft (at that time UNESCO-IHE) and obtained

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• Peer-reviewed publications

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Mehvar, S., Dastgheib, A., Filatova, T., and Ranasinghe, R. A practical framework of Quantifying Climate Change-driven Environmental Losses (QuantiCEL) in coastal areas of developing countries. *Environmental Science and Policy*, (Under review).

Mehvar, S., Dastgheib, A., Bamunawala, J., Wickramanayake, M., and Ranasinghe, R. Quantitative assessment of the environmental risk due to climate change-driven coastline recession, a case study in Trincomalee coastal area, Sri Lanka. *Climate Risk Management*, (Under review).

• **Other publication**

Mehvar, S. (2014). Validation of XBeach model for wave overtopping discharge. MSc Thesis WSE-HECEPD, UNESCO-IHE, 14.

• **(Selected) Conference attendance and proceeding**

Mehvar, S., Dastgheib, A., and Ranasinghe, R. (2018). Potential inundation-driven changes in the value of coastal ecosystems in the Sundarbans region in Bangladesh. In 6th International Conference on Marine Science, Coastal Dynamics and Management, Dallas, Texas, USA (Oral presentation).

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D I P L O M A

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Prof. dr. Martin Wassen

the SENSE Director of Education

Dr. Ad van Dommelen

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

K O N I N K L I J K E N E D E R L A N D S E
A K A D E M I E V A N W E T E N S C H A P P E N

The SENSE Research School declares that **Seyedabdolhossein Mehvar** has successfully fulfilled all requirements of the Educational PhD Programme of SENSE with a work load of 30.0 EC, including the following activities:

SENSE PhD Courses

- o SENSE Writing Week (2016)
- o Environmental research in context (2016)
- o Research in context activity: 'Co-organizing UNESCO-IHE PhD Symposium on: From water scarcity to water security (Delft, 3-4 October 2016)'
- o Workshop on Transdisciplinarity for the Sustainable Development Goals (2018)

Other PhD and Advanced MSc Courses

- o Summer school on estuarine and coastal processes in relation to coastal zone management, Netherlands Centre for Coastal Research (NCK) (2017)

Management and Didactic Skills Training

- o Supervising MSc student with thesis entitled 'Quantifying The Environmental Value in Western Coast of Semarang City, Central Java, Indonesia' (2016)

Selection of Oral Presentations

- o *Relative sea level rise scenarios in central coast of Bangladesh*. Collaborative Applied Research workshop, 26 November 2016, Dhaka, Bangladesh, ,
- o *Valuation of ecosystem services in coastal area*. Seminar on coastal ecosystem valuation, 28 November 2016, Buett University, Bangladesh
- o Valuation of the environmental damages due to climate change impacts in the coast of Central Java, Indonesia. Third international conference on Environment, Engineering & Energy, 16-17 September 2017, Toronto, Canada

SENSE Coordinator PhD Education

Dr. Peter Vermeulen