Quantitative assessment of the environmental risk due to climate change-driven coastline recession: A case study in Trincomalee coastal area, Sri Lanka

Seyedabdolhossein Mehvar\textsuperscript{a,b,}, Ali Dastgheib\textsuperscript{b}, Janaka Bamunawala\textsuperscript{a,b}, Mangala Wickramanayake\textsuperscript{c}, Roshanka Ranasinghe\textsuperscript{a,b,d}

\textsuperscript{a}Department of Water Engineering and Management, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
\textsuperscript{b}Department of Water Science and Engineering, IHE Delft Institute for Water Education, P.O. Box 3015, 2601 DA Delft, The Netherlands
\textsuperscript{c}Coast Conservation and Coastal Resource Management Department, New Secretariat Building, Maligawatte, Colombo 01000, Sri Lanka
\textsuperscript{d}Harbour, Coastal and Offshore Engineering, Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands

\textbf{A R T I C L E   I N F O}

\textbf{Keywords:}
Climate change
Environmental risk
Coastal erosion
Ecosystem service
Sri Lanka

\textbf{A B S T R A C T}

Climate change may exacerbate the environmental damage due to coastal hazards and increase associated risks. This would result in degradation of coastal wetlands, especially in developing countries due to the lack of sufficient resilience to coastal hazards such as inundation and coastal erosion. Environmental damages will lead to a decrease in services provided by the coastal wetland ecosystems that contribute to human wellbeing. To provide better insights on the little known issue of quantifying potential climate change-driven environmental risk, this article presents a stepwise approach to quantify coastline recession-driven risk associated with the tourism service provided by the Trincomalee beaches, dunes and pelagic system (Indian Ocean) along the East coast of Sri Lanka in 2110. To achieve this, here we first estimate the loss value of the tourism service due to sea level rise (SLR) and storm induced erosion in 2110, by using economic valuation techniques followed by a scenario-based approach. This is followed by the quantification of the environmental risk value by combining the result of the aforementioned loss value with the exceedance probability of coastal erosion derived from a prior study. Results show a medium environmental risk value ranging from 0 to 11,000 US$/Ha of beach area due to complete beach loss by 2110. This indicates that SLR and storm induced erosion in 2110 is not likely to pose a very high environmental risk associated with the tourism service of ecosystems in Trincomalee coasts. The approach presented in this study can be directly applied in other coastal areas of interest to gain a better understanding of the likely costs of climate change driven environmental risk, which is an emerging topic in coastal zone management.

1. Introduction

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

Coastal ecosystems provide a variety of goods and services contributing to human wellbeing (e.g. food provision, tourism, amenity, provision of raw materials, flood mitigation, carbon sequestration, etc.), it is of utmost importance to better understand how these services can be affected by climate change impacts, and how the resulting CC driven risks associated with these services can be quantified in monetary terms. However, there is little known yet regarding the quantification of environmental risk due to the climate change impacts on coastal wetland ecosystems. This gap is mainly due to two reasons: (1) quantification of the losses in the value of wetland ecosystems services due to climate change-driven coastal hazards is complex, and thus is very scarce in the literature (Mehvar et al., 2018a); and (2) the uncertainty inherent in deterministic projections of climate change-driven hazards arising from the uncertainty associated with climate change (e.g. probability of the occurrence of sea level rise over time).

To address the above knowledge gap, this study presents and demonstrates an approach that is able to quantify coastal environmental risk associated with the tourism service as one of the most important ecosystem services (among many others mentioned above) along the coast of the Trincomalee district, Sri Lanka. The approach comprises two sequential methodological steps: In the 1st step, (a) the present-day value of the tourism service is estimated by using economic valuation techniques; and (b) the potential impacts of coastline recession on tourism service by 2110 are identified by using a “what if scenario” approach, and the resulting loss is monetized. In the 2nd step, the associated environmental risk is quantified by considering the loss value derived from the 1st step, multiplied by the exceedance probabilities of coastal erosion in 2110. In doing this, the beaches, dunes and marine areas (referred to as pelagic system) in Trincomalee, which provide recreation (tourism) service, are selected as the wetland ecosystems and the associated ecosystem services are considered.

Trincomalee is selected as the study area herein as Sri Lanka is an island nation that is considered to be highly vulnerable to climate change related threats (MOE, 2010; Kottawa-Arachchi and Wijeratne, 2017). For example, sea level is predicted to rise 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; Dastgheib et al., 2018). In particular, coastal erosion has been identified as a persistent problem in Sri Lanka (Lakmali et al., 2017; Dastgheib et al., 2018). The low lying areas of the coastal zone in Sri Lanka with elevations of less than 1 m in most places, extending up to a distance of 1–2 km inland, result in a high level of vulnerability to storm erosion and chronic coastline recession (Dastgheib et al., 2018). This high vulnerability is especially seen in the eastern coast as it is exposed to cyclones, and storms. These coastal hazards already threaten the coastal environment and damage the wetland ecosystems such as the touristic beaches of Trincomalee district. In view of the additional threats associated with climate change, the services provided by these habitats (e.g. tourism, and amenity) which host a large number of scenic and recreational sites (IUCN, 2007) are likely to decrease over time, affecting the socio-economic wellbeing of coastal communities that rely on these ecosystem services. It should be noted that, this study focuses only on sea level rise (SLR) and storm induced coastal erosion, and exclude the impacts of other SLR-induced hazards (i.e. inundation) on wetlands ecosystems, or possible interaction of erosion-inundation with other coastal processes. Therefore, the estimated environmental risk value associated with the tourism service in this study, can be considered as lower overall CC driven risk.

It is envisaged that the approach used in this study can be generically applied to any other coastal areas of interest to quantify the environmental risk due to climate change-driven coastline recession and possibly other associated coastal hazards. The results of this study can therefore enable researchers and policy makers to better understand the likely physical impacts of climate change on coastal wetland ecosystems and the services they provide.

2. Study area

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.

The Trincomalee district (Fig. 1), chosen as the study area herein, is located in the Eastern province of Sri Lanka. The district is divided into 11 Divisional Secretary’s Division (DS Divisions), covering an area of 2727 km² (Resource profile, 2016). There are three main coastal 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). Trincomalee district is also known for its world renowned coasts and popular tourist destinations (Resource profile, 2016). The Trincomalee coastal area, comprising sandy beaches, bays, and picturesque marine landscape, provides an ideal touristic destination for visitors. Uppuveli and Nilaveli located 6 km and 16 km away from the Trincomalee town respectively, are two of the finest beaches in the Trincomalee district with shallow waters, extending tens of meters into the sea (Resource profile, 2016). Alas Garden and Marble beaches which provide scenic landscapes and ample opportunities for relaxation and water-based recreational activities such as snorkeling, scuba diving, surfing, and whale watching, are other beaches that are very popular among visitors.

3. Methodology

Quantification of the environmental risk in this study constitutes of two methodological steps. First, to quantify the environmental loss due to coastline recession along the Trincomalee coast, the effects of coastline recession on tourism service of wetland ecosystems (i.e. beaches, dunes and pelagic system) are quantitatively assessed for the year 2110. In doing this, (a) the Present-day Value (PV) of tourism service is quantified through the application of economic valuation techniques; and (b) the potential changes in tourism
service (due to coastline recession projected by Dastgheib et al., 2018) are identified and monetized for the year 2110 by using a scenario-based approach. Secondly, the environmental risk value is quantified 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 consequence (loss of tourism service). This quantitative assessment is done by multiplying the loss value of tourism service (derived from the previous step) by the exceedance probabilities of coastline recession in 2110 derived from Dastgheib et al. (2018). Notably, the methodology used in this study excludes the effects of coastal hazards other than SLR and storms. Thus the potential effects of low probability events such as cyclones and Tsunamis are not incorporated in this analysis. The methodological steps used in this study are described in detail as follows:

Fig. 1. Trincomalee district located in the Eastern coast of Sri Lanka.
3.1. Quantifying the environmental loss due to coastline recession by 2110

3.1.1. Present-day value of tourism (recreation) service

To quantify the monetary value of the tourism (recreation) service provided by the Trincomalee beaches, dunes and pelagic system (Indian Ocean), the contingent valuation and net factor income methods are used. To achieve this, the sum of consumer and producer surplus (PS) is calculated to estimate the total tourism value, which is based on the approach used by Van de Kerkhof et al. (2014). For this purpose, an on-site survey was conducted by the Coast Conservation Department (CCD) of Sri Lanka, during the period of December 2016 – February 2017, by using a pre-designed questionnaire and on-site interviews with 70 visitors. By using the contingent valuation method, it was aimed to estimate the consumer surplus, but since most of the interviewees stated no contribution and willingness to pay (WTP) to avoid ecosystem degradation, this factor was excluded from the valuation study. Therefore, the total recreation/tourism value here is only equal to the producer surplus value, which is derived from the ecosystem-related tourists’ expenditures. Table 1 indicates information regarding the surveyed beaches, sample size, mean duration of tourist stays, and their origins.

3.1.2. Identifying potential impacts of coastline recession on tourism service in 2110, and quantifying monetary value of the identified change

In the second methodological step of this study, the potential impacts of SLR and storm induced – coastline recession on the tourism service are determined for the year 2110, and the resulting change in its associated value is quantified by using the approach presented by Mehvar et al. (2018b; 2019).

- SLR and storm-induced coastline recession in Trincomalee coastal area

In this step, the results of the study conducted by Dastgheib et al. (2018) are used, in which probabilistic estimates of coastline retreat of the entire Eastern coast of Sri Lanka due to SLR and storm events by year 2110 were computed. A sea level rise of approximately 0.9 m is considered in this study representing the regional relative sea level rise (excluding land subsidence) linked to the RCP8.5 IPCC scenario. This sea level rise estimate was calculated by Dastgheib et al. (2018) for the year 2110 using the “intermediate” assessment methodology suggested by Nicholls et al. (2011). Dastgheib et al. (2018) obtained the probabilistic coastline recession estimates by applying the Probabilistic Coastal Recession (PCR) model (Ranasinghe et al., 2012), and Joint Probability Method, which considered series of data-fitted synthetic storm events (Callaghan et al., 2008). The PCR model framework is designed to calculate a large number of long, realistic sequences of beach erosion and recovery, enabling the statistical analysis of these events.

For calculation of the coastline recession in the PCR model, the structural erosion function proposed by Mendoza and Jimenez (Mendoza and Jiménez, 2006) is used. Mendoza and Jiménez (2006) model provides the magnitude of eroded volume and beach retreat, by means of an aggregated formulation dependent on different storm properties (Hs, Tp and duration) and beach morphology features such as sediment grain size and beach slope (Dastgheib et al., 2018).

The PCR 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 accounts for subsequent profile recovery during the inter-storm periods.

The model output comprises a time series of the coastline location. By performing about 100,000 realisations of 100 years long simulations, a dataset required for statistical analysis is obtained. The value of coastline recession (or retreat) can be defined when it is benchmarked to a Reference Coastline (RCL). The results of PCR model, used here, provide the distance between the changed coastline (after SLR and storm induced erosion) and the location of 1% exceedance probability of run-up in the period of 1979–2009; the latter being the RCL adopted by Dastgheib et al. (2018). Table 2 indicates Dastgheib et al.’s (2018) projections of coastline recession for the year 2050 and 2110 for a selected coastal transect T18 (see Fig. 2). In the present study, the results for the year 2110 are exclusively used. To encapsulate the maximum likely coastline recession, the affected area is considered from the present day coastline to the projected 1% exceedance probability recession in 2110 (i.e. red line in Fig. 2).

Table 1
Summary of the beach survey data.

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

1 More information about the valuation of coastal ecosystem services and the economic valuation methods can be found in Mehvar et al. (2018a).
2 More information about the PCR model can be found in Ranasinghe et al. (2012).
Table 2
Coastline recession magnitudes (m) associated with different exceedance probabilities in 2110 at transects T15-T34 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-15    | 56 | 45  | 34  | 84 | 73  | 62  |
| T-18    | 54 | 42  | 29  | 72 | 60  | 47  |
| T-20    | 70 | 55  | 39  | 95 | 80  | 64  |
| T-23    | 52 | 42  | 31  | 82 | 72  | 61  |
| T-27    | 57 | 44  | 31  | 81 | 68  | 55  |
| T-29    | 81 | 63  | 46  | 117| 99  | 82  |
| T-30    | 160| 104 | 63  | 192| 136 | 95  |
| T-34    | 63 | 48  | 34  | 87 | 73  | 59  |

Fig. 2. Example of computed 1% (red) and 50% (orange) exceedance probability coastline 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
• Identifying potential consequence of coastline recession on the tourism service

The major consequence of coastline recession is the disappearance of the beach, and in severe cases, dunes and back-beach areas, resulting in loss of/damage to the coastal environments and properties. Coastline recession can therefore affect wetland ecosystems and the services they provide due to the landward migration of wetlands (Runting et al., 2017). Since there is a little known about how coastline recession will quantitatively affect the monetary value of coastal ecosystem services (CES) (here referred to as tourism service), in this step, the “what if scenario” approach presented by Mehvar et al. (2018b; 2019) is used. In doing this, key tourism-related attributes are defined and the potential impacts of coastline recession and beach loss are identified on each of these attributes. A total beach loss is considered here, as the projected coastline recession for Trincomalee indicates that, the probability of the entire sandy beach area being permanently lost by 2110 exceeds 50% all along this coast.

Following Mehvar et al. (2018b; 2019), the impact (i.e. change) is quantified by assigning a percentage “range of change” for each attribute, resulting in a corresponding change in the value of tourism service. 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. Assignation of these impact indications is based on a “what if scenario” approach depending on the tourism-related attributes and the 2110 coastline recession considered.

• Quantifying monetary value of the identified change in tourism service

After identifying how a complete loss in the extent of beach area of Trincomalee may affect the tourism service of the wetland ecosystems considered, this change is then translated into quantitative monetary value by using the result of valuation study conducted in the Section 3.1 (a).

3.2. Quantifying environmental risk

Risk is widely considered as a combination of the hazard occurrence, the exposure and vulnerability of people, properties, and the environment to those hazards (Smith, 2003; Rotmans, 1998; Jones, 2001; Ness et al., 2007; Covello and Merkhofer, 2013, Oppenheimer et al., 2014). This concept has been adopted by Topuz et al. (2011); Enzenhoefer et al. (2012); Tartakovsky (2013); and Teodosiu et al. (2015), to define environmental risk (ER) as a function of the environmental impact (EI), and its probability of occurrence (P), as presented in Eq. (1):

\[ ER = EI \times P \] (1)

The ER considered in this study is due to coastline recession-driven losses in the monetary value of tourism service for the selected beaches of Trincomalee coastal area by 2110. To quantify the environmental risk, Eq. (1) is used, considering: (1) the loss value estimated for the tourism service of wetland ecosystems due to coastline recession by 2110, which is derived from the Section 3.1; and (2) the probability of the coastline 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: Nilaveli, Trincomalee, and Alas Garden. Altogether, the total beach area considered is approximately 1.63 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, cafés, parks, tourist centers, water parks, and centers for water sports and marine recreational activities (i.e. 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 a 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 transect defined by Dastgheib et al. (2018), spanning from transect T-15 (northern end of Nilaveli beach) to transect T-34 (southern end of Trincomalee beach).

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 then 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, by the total extent of the three considered beaches. The distribution of loss values is presented in detail in Appendix - Table A1. Fig. 3 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.

In the second step, the exceedance probabilities of coastline recession in 2110 are combined with the loss values, calculated 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
Fig. 3. Study area showing the three beaches (Nilavelli, Trincomalee, and Alas Garden) considered for quantifying the value of coastline recession driven risk for tourism service of wetland ecosystems, showing the cross-shore transects (T15–T34) with 1% exceedance probability by 2110 (a). Zoom in of T29−T34 showing the extent of beach erosion in white (b).
cross shore direction (due to the cross-shore variation in recession exceedance probability from 1% to 100%), as well as in the alongshore direction (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 the cross shore transects, the following approach is used. The Delft3D software (Quick-in Menu) is used, in which, 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 coastline recession within the grid, and combining them 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.

4. Results

The results of this study are presented in three parts; (1) present-day value of the tourism service provided by the wetland ecosystems of Trincomalee district; (2) potential loss value of the tourism service due to coastline recession in 2110; and (3) environmental risk value associated with the tourism service of the wetland ecosystems due to coastline recession in 2110.

4.1. Present-day value of tourism (recreation) service

Recreation or tourism value is estimated by calculating the producer surplus value. To calculate the PS (see Table 3), 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 is 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 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 ecosystems is taken as 80% and 60% for direct and indirect values, respectively.

Total net revenue is then estimated by considering the 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 (estimated as 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), amounting to a total annual recreation value of US$ 28 million, which is equal to approximately 1 US$ per m² of beach.

4.2. Changes in the value of tourism service due to coastline recession in 2110

Table 4 shows analysis of the coastline recession impacts on the recreation value of wetland ecosystems in the Trincomalee district. Here, different impact indications are assigned to the various tourist related attributes, which vary due to the different 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 3. 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, thirteen (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 best.

Change in tourist value is ultimately calculated for each attribute, by multiplying ‘potential impact indications’ (as defined in Section 3.1–b), ‘contribution to the total value’ and PS (US$ 28 million - from Table 3) together. The total change is quantified by summing the changes for each attribute. Table 4 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.

Table 4 indicates that coastline 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 water sports. Such impact assignation can be justified by the fact that a reduced number of visitors will 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, the loss of beaches due to coastline recession will decrease the revenue earned from 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%) being assigned for these two attributes as indicated in Table 4.

4.3. Environmental risk value due to coastline recession in 2110

In this section, the results of quantifying coastline recession-driven risk associated with the tourism service of considered beach areas (Trincomalee, Alas garden, and Nilaveli) are presented for the year 2110. Table 5 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 3.24.

Since the loss value of the 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 Fig. 4 for the three considered beach areas (divided into 6 beach zones). 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) up to US$1.10 per m² as the maximum risk value on the coastline with 100% exceedance probability of coastal erosion. As shown in Fig. 4, the maximum risk value is for the Alas Garden beach (T29), which is in fact the most touristic beach in Trincomalee with more than 60 recreational venues and facilities for tourists, leading to a higher number of visits, and consequently garners a higher tourism revenue.

### Table 3
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                      |

Table 4
Potential change in the tourism value of coastal wetlands in Trincomalee due to coastline 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 coastline 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                       |

Table 5
Estimates of the loss value of tourism service due to coastline 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 the 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 Fig. 4 for the three considered beach areas (divided into 6 beach zones). 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) up to US$1.10 per m² as the maximum risk value on the coastline with 100% exceedance probability of coastal erosion. As shown in Fig. 4, the maximum risk value is for the Alas Garden beach (T29), which is in fact the most touristic beach in Trincomalee with more than 60 recreational venues and facilities for tourists, leading to a higher number of visits, and consequently garners a higher tourism revenue.

---

4 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 4 (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).
5. Discussion and conclusion

This study presents an approach that may be generically used to obtain quantitative assessments of climate change driven environmental risk in coastal areas. A demonstration application of the approach resulted in the quantification of the coastline recession-driven environmental loss and risk along the coast of Trincomalee by the year 2110. Trincomalee beaches, dunes and pelagic

Fig. 4. Minimum and maximum risk value of ecosystem related-tourism service, due to SLR and storm induced coastline 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, which results in a risk value of tourism service upto US$ 1.10 per m² of the beach area.
system (Indian Ocean), which provide a recreation (tourism) service, comprised the wetland ecosystems considered in this demonstration application. Consideration of other wetland ecosystems services such as storm protection, climate regulation, etc. is outside the scope of this study, due to data scarcity for conducting valuation studies.

In this study, we intentionally focused the effects of coastal recession on CES. While, there are a few studies that specifically focus on inundation impacts on CES’s value (Wang et al., 2015; Mehvar et al., 2018b; 2019), there are virtually no reported studies focusing on coastal erosion impacts on the monetary value of CES, and its associated risk value. This is enabled here by the selection of a study area that has historically been prone to coastal erosion, but not so much to coastal inundation. Moreover, along the sandy beaches of Trincomalee, permanent inundation is part of the overall coastal retreat, and periodic inundation due to wave action, is taken care by the definition of reference coastline. Also in this case study, as there are no lower lands behind dunes, erosion that can cause extra
inundation (dune breach) will not occur.

In the first step of this study, the present-day value of the tourism (recreation) service provided by the Trincomalee beaches, dunes and pelagic system (Indian Ocean) was quantified. This quantification shows that the tourism value is only based on estimates of the net revenue generated by tourism, since no consumer surplus is considered in the valuation of this service. This resulted in a reduction in total present-day value of this service estimated at US$ 28 million. The reduction in estimated total present-day value is rooted in the reluctance presented by the visitors to contribute to the environmental preservation and maintenance plans as stated in the interviews. In this step, it was assumed that 25% of the average expenditure reflects the ecosystem’s added value to the tourism industry. This assumption is necessary due to data scarcity on the cost structure of the tourism industry in the study area. In addition, the unavailability of data on the dependency level of the direct and indirect values on the considered ecosystems necessitated the assumption of two rates for direct (80%) and indirect (60%) values. The assumptions were adopted from Schep et al. (2013), and van de Kerkhof et al. (2014), in which the same added value (i.e. 25%) was assumed, and varied dependency levels for different recreational activities were determined in ranges similar to those used in this study.

Fig. 4. (continued)
The sample size of 70 visitors used in this study is considered to provide a reasonable representation of the whole number of visitors, although some limitations were observed in the data collection period. For example, the interviews with visitors were repeated a few months after (February 2017) the first data collection phase, because there were very few people visiting the Trincomalee beaches during the first interview phase. Having considered this limitation as well as the multiple destinations chosen by most of the visitors (to visit other beaches, out of the study area), the results of the second round interviews show a reasonable average visitor’s expenditure per day (US$), and average duration of stay (day), which are comparable with the results of similar studies having larger sample sizes (i.e. Schep et al., 2013; van de Kerkhof et al., 2014).

The second step of this study shows that the tourism value is likely to decrease between US$ 0.5–0.6 per m$^2$ of the total beach area in Trincomalee’s district in 2110. Notably, here it is assumed that even with a total beach loss, coastal wetlands such as the pelagic system may still provide tourism service, and hence generate revenues by providing opportunities for water sports and marine related recreational activities.

Quantifying coastline recession-driven risk associated with the value of the tourism service provided by wetland ecosystems of Trincomalee, shows a medium risk value ranging between 0 and 11,000 US$/Ha. This implies that SLR and storm induced erosion in 2110 is not likely to considerably decrease the value of tourism service, leading to an environmental risk. This is mainly due to three factors: (1) the present-day estimated value (with a rather medium range magnitude) in the first step of this study, is only based on the ecosystem-related revenue generated from the tourism in Trincomalee (producer surplus); (2) the relatively medium magnitude of the estimated loss in tourism value of the beach area; and (3) the low probability of the entire extent of the beach being lost. The third factor implies that the loss value of the tourism service estimated here is compensated by the low probability of occurrence, resulting in a moderate environmental risk. However, high environmental risk values may prevail in situations where the probability of the entire beach being lost due to climate change driven coastline recession is high.

Notably, in this study, the current shoreline is assumed to be in equilibrium condition and no longshore sediment transport gradients or other evolutionary processes are considered to change the current morphodynamic of the shoreline. Thus, for the estimation of the future coastline recession trends, storms and SLR-induced erosion are the only drivers of change, resulting in beach retreat and recovery by 2110. Apart from the shoreline behavior, here it is assumed that there will not be an accommodation space for potential landward migration of the ecosystems (i.e. beach area and mangroves). Therefore no favorable habitat could be created as a result of this assumption, and the estimated erosion is expected to occur in relation to the current reference coastline (beach extent) with no landward beach expansion.

Considering the results of this study, some suggestions can be made for the betterment of management practices to minimize the tourism loss value and its associated risk. For example, since SLR and storms are the main drivers of erosion and beach loss here, coastal protection structures (i.e. groynes, breakwaters, etc.) can be a solution to reduce the magnitude of erosion and the probability of its occurrence. Apart from structural measures, creating a living shoreline (planting seaweed and beach vegetation) can also mitigate the effects of erosion, especially in the sandy beaches and dune systems of the study area. In addition, beach nourishment is another way of coping with coastal erosion which can prevent the beach area from being completely eroded in the future.

Finally, it should be noted that there are some residual uncertainties associated with the risk quantification presented here. These mainly include: (1) the methods that determine recession exceedance probabilities, and (2) the methods by which loss values are estimated per m$^2$ of the beach area. The presence of storm protection structures, and wave attenuation - erosion stabilization services, which can be provided by other wetland ecosystems such as mangroves, seagrass beds, coral reefs, and beach vegetation may also change the valuation results. In addition, other factors that can affect the results of this study include changes in tourist expenditure (associated with valuation of tourism service), ticket price for recreational activities (e.g. snorkelling, and whale watching), visitor’s income and its distribution (affecting WTP), economic discount rate for the future value of ecosystem services (here is considered zero), added value of recreational services to the tourism industry, dependency level of tourism on the health status of ecosystems, expert opinions and their expectations of CC driven impacts on ecosystems, ecological responses over a very long time span, and social norms. Having considered all these factors, the estimates of losses and risks are presented here as a value range, and not as single deterministic values. Therefore, the outcomes of this study should be considered in the light of the presented data and assumptions used in the three methodological steps. For other applications, modification of the approach might be needed depending on the study area and data availability.

Declaration of Competing Interest

None.

Acknowledgments

The authors are thankful for the financial support from the ADB-IHE Knowledge partnership (via the CRISP project), and the AXA Research fund. RR is supported by the AXA Research fund and the Deltares Strategic Research Programme ‘Coastal and Offshore Engineering.’ This study could not have been possible without the excellent support provided by the staff of the Research and Design section of the Sri Lanka coast conservation department throughout this study, for which the authors are very grateful.

Appendix

See Table A1.
| Class/Zone | Name of the beach | Transect No. | Hotel/Restaurant                                                                 | Other tourism related places (National park Resort/Church/Tourist Centre)                                                                 | No. of places | Weighted factor | Total loss value (US$) | Area (m$^2$) | Loss value/m$^2$ (US$) |
|------------|-------------------|-------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|--------------|------------------|------------------------|---------------|------------------------|
| Class 1    | Nilaveli          | T15-T16-T17 | Hotel Sadham, Serendib Hotel Nilaveli, Eastwest Restaurant, Spicy Way Restaurant | Nilaveli Ayurveda Resort, Pigeon Island Beach Resort, Nilaveli Palm House, Irakkandi Bridge, Victory Life Church, Dilaxshan Store          | 10           | 0.05             | 43583–52300            | 263000         | 0.166–0.199            |
| Class 2    | Nilaveli          | T18-T19     | Serendib Hotel Nilaveli, Nilaveli Beach Hotel, Organic Farm of Nilaveli Beach Hotel, Nilaveli Crystal Blue Hotel, Shahana Hotel, Samudrthi | Pigeon Island Beach Resort, Nilaveli Ayurveda Resort, Nagenahira Beach villas, Nilaveli Beach, Anilana Nilaveli (statue) Seadoo rental, Pigeon Island tour, Boat Service | 15           | 0.08             | 65374–78450            | 139000         | 0.470–0.564            |
| Class 3    | Nilaveli          | T20-T21-T22 | Cafe Nilaveli, Nilaveli Hybrid Holiday Hotel, Pearl Inn Green Nilaveli, Gopalapuram Guest House, Seaway Hotel, Luna Beach Hotel, Shahira 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, Mittys Round House, Nilaveli Hybrid Holiday Hotel, Cardamon Hotel, Nilaveli Ocean Condos, Ocean 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 | 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 | 36           | 0.19             | 156898–188278          | 366000         | 0.429–0.514            |
| Class 4    | Nilaveli          | T23-T24-T25-T26-T27 | Blue Whale Nilaveli, Nilaveli Beach Hostel, Hotel Coral Bay, Walnut Beach Nilaveli, Ocean Way Nilaveli, Restaurant & Beach Cabanas, Leo's café, NN Beach Hotel, New Retreat Guesthouse, Nilaveli Gates Restaurant, Nilaveli Seafood Restaurant | Nilaveli Diving Centre, Aquacreed Scuba, Public Playground, Catamaran Beach Tour, Veloor Thirumurugan Temple, Umair Food Centre, Bella Nilaveli Beach, Periyakulam, lake H.A.M Stores | 20           | 0.10             | 87166–104600           | 232000         | 0.376–0.451            |

(continued on next page)
| Class/Zone | Name of the beach | Transect No. | Hotel/Restaurant | Other tourism related places (National park Resort/Church/Tourist Centre) | No. of places | Weighted factor | Total loss value (US$) | Area (m²) | Loss value/m² (US$) |
|------------|-------------------|--------------|------------------|-------------------------------------------------------------------------|---------------|----------------|----------------------|----------|-------------------|
| Class 5    | Alas garden       | T29          | Trinco Blu by Cinnamon, The Secret Garden Guest House, Summer Guest House, Golden Beach Cottages (PVT) Ltd, Anantamaa 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, Savi Cabana, French Garden Regish Guest House, Scuba Lanka, Silsa 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, Sunway holiday inn, Athena Guest Inn, Nero Kitchen, Theepam - Rooms and Hall, Kashe 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, Oyster Indian Restaurant, Ganga 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 | 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, Isha Water Park, Sri lanka diving tours | 67 | 0.36 | 292005–350406 | 323000 | 0.904–1.085 |
| Class 6    | Trincomalee       | T30-T31-T32-T33-T34 | Savi Holiday Inn, Inn Seabreeze, Pleasant Park Holiday Inn, Trinco Huts restaurant, Blue Wings Beach Hotel, Trinco Hemach Beach Hotel, Motel Apple Five, Hotel Green Garden, JKAB Park Hotel, Jayalaya Muslim Maha Vidyalayam, Prasanth Rest Inn, Trinco Villas, Kamal & Mular Guest, My Hot Burger, Mean Blue Restaurant, Linganagar maha vidyalayam, Svyree Chinese restaurant, Kiri Restaurant and Backers | Carne’s Beach Resort, Savi Cabana, Colombo Diven Trincomalee, Craft Window, Trinco Mitra Inn, Pastoral Centre, Velankanni Church, Skandig Beach Resort, Amila Guest House, JKAB Beach Resort, V.M Beach resort, RBM rest house, Ganesh Store, Fashion Hut, Vegan Beach Resort, Abhayaramaya Temple, Abhayarama Temple, Sri Anandaramaya, Abans Service Centre, R.P. Trade Center, Linganagar Church, Trincomalee Railway Station | 39 | 0.21 | 169973–203968 | 310000 | 0.548–0.658 |
References

Ahmed, M., Suphachalasai, S., 2014. Assessing the Costs of Climate Change and Adaptation in South Asia. Asian Development Bank.

Bakker, P., 2018. Future Coastline Recession and Beach Loss in Sri Lanka. MSc. Thesis. University of Twente.

Buulijens, J., Ratnayake, I., Gnanapala, W.A., 2017. In: 17 Study site Sri Lanka, Climate Change Challenges for the Sri Lankan Tourism Industry. Global Climate Change and Coastal Tourism. Recognizing Problems, Managing Solutions and Future Expectations, pp. 200.

Callaghan, D.P., Nielsen, P., Short, A., Ranasinghe, R., 2008. Statistical simulation of wave climate and extreme beach erosion. Coastal Eng. 55 (5), 375–390.

Covelo, V.T., Merkhofer, M.W., 2013. Risk Assessment Methods. Approaches for Assessing Health and Environmental Risks. Springer Science and Business Media.

Dastgheib, A., Jongejan, R., Wickramanayake, M., Ranasinghe, R., 2018. Regional scale risk-informed land-use planning using probabilistic coastline recession modelling and economical optimisation, East Coast of Sri Lanka. J. Mar. Sci. Eng. 6, 120.

Dawson, R.J., Dickson, M.E., Nicholls, R.J., Hall, J.W., Walkden, M.J., Stansby, P.K., Mokrech, M., Richards, J., Zhou, J., Milligan, J., Jordan, A., 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Clim. Change 95 (1–2), 249–288.

Enzenhofer, R., Nowak, W., Helmg, R., 2012. Probabilistic exposure risk assessment with advective-dispersive well vulnerability criteria. Adv. Water Resourc. 36, 121–132.

Green Tech Consultants (GTC), 2015. Comprehensive Environmental Profile for Thambalagamuwa Coastal Bay, Final Report.

IUCN, 2007. Environmental and Socio Economic Value of Mangroves in Tsunami Affected Areas: Rapid Mangrove Valuation Study, Panama Village in South Eastern Coast of Sri Lanka. IUCN.

Jones, R.N., 2001. An environmental risk assessment/management framework for climate change impact assessments. Natural Hazards 23 (2–3), 197–230.

Kellen, W., Zaalberg, R., Neutens, T., Vannesville, W., De Maeyer, P., 2011. An analysis of the public perception of flood risk on the Belgian coast. Risk Anal., Int. J. 31 (7), 1055–1068.

Kottawa-Arachchi, J.D., Wijeratne, M.A., 2017. Climate change impacts on biodiversity and ecosystems in Sri Lanka: a review. Nature Conserv. Res. 2 (3), 2–22.

Lakmali, E.N., Deshapriya, W.G.A., Jayawardene, K.G.A., Raviranga, R.M.P., Ratnayake, N.P., Premasiri, H.M.R., Senanayake, I.P., 2017. Long term coastal erosion and shoreline positions of Sri Lanka. Survey Fish. Sci. 3 (2), 1–6.

McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide, assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urbanization 19 (1), 17–37.

Mehvar, S., Filatova, T., Syukri, I., Dastgheib, A., Ranasinghe, R., 2018b. Developing a framework to quantify potential Sea level rise-driven environmental losses, a case study in Semarang coastal area, Indonesia. Environ. Sci. Policy 89, 216–230.

Mehvar, S., Filatova, T., Dastgheib, A., De Ruyter Van Steveninck, E.D., Ranasinghe, R., 2018a. Quantifying economic value of coastal ecosystem services, a review. J. Marine Sci. Eng. 6 (1), 5.

Mehvar, S., Filatova, T., Sarker, M.H., Dastgheib, A., Ranasinghe, R., 2019. Climate change-driven losses in ecosystem services of coastal wetlands: a case study in the West coast of Bangladesh. Ocean Coastal Manage. 169, 273–283.

Mendoza, E.T., Jiménez, J.A., 2006. Storm-induced beach erosion potential on the Catalanian coast. J. Coastal Res. 48, 81–88.

MOE, 2010. Biodiversity and ecosystem services: sector vulnerability profile. In: Strengthening Capacity for Climate Change Adaptation: ADB TA 7326 (SRI). Ministry of Environment. Climate Change Secretariat, Sri Lanka, pp. 1–90.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60 (3), 498–508.

Nicholls, R., Hanson, S., Lowe, J., Warrick, R., Lu, X., Long, A., Carter, T., 2011. Constructing sea-level scenarios for impact and adaptation assessment of coastal area, a guidance document. Supporting Material, Intergovernmental Panel on Climate Change Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA). Geneva, Switzerland.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O’Neill, B., Takahashi, K., 2014. Emergent risks and key vulnerabilities. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Cambridge Univ Press, Cambridge, UK, pp. 1039–1099.

Ranasinghe, R., Callaghan, D., Stive, M.J.F., 2012. Estimating coastal recession due to sea level rise, beyond the Brun rule. Clim. Change 110 (3), 561–574.

Resourse profile, Trincomalee District, 2016. District Planning Secretariat, Kachcheri, Trincomalee.

Rotmans, J., 1998. Methods for IA. The challenges and opportunities ahead. Environ. Modeling Assesessment 3 (3), 155–179.

Rutting, R.K., Lovelock, C.E., Beyer, H.L., Rhodes, J.R., 2017. Costs and opportunities of preserving coastal wetlands under sea level rise. Conserv. Lett. 10 (1), 49–57.

Scheep, S., van Beukering, P., Brander, L., Wolfs, E., 2013. The Tourism Value of Nature on Bonaire Using Choice Modelling and Value Mapping. IVM Institute for Environmental Studies, Amsterdam, The Netherlands.

Smith, K., 2003. Environmental Hazards, Assessing Risk and Reducing Disaster. Routledge.

Tartakovsky, D.M., 2013. Assessment and management of risk in subsurface hydrology, a review and perspective. Adv. Water Resourc. 51, 247–260.

Teodosiu, C., Robu, B., Cojocariu, C., Barjoveanu, G., 2015. Environmental impact and risk quantification based on selected water quality indicators. Natural Hazards 75 (1), 89–105.

Topuz, E., Talinli, I., Aydin, E., 2011. Integration of environmental and human health risk assessment for industries using hazardous materials, a quantitative multi criteria approach for environmental decision makers. Environ. Int. 37 (2), 393–403.

Van de Kerkhof, S., Scheep, S., van Beukering, P., Brander, L., Wolfs, E., 2014. The Tourism Value of Nature on St Eustatius. IVM Institute for Environmental Studies. Report R14-07.

Wang, J., Gao, W., Xu, S., Yu, L., 2012. Evaluation of the combined risk of sea level rise, land subsidence, and storm surges on the coastal areas of Shanghai, China. Clim. Change 115 (3–4), 537–558.

Wang, B., Su, S., Peng, Z., Yang, F., 2015. Impact of sea level rise on ecosystem services values and adaptation measures. Shengtai Xuebao/Acta Ecol. Sin. 35 (24), 7998–8008.