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REPORT

Sea-Level Rise and Coastal Wetlands

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Abstract This paper seeks to quantify the impact of a 1-m sea-level rise on coastal wetlands in 86 developing countries and territories. It is found that approximately 68 % of coastal wetlands in these countries are at risk. A large percentage of this estimated loss is found in Europe and Central Asia, East Asia, and the Pacific, as well as in the Middle East and North Africa. A small number of countries will be severely affected. China and Vietnam (in East Asia and the Pacific), Libya and Egypt (in the Middle East and North Africa), and Romania and Ukraine (in Europe and Central Asia) will bear most losses. In economic terms, the loss of coastal wetlands is likely to exceed $703 million per year in 2000 US dollars.

Keywords Wetlands · Valuation · Climate change · Sea-level rise · GIS

INTRODUCTION

Coastal wetlands provide a large number of goods and services contributing to the economic welfare of local and global communities (Millennium Ecosystem Assessment 2005).[1] Services provided by these ecosystems include shorelines protection, storm buffering, sediment retention, water quality maintenance, nutrient recycling, preservation of biodiversity, provision of natural environmental amenities, climate regulation, carbon sequestration, as well as cultural heritage and spiritual benefits.[2]

However, coastal wetlands are rapidly declining. Studies indicate that in the late twentieth century, approximately 1 % of the global coastal wetland stock was lost annually (Hoozemans et al. 1993; Nicholls 2004). While the causes of such losses are often numerous and complex,[3] the rapid loss coastal wetlands was primarily caused by land

The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

[1] Coastal wetlands comprise marshes, swamps, mangroves, and other coastal communities. However, a precise and widely agreed upon definition of wetland is not available. The RAMSAR Convention (a UNESCO-based intergovernmental treaty on wetlands adopted in 1971) defines wetlands as "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 with the depth of which at low tide does not exceed six meters" (Article 1.1). Article 2.1 of the convention highlights that wetlands 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 islands.

[2] See Larson et al. (1989), Williams (1990), Barbier (1991), Barbier et al. (1997), Brouwer et al. (1999), Woodward and Wui (2001), McLeod et al. (2005), Brander et al. (2006), Laffoley and Grimsditch (2009), and Mcleod et al. (2011).

[3] In addition to SLR, causes include waves, erosion, subsidence, and storms and biotic effects. Human actions include drainage for agriculture and forestry; dredging and stream channelization for navigation flood protection, conversion for aquaculture and mariculture, construction of schemes for water supply, irrigation and storm protection, discharges of pesticides, herbicides and nutrients, solid waste disposal, sediment diversion by deep channels and other structures, mining of wetland soil, groundwater abstraction, hydrological alteration by canals, roads and other structures, and mosquito control.

reclamation. While significant losses due to human actions are likely to continue in the future, it is projected that stresses on wetland areas may be further aggravated in the twenty-first century due to climate change. Wetlands face a number of hazards resulting from a rise in sea levels, increases in air and water temperature, and changes in the frequency and the intensity of precipitation and storm patterns.

Understanding the impact of climate change and more specifically of sea-level rise (SLR) on coastal wetlands must take into account factors that affect the ecological balance of wetland ecosystems such as the history of sea levels in regard to the development of coastal gradients, relative geomorphic and sedimentologic homogeneity of the coast, the coastal processes including the tidal range and its stability, the availability of fresh water and sediment, and the salinity of soil and groundwater (Belperio 1993; Semeniuk 1994; Blasco et al. 1996; Alongi 2008). It must also account for the capacity (or lack thereof) of wetlands to migrate as SLRs.[4]

The threat posed by the rise in sea levels to coastal wetlands has received some attention in the literature.[5] Alongi (2008) presents a maximum global loss of mangrove forests ranging between 10 and 15 %. This estimate applies for the upper end of the SLR projection presented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). Alongi (2008) does not discuss possible impacts on other types of coastal wetlands, does not present a quantified assessment of losses at regional levels and does not estimate economic losses associated with this loss of mangroves. Similarly, Gilman et al. (2006) focuses solely on mangroves of the Pacific islands. Their analysis predicts a 13 % decline in mangroves of the Pacific islands assuming the upper end of the IPCC SLR scenario of the Fourth Assessment Report. Snedaker (1995) focuses on mangroves of the Caribbean region and estimates a loss of approximately 15 % of mangroves area in the Caribbean region (in addition to Florida) for a similar SLR scenario.

Nicholls et al. (1999), Nicholls (2004), and McFadden et al. (2007) extend the analysis of the impact of SLR beyond mangroves to include all coastal wetlands. Nicholls et al. (1999) estimated that a 38-cm rise in global sea level would lead to an approximate 22 % loss of the coastal wetlands, and that a 1-m SLR would yield a loss of 46 % of the coastal wetlands. Nicholls (2004) further estimated that a 34-cm rise in global mean sea level would lead to a 20 % loss of coastal wetlands. Both of these analyses are based on wetland losses derived from the Global Vulnerability Analysis (Hoozemans et al. 1993) that includes an incomplete coverage of global coastal wetlands, which is duly noted by McFadden et al. (2007). The modeling of all coastal wetlands by McFadden et al. (2007) suggests global wetland losses of 32 and 44 % by for a 50-cm and 1-m rise in sea level. Hoozemans et al. 1993 estimated a loss of approximately 50 % of global coastal wetlands following a 1-m SLR. However, their analysis focused solely on coastal wetlands "of international importance" (following the criteria defined in the Ramsar Convention). All of the above estimates are not delineated by types of wetlands and by regions of the world. Furthermore, none of the above analyses present estimates of the economic cost associated with these estimated losses of coastal wetlands.

In this paper, we provide an estimate of the potential impacts of a 1-m SLR[6] on coastal wetlands in the 86 developing countries of the 6 regional country groupings used by the World Bank.[7] We believe this paper contributes to the literature in four different and significant ways. First, unlike previous efforts of a similar nature, this estimate of the impact of SLR is performed for different types of coastal wetlands obtained from the recent *Global Lakes and Wetlands* database (GLWD-3).[8] Second, this analysis presents quantified estimated losses for each region of the world (as defined by the World Bank). Third, this analysis explicitly accounts for the estimated capacity of coastal wetland ecosystems to move (or migrate) inland as the coastline recedes. Finally, this paper provides an estimate of the economic value of the adversely impacted wetlands.

Our estimates indicate that a 1-m rise in sea level may lead to a 68 % loss of the present coastal wetland stocks. A large percentage of this estimated loss is found in Europe and Central Asia, East Asia and the Pacific, as well as in the Middle East and North Africa. A small number of countries will be severely affected. China and Vietnam (in the East Asia and the Pacific), Libya and Egypt (in the

[4] See Alongi (2008), Erwin (2009), and Gilman et al. (2006). McIvor et al. (2013) provide an excellent discussion of the physical processes guiding the resilience of coastal wetlands to SLR.

[5] See Nicholls et al. (2007) for a comprehensive review.

[6] The Fourth Assessment Report of the IPCC projected a rise in global mean sea level ranging from 18 to 59 cm by 2100. A final draft of the Fifth Assessment Report may consider likely a 26–82 cm rise in sea levels by the end of the twenty-first century. However, these ranges have been criticized as being too conservative and not sufficiently reflective of the large uncertainty pertaining to SLR (Krabill et al. 2004; Overpeck et al. 2006; Rahmsdorf 2007). Numerous studies suggest that SLR could reach 1 m or more during this century (Pfeffer et al. 2008; Vermeer and Rahmstorf 2009; Hansen and Sato 2012). The IPCC itself noted that the upper values of projected SLR presented in its reports are not to be considered upper bounds and that higher rises in sea level cannot be ruled out.

[7] These are East Asia and Pacific, Europe and Central Asia, Middle East and North Africa, Latin America and Caribbean, South Asia, and Sub Saharan Africa.

[8] Coastal wetlands in this analysis comprise freshwater marshes, swamp forests, GLWD Coastal Wetlands, and Brackish/saline wetlands located at elevation of 1 meter or less above sea level.

Middle East and North Africa), and Romania and Ukraine (in the Europe and Central Asia) will bear most losses. The economic value of the wetlands at risk from 1 m SLR in the 86 developing countries considered in this analysis is estimated to be approximately USD 702 million per year (in USD 2000).

At the outset, we acknowledge the following limitations. First, while the geographical coverage of the analysis is global, it does not include developed countries of the world. This focus is partly explained by the fact that estimates of the impact of SLR in developing countries are typically lacking while estimates based on country-level data are available in many developed countries.[9] Second, this analysis does not assess nor account for the time profile of a 1-m rise in sea-level. Instead, we take this scenario as given, and assess the possible impacts of the present wetland stock to a 1-m SLR, accounting for the different migration potential of different types of coastal wetlands. Third, the digital elevation (90 m DEM V2) data used in the analysis prevents estimating losses from sub-meter SLR modeling.[10] Fourth, the lack of wetland and digital elevation data with a spatial resolution higher than 90 m prevented us from including small islands countries in our analysis.[11] Fifth, it is recognized that the migratory potential of wetlands depends on a wide range of factors that are site-specific and highly variable such as the continued flow of sediment and nutrients from inland stream as well as human activities. Such detailed information was not available on a global scale.

Despite these noted limitations, we believe this analysis to be of interest to developing countries and to those experts and organizations concerned with the impacts of SLR on coastal wetlands in developing countries. Given its low level of resolution and its wide (global) coverage, this study does not aim to be a substitute to country-level, high resolution studies. Instead, given the general lack of such studies in the developing world, it aims to raise awareness and prompt those countries (at least those for which high losses are estimated) to initiate a detailed, country-level assessment of the impacts of SLR on these key coastal ecosystems. Such estimates may then trigger action aimed at protecting or facilitating an increased resilience of coastal wetlands to climate risks, which may include preventing further declines resulting from human actions. The remainder of the paper is organized as follows. "Materials and Methods" section summarizes the data sources and describes the methodology. "Results" section presents area estimates of wetlands at risk from SLR as well as the economic value of these projected losses. "Conclusion" section briefly concludes.

MATERIALS AND METHODS

Data

In order to assess the exposure of coastal wetlands at risk from SLR, we employed Geographic Information System (GIS) software to overlay the area of the wetlands with the inundation zones projected for a 1-m SLR. We have used the best available spatially disaggregated global data sets from various sources, including the National Aeronautics and Space Administration (NASA), the US Geological survey (USGS), the World Wildlife Fund (WWF), and the Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise (DINAS-Coast) project. In particular:

[9] For example in the United States, Craft et al. (2009) estimate of the impacts of SLR on coastal wetlands of the state of Georgia while Day et al. (2000) reports estimates for the Mississippi Delta. Day et al. (2011) reports estimates for specific areas of the Mediterranean deltaic region. Technical limitations also impaired the inclusion of developed countries in this analysis. For example, the elevation data used in this analysis (90 m Shuttle Radar Topography Mission data) is restricted to latitude 60°N to 56°S. These data thus result in automatically excluding countries such as Canada, Iceland, Sweden, Norway, Finland, and Russia. In addition, while the wetlands data used in this analysis (GLWD-3) assemble a large number of attributes and polygon datasets to produce the most comprehensive database of lakes, reservoirs and wetlands, we have found that data for the developed and developing countries are not directly comparable. For example, the bulk of the coastal wetlands data for the USA is classified solely into two categories "50–100 % wetland" and "25–50 % wetland." The data on coastal wetlands for the USA have not been classified into types of coastal wetlands (such as freshwater marsh, swamp forest, and Brackish/saline wetlands). Given the inclusion of wetlands migration capacity in our analysis (and not simply exposure as has been done in existing literature thus far), information on wetlands type is important as different wetland types have different migration capacity. Information on wetland types is available for developing countries, but is not systematically available for developed countries, including the USA.

[10] The potential use of LIDAR survey (laser-based elevation measurement from low-flying aircraft) was beyond the scope of this analysis.

[11] It is not immediately possible to assess the impact of excluding small islands countries in the analysis. However, according to the estimates of the World Resources Institute (WRI) based on the data from the World Vector Shoreline, the total length of the world coastline would reach approximately 1.6 million kilometers (WRI 2000). According to the same estimates, the total coastline length of small island countries was estimated to reach approximately 105 000 km, or 6 % of the world total. Furthermore, the largest 15 countries in terms of coastline length (none of them being small islands states) represent approximately 60 % of the world's total coastline. As a result, we expect that the exclusion of small islands countries from this analysis does not significantly impact the results of the analysis. A limited number of country-level studies have aimed at estimating the impacts of climate change and SLR in small island states. For example, see Ellison (1993) and Schleupner (2008) and for the Caribbean islands of the Martinique and Bermuda, respectively.

- country coastlines were extracted from the World Vector Shoreline, a standard National Geospatial Intelligence Agency (formerly Defense Mapping Agency) product at a nominal scale of 1:250 000. World Bank (2010) information is used in the regional classification and boundaries. In addition, Exclusive Economic Zone data from VLIZ (2011) identifies the maritime boundaries of countries;
- for purpose of assessing elevation, all coastal tiles of 90 m Shuttle Radar Topography Mission (SRTM) data were obtained from http://srtm.csi.cgiar.org/. The resolution of this data is 5 geographic degrees latitude and longitude (approximately 500 km by 500 km);
- data on wetlands were extracted from all wetlands Global Lakes and Wetlands Database (GLWD-3) produced by the Center for Environmental Systems Research (CESR), University of Kassel, Germany, and the World Wildlife Fund US (WWF-US), Washington DC, USA (Lehner and Döll 2004). In the generation of the global map of lakes and wetlands from a grid at a spatial resolution of 30 s (approximately 1 km by 1 km at the equator), the GLWD-3 followed the definition of wetlands adopted by the Ramsar Convention and the International Union for Conservation of Nature. Our analysis focuses on freshwater marsh, swamp forests, GLWD Coastal Wetlands[12] and Brackish/saline wetlands; and
- in order to assess the impact of SLR on wetlands and the potential for adaptation, the wetland migratory potential (WMP) characteristics in the Dynamic Interactive Vulnerability Assessment (DIVA) database from the DINAS-COAST project was used (Vafeidis et al. 2008). Different types of wetlands are expected to have different migratory potential depending on their own natural characteristics as well as the characteristics of their surrounding environment. For example, it is expected that SLR will have its most pronounced effects on brackish and freshwater marshes in the coastal zone through alteration of hydrological regimes (Burkett and Kusler 2000; Baldwin et al. 2001; Sun et al. 2002). Similarly, SLR may not lead to losses of saltmarsh areas since these marshes accrete vertically and maintain their elevation relative to sea level where the supply of sediment is sufficient (Hughes 2004; Cahoon et al. 2006). The WMP value indicates the potential for wetlands to migrate landward in response to a 1-m rise in sea level. The migratory potential is based on a few geophysical characteristics of the coastline as described in Hoozemans and Hulsbergen (1995).

Five possible responses to SLR corresponding to categories of wetland migratory potential are defined for the DIVA database:

1. no change or no significant change;
2. a retreat of the coastline with inland migration of coastal ecosystems;
3. a retreat of the coastline without the possibility of inland migration;
4. a possible retreat of the coastline but increase of flooding area behind the coastline (“ponding”); and
5. total loss of the coastal ecosystem.

Methodology

The procedure used in this analysis followed the following four steps: (1) the SRTM database was used to identify inundation zones;[13] (2) a country surface for wetlands was extracted from the Global Lakes and Wetlands database; (3) migratory potential of wetlands were assigned from the WMP classification of the coastline from the DIVA database; and (4) the country surface of wetlands was overlaid with the inundation zone layer. The analysis then determined the area of wetlands that would be exposed to increased SLR and the area of wetlands that may be lost due to SLR given its specific migration potential. More specifically:

- countries and regions were identified with data from the World Bank and Exclusive Economic Zones from VLIZ (2011). The coastlines are derived from the SRTM 90 m digital elevation model (DEM) data files used as a mask for calculating country totals for wetlands. Information on WMP categories for the Coastline was downloaded from the DIVA GIS database;
- coastal terrain models derived from the SRTM 90 m DEM data files were converted into an ESRI ArcGIS data format, and merged to conform to country boundaries in the ArcGIS environment. The analysis includes SRTM tiles, which are 5 × 5 decimal degrees, with a coastline;
- inundation zones were derived from the DTM by setting the value to 1 for SLR equal to 1 m;

[12] GLWD Coastal Wetlands is a term used in this paper to distinguish coastal wetlands from the specific coastal wetlands type in the GLWD. GLWD Coastal Wetlands type is derived from a number of data sources and categories: “Lagoon” from ArcWorld; and “Delta,” “Lagoon,” “Mangrove,” “Estuary,” “Coastal Wetland,” and “Tidal Wetland” of WCMC wetlands map—see Lehner and Döll (2004) for a detailed description.

[13] It should be noted that the SRTM database suffers from known limitation in urban as well as forested areas where the SRTM elevation data may capture the height of building or trees instead of ground level elevation. A similar limitation is noted by Nicholls et al. (2007).

- delineated inundation zones were overlaid with wetlands to calculate exposure of wetlands to a 1-m SLR. Low elevation wetlands are within the Low Elevation Coastal Zone.[14] For the area calculation, grids representing cell areas in square kilometers at different resolutions were created, using the length of a degree of latitude and longitude at the cell center;[15] and
- if wetlands can migrate (WMP category 2), then they may also survive in their current location to the extent that natural migration or wetland accretion keeps pace with SLR (Titus 1988). Wetlands in WMP category 3 cannot migrate, and the human resources associated with them will lose their services. Wetlands in WMP category 4 are at great risk, but may survive, depending on the effect of flooding behind the coastline. If the flooding is severe enough and persists long enough to seriously disrupt the trapping of the sediment or building upon the peat the sediment creates, the wetlands will be severely degraded and may perish. Hence, the wetlands in WMP categories 3 and 4 exposed to the inundation zone for 1 m SLR are the estimates of wetlands at inundation risk in a changing climate.

RESULTS

For the 86 coastal developing countries and territories included in this analysis, estimates indicate more than 60 % of freshwater marsh, GLWD Coastal Wetlands and Brackish/saline wetlands (henceforth saline wetlands for brevity) might be lost as a result of a 1-m SLR. In terms of area estimates, this would translate to a loss of 16 558 square kilometers (km^2) of freshwater marsh, 23 320 km^2 of GLWD Coastal Wetlands and 10 969 km^2 of saline wetlands. Among the four coastal wetland categories, only swamp forests appear less vulnerable to SLR and more capable of migrating as the coastline is receding and henceforth dropped from further analysis.[16]

Regional Level Analysis

Estimates indicate impacts of SLR on wetlands are not uniformly distributed across the regions and countries of the developing world.

[14] Coastal zone with elevation derived from SRTM, which is 10 or less meters above sea level.

[15] Latitude and longitude were specified in decimal degrees. The horizontal datum used is the World Geodetic System 1984.

[16] Swamp Forest results are also dependent on the elevation from SRTM, which can have interference from features such as a dense tree canopy.

Table 1 Area of wetlands lost as a % of total wetlands area—1 m SLR

	Freshwater marsh	Swamp forest	GLWD Coastal Wetlands	Brackish/ saline wetlands
EAP	62.2	20.3	70.7	–
ECA	100	–	100	–
LAC	74.0	0.5	22.9	97.2
MENA	100	–	96.0	100
SA	0.2	–	48.7	11.3
SSA	72.5	26.7	54.0	99.9
Total	63.7	1.8	71.7	60.7

EAP East Asia and Pacific, *ECA* Europe and Central Asia, *LAC* Latin America and the Caribbean, *MENA* Middle East and North Africa, *SA* South Asia, *SSA* Sub Saharan Africa

Table 1 clearly indicates that the impacts are particularly severe in a limited number of regions. GLWD Coastal Wetlands in Europe and Central Asia (ECA), Middle East and North Africa (MENA), and East Asia and Pacific (EAP) would experience the largest percentage impacts from SLR with 100, 96.0, and 70.7 % losses, respectively. Similarly, ECA and MENA may lose all of their freshwater marshes, with losses in excess of 70 % in Sub Saharan Africa (SSA) and Latin America and the Caribbean (LAC). Most saline wetlands in all regions might also be lost except for South Asia (SA). It should, however, be noted that South Asia (SA) holds approximately 57 % of all saline wetlands of the countries included in this study. Our overall results compare well with those obtained by McFadden et al. (2007), which estimated a wetlands loss of 44 % for a 72-cm SLR.

Figure 1 presents area estimates in absolute terms of vulnerable coastal wetlands across regions. Results suggest that among all regions, EAP is at risk of losing the largest quantities of freshwater marsh and GLWD Coastal Wetlands: up to approximately 10 000 and 12 400 km^2, respectively. MENA is projected to lose approximately 7200 km^2 of its saline wetlands and 2600 km^2 of its GLWD Coastal Wetlands. ECA is also projected to lose a large area of GLWD Coastal Wetlands (5900 km^2). SSA is likely to lose approximately 2000 km^2 of its saline wetlands and the projected loss of saline wetlands and GLWD Coastal Wetlands of SA amounts to 900 and 840 km^2, respectively.

Country-Level Analysis

The impacts of SLR on coastal wetlands were also estimated for individual countries. Table 2 summarizes our results by presenting the 10 most vulnerable countries in terms of wetlands area lost in square kilometer by types of wetlands.

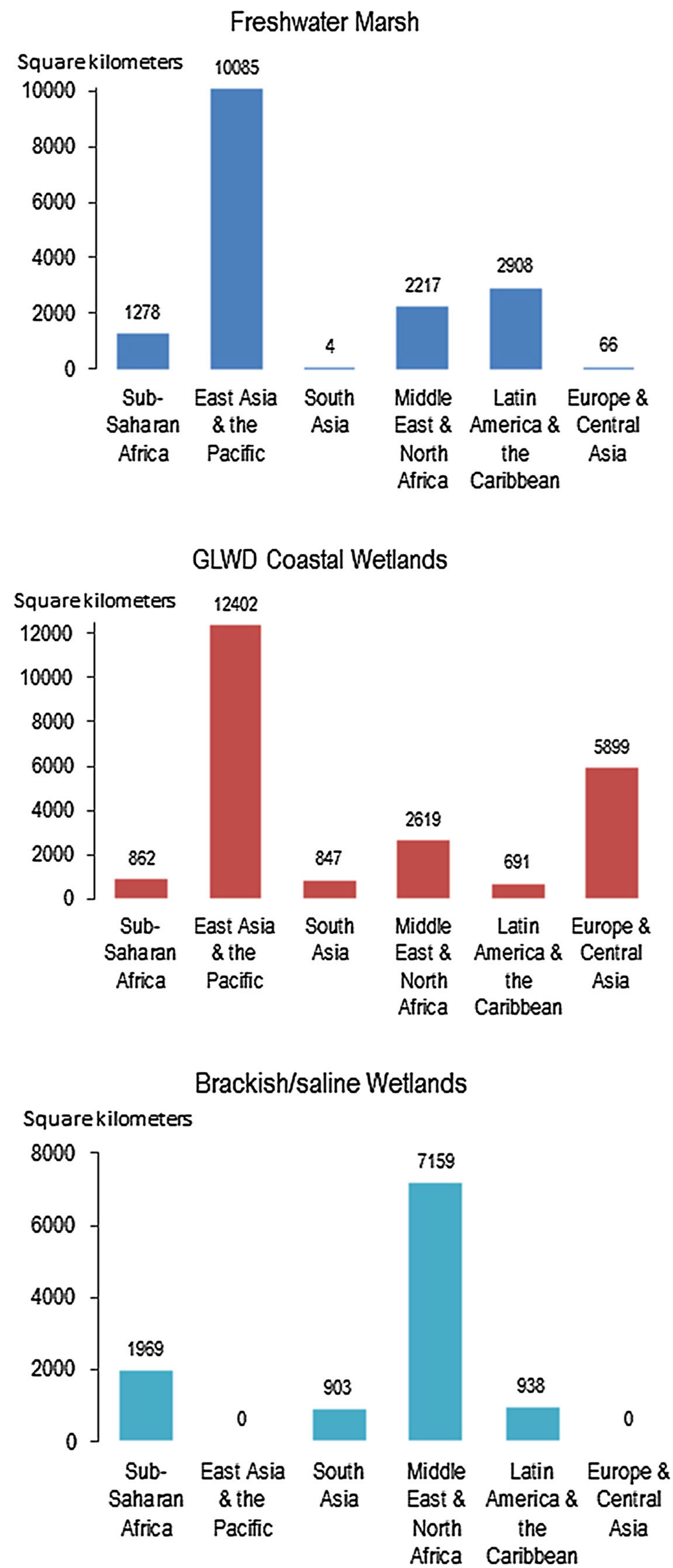

Fig. 1 Lost wetlands by types of wetlands and regions, for a 1-m SLR

Table 2 Expected loss of wetlands in square kilometers by types of wetlands for most impacted countries (with expected percent loss in parenthesis)

Rank	Freshwater marsh	GLWD Coastal Wetlands	Saline wetlands
1.	Vietnam 8583 (65 %)	China 9810 (76 %)	Libya 3725 (100 %)
2.	Argentina 1335 (100 %)	Romania 3451 (100 %)	Arab Rep. of Egypt 2914 (100 %)
3.	Islamic Rep. of Iran 1256 (100 %)	Ukraine 2324 (100 %)	Mauritania 1947 (100 %)
4.	China 751 (91 %)	Myanmar 1922 (56 %)	India 889 (13 %)
5.	Mexico 745 (100 %)	Arab Rep. of Egypt 1433 (100 %)	Argentina 745 (100 %)
6.	Brazil 601 (61 %)	Islamic Rep. of Iran 704 (87 %)	Tunisia 235 (100 %)
7.	Arab Rep. of Egypt 538 (100 %)	India 669 (84 %)	Morocco 208 (100 %)
8.	Benin 412 (100 %)	Mauritania 430 (100 %)	Peru 90 (100 %)
9.	Senegal 368 (96 %)	Mexico 415 (100 %)	Dominican Republic 80 (100 %)
10.	Papua New Guinea 337 (84 %)	Tunisia 368 (100 %)	Republic of Yemen 77 (100 %)

Estimates indicate large effects of SLR on coastal wetlands are much more concentrated in some countries than others. The 5 most vulnerable countries are: Viet Nam, Argentina, Iran, China and Mexico. These countries represent 77 % of the total freshwater marshes at risk from a 1-m SLR. Vietnam is by far the most vulnerable country with close to 65 % of its freshwater marshes at risk. For vulnerable GLWD Coastal Wetlands, the top-ranked country (China) accounts for 76 % of GLWD Coastal Wetlands at risk. Of all vulnerable saline wetlands, Libya, Egypt, Mauritania, India and Argentina account for 93 %, with Libya and Egypt representing 61 %.[17]

On the whole, our results suggest a significant asymmetry in the burden of SLR on wetlands: a small number of developing countries is expected to bear the additional burnt of SLR, while many other coastal countries will experience little change.

[17] We have attempted to validate our estimates of country-level impacts with country-level detailed assessments available in the literature. However, an extensive search of the existing literature has revealed the rarity of such an assessment (which indeed is a key rationale for this paper). In India, Dwidedi and Sharma (2005) have reported a potential loss of 58 % of coastal wetlands in West Bengal. Our estimates are that India would lose 84 % of its GLWD Coastal Wetlands and 13 % of its freshwater marsh. Snidvongs et al. (2003) study the impacts of climate change on wetlands of the Mekong River Basin, but do not report quantified estimates of the potential impacts of SLR.

Economic Losses

As indicated earlier, wetlands provide a flow of goods and services, which contribute to the welfare of local and global communities. Hence, wetlands losses translate into lost welfare. However, economic valuation of lost welfare is difficult due to the uncertainties in the time profile of future SLR and the rate of time preference; sea level is expected to rise gradually. Although sea level is widely expected to continue to rise over the coming decades (IPCC 2007), it is nearly impossible to predict the sea level change on a specific date due to the nonlinearity of climate processes and feedbacks (Hansen 2006, 2007). In light of these uncertainties, we have estimated the economic value of the annual wetland losses for a single scenario of 1 m SLR. This exercise draws upon the current literature on the valuation of wetlands.

Numerous studies have provided estimates of economic value of wetlands (see for example Brouwer et al. 1999; Woodward and Wui 2001). However, the meta-analysis reported in Brander et al. (2006) is most suitable for valuation of vulnerable wetlands of our interest.[18] This meta-analysis used a collection of 80 valuation studies comprising 215 separate observations of wetland value from 25 countries and all continents. As expected, the distribution of values display considerable variation by continent, wetland type, wetland service and valuation methods used, with the average annual wetland value reported to be approximately USD 2800 ha^{-1} $year^{-1}$ at 1995 USD (see Brander et al. 2006 for details). However, Brander et al. (2006) pointed out that the median value in their sample is USD 150 ha^{-1} $year^{-1}$ at 1995 USD, thus suggesting a skewed distribution of values with a long tail of high values. It should also be noted that the authors found that higher values per hectare were observed in North America and Europe, all other things being equal.

For the purpose of this analysis, we first assumed that a value of USD 150 ha^{-1} $year^{-1}$ at 1995 USD applies to all wetlands in all regions as the median is a better measure of the central tendency for positively skewed distributions, converted this number to USD 2000[19] and used this

[18] Brouwer et al. (1999), in their analysis, selected their sample exclusively from studies using contingent valuation as the means of valuation. Woodward and Wui (2001) included 39 valuation studies in their analysis with of these studies from the United States, thus focusing on temperate wetlands. Woodward and Wui (2001) reported an average value of approximately USD 2200 ha^{-1} $year^{-1}$ (1995 USD).

[19] The year 2000 was selected as the year of analysis in order to make the valuation comparable with the base year of the valuation study by Schuyt and Brander (2004) used in Table 4 in this paper. USD 150 (base year 1995) is equivalent to USD 163.4 (base year 2000) according to World Bank estimates. US GDP deflator has been used in the conversion.

Table 3 Economic value of lost wetlands by region and type of wetlands (million 2000 USD)

	Freshwater marsh	Swamp forest	GLWD Coastal Wetlands	Saline wetlands	Total
EAP	164.8	0.8	202.6	–	368.3
ECA	1.1	–	96.4	–	97.5
LAC	47.5	0.3	11.3	15.3	74.4
MENA	36.2	–	42.8	117.0	196.0
SA	0.1	–	13.8	14.8	28.7
SSA	20.9	0.1	14.1	32.2	67.2
Total	270.6	1.2	381.0	179.2	832.1

Table 4 Economic value of lost wetlands by region and type of wetlands (million 2000 USD)

	Freshwater marsh	Swamp forest	GLWD Coastal Wetlands	Saline wetlands	Total
EAP	146.2	1.1	148.8	–	296.1
ECA	1.0	–	70.8	–	71.7
LAC	42.2	0.4	8.3	15.5	66.3
MENA	32.1	–	31.4	118.1	181.7
SA	0.1	–	10.2	14.9	25.1
SSA	18.5	0.1	10.3	32.5	61.4
Total	240.1	1.5	279.8	181.0	702.5

number to estimate the economic value of the quantity of vulnerable wetlands presented in Fig. 1. Our computation indicates that the total economic value of the wetlands at risk associated with a 1-m SLR amounts to approximately USD 832 million per year Table 3. Of this, the lost economic value from degraded GLWD Coastal Wetlands is approximately USD 381 million per year, followed closely with freshwater marshes (approximately USD 271 million) and saline wetlands (approximately USD 179 million). Given their high capacity to migrate, swamp forests do not lose significantly.

Given the assumption that the economic value per hectare applies equally to all wetlands and to all regions, this total economic loss is distributed across regions according to the regional distribution of the quantity of lost wetlands. Namely, the EAP region faces the maximum potential economic loss. Within EAP, Viet Nam, China and Myanmar experience a large share of the estimated loss.

However, the above estimates ignore that the economic value of wetlands differs across types of wetlands. Schuyt and Brander (2004) reported median values of USD 206 ha^{-1} $year^{-1}$ for freshwater wood, USD 165 ha^{-1} $year^{-1}$ for saline wetland, USD 145 ha^{-1} $year^{-1}$ for freshwater marsh and USD 120 ha^{-1} $year^{-1}$ for GLWD Coastal Wetlands at 2000 USD. Using these median values, the total economic value of the flow of goods and services produced by wetlands that are vulnerable to SLR is estimated to approximate USD 703 million per year (Table 4). EAP and MENA together represent approximately 68 % of this overall loss.

CONCLUSION

Coastal wetlands will decline with rising sea level. In this paper, we have quantified the vulnerable freshwater marsh, swamp forest, GLWD Coastal Wetlands, and Brackish/saline wetlands taking into account the exposure of wetlands to 1 m SLR and the estimated capacity of the coastline to retreat and for coastal wetlands ecosystems to migrate inland as the coastline is receding. We have also made attempts to estimate the economic loss, which may be associated with adversely impacted wetlands.

Our estimates indicate that for a 1-m SLR, approximately 64 % of the freshwater marsh, 72 % of GLWD Coastal Wetlands, and 61 % of Brackish/saline wetlands in 86 developing countries are at risk. The economic value of the annual flow of goods and services produced by these wetlands has been estimated to be approximately $703 million (in 2000 US dollar).[20] The most striking feature of our results is the extreme concentration of the effects in a handful of countries. Our findings indicate that a large percentage of this loss would take place in Europe and Central Asia, East Asia and the Pacific, and the Middle East and North Africa. In East Asia and the Pacific, China, and Viet Nam bear the brunt of these losses. In the Middle East and North Africa, Libya and Egypt experience most losses (saline wetlands), while Romania and Ukraine in Europe and Central Asia would experience large losses.

Two important sources of uncertainty remain. First, as indicated earlier, this analysis assumes a 1-m SLR taking place while not accounting for the time period over which such rise may take place. All other things being equal, a higher increase in SLR and a more rapid rise will limit the capacity of coastal wetlands to adapt and migrate. While the IPCC's assessment of SLR fall short of 1 m by the end of this century, a large number of experts expect such rise to be higher than 1 m by 2100, and to continue to rise well-beyond 2100. To this extent, our results may under-estimate the impacts of SLR on coastal wetlands. Second, and as indicated earlier, the processes shaping coastal wetlands and their capacity to migrate are complex. Reed (1995) and Morris et al. (2002) present extensive discussion of these

[20] In all likelihood, this is a conservative estimate as the recent studies on the dynamic implications of ice sheet stability are indicating sea-level may rise more than 1 m in the twenty-first century and opportunity cost of wetlands is likely to increase with the scarcity of coastal wetlands in future.

issues, while Kirwan et al. (2010) aim to assess threshold rates of SLR for marsh survival. Our knowledge remains far from complete and such assessment deserves further analyses. However, the results presented in this paper do suggest that further research should remain a priority and that individual countries should aim to assess the potential impacts of SLR on their coastal wetlands using locally available data.

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