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Sea-Level Rise and Coastal Wetlands

Impacts and Costs

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Abstract

Scientific evidence indicates that global warming could well lead to a sea-level rise of 1 meter or more in the 21st century. This paper seeks to quantify how a 1-meter sea-level rise that would affect coastal wetlands in 76 developing countries and territories, taking into account how much of wetlands would be submerged and how likely the wetlands would move inland as the coastline recedes. It is estimated that approximately 64 percent of the freshwater marsh, 66 percent of Global Lakes and Wetlands Database coastal wetlands, and 61 percent of brackish/saline wetlands are at risk. A large percentage of this loss would be shouldered by two regions: East Asia and the Pacific, and the Middle East and North Africa. At the country level, the results are extremely skewed with a small number of countries being severely affected. In East Asia, China and Vietnam would bear the brunt of these losses. In the Middle East and North Africa, Libya and Egypt would see the most losses. A rough estimate of the economic value of the goods and services produced by wetlands at risk is approximately $630 million per year in 2000 U.S. dollars.

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Sea-Level Rise and Coastal Wetlands: Impacts and Costs[*]

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Introduction

Coastal wetlands, which are comprised of marshes, swamps, mangroves and other coastal plant communities, provide a large number of goods and services that contribute to the economic welfare of the local and global communities (Millennium Ecosystem Assessment, 2005).[4] Examples of ecosystem services include the protection of shorelines from erosion, 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 (Larson et al., 1989; Barbier, 1991; Williams, 1990; Barbier et al., 1997; Brouwer et al., 1999; Woodward and Wui, 2001; McLeod et al., 2005; Brander et al., 2006). However, coastal wetlands are declining rapidly. Recent estimates indicate that approximately 1% of the global coastal wetland stock was lost each year in the late 20th century (Nicholls, 2004; Hoozemans et al., 1993).

The causes of wetland loss are numerous and often complex.[5] The rapid loss of the global coastal wetland stock in the 20th century was primarily caused by direct land 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 21st century due to climate change. Wetlands face a number of hazards including rise in sea-level, increased atmospheric

[4] A precise and widely agreed upon definition of wetland is not available. RAMSAR convention, a UNESCO-based intergovernmental treaty on wetlands adopted in 1971, defines wetlands as (Article 1.1): 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, and highlights (in Article 2.1) 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.

[5] These causes include sea-level rise, waves, erosion, subsidence, storms and biotic effects. Human actions include drainage for agriculture & forestry, dredging & stream channelization for navigation, flood protection, conversion for aquaculture/ mariculture, construction of schemes for water supply, irrigation & storm protection, discharges of pesticides, herbicides & nutrients, solid waste disposal, sediment diversion by deep channels & other structures, mining of wetland soil, groundwater abstraction, hydrological alteration by canals, roads & other structures and mosquito control among others.

concentration of carbon dioxide, rise in air and water temperature, and changes in the frequency and the intensity of precipitation and storm patterns (Alongi, 2008).

Among these various natural threats of a changing climate, the threat posed by the rise in sea level has received increased attention (Titus, 1988; Hoozemans et al., 1993; Nicholls et al., 1999; Nicholls, 2004; Alongi, 2008).[6] In combination with human activities, it is estimated that a 1 m global-mean sea level rise (SLR) could threaten half of the world's coastal wetlands, which are designated as wetlands of international importance, while those that survive could be substantially changed (Hoozemans et al., 1993; Nicholls et al., 1999).

Since periodic flooding is the essential characteristic of coastal wetlands, sea-level rise (henceforth SLR) can disrupt wetlands in three significant ways: inundation, erosion, and salt water intrusion. The natural impact of SLR causes coastal wetlands to migrate to upland areas. The net change in the area of total wetlands depends on the slopes of the wetlands and characteristics of these areas. If the land has a constant slope all the way through the wetlands and the upland areas, then the area lost to wetlands drowning in the sea may be equal to the area acquired by the landward encroachment of high tides.[7] If the slope above is steeper than the wetlands, then the SLR causes a net loss of wetland area. However, wetland migration is only possible if the adjacent upland areas are not developed, otherwise all the wetlands may be lost (Titus, 1988).

Understanding the impact of SLR on coastal wetlands must therefore take into account factors that affect the ecological balance of the wetland ecosystem 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

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[6] Sea-level rise due to climate change is a serious global threat: The scientific evidence is now overwhelming. Sea-level rise will continue for centuries even if greenhouse gas concentrations were to be stabilized today (IPCC, 2007a).

[7] Coastal wetlands are generally less than one tidal range above mean sea level. Hence, an important determinant of the vulnerability of coastal wetlands to SLR is the tidal range, the difference in elevation between the mean high tide and mean low tide (Titus, 1988).

availability of fresh water and sediment, and the salinity of soil and groundwater (Belperio, 1993; Semeniuk, 1994; Blasco et al., 1996; Alongi, 2008).[8] Even though location-specific studies are needed to define the specific details, experts and scientists agree that adaptation of wetlands to future sea-level rise depends on its success in landward progression and is conditioned by the availability of adequate and suitable space for expansion/ migration, and a rate of sea level rise that is not greater than the rate at which wetlands can migrate.[9]

This paper is an effort to quantify the coastal wetlands of different types[10] at risk from 1 m SLR[11] in 76 developing countries and territories in the five regions[12] of the world. Our estimates take into account the exposure of wetlands derived from the recent GLWD-3 database to 1 m SLR and the estimated capacity of the coastline to retreat and for coastal wetlands ecosystems to move (or migrate) inland as the coastline is receding. Attempts have also been made to estimate the economic loss, which may be associated with adversely impacted wetlands.

Our estimates indicate that a 1 m rise in sea level would lead to a loss of present coastal wetland stocks of 60% or more, depending on wetland type. Human activity is generally

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[8] Further development in coastal areas may also close off wetland migration.

[9] Historically, mangroves have shown considerable resilience to adapt to fluctuations in sea-level rise (Alongi, 2008; Erwin, 2009; Gilman et al., 2006).

[10] Coastal wetlands in this analysis are defined as the following wetland types in a low elevation (with elevation 10 m or less from sea level) zone: freshwater marsh, swamp forest, GLWD coastal wetlands and brackish/saline wetlands, as delineated in the Global Lakes and Wetlands (GLWD-3) database. See the data section for details.

[11] The IPCC's Fourth Assessment Report (AR4) projects increased SLR between 0.18m and 0.59m across various emission scenarios over the next 100 years. However, this range has been criticized by many experts as being too conservative and not sufficiently reflective of the large uncertainty pertaining to SLR (Krabill *et al*., 2004; Overpeck *et al*., 2006; Rahmstorf, 2007). The most recent evidence suggests that sea-level rise could reach 1 meter or more during this century (Hansen and Sato, 2011; Vermeer and Rahmstorf 2009; Pfeffer et al., 2008). The IPCC itself pointed out that its projections did not include changes within the polar ice sheets. The IPCC noted that the upper values of projected sea level rise presented in its report are not to be considered upper bounds and that higher rises in sea level cannot be ruled out.

[12] These being the five regions used by the World Bank: East Asia and Pacific, Middle East and North Africa, Latin America and Caribbean, South Asia, and Sub-Saharan Africa

increasing rapidly in coastal areas and thus the coastal wetlands are also likely to be impacted by direct and indirect human actions. However, it is difficult to predict location-specific socio-economic changes and patterns of land use in the future. In our study, we refrain from making simplistic assumptions about future states of coastal wetlands.

The sea level will rise gradually over time. Although there is a scientific consensus that the sea level will continue to rise for centuries due to the time scales associated with climate processes and feedbacks even if green house gas emissions were to be stabilized today (IPCC 2007), the time profile of SLR is uncertain. It is difficult to predict the sea level change on a specific date with confidence due to the nonlinearity of the process (Hansen 2006, Hansen 2007, Maslanik 2007). Uncertainty about the time profile of SLR makes valuation of wetland loss over time difficult. Valuation of a future loss is also complicated due to ambiguity in the rate of time preference. In light of these uncertainties, we estimated the economic value of the wetlands at risk for a single scenario of 1 m SLR using the current literature on valuation of wetlands. The economic value of the wetlands at risk from 1 m SLR in the 76 developing countries considered in this analysis is around USD 630 million per year (in USD 2000). It is hoped that the estimates of wetlands at risk from SLR reported in this paper would offer insights into the extent to which countries may be willing to invest to protect coastal wetlands or facilitate their migration as sea level rises.

At the outset, we acknowledge several important limitations of our analysis. First, we have not assessed the time profile of 1 m SLR. We take this scenario as given, and assess the *exposure* of the present wetland stock for each of the 76 developing countries and five regions. Second, the digital elevation (90m DEM V2) data we use in our analysis gives altitude in 1-meter increments, preventing us from sub-meter SLR modeling.[13] Third, the lack of resolution of spatial data of the wetlands and digital elevation higher than 90 m prevented us from including small islands in our analysis. Fourth, our analysis does not estimate potential destruction of wetlands from

[13] One can interpolate the elevation data we have used for sub-meter SLR modeling, but in that case, precision of the estimates would be difficult to justify. The potential use of LIDAR survey (laser-based elevation measurement from low-flying aircraft) was beyond the scope of our analysis.

direct and indirect human actions. Fifth, we have not estimated the net present value of the coastal wetland loss over a period of time.

The remainder of the paper is organized as follows. Section 2 summarizes the data sources and describes the methodology. Section 3 presents area estimates of wetlands at risk from sea-level rise (SLR) as well as the economic value of these projected losses. Section 4 briefly concludes.

Data and Methodology

II.1 Data

In order to assess the exposure of 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 1m 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:

Country boundaries and regions and coastlines. 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 classifications and boundaries. In addition, Exclusive Economic Zone data from VLIZ (2011) identifies the maritime boundaries.

Elevation. For elevation, all coastal tiles of 90m Shuttle Radar Topography Mission (SRTM) data, which are 5 geographic degrees latitude and longitude (approximately 500 kilometers by 500 kilometers), were downloaded from http://srtm.csi.cgiar.org/.

Wetlands. 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 seconds (approximately 1km by 1km at the equator), the GLWD-3 followed the definition of wetlands adopted at the Ramsar Convention, the International Union for Conservation of Nature. Our analysis focuses on freshwater marsh, swamp forests, GLWD Coastal Wetlands[14] and Brackish/ saline wetlands.

Response of wetlands to SLR. In order to assess the impact of SLR on wetlands and the potential for adaptation, the wetland migratory potential (WMP) characteristic in the Dynamic Interactive Vulnerability Assessment (DIVA) database from the DINAS-COAST project has been 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, sea-level rise may not lead to loss 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).

WMP indicates the potential for wetlands to migrate landward in response to a 1-meter rise in sea level. The migratory potential is based on a few geophysical characteristics of the coastline: coastal type, topography, tidal range, and other information when available (e.g., whether

[14] 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 (ESRI, 1992: referenced in Lehner and Döll 2004); 'Delta', 'Lagoon', 'Mangrove', 'Estuary', 'Coastal Wetland', and 'Tidal Wetland' of WCMC wetlands map (Dugan, 1993; WCMC, 1993; referenced in Lehner and Döll 2004) - see Lehner and Döll (2004) for a detailed description.

wetlands are associated with an island or mainland coast), as described in Hoozemans and Hulsbergen (1995).[15]

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

1. No, or hardly any change;
2. A retreat of the coastline, combined with inland migration of coastal ecosystems;
3. A retreat of the coastline without the possibility of inland migration due to topography (e.g., coastlines with relatively high relief);
4. A possible retreat of the coastline but increase of flooding area behind the coastline ("ponding"); and
5. Total loss of the coastal ecosystem (Hoozmans et al. 1993).

II.2 Methodology

The procedure used in this analysis followed several steps. First, the SRTM database was used to identify inundation zones.[16] Second, a country surface for wetlands was constructed from the polygons extracted from the Global Lakes and Wetlands database. Third, migratory potential of wetlands were assigned from the WMP classification of the coastline from the DIVA database. Fourth, 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. More specifically:

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[15] We acknowledge that the migratory potential of wetlands also depends on a wide range of additional 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.

[16] 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).

Preparing country boundaries and coastlines. 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 meter 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.

Building coastal terrain models (DTM). Coastal terrain models derived from the SRTM 90 meter 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 x 5 decimal degrees, with a coastline.

Identifying inundation zones: Inundation zones were derived from the DTM by setting the value to 1 for SLR equal to 1 m.

Calculating exposure indicators. 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[17]. 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.[18]

According to the GLWD-3 and the DTM, 76 countries and territories in five World Bank regions have coastal wetlands which are currently at 1 m from sea level.

In the DIVA database, wetlands are not located within the most extreme responses: WMP1 or WMP5. If wetlands can migrate (WMP category 2), then they may survive in their current location to the extent that natural migration or wetland accretion keeps pace with sea-level rise (Titus, 1988). Wetlands in WMP category 3 cannot migrate, and the human resources

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

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

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 meter SLR are the estimates of wetlands at inundation risk in a changing climate.

Results

For the 76 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 1m SLR. In terms of area estimates, this would translate to a loss of 16,492 square kilometer of freshwater marsh, 17,421 square kilometer of GLWD Coastal Wetlands and 10,969 square kilometer of saline wetlands. Among the four coastal wetland categories, only swamp forests appear less vulnerable to SLR and more capable of migrating as the coast line is receding and henceforth dropped from further analysis[19].

Our findings on wetland areas at risk from 1 m SLR are presented first at the regional level, and then at the country level. These areas are then transformed into lost economic values in Section III.3. Section III.4 presents relevant prior research on impacts of SLR on coastal wetlands.

III.1 Regional level analysis

The percentages of regional wetlands at risk from SLR out of the present wetland stock for the 76 coastal developing countries and territories included in this analysis are summarized in Table 1. As expected, estimates indicate impacts of SLR on wetlands are not uniformly distributed across the regions and countries of the developing world. Table 1 clearly indicates that the

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

impacts are particularly severe in a limited number of regions. GLWD Coastal Wetlands in Middle East and North Africa (MENA) and East Asia and Pacific (EAP) would experience the largest percentage impacts from SLR. For example, approximately 96% of MENA's GLWD Coastal Wetlands would face the risk of extinction followed by the EAP (70.7%), Sub Saharan Africa (54%) and South Asia (48.7%). Similarly, MENA might lose all of its freshwater marshes while Sub Saharan Africa (SSA) and Latin America and the Caribbean (LAC) have more than 70% and EAP has 62.2% at risk. 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. In general, our estimates compare well with those obtained by McFadden et al. (2007) which estimated a wetlands loss of 44% for a 72 cm SLR.

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
SSA	72.5	26.7	54.0	99.9
EAP	62.2	20.3	70.7	-
SA	0.2	-	48.7	11.3
MENA	100	-	96.0	100
LAC	74.0	0.5	22.9	97.2
Total	**63.6**	**1.8**	**65.5**	**60.7**

In Figure 1, we present area estimates 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 square kilometer respectively. MENA is projected to lose approximately 7,400 square kilometer of its saline wetlands and 2,600 square kilometer of its GLWD Coastal Wetlands. SSA is likely to lose approximately 2,000 square kilometer of its saline wetlands and the projected loss of saline wetlands and GLWD Coastal Wetlands of SA amount to 900 and 840 square kilometers respectively.

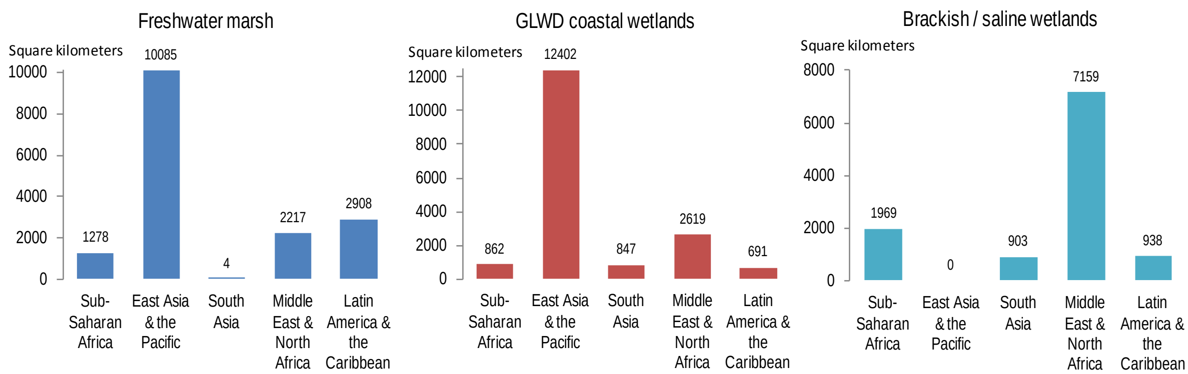

Figure 1. Lost wetlands by types of wetlands and regions, for a 1m SLR

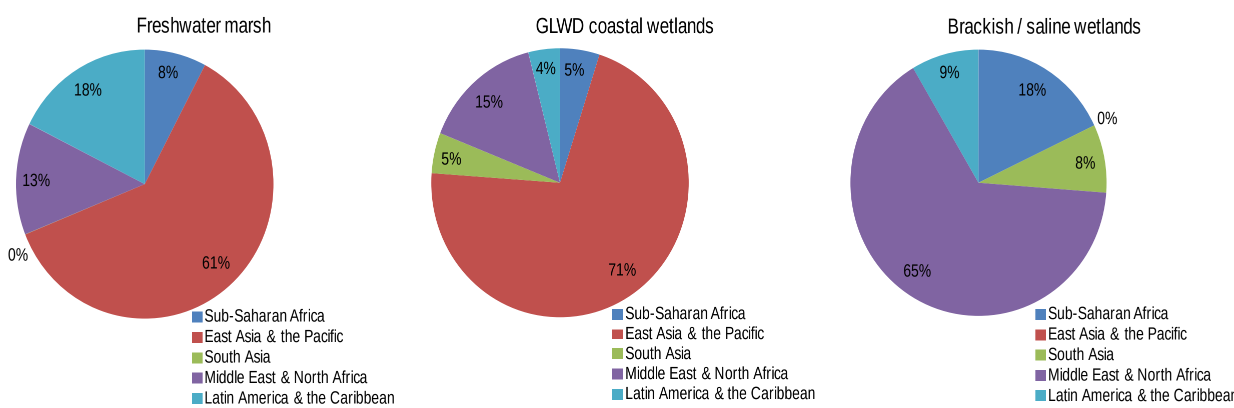

Figure 2. Distribution of lost wetlands by types of wetlands across regions, for a 1m SLR

We have also presented the percentage of wetland types at risk by region in Figure 2, which is revealing. Once again, it is apparent that among the various regions, EAP faces the greatest risk of overall loss of wetlands: for a 1 m SLR scenario, 61% and 71% of vulnerable freshwater marsh and GLWD Coastal Wetlands are in EAP. On the other hand, 65% of saline wetlands at risk is in MENA. After EAP, MENA represents the second largest proportion of GLWD Coastal Wetlands at risk (15%). LAC also represents a significant share (18%) of vulnerable freshwater marshes.

III.2 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. 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 that 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 56% 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%.

Also within the regions, vulnerability is clearly far from balanced across countries. Viet Nam represents 85.1% of all vulnerable freshwater marshes and China represents 79.1% of all vulnerable GLWD Coastal Wetlands within EAP. Within MENA, 92.7% of all regional vulnerable saline wetlands are in Libya and Egypt.

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 sea level rise, while many other coastal countries will experience little change.

It should be noted that numerous studies on impacts of climate change have indicated that small island nations are particularly susceptible to the impacts of SLR (for example, see Anthoff et al 2010; Nicholls et al 2010; Anthoff et al 2006; Church et al 2006; Nicholls et al 1999). However, limitations of the resolution of the global spatial datasets make quantification of the vulnerability of wetlands of small island nations particularly difficult.[20] Even though the SRTM elevation data are at approximately 90m spatial resolution, the global wetlands data are compiled from a range of sources resulting in generalized areas. Also, the correspondence

[20] Tol 2007 drew on the Global Vulnerability Analysis and other country studies for quantification of wetland loss from 1 m SLR for a global analysis including small island nations.

between the SRTM and GLWD are not always in complete agreement due to differences in scale; so some wetlands are underrepresented on an island when the geographic areas do not completely match.

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 8,583 (65%)	China 9,810 (76%)	Libya 3,725 (100%)
2.	Argentina 1,335 (100%)	Myanmar 1,922 (56%)	Arab Republic of Egypt 2,914 (100%)
3.	Islamic Republic of Iran 1,256 (100%)	Arab Republic of Egypt 1,433 (100%)	Mauritania 1,947 (100%)
4.	China 751 (91%)	Islamic Republic of Iran 704 (87%)	India 889 (13%)
5.	Mexico 745 (100%)	India 669 (84%)	Argentina 745 (100%)
6.	Brazil 601 (61%)	Mauritania 430 (100%)	Tunisia 235 (100%)
7.	Arab Republic of Egypt 538 (100%)	Mexico 415 (100%)	Morocco 208 (100%)
8.	Benin 412 (100%)	Tunisia 368 (100%)	Peru 90 (100%)
9.	Senegal 368 (96%)	Indonesia 287 (53%)	Dominican Republic 80 (100%)
10.	Papua New Guinea 337 (84%)	Philippines 229 (100%)	Republic of Yemen 77 (100%)

In order to improve the situation, ideally information on (i) high spatial resolution of the coastal zone elevation, (ii) high spatial resolution of wetlands, (iii) clear delineation of current wetlands and (iv) location specific information on the wetland migratory potential are necessary. High spatial resolution of the coastal zone elevation will refine the estimates of exposed area to SLR. High spatial resolution wetlands information would allow a more accurate correspondence between the exposed area of SLR and wetland area. Precise delineation of wetlands is generally difficult from remotely sensed data and land cover data. Remotely sensed data measure the vegetation, but may not account for the soil type and the wetland plants may not be easily distinguished by remote sensing. Land cover products are often produced from composite imagery over a time period, so the frequency of the data or the smoothing of multiple observations may make the wetland delineation difficult. In addition, location specific information on the Wetland Migratory Potential would add accuracy to the areas where wetlands can migrate (e.g. excluding human altered landscapes such as urban areas).

III.3 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 there is a scientific consensus that the sea level will continue to rise even if green house gas emissions were stabilized today (IPCC 2007), it is nearly impossible predict the sea level change on a specific date due to the nonlinearity of climate processes and feedbacks (Hansen 2006, Hansen 2007, Masalanik 2007). In addition, there is ambiguity also in the rate of time preference. In light of these uncertainties, we have estimated the economic value of the annual wetland losses for a single scenario of 1 m SLR.

A review of the literature on economic valuation of wetlands suggests that a large number of case (location) specific studies have been conducted to estimate the economic value of the goods and services provided by wetlands. In addition, a number of these studies have been used to conduct meta-analyses to understand the extent of the economic value of the flow of goods and services provided by wetlands, and the determinants of those values. Among these, analyses conducted by Brouwer et al. 1999; Woodward and Wui, 2001; and Brander at al., 2006 have relevance to this analysis. It should be noted, however, that all of these studies involve the valuation of current wetland losses. How these values relate to the potential losses occurring in the future is a matter of debate, but we believe the estimates are conservative, as explained below.

For our purposes, the meta-analysis reported in Brander et al. (2006) is most suitable for valuation of vulnerable wetlands.[21] 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 2,800 ha^{-1} yr^{-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} yr^{-1} at 1995 USD, thus suggesting a skewed distribution of values with a long tail of high values. The authors also 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} yr^{-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. We converted this number to USD 2000[22] and used this number to estimate the economic value of the quantity of vulnerable wetlands presented in

[21] Brouwer at 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 2,200 $ha^{-1}yr^{-1}$ (1995 USD).

[22] 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 USD163.4 (base year 2000) according to World Bank estimates. US GDP deflator has been used in the conversion.

Figure 2. Our computation indicates that the total economic value of the wetlands at risk associated with a 1 m SLR amounts to approximately USD 735 million per year (Table 3). Of this, the lost economic value from degraded GLWD Coastal Wetlands is approximately USD 285 million per year, followed closely with freshwater marshes (approximately USD 270 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 East Asia and the Pacific (EAP) region faces the maximum potential economic loss. Within EAP, Viet Nam, China and Myanmar experience a large share of the estimated loss.

Table 3

Economic value of lost wetlands by region and type of wetlands assuming equal loss value for all wetlands

(million 2000 USD)

	Freshwater marsh	Swamp forest	GLWD Coastal Wetlands	Saline wetlands	Total
SSA	20.9	0.1	14.1	32.2	67.2
EAP	164.8	0.8	202.6	-	368.3
SA	0.1	-	13.8	14.8	28.7
MENA	36.2	-	42.8	117.0	196.0
LAC	47.5	0.3	11.3	15.3	74.4
Total	**269.5**	**1.2**	**284.7**	**179.2**	**734.6**

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 $ha^{-1}yr^{-1}$ for freshwater wood, USD 165 $ha^{-1}yr^{-1}$ for saline wetland, USD 145 $ha^{-1}yr^{-1}$ for freshwater marsh and USD 120 $ha^{-1}yr^{-1}$ 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 630 million per year (Table 4). EAP and MENA together represent approximately 76% of this overall loss (Figure 3). When compared to the result presented in Table 2, these 2 regions continue to represent the large majority of the estimated losses.

Table 4

Economic value of lost wetlands by region and type of wetlands assuming median loss values differentiated by wetland type

(million 2000 USD)

	Freshwater marsh	**Swamp forest**	**GLWD Coastal Wetlands**	**Saline wetlands**	**Total**
SSA	18.5	0.1	10.3	32.5	61.4
EAP	146.2	1.1	148.8	-	296.1
SA	0.1	-	10.2	14.9	25.1
MENA	32.1	-	31.4	118.1.	181.7
LAC	42.2	0.4	8.3	15.5	66.3
Total	**239.1**	**1.5**	**209.1.**	**181.0**	**630.7**

The use of economic values for current wetland losses to characterize future wetland loss values obviously ignores a number of factors that could lead to unit values changing over time. Nevertheless, we believe that this is a conservative estimate because the opportunity cost of wetland loss per hectare seems likely to increase with the scarcity of coastal wetlands in future. Moreover, we have used the more conservative median estimates of loss values in the literature in lieu of high mean loss values, thus reducing the weight given to large upper tails in the loss distributions. We also note that some recent studies on the dynamic implications of ice sheet stability are indicating sea-level may rise more than 1 m in the 21st century. In that case, of course, the total losses would be larger than our rough estimates in Table 4.

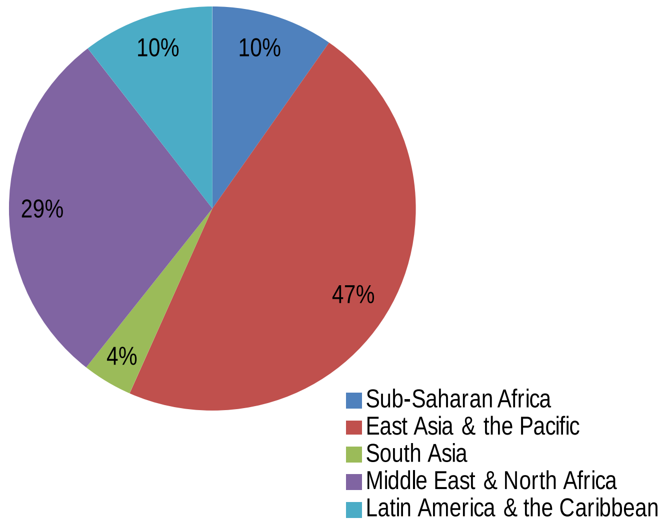

Figure 3. Regional distribution of economic losses

III.4 Prior research on impacts of SLR on coastal wetlands

The papers most immediately related to this analysis are those of Nicholls at al. (1999), Nicholls (2004), McFadden et al. (2007) with estimates of exposure of coastal wetlands to SLR, and Tol (2007), Anthoff et al. (2010) on valuation of wetland losses due to SLR.

It should be noted that Nicholls (1999) and Nicholls (2004) are based on wetland losses derived from the Global Vulnerability Analysis (Hoozemans et al. 1993)[23] – "a first-order perspective on wetland loss rates with incomplete coverage and wetland losses controlled only by tidal range and accommodation space" - as pointed out by McFadden et al. (2007). Nicholls et al. (1999) estimated that a 38 cm rise in global sea level from 1990 to the 2080s will lead to an approximate 22% loss of the coastal wetlands,[24] and 46% of the coastal wetlands would be lost if the sea level rises by 1 m. Nicholls (2004) further estimated losses of wetlands under various greenhouse emissions scenarios and found that a 34 cm rise in global mean sea level by the 2080s relative to 1990 under the A1FI scenario would lead to a 20% loss of coastal wetlands.

[23] Hoozemans et al. (1993) estimated that 55% of the global coastal wetlands are at risk from 1 m sea-level rise.

[24] When combined with other losses due to direct human action, these estimates indicate up to 70% of the world's coastal wetlands could be lost by the 2080s. (Nicholls et al. 1999).

The modeling of all coastal wetlands by McFadden et al. (2007) suggests that global wetland losses are 32% and 44% by the 2080s for a 50 cm and 1 m rise in sea level between 1990 and 2100 accounting for human impacts, such as dike construction or wetland nourishment. The estimates presented by McFadden at al. (2007) are not delineated by types of wetlands or by regions of the world. As for McFadden et al. (2007), the estimates of Nicholls (2004) and Nicholls et al. (1999) are also not disaggregated by types of wetlands. Furthermore, while Nicholls (2004) asserts the largest loss of coastal wetlands to be expected around the Atlantic coast of Central and North America, the small Caribbean islands, and most particularly the Mediterranean and the Baltic, the paper does not present estimates of lost wetlands by regions of the world. It should also be noted that neither of these analyses present estimates of the economic values, which may be associated to these lost wetland areas around the world.

The valuation studies by Tol (2007) and Anthoff et al. (2010) are also based on wetland losses derived from the Global Vulnerability Analysis (Hoozemans et al. 1993). Wetland value is assumed to be logistic in per capita income, with a correction for wetland scarcity, and a cap in these studies and the rate of pure time preference is assumed to be 1%. For a 1m SLR by 2100, Tol (2007) estimated annual costs of wetland loss as a percentage of GDP, per country and Anthoff et al (2010) assessed the net present value of global coastal wetland damage costs for the period 2005-2100 with dikes to protect against SLR can be as high as USD 160 billion. [25]

Due to uneven coverage of the wetland stock and different assumptions of coastal protection, comparison of the prior research with our estimates proved to be difficult.

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

[25] Anthoff et al. (2010) has not reported exposure estimates of coastal wetlands to SLR.

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, 66% of GLWD Coastal Wetlands, and 61% of brackish/saline wetlands in 76 developing countries are at risk. The economic value of the annual flow of goods and services produced by these wetlands has been estimated – crudely but we believe conservatively – to be approximately $ 630 million (in 2000 US dollars). The most striking feature of our results is the extreme concentration of effects in a handful of countries. Our findings indicate that a large percentage of this loss would take place in East Asia and the Pacific, and the Middle East and North Africa. In Asia, 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).

As noted by Nicholls (2004), the processes shaping these coastal wetlands are complex and our knowledge remains far from complete. 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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