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Review

Sea-level rise impact models and environmental conservation: A review of models and their applications

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ABSTRACT

Conservation managers and policy makers need tools to identify coastal habitats and human communities that are vulnerable to sea-level rise. Coastal impact models can help determine the vulnerability of areas and populations to changes in sea level. Model outputs may be used to guide decisions about the location and design of future protected areas and development, and to prioritize adaptation of existing protected area investments. This paper reviews state-of-the-art coastal impact models that determine sea-level rise vulnerability and provides guidance to help managers and policy makers determine the appropriateness of various models at local, regional, and global scales. There are a variety of models, each with strengths and weaknesses, that are suited for different management objectives. We find important trade-offs exist regarding the cost and capacity needed to run and interpret the models, the range of impacts they cover, and regarding the spatial scale that each operates which may overstate impacts at one end and underestimate impacts at the other. Understanding these differences is critical for managers and policy makers to make informed decisions about which model to use and how to interpret and apply the results.

1. Introduction

Sea-level rise has been identified as a major threat to coastal habitats and communities worldwide [1]. Sea-level rise projections based on the use of General Circulation Models (GCMs) for the end of the 21st century (relative to 1980–1999) range from 0.18 to 0.59 m, although this is not an upper bound as the Greenland and West Antarctic ice sheet contributions are uncertain [2]. The IPCC has recognized that sea-level rise by 2100 may be 0.10–0.20 m higher than predicted based on uncertainties of ice sheet melt and glacier dynamics. Scientists suggest that a 1–5 m rise in sea level by 2100 is more realistic when taking into account thermal expansion of ocean water, melting of ocean glaciers, ice sheet disintegration, and an acceleration of sea-level rise in the 20th century [3–9].

Sea-level rise has both biophysical and socioeconomic impacts, threatening coastal landscapes, their ecosystem services, and coastal populations [10,11]. The primary biophysical impacts of sea-level rise include inundation and displacement of wetlands and low-lying lands [12], increased coastal erosion [13,14], increased coastal flooding [12,15], and saltwater intrusion into estuaries, deltas, and aquifers [16,17]. Ecosystems may adapt naturally to sea-level rise in coastal areas with limited human influence because habitats may have room to migrate landward or accrete vertically in response to rising seas; however, densely populated coastal areas are characterized by infrastructure that is less mobile and more vulnerable. Socioeconomic impacts of sea-level rise may include: direct loss of economic, ecological, cultural, and subsistence values through loss of land, infrastructure, and coastal habitats; increased flood risk of people, land, and infrastructure; and other impacts related to changes in water quality, salinity, and biological activity [17,18].

Development planning, land-use, and conservation agencies need reliable scientific tools to conduct vulnerability assessments

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Table 1
Key objectives of coastal impact models to sea-level rise

Interested party	Objectives	Scale	Model
UNFCCC and other international organizations	Informing international negotiations and national governments regarding mitigation, (e.g., limiting fossil fuel emissions) and adaptation (e.g., land-use policies and funding appropriations for adaptation responses), and policy development • providing information that allows comparison of broad scale (e.g., regional) variations of sea-level rise related risks • identifying vulnerable areas that cross national boundaries which require collaboration across administrations	Global/regional	DIVA, SimCLIM
Government agencies	Development of national adaptation policies (e.g., meeting a government's obligations under UNFCCC to reduce vulnerability to climate change)· • conducting national assessment of vulnerability in small island nation • prioritizing vulnerable areas that require more in-depth studies	Global/regional/local	DIVA, SimCLIM
Conservation organizations	Identifying potential future conflicts among communities and coastal habitats based on migration and uses of habitats	Local	SLAMM, BTELSS, Inundation model (e.g., GIS)
Conservation organizations	Assessing the vulnerability of coastal habitats (e.g., mangroves, other tidal wetlands, barrier islands, beaches) and species (e.g., sea turtles, nesting birds) to sea-level rise impacts	Local	SLAMM, BTELSS, Inundation model (e.g., GIS)
Conservation organizations and development/land-use agencies	Identify which ecosystems, coastal people, and infrastructure, agriculture, and water resources must be relocated due to sea-level rise impacts	Local	SimCLIM, Inundation model (e.g., GIS)
Conservation organizations, educational institutions	Raising awareness of the impacts of sea-level rise on coastal habitats and communities	Global/regional/local	All models above

The term "local" refers to geographic areas ranging from <1 km^2 to 10 km^2.

that identify which coastal areas are threatened by sea-level rise. Coastal impact models provide a useful mechanism for predicting environmental responses to changes in sea level and the impacts of alternative management policies on future ecosystem behavior [19,20]. Such tools enable planners and practitioners to proactively plan for sea-level rise, take immediate actions to ensure the security of coastal communities, and work towards the persistence of ecosystem services by reserving lands less vulnerable to sea-level rise for coastal communities and critical coastal habitats.

2. Challenges faced when conducting coastal vulnerability assessments

Coastal managers, development planners, and government officials face a number of challenges when conducting coastal vulnerability assessments. One particular challenge is associated with the uncertainties regarding global projections of sea-level rise as well as the contribution of local factors such as subsidence and fluid extraction. Relevant datasets, such as elevation (see Appendix A for sources and resolutions of elevation data), habitat distribution and condition, species distributions, sediment availability and transport, human settlements, infrastructure, and socioeconomic indicators are often incomplete, unavailable, not the appropriate scale for conducting vulnerability assessments, or may be incompatible (datasets of vastly differing resolutions that pose challenges for integration). The adaptive capacity and response of species, habitats, and human communities to sea-level rise impacts are often unknown. Funding and capacity are often insufficient to conduct coastal vulnerability assessments. Finally, managers and policy makers are currently confronted with a variety of different modeling approaches for conducting coastal vulnerability assessments [21–25].

Approaches for modeling vulnerability differ in complexity, ranging from simple extrapolations of present sea-level impacts to more complex process-based simulation models that include ecological or socioeconomic feedbacks. Modeling approaches differ in the array of processes that they include (see Appendix B), are applicable at various scales, and all encompass strengths and limitations. Few guidelines exist to help managers and policy makers identify an appropriate method for modeling sea-level rise impacts, and those that do exist are outdated [18], too generic to provide practical advice [2] or are specific to a particular geography [26]. To assist in the selection of an appropriate method for conducting a coastal vulnerability assessment using coastal impact models, this paper provides a systematic comparison of modeling approaches with respect to their applicability to differing needs of managers and policy makers.

3. Key objectives influencing coastal impact model selection

Conservation managers, government officials, and development planners may be interested in modeling the vulnerability of coastal habitats and communities to sea-level rise for a variety of reasons. Table 1 highlights key objectives that assess the impacts of sea-level rise and suggests which type of coastal impact models may be most appropriate for addressing those objectives.

4. Overview of models

To help determine which model is most appropriate for a given objective, the following section provides a description of the models included in Table 1 and includes the appropriate use, scale, cost, and technical expertise needed to run the models.

4.1. Inundation models

Inundation models can be used to predict areas that will be flooded based on quantitative relationships between climate and the exposure unit [23]. They can rely on topographic maps to identify potential impact zones, where these are identified as those areas that lie below a given elevation contour [27–30]. These models may be applied at local, regional, or global scales and can address a range of objectives including predicting sea-level rise impacts and raising awareness of these impacts (see Table 1).

Inundation models incorporate various sea-level rise scenarios [28,31] providing an approximation of coastal vulnerability to sea-level rise. Potentially inundated areas can be calculated (e.g., in GIS) based on both elevation and proximity to shoreline. For example, Rowley et al. [31] developed an algorithm in GIS to 1) identify all raster cells in a Digital Elevation Model (DEM) that lie adjacent to the ocean, and 2) reclassify all cells as ocean cells (inundated) that are within that group and have an elevation less than or equal to a given sea-level rise increment. This process was repeated until all cells connected with cells adjacent to the ocean were inundated. Rowley et al. [31] produced raster GIS layers showing the world's shorelines using sea- level increases from 1 to 6 m, calculated inundation zones for each incremental sea-level rise, and estimated area of land inundated and population affected in each scenario. A similar approach was also used to create dynamic maps freely available online that identify areas susceptible to sea level rise of 1 to 6 meters for regions around the globe. [32].

An advantage of inundation models for vulnerability mapping is that they are relatively inexpensive to run. Some only require Internet access [32], while others require GIS software and programming scripts, elevation datasets, and sea-level rise projections [31]. Other advantages include the ability to produce vulnerability maps quickly (e.g., within several days or weeks) using freely available elevation datasets (e.g., ETOPO5, ETOPO2, and GLOBE elevation datasets from the National Geophysical Data Center, GTOPO30 from the United States Geological Survey (USGS) [33], and SRTM from the National Aeronautics and Space Administration [34]; Appendix A). This type of modeling approach provides rapid information regarding where coastal landscapes are most vulnerable to sea-level rise at global, regional, and local scales and can inform decision makers and policy makers about setback limits, zoning, future development plans, local and regional action plans [35].

Although inundation models can provide quick analyses of vulnerability to sea-level rise, their results must be interpreted with the recognition that important feedbacks may be missing. For example, these approaches typically ignore possible feedbacks on wetland accretion (e.g., ability of wetlands to offset increases in sea level through soil building), thus they do not address the geomorphic role that wetlands play in landscape development and maintenance [36]. These models are also limited by uncertainties in global sea-level projections and elevation data, lack of data on sediment transport regimes [37] and lack of feedbacks among biological, ecological, and social systems (e.g., human-adaptation responses). For example, models that use GIS to identify inundated areas [28,29] may 1) over-estimate potentially inundated areas because water connectivity is not considered (i.e., some areas may have a lower elevation than projected sea level increases but land barriers may exist that would prevent inundation [31]; and 2) some areas with lower elevations than projected sea-level rise are inland bodies of water, thus not threatened by inundation [38].

4.2. SLAMM

The Sea Level Affecting Marshes Model (SLAMM) [39] is a GIS-based model developed in the mid 1980s to determine the potential impacts of global climate change on the coast of the contiguous United States [40,41]. The model has been refined and subsequently used for more detailed studies in Florida, Georgia, Washington, California, and South Carolina [11,42–47].

SLAMM projects habitat changes in response to sea-level rise at local to regional scales. The model uses cells (usually 30 m by 30 m) based on the cell-size of the USGS Digital Elevation Model. Developed specifically for projections of different environmental processes that affect wetland vegetation under different scenarios of sea-level rise, SLAMM has the ability to allow marsh migration, resulting in spatial maps that forecast cumulative effects on diverse types of marshes [48]. SLAMM uses a variety of datasets including: global sea-level rise data, NOAA tidal data, detailed wetland information, regional Light-imaging Detection and Ranging (LiDAR) data, and USGS DEMs. The model calculates water elevation at a particular location using a combination of linear relationships and decision rule trees [11]. The standard time step for this model is 5–25 years, and it can compute sea-level inundation and habitat response for large areas (hundreds of square kilometers) at high-resolution [49] using minimal computational time. Several statistical and logic algorithms for environmental factors (e.g., inundation, erosion, overwash, and soil saturation) have been added recently to the SLAMM model to produce more realistic model outputs. The cost to run SLAMM is dependent upon the geographic scale of the project, available datasets, and degree of calibration required. Previous projects have ranged in price but have been <$50,000 USD, based on the degree of calibration (and potentially validation hindcasting), quality assurance, discussion with local experts regarding inputs, availability and format of local data, and geographic scale of the model application. Although training may be arranged, experts that are familiar with the model typically are needed to run the model and process the results.

Advantages of the most current version of the model, SLAMM version 5.0 (http://warrenpinnacle.com/prof/SLAMM/), are that it can be applied at scales ranging from <1 km^2–100,000 km^2, can provide detailed information about the vulnerability of coastal habitats (e.g., mangroves, other tidal wetlands, barrier islands, beaches) and species (e.g., sea turtles, nesting birds) to changes in sea level, and can provide detailed information regarding how habitats may shift in response to these changes. This information can be used to identify potential future conflicts among communities and coastal habitats based on migration and uses of habitats. The model also is able to capture the equilibrium between coastal vegetation and environment by assessing the extent to which saltwater intrusion contributes to habitat conversion based on elevation, habitat type, slope, sedimentation and accretion and erosion rates, and existing seawalls. The model includes an assumption that currently developed areas will not be inundated because they will remain protected by seawalls and other coastal armoring. The model assesses the influences of wave action on erosion patterns and accounts for relative sea-level change for each study site by taking into account local rates of subsidence, isostatic adjustment, and sedimentation and accretion rates.

SLAMM lacks feedback mechanisms between hydrodynamic and ecological systems that may be altered by changes in sea level [11,50]. Because SLAMM requires changes in sea level to be prescribed, changes in wave regime from erosion or sub-surface vegetative properties are not modeled. In addition, feedback mechanisms such as saltwater intrusion into freshwater marshes can accelerate decomposition rates and lead to reduced vertical accretion [51,52], or conversely, increasing inundation of salt marshes may increase macrophyte production leading to increased vertical accretion [53]. SLAMM also does not include a socioeconomic component that can estimate costs in response to changes in sea level, thus is not useful for informing adaptation policies. Despite these limitations, the SLAMM model provides useful, high-resolution, insights regarding how sea-level rise may impact coastal habitats [11].

4.3. *Ecological landscape spatial simulation models (e.g., BTELSS; http://ecobas.org/www-server/rem/mdb/btelss.html)*

Since the 1980s, a suite of models generally known as ecological landscape spatial simulation models [19,54] have been developed to examine diverse environmental forcings, such as, subsidence, sea-level rise, changes in river discharge, and climate variability and their cumulative effects on coastal habitats. Specifically, they model elevation changes in response to sea-level rise in tidal marshes at fine scales (100s m^2) [53,55,56], and calculate the rate of elevation change as a function of inundation depth and sediment supply. The models incorporate environmental and biotic feedbacks that influence marsh platform accretion and compaction [57,58]. Most of these models are implemented to examine the long-term effects (hundreds of years) of inundation and variations of tidal cycle on marsh platform evolution. The development of such models has stimulated experimental research [59] and empirical analyses [57,60–64] on the effects of long-term accelerated sea-level rise.

Ecological landscape spatial simulation models may be used for a variety of applications. For example, Reyes et al. [65] examined land-use change for tropical ecosystems in Mexico, and Voinov et al. [66] developed a model for river-influenced watersheds which included an economic component that estimated the probabilities of land conversion from forest or agriculture to different densities of residential use [67]. Examples of such models include the Barataria–Terrebonne ecological landscape spatial simulation model (BTELSS [68], the Mississippi Delta Model [70] and the Caernarvon diversion [65]). The Barataria–Terrebonne ecological landscape spatial simulation (BTELSS) model was developed to predict wetland habitat change in the Mississippi delta over a 30 year time period and was designed to address regional scale coastal processes and incorporate large scale factors such as salinity, relative sea-level rise, and sediment transport. Nine forcing functions were included in the model: wind speed, wind direction, rainfall, evaporation, tide, salinity, temperature, river discharge, and inorganic sediment concentrations. The spatial resolution of the BTELSS is 1 km^2. The model proved useful for predicting the effects of regional management plans such as water diversions and structural-landscape-level changes [70].

Advantages of models such as BTELSS are that they incorporate a range of factors including coastal and estuarine hydrodynamics, water-borne particle transport, vegetation growth and infrastructure risk exposure can be added along with feedbacks among them [71], thus can provide detailed projections of wetland habitat change at local scales. Disadvantages of such models are that they require expertise to run (due to model complexity) and can be extremely expensive (>$150,000 USD). Also, these models may create over-confidence among users who may assume that the increased data and feedbacks incorporated in the model provide more robust outputs. These models can be difficult to validate and calibrate due to the high level of aggregation, the dynamic long-term nature of the model, and the complexity of the subsystems and their interactions, thus their primary application is for research.

Models like BTELSS and the Mississippi Delta Model [72] are used extensively in research to understand plant community response to variable sea-level rates and other climate change factors (e.g., droughts, reduced river discharge). They represent the state-of-the-art regarding knowledge of physical and biological interactions and serve as computational experiments. This type of regional model is data intensive and tends to be more costly than administrative or management-oriented modeling exercises. However, given the holistic approach to ecological feedbacks, incorporation of recent advances on physiological and population research, and strict historical calibration and validation, they present a robust option for science-based management. Because these regional models were developed for experimental purposes, the addition of management scenarios (e.g., river diversions, manipulation of discharges, barrier island breaches) is straightforward, and they provide comprehensive assessments of long-term effects of climate change and anthropogenic modifications.

4.4. *DIVA model*

DIVA (Dynamic Interactive Vulnerability Assessment [73]; http://www.diva-model.net) is a state-of-the-art integrated research model of coastal systems that assesses biophysical and socioeconomic consequences of sea-level rise and socioeconomic development as well as costs and benefits of adaptation to these impacts. The first version of DIVA was developed within the European-funded project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Sea-Level Rise). DIVA produces quantitative information on a range of ecological, social, and economic coastal vulnerability indicators from sub-national to global scales, covering all coastal nations. The model is driven by climatic and socioeconomic scenarios and covers the following processes: coastal erosion (both direct and indirect), coastal flooding (including rivers), wetland change, and salinity intrusion into deltas and estuaries [74,75].

DIVA first computes relative sea-level rise by combining the sea-level rise scenarios with the vertical land movement resulting from glacial-isostatic adjustment and subsidence in deltas. The loss of dry-land is then assessed due to direct and indirect coastal erosion. Indirect coastal erosion can be caused when sediment flows from the open coast into nearby tidal basins, allowing the basins to keep pace with increases in sea level. Changes in wetland area and type are assessed based on the rate of sea-level rise, the available accommodation space and the available sediment supply. The social and economic damage of coastal flooding is assessed based on data of storm surge characteristics (return periods and flood levels) as well as the exposed people, area and assets. Sea-level rise leads to shorter average return periods of higher flood levels. DIVA takes this effect into account through displacing the present storm surge characteristics upwards with the rising sea level following 20th century observations [76,77]. The damage of salinity intrusion into the coastal parts of rivers is assessed in form of the area of agricultural land that is affected by saltwater traveling up the lower reaches of rivers. The assessment of these impacts also takes into account coastal adaptation in terms of raising dikes and nourishing beaches and is based on several predefined adaptation strategies such as no protection, full protection, or optimal protection.

DIVA is designed for global, regional, and national-level assessments. With an average coastal segment of 70 km, the resolution is not appropriate for local scale coastal management decisions and analysis, although model results may help to prioritize where local scale studies are needed [79]. The DIVA model has been applied in a number of academic, educational, and policy contexts, including the UNFCCC National Communications Support Program, the Hadley Center, MIT, the European-funded CLIMATE-COST and PESETA projects [80]. The cost and time needed to run DIVA and process its results vary based on the geographic scale of the project and, in particular, on the datasets available. Due to its complexity, DIVA can only be applied by experts that are familiar with the model and data structure. The financial resources needed to apply the model depend on how much pre-processing is necessary for the available GIS data, because DIVA requires a long list of spatially-explicit socioeconomic, biophysical and ecological input parameters.

The DIVA model is a useful tool for global to national scale integrated analysis of coastal vulnerability, because it covers all coastal nations, and includes relevant social, economic and ecological processes. It allows users to explore the effects of climate change on coastal environments and societies, explore the costs and benefits of coastal adaptation options, set priorities for international cooperation with respect to climate change and development, and use results for further scientific and policy analysis. DIVA is also useful for regional comparisons of vulnerability to sea-level rise within or among countries.

Due to a lack of general global scale models, DIVA excludes a number of processes that affect changes in sea level. The model does not consider changes in storm frequency and intensity, which are expected under future climate change [1]. These changes would increase coastal flooding, coastal erosion and associated damage and adaptation costs. However, reliable projections of changes in storm characteristics cannot be made currently with confidence [78]. For the same reason, accretion and human-induced subsidence (e.g., groundwater extraction) are not included in the model due to limited data, which do however play an important role for some regions such as densely populated river deltas.

Due to the global scope of the model and the lack of general models at this scale, DIVA only considers a limited range of adaptation options whereas coastal management would include a much wider range of options (cf., [81]). For example, DIVA does not consider ecosystem-based adaptation (e.g., the protection of wetlands which are as critical coastal buffers that provide protection from the impacts of storm surge and sea-level rise) or other adaptation measures such as the building of saltwater intrusion barriers to prevent saltwater traveling up rivers basins and damaging agricultural land.

4.5. SimCLIM model

SimCLIM (http://www.climsystems.com) is a software modeling system that simulates, temporally and spatially, biophysical impacts and socioeconomic effects of climatic variability and change [82]. The system was originally developed by the International Global Change Institute (IGCI, University of Waikato, New Zealand [83]) and is now maintained and distributed by CLIM systems Ltd., Hamilton, New Zealand [84]. The SimCLIM software allows users to generate scenarios of future climate and sea-level changes and to examine sectoral impacts or conduct sensitivity analyses. The modeling system can use outputs from individual GCMs or “ensembles” of GCMs (i.e., averages of multiple GCM runs). These data and models include, for example, elevation data, site time-series data, patterns of climate and sea-level changes from GCMs, and impact models that are driven by climate and other variables. Adaptation measures can be tested for present-day conditions and under future scenarios of climate change and variability. In some specific customized applications of SimCLIM, the monetary costs and benefits of adaptation options for reducing the risks have been estimated, useful for supporting tool decision-making and assessing adaptation options.

SimCLIM can be applied from local to global scales. The size of geographical area and spatial resolution is determined by data availability and computational demands. Tools within SimCLIM can be used to interpolate to different spatial resolutions. In terms of coastal impacts, SimCLIM includes a sea-level scenario generator which allows the inclusion of regional and local components (e.g., vertical land movements) of sea-level change. Areas of potential inundation can be identified using SimCLIM's custom-built GIS tools along with a digital elevation data (as described above). SimCLIM also includes a simulation model of shoreline changes for beach and dune systems. This model is based on a variant of the Bruun Rule [85] which takes into account storm effects, local sea-level trends and lag effects in order to produce time-dependent responses of the shoreline to sea-level rise at selected sites [26]. Data inputs include shoreline response time (in years), closure distance from the shoreline (m), depth of material exchange or closure depth (m), dune height (m) and residual shoreline movement (m/year). The output is year-by-year change in relative shoreline position (m) to the year 2100. Because of the effects of random storminess and lag effects on shoreline response, realistic inter-annual and inter-decadal variations in shoreline position can be simulated and combined with longer-term trends due to mean sea-level change.

The applications of SimCLIM are diverse. For example, using the climate and sea-level rise generators along with custom-built impact models, SimCLIM was used to assess coastal flood risk from tropical cyclones and river flooding in the Cook Islands and Federated States of Micronesia [82,86]. Applications using the readily available generic tools in SimCLIM include the effects of rainfall change on the Border Ranges World Heritage Area in Queensland, Australia, and the risks of climate variability and change to domestic water supply tank systems in Southeast Queensland [87,88].

SimCLIM is licensed commercially and has been built for over 30 countries. User groups include government agencies, local councils, students, academics, engineers and environmental consultants. License fees vary widely, from student licenses through to full commercial licenses. Training courses on the SimCLIM software system are available and vary from initial orientation to full training and technical assistance, and the costs vary accordingly.

Advantages of SimCLIM are: it can be run at a variety of geographic and temporal scales appropriate for impact and adaptation assessment; it is user-friendly and quick-running; it is flexible in generating scenarios and examining uncertainties; it has tools for both time-series and spatial analyses; and it allows the user to examine climate variability and extremes as well as long-term change. These attributes make it useful for informing adaptation strategies. Additionally, the sea-level scenario generator allows for rapid generation of place-based sea-level scenarios, which account for some uncertainties associated with emissions scenarios and regional differences in oceanic thermal expansion, but may not account for isostatic change. The structure of SimCLIM is useful because users have the flexibility of incorporating their own datasets and models to customize the system for specific uses. SimCLIM also links directly to other models; for example, the DHI hydrologic models [89] and DSSAT crop models, which allow users of those models to account for future climate change in their analyses. The system allows for the creation of multiple scenarios and is easily updated as new data are made available.

Because SimCLIM is a modeling system that contains arrays of data, models and tools, and not a model explicitly, the limitations pertain more to the quality of the input data and tools. The scenario generators use the pattern-scaling approach and this approach is limited because it assumes patterns of climate change remain constant over different forcings and time periods. This assumption is valid for most GCM runs, but not all. The coastal erosion model included in SimCLIM only considers a modified version of the Bruun rule and might be improved if other shoreline models (e.g., those by Cowell et al. [90]) were also included [26].

4.6. Other relevant models

The models identified above are clearly not exhaustive. Recently, a number of numerical two- and three-dimensional models have been used for comprehensive shoreline change and storm impact simulations such as Delft3D [91], and MIKE 3FM [92]. DELFT3D (http://delftsoftware.wldelft.nl/), developed by WL|Delft Hydraulics, is a modeling system to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. It includes a number of processes such as wind shear, wave forces, tidal forces, density-driven flows and stratification due to salinity and/or temperature gradients, atmospheric pressure changes, and drying and flooding of intertidal flats [93]. Delft3D has been used to reproduce observed sediment transport patterns [93], and to reproduce detailed hydrodynamic behavior [94,95]. MIKE 21 and MIKE 3 Flow Model FM (http://www.mikebydhi.com) are 2D and 3D modeling systems developed by DHI Water and Environment for complex applications within oceanographic, coastal and estuarine environments [92]. Mike 3 Flow Model FM includes the following modules: Hydrodynamic Module, Transport Module, Ecology and Water Quality Module, Sand Transport Module, Mud Transport Module, and a Spectral Wave Module. Mike 3 Flow Model FM is able to model coupled processes, e.g., coupling among currents, waves, and sediments. MIKE 3FM has been used to study coastal and oceanographic circulation, optimization of port and coastal protection infrastructures, lake and reservoir hydrodynamics, environmental impact assessments, sedimentation, and coastal flooding and storm surge [92,96].

Numerical 3D models (e.g., such as Delft3D and MIKE 3 FM) are still in the early stages of development [97], and much additional research and testing against both the geologic record and present-day processes are needed before they can be used to inform management [98]. Such models require site-specific values for parameters such as wave climate, alongshore and cross-shore sediment transport and sediment budget [97], data often unavailable to coastal planners and managers. The increased computational time that is required for full 3D modeling also may make them impractical for managers and policy makers [99]. Finally, results from numerical models may be inaccurate if local data and engineering expertise are not available, as these models require extensive local experience by the user at the site being modeled [97].

5. Discussion and conclusions

Ideally, conservation managers and policy makers would be able to access a coastal impact model that would take into account trade-offs between scale and complexity, require little to no cost and expertise to run, and would be scientifically sound, taking all relevant biophysical and socioeconomic processes into account to accurately predict sea-level rise impacts. The reality is that conservation and development projects are limited often by financial and human resources and short timelines. Therefore, an understanding of the most appropriate applications, strengths, and limitations of coastal models is essential. Table 2 highlights the key attributes of the coastal impact models described above.

If a quick assessment is needed to identify coastal vulnerability to sea-level rise (from local to global scale) that requires limited human and financial resources, an inundation model using GIS is the most efficient option. Elevation datasets can be downloaded freely and global sea-level rise scenarios can be used [2,100]. Estimates for global sea-level rise by 2100 are likely to range from 1 to 2 m [3–8]. Results from empirical approaches can also be used as input for more complex models or coupled hydrologic models [101]. Although this type of modeling provides a useful communication tool for policy makers, coastal communities, and conservation practitioners, it is unlikely to represent future conditions accurately because it does not take the full range of biophysical or socioeconomic factors and feedbacks among these into account, specifically adaptation responses. Therefore, this type of modeling is not suited for informing international negotiations and national governments regarding mitigation, adaptation, and policy development.

If a detailed assessment of vulnerability of wetland habitats to sea-level rise is needed, then models such as BTELSS or SLAMM may be useful. These models are useful for local and regional scale studies that assess the vulnerability of coastal habitats (e.g., mangroves, other tidal wetlands, barrier islands, beaches) and species (e.g., sea turtles, nesting birds). They can identify potential future conflicts among communities and coastal habitats based on migration and uses of habitats and are important for raising awareness of the impacts of sea-level rise on coastal habitats and communities. Both BTELSS and SLAMM require a consultant to run and apply, although an advantage of SLAMM is that it is considerably less expensive than BTELSS and can provide detailed information at a local scale. BTELSS includes important ecological feedbacks between water, soil, vegetation, and habitat, and the inclusion of multiple feedbacks may provide a more realistic estimate of sea-level rise impacts on coastal habitats and populations. However, models such as BTELSS have high data demands due to the inclusion of feedbacks which restrict their use to limited geographic areas where relevant data are available. Generally, higher resolution models that are more complex will provide more detail, but are more difficult and time consuming to calibrate and run, although increased computing capabilities have made these models more practical to run. Based on their included datasets, neither SLAMM nor BTELSS are suited for global scale analyses or for supporting international negotiations and national governments regarding mitigation, adaptation, and policy development.

If an integrated assessment of vulnerability is needed (i.e., an assessment that takes into account relevant social, ecological and economic aspects of sea-level rise), then DIVA and SimCLIM would be most appropriate. An integrated vulnerability assessment is needed, for example, in areas where conservation targets are closely integrated with local communities and resources uses or if comprehensive information is needed to support the development of mitigation and adaptation policies. DIVA and SimCLIM also provide useful tools for communicating sea-level rise impacts among scientists, the public, and policy makers. One main difference between DIVA and SimClim is that DIVA is a state-of-the-art research model that is steadily being further developed by a consortium of European climate change and coastal research institutions, while SimClim is a commercial tool for which licenses and training courses are available. SimClim ranges in price from inexpensive for a single student license, to significantly more expensive for a commercial corporate license and training.

SimClim and DIVA also differ in the range of impacts considered. A simple impact model for coastal erosion is included in SIMCLIM and further impact models can be added. DIVA does not include a scenario generator but external scenarios are needed for running the model. In terms of impacts, DIVA is more comprehensive in that it considers a wider range of impacts including coastal flooding, wetland change, and salinity intrusion as well as a wide range of effects and interrelations. The assessment of coastal erosion, for example, also takes into account the influence of a warming climate on global tourism flows, because the revenues generated by arriving tourists determine whether it is cost-effective to maintain eroding sandy beaches through beach nourishment.

Both DIVA and SimCLIM are suited to global, regional, and national scale assessments, although SimCLIM is also applicable at local scales. DIVA is currently not appropriate for conducting local scale assessments due to the resolution of the data but work is in progress to down-scale the model and data for local applications. SimCLIM also requires few datasets (elevation data and global-mean temperature and sea-level projections for the SRES emission scenarios are preloaded when possible), but site-specific socio-economic and biophysical data are not included in model and must be added on a case-by-case basis. The flexible structure of SimCLIM allows users to customize the model to meet their specific objectives, and the model requires limited training to run and process.

Table 2
Key attributes of coastal impact models.

Model	Appropriate scale	Spatial resolution	Temporal scale	Input parameters	Outputs parameters	Time to run	Cost to run (USD) low: <$10,000 Medium: <$50,000 high: >$100,000	Examples of applications
Inundation model (e.g., GIS)	Local, regional, global	Varies	Variable (user defined)	Elevation, sea-level rise scenarios, socioeconomic data	Maps of areas/habitats potentially vulnerable to inundation, population flooded	Several seconds to minutes	Low	U.S. Atlantic and Gulf Coasts [28]; Global [31,32]
SLAMM	Local, regional (e.g.,<1 km^2–100,000 km^2)	10–100 m	Time-steps of 5–25 years can be used based on the sea-level rise scenario	Elevation maps (LIDAR preferred), wetland land cover (e.g., NWI), development footprint, and dike location	Maps of areas/habitats potentially vulnerable to inundation (land cover and elevation maps)	Several seconds to 36 h (function of # of cells, time-steps, and processor and memory speed)	Variable (low to medium)	20% of the coast of the contiguous United States [40]; San Francisco Bay, Humboldt Bay, and large areas of Delaware Bay and Galveston Bay [45,46]; Florida [47]
BTELSS	Local, regional (e.g.,<1 km^2–100,000 km^2)	1 km2	Variable time-steps (12 s to daily), simulation time up to 100 yrs	Elevation and bathymetry, air temperature, wind speed and direction, precipitation, river discharge, sediment load, wetland land cover, regional salinity, plant growth and mortality rates, salinity and flooding tolerances of plants	Maps of land change, (habitat switching), flooded and eroded areas, plant productivity, salinity, open water circulation, and sediment transport	Desktop environment. 1–30 days (function of # of cells, time-steps, and processor and memory speed)	High	Barataria and Terrebonne basins, Louisiana [68,69]; Centla wetlands, Mexico [70]; Patuxent River watershed [66,120,121]
DIVA	National, regional, global	Coastline segments (12,000 globally and average segment is 70 km)	5 year time-steps, simulation time up to 100 years	Elevation (SRTM), geomorphic and landform types, coastal population, land-use, administrative boundaries, GDP	Estimates of population flooded, wetland changes, damage and adaptation costs, amount of land lost	20 min	Medium	Indonesia [122]; Europe [123]; Coral Triangle in Southeast Asia [123]
SimCLIM	Local, regional, global	Varies, determined by data availability and computation demands	Variable depending on impact model being run	Elevation, climatologies, site time-series data, patterns of climate and sea-level changes from GCMs, impact models	Maps of areas/habitats potentially vulnerable to inundation. May estimate adaptation costs.	Several seconds to minutes	Variable (low to medium)	Kosrae, Federated States of Micronesia (FSM), Rarotonga in the Cook Islands [124], and the Border Ranges World Heritage Area in Southeast Queensland, Australia [89]

As new models and approaches are developed that address sea-level rise impacts, it would be useful if their appropriate uses and scales, key inputs/outputs, costs, and expertise needed could be clearly articulated in the model documentation. This information is often buried in technical documentation if available at all, and when available, it is often difficult to find. The ability to understand this technical documentation and to run and interpret correctly the results of complex models is likely to be a major obstacle to their application in many countries of the world. To address these issues, managers and academic researchers should partner and jointly participate in model development and application to ensure that the models satisfy research, capacity, policy, planning, and other application needs. Papers that compare current methodologies of coastal impact models and coastal vulnerability assessments, such as this and others [26,102], should consider cost and technical capacity along with scale and complexity issues if they aim to ensure that the most appropriate tools are used to address specific objectives, encourage the broader application of existing tools, and allow for comparisons of different approaches.

Appendix A. Sources and resolutions of elevation data

Name	Horizontal resolution	Vertical accuracy (std dev.)	Source
ASTER GDEM (from ∼83° N to 83° S)	1 arc second (∼30 m)	±7 m	ASTER (available mid-2009) http://www.ersdac.or.jp/GDEM/E/1.html
GTOPO30 (global)	30 arc-seconds (∼1 km at equator)	±30 m	USGS http://edc2.usgs.gov/geodata/index.php
ETOPO5 (global)	5 arc-min. (∼10 km at the equator)	Vertical accuracy varies by source materials used. Values range from˜5 to 500 m	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML
ETOPO2 (global)	2 arc-min. (˜4 km at the equator)	Vertical accuracy varies by source materials used. Values range from˜2 to 250 m	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/global/etopo2.html
ETOPO1 (global)	1 arc-min (∼2 km at equator)	Vertical accuracy varies by source materials used. Values range from˜1 to 100 m	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/global/global.html
Global Land One-Kilometer Base Elevation (GLOBE) (global)	30 arc-seconds (∼1 km at equator)	Vertical accuracy varies by source materials used. Values range from 10 to 250 m (and in rare cases, to over 500 m)	National Geophysical Data Center (NGDC) http://www.ngdc.noaa.gov/mgg/fliers/globedem.html
USGS National Elevation Dataset (US only)	1 arc second (∼30 m)	4.75 m at 95% confidence level (Gesch 2007)	USGS http://seamless.usgs.gov/website/seamless/products/1arc.asp
Shuttle radar topography mission (SRTM) (from ∼60° N to 60° S)	1 arc second (∼30 m) for continental United States, southern Alaska, and Puerto Rico and 90 m for remaining data	±10 m	National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html
LIDAR (Light Detection and Ranging)	∼0.20 m	Dependent on vegetation cover, typically 0.05–0.10 m	National Oceanography and Atmospheric Agency (NOAA) Coastal Services Center. http://www.csc.noaa.gov/digitalcoast/data/coastallidar/index.html Available locally through various government agencies (State and Federal)

Appendix B. Key processes that affect vulnerability to sea-level rise

Sea-level rise (eustatic and relative)

Sea-level changes are differentiated into eustatic changes and relative changes. Eustatic changes refer to changes in global-mean sea level and are caused by physical changes to the oceans, like thermal expansion of seawater and melting of glaciers and ice sheets. Relative sea-level changes are local changes in the level of the ocean relative to land and include the sum of global, regional and local factors [103]. Relative sea-level changes are influenced by changes in land surface elevation (due to plate tectonics, sediment deposition and compaction, and underground fluid extraction) and changes in the height of the adjacent sea surface. Relative sea-level rise is impacted by glacial-isostatic adjustment, the rise of the Earth's crust in response to the gradual melting of ice sheets since the end of the Last Glacial Maximum [104], atmospheric pressure, ocean currents, and local sea temperature changes.

Sediment dynamics

The dynamics of sediment are a critical factor determining shoreline change in response to sea-level rise [60]. Whether there is an overall gain or loss in the sediment budget can determine whether a shoreline is accreting or eroding. Sources of sediment include rivers, cliff erosion, offshore, or alongshore. Sources of *in situ* sediment include production by calcareous organisms (e.g., shells) and erosion of foredunes [105]. Sediment loss can occur when winds blow sediment into dunes, offshore losses, and long-shore transport to adjacent regions. Human impacts can add to the sediment budget (e.g., beach nourishment) or can reduce the sediment budget (damming of rivers, sand mining).

Coastal erosion – tidal basin dynamics

Coastal erosion refers to the physical removal of sedimentary material from e.g., wetlands, beaches, dunes, and cliffs [106]. Coastal erosion can be caused by multiple factors including sea-level rise, storm surge, waves, tides, and currents that transport sediment, currents that transport sediments into tidal basins (indirect erosion [107]), and winds that blow sand inland from the coast [108].

Coastal flooding – storm surge and waves

Storm surges are temporary increases in sea level above the expected tidal levels and are caused by strong waves on the water surface and reduced atmospheric pressure [109]. Storm surges may result in sea-level changes of up to several meters causing major coastal flooding (defining the upper range of land elevations for coastal vulnerability), especially when they occur in conjunction with high tides.

Salinity intrusion

Sea-level rise and associated storm surges can lead to salinity intrusion into coastal aquifers and surface waters (e.g., rivers, estuaries, and deltas), which has negative impacts on human water usage and ecosystems [1,110]. Salinity intrusion is modified by other factors including groundwater abstraction, surface water discharge, and precipitation. Increased salinity decreases agricultural productivity and freshwater availability and can result in the replacement of freshwater species by salt-tolerant species (e.g., salt marsh or mangroves) in coastal habitats as well as the contamination of groundwater.

Wetland change – migration of wetlands

Coastal habitats will change or migrate as a result of erosion, changes in salinity, and inundation caused by sea-level rise. Wetlands respond to sea-level rise by horizontal inland migration, vertical elevation change and transitions to other wetland types [111]. For example, wetlands may be converted into open water if inundation occurs, or vegetation may change but an area may stay wetlands if salinity increases. However, coastal wetlands may be able to adapt by growing upward or landward if sea-level rise occurs slowly enough, if adequate expansion space exists, and if other environmental conditions are met (e.g., adequate sediment for vertical accretion) [112]. The ability of wetlands to migrate landward may be constrained by local conditions (e.g., roads, agricultural fields, dikes, urbanization, seawalls, and shipping channels) and topography (e.g., steep slopes, cliffs). Wetlands with an adequate sediment supply where coastal development and topography do not prevent landward migration are likely to be less vulnerable to increases in sea level.

Socioeconomic development (e.g., population growth, GDP growth, land-use change)

Socioeconomic development is a key driver of coastal vulnerability [1] and affects coastal vulnerability primarily in three ways. First, socioeconomic development, including mitigation, determines the level of future greenhouse gas emissions and, in turn, sea-level rise. Socioeconomic variables such as population growth, GDP growth, and land-use change are key drivers of projected changes in emissions and climate [113]. Due to the delayed response of the ocean system, this effect does not become significant until the middle of the 21st century. Second, socioeconomic development determines the capital and the number of people that will be exposed to sea-level rise. Estimates of coastal population, for example, range under the SRES scenarios from 1.8 to 5.2 billion people by 2080 [1]. Third, socioeconomic development determines the potential levels of adaptation to the impacts of sea-level rise.

Adaptation

Adaptation is defined as the “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” [114]. Adaptation includes three primary strategies: protection to help control erosion, flooding, salinity intrusion etc. (e.g., building of hard structures such as dykes and seawalls and soft structures such as beach nourishment or wetland or dune restoration), retreat (e.g., establishing setback zones, relocation of development, and easements that restrict coastal development), and accommodation (e.g., early warning systems for extreme weather events and development of agriculture using salt-resistant crops [80,115]). Although building hard structures may actually increase erosion by changing circulation patterns and sediment distribution, adaptation responses have the potential to significantly reduce the impacts of sea-level rise in coastal areas [1,116,117].

Further human activities

Human activities (e.g., drainage of wetlands and lakes, groundwater exploitation, and construction of reservoirs behind dams) can cause local changes in sea level by contributing water to the oceans or by impounding water on land [118]. Coastal wetlands may be drained for agricultural, residential, or industrial development and may result in subsidence of soils and reduced elevation, thus exacerbating sea-level rise. Groundwater exploitation, such as the mining of groundwater aquifers, contributes to changes in sea level, and some suggest that it is the largest positive human contributor to sea-level rise other than human-induced climate change [119]. Deforestation and urbanization contribute to sea-level rise by increasing runoff from land. Urbanization increases total runoff and impedes groundwater replenishment due to the increase in impermeable ground (e.g., concrete, tile, and tarmac). Water may also be removed from urban areas through sewers and storm water drains [118]. Human activities such as the storage of water behind dams and the irrigation of agricultural lands may prevent water from reaching the ocean thus reducing the impacts of sea-level rise.

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