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Sea-level rise and coastal flooding: A review of models and their applications

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Abstract:
In the face of current uncertainties about the processes of climate change and its consequences, the search for possible response strategies is urgently needed. One of the most serious repercussions of climate change, which threatens many coastal areas globally, is the sea-level rise (SLR). To deepen understanding of this phenomenon and its related impacts, several models have recently been developed to satisfy the unique needs of coastal zone management. These models are very useful because of their visualization and prediction capabilities as they aid in decision-making regarding the adaptation of current protected area investments. This review, therefore, provides evidence of the potential and effectiveness of recent mapping models for managing the effects of sea-level rise. This study examined current models for mapping flood risk areas as a result of sea-level rise. It also provides guidelines to help coastal zone managers and policymakers decide the applicability of various models at local, regional, and global scales. There is no universally approved model, and each of the models examined in this article has its own set of advantages and limitations. However, relevant resources from the National Oceanic and Atmospheric Administration are more frequently utilized for organizations and beyond, and they are easier to understand and relate with by scientists and those with less scientific knowledge on sea-level rise.

Keywords:
Sea-Level Rise impacts, Modelling, Coastal zone management, Flooding.

1. Introduction

Throughout the twentieth century, climate change caused an 11-16 cm rise in global mean sea level (HAY *et al*., 2015; DANGENDORF *et al.,* 2017). Even with immediate and drastic diminutions in carbon (CO2) emissions, sea-level rise is likely to increase to 0.5 m in the 21st century (KOPP *et al*., 2014; JEVREJEVA *et al*., 2016). In the case of early-onset Antarctic ice sheet instability, the rise in the twenty-first century might approach or perhaps exceed 2 meters under higher emissions scenarios (KOPP *et al*., 2017; WONG *et al*., 2017). However, considering that large increases in coastal flooding have been noticed in recent years, focusing on Sea-Level Rise (SLR) projections and their repercussions by 2050 or 2100 may be inaccurate (ABATE, 2015; PARDAENS *et al*., 2011; RAMACHANDRAN *et al*., 2017; SWEET *et al*., 2020; SWEET & PARK, 2014). Furthermore, these occurrences are anticipated to change drastically in the coming decades, despite the fact that long-term planning rarely exceeds thirty years (STORLAZZI *et al*., 2015, 2018; VITOUSEK *et al*., 2017; THOMPSON *et al*., 2019). Fortunately, data from systems such as the Coordinated Ocean Wave Climate Project (COWCLIP) (HEMER *et al.,* 2013), the Global Tide and Surge Reanalysis (GTSR) (MUIS *et al*., 2016), the Global Extreme Sea Level Analysis (GESLA2) (WOODWORTH *et al*., 2016) and satellite altimetry (CIPOLLINI *et al*., 2018) are readily available. They have made it possible to understand and predict the challenges associated with sea-level rise and its consequences for coastal areas.

A variety of coastal hazards threatens the coastal zones (OPPENHEIMER *et al*., 2019), including (i) persistent land submergence as a result of rising mean sea levels or mean high tides (IPPC, 2019); (ii) Coastal flooding that is more regular or powerful (HSIAO *et al*., 2021) ; (iii) increased coastal erosion (CAI RONG-SHUO *et al*. 2020); (iv) Coastal ecosystem loss and modification (HE & SILLIMAN, 2019; MACURA *et al*., 2019); (v) Soil, groundwater, and surface water salinization (HARPER *et al*., 2021). According to (Climate Change Indicators: Coastal Flooding, US EPA, 2020-2021), of all these, coastal flooding is more frequent and noticeable. Global flood damages, as a result, are estimated to be over US$6 billion per year on average and will rise to about US$52 billion by 2050 due to projected socio-economic change alone (HALLEGATTE *et al*., 2013). According to GOLLEDGE *et al*. (2019), without adaptation, most low-lying islands, coasts, and towns, whether urban or rural, continental or island, at any latitude, and regardless of development level, face severe risk from these coastal hazards on a century-scale.

Coastal flood mapping models have therefore been developed in response to the flooding risk. These coastal mapping models can be used to forecast environmental reactions to changes in sea level as well as the effects of different management approaches on future ecosystem behavior (COSTANZA *et al*., 1993; FITZGERALD *et al*., 2008).

As a result, the purpose of this study developed through the main lines such as: Models of inundation and simulations flooding due to Sea-Level Rise; Model application by location; Application areas of sea-level rise models and Model guidance is to assist coastal managers and researchers in better identifying appropriate models and understanding which ones may be applicable for the identification of flood risk zones, as well as when to use these models and methods for modeling the link between sea-level rise and coastal floods. Planners and practitioners can take steps now to prepare for sea-level rise and ensure the security of coastal communities, and with this detailed understanding of these models, we can work for the long-term survival of ecosystem services.

2. Methods

The study reviewed publications from refereed journals in online repositories such as Google Scholar, Science direct and Elsevier, Scopus. The terms used in the search were "Sea level modelling", "Wave flooding", "Sea level rise and impact", "Mapping of flood risk areas", "Coastal hazards and flooding" and "Coastal Zone Mapping Model".

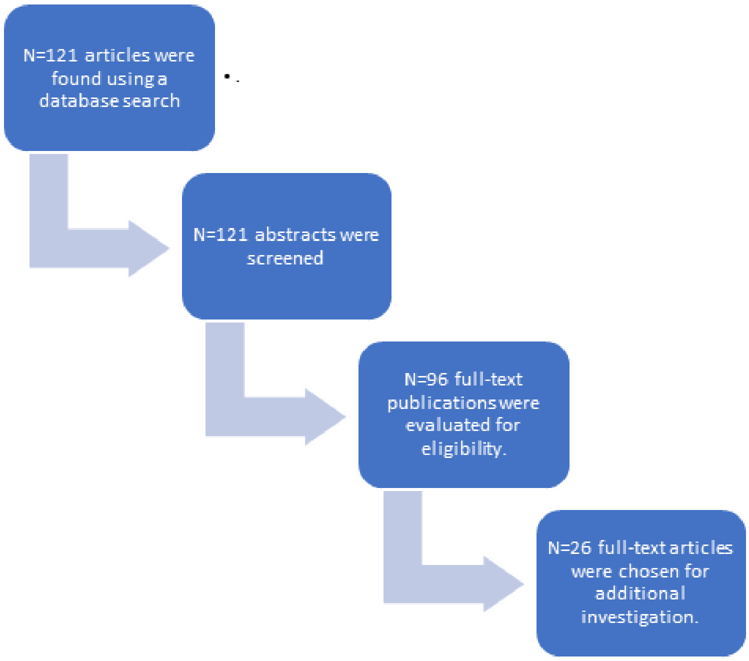

Figure 1. Literature search workflow for the study.

Only articles written in English were included in the search, and the first three pages of these engines were consulted. The studies that pertained to the flooding in non-coastal areas were systematically excluded. The research also excluded dissertations that employed indices to map flood zones as a result of rising sea levels. There were 121 published documents on mapping flood risk zones in line for the sea-level rise during the search. Ninety-six papers satisfied the study's inclusion criteria and were considered for publication. The papers were grouped into models for flood mapping due to Sea-Level Rise (n=61), Sea Level Rise and its impacts (n=22), coastal management (n=6), and Spatial and temporal aspects of SLR impact (n=7). Twenty-six papers were chosen for additional examination (figure 1).

3. Results and discussion

3.1. Models of inundation and simulations flooding due to sea-level rise

As no one model is officially recommended, the characteristics of different models should be evaluated to determine which one is most suitable for a given situation.
In order to generate future sea-level estimates that may be used to predict shoreline flooding and other modeling studies, some hydrological models have been constructed. Models include everything from sheer speculation to calculated projections based on tide gauge data, glacier melt calculations, and climate change models that predict future sea-level rise (table 1). We exclude tidal simulation methods and more advanced hydrodynamic models utilized in wave studies, storm surge, or high flood forces from this topic because they are primarily employed for engineering bridges and other coastal infrastructure. These models have been excluded not because they are among the least because it should be noted that coastal flooding episodes can be due to a conjunction of the tide, a storm overhang. But given the size (data, literature) of the models considered if these parameters were considered since we know given the objective of testing these models, we had therefore been more specific in the objectives of the study.

3.2. Model application by location

Several studies have been carried out around the world in various domains and have therefore tested the highlights and weaknesses of the models discussed in this study (table 2 and figure 2). The American continent has explored and applied mapping models the most, with 66% of the studies reviewed in this paper. The application domain of the reviewed studies on this continent range from inundation mapping due to Sea-Level Rise (7 papers) to Sea Level Rise and its impacts (4 papers) to coastal management (3 papers) and Spatial and temporal aspect of SLR impact (5 papers). This is followed by the continents of Africa and Asia, where 10% of our review has been assessed each. SLR and flooding mapping was most discussed in Africa while SLR and Impact was studied in Asia. Only 7% of our review explored Oceania and the UK. Nevertheless, the key domain of our review, namely SLR and flooding mapping and SLR and Impact, were reviewed in these continents.

Table 1. Selected sea-level rise simulation and inundation models' attributes.

Model	Agency/ Organisations	Appropriate Scale	Spatial resolution	Temporal scale	Input parameters	Output parameters	Citations
Sea-Level Simulator CoastCLIM (component of the SimCLIM system)	CLIMsystems	Local, regional, global	Depending on data availability and computing demands.	Depending on the impact model that is being used.	Elevation, climatology's, site time-series data, climate and sea-level change patterns derived from GCMs, and impact models	Elevation, climatology's, site time-series data, climate and sea-level change patterns derived from GCMs, and impact models	(TEROROTUA et al., 2020) (WARRICK et al., 2012)
National Oceanic and Atmospheric Administration's (NOAA)	NOAA	Local	Not applicable	month–5 years	Date range, tide station, reference elevation	Duration of inundation, frequency of high-water elevation, or duration of high-water elevation (tabular or graph format)	http://tidesandcurrents.noaa.gov/inundation/, Inundation Analysis Users' Guide. NOAA 2020
Rectification of Sea-Level Rise Program (SLRRP)	U.S. Geological Survey	Local, regional	Not applicable	Monthly to annual time step, historical tide range plus projection to 2100	Tide station, historical or customary local subsidence rate, GCM sea-level increase rate	Flood flooding potential for a particular elevation as a result of cumulative sea-level rise	KEIM (2008) (ALLEN, 2008.)
2D depth-integrated hydrodynamic models		Local	Not applicable	-	-	Inundation duration	RAHIMI et al., (2020)
Coastal Storm Modeling System (CoSMos)		Regional, global	Big resolution	Hindcast studies	-	Inundation duration	TEHRANIRAD et al., (2020)

Table 2. Some locations for using the models.

Model	***Oceania***	***America***	***Asia***	***Africa***	***UK***
CoastCLIM/SimCLIM	*1*	*1*	*3*	*1*	
NOAA/SLAMM	*1*	*8*		*1*	
SLRRP		*1*			
2D depth-integrated hydrodynamic models		*3*		*1*	*2*
CoSMos			*6*		

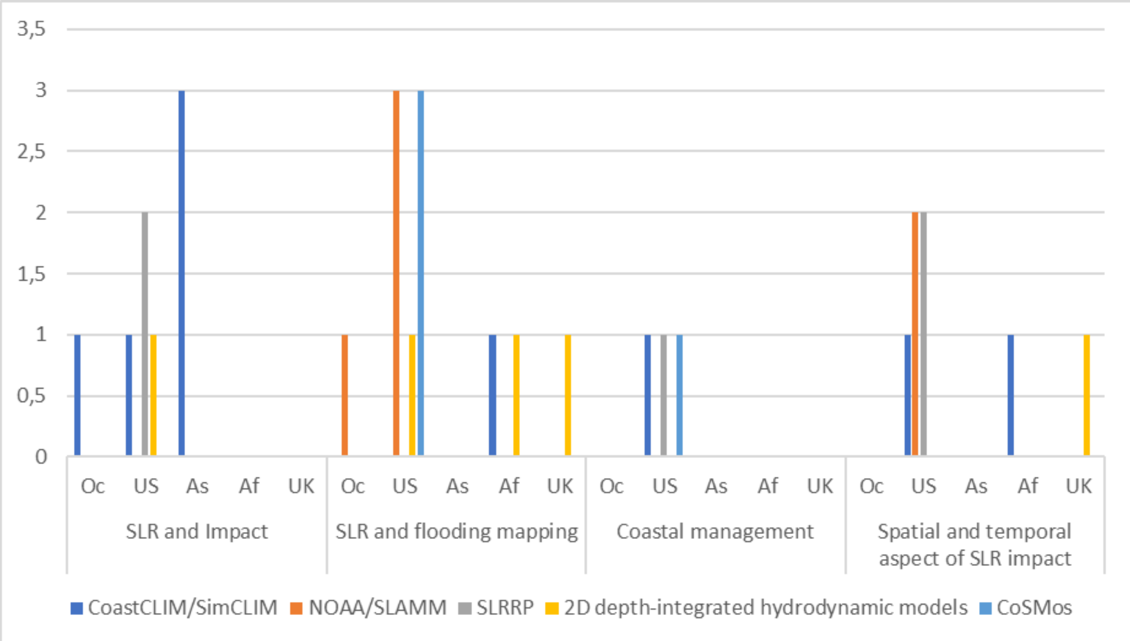

Figure 2. Domain of application, model and by location.

3.3. Model guidance

To fully understand Sea Level Rise and how they can inform regional planning polices require a link between the best available scientific tools and governments (table 4). It would be ideal for conservation managers and policymakers to access an SLR and coastal impact model that considered the trade-offs between scale and complexity, cost, and operational competence (table 3). In order to effectively estimate the effects of sea-level rise, this model must be scientifically valid, taking into consideration all important biophysical and socio-economic processes. Conservation and development efforts are frequently hampered by a lack of financial and human resources, as well as tight timelines. Due to limited financial and human resources and short time restrictions, managers must have a full awareness of the most relevant applications, as well as the strengths and limits of coastal models.

If a rapid examination of the susceptibility of coasts to sea-level rise (from local to global scale) is required and limited human and financial resources are available, a flood

model based on GIS is the most efficient option. Elevation data is freely available, and global sea-level-rise scenarios can be used to forecast future rises in sea level. In fact, inundation models mapping can be quite low-cost to operate. Others require GIS software and programming scripts, elevation databases, and sea-level rise estimates, while others merely need the connection to the Internet. Other benefits include the ability to quickly create flooding maps (e.g., within days or weeks) using freely available elevation datasets (e.g., the National Geophysical Data Center's ETOPO5, ETOPO2, and GLOBE elevation datasets, the USGS' GTOPO30 (https://pubs.usgs.gov/of/2001/of01-470/nybgis/metadata/ngdc.htm), and the National Aeronautics and Space Administration's SRTM). This type of modeling approach can provide information to national development planners to fuse into their future plans concerning the coastal areas where the landscapes are most vulnerable to sea level rise. Under the aforementioned conditions, models that use GIS, such as SLRRP, 2D model, and SIM Coast, will be recommended. The use of a GIS-based model does not come without consequences. Models that use GIS to identify inundated areas, for example, may overestimate potentially inundated areas because water connectivity is not considered (i.e., some areas may have a lower elevation than projected sea level rises, but land barriers may exist to prevent inundation) and some inland places have lower elevations than expected sea-level rise.
Other models, such as the Coastal Storm Modelling System (CoSMoS), provide detailed forecasts of storm-induced coastal floods, erosion, and cliff failure on a wide scale. However, not everyone has access to the requirements for use, the data required, the fees involved, or the knowledge required. Since its inception in the mid-1980s, the Sea Level Affected Marsh Model, or SLAMM, has been employed in a variety of geographical areas and applications across the country. Optional inputs in the model include information about the placement of dikes or other protected areas, accretion rates, erosion rates, and other factors. True, ArcGIS is required to display the output in a cartographic environment, and Microsoft Excel and Word are required to display the text and tabular output. However, its capabilities, which include visualizing the impacts of multiple sea level rise scenarios, comparing the effects of several scenarios and timeframes, displaying map outputs for additional study, and doing so at a low cost, make it the most promising model for a variety of management needs.
To run and apply, both CoSMos and SLAMM require the aid of a specialist. SLAMM, on the other hand, is not as much of CoSMos and can deliver precise information on a local scale.

Table 3. Key parameters for model selection.

Model	***Limitations***	***Highlights***	***Flexibility***	***Accessibility***	***Cost***
NOAA	*• No Mass Balance of Solids – i.e. accretion rates not affected by bank sloughing – Storms do not mobilize sediment • Accretion Rates Based on Empirical Relationships – Not a mechanistic model • Overwash component is subject to considerable uncertainty – Timing and size of storms is unknown – Based on observations of barrier islands after large storms*	*• SLAMM 2 was used to replicate 20% of the coast of the contiguous United States for the 1991 EPA Report to Congress (Peer Review, Model Validation using LA Coast) • Over a three-year period, the EPA STAR Grant (2005-2008) provided financing for major model development (SLAMM5) • US Fish and Wildlife Service funding for refuge simulations (Ongoing) • GOMA and TNC are funding two Gulf of Mexico simulations (2009) • The model and the code are both open source.*	*Very high*	*Very high*	*Low*
2D	*simplification may overestimate flood propagation and underestimate maximum depths*	*Can be used even if you don't have a lot of hydraulic expertise.*	*Very high*	*Very high*	*Medium*
SLRRP	*Tools are almost exclusively unrectified and unverified*	*It makes it easy for the user to select a specific tide station by using a graphic user interface with many pop-up windows. - The user can choose a specific tide station in the customized SLRRP mode. A local subsidence rate and eustasy can be manually entered. -Rather than employing a defined pace or elevation for a certain amount of time, -The model's defaults -It provides the user with a number of options. -saved sea-level images and projections in digital formats*	*High*	*Very high*	*Low*
CoastCLIM		*-user-friendly interface*	*High*	*Very high*	*Low*
CoSMos	*Access to the requirements for use, the data required, the fees involved, or the knowledge required. S*	*Regional coverage*	*Low*	*Medium*	*High*

Table 4. Major objectives for assessing the effects of SLR and appropriate model.

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, CoSMos*
Government agencies	*Development of national adaptation policies (e.g., meeting a government's obligations under UNFCCC to reduce vulnerability to climate change) conducting a national assessment of vulnerability in the 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 mpacts*	*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 in size from 1 to 10 square kilometers.

4. Conclusion

Despite significant advances in monitoring global and regional sea-level change and understanding the climate-related causes of observed changes, new obstacles in measurement, modeling, and impact assessments have emerged. It's tough to plan for rising sea levels. As a result, the greatest technique is to rely on the most up-to-date science to assist in the procedure. Selecting an SLR model is a crucial initial step in

constructing the Vulnerability Assessment. There is no universally approved model, and each of the models examined in this article has its own set of benefits and drawbacks.
In conclusion, NOAA is more frequently utilized by organizations and beyond, and it can be easier to understand by the general public, even those with less scientific knowledge on SLR. Also, SLAMM is significantly less expensive than other models and provides detailed data at a local level. As a result, it is thought to be the most useable.
SLAMM is not ideal for world-scale analysis or helping international discussions because of the datasets it uses, but it is suitable for national governments on mitigation, adaptation, and policy creation because of the datasets it uses. By providing rapid information about where coastal landscapes are most vulnerable to sea-level rise at global, regional, and local scales, this modeling approach can inform decision-makers and policymakers about setback limits, zoning, future development plans, and local and regional action plans. Although inundation models can give fast assessments of sea-level rise risk, their conclusions must be evaluated with the understanding that key feedbacks may be lacking. These techniques, for example, often neglect potential feedbacks on wetland accretion, obviating the geomorphic significance of wetlands in landscape evolution and maintenance. Uncertainties in global sea-level forecasts and elevation data, a lack of data on sediment transport regimes, and a lack of feedbacks between biological, ecological, and social systems all limit these models.

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