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A Review of the Risks Associated with Accelerated Sea Level Rise - Induced Hydro - Geomorphism

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Abstract: ***Records showed that over the last 100 years, global sea level has risen gradually, especially due to thermal expansion and melting ice caps in glacial regions. Sea level has risen since the late 19th century, while it increased in 1993 - 2009 and the greater part of the 20th century. The 2021 projection sets sea level rise above the 1993 level. These scenarios are a clear indication that sea levels are accelerating globally at rates that could be problematic for human settlement and coastal environments. The aim of this study is to illustrate how accelerated sea level rise (ASLR) - induced hydro - geomorphic processes present risks at different levels in various parts of the world and to explain the utility of spatial technologies in assessing the risks posed to coastal environments by this phenomenon. The methodology used involved an in - depth analysis of selected reports and refereed journal articles on ASLR, the potential risks it poses to low - lying coastland and ecosystems and spatial tools and models used to provide a better understanding of its contribution to physical changes in coastal environments. A survey of the literature and analysis of selected documents showed that various hydro - geomorphic parameters, such as increased tidal ranges and prisms which become accentuated during ASLR, alter sediment transport patterns and change coastlands shorelines. It also revealed that ASLR has implications not only for shorelines and low - lying coastlands which become inundated as a consequence of increased shoreline erosion and destruction of protective coastal vegetation during storm events but also human habitation. The review showed that the processes are better understood when a combination of spatial technologies and modelling, such as Digital Shoreline Analysis System (DSAS), Delft3D modelling and 3D and 4D hydrodynamic modelling, is applied.***

Keywords: Accelerated sea level rise, hydro - geomorphic processes, spatial technologies and modelling

1. Introduction

Accelerated sea - level rise (ASLR) threatens not only human populations in low - lying coastal areas but also coastlands and shorelines which are very sensitive to geomorphic processes, such as storm surges and erosion. Physical changes in the climate in different parts of the world have been widely observed and the trends have been projected to continue in the future. Global models and projections for the next six decades (2080s) clearly show that about 20 percent of all coastlands will be destroyed (Goodwin, et al., 2017; Jackson & Jevrejeva, 2016; Slangen, et al., 2014).

Records have confirmed that over the last 100 years, global sea levels have risen gradually, especially due to thermal expansion and melting ice caps in glacial regions. For example, sea levels have risen by 8 to 9 inches since 1880 (Chambers et al., 2014; Orlić & Pasarić, 2013). The period 1993 - 2009 has recorded 0.1 rise per annum, while sea levels have increased double times from 0.06 inches per year for the greater part of the 20th century to 0.14 inches per year from 2006 to 2015. The 2021 projection sets it at 3.8 inches above 1993 levels (NOAA, 2022; IPCC, 2019; Jackson, et al., 2018; Mengel, et al., 2016; Kopp, et al., 2016; Jevrejeva, et al., 2014; Mitrovica, et al., 2011). These trends point to sea levels not only increasing but doing so at an accelerated rate; hence the use of the concept accelerated sea level rise (ASLR) in this paper. Accelerated sea level rise (ASLR) is a concept used to describe the increased average annual rate in which the world's ocean level elevates due to the effects of global warming.

Many studies have shown that should sea levels continue to rise along the projected trajectory, destruction of coastal ecosystems and arable lands is inevitable as a consequence of increased exposure to agents, such as storm surges, and likely to have a rippling effect (Rasmussen, 2018; Jevrejeva & Moore, 2014; Orlić & Pasarić, 2013). The ultimate consequence, therefore, is increasing costs for adaptation and/or mitigation. A 1 - meter rise in sea level could affect 6.1 million people living on the Nile delta while a 1.5 metre increase could lead to inundation and flooding of about 22, 000 km^2 of the deltaic areas of Bangladesh, affecting approximately 17 million people (Buitrago, 2014; Chambers et al., 2014; Orlić & Pasarić, 2013; Church & White, 2011).

Recent data indicate that in the last decade of the 20th century, sea level has increased two to three times more at the regional and local levels than at the global level. This has implications for Small Island Developing States (SIDS), most of which are located in the Oceans in the tropics and have limited land (a few km^2) above sea level. SIDS territories include St. Kitts, Kiribati and Mauritius in the Atlantic, Pacific and Indian Oceans respectively. These are low - lying Islands, Islets and Atolls where most of them have the highest elevation ranging between 1 m and 2 m above sea level; making them among the most vulnerable to ASLR (Nayak, 2018; Kopp, et al., 2014; Merkens, et al., 2016). These small Islands already face surges from low pressures in the higher latitudes during the months of May/June and September/October, giving rise to occasional flooding of the coastal regions. In the Caribbean, it is estimated that sea level will be about 0.6 meters by the end of the century, thereby posing a threat to many critical sectors, including tourism and agriculture. The probability of coastal dwellers developing the capacity to cope with close to a 1 - metre rise in sea level, for instance, appears to be very low (NOAA, 2019; Kopp, et al., 2014; Chambers et al., 2014; Church & White, 2011).

The management of coastlands is imperative not only for the protection of natural resources and ecosystems, such as fishes and mangroves, but also social and economic assets, including infrastructure, beaches and agricultural lands. In an attempt to manage coastal resources and safeguard assets, many countries have undertaken various initiatives over the last decades to protect and where necessary rehabilitate sea defense infrastructure and restore mangroves in various sections of the coast. The ultimate goal has been to reduce the impact of sea level rise on coastal areas. In many instances, however, not all of the initiatives have been sustained as a result of financial, human resources, regulatory and technology challenges. The result is that the targets set for coastal protection have not fully materialized and some of the challenges persist today. If these are not addressed efficiently and effectively, the ecosystems and social and economic infrastructure will continue to be exposed to various risks and vulnerabilities, such as land degradation resulting from ASLR (Jevrejeva & Moore, 2014; Slangen, et al., 2014; Anthony & Gratiot, 2012).

There is a compelling need to increase understanding of the risks of sea level rise and the resultant vulnerabilities to coastal zones in low - lying jurisdictions. It is also important to incorporate geospatial technologies to assess the impacts of sea level rise since there is increasing demand for up - to - date and robust scientific data to inform planning, decision - making, and interventions to respond to the problem of ASLR.

This review focuses on the risks associated with ASLR as a major climate - induced change affecting coastal areas. The main objective is to illustrate how coastal ecosystems and land uses have become more susceptible to ASLR - induced hydro - geomorphic systems by focusing on the processes of erosion and sedimentation and the potential risks associated with the phenomenon in various parts of the globe. It also presents a contextual framework for low - lying coastland and ecosystems management associated with ASLR. Finally, the study illustrates the utility of conducting studies related to ASLR - hydro - geomorphic processes.

2. Methodological Approach

Research Design and Approach

This review was conducted through an in - depth analysis of selected scholarly research undertaken on ASLR, its risks to low - lying coastland and ecosystems conservation and land use management, and spatial tools and models used to aid in the understanding of the contribution of ASLR to physical changes in coastal environments. The literature analysed include publications from the Intergovernmental Panel on Climate Change (IPCC), National Oceanic and Atmospheric Administration (NOAA) and refereed journals on such thematic areas as principles of hydro - geomorphism, ASLR - induced hydro - geomorphic processes and associated risks to low - lying coastal areas, and the application of Digital Shoreline Analysis System (DSAS), Delft3D Modelling, and Three - (3D) and Four - dimensional (4D) hydrodynamic modelling for ASLR - induced hydro - geomorphic systems. The conceptual framework in Figure 1 outlines the main concepts and various issues associated with coastland and ecosystems management in dealing with ASLR.

Principles of Accelerated Sea Level Rise (ASLR)

Records showed that since the late 1800s, the oceans have already risen by approximately 0.2 meters with the rate of SLR accelerating in recent decades, and projections illustrate a worse - case scenario of about 2 meters by the end of the 21st century (American Geophysical Union, 2024; IPCC, 2019; Hall, et al., 2019; Brown, et al., 2018; Bakker, et al., 2017; De Winter, e al.; 2017; DeConto, et al., 2016). In fact, some other studies project the increase to be higher the IPCC's estimates using both satellite imagery and tidal gauge data (IPCC, 2019; Kopp, et al., 2016; Kopp, et al., 2014). The principles that explain accelerated sea level rise (ASLR) are accounted for in various theories, such as the Physical Vulnerability Theory and Bruun Theory. While the former is dubbed by researchers as futuristic and provides more accurate long - term assessment of sea level rise (NOAA, 2019), the latter is dated and limited to short - term modelling of the phenomenon, but it views sea level rise as a cause of shore zone erosion (Kopp, et al., 2014; Church et al., 2011). Each theory in its own right provides insight into the physical factors that contribute to sea level rise.

According to the Physical Vulnerability Theory, accelerated sea level rise is a phenomenon that occurs as a consequence of two major factors. These factors are melting of ice found on land and thermal expansion of water (NOAA, 2019, Goodwin, et al., 2017; Church et al., 2013; Mitrovica, 2011). Other contributory factors include a decrease in the velocity of the Gulf Stream in the future - as melting ice sheets in Greenland disrupt the system with discharges of cold fresh water - and land sinkage. With respect to decrease in the velocity of the Gulf Stream, it is possible because less water is taken from the coast, leaving more water to pile up and causing the sea level to rise along the coast in various countries, such as Mexico and Florida (NOAA, 2019; Slangen, et al., 2014). As it relates to land sinkage, although it is not directly associated with climate change and therefore, will not be discussed in this study, it is worthy to note that local rates of land height change have also varied dramatically on decadal timescales in some locations, such as along the western Gulf Coast, where rates of subsurface extraction of fossil fuels and groundwater have varied temporally.

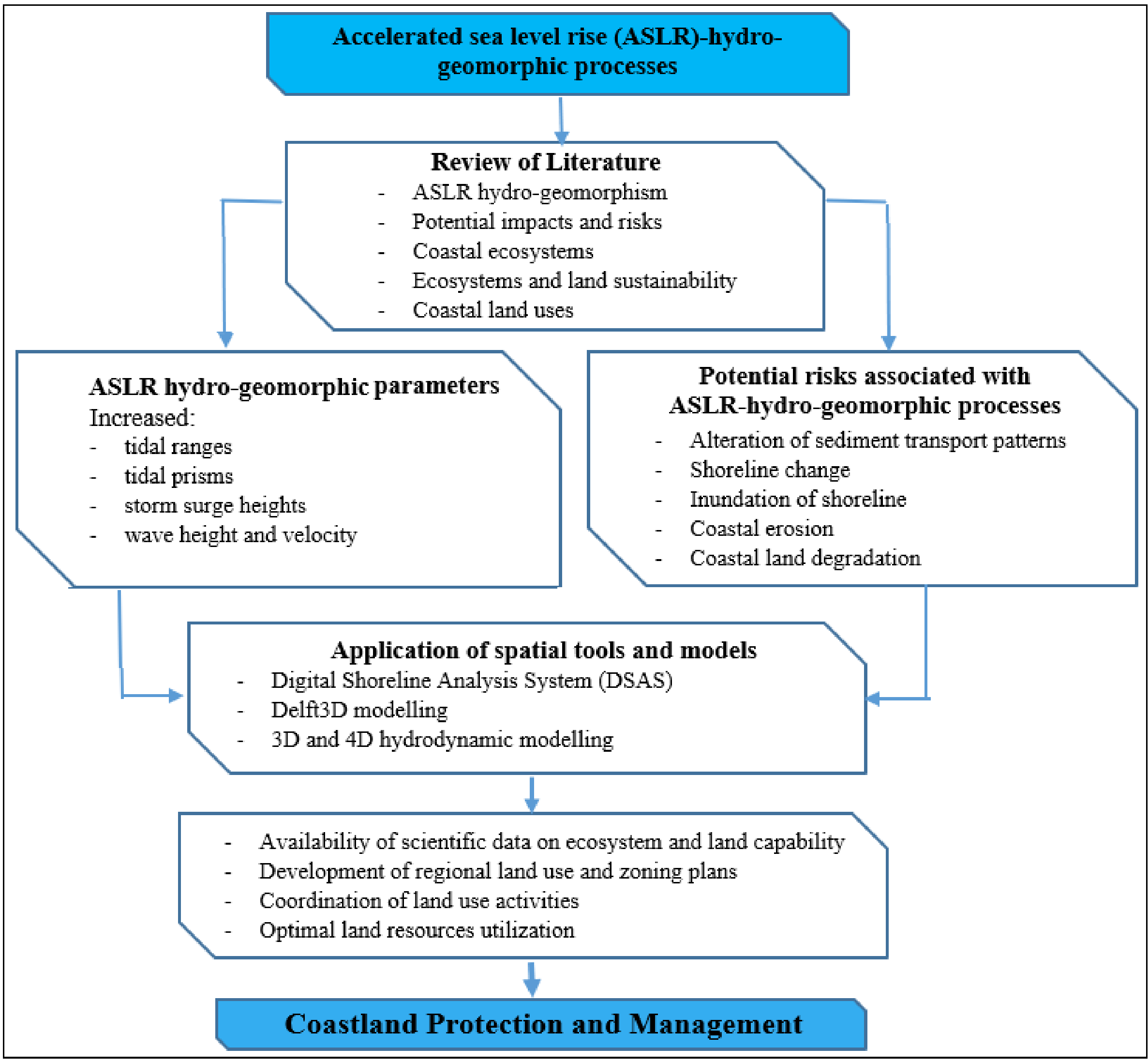

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Figure 1: Conceptual framework for coastland and ecosystems management associated with ASLR
Source: Compiled by the Author

The Intergovernmental Panel on Climate Change (IPCC) in its assessment of climate change provides further insight into the relationship between climate systems and temperature of the oceans. The First IPCC Assessment Report illustrates two interrelated scenarios. First, sea level increased progressively from the 19th century onwards and second, the rate of thermal expansion of the ocean in the 19th century occurred slower than the 20th century. In the case of the former, the overall quantum of ocean water and the sea level become affected, but to a lesser extent by changes in global land - water storage and precipitation patterns that coincide with the phases of the El Niño–Southern Oscillation (ENSO) (Goodwin, et al., 2017; Wada et al 2017; Reager et al 2016; NOAA, 2022). In the latter case, as it relates to the rate of thermal expansion of the ocean in the 19th century, direct observations from long - term tide gauges and global satellite altimetry also show that sea level continued to increase. Analyses of tide gauge records indicate a global mean SLR between 1.6 and 1.8 mm/yr. over the 20th century (Church and White, 2011; 2006; Jevrejeva et al., 2008; 2008).

Further, the IPCC Assessments projected an upward trend for the 21st century compared to the 20th century, attributed mainly to continuous ocean thermal expansion and the melting of glaciers. The quantity of heat - trapping gases, commonly known as greenhouse gasses - (GHG) in the Earth’s atmosphere affects the amount and rate of sea level increases. When land ice melts from ice sheets and mountain glaciers, liquid water is added to the oceans. For instance, melting ice sheets from the West Antarctica and Greenland regions elevate sea level. It is projected that sea levels will likely rise 0.6 m – 1.3 m (2 - 4 feet) by 2100 relative to average sea level during the period 1986 – 2005, if there is a 2 °C (Rasmussen, et al., 2018; Jackson, et al., 2018; Passeri et al., 2015). Archimedes principle states that the when ice melts, the change in volume exactly counterbalances the extra volume of the ice that was up above the water's surface and that melting of the polar sea ice acts as climate feedback. If this principle holds true, then the probability of the interaction causing an increase in sea level due to the presence and buoyancy of ice on water is high. Ice has a density of 0.9 g/cm^3 which is less than the density of water (1 g/cm^3). Figure 2 illustrates possible pathways for ASLR by 2100 based on projected rates of greenhouse gas (GHG) emissions and global warming, and differences in the possible rates of glacier and ice sheet loss.

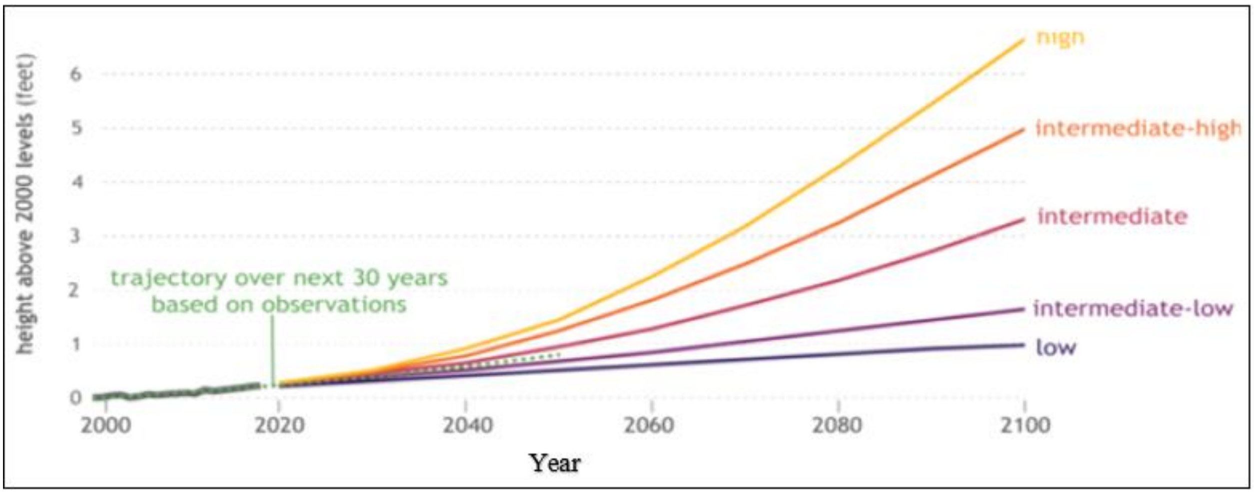

Figure 2: Likelihood of sea level rise versus projected rates of GHG emissions and global warming
Source: NOAA, 2022

Five pathways have been created for possible future global mean sea level (GMSL) rise by 2100 ranging from low to high probability of GHG emissions and warming of 1.5 degrees Celcius, global mean sea level would rise at least 0.3 m to 6.6 feet than it was in 2000.

While some researchers posited that if the polar ice sheets become less stable than currently expected, sea level rise will increase significantly instead of approximately 0.3 m – 0.6 m (1 - 2 feet) projected by the end of the century. These figures seemed to reflect the IPCC's lowest emissions values. The IPCC's 5th Assessment Report, which utilized a range of scenarios and multiple conditions, projected a global mean SLR between 0.5 m and 1.0 m by the year 2100 under the highest emissions scenario, and 0.3 m to 0.6 m under the lowest emissions scenario (Goodwin, et al., 2017; Church et al., 2013). Figure 2 illustrates a range of 0.3 m to 1.3 m, as projected by the IPCC 5th Assessment Report (AR5). However, the figures are questionable based on the exclusion of detailed estimates including marine ice sheet and marine ice cliff instability. Researchers also found that a global SLR exceeding 2 m by 2100 falls in the 90 percent uncertainty band for a high - emission scenario. This is more than twice the upper value recorded in the same IPCC AR5, which used Representative Concentration Pathways (RCP) (projections of future SLR under different emissions scenarios).

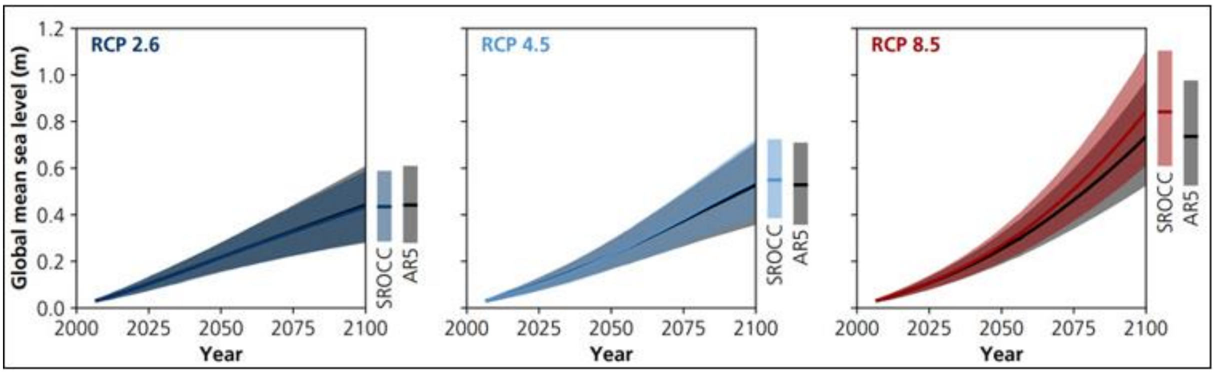

Figure 2: Projected change in global average sea level during the 21st century (metres)
Source: Carbon Brief Ltd, 2024

Figure 2 illustrates the global average sea level projected change (in metres) during the 21st century. Each panel shows projections from the current IPCC Special Report Ocean and Cryosphere in a Changing Climate (SROCC) – (coloured line and area) relative to the projections made in AR5 (black line and grey area). Three (3) scenarios were used:

- Low emissions RCP2.6 (Left);
- Medium emissions RCP4.5 (Centre); and
- Very high emissions RCP8.5 (Right).

Sea level trends have never been uniform or constant globally and this is due to several reasons, including atmosphere - ocean dynamics driven particularly by circulation of ocean current and wind systems, the locations of land ice melting and land water reservoir changes, and movement of the mantle in response to the loss of the great North American (Laurentide) and European ice sheets of the Last Glacial Maximum (LGM). Therefore, projecting ASLR is complex due to uncertainty in modeling of the various contributory processes, including thermal expansion of ocean water, land ice loss, and changes in land water storage (Mengel, et al., 2016; Passeri et al., 2015). In many cases, historical SLR data are used to project future trends and the level of accuracy could be affected by various intervening factors. However, Mengel, et al., 2016 and Parris (2012) emphasized that although historic sea level trends provide valuable information for determining future changes, they are inadequate for assessing risk under future uncertainties. The trend signal for sea level change, when compared to many climate variables, tends to be large relative to natural variability. However, at inter - annual timescales, changes in ocean dynamics, density, and wind can cause substantial sea level variability in some regions. For instance, there has been a multi - decadal suppression of sea level rise off the Pacific coast and large year - to - year variations in sea level along the Northeast U. S. coast due to these changes.

Accelerated sea level rise - induced hydro - geomorphism

Sea level rise induces nonlinear changes in hydrodynamics leading to changes in tidal ranges, tidal prisms, tidal asymmetries, erosion, sediment transport and ecological processes. These processes in turn increase flooding depths and inundation extents during storm events. More recent efforts have begun to consider the dynamic effects associated with ASLR (e. g., the nonlinear response of hydrodynamics under ASLR), but little research has considered the integrated feedback mechanisms and co - evolution of multiple interdependent systems (e. g., the nonlinear responses and interactions of hydrodynamics, morphology, and ecology under ASLR) (Oppenheimer & Alley, 2016). Mengel, et al., 2016; Jevrejeva & Moore, 2014; Passeri et al., 2015). Hydro - geomorphic processes influence inundation, circulation patterns, and sediment transport; all of which are in turn associated with hydrodynamics.

The concept of hydro - geomorphology has not been well - integrated into the hydrologic or geomorphic disciplines and is certainly a unfamiliar concept to the general public. Hydro - geomorphology is the study of the interaction and linkage of hydrologic processes with landforms or earth materials and the interaction of geomorphic processes with surface and subsurface water in temporal and spatial dimensions. Jackson, et al., (2018) and Passeri et al. (2015) posit that the effects of sea level rise are felt mainly on low - gradient coastlines as it relates to the nature of the environment. The interdependence and integrated feedback mechanisms associated with the hydrodynamic processes, morphology of the coast, and vegetation ecology provide much needed information for understanding the ways in which sea level rise alters the coastline and ultimately affects the natural and built environments. For example, climate models project that sea level rise will be higher than the global average along the eastern coast of the USA by 2100, thereby impacting negatively on the coastline and ecosystems particularly in Florida (American Geophysical Union, 2024; IPCC, 2019; Hall, et al., 2019).

Hydro - geomorphic processes influence the manner in which inundation occurs, ocean water circulates, and sediments are transported, thereby affecting coastal estuaries and tidal range (Goodwin, et al., 2017; Passeri et al., 2015). Increased tidal ranges causes tidal current velocities to accentuate and a significant increase result in shorelines erosion and consequently changes to habitats and their organisms (Stevens, 2010). Additionally, changes in tidal propagation, which is strongly influenced by coastal morphology, influence sediment balance in systems, and may modify the potential of the system to export sediment (Jackson, et al., 2018; Jevrejeva & Moore, 2014; Dias and Picado, 2011). In bay areas that are surrounded by Pleistocene uplands, steep slopes exist and assist in mitigating the impacts of SLR. Shallow bays surrounded by wetlands broaden under SLR due to their gently sloping shoreline.

Rising seas also have the potential to increase coastal flooding as a result of storm surges. In addition, storm surges of a given height are expected to occur more frequently, according to Fitzgerald et al. (2008). Although there is evidence that tropical cyclones will intensify in the future, ASLR is expected to become a dominant driver in increased tropical cyclone flooding (Woodruff et al., 2013; Houston, 2013). It is expected that resulting storm damage will be the most severe where morphology along populated shorelines heighten storm impacts, as opposed to where tropical cyclone activity is the highest (Woodruff et al., 2013). While preliminary conclusions from the most recent regional sea level projections by the IPCC can be drawn about the potential impacts of ASLR, such conclusions on future regional risks cannot be drawn.

Overall, it is imperative to understand changes that occur to residual circulation under ASLR since it allows for a deeper understanding of the risk to coastlands, coastal systems, and ecosystems (Jackson, et al., 2018; Valentim et al., 2013). Hydro - geomorphic processes have important implications for navigation, fisheries, flooding, water quality and the evolution of coastlines. Rising seas increase channel depths near coastlines or alter the volume of water stored in the intertidal zone and the resulting sediment transport patterns in coastal and marine areas become fundamentally altered. Inshore wave heights in shallow areas may increase with ASLR in some coastal areas thereby affecting nearshore sediment transport processes (Moritz, et al 2015; Sweet, et al., 2015; Chini et al., 2010).

Potential risks of ASLR - induced hydro - geomorphic processes to coastal lowlands and ecosystems

Discussion on the potential risks associated with ASLR - induced hydro - geomorphic processes requires consideration of physical causes, historical evidence, and projections. Many studies, including those conducted by Hall, et al. (2019), Mogensen & Rogers (2018), Merkens, et al. (2016), have provided succinct summaries of the risks of these processes to coasts, coastlines, estuaries, and ecosystems. They showed that almost all low - lying areas globally are likely to be in danger of hydro - geomorphic processes that could be accentuated by ASLR.

The International Geographic Union (IGU), United Nations Framework Convention on Climate Change (UNFCCC) and the IPCC for instance, explain this well in their observations of coasts and shoreline changes worldwide. They revealed that the majority of these areas have begun to experience an erosion crisis, and that for each type of risk associated with it, the dynamic response of coastal systems remains highly uncertain. The observations illustrate that a combination of a storm surge at high tide with additional dynamic effects from waves creates the most damaging coastal hydraulic conditions. It is estimated that almost 70 percent of the world’s beaches have been eroding and are likely to continue along this trajectory, whereas only about 10 percent were accreting (Jackson, et al., 2018; Horton, et al., 2015). Added to this scenario is that the studies reported continuous retreat of erodible cliffs and erosion of many coastal swamps and deltaic environments. The statistics are disquieting, taking into consideration the importance of coastlands and shorelines and in most regions, shoreline monitoring remains sparse, such that neither accurate real time consolidated data nor quantified information about regional and local shoreline change is available today. Nevertheless, it is still possible to map the potential vulnerable localities or hotspots affected by ASLR.

Miller et al. (2013) and Gibbons & Nicholls (2006) explain that some regions in the mid - latitudes are likely to experience a sea level elevation close to the global mean in the range of a few decimeters to approximately 1 m by 2100 depending on model dispersion and warming scenarios. In the tropics, the combined steric and static effects, which account for the enlargement of the oceans due to expansion of water molecules, will amplify global average sea level rise by about 20 percent to 30 percent (Moritz, et al., 2015; Sweet, et al., 2015). In this range of sea level elevation (projected to be from decimeters to meters), it is difficult to accurately assess the risks at the regional and global scales, as explained below. Global SLR scenarios are therefore less effective for determining coastline changes at a local scale.

Similarly, existing coastal databases underscore the heterogeneity of mid - latitude and tropical coastlines behaviours depending on the geomorphological settings. However, it is very important to take into consideration not only the geomorphological setting but rock structure and composition in various sections of the coastal areas as well, because these factors also help to determine the rate at which erosion occurs (Jackson, et al., 2018; Houston, 2013; Hunter, 2010). This explains why coastlines are eroding at a faster or a slower rate in some jurisdictions, leading to variation in the statistics provided in different databases. For example, European databases demonstrated that about 30 percent of European beaches are currently eroding, but 60 percent of wetlands are accreting. Some other researchers confirmed that for coastlines in many European countries almost half (40 percent) of the beaches are eroding. These figures are significantly less than the 70 percent found at global scale from the early 1990s to the 2000s (Grinsted, et al., 2015; Moritz, et al 2015; Sweet, et al., 2015).

The review revealed that analysis of the changes extended to include the spatial extent of risks to the shore zone. These are: (i) the area of complete submergence or inundation via rising mean sea - level or mean higher - high water (MHHW); (ii) area within the 100 - year floodplain; and (iii) the area of the Low Elevation Coastal Zone (LECZ). The risks posed to each of these geographical units range from low to high and have immediate to long - term implications. Submergence and inundation, increased flooding, and saline water intrusion into surface water, increased shoreline erosion and induced saltwater intrusion into groundwater resulting from coastline adjustments have a high probability with long - term impacts as well. Further, as a consequence of this dynamic regime of interrelated processes, mangrove wetlands will be at stake and will struggle to keep pace with ASLR, if sediment supplies are inadequate. This shows clearly that increasing higher - than - normal sea levels and wave action will ultimately result in extensive coastal erosion (Theuerkauf, et al., 2014; Hoeke, et al., 2013). To elaborate on this point, when wave impacts are correlated across the Pacific Ocean with phases of the El Nino Southern Oscillation (ENSO), coastal erosion accentuates. For instance, a study which was conducted from the east coast of Australia to the west coast of California to Chile over a 38 - year period using Landsat satellite images showed correlations in beach width and El Niño and La Niña cycles across more than 8000km of sandy coastline. Beaches experienced erosion during El Nino and recovering during La Niña. Other studies recorded a similar correlation (Tebaldi,. et al., 2012; Bakker, et al., 2017). In terms of future conditions, increases in mean and maximum seasonal wave heights are projected for sections of the northeast Pacific, northwest Atlantic, and the Gulf of Mexico.

Submergence, inundation and increased flooding are associated with increased wave heights and erosion of sediments in low - lying coastal areas. Generally, sediment processes in many tropical estuaries and some coasts are still poorly understood (Kitheka et al., 2005; Bryce et al., 2003). A good example of tropical mangrove environment where loss of coastal plain areas is due to flooding and erosion associated with climatic and eustatic sea level rise is the Konkouré Estuary, Republic of Guinea. In West Africa, the states of Guinea - Bissau, Guinea and Sierra Leone are characterized by large low - lying coastal plains that are particularly exposed to flooding due to the rise of global sea - level (Anthony, 2004). Capo, et al (2006) posited that coastal estuarine environments reveal dissimilar hydro - geomorphic systems compared to non - estuarine coastal ones, and as such, it is essential to have local projections of ASLR that caters for various mangrove wetland risk tolerances and cover a range of timescales relevant for land use planning and other purposes (Passeri et al., 2015; Kopp et al., 2014).

As it relates to saline water intrusion, researchers explained that the problem affects the coastal zone of Bangladesh, which comprises part of the Ganga delta. Salinity in the region was identified to be mainly caused by cyclone, storm surges, and high spring tide inundation. Recent studies ~~done~~ also showed that saline water intrusion is already an issue for food security, and they noted that saline water intrusion into surface water as a result of ASLR is highly possible over the long - term (Merkens, et al., 2016). About 2 percent seawater and 35, 000 parts per million (ppm) total dissolve solids (TDS) mixed with fresh water makes the mixture useless for daily needs (standard 500 ppm TDS) and 5 percent mixing makes it unsuitable for irrigation (Ashrafuzzaman et al.2022; Paul et al.2021; Hasan et al 2021; Rabbani et al.2019; Fatema et al.2018). Other researchers extended the list of factors that contribute to saline water intrusion to include freshwater extraction leading to capillary action (Mahmuduzzaman et al., 2014); Rahman & Bhattacharya, 2014; Baten et al., 2015). However, this factor is not germane to the review, hence it has not been elaborated in the narrative that follows.

In summation, as recognized by the IGU, UNFCCC, IPCC, and other researchers aforementioned, in the case of worldwide observations, while there are obviously regional differences in risks associated with ASLR - induced hydro - geomorphism, the representativeness of coastal sites in countries with low - lying coasts which are included in any global study is limited by the number of local observations. This highlights the need for more observations on contemporary shoreline changes; an action that could lead to the collection of new precise coastal data, updating current databases and sharing the information among the scientific community. A risk - based perspective on sea level rise points to the need for emphasis on how changing sea levels alter the coastal zone and interact with coastal inundation and flood risk at local scales. Coastal risk generated from impacts of ASLR must be considered at various spatial scales and multiple types of data as well (Jackson, et al., 2018). There is no one - size - fits - all method to measure coastal risk associated with ASLR - induced hydro - geomorphic processes, and the utility of the assessment methods varies with scale (Merkens, et al., 2016; Ramieri, et al., 2011).

Spatial tools and models for assessing ASLR - induced hydro - geomorphic systems

Although there is a relatively substantial body of literature on the use of various spatial applications for coastal and marine studies at a global scale generally, few have provided overviews on their utility particularly for studying ASLR - induced hydro - geomorphic processes and their implications at regional and local scales in low - lying unsheltered tropical coastal environments. Fewer studies have identified potential avenues for further research in this area (De Winter, et. Al., 2017; Jackson & Jevrejeva, 2016); Passeri et al., 2015; Ding et al., 2013). These coastal environments are challenged by erosion and sedimentation cycles which have a spatial dimension and as such, addressing them without the aid of spatial technologies and models has proven to be extremely challenging, as experienced in the past decades when many of the tools and technologies were limited (Kupilik et al., 2018; Ding et al., 2013; Rogers, et al., 2012; Tebaldi, et al., 2012). Three of the more frequently used ones are Digital Shoreline Analysis System (DSAS), Delft3D modelling and One, two, three and four - dimensional hydrodynamic modelling.

The rapid development and use of the technologies and models over the past years have led to a better understanding of some hydro - geomorphic systems that were once difficult to map, track and monitor (Kupilik et al., 2018; Passeri et al., 2015). In the past, their use has been constrained by limited data availability, high cost for the acquisition of software, limited training opportunities, and lack of interest and knowledge about the utility of the technologies and models. Today, their use is widespread and data access and data application scales are no longer limited. Many researchers have come to the realization that the usefulness of the technologies extends to include tools for database management, sharing, and making them among the most sought - after technologies (Toorman & Troch, 2018; Serafin & Ruggiero, 2014; Thieler, et al., 2009).

One aspect that is clear to scientists, Physicists, Oceanographers, Geomorphologists and other specialists is the application of various spatial technologies and models, and interpretation and communication of the outputs to enhance knowledge and understanding about the hydro - geomorphic processes and their effect on low - lying coasts (Schile et al., 2014; Lovelock et al., 2015; Passeri et al., 2015). These are two undisputed uses of technologies and models generally. In contrast, there has been much less research concerned with using DSAS and Delft3D modelling, for example, to effectively simulate, quantify and predict shoreline changes with the option to generate 10 - and/or 20 - year shoreline horizons and uncertainty bands (Mogensen & Rogers 2018; Nguyen, 2004). In fact, the Delft3D model has a very high predictive capability, having the capacity to simulate not only hydro - geomorphic systems but also transport processes including currents, waves, and sediments in coastal and estuarine environments.

Studies have also proposed the use of one - and two - dimensional models to simulate flood floods resulting from ASLR. One - dimensional (1D) hydrodynamic models can be used to model flood flows in estuaries and channels, but these can be computationally expensive and less flexible for including complex channel networks. Although useful, a major limitation is that they are depth - integrated and are unable to simulate vertical components of currents or density variations in the water column and oceans. Three - (3D) and Four - dimensional (4D) hydrodynamic models are able to simulate horizontal and vertical currents as well as transport of suspended matter (Nayak, 2018; Nguyen, 2003). Three and four - dimensional hydro - geomorphic models have been widely applied to simulate the dynamic responses to ASLR scenarios also (Ding et al., 2013; Bilskie et al., 2014; Passeri et al., 2015). However, there is neither a vetted framework for incorporating ASLR into hydro - geomorphic studies nor critical reviews comparing various methodologies and outcomes.

3. Conclusions

This review examined the dynamics associated with ASLR through various studies in the context of hydro - geomorphic processes and risks to coastland and coastlines in various parts of the world. Hydro - geomorphic response to ASLR is dynamic, with nonlinear changes in parameters such as tidal ranges, tidal prisms, thereby increased flooding depths and inundation. ASLR threatens coastlands and shorelines and ultimately human populations inhabiting low - lying coastal spaces by disrupting lives and livelihood activities and destroying coastal wetlands and ecosystems. Physical changes to coasts as a consequence of ASLR in different parts the world have been widely observed and the trends have been projected to continue in the future. Global models and projections for the next six decades (2080s), for instance, clearly show that a significant percentage of all coastlands will be severely affected.

The studies surveyed showed that although there is an improved understanding of the effects of ASLR on coastal environments, studies that integrate multiple spatial technologies and models allow for more comprehensive assessments of the erosion, sedimentation, for example, and the risks that are presented. Such studies can contribute to a general paradigm shift in how geomorphologists, conservationists, and engineers approach ASLR data acquisition. DSAS, Delft3D modelling, and 3D and 4D hydrodynamic modelling, although proven to have high predictive capacity in terms of simulating hydro - geomorphic processes, including sediments erosion and transport in coastal and estuarine environments, are seldom used to conduct such studies at the regional and local scales or levels. The data generated from their application could be valuable for the preparation of land use and zoning plans, streamline and coordinate land use activities, and optimize the utilization of land resources utilization.

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