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From Source to Sink: How Linking Upstream Fluvial Processes to Mangrove Sedimentation Can Improve Mangrove Management Strategies

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Abstract

Although recent attention has been given to accelerated sea level rise (SLR), anthropogenic activity disrupts incoming flow and sediment critical to maintaining the mangrove ecosystem. Deforestation and conversion to agriculture and urban landscapes can increase sedimentation rates of mangroves. Excess sedimentation of mangroves causes upland species invasions, aerial root burial, and tree die-off. Conversely, dams and diversion of flow decrease the influx of sediment into mangroves and limits the effectiveness of mangroves to respond to SLR. Predicted increases in precipitation, erosion, and flooding due to climate change further exacerbates these issues, yet current hydrologic models do not fully incorporate the interrelations and amplification of these processes from anthropogenic activity and climate change. Despite significant literature of fluvial, coastal, and marine processes and their effects on mangroves, there is limited understanding of the complex integrations and interactions between these processes and their effect on mangrove sedimentation. Although improving, hydrometeorological monitoring is often spatially and temporally limited, therefore extracting mangrove sediment records can provide information on sediment accretion rates in relation to SLR. Additionally, hydrologic models, created primarily by and for temperate environments, often do not effectively model tropical processes, seasonal effects of rainfall, or compound fluvial and coastal flooding from tropical cyclones. The lack of integrated hydrologic modelling and monitoring leaves local communities ill-prepared to make effective management decisions. Globally, to make significant advancement towards effective mangrove management, upstream river management is needed in addition to limitations on mass tourism, deforestation, and rapid development in areas hydrologically connected to the mangroves.

Kewords: Mangrove; Vulnerability; Erosion; Coastal Management; Sedimentation; SLR; Fluvial; Flooding

Abbreviations: SLR: Sea level rise

Introduction

Tropical and subtropical mangroves are among the most biologically productive ecosystems in the world [1,2]. They provide important ecosystem services, such as stabilizing and protecting shorelines from natural disasters, provide breeding grounds for numerous marine and riverine species, and sequester carbon [1]. Despite their ecological, biological, and economic value, mangroves are significantly degrading and declining at a faster rate than inland tropical forests and coral reefs, with only 6.9% protected under existing protected area networks [1,2]. Recent attention has been given to accelerated sea level rise (SLR) on the decline of mangrove forests [3-5]. However, disruption of upstream supply of fluvial flow and sediment have more extensive and immediate effects on mangrove survival rates [6-10].

The extent and health of mangroves rely on a balance of upstream fluvial processes and coastal processes to supply incoming sediment. Mangrove sediment accretion increases the surface elevation of mangroves which can help offset local SLR and protect coasts and adjacent land from erosion and storm surges [9]. However, rapid coastal and inland land use change alters upstream fluvial systems and shifts the balance of incoming sediment to mangroves. Thus, managing riverine sediment sources is critical for maintaining the long-term sustainability of mangrove ecosystems [11].

Although there is significant literature of fluvial, coastal, and marine processes and their effects on mangroves, there is limited understanding of the complex integrations and interactions between these processes and their effect on mangrove sedimentation. Furthermore, processes within mangrove estuaries that affect sediment accretion rates, such as sedimentation, suspension, accretion, erosion, and biologic activity, are not well modelled [9]. This creates significant challenges to modelling predicted changes and to effectively conserve and manage mangrove ecosystems. Therefore, there is an urgent need for improved modelling, monitoring, and management of fluvial processes linked to mangrove sediment accretion.

Sedimentation vs Sediment Accretion

While often used interchangeably, sedimentation is measured on a shorter timescale, often hours to days, and sediment accretion rates are measured over months to years [9]. Sediment accretion rates depend on sedimentation and resuspension and the shear strength of the deposited material that bind it more firmly in place [9]. There is also a lateral change in sedimentation rates, with the highest rates often occurring along the mouth of rivers. Sediment size also decreases with a decrease in flow velocity away from the riverbank into the mangroves [12,13].

Anthropogenic changes have shorter-term implications for the long-term sustainability of mangroves [11,14,15]. Deforestation and upstream conversion to agriculture, aquaculture, mass tourism, and urban development can significantly increase the rate of sedimentation of mangroves [1,16-18]. Excess sedimentation negatively effects ecosystem productivity by reduced the vigor of mangrove trees, burial of aerial roots, tree die-offs, and invasion of upland species [9,19-21]. The increased freshwater inputs decrease salinity which can alter species composition in mangrove ecosystems [22].

Alternatively, dams, reservoirs, sand mining, and agricultural diversions can significantly reduce sediment supply to the mangroves and can cause subsidence [11,23]. Harbors, ports, and coastal structures also disrupt sediment supply [23]. Groundwater extraction and saltwater intrusion exacerbate the issue since more sediment is needed to counteract subsistence and SLR [3,9,11,24]. Increased SLR and subsistence cause landward retreat of mangroves; however, anthropogenic changes further inland limits the area in which mangroves can retreat, further threatening their survival [4, 25-27].

Natural processes, such as seasonality and tropical cyclones, also influence sedimentation and accretion rates, with lower rates during the dry season and higher rates during the rainy season [9, 28]. Seasonal rainfall increases runoff, groundwater inflow, river flow, and sediment discharge. Predicted increases in precipitation rates from climate change increases these processes and could result in excess sediment accretion rates in the mangroves [29,30].

Tropical cyclones often occur during the rainy season and can deliver large amounts of sediment to mangroves [9,31]. These lower frequency, high intensity events could be critical in maintaining mangroves in regions with less sediment inputs and higher subsistence rates [9,32-34]. Heavy rainfall from intense storm events cause surface runoff, subsurface flow, and river flooding. Simultaneous tides and storm surges, along with underlying conditions, can cause compound flooding that amplifies sea levels and leads to prolonged and widespread flooding along the coast and further inland [29,30,35].

Although incoming sediment is increased by large storm events, excess sedimentation and prolonged inundation can cause compression and lead to the decline of mangroves, which lowers surface elevation [9,36,37]. Moreover, large storms can affect erosion thresholds by lowering the shear strength of mangrove soils and increasing shear stress from waves and currents [9,38]. Predicted increases of intensity of flooding and tropical cyclones due to climate change is expected, further supporting the need for long-term monitoring and management of hydrologically connected rivers associated with mangroves [38].

Mangrove sediment records can be used to reconstruct the paleoenvironmental records of sea level and climate change fluctuations as well as mangrove sediment accretion rates and survival overtime [9,25,28]. In several locations, mangrove sediment records indicate mangrove accretion rates have kept pace with SLR for thousands of years, but there is limited spatial and temporal frequency of this data [9]. Mangrove sediment records can also indicate large storm events by the thickness of sand layers [39]. Because mangroves are also major producers and sequesters of organic carbon, radiometric dating can also provide evidence of sea level when the peat was formed and SLR can be reconstructed using multiple dates [9,25, 40-45].

The Need for Improved Modelling

Tropical and sub-tropical regions, where mangroves exist, are at a significant risk from the combined anthropogenic and climate change effects. Yet, current modelling of mangrove sedimentation is insufficient to account for the hydro-geomorphic connection between mangrove sediment accretion and upstream hydrology. Additionally, mapping techniques, although rapidly improving, have limited precision to track sediment accretion, subsurface processes, stormwater infrastructure, or to quantify compound coastal and riverine flooding [4,30,46]. The complex interrelations between regional to local scales of fluvial, coastal, and sedimentation processes and the compounding and amplifications of these processes due to climate change and anthropogenic activity provides an added constraint to current modelling efforts [4,9,30-32].

Furthermore, most hydrologic models have been created in and primarily for temperate regions with extensive hydrometeorological monitoring networks. Particularly in developing regions in the tropics, hydrometeorological monitoring networks are often spatially and temporally limited to fully identify the upstream hydrology and sediment fluxes that affect mangrove estuaries [47,48]. Furthermore, upstream modifications, such as impervious surface, altered stormwater conveyance, and dams are not adequately represented [49]. Consideration should also be given to the accuracy of limited data or single-point observations, modelling, and numerical values that are extrapolated spatially and temporally to represent upstream

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fluvial, coastal, and sediment processes. There are also critical knowledge gaps between small-scale mechanisms of mangrove sediment flux and vulnerability in relation to large scale processes [4,11,50].

Conclusion

Although mangroves are threatened by SLR, the persistence of mangroves show they are reasonably capable of adapting and responding; however, anthropogenic changes along the coast and inland represent a greater threat to mangroves [9,25]. Global monitoring of riverine sources is needed in addition to limits to mass tourism, deforestation, and upstream land use change [22]. Land should also be provided for mangroves to retreat landward [9]. Rapid development and expansion of urbanization further exacerbates negative effects of sedimentation and loss of mangroves, thus, there is a need for improved monitoring as well as an integrated modelling approach for better management decisions. The lack of integrated flood modelling leaves local communities ill-prepared to make effective management decisions [30]. Increased collaboration is needed between researchers, local, regional, and international agencies, and local communities to ensure resiliency of coastal areas, including mangroves, and connected land and water upstream.

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