Review of sea level rise science, information and services in Pakistan

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Executive Summary

Sea level rise over the coming decades and centuries was identified in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) as one of the most important risks facing coastal nations and communities. The low-lying islands and densely populated coastal areas of South Asia are vulnerable to the impacts of sea level rise, such as coastal erosion and increased inundation from tropical cyclone storm surges. Those tasked with formulating and implementing coastal adaptation measures will require information about observed and projected sea level rise, over a range of temporal-spatial scales.

As part of the Climate Analysis for Risk Information and Services in South Asia (CARISSA) project, under the Asia Regional Resilience to a Changing Climate (ARRCC) programme[1], the Met Office is working in partnership with organisations in South Asia to enhance the use of regional climate information in vulnerability assessments and adaptation planning. In order to understand the sources of future climate information available for use in the South Asia region, the Met Office has been engaging with scientists and intermediaries in the region through a series of workshops and visits. To support this work, a review has been conducted to assess studies from the last 10 years linking climate change science to changing coastal risks in the region.

This report reviews the scientific literature published between 2010 and 2020 on sea level rise and the cascading impacts of sea level rise in Pakistan. This includes vulnerability and risk assessments of the natural and human coastal environments, along with adaptation or mitigation responses. The report is intended to provide a baseline understanding of what is known about sea level rise in Pakistan along with

[1] https://www.metoffice.gov.uk/services/government/international-development/arrcc

the types of sea level rise information being used for impact, vulnerability and adaptation assessments.

A systematic literature review process was adopted, consisting of pre-specified search protocol and eligibility criteria. Sources were categorised based on the spatial-temporal scale and geographic areas under consideration.

The results revealed a need for more sea level information and projections that are specific to Pakistan. Nearly all studies in this review used sea level rise estimates from a single tide gauge record at Karachi port. While this record dates back as far as 1916, there are large gaps and inconsistencies in the data and the tide gauge instrument itself was relocated in 2007. In 1988, the sea level trend at Karachi was calculated as 1.1 mm/yr and is widely considered by studies as the current trend across Pakistan. Recent records show that as global mean sea levels have increased, the trend at Karachi has also accelerated.

Many studies recommended regions where sea level protection measures could be prioritised. The Indus Delta Region (IDR) is such a locality, its mangrove ecosystems and vulnerability to erosion being topics of concern. The low-lying coast in this region makes it particularly susceptible to seawater intrusion and storm surges. Seawater intrusion has already been induced here by other anthropogenic factors, such as diversion of freshwater upstream for irrigation. Sea level rise is likely to exacerbate these hazards. Although a recognised threat, there is a lack of future sea level projection data used within research as an attempt to measure these impacts.

Although coastal vulnerabilities in Pakistan are outlined by many studies, it is not clear whether coastal projects are actively being carried out. Previous policy documents suggested constructing walls and barriers to protect against extreme sea level events. Certainly, there is scope for more sub-national and local sea level projections to feed into the decision making of coastal planners and communities in Pakistan.

1. Introduction

Sea level rise over the coming decades and centuries was identified in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) as one of the most important risks facing coastal nations and communities. The low-lying islands and densely populated coastal areas of South Asia are vulnerable to the impacts of sea level rise, such as coastal erosion and increased inundation from tropical cyclone storm surges. Those tasked with formulating and implementing coastal adaptation measures will require information about observed and projected sea level rise, over a range of temporal-spatial scales.

This review aims to provide a baseline indication of the available sea level rise information in Pakistan, and the use of sea level rise information for vulnerability, impact and adaptation studies. The review also aims to establish what is known about the impacts of sea level rise in different sections of the Pakistan coastline. It is intended to support the development of coastal climate services in Pakistan, by identifying barriers preventing the use of sea level rise information and highlighting where national or sub-national scale sea level projections could potentially enhance coastal management or adaptation assessments.

The review has the following three main objectives:

1) To establish what is known about the impacts of sea level rise on different sections of Pakistan's coastline;

2) To identify the types of sea level information used for assessments of vulnerability and projected exposure at the national, sub-national and local scale; and

3) To identify applications where additional sea level rise information or sea level rise services may have the potential to enhance vulnerability and adaptation assessments in Pakistan.

2. Methods

A systematic literature review was conducted to identify, assess and synthesise literature on sea level rise in Pakistan using a pre-defined search protocol and inclusion/exclusion criteria. The method has also been applied to Bangladesh (Harrison 2020[2]), as the other coastal country in the South Asia region covered by Asia Regional Resilience to a Changing Climate (ARRCC) programme. Since the aim was to generate results on a country by country basis, studies with a regional focus (i.e. covering multiple South Asian countries) were omitted (see Section 2.2).

2.1 Search Protocol

The review considered only peer reviewed research papers published between 2010 and 2020. Although the grey-literature could contain more information relating to the practice of coastal management and adaptation practice, these documents may not have been reviewed to the same standards as the scientific literature. The search was restricted to studies published during the previous decade (2010-2020) to narrow the scope of the review and cover the time between the first Pakistan Task Force on Climate Change report in 2010 and the IPCC Special Report on Oceans and Cryosphere in a Changing Climate (SROCC) in 2019 and other current research.

Relevant publications from the scientific literature were identified using key word searches on Clarvirate Web of Science[3]. The Web of Science database has previously been used to gather information for development of coastal decision support systems in Australia (NCCARF 2015; Leitch *et al.*, 2019) and reviews of climate change research in Bangladesh (Rahman *et al.*, 2018; Harrison 2020). The search protocol

[2] Harrison, B. (2020): Review of Sea Level Rise Science, Information and Services in Bangladesh, ARRCC

[3] Web of Science: https://apps.webofknowledge.com

was adapted from a State of Play report produced as part of the Australian CoastAdapt[4] project (NCCARF, 2015).

The search protocol for this review included the following key word search terms:

1. "climate change" AND "Pakistan" AND "coast"
2. "sea level" AND "Pakistan" AND "climate change"
3. "coast AND "sea level" AND adaptation AND "Pakistan"

The search returned 59 published articles.

2.2 Inclusion and Exclusion Criteria

Additional criteria were used to further subset the papers returned through the search.

1. Articles peer reviewed and written in English
2. Coastal climate variability or change the primary focus of the article
3. Multi-country studies are not included in the review

All 59 published articles were peer reviewed and written in English. Following a review of title, abstract and subject matter, a total of 16 articles were retained based on the inclusion-exclusion criteria. Most articles were excluded since they did not focus on coastal variability, instead covering topics such as fluvial systems in the Karakorum Himalaya mountainous region of Pakistan, or the inland biological and ethical impacts of climate change. The excluded multi-country studies were not relevant for Pakistan.

2.3 Research scale and geographic focus

Each reference was categorised by research scale (national, sub-national or local) and timescale (case study, geological, multi-timescale or future). The coastline of Pakistan is approximately 1000 km long, stretching from its western border with Iran at Gwadar

[4] CoastAdapt: https://coastadapt.com.au/

Bay to its eastern border with India at Sir Creek (see Figure 1). For the purposes of this review, the coastline was divided into two physiographic zones, corresponding to the two coastal provinces in Pakistan: Balochistan (720 km) and Sindh (270 km) covering the western and eastern sections respectively. The Balochistan-Sindh border follows the Hub River path towards the Arabian Sea. Localised studies were further categorised by those focussing on the Indus Delta Region (IDR), located in Sindh, and on the Hub River catchment area. The IDR covers approximately 2660 km^2 of the Sindh coastal area, comprising a network of tidal creeks and has great ecological importance. Karachi, as the country's largest city and port, was also a locality of interest in numerous studies. The city is situated on the western side of the IDR and has a population of nearly 15 million, based on the 2017 census (Pakistan Bureau of Statistics 2017). This census also outlined Karachi's population growth, being ~2.5%, which contributes to Pakistan's rapidly increasing coastal population density.

Figure 1 – Coastline of Pakistan, showing the Balochistan (west) and Sindh (east) coastlines, the provincial boundary defined by the path of the Hub River. The Indus Delta Region (IDR) is located east of Karachi city. Active tide gauges are located at Gwadar, Ormara and Karachi. The Makran subduction zone follows approximately the Balochistan yellow marker line in the Arabian Sea. Sentinel-2 Multi Spectral Image (MSI) sourced from Google Earth Engine.

The temporal scale of each study was described by three categories (Table 1). Historical studies which evaluated trends on timescales over a century were classified as 'geological'. Studies at a specific location typically involving research over a defined time period within the last century were labelled as 'case study'. Studies using future projections, predictions or scenarios were designated as 'future.' Studies covering work from multiple timescales (past, present and/or future) were assigned to a fourth category called 'multi-timescale'. For each of the studies, the stated timescales (geological, case study, future or multi-timescale) were recorded for further analysis (see Section 3.3, Table 3). The temporal scale classification was intended to help identify sources of information about past, present and future sea-level rise available in Pakistan, along with information about changing coastal hazards or risks.

Temporal scale	Definition
Geological	Historical studies on geological timescales (>100 yrs)
Case study	Studies on a specific location within the last century (<100 yrs)
Future	Future projections or scenarios
Multi-timescale	Multiple timescales (past, present and/or future)

Table 1 - Definitions for the temporal scale of studies

A grey-literature review could provide a better indication of the types of sea level rise used by policy makers and coastal management practitioners. However, the information used in grey-literature is typically taken from published scientific datasets in peer-reviewed literature. A lack of peer-reviewed studies based on global or regional climate projections for example, could suggest that information from sea level projections is not available for use by decision makers or that the sources of information being used are not based on peer-reviewed science.

2.4 Qualitative Analysis: Research scope and relevance

For each paper we sought to answer the following set of questions.

1. What problems or questions does the paper seek to address?
2. What were the main findings or outputs?
3. What limitations were identified by the authors?
4. What research requirements and information needs were identified?
5. What gaps in the literature have been identified?

3. Results and discussion

3.1 Research scale: National, sub-national and local trends

Of the 16 reviewed articles, there were four national level studies, three sub-national (provincial) studies and nine local studies (Table 2). Eight local studies focussed on the Sindh province; of these five specifically investigated the IDR. In contrast, the Balochistan province, was the subject of only three studies overall.

Research scale			
National Level Studies	Sub-national studies	Local studies	Total
4	3	9	16
Geographic focus			
Coastal Zone	Sub-national studies	Local studies	Total
Balochistan	2	1	3
Sindh	1	8	9
Indus Deltaic Region (IDR)	-	5	5
Hub River	-	2	2

Table 2 - Publication research scales and geographic focus areas. Note the province of the local studies have also been counted.

Projections of global mean sea level rise[5] were mainly used within the literature for contextual basis and to explain how current coastal hazards could be exacerbated in the future. Some studies used global mean sea level rise projections from IPCC assessment reports, as in Akhtar (2015) and Bakhsh *et al.* (2017). However, rather than the most recent fifth assessment report (AR5, IPCC 2013), studies often cited earlier reports such as the third (TAR, IPCC 2001a) or fourth (AR4, IPCC 2007) assessment reports.

The observed trend of mean sea level rise recorded at Karachi tide gauge station was the dataset used by most studies in this review. The value of this trend was calculated at 1.1 mm/yr from 1916 to 2000 (Quraishee 1988; NOAA[6]) which was in line with global mean sea level rise for that time period, taken as 1-2 mm/yr in TAR and AR4. The sea level trend determined at Karachi tide gauge in 1988 has been assumed as representative both for the current trend and for the entire coastline in Pakistan.

The IDR is suggested to have specific vulnerability to coastal hazards due to its morphology, coastal population and ecosystems. Nearly all IDR publications were case studies, mainly looking at past evolution of delta creeks, sea water inundation and Indus River sediment discharge (Lückge *et al.*, 2012; Ijaz *et al.*, 2018). The effects of subsidence and erosion in the IDR were also discussed. The Hub River catchment was the subject of two studies, on whether future sea level rise will cause flood inundation to Karachi (Bakhsh *et al.*, 2017) and on sedimentation in the Arabian Sea on geological timescales (Burdanowitz *et al.*, 2019). Both the IDR and the Hub River

[5] The definition for 'global mean sea level rise' used throughout this review is described in (Gregory *et al.*, (2019) in line with the latest definition used within IPCC reports. Most studies within this review used the outdated term 'eustatic' to describe the same phenomenon.
[6] National Oceanic and Atmospheric Administration (NOAA): https://tidesandcurrents.noaa.gov/sltrends/sltrends.html

catchment border the populated city and port of Karachi, which would explain the interest for coastal research in these locations.

Many studies stressed the importance of mangroves, fishing and marine ecosystems in Pakistan. Mangrove ecosystems, in particular the dense cover in the Sindh province, were the primary subject of two studies which aim to support decision making and conservation efforts (Abbas *et al.*, 2011; Rafique, 2018). One study sought to understand modern coral decline in the Arabian Sea (Ali *et al.*, 2017).

Pakistan exhibits tectonic instability, due to the convergence of the Arabian and Eurasian plates. Numerous onshore and offshore earthquakes have occurred and occasionally, small islands have appeared after earthquakes in the adjacent Arabian Sea, for example the Zalzala Koh mud volcano off the coast of Gwadar. The Balochistan coast is in the Makran subduction zone (see Figure 1), where the Holocene (past ~10 kyr) average uplift rate was calculated at 1-2 mm/yr (Page *et al.*, 1979). As demonstrated by the earthquake events, tectonic uplift is discontinuous, resulting from irregular peaks in seismic activity; the uplift rate was calculated as an average of uplift events tracked in the geology. The uplift rate consequently varies both spatially and temporally along the coastline, depending on the location and timing of exact events. Mokhtari *et al.* (2019) noted that in the last century, the seismicity rate was higher in the east of the Makran subduction zone compared to the west. Therefore, assumptions of constant rates of change, present also for sea level rise, may not apply for the entire coastline.

In this review, there were considerably less studies focussed on the coastal province of Balochistan compared to Sindh. Since the tectonic uplift is in the range of the sea level trend taken at Karachi tide gauge (1-2 mm/yr), the two processes are assumed to balance each other out and Balochistan is not perceived to have vulnerability to coastal hazards. In contrast, the Sindh coastline is not associated with the Makran subduction zone and is tectonically passive, meaning sea level rise is not balanced by tectonic uplift. This increased exposure to the effects of sea level rise would indicate why nearly all local studies were focussed on the Sindh province.

Kanwal *et al.* (2020) noted that there has not been an assessment of the degradation of Pakistan's entire coastline, and that studies on accretion and erosion have been more localised. Kanwal *et al.* (2020) attempted to address this limited assessment by analysing the rate of erosion for the whole Sindh province coastline using Landsat satellite images over three decades. The study proposed that their method should be used as a template for more scaled-down and detailed further assessments. Another study (Zia *et al.*, 2017) also used Landsat images to identify the erosional effects in the Sindh region, to evaluate changes in land use and cover. The images were used in combination with both sea surface temperature (SST) and salinity from field surveys along from the mouth of Daboo creek towards inland as an indirect indicator of sea level rise which would have intruded from the open sea. No studies mentioned the use of satellite altimetry to measure sea level height.

All multi-timescale articles were at the national scale (three in total) and were more policy oriented than other articles. Often studies presented recommendations for decision makers, suggesting sectors or regions which should be prioritised. For example, Ijaz *et al.* (2018) found the eastern side of the Indus delta to be richer in ecological features, suggesting it should have priority for restoration and conservation. Many studies focussed on the effects of coastal hazards, particularly on seawater intrusion (e.g. Bakhsh *et al.*, 2017 and Zia *et al.,* 2017) and commented on the effects on coastal communities, such as contamination of coastal freshwater resources.

Most studies stressed the negative impacts of extreme sea level events in Pakistan such as tropical cyclones and storm surges and how the effects of these will increase under climate change. Although the frequency of storms in Sindh may be low, the amplitude of surge events which do occur may be several metres high. Since rising sea level creates a higher base for storm surges to form, the effects may become exacerbated under climate change. In the past, tsunamis and storm surges have caused infrastructure damage, disruption of transportation and wetland loss, even forcing whole communities in Pakistan to relocate. The safety of the coastal population to these hazards is also at risk. Hence these extreme sea level events are a topic of concern in many studies.

Tsunamis as a secondary effect of earthquakes on the seafloor have also caused previous devastation to coastal communities and could similarly increase in intensity under sea level rise. Due to the tectonic activity of the Makran subduction zone, a tsunami of great magnitude could feasibly occur in the future. Following the Indian Ocean tsunami in 2004, sea level and seismic monitoring across the Arabian Sea has improved. One study in this review analysed storm surges (Khan *et al.*, 2020), however no studies investigated the impacts of future tropical cyclones or tsunamis on Pakistan's coastline. Bakhsh *et al.* (2017) simulated flood inundation depths in the Hub River watershed under rising sea levels and suggested further modelling studies should include future precipitation patterns from global warming or the effects of tsunamis.

3.2 Geographic focus

3.2.1 Sindh

The Sindh province spans the eastern section of the Pakistan coastline, from the mouth of the Hub River by Karachi up to Sir Creek near the India-Pakistan border. The Sindh coastline itself can be split into the Karachi coast and the IDR and has both a relatively denser population and different morphology compared to Balochistan. As mentioned, a sea level rise of 1.1 mm/yr was observed at Karachi tide gauge station from 1916 to 2011 (Quraishee 1988; NOAA) and was considered the current rate of mean sea level change for Pakistan by most studies. Seawater intrusion to the Sindh coastal region is expected to cause a loss of 1,700km^2 of land (Rabbani *et al.*, 2008).

Kanwal *et al.* (2020) was the only study in this search to focus on the whole Sindh coastline: all other Sindh studies focussed on localised regions within the province. Kanwal *et al.* (2020) evaluated the coastal degradation using Landsat satellite images from 1989 to 2018 at decadal intervals. These satellite images were deconstructed using ocean tide height data from a fixed tide gauge at Pakistan's second busiest port, Port Muhammad Bin Qasim, provided by the National Institute of Oceanography (NIO). The coastline was found to be highly erosional, especially in the IDR. In Karachi, the coastline oscillated between erosion and accretion, the mean shoreline linear regression rates being -2.43 m/yr and 8.34 m/yr in the east and south respectively, with an uncertainty of +/-0.45 and an overall progradational mean rate of 2.24 m/yr. The accretion in the south of Karachi was caused by developments in coastal infrastructure.

The IDR was found to be dominantly erosional, with mean erosion rates up to -14.17 +/-0.55 m/yr and -19.96 +/-0.65 m/yr on the western and eastern sides respectively. The highest average erosion rate reached -27.46 m/yr in the east of the IDR, and the trend increased from west to east in the IDR. Spatially, the trend of erosion was found to be positively correlated with increasing mean sea level rise and negatively correlated with the topography which decreases towards the east. This showed that without preventative measures, the effects of sea level rise along the Sindh coastline could be significant for coastline retreat. The eastern side of Karachi would be particularly at risk, including Korangi Creek and the outlying barrier islands. This side is closest to the IDR (see Figure 1). The study suggested that protection measures should be prioritised in the high erosion areas to prevent seawater intrusion in the IDR and called for further, more detailed studies using the same methodological template.

Nazeer *et al.* (2020) also assessed accretion and erosion in a localised study around Karachi from 1942 to 2018 and divided the city into eastern and western zones. The study found that 95% of the total transects for the eastern zone of Karachi underwent accretion, at a mean rate of 14 m/yr, where the uncertainty was 0.43 m/yr, similar to Kanwal *et al.* (2020). This again indicated rapid shoreline progression due to urban development in the coastal regions. In comparison, 74% of transects for the western zone showed marine erosion of the rocky and sandy beaches, at a mean rate of -1.15 m/yr. These rates for erosion and accretion in Karachi differed slightly to the results of Kanwal *et al.* (2020), possibly since Nazeer *et al.* (2020) was a more localized study over a longer timescale. The methodology between the studies also contrasted: Nazeer *et al.* (2020) assessed the historical shoreline position from 1942 to 1966 using topographical maps, as opposed to using satellite imagery for all years. Both studies acknowledged the effects of sea level rise however did not use projections to indicate future rates of erosion and accretion.

3.2.2 Indus Deltaic Region (IDR)

The IDR is a wave dominated, fan-shaped delta comprising a complex network of creeks, located in the Thatta and Badin districts of the Sindh province. The delta coastline stretches 220 km long where it meets and discharges into the Arabian sea. The IDR supports 97% of Pakistan's total mangrove cover, as well as being a habitat for migrating birds, marine turtle nesting sites and the freshwater Indus river dolphin (MFF Pakistan 2016). It has great potential to sequester carbon, storing a total of 1,160 - 2,110 MtCO_2 in soils and plants (Crooks *et al.*, 2011). The IDR has been identified as being as relatively very high risk for relative sea level rise (UNEP 2016) and has legal protection, although there are currently no designated Marine Protected Areas in Pakistan.

The Indus River historically carried large fluvial fluxes from the Himalayan mountain range through to the IDR, amounting to more than 270 Mt/yr of sediment. In recent times, the river has carried significantly less sediment (~13 Mt/yr) due to urbanization and construction projects. Infrastructure upstream includes artificial flood levees, irrigation and inter-basin diversion, which has caused a reduction in distributary channels – from 17 in total to just one single channel (Syvitski *et al.*, 2013). The mouth of the Khobar Creek is now the dominant freshwater flow into the Arabian Sea.

The restriction of freshwater flow in the Indus River has meant that in some dry seasons, the river itself may run dry. This allows seawater to travel upstream, to almost 80 km in some cases (Kidwai *et al.*, 2016). As a secondary impact, this seawater intrusion has caused freshwater and brackish lakes in Thatta and Badin to become hypersaline.

The alteration of the IDR's natural morphology has caused it to be exposed to coastal erosion and reduced sediment supply has caused subsidence. This subsidence is a common feature of low-lying deltas and can contribute to relative sea level rise (Oppenheimer *et al.*, 2019). Since the Indus River is the main supply of freshwater and nutrients to the Arabian Sea, changes in load significantly impact productivity. Lückge *et al.* (2012) found the redistribution of Indus River flow has considerably affected sediment discharge, productivity and redox conditions over the last century, despite the monsoon strength being favourable enough for enhanced production and preservation. This was determined using a well-preserved sediment core from the Indus Canyon near the river mouth and using organic and inorganic proxies for productivity such as Total Organic Carbon (TOC) burial. Therefore, it was shown anthropogenic-influenced sediment and hence nutrient changes to the river discharge have been negatively impacting productivity, independent of the monsoon effects. This showed anthropogenic impacts on the hydrological cycle are significant and require further careful monitoring. Figure 2 shows the critical reliance on the Indus River for irrigation and how the monsoon can be a significant influence for water supply.

Figure 2 – The Indus River around the Guggu Barrage dam, in April (left) and September (right) for 2010. In general, water is sparse and depended on for irrigation. In 2010, anomalous heavy monsoon rains caused historic floods. Satellite images obtained from Landsat 5 Thematic Mapper (TM). [7]

Mangroves, which are coastal wetlands comprising of salt-tolerant trees and shrubs, occur in naturally sheltered coastal areas at the land-ocean transition zone. They have an important role in protecting the coastline from extreme weather events such as tropical cyclones and from erosion (Oppenheimer *et al.*, 2019), as well as storing carbon (Ruiz-Fernández *et al.*, 2018). They are also highly productive and are a habitat to a great variety of flora and fauna, including fish, molluscs and shrimp. Consequently, mangroves are beneficial to the economy for supporting marine fisheries.

The total area of mangroves in Pakistan has been decreasing continuously over the past 50 years, at one of the highest rates in the world. Rafique (2018) estimated that the mangrove forest area decreased by 72% in Pakistan from 1980-2015. This depletion has been caused by numerous anthropogenic factors, such as global warming, reduction of freshwater flow towards the sea, pollution, urbanization and overgrazing. Some wetlands have also turned into mudflats or have been filled and turned into development land. The number of mangrove species in the IDR have

[7] Landsat image viewer: https://landsat.visibleearth.nasa.gov/view.php?id=52076

halved due to the increasing salinity levels. The species that remain are those able to tolerate higher salinity levels, such as *Avicennia marina* in the Isaro, Wadi, Khuddi, Patiani and Dabbo creeks (MFF Pakistan 2016). If sea level rise is at the lower end of projections, then the wetlands could have time to migrate inland, but only if the path is clear of anthropogenic infrastructure.

In this review, two studies directly focussed on mangrove ecosystems in Pakistan, whilst other studies stressed the importance of these areas. Rafique (2018) reviewed the vulnerability of these ecosystems to coastal hazards, stressing the need for 'conservation, management and rehabilitation.' The second study (Abbas *et al.*, 2011) provided a full assessment of the mangrove cover in Pakistan, to help inform decision making in sustainable coastal development. It is clear mangroves are widely recognised for their ecological significance and need to be prioritised in coastal conservation efforts and developments. Neither study considered directly the effects of sea level rise on the mangrove ecosystems, more than acknowledging the current impacts will worsen under sea level rise.

Salik *et al.* (2015) discussed the vulnerability of mangrove-dependent communities in the sub-district Keti Bandar of the IDR to coastal hazards. This particular area has experienced the impacts of droughts, floods, storms, tsunamis and sea intrusions, and local communities have in the past been forced to migrate after their settlements were destroyed. The study used the TAR (IPCC 2001b) definition of vulnerability (being a function of exposure, sensitivity and adaptive capacity) to create a 'composite vulnerability index' for coastal communities. This index was driven by community perceptions and both observed and projected climate change scenarios. The main coastal impacts identified in this study included a decrease in freshwater flows and in access to clean drinking water, and the extinction of mangrove species due to the increased saline conditions. The study recommended that both safe drinking water and environmental flows should be ensured in adaptation options for national climate change action. Despite the recognised importance of hydrology within this region, sea level rise projection data was not directly used within the vulnerability assessment. Instead, the study used the IPCC A2 ‘business as usual’ global mean SST change to account for the effects of sea level rise, a scenario taken from the Special Report on Emissions Scenarios (SRES, IPCC 2000).

Kidwai *et al.* (2016) found the productivity of fisheries in the IDR to be decreasing due to factors such as the use of illegal practices and destructive fishing equipment, over-exploitation and violations of fishing closures. The productivity is also associated with the strength of the mangrove ecosystem, since the creeks are vital breeding grounds for shallow- and deep-water inhabitants. Shrimp in particular have been commercially important in Pakistan. Kidwai *et al.* (2016) used observations from the Fishery Resource Appraisal Project of Pakistan, a fishery stock assessment from 2009 to 2015, and the Creek Survey Program (2013-2014) to show the fish and shrimp population declined in response to a weakening mangrove ecosystem, both in diversity and volume. For example, shrimp catches declined from 29,000 t/yr (mid-1980s) to 18,500 t/yr (since 2008). The number of species declined from 150 (late 1980s) to 70 species (2013-2014). The study showed a need to restore the freshwater input into coastal mangrove communities, in order to support the brackish and estuarine conditions needed to sustain fishing systems.

Zia *et al.* (2017) studied the effects of sea water inundation on Daboo Creek, which is 55km southeast of Karachi and spans nearly 4km wide at its mouth. It was noted how few studies have evaluated the impacts of sea water intrusion on the IDR creeks. The study used Conductivity-Temperature-Depth (CTD) profiles from 1986 and 2010 from the creek mouth towards inland to show the average salinity increased in coastal sea water by 33.3% and average SST decreased by 13.79%. The change in SST and salinity was used to infer seawater had intruded into the creek. The creek area had increased by 9.93% and the shrimp farming area had decreased by 40%. By analysing land use changes by Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced TM+ imaging to show eroded areas along creek banks and to detect temporal change, the study found the creek had changed its path over time. Seawater was found to be intruding at a rate of 260 m^2 per year from 1987 to 2010. The coverage also revealed the change of mangrove cover from dense to sparse, with the area of dense coverage decreasing by 6.7% from 55 to 47 km^2. The extent of mud flats increased from 2001 to 2014, by 29.7%. Wet mudflats increased whilst dry mudflats and sand dunes decreased, which demonstrated the impacts of seawater intrusion. This study showed seawater intrusion has already had a great impact on the fishing economy of the IDR.

Ijaz *et al.* (2018) examined the evolution of the tidal creeks network in the IDR and investigated how the contrasting morphology on either side of the delta is affected. The topography of the IDR is generally low-lying and flat. The western side of the delta has irrigated and dry lands between the river bank and the Khirther mountains of the Sulaiman range. The eastern side also has irrigated plains ranging from the left bank to the Thar desert. The study used satellite, hydrologic and topographic data, such as Landsat MSI to deduce the impacts on the Indus Delta creeks from 1972 to 2017. They also analysed relative mean sea level data from 1916 to 2014 from the Sea Level Center of the University of Hawaii to demonstrate the increasing trend, with a spike since the 1980s. The study found that the western side of the delta is more resistant to coastal impacts. The banks of the eastern creeks were found to be sharper due to wave-dominated processes. Along with subsidence and lower elevation topography (5m above sea level), an embayment effect is produced. Hence, widening and elongation of the creeks was degrading the alluvium of the IDR more rapidly on the eastern side. Additionally, more than 20% of the western side is occupied by mangroves, which offer protection to the tidal basins from coastal erosion. This finding, of the eastern side being more susceptible to erosion, is consistent with that of Kanwal *et al.* (2020). The authors suggested a priority of conservation and restoration activities on the eastern side due to its vulnerability to coastal hazards and its ecological importance. They suggested this could be achieved by planting mangroves along the channel banks and mudflats and constructing levees to prevent the creeks expanding landwards. This is further support for the conservation of mangroves. In addition to its benefits for marine life, mangroves are protection against erosive effects of the sea level rise.

A further potential vulnerability of the IDR is its location on the expected path of cyclones in the Arabian Sea. Associated storm surges with high tides can cause large scale destruction to the environment and the local communities. It has been indicated in the broader literature the occurrence of tropical cyclones in the Arabian Sea is likely to increase (Murakami, Vecchi and Underwood, 2017). Only one study in this review looked at storm surges and extreme high tides linked to sea level rise (Khan *et al.*, 2020).

3.2.3 Hub River Catchment

The Hub River has a catchment area of about 1825 km^2 which encompasses the western region of Karachi. Since the river itself follows the Balochistan-Sindh border, this explains why two studies on the Hub River were grouped by different provinces. Minor streams flow southward and westward from the Hub River system before discharging into the Arabian Sea. New settlements are being constructed along this region due to a housing shortage in Karachi city from its growing population. Flooding in the Hub catchment during the monsoon season could also affect Karachi city.

Bakhsh *et al.* (2017) used TAR (IPCC 2001a) global mean sea level projections to simulate flood inundation depths in the Hub River watershed for periods up to 2100. This is the only study in the review to have incorporated estimates of future sea level rise within the research itself. Global mean sea level rise of 14 cm, 32cm, 57cm, and 88cm for 2025, 2050, 2075 and 2100 were simulated to produce flood inundation maps. A 600 cm mean sea level rise was also simulated as a downstream boundary condition. They found the flood inundation depths within the Hub River catchment are not expected to increase with projection mean sea level rise in the next hundred years. The maximum simulated depth was 696 cm for 2025-2100, the same as a rainstorm in August 1977. Consequently, it was concluded that the region of Karachi would not be severely impacted by flooding from the Hub catchment. In the study, the effects of tsunamis, future precipitation patterns induced by global warming and storm surges were not taken into account and the authors did not discuss impacts other than flooding. Since sea level rise is likely to exacerbate coastal hazards, the omittance of these effects in the study could give a false impression of risk for the Hub River catchment.

A second study, focussing on the Balochistan province, discussed the historical path of the Hub River. Burdanowitz *et al.* (2019) analysed a Holocene sediment core offshore Pakistan to investigate the influence of the Indian Monsoon and westerlies on sedimentation in the north-eastern Arabian Sea. The core revealed historical sedimentation discharge of the Hub River and the impacts of post glacial sea level rise on sedimentation patterns. Three stages of sedimentation were deduced. The early Holocene was characterised by a transition from terrestrial to marine dominated sedimentation from post glacial sea level rise and a strengthened Indian Summer Monsoon. The mid-Holocene saw a change from wet to arid conditions and more influence from westerlies. The late Holocene, from 4.2 ka to recent times, was marked by a weakening of the Indian Summer Monsoon and enhanced aridification of the catchment of the Hub River. The Indian monsoon, westerlies and the astronomical-tidal cycle were found to be important for sedimentation in the north-eastern Arabian Sea. However, the authors did not hypothesise how this sedimentation and related impacts in the Hub River could change in the future with rising sea level or future changes in the monsoon, despite acknowledging dramatic links between past sea level and sedimentation.

3.2.4 Balochistan

The Balochistan province coastline, which is influenced by the Makran subduction zone in the Arabian Sea, extends from the Gwadar Bay in the west to the mouth of the Hub River in the east. The area is arid, with cliffs, rocky headlands and sandy beaches. The small Hingol, Basol, Shadi Khor and Dasht rivers activate and drain the region during the rainy season. Erosion processes may be more severe along the Balochistan where the cliffs are composed of soft rocks.

Seismic activity around the Balochistan region often causes the appearance of offshore islets in the Arabian Sea, as a result of pressurized gas hydrates which escape during earthquakes. Due to subduction of the Indian plate, the Balochistan coast experiences a spatially variable, long-term average uplift of around 1-2 mm/yr, measured at Ormara (Page *et al.*, 1979) over the Holocene (past ~10 kyr). This value, in the same range as the observed sea level rise at Karachi, Sindh, is assumed to counteract that of sea level rise. Hence, the coast in Balochistan is thought to be less vulnerable to coastal hazards in comparison to Sindh (where tectonic uplift is relatively stable). A recent study suggested the uplift of southeast Iran to be 2.18 ± 1.37 mm/yr since the late Holocene (He *et al.*, 2020). It would be useful to reassess the relative sea level rise regarding current, regional rates of uplift and in response to the more recent, higher global mean sea level trend.

In comparison to Sindh, the Balochistan coast supports just 3% of the total mangrove cover in Pakistan, which is found at Miani Hor, Kalmat Hor and Jiwani. (MFF Pakistan 2016). Since the Balochistan coast exhibits tectonic uplift and has a sparser mangrove cover, the area is deemed less vulnerable to sea level rise. There were subsequently less publications in this search with Balochistan as the primary focus area. Two studies focussed on the whole region and a third discussed the Balochistan section of the Hub River. Interestingly, all Balochistan studies were historical studies on geological timescales. This could be because Balochistan is perceived as a region of tectonic risk rather than vulnerable to climate change. No study assessed the current or future risks of sea-level rise in Balochistan.

Ali *et al.* (2017) conducted analysis on uplifted Quaternary fossilised corals from sites at Gwadar and Jiwani to determine the paleoclimatic and geological changes at the Balochistan coast. Gwadar and Jiwani are located around 543 km and 720 km west of Karachi respectively. The study determined the relative distribution and diversity of scleractinian corals and the reasons for their decline in comparison with modern corals from the author's previous 2014 study. The coral diversity had reduced from 62 species in the past, to 29 species of modern corals. It was suggested that marine habitats may have been destroyed by tectonic events, particularly the collision of the Arabian and Eurasian plate during the middle to late Miocene. This was exacerbated more recently by additional Pleistocene events and anthropogenic impacts. The authors noted that many species occur at greater depths so a wider area could be investigated and recommend for further, more detailed studies, on a larger scale with more submerged habitats. Ali *et al.* (2017) also noted the anthropogenic impacts on coral decline, such as the effects of exploitation, pollution, overfishing and anchor damage from boats. Tectonic activity could clearly cause further damage to corals already under stress from anthropogenic activities.

3.3 Temporal Scale: Sea-level projection use and uptake

The number of publications by temporal scale for each coastal zone are shown in Table 3. Over half of the total publications were case studies, looking at coastal impacts at specific locations over timescales within the last century. Three out of four geological studies focussed on Balochistan, which is expected due to active tectonics in the region. All three of the multi-timescale studies were national-based studies in a review style, covering the whole of Pakistan's coastline. There were only two future studies – one using sea level projections and the other using an index to predict coastal vulnerability.

	Geological	Case study	Future	Multi-timescale
All	4	7	2	3
Pakistan (National)	0	1	0	3
Balochistan	3	0	0	0
Sindh	1	6	2	0
IDR	1	3	1	0
Hub River	1	0	1	0

Table 3 - Number of publications by temporal scale for: All publications; national; sub-national; and local studies.

3.3.1 Process based sea level projections from Global Climate Models (GCMs)

Only one study retained in this search used sea level projection data within the research itself Bakhsh *et al.* (2017). In this study, global mean sea level projections from TAR (IPCC 2001a) were used as the best available estimate for future sea level rise in Pakistan. The projected global mean sea level rise was 14 cm, 32 cm, 57 cm and 88 cm for 2025, 2050, 2075 and 2100 respectively.

As mentioned, many studies cited IPCC sea level projections, yet cited earlier reports such as TAR (IPCC 2001a) or AR4 (IPCC 2007), rather than the most recent AR5 (IPCC 2013). From these references, global rather than regional projections were used, and mainly to inform as context rather than to frame research into coastal impacts. This could be due to lack of regional data and the understanding that relative sea level rise in Pakistan is in line with global mean sea level rise. Akhtar (2015) even referred to IPCC's first assessment report (FAR, IPCC 1990), citing a global mean sea level rise of 1-2 mm/yr and outlined arguments against AR4 reports, suggesting figures were disputed between scientists. This particular paper exhibited a clear doubt over whether IPCC reports can be trusted and a dismissal for current coastal impacts caused by sea level rise. It would be valuable to assess the opinions of various stakeholders in Pakistan to understand how IPCC reports and climate change are perceived.

3.3.2 Empirical sea level projections

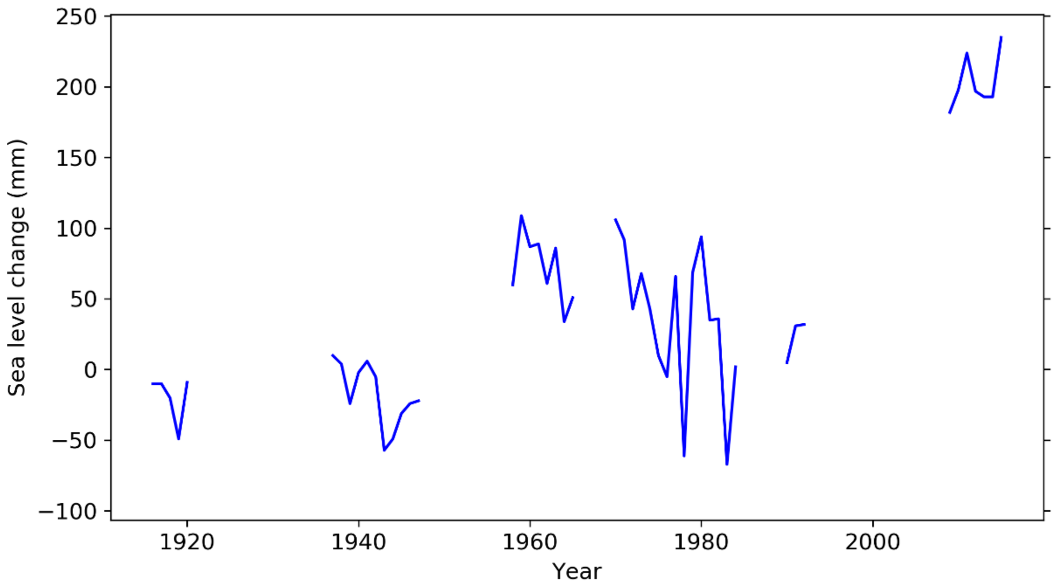

Figure 3 – Tide gauge record for sea level change (mm) taken at Karachi tide gauge station from 1916 to 2016. The record has large gaps in the record and was relocated in 2007. Data obtained from PSMSL.

Tide gauges in Pakistan are located at Karachi (data available from 1916) as well as Ormara, Gwadar and the creek areas (which were all established after the 2004 Indian Ocean tsunami). The majority of studies used the relative sea level from the Karachi tide gauge station, where a sea level rise of 1.1 mm/yr was observed from 1916 to

2000 (Quraishee 1988; Rabbani *et al.*, 2008). Data for this tide gauge was obtained either from the Permanent Service for Mean Sea Level (PSMSL) or the University of Hawaii Sea Level Center/ NOAA. This trend was inferred as the current relative sea level rise along Pakistan's entire coastline in numerous studies, e.g. Rafique (2018). The Karachi tide gauge however exhibits large discontinuities and was also relocated in 2007. There are large gaps in data from 1921 to 1936, 1948 to 1957 and 1994 to 2007 as well as numerous, sporadic gaps throughout. More recently, an estimation of mean sea level rise using the same tide gauge from 1916 to 2016 was calculated at 2.0 mm/yr (NOAA), which shows that sea level rise has accelerated in later years. The time series for sea level change recorded at the Karachi tide gauge from 1916 to 2016 can be seen in Figure 3. This observed trend of increase is in line with global mean sea level trend mentioned in SROCC (Oppenheimer *et al.*, 2019) which was 1.44 mm/yr from 1901-1990 and has increased to 3.6 mm/yr from 1993-2015 (Table 4).

Time period	Rate of global mean sea level rise (mm/yr)
1901 - 1990	1.4
1970 - 2015	2.1
1993 - 2015	3.2
2006 - 2015	3.6

Table 4 – Rates of global mean sea level rise at different time periods, from SROCC (2019).

Khan *et al.* (2020) used statistical analysis to calculate the return periods of extreme sea level events, using Karachi tide gauge data. From 2007-2016, the extreme sea level maxima showed an increasing trend, with observed increment rates of 3.6 mm/yr for mean sea level and 2.1 mm/yr for extreme sea level. The return levels for the 50, 100 and 1000 year periods were found to be 3.73 m, 3.76 m and 3.93 m respectively, using the joint probability method. The analysis showed that Karachi coast is tidal dominated and corresponds with rates of global mean sea level rise from SROCC. IPCC reports also mention that in some cases globally, extreme sea level events which may have a return period of 100 years, may occur annually by 2100 under all emission scenarios, such as the Bay of Bengal (Oppenheimer *et al.*, 2019). This was not outlined in Khan *et al.* (2020) but should be considered in future assessments. The IPCC return periods only considered tide gauges with a long duration timeseries, of which the Karachi tide gauge was omitted. Future analyses of return periods around Pakistan should consider data from multiple tide gauge sources.

Since studies cited the outdated sea level rise (1-2 mm/yr), there should be an updated evaluation of how the increased trend is impacting the coastline. In addition, by assuming the sea level rise at Karachi is consistent across the whole of Pakistan's coastline, studies neglect localised effects such as subsidence or erosion. Localised subsidence would lead to higher rates of relative sea level rise. Khan *et al.* (2020) suggested tide gauges should be installed along Pakistan's entire coastline in Balochistan and Sindh to better understand and analyse the effects of extreme sea levels.

Instead of tide gauge data, one study used Conductivity-Temperature-Depth (CTD) instruments to measure mean SST and salinity and infer sea level rise. This was combined with Landsat 5 TM and Landsat 7 ETM+ images to identify the spatio-temporal changes in land use and land cover due to erosion. The data was taken from the NIO in Pakistan and used to show the extent of seawater intrusion (Zia *et al.*, 2017b). Kanwal *et al.* (2020) also used Landsat TM and Operational Land Imager (OLI) images to analyse the coastal erosion along the Sindh coastline. Similarly, Nazeer *et al.* (2020) used data from Landsat at medium spatial resolution and data from Planet Scope at a finer spatial resolution. The Landsat datasets included Multispectral Scanner (MSS), TM, ETM+ and OLI images. The satellite datasets were combined with historical topographical maps at a 1:250,000 scale to assess accretion and erosion rates around Karachi. Although a clear hazard of concern for coastal communities, these studies did not investigate the impacts of future sea level rise on coastal erosion or use satellites to look at sea surface height.

Figure 4 shows satellite altimeter records for sea level change taken at points near the Gwadar and Karachi tide gauge stations. It is clear the records are not entirely the same: the sea level trend for Gwadar is consistently higher than Karachi. This demonstrates the spatially and temporally variable nature of sea level rise along Pakistan's coastline.

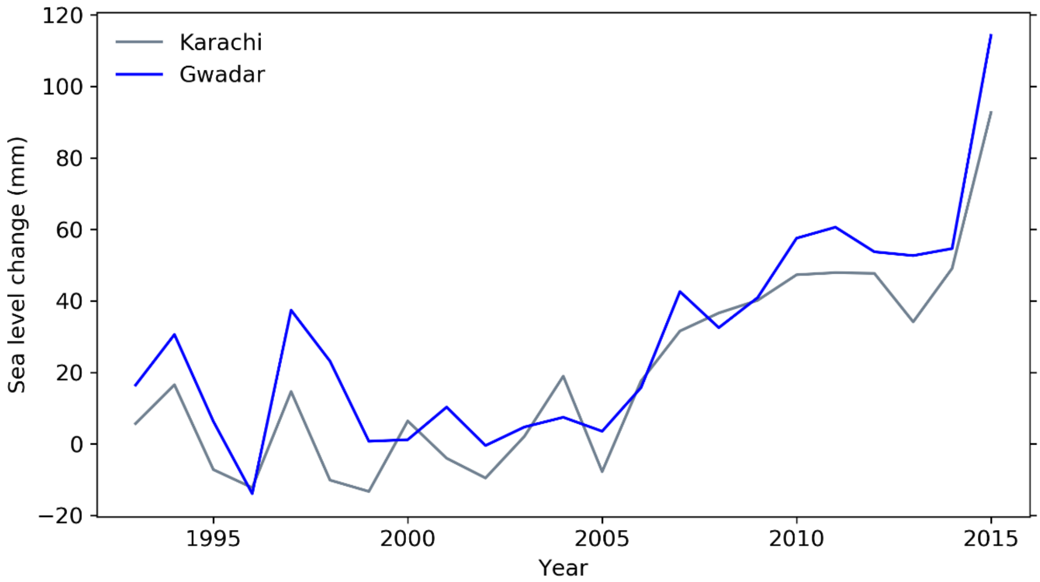

Figure 4 – Satellite altimeter records for sea level change (mm) taken at points near Karachi (grey) and Gwadar (blue) from 1993 to 2015. Data obtained from European Space Agency (ESA)[8].

3.3.3 Historical (geological) trends

Four studies retained in the search focussed on historical trends on geological timescales, longer than the past century. Three of these are both based in the province

[8] European Space Agency (ESA) satellite altimetry: http://www.esa-sealevel-cci.org/

of Balochistan (Ali *et al.*, 2017; Burdanowitz *et al.*, 2019; He *et al.*, 2020) and one focussed offshore in the IDR (Lückge *et al.*, 2012). The studies typically provided analysis of sediment cores. Sediment cores provide information on past changes in sea level with relation to oxidation states, productivity and sedimentation. In addition, knowing the regional effects of rising sea level in the past may be useful to gauge what the environmental and morphological changes may be in the future.

He *et al.* (2020) analysed clay minerals and grain size in a gravity core from the Makran continental margin to assess the effects of relative sea level on sedimentation over the past 13 kyr. The study found that Indus-derived sediments have a negligible influence on sedimentation at the Makran continental margin, instead the relative sea level in the Holocene controlled the deposition. The study noted that sediment records in this region are more useful for studying past earthquakes or tsunamis. The historical, geological studies in this search provided important linkages between geological processes and sea level (as demonstrated in both Burdanowitz *et al.*, 2019 and He *et al.*, 2020), however did not infer the relationships with future sea level rise.

4. Coastal risk assessments and risk reduction

The coastal hazards and impacts discussed by the publications in this review identified the six main concerns for low-lying coasts in SROCC: (i) permanent submergence of land by mean sea levels or mean high tides; (ii) more frequent or intense flooding; (iii) enhanced erosion; (iv) loss and change of ecosystems; (v) salinization of soils, ground and surface water; and (iv) impeded drainage. These were referred to as “the main cascading effects of sea level rise” in the SROCC. It was widely acknowledged in studies that anthropogenic and tectonic factors contribute to subsidence and sea water intrusion in Pakistan, and that storm surges and flooding are likely to increase and be exaggerated by sea level rise under climate change.

Pakistan has long been recognised as a country with considerable vulnerability to climate change. In 1984, the United Nations Environment Programme (UNEP) released a report on the environmental problems of the marine and coastal area of Pakistan as part of their Regional Seas Program. Recently, Pakistan was ranked 5th on a list of countries most affected by climate change from 1999 to 2018 (Eckstein *et al.*, 2019), despite having a relatively small per capita share of global greenhouse gas emissions, ranking 135th in the world (Abas *et al.,* 2017).

The extended coastline of Pakistan places the country at risk to rising sea level and consequently to more intense storm surges and sea water inundation. Karachi, as the country's largest port and city, is at particular risk from these hazards. Pakistan has been affected in the past by tsunamis and damaging cyclones. Since Sindh has a low-lying coastline, the effects of these have potential to travel far inland. The largely agrarian based economy of Pakistan also makes it susceptible to extreme weather events such as droughts or flooding (Khan 2015).

Sea level rise may also cause numerous socioeconomic impacts, on food security, energy security, infrastructure and health. For example, there may be impacts on water availability for hydropower generation or cooling, or on infrastructure such as thatched or mud houses. The Karachi Nuclear Power Plant is located along the coast, as well as naval installations (PNS Himalaya) and the Port Qasim Authority, all of which could suffer huge economic damages if their processes were disrupted. Wastewater treatment plants located by the coast are at risk from corrosion from seawater intrusion and from flooding. Sewer pipes could be eroded or damaged by a rising water table.

Seawater intrusion has also impacted freshwater fisheries. Traditional approaches to tackling declines in fish catches are no longer suitable against the impacts of climate change. In coastal regions, the groundwater has become brackish and the groundwater table has fallen considerably in areas that are prone to drought, for example in Khuzdar. Since there is already a scarcity of water in the Indus River (see Figure 2), as extreme events increase in the future, this water will need to be conserved as much as possible.

The Framework for Implementation of Climate Change Policy (GOP[9], 2013) outlined the status of climate change in Pakistan and a schedule for adaptive and mitigating actions from 2014-2030. The plan included conducting an environmental, socioeconomic profile of the coastline as a priority and to identify and design structural barriers to withstand cyclones, tsunamis, moisture corrosion and other extreme weather events. Conserving the marine ecosystem and fisheries, developing salinity tolerant crops and maintaining optimal river flow were also proposed. The NIO, the Sindh and Balochistan Coastal Development Authorities, Geological Survey, the Provincial Forest, Wildlife and Fisheries Departments, Civil Society Organizations, Environmental Protection Agencies (EPAs), World Wide Fund for Nature (WWF) and International Union for the Conservation of Nature (IUCN) were identified as implementing organisations. The Global Change Impact Studies Centre (GCISC) and Pakistan Meteorological Department (PMD) are institutions undertaking climate change research in Pakistan, however future sea level risk does not seem to be included in their active projects. A National Action Plan based on the UN Sustainable Development goals was released in 2017 by the Ministry of Climate Change, including a Marine Ecosystem Action Plan which suggested embankments, barriers and vegetative cover to protect against rising sea level.

Studies primarily addressing the vulnerability of Pakistan to climate change were mainly national studies in a review format. Localised studies also focussed on vulnerability, particularly in the IDR, with respect to saltwater intrusion and ecosystems such as mangroves or fishing. Many studies provided recommendations for policy or decision makers, or coastal planners. For example, Kanwal *et al.* (2020)

[9] Government of Pakistan (GOP) - http://www.pakistan.gov.pk/

recommended that adaptation measures to mitigate the coastal impacts should be prioritised by vulnerability to coastal erosion.

While it is recognised in most that sea level rise will cause certain impacts, studies often do not attribute sea level rise as the driving factor to observed hazards. Akhtar (2015) attributed reduction of flow in the Indus River as the primary cause for sea water intrusion into the IDR, as opposed to sea level rise. This effect has been observed in other rivers too, such the Hub River following construction of the Hub dam in 1985. The study concluded that Pakistan is not as exposed to sea level impacts in comparison to other low-lying countries such as Bangladesh or the Maldives. Since this study had already dismissed IPCC research as being controversial, it is indicative that their approach is biased against global warming impacts. Even though Pakistan's exposure to sea level rise may be relatively lower than other countries, this doesn't quantify the impacts or eliminate risk.

Khan (2015) also attributed insufficient flow in the Indus River as the current cause of seawater intrusion. Subsidence due to a lack of sediment flux, excessive groundwater extraction infrastructure and active faults exacerbate seawater intrusion. Insufficient flow in the Indus River is also caused by the diversion of water upstream into the canal system. Anthropogenic factors are causing coastal hazards, however sea level rise as a result of global warming are clearly not currently considered a primary driver.

Nevertheless, current sea water intrusion will likely be aggravated by future sea level rise (Khan 2015). Kidwai *et al.* (2016) suggested that impacts on the IDR could be addressed by managing the upstream demands for water and recognising that downstream systems are equally dependent, such as mangroves. The authors suggested that national policy changes will need to be implemented, involving a commitment of the local community, who would see substantial changes to their livelihoods and lifestyles. The authors proposed that parts of the IDR should be declared as a Marine Protected Areas to help restore the damaged mangrove ecosystems and build resilience.

The morphology of the IDR creeks were evaluated in more detail by Ijaz *et al.* (2018). On the eastern side of the IDR, extensive mining for petrological exploration had caused subsidence, whereas on the western side, mangroves had provided a protective barrier against tidal erosion. The study recommended that conservation and restoration should be concentrated on the more vulnerable eastern side of the IDR (also discussed by Kanwal *et al.,* 2020). Mangroves were recommended as reinforcement on channel banks and over mud flats, as well as the construction of levees to prevent the creeks evolving landward.

Salik *et al.* (2015) conducted a vulnerability assessment of the Keti Bandar sub-region of the Indus delta. This was based on the IPCC (2001b) definition of vulnerability, to create a composite vulnerability index of the communities to a changing climate in Keti Bandar. In the past, the community has had to migrate frequently due to natural hazards. The study concluded that the community had a high adaptive capacity, being successful in finding appropriate shelter and alternative jobs. The study recommended that national adaptation plans for climate change should include the provision of safe drinking water and sanitation, environmental flows to the Indus delta, as well as education and innovative strategies for resilience.

Nazeer *et al.* (2020) found 94% of the shoreline around the eastern zone of Karachi to be vulnerable to sea level rise, equating to 23.5 km. In comparison, the western zone of Karachi was relatively stable due to there being less infrastructure and land reclamation. Disregarding the future impacts of sea level rise, anthropogenic influence is already changing the morphology of the coastline in the Sindh province. The study called for more coastal protection and management to defend against marine erosion, and measures to combat illegal sea encroachments.

Some major residential, business and recreational construction projects are being undertaken along the coastline around Karachi, for example along the Clifton Beach Akhtar (2015). The Centre for Coastal and Deltaic Studies noted a “lack of proper understanding” of coastal issues and the “administrative setup” have resulted in no well-established plan for coastal development in Pakistan (Mahar 2018).

5. Conclusions

Over the period of 2010 to 2020, the scientific literature on sea level rise in Pakistan and the impacts of sea level rise on the Pakistan coast has been relatively sparse compared to other Asian regions, such as Bangladesh (Harrison 2020). Since the number of publications returned in the search was small, an indication for how the literature has changed in terms of volume and disciplinary diversity is hard to discern.

The publications demonstrate the perception of coastal impacts in Pakistan, by the temporal-spatial scale of the research. Most studies were localised case studies, focussing on vulnerabilities for coastal communities over recent decades. The Sindh province (particularly the IDR) is of interest due to its morphology, ecosystems and local population. In contrast, the Balochistan region is deemed to be less at risk, exhibiting tectonic uplift which balances sea level rise. Most studies mentioned sea level rise for context and acknowledgement of future impacts, however only one study uses projections to frame the research itself. No studies attributed specific impacts to sea level rise, yet it is understood its effects will increase current hazards in the future. SROCC mentions that “attribution of current coastal impacts on people to sea level rise remains difficult in most locations” (Oppenheimer *et al.*, 2019), suggesting that this is a generalised issue between countries. Such impacts are “exacerbated by human-induced non-climatic drivers, such as land subsidence, pollution, habitat degradation, reef and sand mining”. Most of these drivers are relevant to Pakistan and were mentioned in the studies.

Studies did present recommendations for policy makers to protect the coastline from further coastal impacts, such as erosion and ecosystem damage and how construction should be managed. There is certainly an awareness that sea level rise will have severe impacts in the future, despite these not being seen currently. It is apparent that conservation and adaptation decisions for coastlines in Pakistan are taking place and therefore it would be useful to identify the sources of sea level rise information that are available.

This report aimed to answer to three specific questions (see Section 1). Here, we take each of these questions in turn and discuss our conclusions based on the review.

- *What is known about the impacts of sea level rise in different sections of the Pakistan coastal zone?*

This review assigned the current literature to the two coastal provinces of Pakistan, which are Sindh and Balochistan. Some studies could be further classified into the localised IDR and Hub River catchment. Most studies were conducted in the IDR and featured examples of current coastal hazards presented in SROCC. Although anthropogenic factors are the likely the driver of these hazards, no studies attributed relative sea level rise or global warming as the primary cause. From these hazards, seawater intrusion and its secondary effects on freshwater and agriculture were discussed the most and mangrove ecosystem destruction was also a topic of interest. No studies attempted to quantify the contribution of sea level rise in exacerbating these hazards, despite being widely recognised. Non-climatic drivers such as subsidence driven by infrastructure and mining activities were also recognised but not investigated.

There was notably less concern for Balochistan regarding the effects of future sea level rise. Studies in this region discussed sea level change on geological timescales. This reflects how this provincial coastline’s vulnerability is deemed to be associated tectonic timescales associated with the Makran subduction zone. Most publications used Karachi tide gauge data for sea level rise, taking the value calculated in 1988 as an indication for the current trend, and this is in the same range as estimates of tectonic uplift. The publications within this review did not give an indication of how sea level rise rates differ between Balochistan and Sindh and spatially along the coastline. The lack of information on sea level trends for the coastline means that it is difficult to understand the contribution of local processes such as tectonic movement and subsidence to relative sea level rise. The absence of the local contextual information could present a challenge to communicating information about sea level rise in these locations over the near and mid-term.

- *What types of sea level information are used for assessments of vulnerability and projected exposure at the national, sub-national and local scale?*

Section 4 discussed the vulnerability and adaptation assessments featured in this review. As mentioned, sea level rise is not currently considered a primary driver or indeed directly causing the observed coastal hazards in Pakistan. Most sea level projections were mentioned by studies to provide a contextual basis or acknowledge how hazards may be exacerbated in the future. Projections were mainly referenced from various IPCC reports, yet only one study used values from the recent SROCC (Oppenheimer *et al.*, 2019). Instead, studies referenced older reports, such as TAR (IPCC 2001a) or AR4 (IPCC 2007). Moreover, these projections were global as opposed to regional – the latter case would be more relevant for different sections of Pakistan's coastline. Most studies relied on the observed 1.1 mm/yr as an indication of current sea level rise, measured from 1916 to 2011 from Karachi tide gauge station, which has large discontinuities in its data. This observation has recently been updated to 2.0 mm/yr from 1916 to 2016 after relocation of the station in 2007, and it also may not be representative of the whole Pakistan coastline where there are localised tectonic or subsidence (Akhtar 2015). Consequently, there is a need for more regional and reliable data sources for future sea level to enable a more realistic understanding of sea level change along the coastal provinces.

- *For what applications could additional sea level rise information or sea level rise services have the potential to enhance vulnerability and adaptation assessments in Pakistan?*

Numerous studies recommended how policy or decision makers, or coastal planners should prioritise conservation and adaptation measures in Pakistan. However, the majority did not provide these recommendations based on sea level projections. Sea level projections taken from IPCC reports were all global mean sea level projections, and this may not be representative of sea level change across the whole of the Pakistan coastline. The assessments also did not incorporate the contribution to relative sea level rise from local non-climate processes such as subsidence.

Studies noted the impacts of human infrastructure both upstream and downstream of the IDR. Upstream, the construction of dams and diversion projects have caused both reduced flow and sediment supply downstream. This has led to increased seawater intrusion and impacts on ecosystems. Downstream, construction of large buildings and extraction of natural gas has caused subsidence. The effects of this could be exacerbated by sea level rise. Therefore, there is scope for sub-national to local sea level rise information to feed into coastal management and construction projects.

Mangrove ecosystems and fisheries were identified as having great importance in publications, especially in the Sindh province. Mangroves provide resistance against coastal erosion and were recommended to be planted on channel banks (Ijaz *et al.*, 2018). They are valuable habitats for marine life, and it has been found that fish and shrimp production is linked to mangrove health (Kidwai *et al.*, 2016), so their sustainability is important for the fishing industry. Therefore, publications stressed the need for conservation and restoration of these ecosystems. Kidwai *et al.* (2016) recommended that a process for rebuilding and sustaining the ecosystems must "work with the community nexus and recognize their traditional bond and social-economic ties". Deeper stakeholder engagement in decision-making must also be established.

Local scale information on sea level rise would therefore be beneficial for conservation efforts in the IDR. This could inform coastal planners as to where urgent action is required.

Although studies provided recommendations for how coastal risks should be managed in Pakistan, there is little mention of projects that are already being carried out. Perhaps the observational tide gauge data gives the perception that sea level rise is not a current threat, or perhaps more specific, localised research needs to be conducted. There is a definite need for the installation of further tide gauges in both Sindh and Balochistan along the Pakistan coastline in order to fully assess the regional sea level change. Moreover, satellite altimetry was not mentioned by any of the studies and could provide additional information on sea surface height.

It has been mentioned that increasing sea level exacerbates coastal hazards and extreme weather events such as storm surges. Therefore, more research into and quantification of these hazards is required to fully understand how communities could be affected, to establish risk and to create adaptation plans. This information would be useful for coastal planners and local councils.

A review of the grey literature and consultation with policymakers and coastal management professionals in Pakistan may provide more detail on current adaptation measures. It is clear sub-national and localised sea level information is required to gain a reliable understanding of current and future sea level changes along Pakistan's coastline.

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