BEFORE THE HON'BLE NATIONAL GREEN TRIBUNAL

SOUTHERN ZONE BENCH AT CHENNAI

ORIGINAL APPLICATION NO. 74 OF 2020

IN THE MATTER OF:

D.PAL & ORS. ...APPLICANTS

VERSUS

STATE OF ANDHRA PRADESH & ORS. ...RESPONDENTS

	Odisha-S. Das (B) Institute of Economic Growth, Delhi, India A. K. Enamul Haque et al. (eds.), *Climate Change and Community Resilience*, https://doi.org/10.1007/978-981-16-0680-9_17	
6.	**ANNEXURE-A 13:** Copy of the study by Jeffrey Chow (2017): Mangrove management for climate change adaptation and sustainable development in coastal zones, Journal of Sustainable Forestry, DOI: 10.1080/10549811.2017.1339615	53-72
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THROUGH

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OBJECTIONS ON BEHALF OF APPLICANTS TO THE REPORTS OF THE JOINT COMMITTEE UPLOADED ON 19.03.2021 AND 17.08.2021

MOST RESPECTFULLY SHOWETH:-

1. That the Applicants have filed the present Original Application under Section 14 and 15 of the National Green Tribunal Act, 2010 raising substantial questions relating to environment regarding the blatant violation of the provisions of the CRZ Notification, 2019 as well as CRZ Notification, 2011 by the State of Andhra Pradesh in Kakinada, East Godavari District, Andhra Pradesh whereby large scale clearing of mangrove forests and reclamation of a creek is being carried out for the purpose of a housing project for low income group population as well as container depot for the railway. The Application also seeks compensation under Entry (m) of the Schedule II of the National Green Tribunal Act, 2010 for the loss of livelihood of the fisherfolk community of Kakinada due to the ongoing illegal activities by the State of Andhra Pradesh.

OBJECTIONS TO THE REPORTS OF THE JOINT COMMITTEE UPLOADED ON 19.03.2021 AND 17.08.2021

Mangrove area shown as cleared/disturbed by the Joint Committee has been wrongly calculated

2. The Report of Joint Committee uploaded in March, 2021 at page 7 mentions that " Out of 116 Acres, the work has been taken in 58

Acres. As per the committee's analysis, mangrove cover up to an extent of 30% of the filled up area has been affected."

3. Further, the Report of the Joint Committee uploaded in August, 2021, only 18 acres of the Mangroves is shown to be disturbed and the compensation is assessed on that basis to be Rs. 48.33 lakhs. According to the Applicants this assessment is incorrect as the Mangrove area cleared is much more as per the evidence annexed by the Applicants and corroborated by the Google Earth image dated 14.02.2020 at page 37 annexed by the Joint Committee with it's Report of March, 2021.

4. Infact in the Report of March, 2021 the Joint Committee itself admits that Green Cover has been cleared but neither mentions the said green cover to mangroves nor gives the exact calculation of this area. In the Report the Joint Committee states at page 4 as follows:-

> "For comparing the present condition, the committee used the Google earth image dated 14/02/2020 with 28/10/2019 since data in FSI satellite image was updated during 2017-2019 only **and it is found that some destruction were occurred in the green cover.** The comparative map highlighted with yellow square is at Annexure-VI. The historical map **from 27/05/2005 to till date is also reveals that there were some green patches was there as evident from Annexure-VII.**

5. That the Applicants with their Original Application have filed latest satellite image as Annexure-A 8 and have calculated and shown the area cleared of Mangroves as 8.58 Ha and 19.0 Ha i.e a total of 27.58 Ha as in May, 2020. Upon conversion of 27.58 Ha to acres the figure which comes out to be is 68.15 acres of Mangrove area cleared by the authorities. Copy of Map annexed as Annexure-A8 with the Original Application is being re-annexed as **ANNEXURE-A9**

6. Therefore, the area calculated by the Joint Committee in which the Mangroves have been cleared is incorrect and the Joint Committee needs to relook in the matter on this particular issue.

7. **Calculation of past violation has not been done as far as assessment of Environmental Compensation is concerned alongwith the CPCB formula by the Joint Committee:** In *Meenava Thanthai vs. The Director, Ministry of Environment, Forest & Climate Change & Ors., Original Application No. 234 of 2017 (SZ)* which is a case related to CRZ violation, this Hon'ble Tribunal vide it's Order dated 12.09.2020 had directed the Tribunal appointed Committee to look into past violations as well as to apply the formula evolved by the Central Pollution Control Board to assess the compensation. The Tribunal in it's Order states that:-

> 11. **The committee is also directed to revisit the question of compensation for past violation as directed by this Tribunal in several cases of this nature applying the formula evolved by the Central Pollution Control Board in this regard** and also taking into the consideration the nature of damage caused to the coastal zone on account of such activities and the amount required for restoration of the same to its original position.
>
> (Emphasis supplied)

8. The Committee later gave an assessment of the environmental compensation for violation of the provisions of Environment (Protection) Act, 1986 considering the CPCB in house calculation methodology. The Calculation of environmental compensation based on the CPCB guidelines is as follows:-

Environmental Compensation Formula EC = PI x N x R x S x LF

Where EC = Environmental compensation
PI = Pollution Index of Industry Sector
N = Number of days of violation took place R = A factor of Rs for EC
S = Factor for scale of operation
LF = Location factor

Copy of the Order dated 12.09.2020 in ***Meenava Thanthai vs. The Director, Ministry of Environment, Forest & Climate Change & Ors., Original Application No. 234 of 2017 (SZ)*** is annexed as **ANNEXURE-A10**

9. It is stated that calculation of past violation is also an important point as far as assessment of Environmental Compensation is concerned alongwith the CPCB formula. The Joint Committee has failed to apply this criteria which has been propounded by the Hon'ble NGT in several cases.

10. **Compensation calculated by Joint Committee is only as per Carbon sequestration method:** That a perusal of Report of the Joint Committee uploaded in August, 2021 shows that compensation is calculated only as per carbon sequestration method taking into account the loss of biomass and carbon credits. It is stated that the Mangroves provide a number of ecological services.

11. It is stated that based on various studies on Indian mangroves by Badola & Hussain (2003), Das (2009) and Hussain & Badola (2010) on Bhitarkanika mangroves, Ghosh *et al.* (2016) on Indian Sundarbans, and Santhakumar *et al.* (2005) generally on mangroves of the south Asia, the ecosystem services of mangroves in India can generally be summarised as follows:-

Ecosystem Services of Mangroves

Ecosystem Service	**Classification of Services**
Fishery production	Provisioning service
Prawn larva	Provisioning service
Honey	Provisioning service
Crab and crustacean species	Provisioning service
Fuel	Provisioning service
Fodder	Provisioning service
Medicinal plants	Provisioning service
Genetic resources	Provisioning Service
Carbon sequestration	Regulating Service

Storm surge protection	Regulating Service	
Tourism	Cultural services	
Aesthetics	Cultural services	
Religion	Cultural services	
Breeding of species	Supporting Services	(Habitat)
Spawning	Supporting Services	(Habitat)
Nursery habitat	Supporting Services	(Habitat)
Biodiversity	Supporting Services	(Habitat)

Copy of relevant pages of a study Ecosystem Services of Mangroves and their valuation by Nilanjan Ghosh, Ph. D Observer Research Foundation is annexed herewith as **ANNEXURE-A11**

12. Infact according to another study "Valuing the Role of Mangroves in Storm Damage Reduction in Coastal Areas of Odisha" by Saudamini Das, mangrove forest valuation - storm damage reduction $ 4000 plus/ha. According to this study, storm protection service of mangroves is very high for cyclone prone regions. During 1999 super cyclone in Odisha, every hectare of mangroves provided storm protection in the range of USD 4335 to USD 43,352 to the Kendrapada district, which is 25–249 times the 1999 per capita income of the district (USD 174). The annualized storm protection value of a mangrove hectare is more than two times the land price of cleared forests and more than twenty times the annual return from alternative land uses clearly justifying mangrove conservation to receive storm protection. Like Odisha the present area too is cyclone prone and the mangroves have an important role tom play in storm protection which cost too has not been evaluated.

Copy of a study- Valuing the Role of Mangroves in Storm Damage Reduction in Coastal Areas of Odisha-S. Das (B) Institute of Economic Growth, Delhi, India A. K. Enamul Haque et al. (eds.), *Climate Change and Community Resilience*, https://doi.org/10.1007/978-981-16-0680-9_17 is annexed herewith as **ANNEXURE-A 12**

13. **Mangroves management have an important role as an adaptation strategy under climate change:** In a study by Jeffrey Chow (2017): Mangrove management for climate change adaptation and sustainable development in coastal zones, Journal of Sustainable Forestry, it has been stated that mangroves management has an important role as an adaptation strategy under climate change. Mangroves align with several of the UN Sustainable Development Goals— specifically Goals 13, 14, and 15—which concern adaptation to climate change and the sustainable management of forest and coastal resources. The study states :-

> "Due to their prevalence in developing countries and the range of ecosystem services they provide, projects aimed at promoting mangroves align with several of the UN Sustainable Development Goals— specifically Goals 13, 14, and 15—which concern adaptation to climate change and the sustainable management of forest and coastal resources. Although mangroves themselves are sensitive to climate change, they also provide services that would help reduce damages, by sequestering carbon, enhancing coastline stability, and protecting coastal settlements from tropical storm surges. In particular, mangroves can rapidly colonize and stabilize intertidal sediments, promoting coastal accretion to reduce the impact of sea level rise. The Government of Bangladesh has established mangrove plantations with the intent to accelerate accretion and stabilize 120,000ha of coastland. As a case study, this paper uses GIS data on coastal dynamics and land cover to evaluate the effectiveness of mangrove plantations for facilitating accretion and preventing erosion in Bangladesh. The results indicate that plantation areas experience greater rates of accretion relative to erosion than non-plantation areas, confirming that mangroves have an important role to play in the sustainable development of coastal regions."

Copy of the study by Jeffrey Chow:Mangrove management for climate change adaptation and sustainable development in coastal zones, Journal of Sustainable Forestry is annexed as **ANNEXURE-A 13**

14. **Mangroves need to be protected to deal with cyclones:** In an article "Protecting mangroves, to deal with cyclones", published in indiawaterportal.org it has been high lighted that Mangroves are best at fighting tropical cyclones globally. Approximately 90 percent of total benefits of mangroves are for protection from tropical cyclones, while 10 percent are from protection from regular (non-cyclonic) conditions https://www.indiawaterportal.org/articles/protecting-mangroves-deal-cyclones. The article further states:-

> "Coastal flooding is rising in India and recent evidence shows that as high as 36 million Indians will be at the risk of chronic flooding by 2050. The Indian coastline extends over 7,500 kmts across nine states, two Union territories and two island territories — Andaman & Nicobar and Lakshadweep.
>
> **The east coast has historically been more vulnerable to cyclones than the west coast. According to the Indian Meteorological Department, the Bay of Bengal has had 520 cyclones between 1891 and 2018, compared with 126 in the Arabian Sea.**
>
> Indeed, the list of cyclones that India has experienced is long with intense cyclones from 1999 to 2020 including the very recent Amphan and others like Kyarr, Maha, Vayu, Fani, Gaja, Titli, Okhi, Varada, Hudhud, Phailin, Helen, Neelam, Phyan and the Odisha cyclone that left a trail of destruction along the coastal states in India.
>
> While factors such as rapid coastal development, population growth, climate change and habitat loss are the main reasons for coastal flooding, an increasing need has been identified to adopt flood mitigation and adaptation strategies to reduce the socio economic and health impacts of coastal flooding. Evidence shows that mangroves can serve as the first line of defense against flooding and erosion in many tropical and subtropical regions and help by reducing waves and storm surges."

(Emphasis supplied)

Copy of the article "Protecting mangroves, to deal with cyclones", published in indiawaterportal.org is annexed herewith as **ANNEXURE-A14**

15. In an Article published in Science the Wire in May, 2020 written by Adam Moolna, titled "How Mangroves Protect People From Increasingly Powerful Storms", it has been mentioned that mangroves protect communities from major storms.

> "Mangroves are incredibly productive coastal ecosystems found in the tropics and subtropics. These dense green forests are known for their bizarre-looking roots that poke up into the air from shallow water. Among the meshed webs of roots are fish nurseries, enabling humans to make a living from the marine life in and around the mangroves.
>
> Mangroves also play another important role for humans, protecting communities from major storms. Climate change is more than rising temperatures, and the increased frequency and intensity of cyclones, hurricanes and typhoons is apparent. Cyclone Fani for example, which recently struck the Bay of Bengal, was one of the strongest to devastate India in the past 20 years.
>
> Mangrove roots can break up the force of a storm surge, soaking up some of its energy and protecting people living on coasts from cyclone damage. Yet it is a challenge to effectively value and protect individual mangrove ecosystems. And we just don't have the people or funds to deliver detailed studies for even a fraction of the villages and towns sheltered by mangroves."

Copy of the Article published in Science the Wire in May, 2020 written by Adam Moolna, titled "How Mangroves Protect People From Increasingly Powerful Storms", is annexed as **ANNEXURE-A15.**

16. In a study titled Mangroves, 'Tropical Cyclones, and Coastal Hazard Risk Reduction' written by Anna McIvor *et all* published in Science Direct, 2015 https://doi.org/10.1016/B978-0-12-396483-0.00014-5 highlights that the most extreme storm impacts in mangrove areas have all pointed to the critical importance of mangroves in risk reduction. It has been stated that:-

"Risks from coastal hazards to people and property are expected to increase with near-future sea level rise, changes in storminess, and increasing coastal populations. Evidence from empirical and modeling studies suggests that mangrove forest vegetation can reduce storm surge peak waters levels where mangroves are present over sufficiently large areas. Mangroves are best used alongside other risk reduction measures (embankments, early warning systems) to ensure the lowest possible level of residual risk.

...

Studies of the most extreme storm impacts in mangrove areas have all pointed to the critical importance of other key elements in risk reduction associated with human behavior these have included long-term policies on coastal development to avoid high-risk settlement and infrastructure, the existence of early warning systems, and clear and well-understood evacuation procedures. (Spalding et al., 2014; Das and Vincent, 2009; Williams et al., 2007)."

Copy of the study titled Mangroves, 'Tropical Cyclones, and Coastal Hazard Risk Reduction', is annexed herewith as **ANNEXURE-A16.**

17. That Susmita Dasgupta wrote an article on the blog of the World Bank titled, 'When cyclones strike: Using mangroves to protect coastal areas', highlighting that mangrove forests can reduce vulnerability of adjacent coastal lands from storm surges by slowing the flow of water, but too little use is made of this natural buffer. The article states:-

"Mangroves, by obstructing the flow of water with their roots/husks and leaves, can reduce the vulnerability of adjacent coastal lands from storm surges. Although the potential utility of mangroves in disaster risk reduction is increasingly recognized by coastal managers, efficient use of this ecosystem-based protection is often hindered by scarcity of location-specific information on the protective capacity of mangroves. The extent of protection from mangroves depends on the width of forest, forest density, diameter of stems and roots of trees along with forest floor shape, bathymetry, spectral characteristics of waves and the tidal stage at which waves enter the forest."

Copy of the article titled 'When cyclones strike: Using mangroves to protect coastal areas', is annexed herewith as **ANNEXURE-A17.**

18. In a Research Paper titled, 'An Overview on Role of Mangroves in Mitigating Coastal Disasters (With Special Focus on Tsunamis, Floods and Cyclones)' written by Davood Mafi Gholami and published in International Conference on Architecture, Urbanism, Civil Engineering, Art, Environment the important role played by Mangroves has been mentioned as one which reduces the adverse effects of hurricanes, storms and tsunamis. The paper states:-

> "Among different ecosystems located on coastal areas, Mangroves play an important role in providing ecological and societal goods and services to local communities, including stabilizing shorelines and helping reduce adverse effects of natural disasters such as tsunamis and hurricanes, serving as breeding and nursing grounds for many marine and pelagic species, and providing food, medicine, fuel, and building materials as well as opportunities for aquaculture. As a
> consequence, mangrove ecosystems have attracted an increasing amount of attention from land and ocean managers, conservation communities and academia in all over the world. The aim of this manuscript is review the role of mangrove ecosystems in minimizing the impact of marine hazards like tsunamis, floods and cyclones. A comparison of the studies concerning effective mitigation of tsunamis and natural disasters by mangrove ecosystems was carried out. Results based on the literature review showed that mangroves occurring near the coast play an important role in the protection of the coastal areas from the natural disasters like tsunamis, floods, cyclones. The conclusion reached is that it is necessary for humans to realize the dangers and consequences of undermining the services provided by the coastal ecosystems in coastal protection and to conserve mangroves in every part of the world. The results of this paper will be helpful for informing conservation efforts, mangrove rehabilitation and national monitoring programs for shoreline protection actions in different coastal areas."

Copy of the Research Paper titled, 'An Overview on Role of Mangroves in Mitigating Coastal Disasters (With Special Focus on Tsunamis, Floods and Cyclones)' is annexed herewith as **ANNEXURE-A 18.**

19. In another research study titled, 'The Global Flood Protection Benefits of Mangroves' written by Pelayo Menéndez *et al* published in Nature on 10 March, 2020. This study highlights that mangroves

can reduce up to 66% of wave energy in the first 100 m of forest width it states that:-

> "In many tropical and subtropical regions mangroves reduce waves and storm surges, and serve as a first line of defense against flooding and erosion. These benefits are provided through bottom friction, the cross-shore width of forests, tree density and shape. The aerial roots of a mangroves forest retain sediments, stabilizing the soil of intertidal areas and reducing erosion. Roots, trunk and canopy dissipates storm surge and waves. Previous studies have shown that mangroves can reduce up to 66% of wave energy in the first 100 m of forest width. Mangroves can also provide adaptive defenses as they can, under the right conditions, keep pace with sea-level-rise through vertical accretion.
>
> Yet, mangroves have experienced significant losses over the last decades, declining globally from 139,777 km^2 in 2000 to 131,931 km^2 in 2014, with even greater losses before 2000. Most of this loss has happened through the conversion for aquaculture or agriculture and coastal development. The loss of these habitats can contribute to increasing coastal risk, particularly in developed areas with great exposure of coastal populations. Quantifying the value of mangroves as natural coastal defenses is crucial for incentivizing their conservation and restoration for the benefit of nature and people."

Copy of the Research study titled, research study titled, 'The Global Flood Protection Benefits of Mangroves' is annexed herewith as **ANNEXURE-A 19.**

20. In another research paper titled 'Protection from Cyclones Thematic paper: Role of forests and trees in protecting coastal areas against cyclones' Hermann M. Fritz, published in www.fao.org it has been highlighted that mangroves are more efficient at attenuating surface waves and wind as well as providing protection against erosion. It states that:-

> "In order to significantly reduce the impact of the storm surge —usually the most devastating cyclone hazard — several kilometres of coastal forests are required. Mangroves are more efficient at attenuating surface waves and wind as well as providing protection against erosion. Typically, the wave energy is attenuated by a factor of two within 50

> metres in front of the mangrove forest at normal sea level. The obstruction density caused by the mangrove wood structure decreases rapidly with height and, therefore, as the water level increases because of the storm surge there is proportionally less flow resistance and less reduction of wave energy. Unfortunately, this effect severely reduces wave attenuation with increasing cyclone intensity, storm surge height and wave period. Finally, the possibility of multiple cyclone hits prior to significant mangrove forest recovery needs to be considered"

Copy of the research paper titled 'Protection from Cyclones Thematic paper: Role of forests and trees in protecting coastal areas against cyclones' is annexed herewith as **ANNEXURE-A 20.**

Therefore, the Joint Committee failed to consider the costs of restoration of mangroves is quite high and certainly much higher than the amount computed by the Joint Committee.

21. **Mangroves serve as Carbon Sinks which also the Joint Committee failed to consider :** Mangrove systems act as carbon sinks. Biomass produced by mangrove forests can ultimately have a number of different destinations such as

(i) Part of the biomass produced can be consumed by fauna, either directly or after export to the aquatic system,

(ii) Carbon can be incorporated into the sediment, where it is stored for longer periods of time,

(iii) Carbon can be remineralized and either emit back to the atmosphere as CO2 , or exported as dissolved inorganic carbon (DIC),

(iv) Carbon can be exported to adjacent ecosystems in organic form (dissolved or particulate) where it can either be deposited in sediments, mineralized, or used as a food source by faunal communities

(v) Blue carbon ecosystems (saltmarshes, seagrasses and mangroves) are characterized by their disproportionately large organic carbon (OC) storage. As such, blue carbon climate change mitigation tool owing to its high carbon sequestration and storage capacity at the plot scale.

Therefore, the costs of restoration of mangroves is quite high and certainly much higher than the amount computed by the Joint Committee.

22. The **Joint Committee has failed to give recommendation regarding penalty for CRZ-1 violation:** In the Report of the Joint Committee uploaded in March, 2021 at page 6 it is admitted that:-

> "As per the CRZ Map, 2011, the area in question is in CRZ-1A. If the project was a permissible activity in CRZ-1A, CRZ clearance is required. But townships and are not permissible in CRZ-1A. area."

The Committee states that there is a proposal to change the CRZ category of the said land from CRZ-1A to CRZ-II. Therefore, it is admitted that there is a violation of provisions of CRZ-1A but no penal action has been proposed.

23. That it is stated that as per para 5.1.1. pertaining to CRZ–IA of CRZ Notification, 2019:

"These areas are ecologically most sensitive and generally no activities shall be permitted to be carried out in the CRZ-I A area, with following exceptions:-

(i) Eco-tourism activities such as mangrove walks, tree huts, nature trails, etc., in identified stretches areas subject to such eco-tourism plan featuring in the approved CZMP as per this notification, framed with due consultative process, public hearing, etc. and further subject to environmental safeguards and precautions related to the Ecologically Sensitive Areas, as enlisted in the CZMP.

(ii) In the mangrove buffer, only such activities shall be permitted like laying of pipelines, transmission lines, conveyance systems or mechanisms and construction of road on stilts, etc. that are required for public utilities.

(iii) Construction of roads and roads on stilts, by way of reclamation in CRZ-I areas, shall be permitted only in exceptional cases for defence, strategic purposes and public utilities, subject to a detailed marine or terrestrial or both environment impact assessment, to be recommended by the Coastal Zone Management Authority and approved by the Ministry of Environment, Forest and Climate Change; and **in case construction of such roads passes through mangrove areas or is likely to damage the mangroves, a minimum three times the mangrove area affected or destroyed or cut during the construction process shall be taken up for compensatory plantation of mangroves.**

(Emphasis supplied)

24. It is stated that the above provision of CRZ Notification, 2019 does not permit construction activities in CRZ 1A areas. Secondly, even for construction of road passing through a mangrove area or is likely to damage the mangroves, a minimum three times the mangrove area affected or destroyed or cut during the construction process needs to mandatorily taken up for compensatory plantation of mangroves. It is stated that the Joint Committee ought to have considered the above provision while recommending the Compensation which has not been done.

25. **The Joint Committee has erred in holding that the project does not require any Environmental and/or Wildlife Clearance: it** is stated that the project is only 116 acres i.e below 50 Ha and hence does not require the EC. It is submitted by the

Applicant that according to the Applicants the project is coming up in an area of 300 acres with dense Mangroves. Further, when Mangrove area cleared itself has not been correctly calculated by the Joint Committee, in all likelihood there is a similar error in calculating the total area of the project. Morever, when the project in question is 2.92 Km away from Coringa Wildlife Sanctuary, it comes within the default ESZ and hence requires a Wildlife Clearance too. Hence, it is important that the Tribunal may direct the calculation of the entire area of the Project from an independent agency in this regard as well as the Mangrove area cleared as the true picture in this regard is not been given by the Joint Committee.

26. **Committee ought to have recommended Compensation under Entry (m) of the Schedule II of the National Green Tribunal Act, 2010:** The Application also seeks compensation under Entry (m) of the Schedule II of the National Green Tribunal Act, 2010 for the loss of livelihood of the fisherfolk community of Kakinada due to the ongoing illegal activities by the State of Andhra Pradesh. The valuation of boat anchoring in the creek which is mentioned in the Original Application would be additional to the general standard ecological value. However, no such recommendation has been given by the Committee and it is important that before the final order on assessment is passed by this Hon'ble Tribunal, this issue may also be kindly dealt with.

27. **Regarding role of regulators in implementing and enforcing the environmental laws :** In ***Indian Council for Enviro-Legal Action Vs. Union of India & Ors. (1996) 5 SCC 281***, the Hon'ble Supreme Court has come heavily on the regulators for non implementing the provisions of the environmental laws in its letter

and spirit and observed that non-implementation of the laws will be more dangerous than non enacting laws itself. If the regulators fail to implement the laws to protect the environment, then it will create anarchy and it may even affect the rule of law as such.

28. Further, in ***Ansari Kannoth Vs. State of Kerala & Ors. 2011(1) KLT 1043,*** the Hon'ble Kerala High Court has held that even if the MoEF&CC had delegated the power under the CRZ Notification, their power to proceed against the violators to the State authorities is not taken away, if the State authorities are not implementing the same in its letter and spirit. But inspite of all these directions by the Hon'ble High Court and Apex Court, the regulators are shutting their eyes against the violation and not taking proper action against such persons.

29. Further, in the recent decision of ***Kerala State Coastal Zone Management Authority Vs. State of Kerala Maradu Municipality & Ors., 2019 (7) SCC 248,*** the Hon'ble Supreme Court has come down heavily on the regulators for not taking action against the violators in accordance with law and the Hon'ble Apex Court has directed the authorities to demolish the building and supervise the same till its implementation. Inspite of all these decisions of the Hon'ble Supreme Court and High Courts, the regulators are not raising to the occasion to fulfil their obligation of protecting environment and implementing the environmental laws in its letter and spirit, as they are obliged to do as a party to the international covenants as providing clean environment is part of Right to Life as enshrined under Article 21 of Constitution of India and also there is a mandate under Article 48 (A) of Constitution of India on the State Government to protect environment.

30. **Construction in violation of the Coastal Regulation Zone Regulations are not to be viewed lightly and he who**

breaches its terms does so at his own peril: The Kerala High Court in ***Ratheesh K.R. v. State of Kerala [Ratheesh K.R. v. State of Kerala, 2013 SCC OnLine Ker 14359 : (2013) 3 KLT 840]***. The same is extracted below: (SCC OnLine Ker paras 98 & 107-108)

> "98. However, we would rather rest our decision without pronouncing on the validity of the permits as such. We have found that the Notification is applicable to the island, the island falls in CRZ-I and construction is impermissible. *By merely getting a permit under the Building Rules, it cannot be in the region of any doubt that the company cannot arrogate to itself, the right to flout the terms of the Notification. We have already noticed Rule 23(4) of the Kerala Municipality Building Rules, 1999 and Rule 26(4) of the Kerala Panchayat Building Rules, 2011. In this case, we may also note that there is no permission sought from the authority.* It is apposite to note that para 3(*v*) clearly mandates that for investment of Rs 5 crores and above, permission must be obtained from the Ministry of Environment and Forests. In this case, the investment of the company is far above Rs 5 crores. In respect of investments below Rs 5 crores, for activities which are not prohibited, permission must be obtained from the authority concerned in the State. The company has not made any such attempt at getting permission. That apart, this is a case where, even if permission had been applied for, the terms of the Notification would stand in the way of any such permission being granted insofar as the island is treated as falling in CRZ-I. Construction of buildings as has been done by the company was absolutely impermissible. The fact that in a situation where the construction activity was permissible under the Notification and if the company had obtained permit from the local body, would have made its activities legal, cannot avail the company for the reason that under the terms of the Notification, such permit obtained from the panchayat will be of little avail to it in the light of the nature of the restrictions brought about by the Regulations in respect of CRZ-I in which zone the island falls. According to the panchayat, no doubt, the conditions have been imposed also as recommended by the Assistant Engineer who is alleged to have even visited the island. Whatever that be, as observed by us, in the light of the view we have taken, namely, that the 1991 Notification applies to the island, it is squarely covered by the same being included in CRZ-I and the constructions were begun even during the currency of the 1991 Notification. The conclusion is inescapable that it is in the teeth of the prohibition contained in the 1991 Notification and, therefore, it is palpably illegal.
>
> ***
>
> *107.* At this stage, we must deal with the argument raised before us by the company. It is submitted that a world class resort has been put up which will promote tourism in a State like Kerala which does not have any industries as such and where tourism has immense potential and jobs will be

created. It is submitted that the Court may bear in mind that the company is eco-friendly and if at all the Court is inclined to find against the company, the Court may, in the facts of this case, give direction to the company and the company will strictly abide by any safeguards essential for the preservation of environment.

108. We do not think that this Court should be detained by such an argument. ***The Notification issued under the Environment (Protection) Act is meant to protect the environment and bring about sustainable development. It is the law of the land. It is meant to be obeyed and enforced. As held by the Apex Court, construction in violation of the Coastal Regulation Zone Regulations are not to be viewed lightly and he who breaches its terms does so at his own peril. The fait accompli of constructions being made which are in the teeth of the Notification cannot present, but a highly vulnerable argument."***

(Emphasis supplied)

31. In ***Piedade Filomena Gonsalves v. State of Goa, (2004) 3 SCC 445*** it has been held that:-

"6. The Coastal Regulation Zone Notifications have been issued in the interest of protecting environment and ecology in the coastal area. Construction raised in violation of such regulations cannot be lightly condoned. We do not think that the appellant is entitled to any relief. No fault can be found with the view taken by the High Court in its impugned judgment."

(Emphasis supplied)

32. The East Godavari has been declared as a Critically Vulnerable Coastal Area under the CRZ Notification, 2011. As per the notification, until the finalisation and notification of the Integrated Management Plan (IMP) for such areas, the respective CZMA would consider permitting very limited activities only after consulting the coastal communities. It is stated that neither is the project in question a permissible activity nor were the coastal communities consulted before commencing work on the project.

33. In ***Vaamika Island (Green Lagoon Resort) v. Union of India,*** **(2013) 8 SCC 760** which was a case related to illegal construction in Vembanad Lake area which lake was scheduled under "vulnerable wetlands to be protected" and declared as CVCA and

the Hon'ble High Court gave directions for demolition of illegal construction which was in violation of the 1991 and 2011 CRZ Notifications, the Supreme Court upheld the Order of demolition passed by the High Court. It was held that:-

> 27. We are of the considered view that the above direction was issued by the High Court taking into consideration the larger public interest and to save Vembanad Lake which is an ecologically sensitive area, so proclaimed nationally and internationally. Vembanad Lake is presently undergoing severe environmental degradation due to increased human intervention and, as already indicated, recognising the socio-economic importance of this waterbody, it has recently been scheduled under "vulnerable wetlands to be protected" and declared as CVCA. We are of the view that the directions given by the High Court are perfectly in order in the abovementioned perspective.
>
> 28. Further, the directions given by the High Court in directing demolition of illegal construction effected during the currency of the 1991 and 2011 CRZ Notifications are perfectly in tune with the decision of this Court in *Piedade Filomena Gonsalves* v. *State of Goa* [(2004) 3 SCC 445] , wherein **this Court has held that such notifications have been issued in the interest of protecting environment and ecology in the coastal area and the construction raised in violation of such regulations cannot be lightly condoned.**
>
> (Emphasis supplied)

It is therefore prayed that the prayer that:

i. The Original Application be allowed in view of the abovementioned facts, circumstances and submissions.

ii. The Hon'ble Tribunal may direct the calculation of the entire area of the Project from an independent agency as well as the Mangrove area cleared as the true picture in this regard is not been given by the Joint Committee, and/or

iii. The Joint Committee may be directed to asses the Environmental compensation for past violations and CPCB formula as has been held by it in several cases, and /or

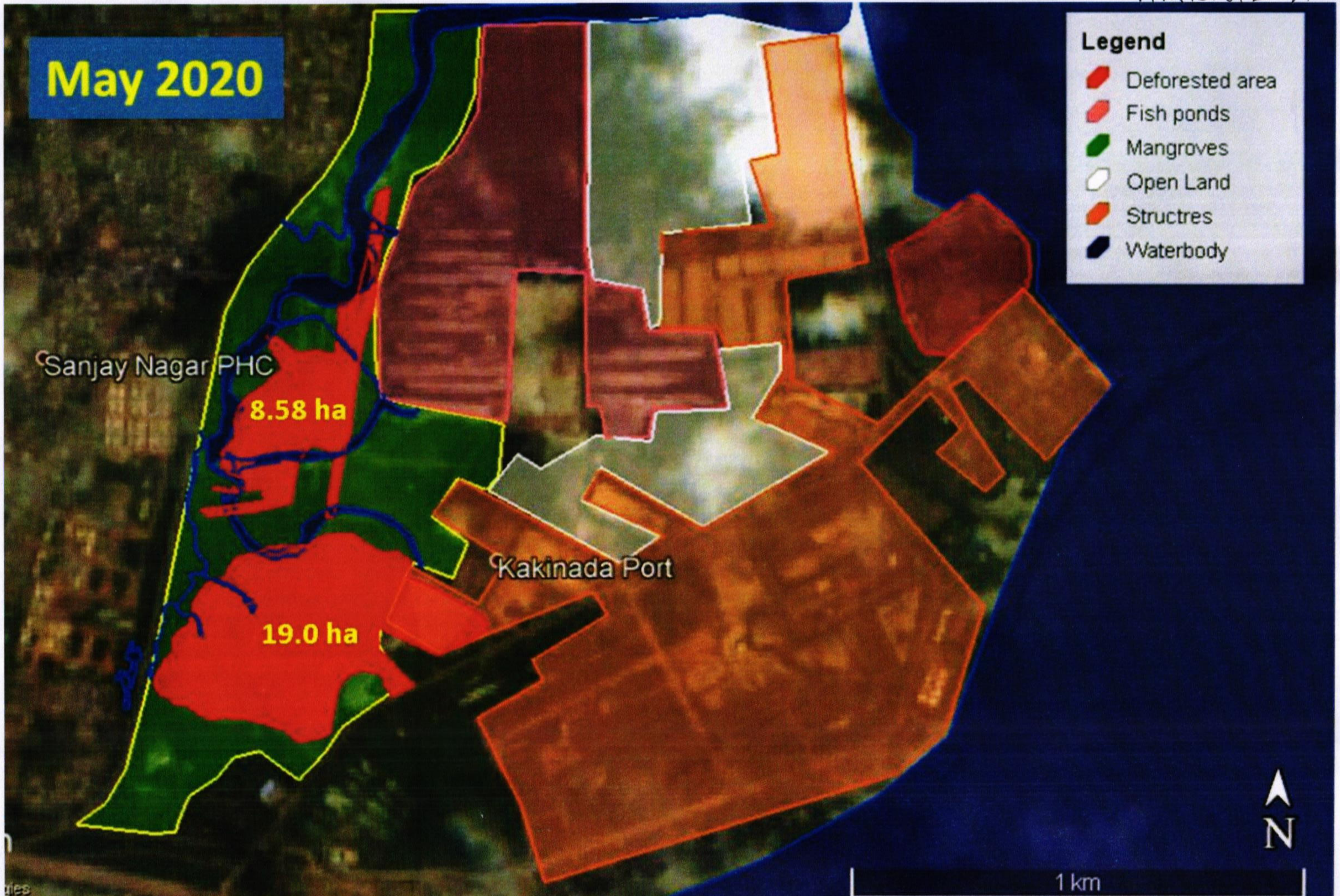
iv. The Joint Committee should be directed to relook the issues in view of the abovementioned submissions and recommend an enhanced compensation in the matter, as well as recommend for penal action against the State and it's agencies for violating the provisions of CRZ-IA, and /or

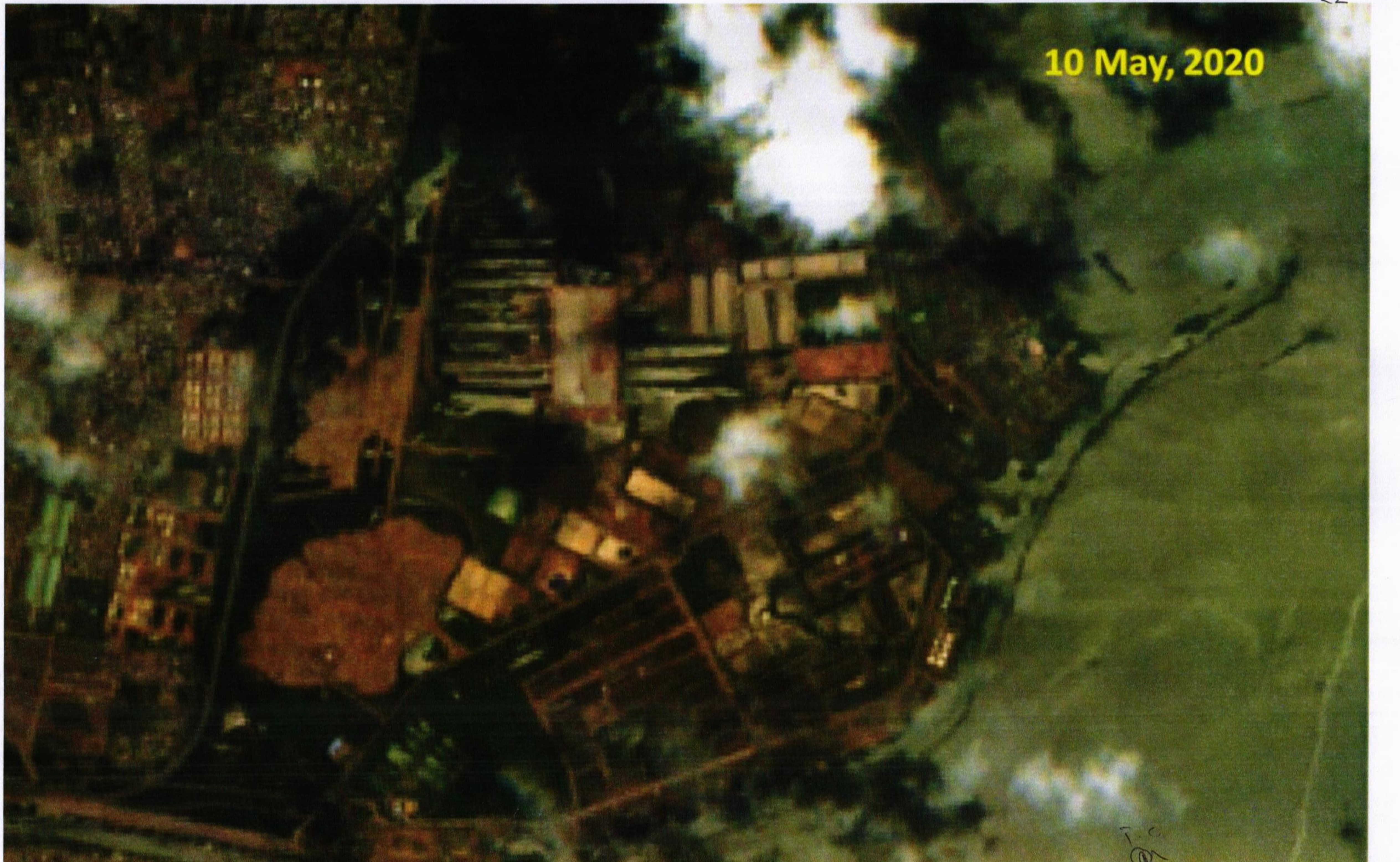
v. The Tribunal may be pleased to order demolition of construction in CRZ – I area as per the law settled by the Hon'ble Supreme Court in ***Vaamika Island (Green Lagoon Resort) v. Union of India (Supra),*** and /or

vi. The Joint Committee should also be directed to recommend compensation under Entry (m) of the Schedule II of the National Green Tribunal Act, 2010 for the loss of livelihood of the fisherfolk community of Kakinada

FILED BY

RITWICK DUTTA SAURABH SHARMA G.STANLY HEBZON SINGH
ADVOCATES
COUNSELS FOR THE APPLICANTS


May 2020
Legend
Deforested area
Fish ponds
Mangroves
Open Land
Structres
Waterbody
Sanjay Nagar PHC
8.58 ha
19.0 ha
Kakinada Port
N
1 km


10 May, 2020

Annexure A-10

Item No.06:

BEFORE THE NATIONAL GREEN TRIBUNAL
SOUTHERN ZONE, CHENNAI

Original Application No. 234 of 2017 (SZ)

(Through Video Conference)

IN THE MATTER OF:

MeenavaThanthai
K.R. Selvarajkumar
MeenavarNala Sangam ...Applicant(s)

Versus

The Director,
Ministry of Environment, Forest &
Climate Change,
New Delhi and Ors.

...Respondent(s)

Date of hearing: 12.09.2020.

CORAM:

HON'BLE MR. JUSTICE K. RAMAKRISHNAN, JUDICIAL MEMBER

HON'BLE MR. SAIBAL DASGUPTA, EXPERT MEMBER

For Applicant(s): M/s. Stanley Hebzon Singh.

For Respondent(s): M/s. G.M. Syed Nurullah Sheriff for R1, R2.
M/s. D.S. Ekambaram through
M/s. Jayalakshmi for R3.
M/s. Kamalesh Kannan for R4 to R6, R9, R10.
M/s. C. Kasirajan through
M/s. Ajith Kumar for R7.
M/s. P.T. Rema Devi through
M/s. Raghul Adithya for R11.

ORDER

1. As per order dated 27.01.2020, after considering the pleadings, this Tribunal had constituted a committee to go into the question and directed them to submit a report and posted to case to 30.03.2020 for consideration of the report. On 30.03.2020, the matter was adjourned to 17.07.2020 and on 17.07.2020, it was adjourned to 20.07.2020 by successive notifications.

2. On 20.07.2020, at the request of the committee, the matter was adjourned to 31.08.2020 for consideration of the report and on 31.08.2020, it was adjourned to today by notification.

3. When the matter came up for hearing today through Video Conference, Sri. G. Stanley Hebzon Singh represented the applicant, Sri. G.M. Syed Nurullah Sheriff represented respondents 1 & 2, Sri. D.S. Ekamabaram through Smt. Jayalakshmi represented 3rd respondent, Sri. Kamalesh Kannan represented respondents 4 to 6, 9 & 10, Sri. C. Kasirajan through Sri. Ajith Kumar represented 7th respondent and Smt. P.T. Rema Devi through Sri. Raghul Aditya represented 11th respondent.

4. We have received the report dated Nil filed on 11.09.2020 which

reads as follows:-

"Report on M/s. St. Peter & Paul Sea Food Exports Private Ltd. No.11A, New Thiruvalluvar Nagar, Royapuram, Chennai – 600 013.

*A case was filed before the Hon'ble National Green Tribunal, Southern Zone, Chennai, vide Original Application No.234 of 2017 (SZ) by Meenava Thanthai K.R. Selvaraj Kumar, Meenavar nALAR Sangam represented by its President, M.R. Thiyagarajan, office at No.48, First Floor, East Madha Church Street, Royapuram, Chennai – 600 013 with the grievance that the unit M/s. St Peter & Paul Sea Food Exports Pvt. Ltd. is conducting a sea food export industry at **No.11A**, New Thiruvalluvar Nagar, Royapuram, Chennai – 600013, which is within the CRZ area without necessary clearance from the CRZ authority, dumping the sea food waste in that area and also extracting ground water without getting necessary permission from the consent authorities. These activities cause air as well as air pollution.*

Hon'ble NGT (SZ) in order dated 27.01.2020 in O.A. No.234 of 2017 (SZ) "Constituted a committee comprising of District Collector, Chennai, State Coastal Zone Management Authority and the Tamil Nadu State Pollution Control Board (TNSPCB) to look into the allegations made in the application and submit a report after making necessary inspection as to whether the allegations are true and if so what is the action taken by them against the violators to this Tribunal within a period of two months".

Based on the orders of the Hon'ble NGT (SZ), Chennai, a joint committee comprising the following members was *constituted to inspect and file the report:-*

1) *Revenue Divisional Officer, Chennai North, Chennai District (Representing District Collector, Chennai)*
2) *Director, Institute of Remote Sensing, Anna University, Chennai – 25 / Member TNSCZMA (Representing TNSCZMA, Chennai)*
3) *District Environmental Engineer, TNPCB, Chennai.*

It is submitted that, Thiru. M.R. Thiyagarajan, President, Meenava Thandai K.R. Selvakumar Meenavara Nala Sangam had filed complaint petition to the TNPCB regarding water pollution caused by the unit during September 2017. During inspection, it was observed that, the unit M/s. St Peter & Paul Sea Food Exports Pvt. Ltd located at No.11A, New Thiruvalluvar Nagar, Royapuram, Chennai – 600 013 was in operation without consent of the Board and the waste water generated by the unit was discharged into the underground drain without any treatment. The unit was advised to produce the land document of the unit in order to verify the applicability of the Coastal Regulation Zone Notification.

As the unit had not submitted the CRZ Clearance for that activity from competent Authority and operated without consent of the TNPC Board, direction for closure and disconnection of power supply to the unit was issued vide Proc. dated 06.07.2018 under Section 33A of the Water (P&CP) Act, 1974 as amended and under Section 31 A of Air (P&PC) Act, 1981 as amended. The EB service connection of the unit Ac. No.002-009-415 Tariff –V, was disconnected on 14.08.2018 as informed by TANGEDCO vide letter dated 18.08.2018. The unit was not in operation and no activity was carried out in that premises.

It is submitted that as per the orders of the NGT (SZ) the committee inspected the site on 18.07.2020. During committee inspection, the following were observed:

1) *The building comprises of G+2 floor and terrace floor was found at that location. In one portion of the ground floor the unit has stored Empty Plastic drums and the another portion was kept idle. 1st and 2nd floor are provided with rooms and used as rest house and terrace floor provided with Water Tank & Toilet facility.*
2) *The ground floor was under closed condition and observed that, the unit was not in operation and no activity was carried out.*
3) *It was found that, EB service connection Ac. No;002-009-415 has been disconnected. However, the unit has provided with another 2 number of EB service connection in the ground floor.*
4) *A team from Institute of Remote Sensing, Anna University, Chennai – 25 has conducted a filed survey on the said location, to find out the co-ordinates of the site so as to superimpose in the existing CZMP (Coastal Zone Management Plan) maps to verify whether the site is located in CRZ area or not.*
5) *As per the field survey and the superimposition of the unit in the CRZ map, it is ascertained that the site is located in CRZ-II area wherein the activity of sea food processing is prohibited in that area. (Copy of IRS map is enclosed)*

During inspection, no violation were noticed as there was no activity carried out in that site, as the unit was closed vide TNPCB order dated 06.07.2018."

5. The learned counsel appearing for the applicant wanted to submit his objection to the same regarding the aspect that it is still

continuing and no environmental compensation was imposed.

6. It is seen from the report and also even from the pleadings that the unit was functioning in that area since 2014 and complaints were received regarding the same.

7. Further, it is also seen from the report that closure order was issued by Proceedings dated 06.07.2018 and electricity was disconnected on 14.08.2018. That shows that the activity was not in conformity of the environmental laws and also against the CRZ Notification, 2011 as the construction was made in that area which is a regulated area without getting prior permission from the Coastal Zone Management Authority (CZMA) and the activity which was said to have been conducted by the unit was a prohibited activity in the CRZ Zone.

8. Inspite of this, no action was taken by the Coastal Zone Management Authority (CZMA) even today either for removal of construction made without clearance in a regulated area and no attempt was made to recover the environmental compensation against that unit for conducting an unauthorized activity in a illegal manner in the prohibited zone.

9. However, the report shows that since there was no violation noticed on the date of inspection, no environmental compensation has been

imposed. They have not considered the question of imposing environmental compensation for the past violation which is recognized under law as directed by the Hon'ble Apex Court in several decisions by applying the "Polluter Pays" principle to recover the compensation against those persons who are illegally carrying out their operation in the prohibited zones.

10. When this was pointed out, the learned counsel appearing for the Coastal Zone Management Authority (CZMA) submitted that he will come with a further report regarding the action taken in this regard. They are expected to follow the principle of natural justice while initiating proceeding against the persons who have committed the violation and they should not proceed with the initiation, without following the procedure under the cover of the direction to implement the law issued by this Tribunal.

11. The committee is also directed to revisit the question of compensation for past violation as directed by this Tribunal in several cases of this nature applying the formula evolved by the Central Pollution Control Board in this regard and also taking into the consideration the nature of damage caused to the coastal zone on account of such activities and the amount required for restoration of the same to its original position.

12. The committee can co-opt any expert member for the purpose of assessing environmental compensation if they feel and submit the report in this regard to this Tribunal.

13. In the mean time, Tamil Nadu Coastal Zone Management Authority is also directed to come with the action taken report for the violation noted in the report in accordance with law.

14. The committee as well as the Coastal Zone Management Authority are directed to submit the report as directed by this Tribunal on or before 26.11.2020.

15. We also feel that a Scientist from Central Pollution Control Board, Regional Office, Chennai can be added to the committee so that it will be helpful for the committee to assess the environmental compensation as directed by this Tribunal. So, the committee is reconstituted including a Scientist/Officer from the Central Pollution Control Board, Regional Office, Chennai as well.

16. The Registry is directed to communicate this order to the members of the committee as well as to the newly added committee member namely Central Pollution Control Board, Regional Office, Chennai by e-mail immediately so as to enable them to comply with the direction.

17. For consideration of further report and objection if any of the applicant to the report, post on 26.11.2020.

..................................J.M.
(Justice K. Ramakrishnan)

...............................E.M.
(Shri. Saibal Dasgupta)

O.A. No.234/2017,
12th September, 2020. Mn.

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Annexure A-11

ECOSYSTEM SERVICES OF MANGROVES AND THEIR VALUATION

Chapter · May 2019

1 author:

Nilanjan Ghosh, Ph.D
Observer Research Foundation

ECOSYSTEM SERVICES OF MANGROVES AND THEIR VALUATION

Chapter 28

NILANJAN GHOSH

ABSTRACT

This paper discusses the various ecosystem services rendered by mangroves, and the values that they yield for the human society. The paper defines the notion of ecosystem services as benefits obtained by the human community from the ecosystem, and delineates the classifications of the notion on the basis of the Millennium Ecosystem Assessment and TEEB. Eventually, on the basis of literature surveys, it documents the various ecosystem services that mangroves provide, and explain the various attempts to place monetary values on them. Finally, the paper provides an exposition of the Indian Sundarbans Delta, where WWF Vision 2050 document talks of planned retreat of population and mangrove ecosystem restoration as modes of adaptation to the vagaries of global warming and climate change. The potential values that may be created by mangrove ecosystem regeneration have been talked of in this case.

Keywords: Valuation, Monetary benefit, Sundarban, Provisioning, Comparative economics.

INTRODUCTION

Mangrove forests are complex ecosystems generally found in the tropical and the subtropical areas. Being adaptive to anaerobic conditions occurring from the brackish to the highly saline water systems, they transpire on the river banks and along coastlines in forms of trees, shrubs, ferns, palms, creepers, etc (Ghosh & Shylajan 2005). They inhabit in the intertidal zones with high salinity, while salt tolerance competency of different species varies. Even congener species usually occupy distinct positions of intertidal zones due to differential ability of salt tolerance. Some species have different ecotypes that adapt well to littoral and terrestrial environments, respectively (Liang *et al.,* 2008). As such, the mangrove ecosystems provide a host of benefits to the human community through their natural functioning. These benefits in the form of goods and services accrued by the human community are called ecosystem services.

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Citation
Ghosh, N. 2019. Ecosystem Services of Mangroves and their Valuation. In: *Faunal Diversity of Indian Mangroves* : 1-19. (Published by the Director, Zool. Surv. India, Kolkata)

- *Valuation helps in better appreciation of the conservation programs that are implemented for safeguarding the various components of the ecosystem:* Conservationists express their deep concerns about development programs that adversely impact ecosystems. Valuation of ecosystem services serves as corroborative and apt arguments that justify for maintaining these services for the benefit of society in the long term.

Valuation of Ecosystem services of Mangroves

Understanding ecosystem services of mangroves

The high level of human dependency on mangrove forests can be discerned from the density of population dwelling around 10 km of significant mangrove areas, which was estimated about 120 million in 2015 (van Bochove *et al.*, 2014). Major share of this population, which depends on the resources from mangroves for livelihood and sustenance, is in the developing countries in South and Southeast Asia, and West and Central Africa (Mukherjee *et al.*, 2014).

On one hand, mangroves emerge as prime sources of fuel and materials for construction in the coastal regions in tropical developing countries (Walters *et al.*, 2008). On the other hand, the importance of the mangrove-fishery linkages has been amply illustrated in ecological economic literature (McNally *et al.*, 2011, Jones *et al.*, 2010, Unsworth *et al.*, 2008).

Mangrove forests have a profound role in the coastal protection, preventing natural hazards like recurrent storms (Das 2011, 2012; Das & Crépin, 2013). In deltaic setting of mangroves, the dense and tangled root-networks trap the soil, sediment and suspended particulate matter (Lee *et al.*, 2014). Mangrove stocks are the most carbon rich forests in the tropics, reportedly having 1023 Mg C per hectare of forest including soil carbon (Donato *et al.*, 2011).

Based on various studies on Indian mangroves by Badola & Hussain (2003), Das (2009) and Hussain & Badola (2010) on Bhitarkanika mangroves, Ghosh *et al.* (2016) on Indian Sundarbans, and Santhakumar *et al.* (2005) generally on mangroves of the south Asia, the ecosystem services of mangroves in India can generally be summarised as given in Table 1.

Table 1. Ecosystem Services of Mangroves

Ecosystem Service	Classification of Services
Fishery production	Provisioning service
Prawn larva	Provisioning service
Honey	Provisioning service
Crab and crustacean species	Provisioning service
Fuel	Provisioning service
Fodder	Provisioning service
Medicinal plants	Provisioning service
Genetic resources	Provisioning Service
Carbon sequestration	Regulating Service

Table 1 contd.

Ecosystem Service	Classification of Services
Storm surge protection	Regulating Service
Tourism	Cultural services
Aesthetics	Cultural services
Religion	Cultural services
Breeding of species	Supporting (Habitat) Services
Spawning	Supporting (Habitat) Services
Nursery habitat	Supporting (Habitat) Services
Biodiversity	Supporting (Habitat) Services

The calamitous Asian tsunami in the Indian Ocean on 26 December 2004 paved the way for major initiatives, since 2005, towards developing and restoring (Vishwanathan 2016). The general perception about the potential of mangrove cover to mitigate the loss of lives and properties, economic damages and other problems caused by such natural disasters (Kathiresan & Rajendran 2005; UNEP 2005) have prompted national governments, international agencies and NGOs to make enormous efforts for the expansion of mangroves in the Indian Ocean region. Efforts were made to replant and rehabilitate mangrove ecosystems as bio-shields or "natural barriers" to future tsunamis and other tropical storms (Barbier 2008).

In the last 50 years, despite our understanding about the socio-economic importance of mangroves, the area under mangrove cover has shrunk to 30-50 %, a higher rate of decline than most other biomes (Balmford *et al.* 2002). The remaining stocks upto 40% are under severe threats with mangrove plant species being highly vulnerable and on the brink of extinction in certain parts of the planet (Polidoro *et al.* 2002). The loss and degradation of mangroves ultimately impinge on human well-being, as ecosystem services are being lost with ecosystem destruction. What best we can do to rein this loss is to adopt a policy and urgent need for better and efficient management to implement the restoration of intact and damaged mangrove ecosystems.

Valuation of mangrove ecosystem services

A host of studies have been conducted estimating the values of mangrove ecosystems. However, it needs to be noted here that the outcome of these studies are not consistent and vary in various aspects. This is because of the variation in the range of mangrove related products, their management methods, assumptions related to the linkage between mangroves and other ecosystems, as also the methodological issues related to valuation.

In one of the formidable studies, Christensen (1982) considers value of different direct use values of mangroves. While the value of variety of local use products like fruits, cigarette wrappers and *nipa* thatch for roofing has been estimated, the value for on-site fisheries that is commercial harvest by small, medium and large scale fishermen dealing with variety of fishes, trash fishes, prawns and shrimp, based

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Annexure A-12

Chapter 17
Valuing the Role of Mangroves in Storm Damage Reduction in Coastal Areas of Odisha

Saudamini Das

Key Messages

- Storm protection service of mangroves is very high for cyclone prone regions.
- During 1999 super cyclone in Odisha, every hectare of mangroves provided storm protection in the range of USD 4335 to USD 43,352 to the Kendrapada district, which is 25–249 times the 1999 per capita income of the district (USD 174).
- The annualized storm protection value of a mangrove hectare is more than two times the land price of cleared forests and more than twenty times the annual return from alternative land uses clearly justifying mangrove conservation to receive storm protection.

17.1 Introduction

In disaster management, resilience has been defined as the "*ability of an entity (individuals, communities, organizations, states) to recover from the effects of exogenous shocks, such as natural hazards, without compromising the long-term prospects of growth*" (Kousky & Shabnam, 2015). This is possible if damage from natural disasters is low (static resilience) or people recover quickly (dynamic resilience).

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A. K. Enamul Haque et al. (eds.), *Climate Change and Community Resilience*,
https://doi.org/10.1007/978-981-16-0680-9_17

With climate change and increased threats from tropical storms to coastal dwellers, resilience building is an urgent need and the conservation of coastal vegetation provides both static and dynamic resilience from storms to people (Das & D' Souza, 2019). This chapter examines whether mangroves should be conserved for building coastal resilience.

Mangrove wetlands are one of the most important tropical and sub-tropical coastal wetlands and provide a range of provisioning, supporting, regulating, and cultural services to humans (MA, 2003). However, mangroves are threatened by change of land use to settlement, agriculture, aquaculture, or industrial uses (Field et al., 1998). This is because most of the important services of mangroves are indirect, invisible and occur off-site, whereas when these wetlands are converted to other land use like aquaculture or coastal development, the returns are visible, instantaneous, direct, and commercially very significant. Population pressure has resulted in high demand for land for different economic activities. Unless the benefits of the ecosystem services are explicitly measured, these benefits would be ignored in decisions on land use and result in underconservation of the mangroves. Ecosystem service valuation is therefore essential for sustainable land-use planning.

This research examines and quantifies the storm protection services of mangroves based on the October 1999 super cyclone damage data related to human lives, residential houses, and livestock loss in Kendrapada district of the eastern Indian state of Odisha.[1] Mangroves are seen to provide static resilience to coastal people by reducing loss of lives and damage to property during this storm and the storm protection value of mangroves is used to examine whether mangrove conservation is economically viable or not. In the coastal zones of Bangladesh which is also affected by frequent cyclones, Mahmud et al., (2021, Chap. 20 of this volume) describe local level learning effects by those affected. While in Indian Sunderbans, Ghosh and Roy (2021, Chap. 26 of this volume) find that younger educated residents and migrating as an adaptation strategy.

17.2 Why Use Averted Damage Approach to Measure Storm Protection Services

The measurement of storm protection value of mangroves, which was earlier equated to only that of constructing a sea wall at the coastline (Chan et al., 1993), has undergone tremendous methodological innovations in course of time. Both stated and revealed preference methods have been used to measure storm protection, the former being less advised due to the fear that people usually overestimate risks (Spanink & Beukering, 1997). Use of surrogate market-based methods like defensive expenditure and hedonic prices are also discouraged as they either overestimate or underestimate the storm protection value of mangroves because of high maintenance cost of substitutable structures or imperfect property markets (Bann, 1997). Researchers have also

[1] Called Orissa before the 113th amendment to the Indian Constitution on 24 March 2011.

used avoided expenditures and replacement costs methods to value this service (Sathirathai, 1998; Tri et al., 1996). However, all such methods measure storm protection indirectly and produce a proxy value. In comparison, the avoided damage approach takes into account the actual damage suffered in mangrove protected areas compared to damage in areas not protected by mangroves and provides a more realistic measure. It follows the production function approach where the storm damage as a function of storm features, location, and socio-economic factors including mangroves is estimated in step 1 and in step 2; the damage averted due to mangrove presence is quantified. It was pioneered by Farber (1987) and has been used to measure the protection provided by mangroves from storm (Costanza et al., 2008) as well as tsunami damage (Kathiresan & Rajendran, 2005). The expected damage function (EDF) has been suggested as an alternative method to measure the protection services of mangroves (Barbier, 2007). Presence of wetlands in some areas will reduce damage, and thus, the amount of compensation to be paid to the household and this change can measure the storm protection value of the wetland. However, the estimation technique as developed by Barbier (2007) is a variant of avoided damage (Costanza et al., 2008, pp 246).

Though the averted damage approach has the advantage of being based on the actual damage, it can estimate the protective service of mangroves accurately provided one controls for the impact of other factors that influence the occurrence of storm damage (Das, 2007). Otherwise, it can generate either a spurious or a highly inflated protection value due to omitted variable biases. The present paper follows this methodology and takes into account a wide range of socio-economic, geo-physical, and meteorological variables as controls to separate the impact of mangroves from those of other factors on storm damage. I arrive at a comparatively lower but possibly more accurate estimate of the storm protection value of the mangroves.

17.3 Study Area and the Mangroves

This study is based on village and gram panchayat level damage data from the *Kendrapada district* in Odisha (Fig. 17.1). This district is one of the most vulnerable districts in India having a high annual probability (nearly equal to one) of being hit by cyclones (Das, 2009) and was severely impacted by a super cyclone in Oct 1999. The cyclone had its landfall at a place called *Ersama*, 20 km southwest of Kendrapada. The district was the ideal choice to measure the storm protection services of mangroves as (1) it was situated north of the eye of the cyclone and path of the cyclone throughout,[2]

[2] In northern hemisphere, the direction of the cyclonic wind is anticlockwise and thus the wind direction in Kendrapada was from sea to land through the mangrove forest.

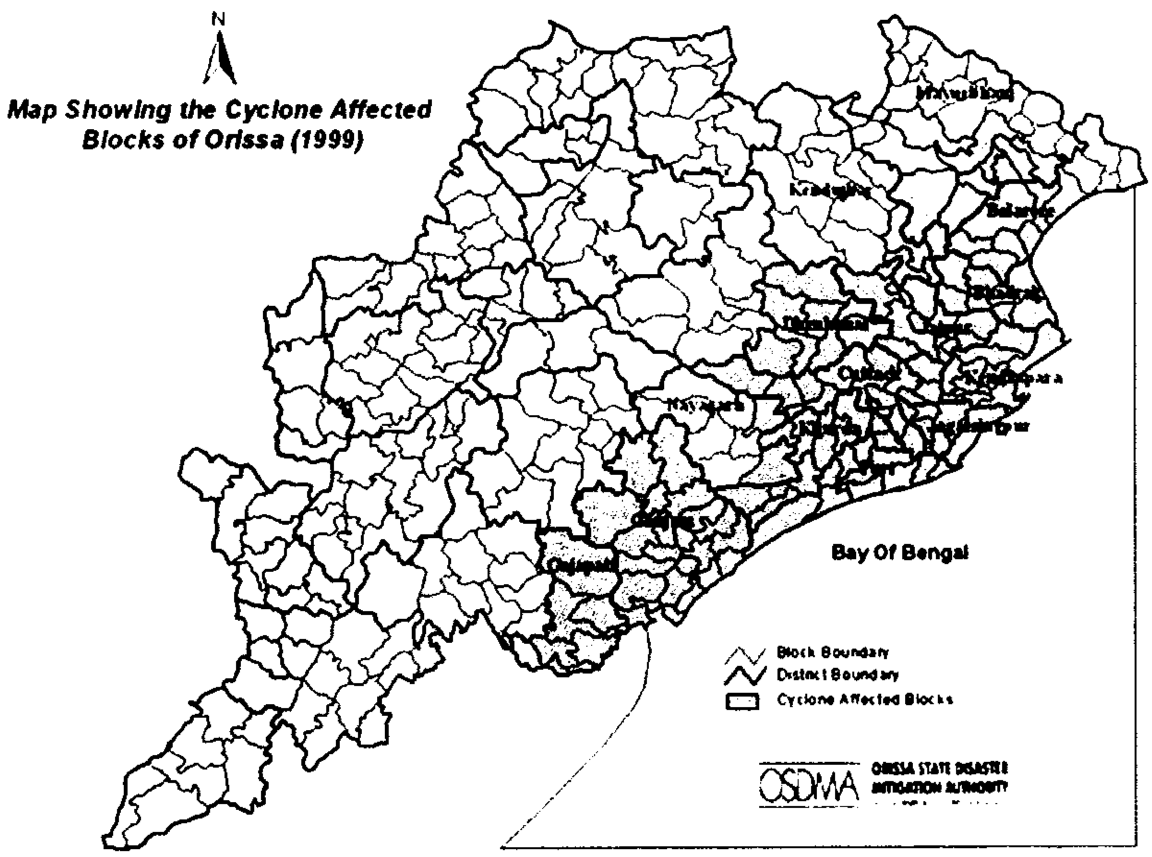

Fig. 17.1 Kendrapada district in cyclone hit Orissa. *Source* Orissa State Disaster Management Authority, Government of Odisha

(2) has mainly mangrove forest[3] and barren areas on the coast line, and (3) is devoid of highlands, the average elevation being less than 10 m everywhere (NATMO, 2000).

Kendrapada was an economically backward district with nearly 50% of the population living below the poverty line, 94% living in rural areas and around 2% of the rural houses having concrete structures when the storm struck in 1999.

17.3.1 The Mangroves of Kendrapada

The State of Orissa has 480 km of coastline covering seven coastal districts and 5133.60 km^2 of coastal wetlands. The state was endowed with rich mangrove cover historically; with nearly 500 km^2 in 1944, which was destroyed over time leaving it with 227 km^2 of mangrove forests, most of which (88%) is located in the Kendrapada district.

[3] The main forests were the mangroves though a few patches of Casuarina plantations were also to be found in the coastal areas before the cyclone. But the width of these plantations everywhere was between 200 and 400 m.

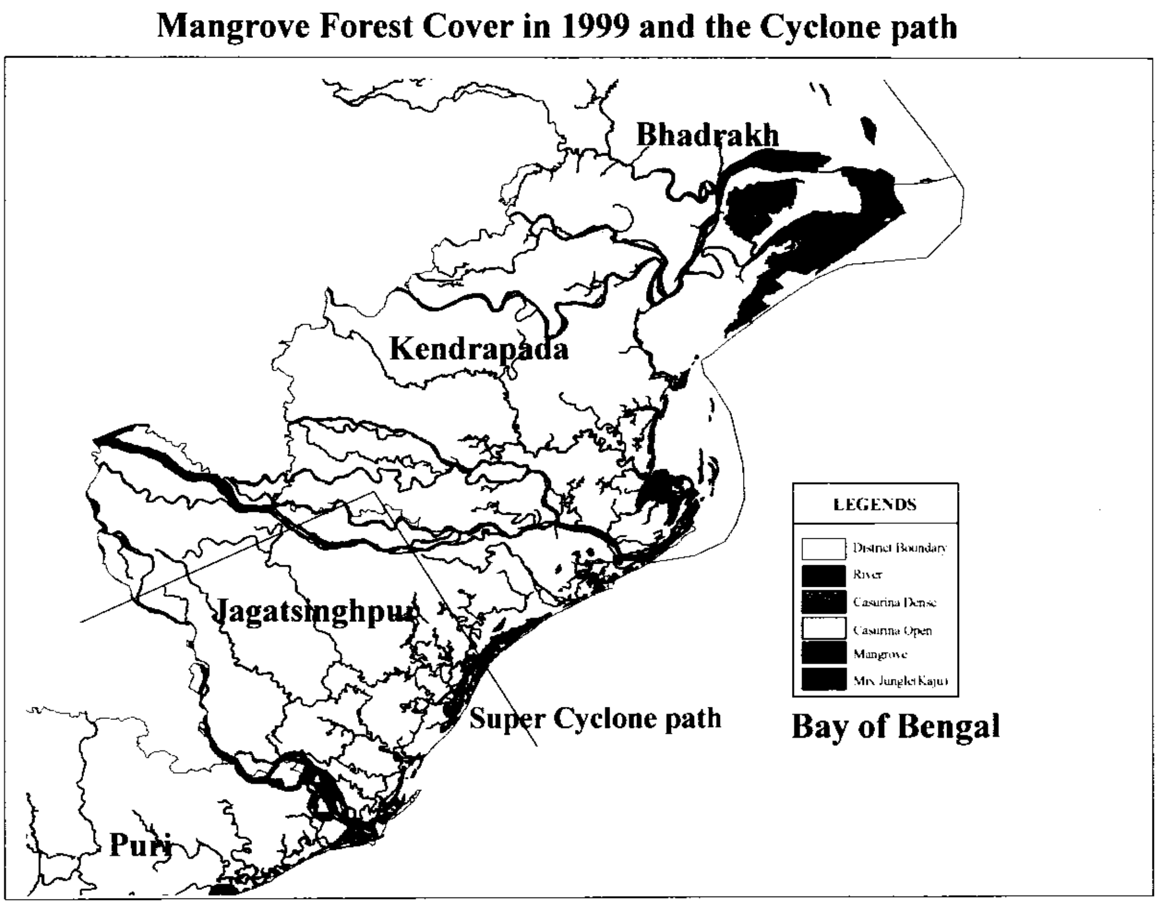

Fig. 17.2 Mangrove and other coastal forests of Kendrapada and Jagatsinghpur districts in October 1999. *Source* Das (2011)

Though both Jagatsinghpur and Kendrapada were the major mangrove districts of the state and witnessed mangrove loss, the loss was nearly 100% for Jagatsinghpur district (from 177.27 km^2 in 1944 to 5 km in 2001), whereas it was around 37% for Kendrapada (from 306.7 in 1944 to 192 km in 2001). In Kendrapada district, the mangroves are found in two patches as seen from Fig. 17.2 that shows the mangrove cover in Jagatsinghpur and Kendrapada districts as it existed on 11 Oct. 1999. In Kendrapada, 89 villages have been established after cutting down the mangroves, which are labelled as mangrove *habitat villages* and have been accounted for separately in the analysis.

17.3.2 Drivers of Mangroves Loss in Orissa

Figure 17.3 shows the mangrove forest map of the districts Jagatsinghpur and Kendrapada as it existed in the year 1944. As evident from the figure, more than 80% of the coastline from the mouth of the river Devi to the mouth of the river Dhamra was covered by mangrove forests of more than 10 km width as these areas are criss-crossed by river channels and their tributaries and rivulets (seen from the figure also). The mangrove forest of Jagatsinghpur district and the Mahanadi delta mangroves of

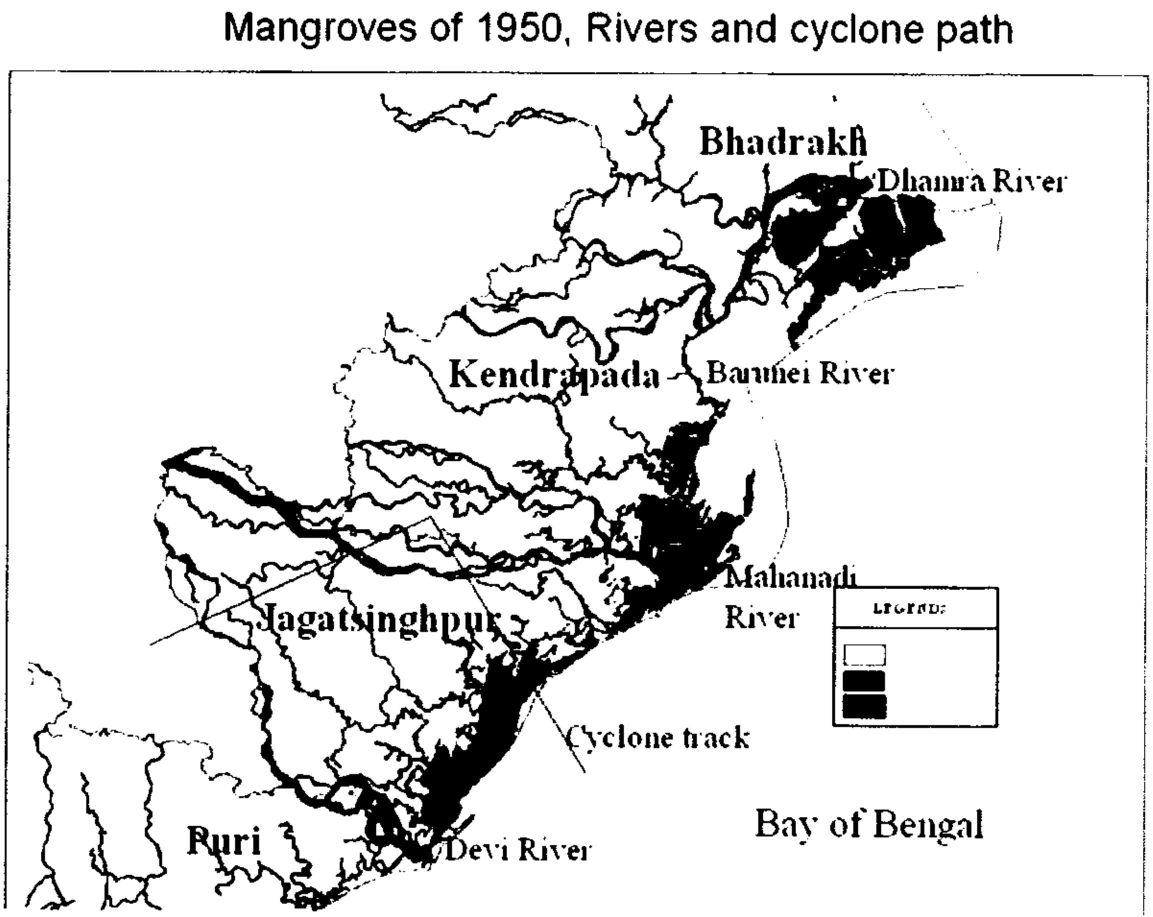

Fig. 17.3 Mangroves of Kendrapada and Jagatsinghpur districts as in 1944. *Source* Das (2011)

Kendrapada district were known historically as the Kujang Forest, and the mangroves of Bhitarkanika region, Bhadrakh, and Balasore districts were known as the Kanika forest after the name of the princely states that used to rule over these areas. Though there is less research on the drivers of mangrove loss in the State of Orissa, local vernacular publications and independent studies done by researchers and NGOs overwhelmingly link the loss of mangrove forests to the political economy of the state. The maximum mangrove destruction occurred during the 1960s and 1970s for various reasons including the lack of proper jurisdiction during the period following the abolition of Zamindari in 1957 till the formation of the Wild Life Division in 1980. The creation of the Paradeep port, rehabilitation of refugees from then East Pakistan (present-day Bangladesh), lack of knowledge of mangrove values, and conversion of mangrove land for betel vine, agriculture, and aquaculture farms, etc. are some of the main reasons for the destruction of the mangroves (Choudhaury, 1990; Das, 2009; Mohanty, 1992). The Ministry of Environment and Forest, Government of India, had listed the existence of 15 different types of threats to mangroves of the region (Das, 2009), the maximum being anthropogenic in nature, with the clearing of the forest due to the subsistence requirements of the people being the most prominent one. Another interesting observation was that the local people were not keen on preserving the mangrove. Though people have realized the importance of mangroves in their day to day life, there are still threats to mangroves from local inhabitants, which is reflected in their unhappiness and anger after the Bhitarkanika area was declared a national park by the government in 1998 (Badula, 2002). The mangroves of Bhitarkanika region probably survived when state protection was missing because of the presence of ferocious animals and interior location of the area. After the announcement of sanctuary and national park, government protection and strict implementation of laws have been able to protect the mangroves there.

17.4 Data

The paper analyses three types of asset damage due to the super cyclone, i.e. human lives, residential houses and livestock, which are collected from various sources (see Das, 2007 for detail). The data set for the human casualty model is at the village level and it consists of 1180 villages. The house damage analysis is based on heterogeneous units covering 451 villages and 138 *Gram Panchayats* and the analysis for livestock is based on data at a *Gram Panchayat* level analysis covering 216 *Gram Panchayats*. These differences in units and coverage area are due to the limitations of data which was only available in that format and for those specific areas.

Estimated cyclone damage models from Das (2011), which were based on Das (2007), are used in this paper to estimate the storm protection value of mangroves. Das (2007) did extensive testing for determinants of human death, three types of house damage (fully collapsed, partially collapsed, and swept away houses), and five types of livestock loss (cattle, buffaloes, sheep, goat, and poultry) suffered during the October 1999 super cyclone. Results for different sample areas were compared to infer the effectiveness of mangrove protection. Sample 1 was the entire study area excluding villages that never ever had mangroves in their coastal distance (called the mangrove non-habitat villages). Mangrove non-habitat areas were excluded as they can never be protected by mangroves or storm protection value of mangroves is meaningless for them. Secondly, by leaving them, I control for the topographic and bathymetric features of the study area[4] as my treatment villages (the ones protected by mangroves) and the control villages (the ones not having mangroves in their coastal distance during the 1999 cyclone, but which used to have mangroves that were destroyed over time) have similar bathymetry and topography. Sample 2 is sample 1 minus the areas falling under the cyclone eye. The wind direction inside the cyclone eye area being circular (anticlockwise before the eye passes and clockwise afterwards), the forest can provide little protection. Hence, the expectation is that the storm protection value per unit of mangroves is accurately captured in sample 2 and sample 1 is the entire area protected by mangroves.[5] Storm damage models based on sample 1 and 2, not others, are used in the paper. For estimating the storm

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[4] Mangroves come up in areas with similar topographic and bathymetric features.

[5] In Das (2007), samples 3, 4, and 5 were parts of sample 2 that were within 10 km distance from coast, beyond 10 km distance from coast and suffered storm surge inundation during the cyclone, respectively. These samples 3, 4, and 5 are not discussed in the present paper.

protection value, I consider only those damage models of Das (2007) for the above two areas where the mangrove was found to have a statistically significant effect, i.e. human death, fully collapsed houses, partially collapsed houses, and losses of both cattle and buffaloes. See Das (2007, Tables 1, 2, 3, 4, 7, 8, and 10) for description of variables and regression results used.

17.5 Methods

First the physical estimates of damage avoided due to mangrove presence have been calculated, and then in step 2, this averted damage is valued to estimate the storm protection value. Averted damage is defined as the difference between the actual damage witnessed and the predicted damage in absence of mangroves. These are measured for different sample areas described above and for three different scenarios, i.e. no mangroves, if historical mangroves were present and if historical mangroves were present and mangrove habitat villages were not there. After measuring the averted damage for the three assets, i.e. human life, houses, and livestock, these damages are valued and summed to measure per unit storm protection value. In the valuation process, the differences in units and coverage of study areas are carefully taken into account to arrive at a realistic and representative value void of ambiguities and biases. Local prices prevailing in the study area and value of statistical life generated for India are used in valuation.

17.6 Results

17.6.1 Averted Damage

In total, 392 persons lost their lives during the 1999 cyclone in sample 1 area but the toll may have been 603 in the absence of the mangrove (Table 17.1). Thus, 211 deaths (54% of the lives lost in that area) were possibly averted due to the presence of the mangroves. The mangroves provided greater protection to areas of sample 2, where 217 deaths (82% of lives lost in sample 2) were estimated to have been averted by mangroves.

If the historical mangrove forest (as existed in 1944) had not been cleared by 1999, only 31 persons would have probably died instead of 392 in sample 1 area, even if the 89 forest villages would have been where they are. However, if the 89 coastal villages had not been permitted in the mangrove area, there would probably have been only 17 casualties.

In the absence of the mangroves, the number of fully collapsed houses may have been higher by 19,936; partially collapsed houses lower by 14,049 indicating that some of the partially collapsed houses would have been completely damaged (see

Table 17.1 Averted human death due to mangrove forests

	Actual deaths 1	Predicted death if mangrove = 0 (Assump-1) 2	Predicted death if mangrove = mhabitat (Assump-2) 3	Predicted death if mangrove = mhabitat and mangrove habitat villages = 0 (Assump-3) 4	Averted deaths (1–2) 5	Averted deaths (1–3) 6	Averted deaths (1–4) 7
Sample-1 ($N = 840$)	392	603	31	17	211 (54%)	361 (92%)	375 (96%)
Sample-2 ($N = 711$)	266	483	25	11	217 (82%)	241 (91%)	255 (96%)

Table 17.2 Volume of house damage and livestock[a] loss averted due to the mangrove forests (figures are numbers)

Damage type	Assumption-1		Assumption-2		Assumption-3	
	Sample-1	Sample-2	Sample-1	Sample-2	Sample-1	Sample-2
Fully collapsed houses	19,936	13,110	178,660	82,225	165,975	74,675
Partially collapsed houses	−14,049	−12,657	−125,900	−79,376	−119,702	−72,087
Buffaloes	704	683	1320	994	1399	1100
Cattle	3844	4668	17,946	12,993	17,385	12,312

[a]Swept away houses, goat, sheep, and poultry have been left out as mangrove was insignificant for them in all models

Table 17.2). Similarly, buffalo and cattle loss would have been higher by 704 and 3844, respectively, in sample-1 area. These figures would have been 13,110, −12,657, 683, and 4668 in sample 2 area. If the 1944 forest had been there, not a single house would have fully collapsed in both the sample areas.[6] We would probably have witnessed only partially collapsed houses.

17.6.2 *Storm Protection Value of the Mangroves*

The valuation of damage is done with the aim of understanding: (a) the saving in government compensation disbursed to victims and (b) the social benefit of

[6] This is inferred from the derivation that the number of averted fully collapsed houses (due to historical mangroves) is higher than the actual number of fully collapsed houses in those areas.

mangroves when valued at market price. Accordingly, the damages are valued @compensation paid, @revised compensation rates, and @prevailing market prices of damaged assets in 1999. What prices are used and how the value of statistical lives is adjusted to value human deaths are described in Das (2009).

17.6.2.1 Average Storm Protection Value

The mangrove variable was measured as kilometre width of the forest, and thus, the average storm protection value (ASPV) of every kilometre width of the existing and historical mangrove forest to a village are measured for sample 1 and sample 2 areas under the three assumptions. First these are measured for each of the damages separately and then added across the damages to measure weighted average storm protection (WASP) value to a village. These are shown in Tables 17.3 and 17.4. The ASPV to a village in sample 1 is Rs. 2239 for protecting human lives and Rs. 1157 for reducing house damage[7] (see Table 17.3, situation 1). If the 1944 forest were still there along with the villages subsequently established (Situation 2), these values would be Rs. 1207 and Rs. 2315, respectively. In situation 3, the corresponding values would be Rs. 1496 and Rs. 2488, respectively. These values are higher for sample 2 areas compared to the sample 1 area for every type of damage and situation. This suggests that the protective services of mangroves are more effective in the cyclone outer eye areas. The areas falling under the cyclone eye receive the strongest winds which are also circular and mangroves can provide little protection there. Thus, our hypothesis of using sample 2 as a more accurate valuation scheme for storm protection services by mangroves is supported by these findings. Another observation is that the average value of present mangroves is much higher than historical mangroves for every sample area but only for averting deaths (both human lives and livestock), whereas the reverse is the case for house damages. The average width of present mangrove is much smaller (approximately 1 km) compared to historical mangrove (approximately 4 km). This suggests that the relation between mangrove width and protection from different types of damages may not be linear. Having more mangroves may not help in averting more deaths but seems to avert more house damages. This allows for calibrating mangrove size depending on the social objective, and an optimum width of the forest can be defined to act as buffer during cyclones.

The WASP value provided by a kilometre of present mangrove in a village is Rs. 3928.43 when valued at market prices (see Table 17.4). However, if government compensation rates were used to determine these values (in terms reduced compensation to be paid), it varies between Rs. 46.55 (@actual amounts paid) and Rs. 183.63 (@revised house damage compensation rates). The average storm protection values of kilometre width of historical mangroves, shown in columns 3 and 4, varies between

[7] This is computed as value for reduced FC houses (Rs 1331)—value for increased PC houses (Rs 174).

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Table 17.3 Average storm protection value per village provided by every km width of present mangrove and historical mangrove (in Rs.)

Type of damage	Value/km of present mangrove/village		Value/km of hist. mangrove/village (coastal villages remaining)		Value/km of hist. mangrove/village (coastal villages removed)	
	Sample-1	Sample-2	Sample-1	Sample-2	Sample-1	Sample-2
Human death	2239.35	2743.95	1207.87	1132.44	1495.68	1478.28
Fully collapsed houses	1331.53	1368.55	2663.52	3143.39	2873.11	3235.85
Partially collapsed houses	−174.42	−245.59	−348.88	−564.03	−385.15	−580.85
Buffaloes	5.91	8.77	2.32	3.97	2.62	4.83
Cattle	26.87	49.94	26.32	43.20	27.17	45.07

Notes Rates (market prices) used are: Value of Statistical life @ Rs. 10,918,132/; Price of FC house @ Rs. 53,800/; Price of PC house @ Rs. 10,000/; Price of Buffalo @ Rs. 6000/; Price of Cow @Rs. 5000/ and) Price of Sheep @ Rs. 1200/

Table 17.4 Weighted average storm protection value for a village by every km width of present mangroves and historical mangroves (in Rs.)

Value @ different valuation rates	Value/km of present mangrove	Value/km of hist. mangrove (coastal villages remaining)	Value/km of hist. mangrove (coastal villages removed)
Value @ government compensation paid	46.55	68.69	72.9
Value @ revised government compensation for house damage	183.63	385.42	399.06
Value @ market price and VSL with $\varepsilon = 0.35$	3928.43	3761.4	4185.68

Note: ε represents the income elasticity of marginal willingness to pay

Rs. 69/ and Rs. 4186/, and the values are the highest if the coastal villages established in mangrove habitat areas are relocated (situation 3).[8]

17.6.2.2 Total Storm Protection (TSP) Value

There are around 1250 villages in Kendrapada district and of which 850 villages had mangrove historically between them and the coast (sample-1) and 580 of these villages were outside the cyclone eye (sample-2). Sample 1 being the entire area that receives storm protection from mangroves, we multiply the unit values of present mangroves shown in Table 17.2 by 850 to get the TSP value (for protecting human lives, residential houses and livestock) of every kilometre width of the forest to the state exchequer and the society.

Dividing the value of total avoided damages of sample 1 area by the mangrove area (17,900 ha), total savings to the state exchequer and to the society by every hectare of the present forest were also calculated (see Table 17.5).[9]

A 1 km width of the forest saved Rs. 3,339,166 for the economy and Rs 3968 to the state government in the form of reduced compensation liability (Table 17.3).[10] In comparison, the savings by every hectare of mangroves forests are Rs.182, 080/

[8] The volume of damages averted due to mangrove presence being low for the mangrove habitat area villages, the unit values increase as these villages are removed from the analysis.

[9] As mentioned before, the per hectare values are the simple averages. To get the value at market price, we simply added the market values of different averted damages of sample 1 area and then divided it by the area of the present mangroves. Only sample 1 area was considered as that is the entire area benefited by mangroves. We did similarly to get values at other valuation rates.

[10] The savings to the state government by the present mangroves would have been Rs 156,083/ if the revised compensation rate was used.

Table 17.5 Total storm protection value (for Kendrapada) by every km width and by every hectare of present mangroves

	Value of damage averted per km (width) of mangrove	Value of damage averted per ha (area) of mangrove
Saving to state government in compensation paid in 1999	Rs. 39,568/(USD 943)	Rs. 2339/(USD 56)
Saving to state government if revised compensation for house damage would have been applicable in 1999	Rs. 156,083/(USD 3716)	Rs. 8550/(USD 204)
Saving to district economy (value of damages at market prices)	Rs. 3,339,166/(USD 79,504)	Rs. 182,080/(USD 4335)

Notes The exchange rate used is IUSD = 42 INR as prevalent in 1999

to the district economy for reducing human death, damage to residential houses, and loss of livestock.[11]

On the basis of these values, we try to analyse one important policy question, i.e. should the remaining mangroves be preserved to receive storm protection given high demand for land for alternate uses?

17.6.3 Is Mangrove Preservation Economically Justified?

This question is analysed by comparing the land price of agricultural land in cleared forest area (opportunity cost of preserving forest) to the storm protection value per ha of the forest. The average land price in Mahakalpada tehsil of Kendrapada, where maximum of the mangrove forests were converted to other uses, was Rs. 172, 970 per hectare during [12] 1999–2000. The partial storm protection value of a hectare of mangroves at market prices being Rs. 18,208 (Table 17.5) to the district for protecting only three assests (human lives, livestock and houses), prima facie, there is a strong case for the preservation of the forest. However, we also compare the annualized returns of these two values.

We assume the three types of averted damages discussed in this paper to constitute one-tenth of the total averted damages of mangroves by a conservative estimate.[13]

[11] Every hectare of mangrove saved the state exchequer Rs. 2339 (actual compensation paid) or Rs.8550 (revised rates) in the form of reduced compensation.

[12] The land price as reported by the land registration office varied between Rs. 70,000/ to Rs. 100,000/ per acre around 1999 (Personal communication with Jatindra Dash, IANS), and the land price in mangrove adjacent area being on lower side, we use the lower limit, i.e. Rs 70,000 per acre and this calculates the price per hectare as Rs. 172,970.

[13] Badola (2002) estimated the total storm protection value of Bhitarkanika Mangroves of Orissa during the same super cyclone of Oct 1999 by considering the protection of mangroves from multiple damages and found the value to be equivalent of USD 116.28 per household. As the average number

By this assumption, the storm protection value of a hectare of mangrove during super cyclone of October 1999 works out to be Rs. 1,820,800 which is much higher than the land price.

17.6.3.1 Probability of Extreme Events and Annualized Benefits

The study area is highly cyclone prone and records of the past 200 years reveal that the frequency of very severe cyclonic storms has gone up significantly in the last 3–4 decades. In between 1903 and 1999, Orissa witnessed 52 cyclones of which eight were Very Severe Cyclonic Storms and one was a Super Cyclone (Chittibabu et al, 2004). Moreover, six of the nine devastating cyclones occurred in the last 30 years so the annual probability of occurrence of a devastating cyclone is 0.2. Thus, the probability adjusted annual storm protection value of a hectare of mangrove (Rs. 364,160) is more than twice the market price of land cleared of forest. If we assume an interest rate at 8% per annum,[14] the annual opportunity cost of preserving mangrove forest at 1999 prices works out to be Rs. 13,837 or Rs. 20,756 if we assume a very high return @12% per annum. The annual benefit from protecting forest is therefore 18–26 times higher than the annual opportunity cost of preserving the forest. These findings support protection of mangrove forest to get storm protection benefit as a socially desirable strategy. Even if we use a lower annual probability of any cyclone (0.09 per annum), the mangrove preservation will still be justified. Under these rates and with the lower cyclone probability (0.09 per annum), the net present benefit to society or welfare gain to society from preserving mangrove forest is Rs. 143,393 and Rs. 215,089 per ha with 12 and 8% discount rates, respectively. These numbers indicate a very high benefit from preservation of the remaining mangroves.

17.6.4 Land-Use Change

Was the destruction of mangrove forest in the past economically justifiable? As mentioned earlier, 12,866 ha of mangroves were converted between 1950 and 1999 mainly for agriculture. We now estimate the net loss in protective cover that could have been averted if the mangrove of 1944 level was not destroyed. We calculate this as the difference between the market values of avoided damages ($\sum$VAD) with historical mangroves and the present mangroves ($\sum VAD_{1944} - \sum VAD_{1999}$).

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of household in her study villages is 37, this gives the total storm protection value as USD 4302 per village which is 45 times higher than the highest storm protection value per village obtained in the present study. So a 10 times escalation of benefits to estimate total benefits is still on the conservative side.

[14] In the absence of information on rate of return from agriculture in coastal Kendrapada, we calculated annual return @8% which is the average of the estimated range of real discount rates (7.6–9.7%) from the Indian labor market studies and also comparable to financial market rates in 1990s (Shanmugam, 2006).

Dividing the above value by the area of the lost mangrove forest (12,866 ha), the extra burden for destroying every hectare of forest comes out to be Rs 706,882 for only three damages. The benefit of forest destruction, which is captured by per hectare land price, is much lower than this. Under the assumption that these three averted damages are one-tenth of the total averted damages of the mangroves, the extra burden for destroying every hectare is Rs 7,068,820. If we multiply this value by the annual probability of devastating cyclones (0.2), the probability adjusted annual burden due to loss of storm protection cover comes out to be nearly seven times higher than the benefit from forest destruction (i.e. the land price of cleared forest land).

We may infer that the social benefit of retaining the forest cover is much higher than the current land value (Rs1, 72,970 per ha). As noted earlier, the benefits estimated are lower bound values, and therefore, actual benefits are likely to be much higher than indicated here.

17.7 Conclusion and Policy Implications

The study quantifies the storm protection services of mangroves of Odisha and the storm protection value of every km width of present mangrove to have been Rs 39,568 to the state exchequer in the form of reduced compensation and Rs 3,339,166 to society for saving human life, livestock, and preventing house damage. The per hectare benefits (for just averting the three damages) were estimated to be Rs 182,080. These three damages are a small proportion of the total damages averted by the mangroves. Making some conservative assumptions, we find the cyclone probability adjusted annual storm protection value per hectare of mangroves to be more than twice the market price of cleared mangrove forest land and 18–26 (or nearly 20) times higher than the annual return from land. All these suggest the preservation of remaining mangroves as a socially and economically viable strategy to receive storm protection services.

Mangroves save lives and properties in the vulnerable coastline areas and thus provide static resilience to society during natural disasters like storms. This is also found by Mahmud et al., (2021, Chap. 20 of this volume) in the context of Bangladesh. Climate change makes it imperative to conserve the mangroves and policy makers need to make arrangements for their protection. Usually, people living in areas around the mangrove do not realize the importance of mangroves as most of the ecosystem services are invisible and indirect. Awareness generation can go a long way in ensuring mangrove conservation, especially in vulnerable coastal areas like the state of Odisha.

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SANDEE working papers to measure the averted damage by mangroves, values them and finally examines the question of mangrove conservation to build resilience. An earlier version of this paper titled "The Case for Mangrove Conservation: Valuing Damage Averted in Orissa's 1999 Super Cyclone" was presented at the 4th World Congress of Environmental and Resource Economists (WCERE) held in Montreal, Canada, during 28th June to 2nd July 2010. The paper has been enriched after addressing the comments received from reviewers, discussant, and from the floor.

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Annexure A-13

Mangrove Management for Climate Change Adaptation and Sustainable Development in Coastal Zones

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Mangrove management for climate change adaptation and sustainable development in coastal zones

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Mangrove management for climate change adaptation and sustainable development in coastal zones

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ABSTRACT

Due to their prevalence in developing countries and the range of ecosystem services they provide, projects aimed at promoting mangroves align with several of the UN Sustainable Development Goals—specifically Goals 13, 14, and 15—which concern adaptation to climate change and the sustainable management of forest and coastal resources. Although mangroves themselves are sensitive to climate change, they also provide services that would help reduce damages, by sequestering carbon, enhancing coastline stability, and protecting coastal settlements from tropical storm surges. In particular, mangroves can rapidly colonize and stabilize intertidal sediments, promoting coastal accretion to reduce the impact of sea level rise. The Government of Bangladesh has established mangrove plantations with the intent to accelerate accretion and stabilize 120,000ha of coastland. As a case study, this paper uses GIS data on coastal dynamics and land cover to evaluate the effectiveness of mangrove plantations for facilitating accretion and preventing erosion in Bangladesh. The results indicate that plantation areas experience greater rates of accretion relative to erosion than non-plantation areas, confirming that mangroves have an important role to play in the sustainable development of coastal regions.

KEYWORDS

Bangladesh; climate change adaptation; coastal erosion; ecosystem service; land accretion; mangrove plantation; Sustainable Development Goals

Introduction

Mangroves are coastal and riverside forests that thrive at interfaces between land and sea in the tropics and subtropics. There currently exists approximately 14 to 15 million hectares of mangroves distributed across 124 countries, most extensively in developing countries in Asia (Food and Agriculture Organization [FAO], 2007; Giri et al., 2011). These ecosystems provide a wide range of goods and services, such as forestry products, fisheries, and non-timber forest products (Agrawala et al., 2005; FAO, 2007; McLeod & Salm, 2006). Other services include flood and erosion control, coastal stabilization, nurseries for marine fisheries, storm protection, and pollution filtering.

Mangrove management projects align with several of the United Nations Sustainable Development Goals (SDGs) (United Nations General Assembly, 2015). These include Goal 13: “Take urgent action to combat climate change and its impacts” (p. 23); Goal 14: “Conserve and sustainably use the oceans, seas and marine resources for sustainable development” (p. 23); and Goal 15: “Sustainably manage forests, combat desertification,

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halt and reverse land degradation, halt biodiversity loss" (p. 24). Mangrove management addresses the first and second targets of Goal 13: to "strengthen resilience and adaptive capacity to climate-related hazards and natural disasters" and to "integrate climate change measures into national policies, strategies, and planning" (p. 23). Also germane is the second target of Goal 14: to "sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts" (p. 23). While mangrove management is related to several targets under Goal 15, it most directly addresses the second: to "promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests, and substantially increase afforestation and reforestation globally" (p. 24).

As a coastal forest ecosystem, the role of mangroves in achieving SDGs 14 and 15 is self-evident. This paper focuses on SDG13, since mangrove management is unique among climate strategies in that it can provide both mitigation, through the sequestration of carbon, and adaptation, through stabilizing shoreline erosion, reducing storm surges, and preventing inland soil salinization. Mangroves are prevalent in developing countries more vulnerable to climate change. Seeking to protect coastal communities, countries anticipating sea level rise (SLR) and more powerful tropical storms due to climate change have undertaken projects aimed at preserving, restoring, and afforesting mangroves. For example, Bangladesh has long recognized the importance of mangroves and has successfully established over 50,000ha of mangrove plantations (Chow, 2015). Nine other least developed countries prioritize mangroves in their National Adaptation Programs of Action (UNFCCC, 2016). Despite such efforts, urban development, conversion to cultivation, and over-harvesting of wood products have resulted in deforestation rates of 1–2% per year—equivalent to about one-third of mangroves worldwide over the past 50 years—with the greatest losses occurring in the Indo-Malay Philippine Archipelago (Alongi, 2002; Duke et al., 2007; Hidayati, 2000; Polidoro et al., 2010).

This paper provides an overview of mangrove preservation, rehabilitation, and plantation projects as mitigation and adaptation strategies for developing countries to cope with climate change, in accordance with SDG13. The following sections review the potential climate change impacts on mangroves; their carbon sequestration capability and emissions from their destruction; and the ecosystem services that may ameliorate climate change damages. As an example, this paper also evaluates an illustrative case study concerning Bangladesh and its use of mangrove afforestation as a strategy for coastal land stabilization in its efforts to adapt to climate change.

Climate change impacts on mangroves

To help achieve SDG13, mangroves will need to be sufficiently resilient to climate change. Geological evidence suggests that mangroves have adapted to previous changes in climate and sea level (Alongi, 2015; Ellison & Stoddart, 1991; Field, 1995; Krauss et al., 2014; Parkinson, DeLaune, & White, 1994; Woodroffe et al., 2016). However, some mangrove species also occur in conditions that approach ecological tolerance limits, with mortality observed following minor variations in hydrological or tidal regimes (Blasco, Saenger, & Janodet, 1996).

The Earth warmed 0.65–1.06°C between 1880 and 2012 and will likely warm another 1.1–3.1°C by 2100 even when assuming stabilization scenarios (Intergovernmental Panel on Climate Change [IPCC], 2013). The temperature increase will favor expanded latitudinal ranges of

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mangroves—via the displacement of salt marshes—but with altered species composition (Alongi, 2002, 2015; Godoy and De Lacerda, 2015; Saintilan, Wilson, Rogers, Rajkaran, & Krauss, 2014). Range expansion would be limited by man-made barriers and by mortality due to extreme winter freeze events, as mangroves are most likely to disperse where temperatures are buffered by large expanses of water and saturated soil (Cavanaugh et al., 2013; Osland et al., 2017). The warming expected over the next century lies within the diurnal oscillation for many mangrove species, which can exceed 20°C, and thus, warming alone is not expected to adversely impact mangroves (Field, 1995; McLeod & Salm, 2006). Likewise, increased atmospheric CO_2 may enhance productivity, though the limited data suggest that not all species will respond similarly (Alongi, 2002; Edwards, 1995; Field, 1995).

Decreases in mean precipitation pose a greater threat to mangroves, which are adapted to a specific balance of fresh and saline water. Global precipitation rates are expected to increase unevenly, with increases and decreases in different regions. A decrease in rainfall (e.g., during winters in Central America and Australia) would reduce freshwater surface runoff and groundwater input to mangroves, resulting in increased soil salinity, decreases in productivity, growth, and seeding survival, and shifts to more salt-tolerant species (McLeod & Salm, 2006).

The intensity of precipitation events and the frequency of major cyclonic storms, resultant surges, and floods are also projected to increase, especially in the tropics (IPCC, 2013). In North America, Africa, and Asia, mass mangrove mortality has been observed following storms that uproot trees and leave soil vulnerable to erosion (FAO, 2007; McLeod & Salm, 2006). Increased tropical storm activity would also likely accelerate saline intrusion into coastal soils (Agrawala et al., 2005). Rapid sea level rise (SLR), the most problematic climate impact, will exacerbate inundation, salinity stress, and erosion, possibly causing mangroves' margins to retreat landwards (Friess, 2015; Gilman et al., 2006). If landward transgression is obstructed by human land uses, then the retreating mangrove could revert to a narrow fringe or be lost entirely.

However, mangroves possess characteristics that would help them adapt. They trap fluvial sediment from upstream sources and decaying litter fall, which accumulates as peat or mud and gradually elevates the soil substrate. Even under potential stabilization scenarios, global mean sea level is projected to rise 0.32–0.63m by 2100, or approximately 3.3–6.6mm per year (IPCC, 2013), with varying local rates (Krauss et al., 2014). These rates can exceed the vertical accretion observed in studies of mangrove peat cores and surface elevation measures, suggesting that some mangroves may not be able to keep pace with accelerated SLR (Lovelock et al., 2015; Sasmito, Murdiyarso, Friess, & Kurnianto, 2015). Resilience to SLR depends on site-specific conditions such as hydrodynamic factors, sediment inputs, plant productivity, and subsidence rates (Woodroffe et al., 2016). For example, limited sediment sources on Pacific low islands result in accretion rates of 0.8mm per year; mangroves there can tolerate under stress a SLR of only 0.9–1.2mm per year (Ellison & Stoddart, 1991). Mangroves on high islands are more resilient and can keep pace with rates of SLR up to 4.5mm per year, depending on the sediment supply (Ellison, 2000a). Mangroves in continental estuaries and deltas are more likely to keep pace with SLR thanks to the large volumes of sediment they receive (Agrawala et al., 2005). Cleared areas are prone to decreases in surface elevation, whereas rehabilitated mangroves have demonstrated increases at relatively high vertical accretion rates (Sasmito et al., 2015). However, other human activities, such as restrictions of upstream flows and groundwater extraction, can reduce accretion or increase subsidence, rendering mangroves more vulnerable to SLR (Woodroffe et al., 2016).

Climate-related damages to mangrove ecosystems also threaten human communities that rely on them for subsistence livelihoods. For example, traditional agriculture and fisheries in Bangladesh associated with the Sundarban mangrove system are well adapted to the tidal and seasonal variation in salinity levels moderated by the mangroves (Agrawala et al., 2005). Many coastal communities become trapped in a positive feedback loop of poverty, lack of livelihood choices, and over-exploitation of natural resources, resulting in degradation of the subsistence resource base and deeper impoverishment (King & Adeel, 2002). For instance, the clearing of mangroves for intensive shrimp aquaculture in central coastal Vietnam led to water pollution, pond failures, and indebtedness among farmers who invested heavily into this enterprise (Hui & Scott, 2008). Lifestyles dependent on mangrove ecosystems are often under additional pressure from conversion to aquaculture and other threats such as excessive logging, water diversion, and urban development. Government policies that encourage these activities often exacerbate the vulnerability of these communities to climate change (Adger, 1999).

Carbon sequestration and emissions

The high carbon (C) content of mangrove forests suggests that their stocks and fluxes should be integrated into national GHG accounting in accordance with Target 2 of SGD13. Mangroves can store carbon at greater densities than other forest types (Winrock International, 2014); thus, deforestation not only generates emissions, but also removes highly productive fixers of atmospheric C. Mangroves fix organic C well in excess of ecosystem needs for respiration, with excess photosynthetic C representing approximately 40% of net primary production (Duarte & Cebrian, 1996). The global average net primary productivity, combining leaf litter, root, and wood production, has been estimated to be approximately 1.8tC/ha-yr (Kristensen, Bouillon, Dittmar, & Marchand, 2008). Carbon accumulates in both tree wood and peat, and mangroves can sequester C at a rate of 1.5tC/ha-yr (Gong & Ong, 1990), with belowground biomass constituting 10–55% of the total biomass (Kristensen et al., 2008). Belowground sequestration rates in natural mangroves can vary from 0.15 to 2.24tC/ha-yr, and sequestration rates in mangrove plantations can exceed 6tC/ha-yr (Fujimoto, 2004). Globally, mangroves store an estimated $16*10^7$tC/yr in biomass and $2*10^7$tC/yr in sediment (Duarte, Middelburg, & Caraco, 2005; Twilley, Chen, & Hargis, 1992). The expansion of mangrove latitudinal ranges—as fewer freezing events fosters their supplanting of salt marshes—could bolster terrestrial C storage and exert a negative feedback on warming (Doughty et al., 2016).

On the other hand, late in the last century, nearly 50,000 square km of mangroves were lost to deforestation, releasing an estimated $3.8*10^8$tC stored as standing biomass (Cebrian, 2002). This number substantially underestimates the total carbon emissions from mangrove deforestation because it ignores belowground and detrital biomass. Due to high density below-ground storage, mangroves are among the most carbon-rich forests in the tropics, containing on average 1,023tC/ha in the Indo-Pacific region (Donato et al., 2011). However, the C density of mangroves varies dramatically by location (Hutchison, Manica, Swetnam, Balmford, & Spalding, 2014). Within Sulawesi, Indonesia alone, the total ecosystem C density can range from 415tC/ha in oceanic mangroves to 2203tC/ha in estuarine mangroves. The C densities of other mangroves worldwide lie within this range, with the density below-ground often greater than above-ground by an order of magnitude (Donato et al., 2011; Murdiyarso et al., 2015). Logging or conversion to agriculture can decrease the above-ground C density of biomass by at least 50% (Lasco & Pulhin, 2003). Conversion to aquaculture requires the excavation of at least 2 meters of sediments of high C content, so digging ponds can release another 70tC/ha-yr (Ong, 2002).

Given their capability and capacity for C sequestration, mangroves are potentially well-suited for generating monetary compensation from reduced emissions from deforestation and degradation (REDD+) (Murdiyarso et al., 2015). In practice, the inclusion of mangroves into REDD+ requires consideration of uncertainties regarding primary productivity, carbon fluxes, and coastal morphodynamics (Alongi, 2011).

Ecosystem services and climate change adaptation

Aside from C sequestration, mangroves produce a variety of other valuable goods and services that benefit local communities. These include services that increase climate resilience as mandated by the first target of SDG13, such as shoreline stabilization and storm protection.

Mangroves can colonize intertidal sediments and promote further vertical accretion and stabilization (Lee et al., 2014). Soil surface dynamics are mediated by both physical (e.g., water flux, inorganic sedimentation) and biological (e.g., plant debris deposition, root accumulation) processes. Extensive aerial root structures help keep soils compact and slow erosion, with the four different types—prop roots, pneumatophores, knee roots, and plank roots—varying in their effectiveness in retaining sediments (Krauss et al., 2014). By increasing sedimentation, reducing wave exposure, and forming peat, mangroves can accelerate land maturation and help mitigate vulnerability to tropical storm surges and SLR. For example, the mangroves of French Guiana help trap the sediments flowing through the mouth of the Amazon River (FAO, 2007). Researchers also have demonstrated that mangrove deforestation caused large-scale erosion in Vietnam (Mazda et al., 2002). Mangrove afforestation can reverse this effect, and plantations in Bangladesh have been used to help stabilize 120,000 hectares of coastland (Saenger & Siddiqi, 1993). Similar restoration programs have been underway in other areas prone to coastal erosion, including in Australia, Thailand, Vietnam, the Philippines, and Benin (Blasco et al., 1996). Results have been mixed, but suggest that plantations can play a vital role towards ecological rehabilitation (Bosire et al., 2008; Ellison, 2000b).

Many countries in South and Southeast Asia also have been increasingly undertaking restoration and preservation of coastal greenbelts as protection against tropical cyclones. Areas sheltered by mangrove forests experience less damage than non-forested areas (Ali, 1996), and mangrove tree species are more resilient to cyclone damage than non-mangrove species (Saenger & Siddiqi, 1993). Mangroves provide storm protection by dissipating and reducing the huge wave energies that occur during storms and typhoons. Their thickly grown leaves and dense networks of trunks, branches, and above-ground roots create drag forces that significantly reduce wave period and height (Mazda, Magi, Ikeda, Kurokawa, & Asano, 2006; Mazda, Magi, Kogo, & Hong, 1997; Quartel, Kroon, Augustinus, Van Santen, & Tri, 2007).

However, their effectiveness in storm protection can be attenuated by habitat degradation, or, in plantations, insufficient age (Dahdouh-Guebas et al., 2005; Mazda et al., 1997). Hence, mangrove shelterbelts can provide protection only if appropriately designed and managed. Degraded mangroves can provide less shelter than expected by local inhabitants, creating a false sense of security. Moreover, nations promoting efforts to utilize mangroves for storm protection must take into account the fact that the ecosystem itself is threatened by climate change and, therefore, must consider alternate or complementary adaptation strategies where appropriate.

Case study: Coastline stabilization in Bangladesh

Mangrove plantations and climate change adaptation in Bangladesh

Socioeconomic, geographical, and climatic characteristics make Bangladesh one of the countries most vulnerable to the damaging impacts of climate change (Agrawala, Ota, Ahmed, Smith, & Van Aalst, 2003; Ministry of Environment and Forest of the Government of Bangladesh [MoEF GoB], 2007). Bangladesh is economically underdeveloped, with an average per capita income less than the average for other South Asian countries, and more than a third of its population lives in poverty. Situated at the end of the Ganges-Brahmaputra-Meghna (GBM) river system, Bangladesh is largely composed of alluvial delta extremely prone to flooding, storm surges, and rapid geomorphological changes (Brammer, 2014). Bangladesh also receives the brunt of tropical monsoons and cyclones which funnel northward through the Bay of Bengal. Between 1991 and 2000, Bangladesh experienced 93 major disasters resulting in nearly 200,000 deaths and causing US$5.9 billion in damages with high losses in agriculture and infrastructure (MoEF GoB, 2007). SLR and a greater frequency of extreme weather events will increase coastal inundation, erosion, and saline intrusion, threatening poor households, coastal infrastructure, and agricultural productivity.

Since 1966, the Government of Bangladesh (GoB) has created mangrove plantations on newly accreted lands, or *chars*, in the coastal zones of Barisal and Chittagong Divisions as a defense against storm surge and to stabilize shorelines (Figure 1) (Iftekhar & Islam, 2004). The two main species used, *Sonneratia apetala* and *Avicennia officinalis*, are pioneers with pneumatophore morphology which establish well in low elevation zones (Sasmito et al., 2015). After assigning jurisdiction over 497,976ha of *chars* to the Bangladesh Forest Department (BFD) in 1976 (Islam, 2000), the GoB, with financing from the World Bank (Saenger & Siddiqi, 1993; World Bank, 2013), established approximately 148,500ha of mangroves by 2001 (Iftekhar & Islam, 2004). However, erosion and encroachment by settlements following land stabilization have destroyed most plantation attempts, especially in Chittagong Division where rapid accretion rendered areas suitable for conversion to agriculture. About 45,000ha of mature plantations remained in 2007, with the plantations in Barisal Division mostly intact (BFD, MoEF, Bangladesh Space Research and Remote Sensing Organization & Ministry of Defense, 2007).

Aligning with SDG13, the BFD continues to establish new plantations as part of a mitigation and adaptation strategy in response to climate change, according to the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) (United States Department of State, 2014) and the National Adaptation Plan (Bangladesh Ministry of Environment and Forest, 2009). The Strategic Program for Climate Resilience aims to

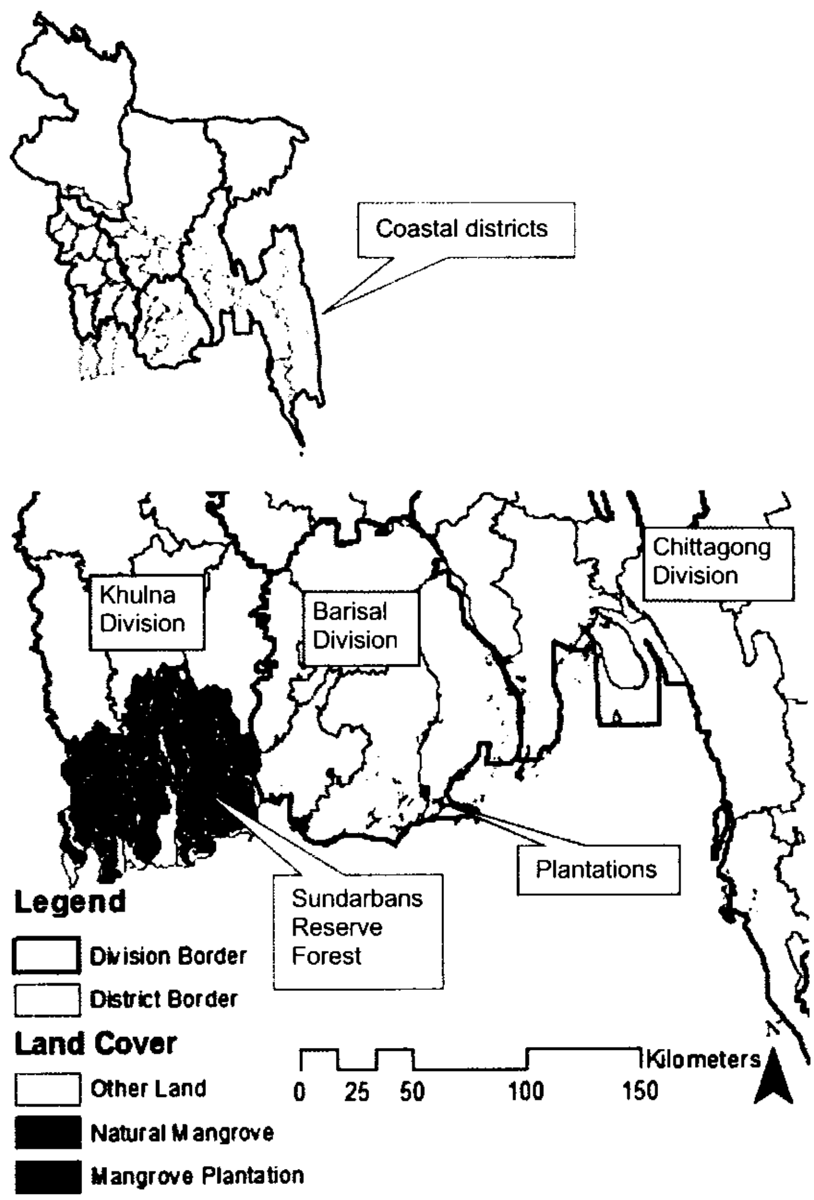

Figure 1. Map showing Sundarbans Reserve Forest and extent of mangrove plantations. Land cover information provided by the Center for Environmental GIS.

afforest 300ha on the seaward side of coastal embankments by 2020 (Forni, 2015; GoB, 2010). Additionally, the Community-Based Adaptation to Climate Change through Coastal Afforestation program afforested 9000ha of mangroves between 2009 and 2014 (United Nations Development Program [UNDP], 2011; P. Nandy, personal communication, 11 November 2015), and the Climate Resilient Participatory Afforestation and Reforestation Project plans to establish 5700ha of new mangroves (World Bank, 2013).

Although the Forest Department prohibits the felling of whole trees, these plantations are the sources of other ecosystem services for coastal villages, through the provision of fuelwood and other goods that constitute substantial value to these communities (Chow, 2015). However, the provision of regulating ecosystem services by these plantations, such as storm surge protection and erosion control, is not robustly supported by available empirical evidence. The lack of systematic and routine inventory and monitoring data in Bangladesh has complicated project assessment (World Bank, 2013). Econometric analyses suggest that any protective function against tropical storms imparted by the plantations generally has not been observable in agricultural and aquaculture production data (Chow, 2016). Moreover, the characteristics which determine the amount of protection are not well understood (Lee et al., 2014). However, anecdotal evidence suggests that the role of plantations in facilitating the stability of coastal land is potentially more promising (Iftekhar & Islam, 2004; Saenger & Siddiqi, 1993), though empirical studies often focus on only small areas limited in scope (e.g., Shaifullah, Mezbahuddin, Sujaiddin, & Haque, 2008). This case study compares erosion and accretion outcomes on coastal land that have mangrove plantations with lands which do not, using data derived from satellite remote sensing covering the entire plantation zone. Via GIS analysis, this case study provides evidence that mangroves in Bangladesh have contributed to enhancing erosion control and land accretion.

Methodology

The study area (20.7–23.0°N, 89.9–92.4°E) encompasses the Tentulia, Meghna, and Feni River estuaries and nearby deltaic islands, spanning the entire plantation zone in Barisal and Chittagong Divisions (Figure 1). Settlers removed almost all of the natural vegetation of this region over a century ago, and thus, the plantations are the only remaining dense vegetation cover (A. Nishat, personal communication, June 2, 2009). Coastal Bangladesh experiences slightly unequal semidiurnal tides, with a terrain generally at or near sea level; tidal heights vary, with tidal ranges reaching 3 meters at the spring equinox (FAO, 1985).

Historically, reliable recordkeeping—on where and when new and supplementary plantings have taken place—has been poor over most of the course of Bangladesh's mangrove plantation programs. There also has been a lack of large-scale follow-up data regarding the results of plantation activities, such as vegetation density and soil accretion, which makes coarser remote sensing-based approaches necessary. To capture the morphodynamics of coastal accretion and erosion, this study uses a GIS dataset created by the Bangladesh Space Research and Remote Sensing Organization (SPARRSO) from LANDSAT MSS imagery recorded in late January and early February of 1973 (60m pixel resolution), LANDSAT TM imagery recorded in January 1989 (30m resolution), and LANDSAT TM imagery recorded in January and March of 2010 (30m resolution) (Sarker, 2013). To encompass the entire area of interest, the following four data frames were used: 136/44, 137/44, 136/45, and 137/45. All data frames were recorded between 9:40AM and 10:40AM to coincide with morning high tides. Image processing was calibrated against tidal data at the date and time of each image capture at four tide gauges: Ramdaspur (22.80°N, 90.65°E), Char Changa (22.22°N, 91.05°E), Lohalia River (22.97°N, 90.50°E), and Sandwip (22.44°N, 91.46°E). Classification methodology is detailed by Sarker (2013), and outputs were verified by visual interpretation of satellite imagery.

The resultant dataset identifies land areas which accreted (i.e., newly exposed at high tide) or eroded (i.e., newly submerged at high tide) within two time periods: 1973 to 1989 and 1989 to 2010. These specific intervals were selected due to availability of unobstructed imagery for all data frames, which needed to also correspond with high tides, as well as span long enough periods to capture observable coastline changes. The first period roughly includes the earliest plantation efforts through the completion of the first major official development assistance-funded plantation effort, Mangrove Afforestation Projects I and II. The second period evaluates the outcome of the surviving plantations from previous efforts, as well as the Forest Resources Management Project and other efforts implemented prior to 2010.

This study also utilizes coastal land cover classification data from 2001 which identifies 66,000ha of mangrove plantations, created by the Center for Environmental Geographic Information Systems (CEGIS) from LANDSAT ETM+ and LANDSAT TM imagery (30m resolution) recorded in January 2001 during the dry season when the denser plantation cover is distinct from any cultivated land. Classifications were verified by visual interpretation of satellite imagery. I included a fifty meter buffer to account for accretion and erosion, beyond the immediate plantation boundaries, which may still be impacted by their presence.

Using ArcGIS 10 software (Esri, Redlands, CA, USA), I overlaid the land cover data identifying mangrove plantations over the dataset depicting changes in accretion and erosion, and calculated the areas within each change category (Figure 2). From this information, I calculated the ratio of erosion to accretion for both time periods for mangrove and non-mangrove (i.e., primarily mudflats, settlements, and agriculture) areas, in order to make comparisons that are independent of scale. Since the BFD selects plantation sites on *chars*, which may be undergoing some accretion even in the absence of mangroves, I also investigate the outcomes in 2010 of planted and unplanted land which was newly accreted between 1973 and 1989. This analysis comprehensively covers the entire plantation zone.

Results and discussion

About 118,000ha of new land accreted in Bangladesh from 1979 to 1989, with around the same amount forming between 1989 and 2010 (Table 1 and Figure 2). Approximately 54,500ha eroded during the first period, and 79,000ha eroded in the second. In both periods, Chittagong Division—particularly mainland Noakhali District, Urirchar island, Nijhum Dwip

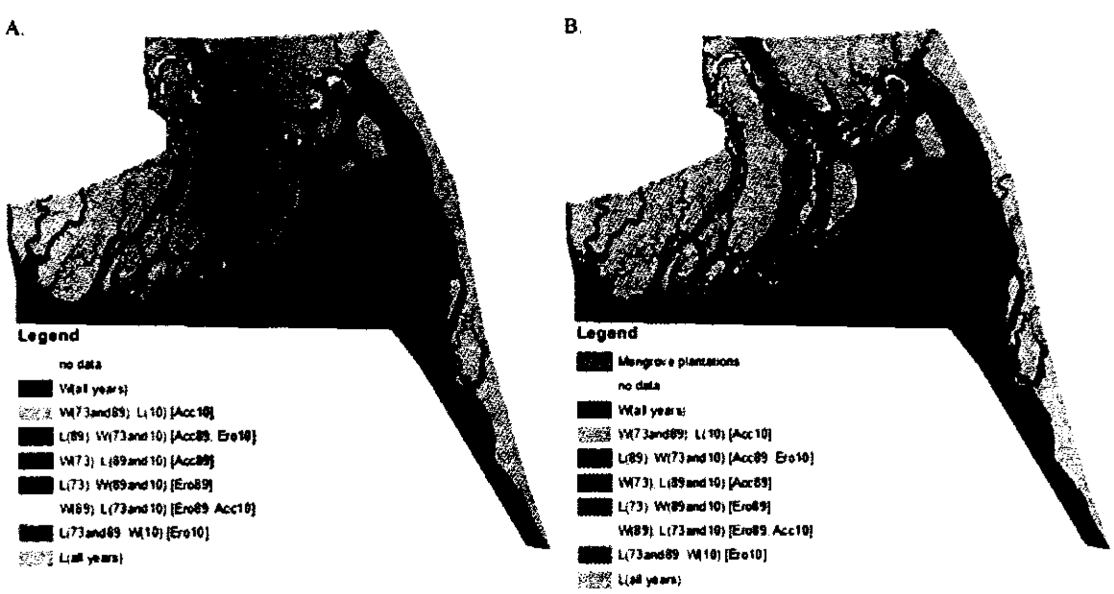

Figure 2. A) Coastal morphodynamics in Barisal and Chittagong Divisions from 1973 to 2010. Data from SPARRSO. B) Mangrove areas in 2001 overlaid on A). W = water. L = land. Years in parentheses. Observed land change (Acc = accretion; Ero = erosion) in brackets.

Table 1. Hectares of land accreted or eroded in plantation and non-plantation areas.

	1973–1989 all land	1973–1989 plantation	1973–1989 non-plantation	1989–2010 all land	1989–2010 plantation	1989–2010 non-plantation
Both divisions						
Accretion	117,848	30,933	86,916	118,477	17,425	101,052
Erosion	54,532	832	53,701	79,177	3,698	75,479
Ratio	2.2	37.2	1.6	1.5	4.7	1.3
Barisal Division						
Accretion	52,860	12,718	40,141	50,578	7,587	42,991
Erosion	31,680	312	31,369	42,082	1,779	40,303
Ratio	1.7	40.8	1.3	1.2	4.3	1.1
Chittagong Division						
Accretion	64,989	18,214	46,775	67,899	9,838	58,061
Erosion	22,852	520	22,332	37,095	1,918	35,176
Ratio	2.8	35.0	2.1	1.8	5.1	1.7

island, and the southern end of Hatiya island—experienced more accretion than Barisal. More land eroded in Barisal, mainly on parts of Char Fasson Island adjacent to the Meghna River. In Chittagong Division, erosion largely occurred on the northern end of Hatiya Island and on Sandwip Island. Hossain, Dearing, Rahman, and Salehin (2016) also report net accretion in the Meghna estuary, whereas, to the west, net erosion has occurred in the coastal Sundarbans during the same time period (Rahman, Dragoni, & El-Masri, 2011).

The results suggest that, compared to unplanted areas, mangrove plantations have promoted accretion while mitigating erosion in coastal Bangladesh. Between 1973 and 1989, plantation areas experienced 37.2 times more accretion than erosion, compared to only 1.6 times in non-plantation areas (Figure 3 and Table 1). From 1989 to 2010, plantation areas underwent only 4.7 times more accretion relative to erosion, whereas non-plantation areas experienced 1.3 times more accretion than erosion. Therefore, in both periods, gains in new land formation were greater than losses from erosion in all zones, but plantation areas achieved far greater rates of accretion relative to erosion than non-plantation areas.

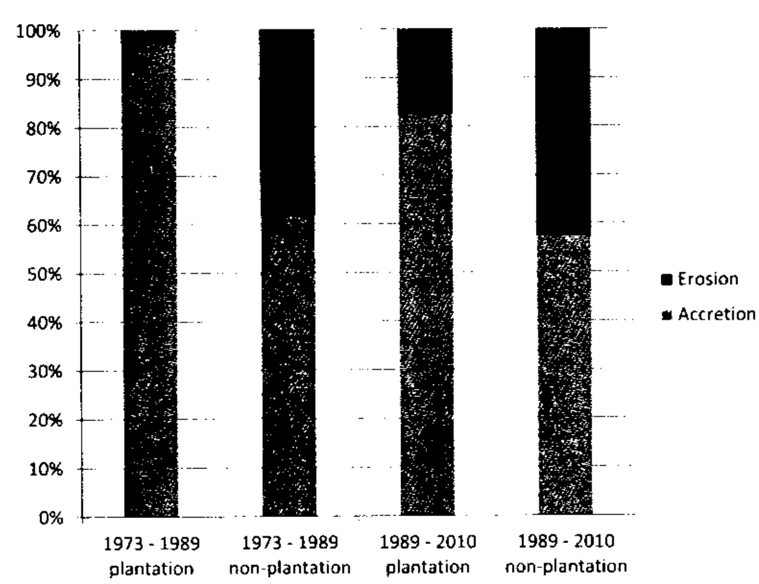

Figure 3. Accretion relative to erosion, scaled to 100% for both time periods, in plantation and non-plantation areas.

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The above result, however, does not necessarily confirm a causal link between mangrove plantations and coastal land stabilization, since it could suggest instead that the BFD is merely skilled at identifying areas to plant which are undergoing the process of net positive accretion. Thus, it is instructive also to consider the fate of lands which are identified as newly accreted in 1989. When considering these areas only, 31% of non-plantation land had eroded by 2010, whereas in comparison, only 10% of plantation had eroded (Figure 4 and Table 2). Combined with the accretion-to-erosion ratios reported above, these results strongly indicate that mangrove plantations in Bangladesh have contributed to coastal land stabilization and erosion control, an important ecosystem service in light of expected SLR and increased intensity of tropical storm surges due to climate change.

Although studies of land accretion in anthropogenic mangrove plantations are rare, these results accord with other research on these and natural mangroves. Shaifullah et al. (2008), investigating the soil impacts from mangrove afforestation in Lakshmipur, Bangladesh, report that plantation areas consistently have higher soil particle densities at multiple depths compared to barren areas, in both seaward and inland zones. Plantation areas also exhibit consistently higher soil organic carbon and greater silt and clay content relative to sand particles, which altogether indicates that the plantations have positively contributed to soil binding. In another South Asian example, Kumara, Jayatissa, Krauss, Phillips, and Huxham (2010) find that among experimental mangrove plantations in Sri Lanka, greater planting densities yield higher rates of accretion. Similarly, McKee (2011) reports that natural Caribbean mangroves with high root densities tend to experience an increase in elevation, whereas those with low root densities tend to experience a decrease. Thampanya, Vermaat,

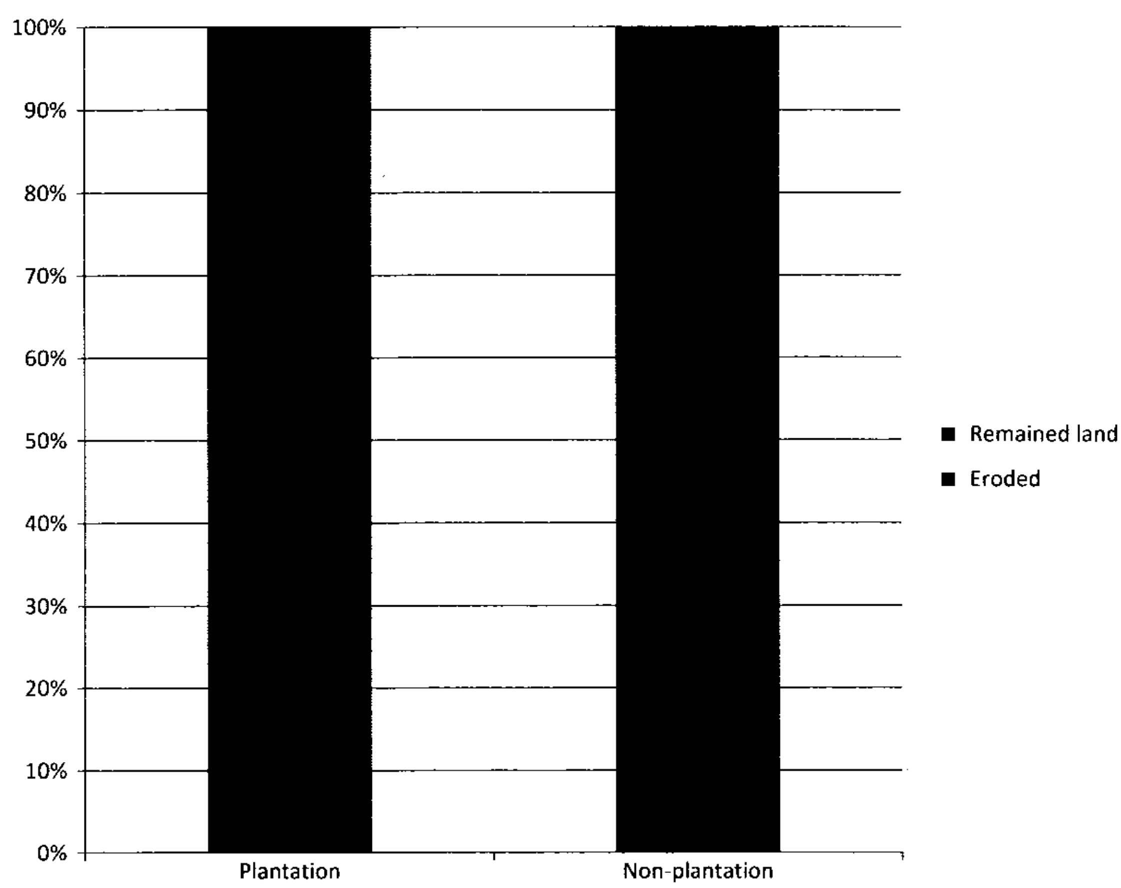

Figure 4. Outcome in 2010 of land which was newly accreted in 1989, plantation and non-plantation.

Table 2. Hectares of land, newly accreted in 1989, which eroded or remained land in 2010.

	all land	plantation	non-plantation
Both divisions			
Remained land	87,532	27,739	59,793
Eroded	30,317	3,193	27,123
Ratio	2.9	8.7	2.2
Barisal Division			
Remained land	39,895	11,324	28,572
Eroded	12,964	1,395	11,570
Ratio	3.1	8.1	2.5
Chittagong Division			
Remained land	47,637	16,416	31,221
Eroded	17,352	1,799	15,553
Ratio	2.8	9.1	2.0

Sinsakul, and Panapitukkul (2006) also report that the presence of mangroves is associated with greater accretion and reduced erosion in the coastal areas of southern Thailand. Aside from plant and root densities, accretion rates in mangroves also depend on their geophysical location relative to local hydrological characteristics (Lynch, Meriwether, McKee, Vera-Herrera, & Twilley, 1989), functional root type (Krauss, Allen, & Cahoon, 2003), and sediment availability (Agrawala et al., 2005; Ellison, 2000a; Ellison & Stoddart, 1991).

Hydrological and hydrodynamic conditions are also primarily responsible for coastal erosion in Bangladesh. Heavy discharge currents through the GBM river system, wave action created by strong southwest monsoon winds, high astronomical tides, and tropical storm surges all immediately contribute to coastal erosion (Ali, 1999). SLR—currently about 1.06 to 1.75 mm per year in the North Indian Ocean (Unnikrishnan & Shankar, 2007)—will also exacerbate erosion with a comparatively subtle but long term impact over the course of the next century.

Coastal mangrove plantations can help mitigate these impacts, but optimizing site selection and management remains a challenge due to lack of information regarding the local hydrodynamic, hydrological, and socioeconomic drivers of accretion and erosion, and more research on these phenomena is necessary. Because the policy goal is the creation and maintenance of contiguous barriers to protect coastal inhabitants and property (Iftekhar & Islam, 2004), natural risks to the plantations themselves are often not primary concerns. Shoreline stabilization and prevention of erosion are important ecosystem services provided by mangrove plantations to the dense populations of rural poor living in coastal Bangladesh. By mitigating the potential loss and damage caused by climate change-induced SLR and storm surges, the preservation, restoration, and afforestation of mangrove forests therefore have an important role to play in sustainable development here and in other tropical coastal zones.

Concluding remarks

When the suite of local ecosystem services is considered, regardless of the services relevant to climate change and SDG13, the benefits of mangrove management to coastal communities can exceed its costs, particularly in developing countries where the costs of labor and other inputs are low (Chow, 2016). Mangrove conservation, restoration, and afforestation are well-suited to help tropical countries with compatible coastlines achieve SDG14 and 15, which pertain to the sustainable management of coastal and forest ecosystems, respectively.

Unfortunately, in many countries where mangroves are threatened, their public, non-marketed ecosystem services do not factor into individual decisions regarding their best

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use. The private calculus that ignores public benefits results in overexploitation of harvestable commodities such as fuelwood or excessive conversion to other land uses like agriculture and aquaculture. In some settings, mangrove loss is driven further by the disproportionate influence of politically well-connected agents who benefit from logging or development at the expense of more vulnerable groups (Allen, 2006). Rates of mangrove loss are slowing, though, as countries increasingly recognize their value and undertake conservation and restoration policies (FAO, 2007). For example, current policy in Bangladesh requires that 25 years after establishment half of mangrove plantation lands remain as reserve forest, while the other half is returned to the Land Ministry for distribution by local administrations (World Bank, 2013). Any conversion of mangroves to cultivation requires approval from the Ministry of Environment and Forests.

Mangrove preservation and plantation also represent promising strategies both to mitigate atmospheric C as well as to help coastal communities in developing countries weather the damages of climate change, in accordance with SDG13. The United Nations Sustainable Development Solutions Network (SDSN) has proposed that GHG fluxes from managed forests be an indicator for progress on SDG13 (United Nations General Assembly, 2015). Mangrove management projects, which are already frequently funded through bilateral and multilateral aid, should be included in climate financing that is incremental to official development assistance, another SDG13 indicator proposed by the UN SDSN. International interventions to place a monetary value on sequestered carbon, such as REDD+, could enhance the ability of developing countries to conserve these important resources. There exist, however, legitimate reasons to caution against promoting mangroves as an ideal mitigation strategy. Mangroves themselves are under substantial threat from climate change, and thus, they may be riskier sequesters of carbon than other ecosystems like tropical rainforests. The permanence of stored carbon is a significant concern where pressures such as storms, SLR, and increased salinity endanger their survival. These risks also complicate efforts to use mangroves to participate in carbon markets. Hence, efforts to increase or sustain mangrove areas may require strategies such as river enhancement to increase freshwater flows and guided sedimentation to augment accretion and lessen the possibility of future subsidence. Such supplementary initiatives would entail additional costs that could make mangrove promotion a less attractive alternative to other mitigation measures.

Likewise, mangrove promotion has been to date an imperfect adaptation strategy due to lack of knowledge and experience. Some rehabilitation and restoration projects have had mixed results, attributed to inadequate site selection, improper soil preparation and planting techniques, and low diversity in species selection (Alongi, 2002). When inappropriately managed, mangroves of suboptimal height, density, or species composition could harm adjacent communities by providing a false sense of security against extreme weather events. Adequate training of coastal managers, adaptive plantation strategies, information sharing, capacity building, and additional research are therefore necessary for mangrove projects to successfully provide climate protection and facilitate the sustainable development of coastal areas.

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Annexure A-14

Protecting mangroves, to deal with cyclones

indiawaterportal.org/articles/protecting-mangroves-deal-cyclones

Mangroves not only help India economically by protecting coastal assets during cyclones, but also help by protecting people in densely populated coastal areas.

Mangroves of the Sundarbans. (Source: Nature Environment & Wildlife Society - NEWS)

Coastal flooding is rising in India and recent evidence shows that as high as 36 million Indians will be at the risk of chronic flooding by 2050. The Indian coastline extends over 7,500 kmts across nine states, two Union territories and two island territories — Andaman & Nicobar and Lakshadweep.

The east coast has historically been more vulnerable to cyclones than the west coast. According to the Indian Meteorological Department, the Bay of Bengal has had 520 cyclones between 1891 and 2018, compared with 126 in the Arabian Sea.

Indeed, the list of cyclones that India has experienced is long with intense cyclones from 1999 to 2020 including the very recent Amphan and others like Kyarr, Maha, Vayu, Fani, Gaja, Titli, Okhi, Varada, Hudhud, Phailin, Helen, Neelam, Phyan and the Odisha cyclone that left a trail of destruction along the coastal states in India.

While factors such as rapid coastal development, population growth, climate change and habitat loss are the main reasons for coastal flooding, an increasing need has been identified to adopt flood mitigation and adaptation strategies to reduce the socio economic and health impacts of coastal flooding. Evidence shows that mangroves can serve as the first line of defense against flooding and erosion in many tropical and subtropical regions and help by reducing waves and storm surges.

What are mangroves

Mangroves can be trees, shrubs, ferns and palms that occupy the boundary between the land and the sea. They mainly grow in or adjacent to areas between the high tide and the low tide. They get regularly covered or immersed in water at high tide and exposed to air at low tide.The roots of mangroves are regularly exposed to saline water. At times, they are also exposed to freshwater surface runoffs and flooding. Mangroves get their nutrition from these tidal saline and freshwater resources and coastal soils and silt that get deposited from the surrounding land after an erosion.

Mangroves cope with coastal flooding

The paper The global flood protection benefits of mangroves published in the journal Nature, Scientific Reports informs that mangroves help in coping with floods by acting as barriers through factors such as bottom friction, the cross-shore width of forests, tree density and shape, which can help in reducing the force of flood waves as they pass through the mangrove forests.

The aerial roots of mangrove forests retain sediments and stabilise the soil in the areas between high tide and low tide (intertidal areas) by reducing erosion during storms and floods. The roots, trunk and canopy of the mangroves can dissipate storm surges and waves. Studies show that mangroves can reduce up to 66 percent of wave energy in the first 100 m of forest width. Mangroves can also cope with sea level rise through gradual vertical growth.

Economic value of mangroves

Threats to mangroves are many. Mangroves world over are declining from 139,777 km2 in 2000 to 131,931 km2 in 2014 because of conversion for aquaculture or agriculture and coastal development. Destruction of mangroves can thus greatly increase coastal risk to infrastructure, livelihoods and lives.

However, the economic value of mangroves for services such as flood protection, is not included within national budgets and wealth accounts in contrast to other services such as timber production. Also, most assessments of the value of mangroves use a benefit transfer (i.e. estimate economic values for ecosystem services by applying available information from studies already completed in one location and/or context to another) or replacement cost method (estimating the costs of replacing mangrove forests by constructing physical barriers to perform the same services) instead of process-based methods that take into consideration local variations in characteristics of storms, mangrove habitat, topography and understanding of the variations in water bodies such as oceans, rivers and lakes.

Understanding and quantifying the contribution of mangroves is crucial for encouraging their conservation and restoration for the benefit of nature and people. This is because the capacity of mangroves to act as natural defenses can vary considerably depending on environmental factors ranging from the sources of flooding in the ocean to mangrove characteristics, coastal topography and also the inland receptors of damage.

The paper presents the findings of a study that aimed at assessing the total expected annual benefits of mangroves considering both cyclonic (tropical cyclones) and non-cyclonic (regular) conditions. Global mangrove benefits were quantified by estimating the difference in flood damages between two scenarios that included damages with mangroves and without mangroves.

The study found that:

Mangroves are best at fighting tropical cyclones globally

> Approximately 90 percent of total benefits of mangroves are for protection from tropical cyclones, while 10 percent are from protection from regular (non-cyclonic) conditions.

For example, mangroves can reduce annual expected flood damages from tropical cyclones by $US 60 billion and protect 14 million people globally. The benefits from mangroves increase as the time between cyclonic events increases and become even more significant during the more intense flood events which can cause significant damage.

If mangroves were not there, property losses produced by 1-in-100-year flood events would increase by 37 million people and US$ 270 billion. Mangrove benefits for tropical cyclones increase sharply after reaching a storm intensity associated to the 1-in-50-year return period events.

Mangrove benefits vary by region

The study finds that flood protection benefits of mangroves vary significantly across regions and countries due to differences in flood characteristics, mangroves expanse and the degree of exposure. Mangroves provide the greatest benefits in the Western Pacific and Caribbean islands.

> The countries that receive the greatest annual economic benefits in terms of high value and protection of coastal assets include United States, China, **India** and Mexico while Vietnam, **India** and Bangladesh benefit the most from mangroves in terms of people protected due to the high density of coastal populations in these countries.

The national importance of mangroves for flood protection varies considerably when calculated as a percentage of national GDP. Mangroves provide critical flood protection benefits in countries with lower GDPs like in Mozambique and Bangladesh, which receive over $US 1 billion in benefits annually from mangroves due to the high number of assets being concentrated in exposed and vulnerable coastlines.

Mangroves help at the local level by protecting cities

Mangroves protect several coastal cities and a considerable number of people from flooding annually.

> Mangroves protect more than 150,000 people from flooding every year in Abidjan and Lagos in West Africa, **Mumbai** and Karachi in South Asia, Wenzhou in East Asia, and Cebu and Denpasar in South-east Asia.

In some cities like Miami in the U.S.A and Cancun in Mexico, mangroves provide more than $US 500 million in avoided property damages every year. Mangrove benefits extend to less populated coastal floodplains as well.

The study provides important insights on identifying areas where restoration efforts need to be prioritised. For example, while mangroves provide benefits throughout the Philippines, these values are higher in the central and northern regions of the country, as they are the areas that receive the greatest annual impact from typhoons. Mangroves also provide benefits in densely populated lowland areas, such as in the Ganges-Brahmaputra delta in India and Bangladesh, in the Mekong delta in Vietnam or in the Amazon delta in northern Brazil. These regions are highly sensitive to climate hazards and therefore need specific risk reduction strategies.

While mangroves continue to disappear at rapid rates around the world, the study demonstrates the urgent need to protect and conserve mangroves where they still exist, by quantifying their value in terms of economic benefits to people and property globally. With climate change, the intensity and frequency of the events like cyclones, floods are predicted to increase thus highlighting the important role of mangroves in averting damage to lives and livelihoods in the future.

A copy of the paper can be accessed from here

Post By: Aarti Kelkar Khambete

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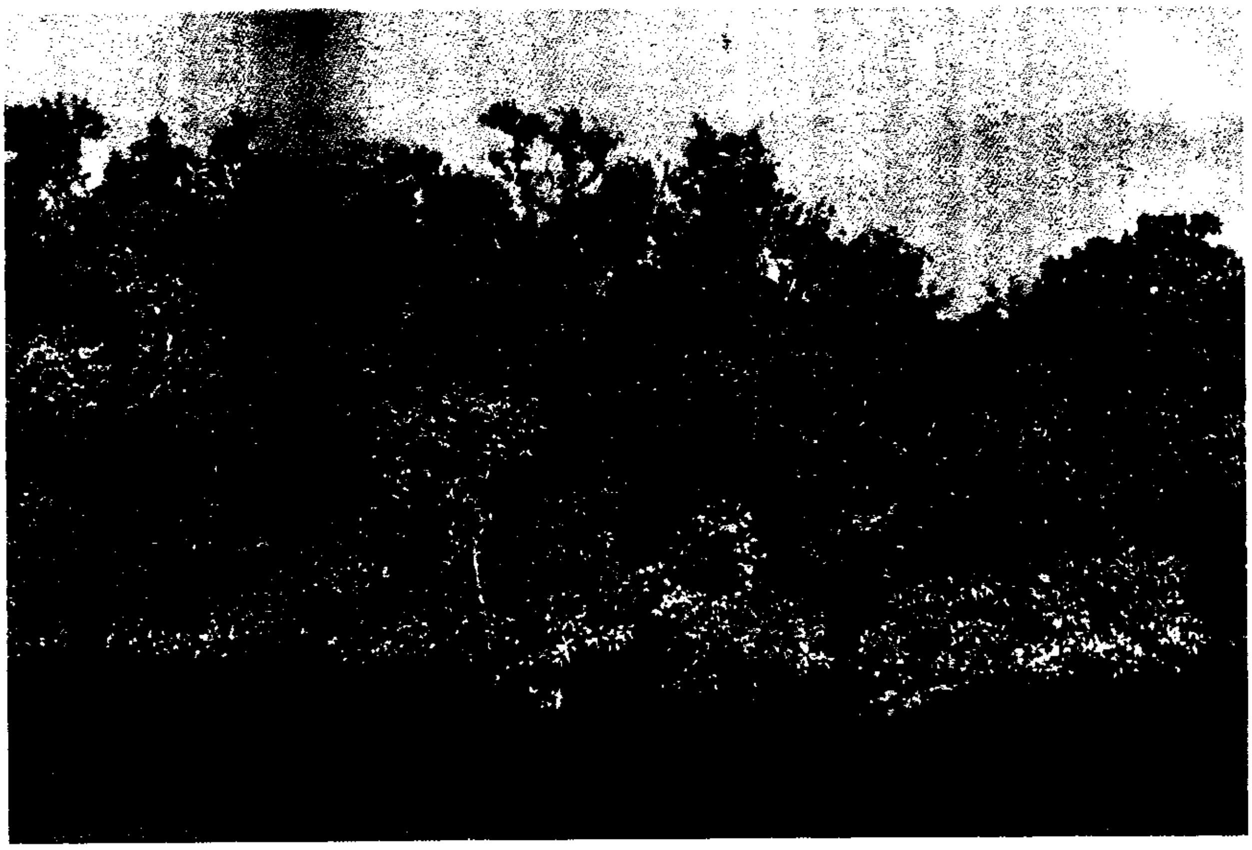
Annexure A-15

How Mangroves Protect People From Increasingly Powerful Storms

science.thewire.in/environment/sundarbans-mangroves-tropical-cyclone-amphan-blue-economy

Adam Moolna

29/05/2020



A part of the Sundarbans mangrove forest. Photo: Biswarup Sarkar/Flickr, CC BY 2.0.

Mangroves are incredibly productive coastal ecosystems found in the tropics and subtropics. These dense green forests are known for their bizarre-looking roots that poke up into the air from shallow water. Among the meshed webs of roots are fish nurseries, enabling humans to make a living from the marine life in and around the mangroves.

Mangroves also play another important role for humans, protecting communities from major storms. Climate change is more than rising temperatures, and the increased frequency and intensity of cyclones, hurricanes and typhoons is apparent. Cyclone Fani for example, which recently struck the Bay of Bengal, was one of the strongest to devastate India in the past 20 years.

Mangrove roots can break up the force of a storm surge, soaking up some of its energy and protecting people living on coasts from cyclone damage. Yet it is a challenge to effectively value and protect individual mangrove ecosystems. And we just don't have the people or funds to deliver detailed studies for even a fraction of the villages and towns sheltered by mangroves.

Also read: Mangroves: The Forests of the Tide

Reliable global rule of thumb

That is where we need a global rule of thumb that can be applied anywhere. It needs to be rigorously evidenced, and trusted enough for economic values to be used in planning calculations by governments and financial institutions. This is provided for coastal mangrove protection by an innovative new study in the prestigious Proceedings of the National Academy of Sciences.

Mangroves are excellent at storing carbon and protecting coasts from storms. Photo: pinpin/Wikimedia Commons, CC BY-SA

Jacob Hochard and colleagues use global data covering nearly 2,000 coastal communities in 23 countries and 194 mangrove areas. Meticulous statistical analysis of cyclones from 2000 to 2012 provides a convincing model of how economic activity is impacted and recovers. It is well established that how brightly lit an area is at night correlates to its economic activity. Hochard's innovation is to compare satellite imagery data of nighttime light levels with a timeline of cyclones. Economic losses are estimated from reduced nighttime light levels.

The area of mangrove protecting a community is divided by the length of coastline to give an average extent of mangrove per metre of coast. The authors compare how typical communities protected by smaller areas of mangrove (6m per metre of coastline average) fared over the long term versus communities with larger areas of mangroves (25m per metre average).

As differing levels of wealth make it tough to directly compare the economic impacts of mangroves in, say, Florida and Haiti, Hochard and colleagues instead express losses not in US dollar value but as relative to months of economic productivity.

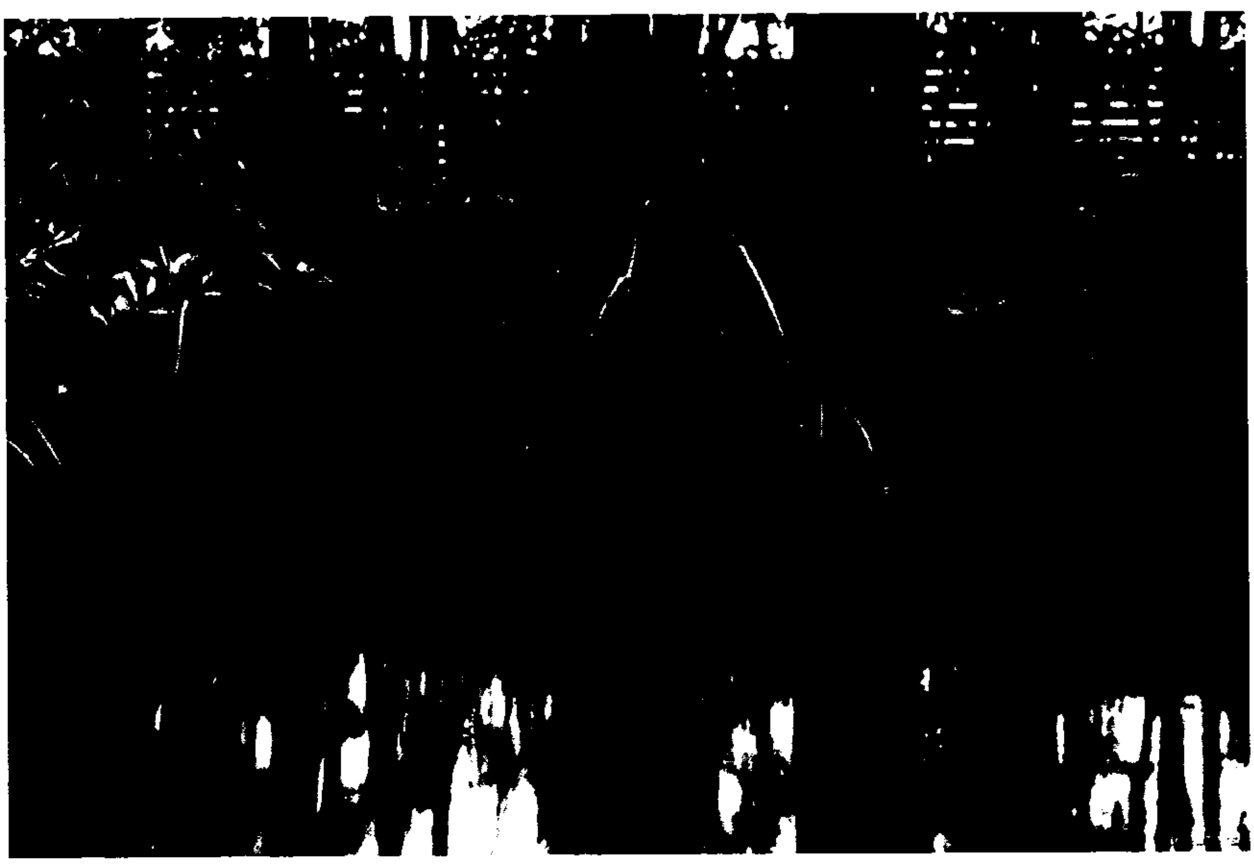
Losses per cyclone for communities with 6m of mangroves per metre of coastline were double that of communities protected by 25m per m of mangroves. In the former group, losses are somewhere between 5.5 and 6.5 months of economic activity. In the latter, the extra mangroves kept cyclone impacts down to between 2.5 and 5.5 months.

Mangroves and the wider blue economy

Mangrove forests cover just 0.5% of the world's coasts but account for an estimated 10-15% of coastal carbon capture. As we try to stop CO_2 levels rising and put the brakes on climate change, protecting mangroves for their blue carbon value is key.

Also read: Amphan in the Sundarbans: How Mangroves Protect the Coast From Tropical Storms

Mangrove protection from cyclones also reduces longer term deterioration of low-lying inland areas with rising sea levels. Storm surges and flooding from cyclones, which deposit salts, are greater without mangrove protection. In Bangladesh, for example, rice agriculture is increasingly impossible as fields are flooded with seawater. One way communities are adapting is to shift production to shrimp farms. Booming shrimp aquaculture, however, ironically requires further mangrove clearance to create space – as seen graphically in Sri Lanka. Loss of mangrove protection from cyclones then worsens coastal deterioration.



The roots of mangrove trees are seen along a river in Pitas, Sabah, Malaysia, July 6, 2018. Photo: Reuters

Mangroves aren't only lost to aquaculture, or harvested for wood, however. Mangroves are strongly affected, for example, by polluted freshwater flowing to the coast. Conflicting objectives at different levels of government and in different locations need joining up. And mangroves are just one aspect of coastal ecosystems and economies – effective management will mean integration with seagrass systems, coral reefs and so on.

The complexity is daunting. We need to be able to act using general principles that can be translated to the great majority of locations for which there are not the resources for local studies. Robustly evidenced global models such as this make that possible. The clock is ticking as mangroves are rapidly lost worldwide.

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Annexure A-16

Chapter 14

Mangroves, Tropical Cyclones, and Coastal Hazard Risk Reduction

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ABSTRACT

Risks from coastal hazards to people and property are expected to increase with near-future sea level rise, changes in storminess, and increasing coastal populations. Evidence from empirical and modeling studies suggests that mangrove forest vegetation can reduce storm surge peak waters levels where mangroves are present over sufficiently large areas. Mangroves are best used alongside other risk reduction measures (embankments, early warning systems) to ensure the lowest possible level of residual risk.

14.1 INTRODUCTION

Risks to lives and livelihoods at the coast, and coastal flood damages, are expected to increase significantly during the twenty-first century with sea level rise (Jevrejeva et al., 2012; Church et al., 2013), possible changes in storminess and potential increases in cyclone intensity (Khairoutdinov and Emanuel, 2013; Woodruff et al., 2013), and increasing population and asset values in the world's coastal lowlands (Seto, 2011; Mendelsohn et al., 2012). A recent modeling study has predicted that, given the maintenance of current sea defenses, but depending on the near-future sea level rise projection used, 0.2–4.6 percent of the global population will be flooded annually by 2100 under 0.25–1.23 m of global mean sea level rise, with expected annual losses of 0.3–9.3 percent of the global gross domestic product (Hinkel et al., 2014). The model suggests that the global costs of protecting the coast with dikes

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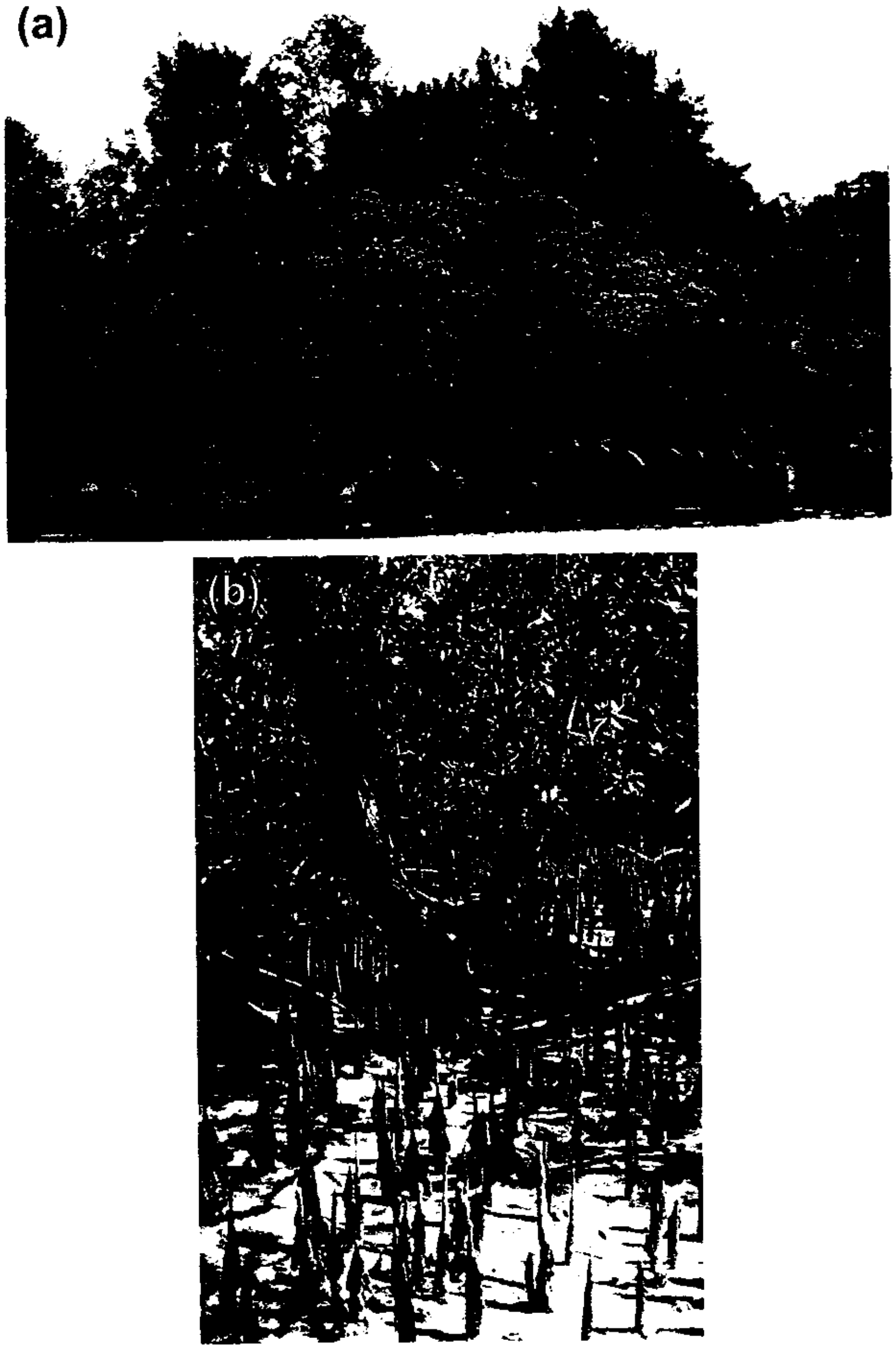

FIGURE 14.1 (a) Upper delta mangrove forest, Berau River, East Kalimantan, Indonesia; highly diverse associations including *Heritiera littoralis*, *Xylocarpus mollucensis*, *Sonneratia caseolaris*, the mangrove trumpet tree *Dolichandrone spathacea*, the spiny holly mangrove *Acanthus ilicifolius*, the palm *Nypa fruticans*, and the fern *Acrostichum aureum (photograph: M. Spalding)* (b) *Sonneratia alba (photograph: M. Spalding)*; (c) *Rhizophora* mangrove species, Sungei Buloh Wetland Reserve, Singapore Island *(photograph: T. Spencer)*; and (d) *Avicennia germinans*, Salamanca National Park, Colombia *(photograph: C. Lacambra)*.

would require annual investment and maintenance costs of US$12–71 billion while at the same time increasing the risk of catastrophic consequences in the case of the failure of these new defenses (Hinkel et al., 2014). These scenarios point to the need for alternative, long-term coastal adaptation strategies which go beyond traditional engineering solutions. If the goal of coastal management

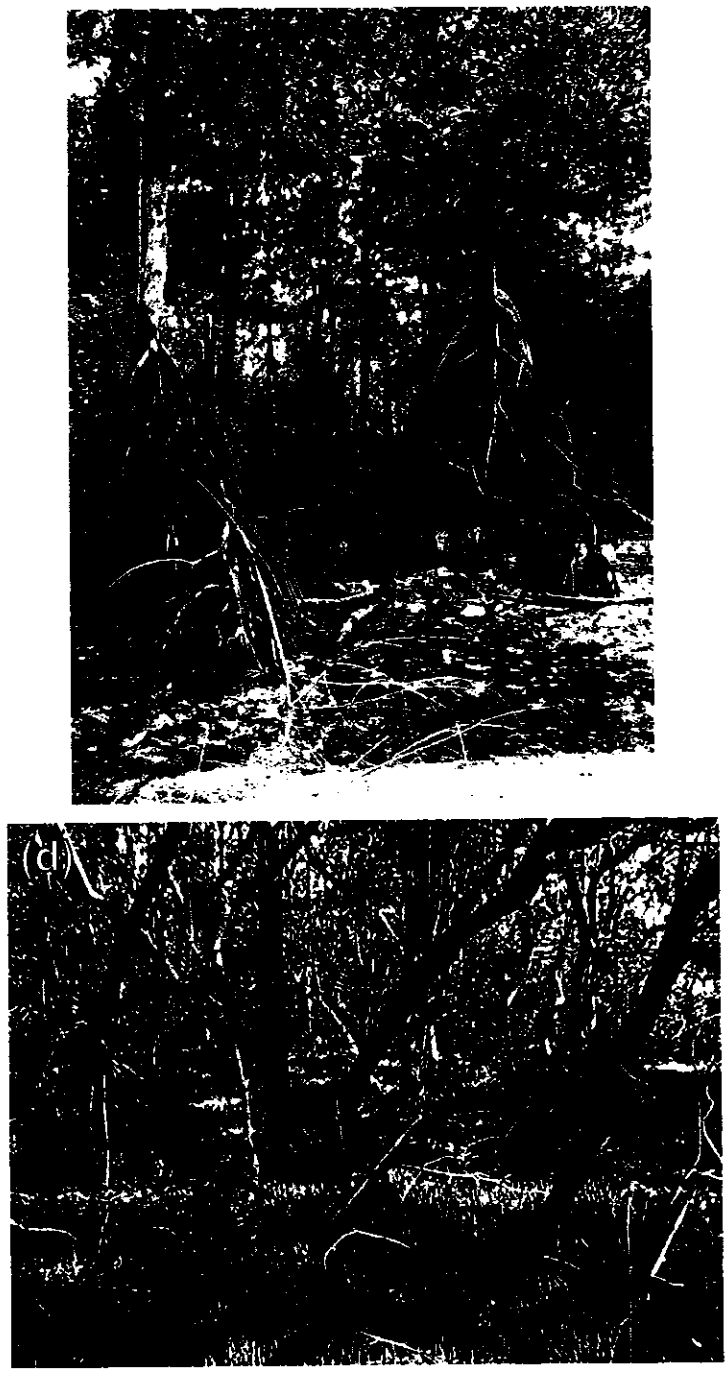

FIGURE 14.1 (*Contiuned*)

is to reduce risk to acceptable levels of residual risk, then a much wider range of risk reduction methods should be considered, beyond only considering structural scenarios. In this context, the role of coastal ecosystems in natural coastal protection should be pursued more vigorously (Spalding et al., 2014). In this chapter we contribute to this debate by reviewing the role of mangrove forests—assemblages of trees and shrubs typical of saline, waterlogged coastal habitats in the tropics and subtropics (Figures 14.1 and 14.2)—in reducing the risks posed to coastal communities by tropical cyclones (also called hurricanes and typhoons).

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Recent estimates of the global coverage of mangrove forests, based on the analysis of Landsat satellite imagery, range from 138 × 10^3 km^2 (Giri et al., 2011) to 152 × 10^3 km^2 (Spalding et al., 2010). However, these estimations are based on 1993–2003 data and are unlikely to accurately reflect current coverage. Mangrove loss rates have been estimated at 0.66 percent per year, with 20–35 percent of the world's mangrove area disappearing since the 1980s (FAO, 2007). Although 25 percent of all mangroves occur in protected areas, rates of loss appear highest in less developed countries where mangroves are being cleared for coastal development, aquaculture, timber, and fuel production (Spalding et al., 2014). The case for the importance of retaining mangrove forests has focused on the multiple social and economic benefits that are likely to be derived from the range of ecosystem services that they provide: fisheries, carbon cycling and sequestration, water purification, and high biodiversity (e.g., Sathirathai and Barbier, 2001; Gunawardena and Rowan, 2005; Barbier et al., 2011; Hutchison et al., 2014). A particularly strong argument, however, has been made for mangrove protection and management through their potential role as dissipaters of incident wave energy (e.g., Badola and Husain, 2005), in relation to storm surges, and in response to tsunami impacts, the last of these three being brought into sharp focus by the Asian tsunami of December 2004.[1]

The mixed messages from the attempts to assess the role of mangroves in mitigating the impact of this tsunami event (e.g., Cochard et al., 2008) provide one example of the underpinning lack of basic information regarding the level of coastal protection that mangrove forests can provide in the face of coastal hazards. Recently, a small number of studies have started to address this need.

1. We do not consider the role of mangroves in reducing the long-period wave trains associated with tsunamis in this chapter. The nature of these impacts has been extensively described elsewhere (e.g., Alongi, 2008; Tanaka et al., 2006; Tanaka, 2009). Following the 2004 Asian tsunami, numerous publications (e.g., Wells and Kapos, 2006; Chatenoux and Peduzzi, 2007; Spencer, 2007; Cochard et al., 2008) attempted to make sense of localized reports of reduced impacts behind vegetation (e.g., Kathiresan and Rajendra, 2005; Danielsen et al., 2005). Much controversy has ensued over the nature of such linkages (e.g., Kerr et al., 2006; Kerr and Baird, 2007; Baird et al., 2009; Feagin et al., 2010), and no consensus has, as yet, been reached. More recently, a large-scale study employing a spatial statistical analysis in Aceh, Sumatra, found that coastal vegetation in front of settlements reduced the number of casualties, whereas coastal vegetation behind settlements had the opposite effect (Laso Bayas et al., 2011). Recent modeling studies have explored the effect of coastal vegetation on various tsunami characteristics (run-up height, flow velocity, inundation extent) using both physical and numerical models (e.g., Apotsos et al., 2011; Ohira et al., 2012; Strusińska-Correia et al., 2013). These studies indicate that coastal vegetation (included in numerical models as an increase in surface roughness) can reduce tsunami run-up height and flow velocities but this depends on tsunami characteristics and local bathymetry (e.g., Apotsos et al., 2011). Furthermore, assessments based on data sets derived from moderate-spatial-resolution (>10 m) satellite sensors (e.g., Landsat TM, Landsat MSS and SPOT XS) (e.g., Iverson and Prasad, 2007) fail to register the finer variation in species composition and tree density that often control extreme event impacts (Dahdouh-Guebas and Koedam, 2006).

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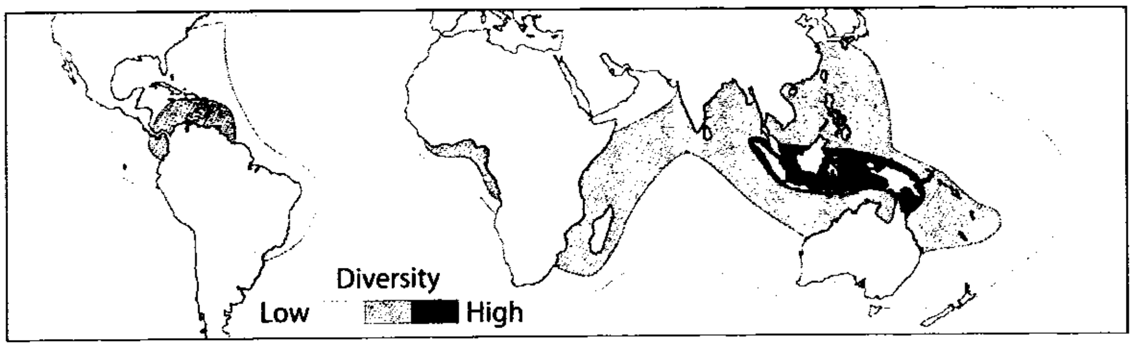

FIGURE 14.2 Global distribution of mangroves *(modified from Veron (1995))*, showing mangrove species diversity. Scale of diversity ranges from 0 to 10 genera (low), 10 to 25 genera (medium), and >50 genera (high). *Adapted from Figure 1.7, Slaymaker, O., Spencer, T., Embleton-Hamann, C., (Eds.), 2009. Geomorphology and Global Environmental Change. Cambridge University Press, Cambridge.*

In particular, Gedan et al. (2011) conducted a broad review of the role of salt marshes and mangroves in coastal protection. They concluded that mangroves and salt marshes can play an important role in reducing risk from coastal hazards. However, they do not address how ecosystems are best incorporated into the design of coastal defense strategies and their implementation. For example, planners and engineers need to know the required mangrove width to reduce a storm surge of a certain height by a certain amount. A review of the evidence for the capacity of mangroves to reduce wave height and storm surge water levels is urgently needed. Here we review studies on the physical processes underlying storm surge reduction, identify important gaps in knowledge, and make some suggestions about the most appropriate ways in which mangroves can be included in coastal defense strategies.

Finally, it is important to note that there are limits to the "biological buffering" capacity of coastal mangroves in relation to storm surge impacts, although at the present time the exact position of these limits in environmental space are poorly known. Cyclones impact mangroves directly through defoliation, branch breakage, toppling, and uprooting (reviewed in Lacambra et al., 2008; Spencer and Möller, 2013) and indirectly, through changes in both tidal and freshwater flushing dynamics and sediment supply (e.g., Paling et al., 2008), processes that disrupt nutrient cycling, and, critically for mangroves, gas exchange between the rhizosphere and the water column/atmosphere (Lugo et al., 1981). Cyclones with typical wind speeds of 120–150 km h^{-1} result in a mosaic of impacted and nonimpacted areas. Damage patterns appear to be related to forest structure, with larger trees more likely to suffer stem breakage or toppling in the path of a cyclone (Roth, 1992; McCoy et al., 1996). However, severe storms, with wind speeds in excess of 200 km h^{-1}, can reduce some areas of mangrove forest cover to little more than residual canopy patches for 50 years or more (Spencer and Möller, 2013). This is partly because such events may lower mangrove surfaces to levels that prevent mangrove seedling reestablishment (Cahoon et al., 2003). However, individual storm tracks are generally narrow (<30 km) and thus damage is invariably spatially restricted. The most intense cyclone ever recorded in the Atlantic basin, Hurricane Wilma (October 2005; up to category 5), destroyed c. 1,250 ha of mangroves (Smith et al., 2009) but this area accounted for only c. 0.4 percent of the total area of mangrove in the Florida. Furthermore, the chance of a particular location being hit in any one cyclone season is very low. Studies of overwash sands and storm surge deposits in lake and coastal marsh sediments in the Northern Gulf of Mexico suggest return periods for catastrophic hurricanes of 300–600 years at particular locations, equating to annual at-a-point landfall probabilities of 0.33–0.6 percent (Liu and Fearn, 2000). Nevertheless, these probabilities rise when one considers that mangrove trees are relatively long-lived in comparison to the time interval between storms. Both Lugo et al. (1976) and Jimenez et al. (1985) have argued that Caribbean mangrove forests can retain a record of past storm impacts in their vegetation canopy structure. Regional maps of historic cyclone tracks across mangrove-populated coasts show a pattern of widespread coverage[2] and when historic frequencies are extrapolated over geological timescales then the total number of landfalls runs into the tens of thousands. Thus, in discussing the Holocene history of the Northern Gulf of Mexico, Conner et al. (1989, p. 46) state "from a long term, regional perspective, hurricanes are not unusual or rare and coastal ecosystems have developed with hurricanes as normal aperiodic events. It is impossible to assess how these systems would have developed without hurricanes, but we believe that they would be different, morphologically and ecologically."

14.2 STORM SURGES

The storm belts of the tropics lie between 5° and 20° north and south of the Equator on the western sides of the ocean basins (Figure 14.3).

In these regions, the high wind stresses experienced over the sea surface and low atmospheric pressures associated with such systems can generate storm surges, i.e., raised water levels, over timescales of hours to days, often well in excess of predicted tidal levels (>1–3 m higher, and >10 m in some extreme cases) (Pugh, 1996; Garrison, 1999; Storch and Woth, 2008) (Figure 14.4). Such events can be particularly marked on coasts with a microtidal range or on coasts with a meso- to macrotidal range when this meteorological forcing coincides with spring high tides (Flather, 2001). Surge events are often enhanced by wind waves, and associated wave run-up, generated by strong onshore winds (Dean and Bender, 2006, Figure 14.4).

2. In a comparable analysis of tropical cyclone impacts on the coral reefs of Australia, Done (1993, p. 126) memorably commented that "maps such as this one (of tropical cyclone paths, 1908–1981) suggests that corals... should have about as much future as a ball of butter in hot spaghetti."

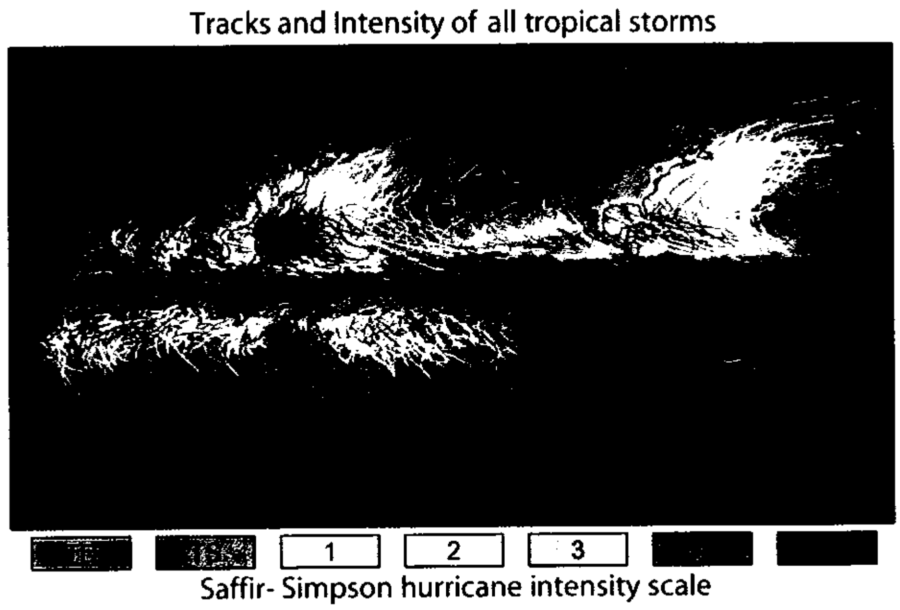

FIGURE 14.3 The tracks of tropical cyclones that formed between 1985 and 2005. The colors represent the strength of the cyclone according to the Saffir–Simpson hurricane wind scale. *Image created by Robert A. Rohde, Global Warming Art; http://www.globalwarmingart.com/wiki/File:Tropical_Storm_Map.png.*

The main atmospheric controls of storm surge height and flood extent include storm intensity, storm size (measured as the radius of maximum wind speed), forward speed of the disturbance, and storm track. Other controls include near-shore bathymetry, coastline geometry (e.g., concave vs convex planform) and orientation, the degree of interconnectivity of coastal water bodies, and the frictional resistance of the land surface (i.e., surface roughness) (Flather, 2001; Dean and Bender, 2006; Resio and Westerink, 2008; Rego and Li, 2009; Spencer and Möller, 2013). Mangroves influence some of these factors; as with

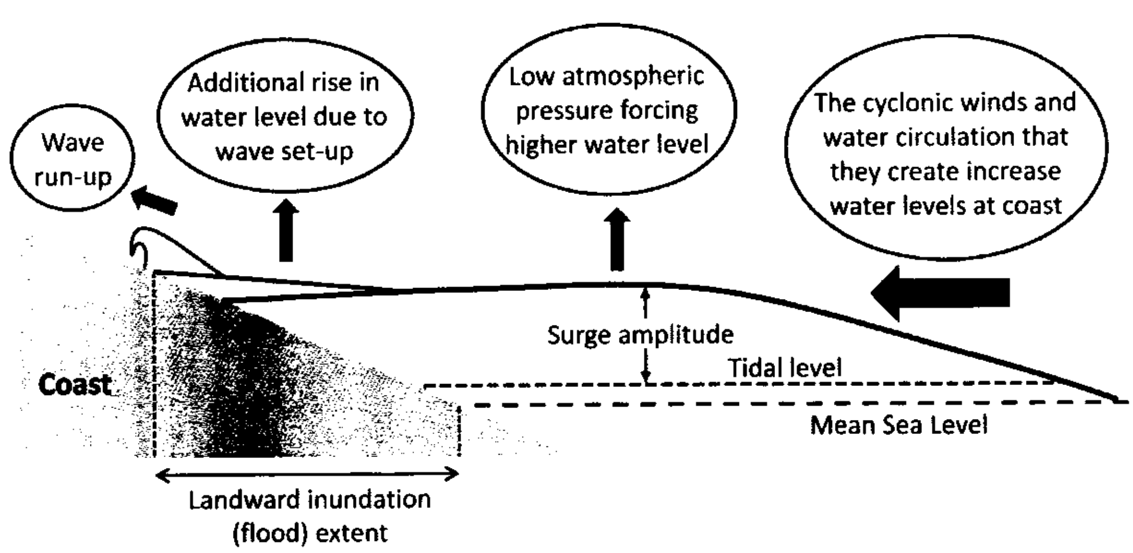

FIGURE 14.4 Schematic diagram showing how storm surges consist of raised water levels at the coast driven by cyclonic winds and low atmospheric pressure. The raised water levels interact with the coastal slope to influence flood extent.

all vegetation, they increase surface roughness (Chow, 1959), reduce the height of surface wind waves (Mazda et al., 2006; Quartel et al., 2007), and reduce the speed of the wind directly over the water surface (Chen et al., 2012) (so long as the vegetation reaches above the water level). Over the longer term (decades to centuries), mangroves can alter the surface elevation of the shore (influencing the bathymetry and topography), the local geometry (e.g., through progradation, the expansion of wetland areas toward the sea), and the location of channels (reviewed in McIvor et al, 2013).

14.3 EVIDENCE FOR REDUCTION OF STORM SURGE IMPACTS BY MANGROVES

Evidence for the ability of mangroves to reduce the impacts of storm surge flooding comes from two sources: (1) direct observations of water levels, and (2) the use of numerical models (with varying degrees of validation) that simulate storm surge behavior in the presence or absence of mangroves.

14.3.1 Observations of Water Level Change

The measurement of storm surge water levels during storms and cyclones presents enormous practical challenges, not least because sensitive (and expensive) equipment may be destroyed or lost during a surge event (Granek and Ruttenberg, 2007). Consequently, very few studies have measured storm surge water levels within mangrove areas. All available measurements are from Southern Florida and hence a rather restricted range of mangrove species compared to the floristically diverse mangrove forests of, for example, Southeast Asia. Here we describe the study by Krauss et al. (2009). Zhang et al. (2012) recorded water level data that they used to validate numerical models of storm surges, and this research is described in Section 14.3.2.

Krauss et al. (2009) analyzed water level measurements collected from a network of water level recorders placed in two wetland areas in Florida during the severe storms of Hurricanes Charley (2004, category 4) and Wilma (2005, up to category 5); Table 14.1 provides detailed information on the recording sites and hurricane characteristics.

As the storm surge from Hurricane Charley passed through the Ten Thousand Islands National Wildlife Refuge, the peak water level reduction was 94 mm km^{-1} through an area that included both mangroves and salt marsh. The following calculations based on data given in Krauss et al. (2009; Figure 14.2 and p. 145) show how the reduction in peak water level through the mangrove area may have been higher. At the first recording point 2.3 km from Faka Union Bay, the peak water level was 786 mm above ground level and 436 mm above the expected high tide level. At the second recording point 3.2 km further inland, at the transition between the mangrove and the marsh, the peak water level was 400 mm above ground level and 296 mm higher than

TABLE 14.1 The Characteristics of Cyclones (in Alphabetical Order), Associated Storm Surges, and the Vegetation they Passed through, which are Discussed in this Review

Location and Source	Cause of the Storm Surge	Wetland type and Width	Water Level Height Reduction if known
Biscayne Bay, east coast of Florida, USA (Xu et al., 2010)	Hurricane Andrew, August 24, 1992, peak wind speed 227 km/h, maximum storm tide 5.2 m	Coastal mangrove zone 1–4 km wide with tree heights of 1–20 m. Species present: *Rhizophora mangle* and *Avicennia germinans* (Smith et al., 1994)	
Ten Thousand Islands National Wildlife Refuge, Florida, USA (Krauss et al., 2009)	Hurricane Charley, August 13, 2004, max winds 240 km/h, peak water level traveled at 0.4 km/h	Mangrove/interior marsh community; dominant species *R. mangle*. Mangrove width 3.2 km	9.4 cm/km across whole area (15.8 cm/km in mangrove area)
Mathbaria, south-western coast of Bangladesh (Tanaka, 2008; ITJSCE, 2008)	Cyclone Sidr, November 15, 2007, maximum wind speed 250 km/h, water levels raised by about 4 m (ITJSCE, 2008)	Forested area, approximately 150 m in width, non-mangrove species *Casuarina equisetifolia* (Tanaka, 2008)	
Along Shark River (Everglades National Park) in Florida, USA (Krauss et al., 2009)	Hurricane Wilma, October 24, 2005, with maximum winds of 195 km/h, peak water traveled at 1.4 km/h, peak water level 5 m	Riverine mangrove, dominant species *R. mangle* (Chen and Twilley, 1999). Distance through mangroves: 14.1 km measured along the Shark River	4.2 cm/km (lower stretch: −0.2 cm/km; upper stretch: 6.9 cm/km)
Gulf Coast, Florida, from Sanibel West to Key West, USA (Zhang et al., 2012)	Hurricane Wilma October 24, 2005, with maximum winds of 195 km/h, peak water level 5 m	Dominant species *R. mangle*, *Laguncularia racemosa*, *A. germinans*. Trees 4–18 m high, stem diameters 5–60 cm. Mangrove width 6–30 km	Models suggest 23–48 cm/km through mangrove area (validated with recorded water levels)

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the water level prior to the arrival of the storm surge. This implies a decrease in peak water level of 140 mm (reduction in water level relative to high tide/antecedent water levels) over 0.9 km, equivalent to a reduction in peak water level through mangrove forest of 158 mm km^{-1}.

As the storm surge from Hurricane Wilma passed through the mangrove forest along the Shark River in the Everglades National Park, three recording stations set back from the river by 50–80 m measured a 42 mm km^{-1} peak water level reduction (Krauss et al., 2009). The highest water level reduction was between the two inland stations that were located 9.9 and 18.2 km from the mouth of the river: peak water level fell from 1.040 to 0.462 m, equivalent to a peak water level reduction of 69 mm km^{-1}. Between the seaward recording stations located 4.1 and 9.9 km from the river mouth, there was a slight increase in water level, presumably because of river water backing up behind the surge (Krauss et al., 2009).

Krauss et al. (2009, pp. 147–148) concluded by pointing out that "while our observations indicate that water levels were reduced as storm surge moved though coastal mangrove ecosystems, uncertainty remains over the relative contribution of mangroves over other wetland types, open water or micro-topographic relief along the Gulf Coast over similar distances." It is unclear, therefore, what the exact contribution of mangroves was to the reduction in peak water level, as it is impossible to control for the other factors that may also have affected water level changes. Because of this difficulty, numerical models that include a greater range of controlling factors have an essential role to play in improving storm surge reduction understanding.

14.3.2 Numerical Modeling of Storm Surge Characteristics in the Presence of Mangroves

Numerical models of storm surges offer a complementary approach to exploring the role of mangroves in reducing storm surge water levels (Resio and Westerink, 2008). When such models can be shown to accurately represent storm surge behavior in the presence of mangroves, they can be used to look at the effect of varying parameters such as the width of the mangrove forest (as described in Section 14.4.1 below). Such models are also needed to predict water level reductions due to existing mangrove forests or planned mangrove restorations, where these are intended for use as part of a coastal defense strategy.

To date, few studies have used numerical modeling approaches to better understand the factors affecting storm surge inundation in mangroves. Here we describe available studies relating specifically to mangroves (the first two studies), as well as two other studies based on models including vegetation that can be regarded as broadly similar to mangrove species. Only in one case is the application related to a less developed country. In such settings, local information is crucially needed to effectively validate models, yet such information is typically very scarce or of doubtful quality.

14.3.2.1 The Eulerian–Lagrangian Circulation Model

Xu et al. (2010) used an unstructured Eulerian–Lagrangian Circulation Model (Zhang et al., 2004; using a multiscale grid with cell sizes increasing nearer the coast, reaching 30 m by 30 m in overland cells) to model the surge resulting from Hurricane Andrew (1992; category 5) at Biscayne Bay, Florida east coast, USA (Table 14.1). They found that their model overestimated peak water levels and flooding extent in the southern part of the bay, an area containing mangrove zones with widths of 1–4 km and tree heights of 1–20 m. This suggested that certain land cover types, in particular the large areas of mangroves, had produced significant effects on flood heights and extent.

Xu et al. (2010) explored the effect of land cover type on flood extent by incorporating a measure of surface roughness into their model. They performed sensitivity experiments using the Manning's roughness coefficient ("Manning's n"), which is a measure of surface roughness (Chow, 1959; Chow et al., 1988; Mattocks and Forbes, 2008). Manning's n was set at 0.05, 0.1, and 0.15 within spatial cells containing mangroves (these values were chosen as being representatives of shrubs, woody wetlands, and dense woods, respectively; Chow, 1959; Mattocks and Forbes, 2008). They found that surge inundation extents (Figure 14.5) varied greatly with Manning's n, and most closely matched the observed debris line when a coefficient of $n = 0.15$ was used. They concluded that changes in roughness due to vegetation can significantly influence the local inundation patterns during storm surges.

14.3.2.2 The Coastal and Estuarine Storm Tide Model

Zhang et al. (2012) used the Coastal and Estuarine Storm Tide (CEST) Model to simulate the passage of Hurricane Wilma (2005, up to category 5; Table 14.1) as it passed over a 200-km stretch of the Gulf Coast of South Florida, USA (the relevant mangrove characteristics are given in Table 14.1). With a maximum storm surge of 5 m, Hurricane Wilma resulted in extensive coastal flooding (Smith et al., 2009).

The geographical extent of mangroves to be used in the model was taken from the National Land Cover Database created by the United States Geological Survey (USGS) in 2001. Following Xu et al. (2010), the drag force from mangroves was included in the model by adjusting Manning's n. While Xu et al. (2010) found that Manning's $n = 0.15$ provided the best fit to observed data, Zhang et al. (2012) reduced the coefficient to $n = 0.14$ because of the large number of lakes, rivers, and creeks inside the mangrove zone in this area.

Simulations were undertaken using: (1) Manning's $n = 0.02$ for all spatial cells (this value is typical of the seabed and thus reflects the "no mangrove" case) and (2) Manning's $n = 0.14$ in cells with mangroves, with other land cover types also included using appropriate values of Manning's n (based on values given in Mattocks and Forbes (2008)). Model outputs were compared with water level data collected by various US Federal Government agencies,

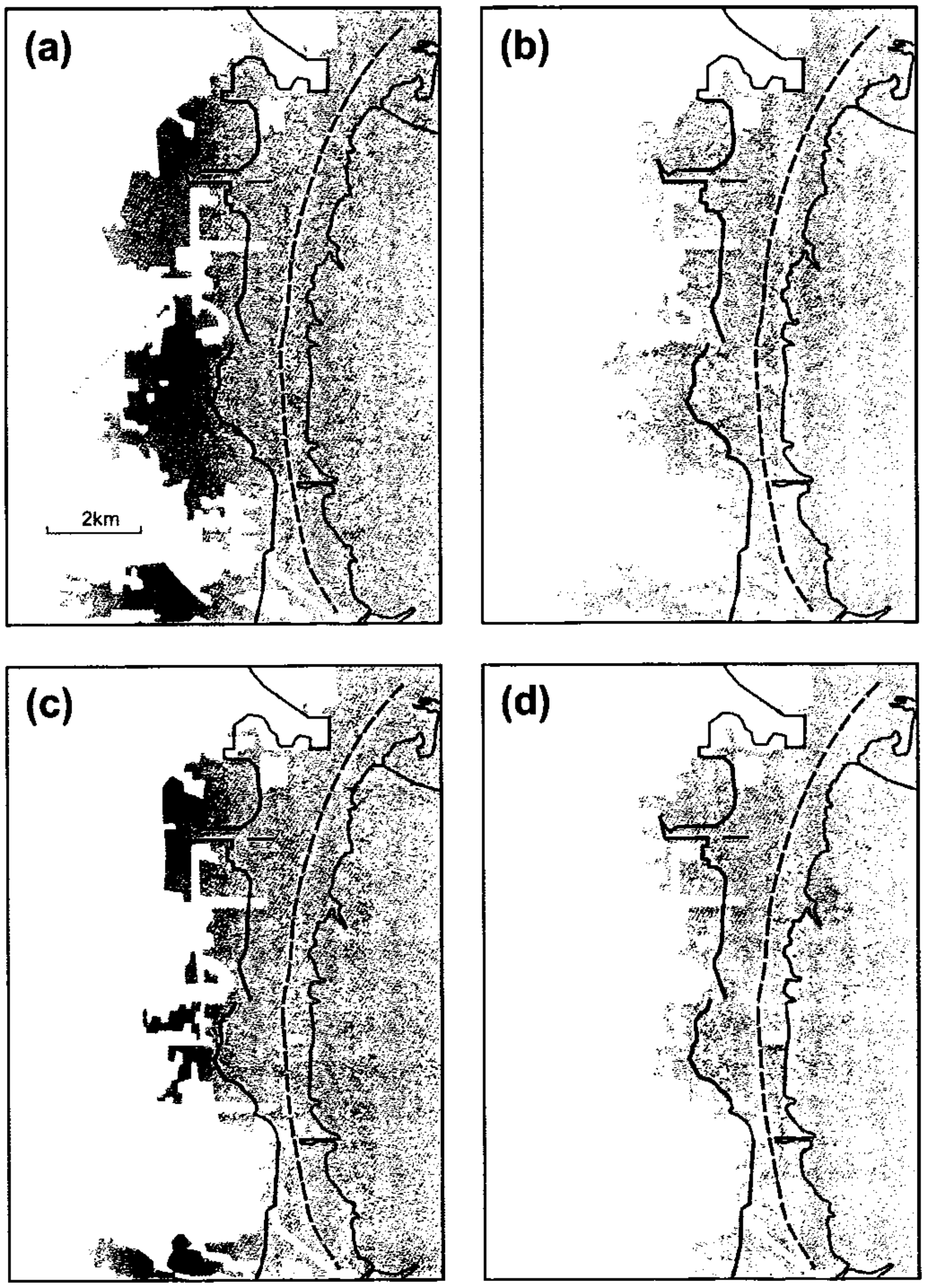

FIGURE 14.5 Flood extents predicted by the Eulerian–Lagrangian Circulation Model *(Xu et al., 2010)* from Hurricane Andrew (1992; category 5) in Biscayne Bay, FL, USA, showing the actual flood extent (red line) and predicted extent from the model, using different values of Manning's n for mangrove areas within the model. (a) $n = 0.02$, (b) $n = 0.05$, (c) $n = 0.1$, and (d) $n = 0.15$. The dashed line shows mangrove extent, and the gray line shows the coastline. *Modified from Xu et al. (2010).*

including the National Oceanic and Atmospheric Administration, USGS, the Federal Emergency Management Agency, and academic researchers. The best match between the simulated water levels and observed water levels was seen when mangroves were included in the model. The root mean square error of computed peak surge heights versus observed ones decreased from 0.60 m (no mangroves) to 0.39 m (with mangroves). Zhang et al. (2012) concluded that including mangroves improved the model's ability to predict storm surge water levels.

The inundation areas predicted by the model were 4,220 km^2 without mangroves, and 2,450 km^2 with mangroves, suggesting that mangroves had a large effect on the inundation extent. Flooding was restricted to within the mangrove zone when mangroves were included in the model (Figure 14.6), and this matched the measured inundation extent taken from surge-induced sediment deposits, which were limited to a zone less than 14 km from the Gulf of Mexico. Storm surge height reduction rates were estimated to have been between 230 and 480 mm km^{-1} across the mangrove areas (Zhang et al., 2012). The simulations indicated that without the presence of a mangrove zone, surge amplitudes would have decreased by 60–100 mm km^{-1}.

However, two further modeling results are noteworthy. First, while the modeled peak water level height was reduced as the storm surge passed through the mangroves, the simulations showed a 10–30 percent increase in water levels in front of the mangrove zone, compared to simulations without mangroves. This is because mangroves can act as an obstruction to the flow of water, causing water levels to build up in front of them. Increased friction within mangroves may also lead to a steeper surge front as the surge moves inland (Resio and Westerink, 2008). Second, Zhang et al.'s (2012) simulations suggested that storm surge reduction was nonlinear across the mangrove width, and this point is discussed in more detail below.

14.3.2.3 Modeling of Wind Wave Set-Up and Set-Down during Surge Events and the Role of Vegetation

In addition to the long-period wave that describes the storm surge itself, short-period wind waves on the water surface often accompany surge events. These wind waves increase the damage caused by the storm surge, and can increase the area that is flooded, through wave set-up and wave run-up. Dean and Bender (2006) used a numerical modeling approach to explore the effect of vegetation (modeled as an array of cylinders) on wave set-up. Their model, based on Airy wave theory (Komar, 1998), predicted that vegetation in shallow water should reduce wave set-up by one-third. Conversely, vegetation in deeper water produces a modeled set-down (i.e., a reduction in water level). The water depth at which this change from a set-up to a set-down occurred can be defined by kh, where k is the wave number ($=2\pi/$wavelength) and h is the still water depth. When waves were modeled using nonlinear wave equations (based on third-order equations, which no longer assume that wave height is small relative to water depth; Stive and Wind, 1982), the presence of vegetation also resulted in a set-down (Dean and Bender, 2006). Dean and Bender's results have not been validated in situ, but they suggest that vegetation, such as mangroves, could have a very large effect on storm surge water levels in those areas where wave set-up makes a

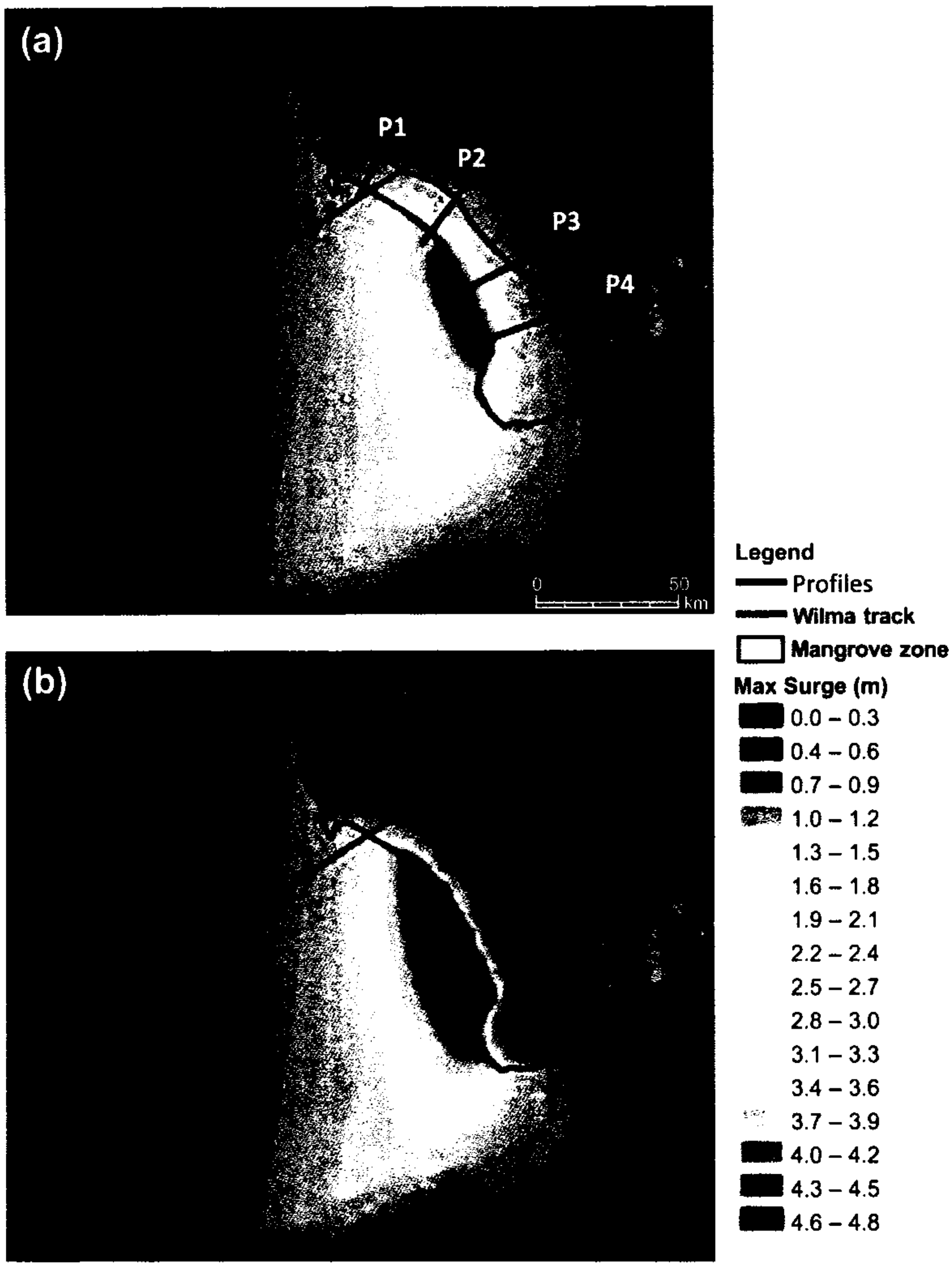

FIGURE 14.6 Peak surge heights over the Gulf Coast of South Florida, USA, from Hurricane Wilma (2005, category 3 on impact) modeled using Coastal and Estuarine Storm Tide *(Zhang et al., 2012)*. (a) Flood extent assuming Manning's $n = 0.02$ across the whole area and (b) flood extent assuming Manning's $n = 0.14$ in mangrove areas (and using appropriate Manning's n values in other land cover types, with land cover taken from the National Land Cover Database). *Adapted from Zhang et al. (2012).*

large contribution to the raised water levels (i.e., areas with relatively narrow continental shelves).

14.3.2.4 Modeling the Storm Surge and Wind Waves from Cyclone Sidr

Tanaka (2008) numerically modeled the storm surge from Cyclone Sidr (Bangladesh, 2007; Table 14.1). A one-dimensional, nonlinear, long wave differential equation was used to explore the effect of a 150-m-wide band of vegetation on a long-period storm surge (wave period 1 or 2 h) and shorter period wind waves (wave period 1 or 2 min). Trees were modeled as cylinders, 10 m high and 0.16 m in diameter, with 0.35 trees m^{-2} in a triangular arrangement. The underlying topography and vegetation measurements matched those seen in transects in Mathbaria, Bangladesh, where the non-mangrove tree *Casuarina equisetifolia* is present.

The model suggested that vegetation had no effect on the water depth ascribed to the long wave component (i.e., the storm surge) over this short distance, although the vegetation slightly decreased the velocity of water inside the vegetation zone and the arrival time of the peak of the storm surge. When wind waves with a period of 1 or 2 min were included on top of the storm surge, the water depth behind the vegetation was reduced by 120 or 280 mm, respectively (compared to no vegetation being present). When the ground slope in the model was reduced from a 1 in 100 gradient to a 1 in 500 gradient, the presence of vegetation reduced maximum water levels by 0.8 m (long wave period 2 h and short wave period 2 min), suggesting that the vegetation reduced flood levels more when present on a shallower slope.

Model results broadly matched field observations: a 150-m-wide band of riverside vegetation near Mathbaria appears to have caused a 0.5–1.0 m difference in water level behind the trees, based on local interviews. This suggests that a relatively narrow band of trees can lower the maximum height reached by storm surge inundation when the effect of vegetation on wind waves is also taken into account, but that further model refinement is required.

14.4 FACTORS AFFECTING STORM SURGE WATER LEVEL REDUCTION IN MANGROVES

Storm surge height reduction through mangroves is likely to depend upon a number of factors, including mangrove characteristics, such as forest width, tree density, and structural complexity (aerial roots, stems, branches, and foliage) of the dominant species; landscape characteristics, such as mangrove surface topography and the presence of channels, ponds, and pools; and storm characteristics, such as the size and forward speed of the cyclone (which may interact with mangroves to influence storm surge reduction). Few quantitative

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data are available (Krauss et al., 2009); where data do exist, they are generally derived from numerical models rather than observations (Zhang et al., 2012; Liu et al., 2013).

14.4.1 Mangrove Width

Measurements of storm surge reduction rates through coastal wetlands are often quoted in terms of centimeters of water level reduction per kilometer of inland distance, generally measured in the direction of travel of the surge (e.g., Wamsley et al., 2010; Engle, 2011). However, such constant attenuation rates imply a linear reduction in water level with distance into the mangroves (i.e., mangrove width). This is rarely true, both because the landscape is usually heterogeneous (i.e., it is usually a mixture of channels, pools, and vegetation with a varied topography) and the underlying rate of reduction might not be linear even if the environment were homogeneous. Consequently, such linear attenuation rates should be regarded with caution as they can be misleading (Resio and Westerink, 2008; Wamsley et al., 2010). At best, they may serve as rules of thumb around which there is generally a high degree of scatter (Resio and Westerink, 2008; Wamsley et al., 2010). Taking this into account and based on the studies described above, the rate of reduction of surges through mangroves appears to range between 40 and 160 mm km^{-1} (observed water level reduction rates; Krauss et al., 2009), and may be as high as 480 mm km^{-1} (validated numerical model; Zhang et al., 2012). Figure 14.7 compares these attenuation rates with similar measures from within salt marshes.

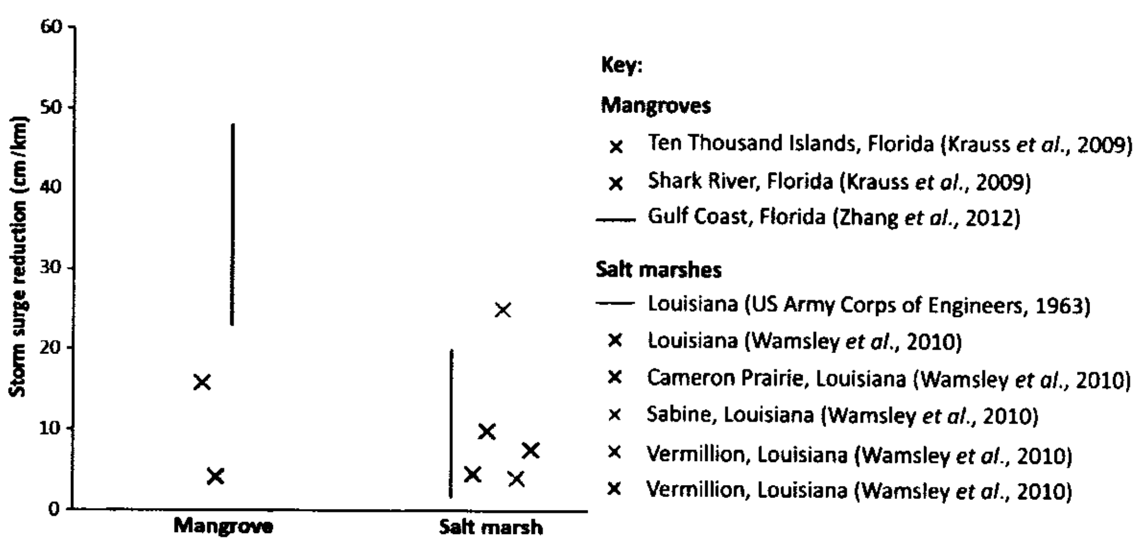

FIGURE 14.7 Summary of storm surge peak water level reduction rates as the surge passes through mangrove and salt marsh vegetation, based on empirical measures or validated numerical models. *(Data sources shown in key; note that Wamsley et al. (2010) combined data from a number of sources.)* Points have been artificially staggered along the x-axis to make them more easily visible.

Zhang et al. (2012) used simulations to explore the effects of different widths of mangroves being present. They found that surge attenuation through mangroves was nonlinear, with the largest reduction in peak water levels occurring close to the seaward edge of the mangroves (i.e., along the western shore, Figure 14.6), whereas further inland the water level changed more slowly (Figure 14.8). They suggest that this might explain the relatively low rates of peak water level reduction measured by Krauss et al. (2009), whose field measurements started some distance into the mangroves. The water level reduction rate in the most seaward mangroves might have been higher.

14.4.2 Mangrove Vegetation Characteristics

The density of mangrove vegetation and the diameter of aerial roots and stems are expected to affect the ability of mangroves to reduce storm surge water levels (Krauss et al., 2009; Alongi, 2008). It might be expected that a dense forest would have a greater effect on water levels than a sparse forest, with trees widely spaced. These properties are dynamic as tree densities typically decline with increasing mangrove forest age: forests become less dense, but individual trees larger, due to self-thinning (e.g., Malaysia: Putz and Chan, 1986; Puerto Rico: Jimenez et al., 1985). This characteristic might be quantified through the measurement of projected area, the silhouette of the vegetation as seen from the direction of oncoming waves (Quartel et al., 2007). Projected area varies with height above the ground, and in the case of

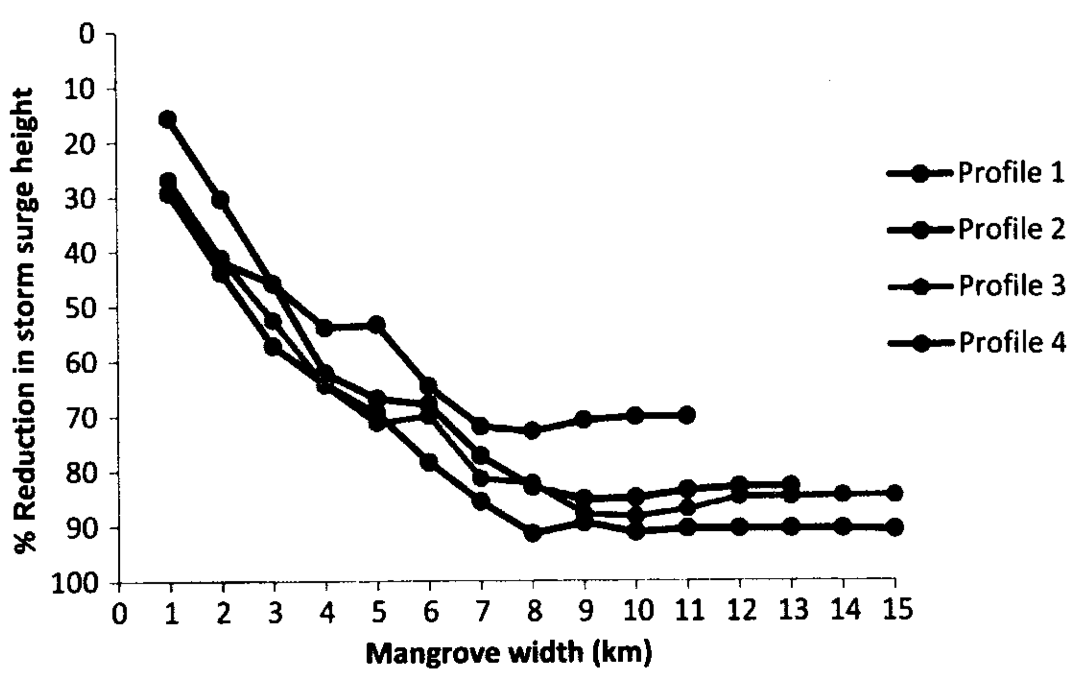

FIGURE 14.8 The reduction in storm surge height as the surge passes through the mangroves along four different shore profiles (shown in Figure 14.6) on the Gulf Coast of South Florida, USA, flooded by a storm surge from Hurricane Wilma (2005, category 3 on impact), and modeled using Coastal and Estuarine Storm Tide *(Zhang et al., 2012). Adapted from Zhang et al. (2012).*

mangroves, the presence (or absence) of aerial roots and low branches is likely to be critical (reviewed in McIvor et al., 2012). However, we know of no data that tests these assumptions under storm surge conditions.

14.4.3 Local Topography and the Presence of Channels and Pools within Mangrove Areas

Mangrove surface topography, and the degree of dissection of such surfaces, is likely to be an important local factor affecting flooding patterns from storm surges, interacting with the peak water level to influence the extent of inundation. However, we know of only two studies which have attempted to assess the importance of these factors. Krauss et al. (2009) and Zhang et al. (2012) consider the presence of channels and pools as likely to decrease the ability of mangroves to reduce peak water levels during surges, because the water is able to pass more easily along the channels and penetrate further inland.

Krauss et al. (2009) recorded higher rates of reduction of peak water levels in intact, relatively unchannelized expanses of mangroves in the Ten Thousand Islands National Wildlife Refuge than through riverine areas along the Shark River (94 mm km^{-1} vs 42 mm km^{-1} respectively). However, they point out that such differences may have been due to differences in the storm characteristics or other factors. The peak water level also propagated more rapidly up the Shark River mangrove area (1.4 km h^{-1} in the Shark River area, compared to 0.4 km h^{-1} in the Ten Thousand Islands National Wildlife Refuge).

Based on their validated numerical model, Zhang et al. (2012) found that surge height decreased at a rate of 230 mm km^{-1} through an area with a mixture of mangrove islands and open water, whereas in areas with less open water, surge height reduction rates ranged from 400 to 480 mm km^{-1}.

14.4.4 Storm Surge Reduction and the Nature of the Generating Mechanism

Reduction in surge heights and flood extent resulting from the presence of mangroves depends in part on the characteristics of the cyclone producing the storm surge (Spencer et al., 2009). CEST model simulations of the passage of storm surges crossing the southern tip of Florida predict that inundation extents associated with a hurricane with high forward speed, small radius of maximum wind speed, and low hurricane category show a greater surge reduction by mangroves than surges created by hurricanes with slow forward speed, large radius of maximum wind speed, and high hurricane category (Zhang et al., 2012; Liu et al., 2013). Thus, for example, the mangroves of south Florida are expected to protect the area behind them against flooding from a category 5 hurricane with a fast forward speed of 11.2 m s^{-1}, but not from a category 5 hurricane with a slow forward speed of 2.2 m s^{-1}. A mangrove forest with a width of tens of kilometers would be needed to attenuate a 2–3 m storm surge from a slow-moving category 5 hurricane (Zhang et al., 2012). Furthermore, the track direction of a hurricane interacts with local bathymetry to determine surge characteristics. Thus, for example, although the south to north track of Hurricane Donna (1960; category 5) produced a 4-m storm surge in the middle Florida Keys as water was driven into shallow Florida Bay, the east to west track of Hurricane Betsy (1965; category 4) across the bay resulted in a lower storm surge in the same region (Perkins and Enos, 1968). Local coastal setting and mangrove area then additionally influences the reduction in flooded area occurring where mangroves are present: Liu et al. (2013) found that the mangrove-induced reduction in flood extent varied between 31.3 and 37.7 percent as the hurricane approach angle varied over 180° in Southern Florida.

14.5 REDUCTION OF SURFACE WINDS BY MANGROVES

It is well known that forest canopies modify near-surface wind speeds (e.g., Raupach and Thom, 1981). Chen et al. (2012) measured wind speed and direction close to mangrove plantations (*Sonneratia apetala* and *Kandelia obovata*) in Sanjiang Bay, Haitian Province, South China. Mean wind speeds of up to 5 m s^{-1}, 2 m above the ground surface and 50 m from the mangrove area, were reduced by more than 85 percent by the mangrove forests. The *Sonneratia* plantation reduced wind speeds more effectively during the warm season, presumably as a result of the denser foliage on the trees at this time of year. During typhoons, mean wind speed and extreme wind speed were reduced by 59.4 percent and 53.2 percent, respectively (the latter in *Sonneratia* forest only; Chen et al., 2012).

It is not possible to directly measure the effect of vegetation-reduced wind speeds on storm surge heights because the effects of reduced wind speeds would never occur independently of other effects, such as the increased drag on the water flow from the vegetation. Using the Advanced Circulation Numerical Model, Westerink et al. (2008) explored how peak water levels varied in hindcasts of Hurricanes Betsy and Andrew when surface wind speeds were modified to reflect the differences in land cover (e.g., dense forested canopies, marshland, or buildings) and the level of local inundation (once a land feature was underwater, it no longer affected wind speeds). Wind direction was also taken into account. Peak water levels were more than 1 m lower in some areas when the modified wind speeds were included, as opposed to wind speeds assuming open-ocean marine conditions. This implies that the effects of vegetation on wind speeds could significantly influence storm surge water levels.

14.6 DISCUSSION, DATA GAPS, AND CONCLUSIONS

Both empirical data and numerical models suggest that mangrove vegetation can reduce storm surge peak water levels where the mangrove canopy is present over sufficiently large areas, usually kilometers in width. Such large areas of mangroves are still present in many parts of the tropics that are affected by cyclones and storm surges, including Mexico, Central America, the Caribbean islands, the Continental Caribbean, Northern South America and Brazil, Florida, Bangladesh, India, Indonesia, and Australia. In these locations, the conservation and restoration of mangroves can contribute to a risk reduction strategy against storm surge inundation and damage.

Reported rates of water level reduction with distance during surge events are sparse. The data that are available give highly variable results. It is difficult to separate out the effects of storm characteristics, the local physical setting, and the characteristics of the mangrove forests themselves. These groupings are not independent of one another. Furthermore, nothing is known about the capacity of mangrove ecosystems to sustain/resist multiple events over time or where the threshold for the protective service may lie in areas prone to such multiple impacts. As a result, it appears that numerical models based on the underlying physics of wind forcing and water movement are best able to represent the impacts of storm surges (Resio and Westerink, 2008), precisely because the interrelationships between storm surge reduction, bathymetry, topography, distance from shore, and width of mangrove vegetation are so complex. Thus, for example, the CEST model used by Zhang et al. (2012) and Liu et al. (2013) demonstrates how such models can be used to better understand the effects of these factors on storm surge reduction rates, and thus to predict flooding extent for different storm types in the presence or absence of mangroves. However, a major challenge is to extend these studies to the full range of geomorphic settings (see Spencer and Möller (2013) for classifications), and mangrove vegetation types, occurring on tropical and subtropical coasts.

These studies also demonstrate an approach for quantifying storm surge reduction by mangroves that can help inform coastal managers, engineers, and insurers about the expected benefits of mangrove presence for risk reduction. However, a limitation of current modeling approaches is their inability to include spatial variation in mangrove characteristics, such as mangrove forest density or the presence of particular mangrove species. It is very likely that the ability of mangroves to reduce peak water levels depends on mangrove characteristics, with sparse, fragmented, or channelized areas reducing storm surge water levels less effectively than dense mangrove vegetation. Including plant and canopy architecture in models would probably improve the prediction of storm surge heights, and would therefore aid in planning the use of mangroves as a form of coastal defense.

Where extensive areas of mangroves currently exist, reducing the threats they face from sea level rise, coastal development, and other anthropogenic factors will help to maintain their coastal defense functions. In other areas, large-scale restoration or afforestation of mangroves can reduce risk from storm surges. Numerical storm surge models will generally be required to calculate the potential benefits of mangroves. Other considerations include the chances of successful mangrove planting, which depends both on the methods employed (Lewis, 2005; Lewis and Perillo, 2009; Twilley and Rivera-Monroy, 2005; Primavera et al., 2012) and on the social and legal frameworks present in a particular region. These frameworks may greatly influence the perception of the roles played by mangroves, and thus their future use and stability of tenure (Primavera and Esteban, 2008).

The most appropriate use of mangroves in coastal defense of high-value or high-vulnerability areas of human occupation is likely to be in combination with other risk reduction measures. Hybrid approaches may be best in many areas: for example, mangroves growing seaward of a sea wall or levee may reduce storm surge water levels and wave energy acting on the wall itself, reducing the likelihood of overtopping or breaching of the structure. This could significantly reduce the design specifications, and therefore the cost, of such engineered works. Such approaches require engineered structures to be built landward of existing mangroves, as planting mangroves in lower elevation settings is rarely successful (Lewis and Perillo, 2009). Mangroves have been used in this way in disaster risk preparedness projects in Vietnam (Figure 14.9), where they have provided significant economic benefits, both in terms of the reduced cost of dike repair and avoided losses to public infrastructure and private property (Jegillos et al., 2005; IFRC, 2011; Powell et al., 2011). Studies of the most extreme storm impacts in mangrove areas have all pointed to the critical importance of other key elements in risk reduction associated with human behavior—these have included long-term policies on coastal development to avoid high-risk settlement and infrastructure, the existence of early

FIGURE 14.9 Mangroves in front of a dike in Vietnam. *Photo: Mai Sỹ Tuấn.*

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warning systems, and clear and well-understood evacuation procedures (Spalding et al., 2014; Das and Vincent, 2009; Williams et al., 2007).

Overall, the understanding of the role of mangroves in mitigating the impacts of large storm surges remains incomplete. Even as such understanding improves, it is likely that, from a perspective of coastal planning, it will be necessary to factor in levels of uncertainty associated with coastal protection performance from coastal ecosystems that may be higher than those derived from engineered coastal defenses. In both cases, however, it is important to remember that a level of residual risk will always be present. A further important consideration in coastal planning must be the cobenefits from mangroves that can be substantial, notably in terms of fisheries enhancement, timber, and other forest products. Such benefits may be of particular importance in postdisaster settings, through provision of food and building materials to coastal communities.

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FURTHER READING

US Army Corps of Engineers, 1963. Overland Surge Elevations Coastal Louisiana: Morgan City and Vicinity. US. Army Corps of Engineers, New Orleans District. File No. H-2–22758, Plate A-4.

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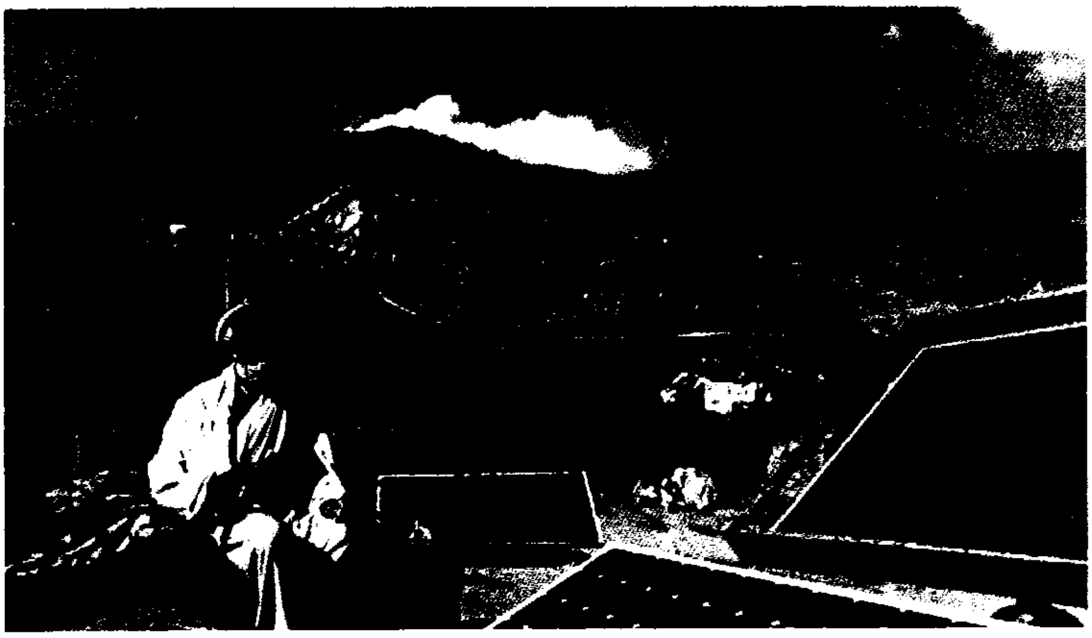
Annexure A-17

When cyclones strike: Using mangroves to protect coastal areas

blogs.worldbank.org/developmenttalk/when-cyclones-strike-using-mangroves-protect-coastal-areas



Massive flooding from storm surges is a major threat to lives and property in low-lying coastal areas during cyclones. Recent examples of devastating cyclone-induced storm surges include Haiyan 2013 (5.2m or 17 feet), Aila 2009 (4m/13ft), Ike 2008 (4.5m-6m/15-20 feet), Nargis 2008 (more than 3m/10ft), Sidr 2007 (4m /13ft), Katrina 2005 (7.6m-8.5m/25-28 feet). The impacts are particularly disastrous when storm surges strike densely populated coastal areas.

Mangrove forests can reduce vulnerability of adjacent coastal lands from storm surges by slowing the flow of water, but too little use is made of this natural buffer

Mangroves, by obstructing the flow of water with their roots/husks and leaves, can reduce the vulnerability of adjacent coastal lands from storm surges. Although the potential utility of mangroves in disaster risk reduction is increasingly recognized by coastal managers, efficient use of this ecosystem-based protection is often hindered by scarcity of location-specific information on the protective capacity of mangroves. The extent of protection from mangroves depends on the width of forest, forest density, diameter of stems and roots of trees along with forest floor shape, bathymetry, spectral characteristics of waves and the tidal stage at which waves enter the forest.

Mangroves found in southwest coastal Bangladesh

World Bank research findings help quantify the protection from mangroves for Bangladesh-the country most vulnerable to tropical cyclones in the world

Mainul Huq from Development Policy Group in Bangladesh and I worked with experts from the Institute of Water Modeling in Bangladesh to quantify the protective capacity of mangroves. We worked in seven coastal locations of Bangladesh, using hydrological models to replicate cyclone Sidr which made landfall in Bangladesh in 2007. We estimated surge height and water flow velocity without mangroves, and then derived estimates using different widths of forests composed of various mangrove species under different densities of planting.

Our estimates indicate varying levels of protection from various species of mangroves, and different width and density of mangrove forests, across the seven locations. The mangrove species that provided the greatest protection in our analysis (*Sonneratia apetala*) reduced the surge height from 4cm to 16.5cm with 50m to 2km wide mangrove strips, and reduced the water flow velocity from 29% to 92% with 50m or 100m wide mangrove forests. Our findings also highlight that the range of protection is location-specific.

Protection by mangrove forests is most useful in combination with built infrastructure

Since surge heights in densely-populated, cyclone-prone Bangladesh can range from 1.5m to 9m, mangroves must be used with built infrastructure, such as embankments. However, even the modest reduction in surge height from mangroves means that embankments with mangroves in the foreshore areas can be lower in height as compared to the ones without mangroves, leading to considerably lower construction costs. The significant reduction in water flow velocity from planting mangroves in front of an embankment will also reduce maintenance costs. Consequently, the benefits and costs of mangrove planting should be considered early in the process of designing new embankments.

For more information about coastal protection provided by mangroves in the current climate as well as in a future climate scenario, please see here.

The original working paper is available here.

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About text formats

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Annexure A-18

An Overview on Role of Mangroves in Mitigating Coastal Disasters (With Special Focus on Tsunamis, Floods and Cyclones)

Conference Paper · March 2016

1 author:

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An Overview on Role of Mangroves in Mitigating Coastal Disasters (With Special Focus on Tsunamis, Floods and Cyclones)

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Abstract

Among different ecosystems located on coastal areas, Mangroves play an important role in providing ecological and societal goods and services to local communities, including stabilizing shorelines and helping reduce adverse effects of natural disasters such as tsunamis and hurricanes, serving as breeding and nursing grounds for many marine and pelagic species, and providing food, medicine, fuel, and building materials as well as opportunities for aquaculture. As a consequence, mangrove ecosystems have attracted an increasing amount of attention from land and ocean managers, conservation communities and academia in all over the world. The aim of this manuscript is review the role of mangrove ecosystems in minimizing the impact of marine hazards like tsunamis, floods and cyclones. A comparison of the studies concerning effective mitigation of tsunamis and natural disasters by mangrove ecosystems was carried out. Results based on the literature review showed that mangroves occurring near the coast play an important role in the protection of the coastal areas from the natural disasters like tsunamis, floods, cyclones. The conclusion reached is that it is necessary for humans to realize the dangers and consequences of undermining the services provided by the coastal ecosystems in coastal protection and to conserve mangroves in every part of the world. The results of this paper will be helpful for informing conservation efforts, mangrove rehabilitation and national monitoring programs for shoreline protection actions in different coastal areas.

Keywords: Mangroves, marine hazards, mitigation.

Introduction

Mangrove forest and wetland ecosystems provide as many as 21 ecological services and 45 natural products (Ronnback, 1999). Services include flood protection, prevention of shoreline erosion and salinity buffering. In addition, mangrove habitats have a diversity-promoting function (Hogarth, 2007). As many as 4100 species of plants, invertebrates and invertebrates inhabit India's mangrove forests (Kathiresan, 2004). Odum et al. (1982) reported that 220 fish species, 24 reptile species, 18 mammal species and 181 bird species use Florida mangrove forests. In addition, about 80% to 99% of commercial and recreational fishes in Florida depend upon mangroves at some stage in their life cycle. Sixty percent of commercial fish in Fiji and India occupy mangroves (Untawale, 1986). The global economic value (USD) of mangrove habitat has been estimated as 181 billion (Alongi, 2002) and 1.6 billion per year in the U.S. (Polidoro et al., 2010). Other annual estimates of value are $9990/ha (Costanza et al., 1997), $10,000/ha (Alongi, 2002) and between $475 to 16750/ha (Ronnback, 1999).

It was recognized at least 30 years ago that mangrove ecosystems were anthropogenically stressed (Lugo et al., 1978) but only 6.9% of mangrove areas are currently protected (Giri et al., 2011). Approximately, 50% of global mangrove cover has been destroyed (Rosen, 2000) and the losses continue (Farnsworth and Ellison, 1997; Polidoro et al., 2010). The loss of coverage is due to a combination of natural and anthropogenic-source stressors. These include hurricanes, disease, deforestation, reclamation projects, canals, marina developments, aquaculture, and the focus of this review, the adverse effects of oil spills and chemical-containing runoff from urban, industrial and agricultural areas (Ellison & Farnsworth, 1997; Schaffelke et al., 2005; Binelli et al., 2007). Tropical ecosystems recover slowly from damage and disasters, between 20 and 50 years for mangroves (Thorhaug, 1989), and symptoms of stress may be delayed for years (Snedaker et al., 1996).

Mangrove forests currently occupy 14,650,000 ha of coastline globally (Wilkie & Fortuna, 2003), with an economic value on the order of 200,000-900,000 USD ha-1 (UNEP-WCMC, 2006). Regardless of their monetary value, mangrove ecosystems are important habitats, especially in developing countries, and play a key role in human sustainability and livelihoods (Alongi, 2002), being heavily used traditionally for food, timber, fuel, and medicine (Saenger, 2002).These tidal forests are often important nursery grounds and breeding sites for birds, mammals, fish, crustaceans, shellfish, and reptiles; a renewable resource of wood; and sites for accumulation of sediment, nutrients, and contaminants (Twilley, 1995; Kathiresan & Bingham, 2001; Manson et al., 2005). The scientific literature for mangroves in recent years has been relatively abundant but mangroves receive less research in the case of protective roles of mangroves. It is believed that mangroves offer protection from waves, tidal bores, and tsunamis and can dampen shoreline erosion (Mazda et al., 2007). The majority of the human population in the world is concentrated in coastal areas which are more vulnerable to natural disasters such as floods, wind generated waves, tsunamis and storm surges (Ramesh & Ramachandran 1999). Although mangrove ecosystems provide various advantages, the most important one is the protection against coastal disasters and tsunamis (Osti et al., 2009). Mangroves prevent coastal erosion, and act as a barrier against typhoons, cyclones, hurricanes, and tsunamis, helping to minimise damage done to property and life (Upadhyay, 2002; Dahdouh-Guebas, 2006; Pearce, 1996; Mazda et al., 1997). Mangrove tree species that inhabit lower tidal zones can block or buffer wave action with their stems, which can measure 30 m high and several meters in circumference (Dahdouh-Guebas, 2006). Mangroves defend the land from wind and trap sediment in their roots, maintaining a shallow slope on the seabed that absorbs the energy of tidal surges (Pearce, 1999). Mangroves protect the coast against waves, currents and storms, and from coastal erosion. Mangroves are like live sea walls, and more effective than concrete wall structures (Kathiresan, 2000). Some of the mangrove species, such as Rhizophora, act as a physical barrier against tidal and ocean influences and shields the coast by means of their large above-ground aerial root systems and standing crop (Dahdouh-Guebas, 2005). It is also found that these mangroves species seem to act as a protective force towards this natural calamity (McCoy et al., 1996).Because of this vital role of mangroves, the aim of this study is review the literatures which focus on the role of mangroves in mitigating marine hazards.Please use the following guidelines in preparing your full paper. If papers are not prepared according to the following guidelines they will be withdrawn from the conference program.

How mangroves protect coastal areas from tsunamis?

The array of features that allow mangroves to sustain substantial environmental challenges such as sea-level rise and storm damage may also function to ameliorate the effects of catastrophes such as hurricanes, tidal bores, cyclones, and tsunamis. The notion that mangroves offer significant protection has become a dictum in tropical coastal ecology (UNEP-WCMC, 2006), yet this ecosystem service has rarely been empirically tested or adequately assessed (Ewel et al., 1998; Valiela & Cole, 2002). The factors determining the extent of protection from tsunamis, for example, offered by mangroves include: width of forest, slope of forest floor, tree density, tree diameter, proportion of above-ground biomass vested in roots, tree height, soil texture, forest location (open coast vs lagoon), type of adjacent lowland vegetation and cover, presence of foreshore habitats (seagrass meadows, coral reefs, dunes), size and speed of tsunami, distance from tectonic event, and angle of tsunami incursion relative to the coastline.

On 26 December 2004 the largest earthquake in 40 yr (seismic magnitude MW ¼ 9.0) produced the most devastating tsunami in recorded history, killing more than 283,000 people throughout the Indian Ocean region. The earthquake was so powerful it wobbled the Earth's rotation (Lay et al., 2005). The tsunami triggered by the seismic event swept across the Indian Ocean at speeds up to 800 km h-1, with succeeding waves reaching heights of up to 30 m. Along with vast numbers of people, man-made and natural structures and habitats were destroyed or damaged, including coral reefs, mangroves, beaches, seagrass beds, and other coastal vegetation. The extent of mangrove damage or loss has been difficult to verify in some areas due to the level of devastation and the focus on restoring human lives and infrastructure.

The impact of the tsunami on the Andaman Islands is most illustrative, being typical of the patchy response to the tsunami due to differences in stand location and angle of impact (Dam Roy & Krishnan, 2005). In South Andaman, 30 to 80% of Rhizophora spp. trees died due to continuous inundation, but stands of Avicennia marina and Sonneratia alba inhabiting the intertidal zone behind the Rhizophora spp. were not affected. In Middle Andaman, mangroves were not affected. In North Andaman, however, the impact of the earthquake elevated the land mass to the extent that the Rhizophora-dominated stands are now not inundated by tides even at highest astronomical tide. These stands are dying and expected to be succeeded by terrestrial flora. Mangrove forests impacted by the 2004 Indian Ocean tsunami were located in sheltered areas (bays, lagoons, estuaries) with very few located on open coast, making it initially difficult to assess whether the areas impacted by the tsunami suffered less because of the intrinsic protective capacity of the forests, or because they were sheltered from direct exposure to the open sea (Chatenoux & Peduzzi, 2007). However, several reports based on initial post-impact surveys in southeastern India, the Andaman Islands, and Sri Lanka (Danielsen et al., 2005; Dahdouh-Guebas et al., 2005; Kathiresan &

Rajendran, 2005; Chang et al., 2006) indicated that mangroves offered a significant defense against the full impact of the tsunami. The conclusions of Kathiresan and Rajendran (2005) and Vermaat and Thanpanya (2006) that the presence of mangroves saved lives along the Tamil Nadu coast of southeast India are invalid however as inappropriate statistical tests were used (Vermaat & Thampanya, 2007). A more proper test of the same data indicated no significant effect of the presence or absence of mangroves on the human death toll (Kerr et al., 2006) and points to the need for caution to avoid overstating the role of mangroves in tsunami protection.

Ground surveys and QuickBird pre-tsunami and IKONOS post-tsunami image analysis (Danielsen et al., 2005) and multivariate analysis of mangrove field data (Dahdouh- Guebas et al., 2005) covering the entire Tamil Nadu coast suggest less destruction of man-made structures located directly behind the most extensive mangroves. Mangrove forests can attenuate wave energy, as shown by various modelling and mathematical studies (Mazda et al., 1997; Massel et al., 1999; Quartel et al., 2007) which indicate that the magnitude of the energy absorbed strongly depends on forest density, diameter of stems and roots, forest floor slope, bathymetry, the spectral characteristics (height, period, etc.) of the incident waves, and the tidal stage at which the wave enters the forest. For instance, one model estimates that at high tide in a Rhizophora-dominated forest, there is a 50% decline in wave energy by 150 m into the forest (Brinkman et al., 1997). Mazda et al. (2006) similarly found that waves were reduced in energy by 50% within 100 m into Sonneratia forests. Mazda et al. (1997) and Tanaka et al. (2007) showed that another important factor is vegetation type, for example, the percentage of forest floor area covered by either prop roots or pneumatophores, as the drag coefficient of these structures is related to the Reynolds number (which differs for each species depending on diameter and aboveground root architecture).

The hydraulic characteristics of tsunamis are, however, likely to be very different from those of wind waves and tidal waves (Latief & Hadi, 2007). The period of a tsunami is usually between 10 min and 1 h as compared with periods of 12e24 h for normal waves (Mazda et al., 2007). A tsunami propagates like a tidal bore in that its momentum increases with movement upstream into shallower water. Model simulations using data from hydrological experiments to predict the attenuation of tsunami energy by mangroves were generated by Hiraishi and Harada (2003) based on the 1998 tsunami that destroyed parts of the north coast of Papua New Guinea. The model output suggests a 90% reduction in maximum tsunami flow pressure for a 100-m wide forest belt at a density of 3000 trees ha-1. Model results obtained by Hamzah et al. (1999), Harada and Imamura (2005), Latief and Hadi (2007), and Tanaka et al. (2007) for various types of coastal vegetation, including mangroves, were very similar.

Tanaka et al. (2007) modelled the relationship of species specific differences in drag coefficient and in vegetation thickness with tsunami height, and found that species differed in their drag force in relation to tsunami height, with the palm, Pandanus odoratissimus, and Rhizophora apiculata, being more effective than other common vegetation, including the mangrove Avicennia alba. These data point to the importance of preserving or selecting appropriate species to act as wave barriers to offer sufficient shoreline protection.

In India and the Philippines, villagers tell how they have been protected from tsunamis, cyclones and other natural disasters in locations where mangroves are intact, but suffer where mangroves have been converted to shrimp farms or were lost due to human activities (Dahdouh-Guebas et al., 2005; Walters, 2004). In Vietnam, mangroves have been observed to limit damage from tsunamis and cyclone waves and have led to large savings on the costs of maintaining sea dykes (Asian Wetland Symposium, 2006). In Chidambaram district in Tamil Nadu, India, the shore protection role of mangroves is recognized by local people where a 113 km2 forest is used as a sacred grove and is traditionally known in Tamil as Alaithi Kadukal, meaning 'the forest that controls the waves' (WWF, 2005). Remains of rows of mangroves planted by Maoris can still be seen in New Zealand with the aim of stabilizing the coast, indicating that mangroves helped in coastal protection (Vannucci, 1997). Wave energy of tsunamis may be reduced by 75 % in the wave's passage through 200 m of mangrove (Massel et al., 1999). It has also been found that 1.5 km belt of mangrove may be able to reduce entirely a wave one meter high (Mazda et al., 1997).

Many observations suggest that mangroves also help to reduce the damage of a tsunami by dissipating the force of the tsunami and preventing the debris washed up by it (IUCN, 2005a,b). In India, bathymetry and coastal profile were most important in determining the impact, but less erosion was observed in the Andaman Islands where mangroves were present than where there were no mangroves (Department of Ocean Development 2005). 63 tsunami events between 1750 and 2004 struck the Indian Ocean area and more than three wind generated waves struck per year (Dahdouh-Guebas et al., 2005). A satellite and field data study done by Selvam (2005) showed that mangrove forest plays important role in mitigating the outcomes of the tsunami disaster, especially in 2004. He showed that 30 trees per 100 m2 might reduce the maximum flow of a tsunami by more than 90 %. Similar results were obtained by Hiraishi (2005) which showed that tsunami flow pressure can be reduced by increasing the density of the planted zone, reproduced by considering drag forces exerted by the individual trunk and leaf parts of trees.

Role of mangroves in flood protection

It has been reported in literature that mangroves even protected villages and reduced death toll during floods and cyclones (Das & Vincent, 2008). A public policy instrument has to be adopted which considers options for mitigation of coastal hazards, and adoption of measures for restoration of coastal sand dunes with sufficient forested shelter belts backshore (Mascarenhas & Jayakumar, 2008). The benefits of mangroves for shoreline protection and storm damage control have been estimated to run into tens of thousands of dollars per km2 in Sri Lanka and Malaysia. Studies carried out in Vietnam show that the value over time of mangroves in protecting against extreme weather events lies around USD 5,000 per km2 (IUCN, 2006).

Role of mangroves in reducing the impact of cyclones

During the 21st century the Intergovernmental Panel on Climate Change projects that there is likely to be an increase in tropical cyclone peak wind intensities and increase in tropical cyclone mean and peak precipitation intensities in some areas as a result of global climate change (Houghton et al., 2001; Solomon et al., 2007). The Sundarbans mangrove forests to the west of the Ganges delta are the largest in the world extending up to 80 kilometres into the Bay of Bengal. They reduce the impacts of cyclones significantly (Hermann et al., 2007). In the case of tropical cyclones (one of the most devastating natural hazard in India and Bangladesh), the role of mangrove forests could be important in reducing the impact from this type of disaster (Kairo et al., 2001). It has been reported in the literature that mangroves reduce cyclone impact by dissipating wave energy and decreasing the impact caused due to cyclone (Badola & Hussain 2005). Das and Bellamy (2007) also concluded that mangroves played an effective role in providing protection against cyclones. In one of the studies done by Narayan et al. (2010), it was concluded that mangroves have a definite positive effect on the port in terms of wave attenuation. From studies conducted worldwide it has been concluded that the cyclone could have been greatly lessened and much loss in life and property damage would have been avoided if healthy mangrove forests had been preserved along the coastlines of the delta (ASEAN, 2009). The role of mangroves in saving coastal lives and property has been well established during the last Orissa super cyclone at Bhitar Kanika and during the tsunami at Nagapattinam and Car Nicober (Ashok et al., 2008). In Orissa, India, a powerful cyclone in 1999 and associated waves caused extensive economic damage and human mortality, but communities living near the mangrove ecosystems were protected by mangrove belts and were less affected (Mangrove Action Project, 2005).

Conclusions

From the literature review that has been carried out, it has been ascertained that mangroves play an important role in coastal protection against various coastal disasters, therefore coastal ecosystem restoration and protection of mangroves forests worldwide is an important issue. Loss of mangrove habitats would have adverse impacts on water quality, coastal protection from waves and storms, and subsequent effects to fishery production and tourism associated with fishing and healthy estuaries. Population awareness is an important issue in this case. Governments should continue monitoring at local level, and research, conservation and restoration programs should be undertaken. The conclusion reached is that it is necessary for people to realize the dangers and consequences of undermining the services provided by the coastal ecosystems such as mangroves in coastal protection. The review has discovered that mangroves play a very positive role during disasters such as tsunamis, floods and cyclones. Every effort should be taken by governments and the private sector of countries with large coastal areas to conserve and restore mangrove ecosystems. The review clearly underlines the valuable role played by mangroves in reducing the impact of various disasters. Participative management of mangrove ecosystems with the active support of local communities can put to the test in various parts of the world. The results of this paper will be helpful for informing conservation efforts, mangrove rehabilitation and national monitoring programs for shoreline protection actions in different coastal areas.

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The Global Flood Protection Benefits of Mangroves

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Coastal flood risks are rising rapidly. We provide high resolution estimates of the economic value of mangroves forests for flood risk reduction every 20 km worldwide. We develop a probabilistic, process-based valuation of the effects of mangroves on averting damages to people and property. We couple spatially-explicit 2-D hydrodynamic analyses with economic models, and find that mangroves provide flood protection benefits exceeding $US 65 billion per year. If mangroves were lost, 15 million more people would be flooded annually across the world. Some of the nations that receive the greatest economic benefits include the USA, China, India and Mexico. Vietnam, India and Bangladesh receive the greatest benefits in terms of people protected. Many (>45) 20-km coastal stretches particularly those near cities receive more than $US 250 million annually in flood protection benefits from mangroves. These results demonstrate the value of mangroves as natural coastal defenses at global, national and local scales, which can inform incentives for mangrove conservation and restoration in development, climate adaptation, disaster risk reduction and insurance.

Coastal flooding impacts are increasing due to coastal development, population growth[1], climate change[2,3], and habitat loss[4–7]. In 2017 alone, overall storm damages were more than $US 170 billion in the North Atlantic[8]. However, development choices often neglect flood risks[3,9,10] and there is growing pressure to adopt flood mitigation and adaptation strategies to reduce these impacts and economic losses[9,11,12].

In many tropical and subtropical regions mangroves reduce waves and storm surges, and serve as a first line of defense against flooding and erosion. These benefits are provided through bottom friction, the cross-shore width of forests, tree density and shape. The aerial roots of a mangroves forest retain sediments, stabilizing the soil of intertidal areas and reducing erosion[13]. Roots, trunk and canopy dissipates storm surge[14] and waves[15]. Previous studies have shown that mangroves can reduce up to 66% of wave energy in the first 100 m of forest width[15,16]. Mangroves can also provide adaptive defenses as they can, under the right conditions, keep pace with sea-level-rise through vertical accretion[17–19].

Yet, mangroves have experienced significant losses over the last decades, declining globally from 139,777 km^2 in 2000 to 131,931 km^2 in 2014[20], with even greater losses before 2000. Most of this loss has happened through the conversion for aquaculture or agriculture and coastal development[21]. The loss of these habitats can contribute to increasing coastal risk[22], particularly in developed areas with great exposure of coastal populations[23,24]. Quantifying the value of mangroves as natural coastal defenses is crucial for incentivizing their conservation and restoration for the benefit of nature and people[25].

The economic value of mangroves for services that rely on conserving them, such as flood protection, is typically not included within national budgets and wealth accounts[26] in contrast to other services such as timber production. Estimates of flood protection benefits have been traditionally limited to local[27,28] and national[29] scale analysis. There are very few global estimates of ecosystem services from wetlands[30,31], and none are based on process-based hydrodynamic flood models. Further, most assessments of the value of mangroves use a benefit transfer or replacement cost method[32,33], instead of process-based methods that can account for local variation in characteristics of storms, mangrove habitat, topography and bathymetry. Field and numerical studies have shown that the capacity of mangroves to act as natural defenses vary considerably depending on environmental variables from the sources of flooding in the ocean to mangrove characteristics, coastal topography and also the inland receptors of damage[34].

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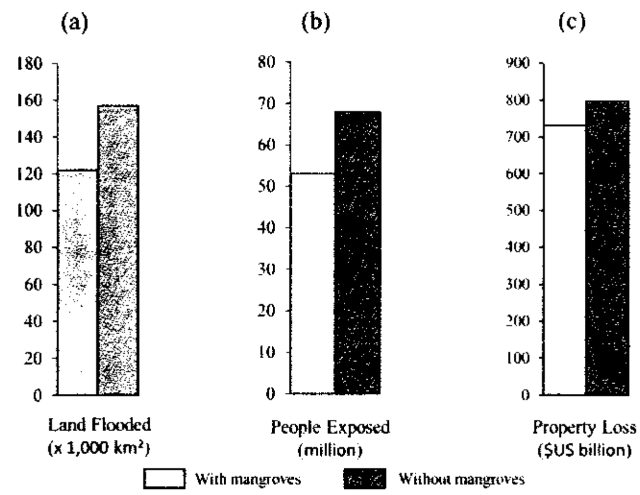

Figure 1. Annual expected benefits from mangroves for flood protection. Estimates of the effects of mangroves on avoided flooding to land (**a**), people (**b**) and property (**c**). The differences between scenarios with and without mangroves are the present flood protection benefits of the habitat.

In a first, we provide a global analysis of the social and economic value of mangroves for flood risk reduction. This work is based on the approaches developed in previous research papers[29,34,35] and the recommendations of the World Bank[36], i.e.: (i) the use of process-based models; (ii) the application of the expected damage function approach for estimation of damages[37,38]; and (iii) the assessment of benefits by measuring the flood damages that mangroves avert[39,40].

We assessed the total expected annual benefits of mangroves considering both cyclonic ("tropical cyclones") and non-cyclonic ("regular") conditions. Global mangrove benefits are quantified by estimating the difference in flood damages between two scenarios: (i) "with mangroves" (current global extent of mangroves) and (ii) "without mangroves". For the two scenarios, we use rigorous process-based models to quantify the coastal flood extents and heights for various storm return periods. We assess the people and property damaged with and without mangroves across 700,000 km of mangrove coastlines globally. The difference between scenarios is the averted damages or benefits provided by current mangroves. We estimate the extent of inland flooding at 30-m resolution globally. For each mangrove scenario, these values are summarized in terms of expected annual damages, a metric that expresses the probability of expected dalmages in any year across the full spectrum of storms. The benefits of mangroves are assessed by the flood damages averted or avoided.

Results

This probabilistic analysis identifies the places most sensitive in terms of coastal risk to the loss of mangroves at 30-m resolution, and aggregate results at global-scale, national-scale (countries) and local-scale (20-km coastal units).

Mangroves and global flood reduction benefits. Mangroves annually reduce property damage by more than $US 65 billion and protect more than 15 million people. If current mangroves were lost 29% more land, 28% more people and 9% more property would be damaged every year (Fig. 1). These values and benefits can be much higher locally (Fig. 2).

The percent risk reduction benefit provided by mangroves is relatively consistent across different return periods with a trend towards greater benefits for the more intense events (1-in-100-year), except for people protected. For example, property savings go from 7.8% (1-in-10-year) to 9.9% (1-in-100-year). Same patterns are observed in land flooded reduction (25.6–29.8%). However, the percentage of people protected from 1-in-10-year is greater than from 1-in-100-year (25.6% vs 19.3%) (Table 1).

Approximately 90% of total benefits of mangroves are for protection from tropical cyclones, while 10% are from protection from regular (non-cyclonic) conditions (Supplementary Tables 1 and 2). For example, mangroves reduce annual expected flood damages from tropical cyclones by $US 60 billion and protect 14 million people (Supplementary Table 1). Meanwhile, they reduce global flooding from regular conditions by $US 5 billion and 1 million people every year (Supplementary Table 2).

In general, the benefits from mangroves increase as the return period increases, becoming more valuable during more intense events (i.e., 1-in-100-year) which are rare but cause significant flood damages (Table 1). If mangroves were lost, property losses produced by 1-in-100-year flood events would increase by 37 million people and US$ 270 billion (Table 1). However, for tropical cyclones, mangrove benefits increase sharply after reaching a storm intensity associated to the 1-in-50-year return period events (Supplementary Table 1).

Mangroves and national flood reduction benefits. The flood protection benefits of mangroves vary significantly across regions and countries due to differences in flood characteristics, mangroves extents and the degree of exposure. Overall mangroves provide the greatest benefits in the Western Pacific and Caribbean islands

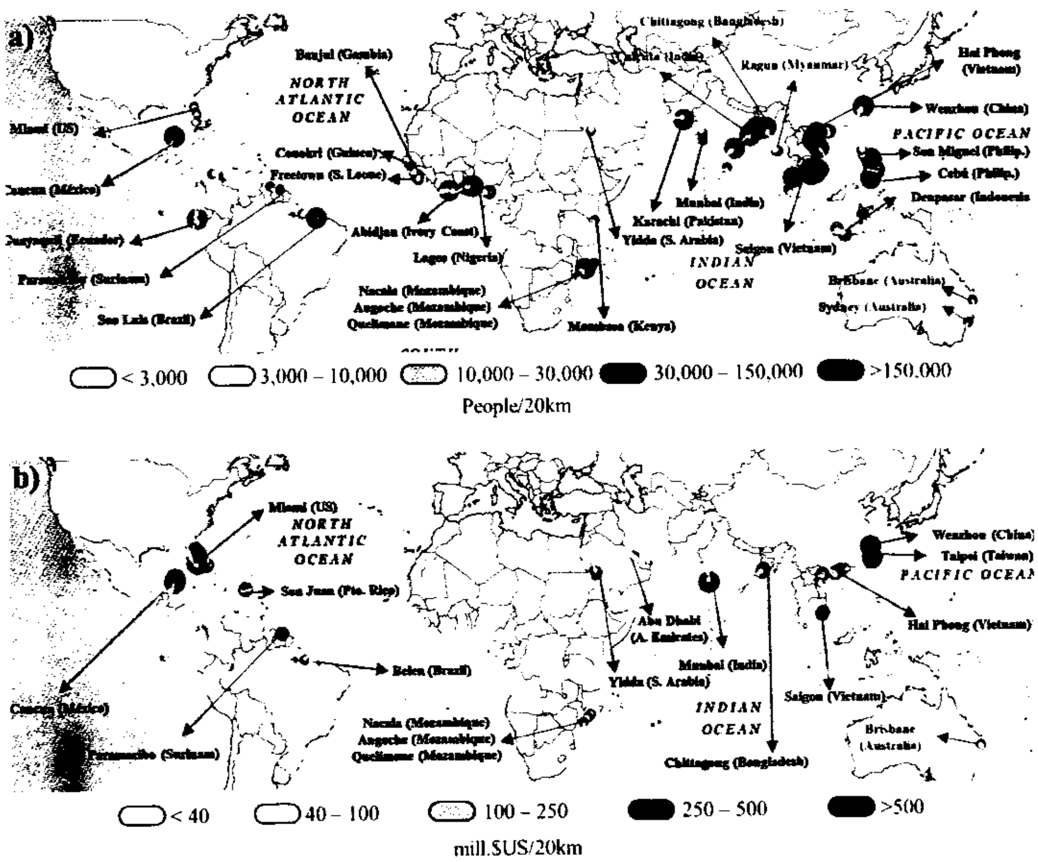

Figure 2. Annual expected benefits provided by mangroves to (a) people and (b) property per 20-km coastal unit. Base maps reprinted from ArcGIS Online maps under a CC BY license, with permission from Esri, original Copyright © 2018 Esri (Basemaps supported by Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus Ds, USDA, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community).

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Annual Expected	122	157	35	53	68	15	732	797	65
10-yr	176	221	45	82	103	21	1200	1293	93
25-yr	209	262	53	107	129	22	1558	1662	104
50-yr	249	318	69	138	166	28	1953	2092	139
100-yr	326	423	97	192	229	37	2714	2984	270

Table 1. Global Benefits of Mangroves in Averted Flooding and Damages. Values are the flooded land and people and damages to property with and without mangroves annually and for catastrophic events. The difference in flooding and damages is the benefit provided by mangroves. The catastrophic events are, for example, the storm event with a 1 in 10-yr return period ("10-yr").

world (Table 2 and Supplementary Figs. 1–3). The countries that receive the greatest annual economic benefits from mangroves are typically more developed states and territories: United States, China and Taiwan. These areas principally benefit from mangroves in terms of the high value and density of coastal assets that are protected. Vietnam, India and Bangladesh benefit the most from mangroves in terms of people protected due to the high density of coastal populations in these countries (Table 2).

Indeed, the national importance of mangroves for flood protection varies considerably when considering these benefits as a percentage of national GDP. For example, in Belize, Suriname and Mozambique, the flood protection benefits from mangroves account for over 15% of the national GDP. Mangroves provide critical flood protection benefits in countries with lower GDPs where exposure is concentrated along vulnerable coastlines; for example, Mozambique and Bangladesh, 7th and 9th respectively in terms of mangroves benefits. These countries receive over $US 1 billion in benefits annually from mangroves due to the high densities of assets in exposed coastal areas (see Supplementary Fig. 3 for relative property benefits distribution).

1	Cuba	3.92	1	Vietnam	7.02	1	United States	11.31	1	Belize	28.86
2	Vietnam	3.12	2	India	2.87	2	China	8.58	2	Suriname	21.35
3	Bahamas	2.47	3	Bangladesh	1.11	3	Taiwan	7.89	3	Mozambique	17.59
4	Cambodia	1.78	4	Philippines	0.61	4	India	7.84	4	Bahamas	13.72
5	India	1.63	5	China	0.52	5	Mexico	7.42	5	Anguilla	4.63
6	United States	1.42	6	Brazil	0.33	6	Vietnam	6.45	6	Guyana	4.57
7	Nicaragua	1.40	7	Nigeria	0.30	7	Mozambique	1.94	7	Madagascar	3.57
8	Mexico	1.13	8	Indonesia	0.25	8	Saudi Arabia	1.61	8	Guinea Bissau	3.24
9	Honduras	1.07	9	Mozambique	0.24	9	Bangladesh	1.56	9	Vietnam	3.14
10	Indonesia	0.84	10	Mexico	0.23	10	Bahamas	1.55	10	Turks and Caicos	2.57
11	Bangladesh	0.82	11	Ivory Coast	0.21	11	Philippines	1.00	11	Sierra Leone	2.02
12	Brazil	0.76	12	Thailand	0.18	12	Australia	0.79	12	Taiwan	1.71
13	Guyana	0.75	13	Ecuador	0.18	13	UAE	0.74	13	New Caledonia	1.16
14	Belize	0.71	14	Taiwan	0.17	14	Brazil	0.72	14	Solomon Islands	1.07
15	Madagascar	0.69	15	Pakistan	0.14	15	Suriname	0.70	15	Ant. & Barbuda	1.06

Table 2. Country ranking. The countries receiving the greatest benefits from mangroves in averted land flooding and damages to people and property. The table also shows the benefits of mangroves (averted flood damages to property) relative to GDP.

The benefits of mangroves from cyclones are particularly high for countries such as Mexico, India and Vietnam. For countries, where cyclones are not as common such Japan and China, mangroves can still provide significant benefits from more common high waves and swell. There are also nations (e.g. Australia and United Arab Emirates) where mangroves protect the same from tropical cyclones and regular climate (Supplementary Tables 3 and 4).

Mangroves and local flood reduction benefits. Mangroves also provide significant flood protection benefits to several coastal cities and regions (Fig. 2). In many of these cities, mangroves protect a considerable number of people from flooding annually (Fig. 2a). For example, in Abidjan and Lagos in West Africa, Mumbai and Karachi in South Asia, Wenzhou in East Asia, and Cebu and Denpasar in South-east Asia existing mangroves protect more than 150,000 people from flooding every year. In some cities like Miami in the U.S.A and Cancun in Mexico mangroves provide more than $US 500 million in avoided property damages every year (Fig. 2b). However, mangrove benefits are not limited to urban areas and extend to less populated coastal floodplains.

Discussion

This study provides the first global analysis of the economic value of mangroves for flood protection. Where they remain, mangroves reduce risks by protecting coastlines against flooding from waves and storm surge. They protect lives, prevent damages to assets critical to livelihoods and reduce socio-economic vulnerability. Many important benefits do go to developed nations particularly to some of those with smaller economies (lower GDP) that are least able to respond to disasters. Mangroves forests around the world have faced extensive loss and degradation due to ditching, loss to open water or conversion to other land-uses[20]. By quantifying the value of mangroves in terms of economic benefits to people and property globally, this study helps demonstrate the importance of conserving mangroves where they exist today. While global scale results are best suited for identifying hotspots in services provided by country or region[34], local and national levels are appropriate for project design, implementation and cost-benefit analysis[29].

Mangroves provide significant annual flood protection savings for people and property both from cyclones and the more regular (non-cyclonic) high wave and swell events. However, cyclonic events are when damages are the greatest and mangroves offer the greatest benefit. With climate change the intensity and frequency of the largest events are likely to increase and thus the role of mangroves will therefore be even more relevant in future scenarios.

The greatest economic benefits are received by USA and China. These are highly developed nations where mangroves have been severely degraded by coastal development. Nonetheless the remaining mangroves provide significant values annually in states, territories and provinces such as Florida (USA). Developing countries and small islands are the most vulnerable to mangroves loss. These countries receive benefit from the greatest economic protection relative to the GDP (e.g. Belize, Suriname, Mozambique, Bahamas, Anguilla, Guyana and Madagascar). The influence of mangroves on flooding varies spatially at a national level. Mangroves in some countries have an apparently greater effect on flooding due to unique combinations of hazard, ecosystem and exposure characteristics. For example, while the total extent of mangroves in Indonesia is nearly 6.5 times that of Cuba[20], Cuba receives significantly higher protection from mangroves in terms of flood extents (4.5 times more land protected). This discrepancy can be explained by the fact that the value of mangroves for flood protection depends significantly on the coastal length of mangroves even more than the width of the mangroves forest. Previous studies have shown that the flood reduction benefits from mangroves and other coastal wetlands, particularly from waves, are highly non-linear on forest width[35,41]. This implies that coastlines with longer mangroves belts, such as in Cuba, may benefit more in terms of flood reduction[42]. Differences in these results can also arise due to differences in inland topography behind these mangroves. Mangrove benefits tend to be higher on flatter floodplains where storm surges travel far, relative to steeper floodplains.

By showing where mangroves are most valuable in terms of both people and property protected, this study provides important insights for where to prioritize restoration efforts. Local scale analysis highlights the hotspots where mangroves provide the greatest benefits. For example, mangroves provide relevant benefits throughout the Philippines, but these values are higher in the central and northern regions of the country, as they are the areas that receive the greatest annual impact from typhoons. In addition, mangroves provide benefits especially in densely populated lowland areas, such as in the Ganges-Brahmaputra delta in India and Bangladesh; also, in the Mekong delta in Vietnam; or in the Amazon delta in northern Brazil. These regions are highly sensitive to climate hazards and therefore need specific risk reduction strategies (e.g. UNISDR 2015[11]). It is in the most vulnerable areas where mangroves play the most important role in reducing risk by minimizing flood exposure and, therefore, the number of people likely to be affected by such events. Mangroves were and are often filled, ditched, diked and dredged to build coastal infrastructure from airports to ports, hotels and housing developments. In these areas few mangroves remain in front of these properties to provide protections. Remaining mangroves however particularly protect communities and sometimes the most socially vulnerable communities at least with respect to poverty and income[29].

Our flood maps "with mangroves" provide some of the current best risk assessments available for many countries (e.g. Supplementary Figs. 4 and 5). This global flood risk analysis improves on earlier global flooding analyses[3,9,10]. Our work is based on a fully probabilistic approach and we followed a multistep methodology based on process models, in combination with statistical downscaling, to simulate wave and surge interaction with mangroves and predict flood impacts along the coast. We examine waves and surge in both cyclonic and more regular (non-cyclonic) conditions. We assess flooding of land at very high resolution (flood maps and risk maps at 30-m resolution worldwide). Valuing mangroves at global, national and local scales provides a consistent screening of the magnitude of ecosystem benefits, allows to identify the greatest nature-dependent areas (priority management zones) and highlights the cost-efficient solutions.

To assess flooding globally, we make a number of key assumptions and simplifications, which are summarized here and cover in depth in Supplementary Table 9. We developed and validated a key storm model with high-resolution analyses for the Philippines[29,43]. A global reanalysis of tropical cyclone storm surges has not been available during the development of this work, we developed and validated a regression model based on the country with the broadest range of storm intensities, mangroves characteristics and coastline (Supplementary Fig. 7). Other regional studies that include tropical cyclone reanalysis underestimate storm surge (e.g. Haiyan typhoon)[44]. However, our model is able to accurately capture these extreme events, as we demonstrated in the Philippines (Supplementary Fig. 11).

In the future, all coastal flood risk models will be improved by better data on bathymetry, topography, and mangroves as well as better models of the two-dimensional propagations of nearshore waves and storm surge. For consistency and computational savings, we have used global datasets and time-efficient modeling tools. We have examined issues of model sensitivities in depth elsewhere[43]. Because this is a global flooding model, we excluded some countries that had very few mangroves (less than 100 ha) and we also capped the benefits per hectare at $US 50,000 as these were the highest values estimated in a high resolution analysis, risk industry model of mangrove benefits in Florida (Narayan *et al.* 2019) (see Supplementary Table 8). This excluded 15 countries in total, including Bahrain and Benin, which had very high values of benefits/ha; as well as eight Caribbean Small Island Developing States (Supplementary Table 9).

These models and results inform new opportunities to pay for the management, conservation and restoration of mangroves to cost effectively reduce risks to people and property. There is strong interest among the management, financing and donor sectors for solutions in disaster risk reduction and climate adaptation particularly as payments from national governments and insurers are growing nearly exponentially for disaster management[45]. Many governments subsidize risk, which creates perverse incentives for greater coastal development, loss of ecosystems, and reduced opportunities for private insurance. By quantifying the values of coastal mangroves, this opens opportunities to align their conservation with coastal protection of existing public infrastructure and private developments.

The approaches we use here for assessing flood risk and the benefits of mangroves as risk reduction solutions are consistent with those used by national disaster risk agencies (e.g., the US Federal Emergency Management Agency), coastal engineers (e.g. the U.S. Army Corps of Engineers), private insurers and re-insurers, climate adaption funders (e.g., Green Climate Fund), and the World Bank[36,47]. By using widely accepted approaches to measure the benefits and cost-effectiveness of mangroves, these results open opportunities to support the management and restoration of mangroves as national coastal infrastructure using hazard mitigation and disaster recovery funds. These values can also be used to underpin the development of innovative insurance options like those being developed and implemented for coral reefs[45,48,49]. These spatially explicit values can be used directly in national adaptation and risk management plans associated with the United Nations Conventions on Climate Change and Disaster Risk Reduction (UNFCCC and UNSIDR). These values could also be used to inform the development of resilience credits for climate adaptation, similar to the development of credits for blue carbon (for climate mitigation) in mangroves. By demonstrating where mangroves provide flood protection benefits across the world, this study helps inform wider discussions on where it is most optimal to invest in efforts to restore and manage mangroves for the critical ecosystem services they provide.

Methods

Methods at a glance. This work measures the flood protection service of mangroves all over the world for two climatic conditions: (1) Cyclonic- i.e., the conditions high-intensity extreme waves and storm surge induced by tropical cyclones and (2) Non-cyclonic, i.e., the "regular" waves generated by low-intensity local storms. We followed the Expected Damage Function (EDF) approach[50], recommended by the World Bank[36], previously applied in coral reefs ecosystems[34] and commonly used in engineering and insurance sectors[51,52]. We examine the role of mangroves in reducing flood risks by measuring the impacts of flooding on people and property under two different scenarios: with and without mangroves. The "without mangroves" scenario assumes the complete loss of mangrove habitat and the consequent erosion of the intertidal area with a smoothened bottom roughness. We use a regression model globally, to calculate coastal flooding by analyzing more than 7,000 historical cyclones[53] and 32 years of regular waves and sea level (storm surge, astronomical tide and mean sea level). Flood impacts (i.e. land flooded) for the with and without mangrove scenarios are combined with global distributions of people and property[11], and with vulnerability based on global "Flood Depth-Damage Functions"[54] to assess baseline flood damages and flood damages after mangrove loss for multiple storm events and on an annual basis.

To identify the mangroves that influence a given coastal region and evaluating nearshore hydrodynamics and flood height we define cross-shore coastal profiles (Supplementary Fig. 6d). Then, we follow a multi-step framework whose key aspects are described here and in the Supplementary Material: (1) Estimate offshore dynamics produced from both, tropical cyclones and regular climate conditions. (2) Estimate nearshore dynamics by downscaling offshore waves and storm surge until shallow water, just before mangrove habitats. (3) Propagate waves and storm surge through mangroves and obtain the flood height behind the mangroves at the shoreward end of each profile. (4) Estimate the land flooded (impact) due to extreme water levels along the shore by intersecting the flood height at the shoreline with inland topography (5) Calculate land, people and property located in the flooded area and, finally, apply the corresponding damage functions to obtain flood damages with and without mangroves.

Study domain description. This global study covers 700,000 km of coastline that includes more than 141,000 km^2 of mangroves, spread over 4 continents and more than 9,500 islands. To reduce the vast computational requirements such a large domain requires, the global domain is divided at three levels, from global to regional and local (Supplementary Fig. 6). The first level is a global division into six macro-regions corresponding to the following ocean basins of tropical cyclone generation[53]: East Pacific, North Atlantic, North Indian, South Indian, West Pacific and South Pacific (Supplementary Fig. 6, panel "a"). The second level divides the 700,000 km of global mangrove coastline into 68 sub-regions considering coastline transects of similar coastal typology (e.g. islands or continental coasts) and similar ecosystem characteristics (Supplementary Fig. 6, panel "b"). The third level of disaggregation is done at a local scale, defining units with 20-km length of coastline and extending up to 30-km inland and 10 km seaward (Supplementary Fig. 6, panel "c"). Within these units cross-shore profiles perpendicular to the mangrove habitats are created for each kilometer of mangrove coastline, totaling 700,000 profiles (Supplementary Fig. 6, panel "d").

Building the global model based on the Philippines results. Global reanalysis of ocean and coastal waves[55,56] and storm surge[57] exist though not for tropical cyclones during the course of this work. We develop the global model based on an extensive re-analysis of tropical cyclone climates developed for the Philippines[29]. We chose the Philippines as the baseline case to develop our own tropical cyclone reanalysis at high resolution and estimate flood damages in presence and absence of mangroves. There are three main reasons that make the Philippines an excellent pilot case for valuation of the coastal protection ecosystem service provided by mangroves: (i) Almost 10% (548 events) of the global tropical cyclone records from IBTrACS database affected the Philippines[53]. The worldwide distribution of tropical cyclone parameters (velocity track, wind speed) closely resemble these events in the Philippines (Supplementary Fig. 7) (ii) The islands of the Philippines present high climatic variability and it is at particularly risk from natural hazards like typhoons and regular storms, which are the cause of 80% of the total losses from disasters [average loss totaling nearly $US 3 billion, 29% of this damage is due to coastal flooding[58]]. (iii) The Philippines ranks in the top 15 most mangrove habitat-rich countries, with 2,630 km^2 in 2010, representing 2% of the world total[59]. These mangrove habitats show extensive variation in both cross-shore length and average depth. Mangroves in the Philippines rage between 0.1 km and 8 km wide and between 0 m and 10 m depth (Supplementary Figs. 8 and 9). We valued flood protection service of mangroves in the Philippines by using the numerical model Delft3D considering both historical tropical cyclones and regular climate conditions with and without mangroves. We use these results to build two global statistical models. The first global model is developed to obtain offshore and nearshore ocean dynamics produced by tropical cyclones (wave height, peak period, storm surge and storm duration), and the second global model to estimate how the presence and profile of mangrove habitats influence the total water level on the shoreline. Further details of the two models are developed below:

Model 1: Offshore and nearshore dynamics generated by tropical cyclones. Offshore waves and storm surge generated by tropical cyclones (IBTrACS database) were numerically simulated in the Philippines by using Delft3D modules "Flow"[60] and "Wave"[61]. Both modules were run simultaneously in a 2-dimensional grid of 5 km cell-size with a time step of 30 s, forced with hourly wind data and sea level pressure fields obtained from parametric model, in which the non-linear interaction processes of tide, wind setup, inverse barometers and wave setup are considered. The model was validated by comparing the storm surge generated by typhoon Rammasun, in Legaspi and Subic Bay. We use tidal gauges registers from the Global Sea Level Observing System (GLOSS, http://www.gloss-sealevel.org) for validation (Supplementary Fig. 11). Using the results of the numerical simulations carried out with the Delft3D model in the Philippines we look for statistical relationships between cyclone parameters and oceanographic variables to create a new predictive model, where oceanographic variables (wave height, period, weather tide and duration of the storm peak) are predicted based on cyclone parameters (distance, wind speed, track velocity, wind angle of incidence). In the Philippines, 548 events were simulated on a two-dimensional grid of 5 km cell size, finally creating a database of 58 million results. We randomly select 90% of the generated results to build our predictive model, and use the other 10% for validating the predictive models. We estimate the correlation between physical tropical cyclone parameters (distance from the trace to the profile D [km], wind speed W [km/h], cyclone travel speed V [km/h], wind direction from north θ_{WN} [in degrees] and the angle between the wind direction-profile θ_{WP} [in degrees]) and the oceanographic variables at the target point (maximum significant wave height produced during the event at the target point H_{smax} [in m], peak period Tp [in s], maximum storm surge SS_{max} [in m] and maximum storm surge duration, T_{SSmax}). We increase the accuracy of the analysis by dividing the data into two groups: Coastal areas directly exposed to tropical cyclones and areas protected from the direct impact of tropical cyclones (Supplementary Fig. 13). For each combination (5 cyclone variables x 3-time instants x 4 oceanographic variables = 60 cases), we estimate the Pearson coefficient (P_{xy}), which statistically quantifies the degree of correlation between the cyclone variables "X" and the oceanographic variables "Y" (equation S.1). We then adjust ocean climate variables (Yi) to our parametric model [equation S.2]. We test this adjustment for one, two, three and four independent variables (Xi), so that we can cover all the alternatives and, based on the correlation coefficient of each one, choose the best regression model.

$$Y_s = a_0 + a_1 \cdot X_1^{\alpha 1} + a_2 \cdot X_2^{\alpha 2} + \ldots + a_n \cdot X_n^{\alpha n} \quad (1)$$

Where Y could be either the maximum wave height (Hs_{max}), the peak period (Tp), the maximum meteorological tide (SS_{max}) and the duration of the meteorological peak produced by the cyclone (Tss_{max}). Meanwhile, X could be any of the following predictor variables (see equations S.3 to S.10): minimum distance between the storm track and the target point (D_{min}), the wind speed when the tropical cyclone is at the closest location to the target point (W_{dist_min}), the average wind speed during along the storm length (W_{mean}), the mean direction of wind respect to the North (θ_{WN_mean}), the wind direction respect to the North at the minimum distance point ($\theta_{WN\ dist\_min}$), the average track velocity (V_{mean}), the track velocity at the minimum distance point (V_{dist_min}) and is the track velocity at the moment of maximum wind speed (V_{wind_max}).

Model 2: The role of coastal habitats in nearshore dynamics (flood height). Coastal vegetation provides resistance to the energy and flow of waves and water as they come onshore which is modeled by using a friction factor. Mangroves are then modeled in terms of an equivalent roughness [e.g. Sheppard friction for coral reefs[62]] based on Manning coefficient. In the Philippines we classify surface types into three groups: sandy soil (n = 0.02)[63], mangroves (n = 0.14)[63] and coral reefs (n = 0.05)[64]. 1-dimensional numerical propagations are carried out using the Delft3D model to obtain flood heights along the coast (Supplementary Figs. 8 and 9). We use these numerical results to create two interpolation tables (for both, regular climate and tropical cyclones) that correlate the climatic information at seaward side of the profile (Hs, Tp, SS and Tss, being this last only specific of tropical cyclones) and the characteristics of the mangrove profiles (width and average depth) with the flood height (i.e. total water level along the coast). These tables contain 37,500 tropical cyclone simulations (50 cyclones × 750 profiles) and 90,000 regular climate simulations (120 sea states × 750 profiles).

These two models described above are integrated in the multi-step framework applied globally for valuing the flood protection role of mangroves:

Step 1: Offshore dynamics. The offshore hydrodynamic conditions (wave height, wave period, storm surge and astronomical tide) were subdivided in two groups: (1) those produced by local extreme events (tropical cyclones) and (2) those produced by less intense local climate or extreme climate generated far away from the study area (regular climate). **Regular climate** is defined by different datasets within the period 1979–2010: a global wave reanalysis[56], a global storm surge reanalysis[57], astronomical tide[65,66] and mean sea level compiled from historical numerical reconstruction and satellite altimetry[67]. Waves and sea level conditions due to tropical cyclones are excluded and studied separately to avoid double counting. **Tropical cyclones** were considered separately from regular climate only if two conditions are satisfied: (1) they are generated within the same ocean basin than the study area and the cyclone passes closer than 500 km from the coastline, and (2) 10-minute sustained wind speeds (W_{10m}) exceed 118 km/h. Tropical depressions ($W_{10m} \leq 62$ km/h) and tropical storms (63 km/h $\leq W_{10m} < 118$ km/h) are studied together with regular climate. For historical tropical cyclones, we used IBTrACS database[53], which provides 6-hourly data of wind speed, atmospheric pressure and position. Since global reanalysis of tropical cyclones that include waves do not exist, we use a statistical model (Equations S.3 to S.10) created from the Philippines results to calculate offshore wave height, peak period, storm surge and storm surge duration just in the limit between deep and shallow water.

Step 2: Nearshore dynamics. Once we resolve offshore dynamics, we obtain waves and storm surge in the seaward side of each cross-shore profile. Waves interact with the bottom and other obstacles (e.g. islands) as they approach the coast and modify height and direction through shoaling, refraction, diffraction and breaking processes. **Regular climate** is propagated following a hybrid downscaling. The 32-year long series, from 1979 to 2010, include 280,000 sea states (1 sea state is 1-hour register of wave height, peak period and total water level). To each profile, we allocate the closest point of the offshore databases. Considering all, the 700,000 coastal profiles and the 280,000 sea states results in an unmanageable number of cases. We reduce the number of sea-state propagations by, firstly, considering only the 3,787 non-repeated combinations of wave height, peak period and total water level (SS + AT + MSL) and, then, applying The Maximum Dissimilarity Algorithm (MDA[68,69]) to finally obtain 120 sea states to be propagated with Snell law and shoaling equation (Eqs. 1 and 2). Meanwhile, **tropical cyclone** nearshore hydrodynamics are obtained by means of the previously derived regression model (equations S.3 to S.10). We apply regression models in each profile, and we obtain the same parameters as for regular climate, in addition to the time duration of the meteorological tide (T_{ss}).

$$H_{s\_perfil} = H_{s\_off} \cdot \sqrt{\frac{C_{off}}{C_{perfil}}} \cdot \sqrt{\frac{\cos\theta_{off}}{\cos\theta_{perfil}}} \quad (2)$$

$$\text{Snell: } \frac{C_{off}}{\cos\theta_{off}} = \frac{C_{perfil}}{\cos\theta_{perfil}} \quad (3)$$

Step 3: Modeling the role of coastal habitats in nearshore dynamics, flood height. The next step consists on propagating ocean hydrodynamics over mangroves forest which dissipate wave and surge energy, and, consequently, reduce flood height. Flood height is a function of mean sea level, astronomical tide and run-up of waves. Mangroves dissipation takes place by means of breaking and friction processes. Given the large scale of this global analysis, we follow a simplified approach for vegetation modeling. We use the interpolation table from the Philippines to infer the resulting flood height given mangrove length and depth, significant wave height, peak period and total water level at the head of each cross-shore profile. Then, we apply the statistical reconstruction technique RBF (Radial Basis Functions)[70] to calculate in each profile the complete historical flood height time series. Next, we carry out an extreme value analysis. First, we select maximum values on a variable threshold (minimum, 1-in-5-year event). We adjust these selected values to a Generalized Pareto-Poisson distribution, and we obtain the flood height vs return period curves for both scenarios: with and without mangroves. We observe a high spatial variability of flood height produced by tropical cyclones along worldwide coastlines, which highlights the importance of addressing global flood risk analysis at high resolutions to consider local topographic and bathymetric variations (e.g. 1-in-100-year flood in Vietnam, Supplementary Fig. 10). We assume that countries with less than 100 ha of mangroves were excluded from the analyses as there were too few mangroves to reliably estimate benefits using a global model. This excluded 15 countries in total, including Bahrain and Benin, which had some of the most over-estimated values of benefit/ha; as well as eight Caribbean Small Island Developing States (Supplementary Table 9).

Step 4: Calculating impacts: flooding maps. Uncoupling wave and surge propagation from the flooding process allows us to freely choose the most accurate flooding method. Other alternative strategies exist, but they are unapproachable at global scale due to its computational cost and high-quality data required, usually unavailable at global scale (e.g. using coupled phase resolving models or phase averaged models). To obtain flood maps by means of uncoupling propagation and flooding processes require: (i) the flood height along the coast with high enough resolution to avoid significant longshore gradients, (ii) a good DTM (Digital Terrain Model) and (iii) a flooding method (flood models). Separating flooding process from waves and sea level propagation gives us more flexibility to adapt the flooding approach to the elevation data. Local scale analyses (< 100 km of coastline) with high resolution DTM (< 10 m) could be addressed by using process-based flood models, like RFSM-EDA (Rapid Flood Spreading Method - Explicit Diffusion wave with Acceleration term)[71,72]. However, larger scale´s (> 100 km) with coarser DTM (> 10 m), require fast and less precise techniques, such as "bathtub" method, based on hydraulic connectivity which consists of merge points below the flood height. We use this last strategy to address global flooding in presence and absence of mangroves. The flood extent is estimated globally by using a 30-meter SRTM-DTM (Shuttle Radar Topography Mission)[73].

Step 5: Assessing global flood consequences in mangroves protected areas. Mangrove benefits are assessed in terms of avoided damages to people and property. Property value is directly obtained as the sum of industrial and residential stock from GAR15, at 5 km resolution worldwide[11]. The suitability of this database to be used in global assessments of coastal flooding exposure and damage lies on the fact that it integrates homogeneous global population and country-specific building typology, use and value data[74]. The consistency of the methodological approach used in the development of GAR15, as well as the choice of the best data currently available for its implementation, have produced a product fully adapted to the needs of the global model of the evaluation of probabilistic risk[74]. Consequently, GAR15 is the most appropriate source of data available for global scale analysis, looking for an order of magnitude of the value of adequate protection for mangroves, usually used by critical stakeholders such as the World Bank[75]. People distribution comes from the freely available 1 km resolution database GPW (Gridded Population of the World), from SEDAC (Socioeconomic Data & Applications Center). To be consistent with flood layer grid resolution (30-m) it is necessary to redistribute people and property over a finer mesh. We apply a downscaling method, in which the re-distributed values are calibrated with the other existing data of people distribution (WorldPop) by imposing as boundary condition that the total sum of the assets re-scaled to 30 meters in each region was equal to the sum of those same assets without re-scaling in the same control zone. The sensitivity of people and stock to different levels of flooding is obtained through different damage functions. Damage functions provide information of the number of people affected by coastal flooding and the stock losses, according to the water depth. We use different damage functions for population and for stock. Population damage is based on the hypothesis that water depths below 0.5 meters do not affect people, while water depths above 0.5 meters affect 100% of people hit by flooding. It is a common practice in the scientific literature not to use damage functions to calculate the population affected by floods[3]. This option overestimates the results obtained; therefore, it is recommended to opt for a certain threshold below which the effects of flooding are not considered[54]. This threshold is set at 0.5 meters because it is a common value used by emergency services (Japan, Netherlands, USA) in determining whether or not it is necessary to evacuate people from an area under threat. In case of stock, we adapted the global flood depth-damage functions from Huizinga/JRC (Joint Research Centre) broken down by continent (Africa, Asia, Oceania, North America, South America and Central America) and by asset type: residential and industrial[54]. Average values of damage at different water depths are provided in Supplementary Table 5. Finally, flood risk (magnitude and probability) is obtained by combining damage curves with people and property exposure distribution. Then, we integrate the return period curves to obtain the Expected Annual Damages and Benefits at each 20-km study unit. We can thus show global information on annual flood damage anywhere and with a spatial resolution high enough to be incorporated into coastal planning and ecosystem conservation policies.

Modeling assumptions. To provide a more nuance discussion of the strengths and weaknesses of the modelling approach, we have included a table with all the assumptions stablished at each step of the methodology, as well as the corresponding reference to the existing literature where this assumption is applied and validated (Supplementary Table 9). This table summarizes the assumptions considered in this work and may help the reader to assess how strong the assumptions are and potentially identify areas for future work.

Data availability

The data that support the findings of this study are available online at: https://osf.io/ecs4p/ (DOI 10.17605/OSF.IO/ECS4P).

Code availability

The MATLAB codes for key analyses are available on request from the corresponding author at pemenend@ucsc.edu.

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Competing interests

The authors declare no competing interests.

Additional information

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Annexure A-20

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CHAPTER 2
PROTECTION FROM CYCLONES

Thematic paper: Role of forests and trees in protecting coastal areas against cyclones

Hermann M. Fritz[1] and Chris Blount[1]

On 26 December 2004, a major earthquake and subsequent tsunami severely damaged coastal communities in countries along the Indian Ocean. Although tsunamis and cyclones are completely different natural disasters in their generation mechanisms, through inundation they both cause primary damage and mortality in coastal areas; in this context the importance of the multi-hazard approach in coastal protection is raised. However, coastal vulnerability is site- and hazard-dependent. The duration of the cyclone storm surge lasts from several hours up to a day and is significantly longer than the tsunami wave period. Narrow coastal forest belts and mangroves are inefficient in reducing storm surge. Kilometres of coastal wetlands or forests are required to significantly attenuate massive inland inundation caused by cyclones. However, mangroves and other coastal forests can reduce wind and storm wave impact as well as current velocities. The additional benefits of these forests include protection from coastal erosion and preservation of wetlands.

1 INTRODUCTION

The Indian Ocean tsunami of December 2004, which killed over 200 000 people and affected livelihoods and coastal resources in 14 Asian and African countries, highlighted the need for coastal protection against tsunamis and other hazards, including cyclones and storm surges. A number of countries have called for the restoration of coastal forests to improve protection of coastal areas. It is difficult, however, to provide specific parametres for protection forests (i.e. width, density and biological characteristics) for effective dissipation of the energy of storm waves and cyclone-force winds because the potential for damage depends on many variables related to the particular site and cyclone. Anecdotal evidence needs to be analysed carefully as reduced impact behind mangrove forests can be attributable to the specific location and setting and not just the forest.

This paper is based on a scientific review of field, experimental and numerical modeling investigations and provides an objective analysis of the roles coastal forests play in protecting lives, natural resources and infrastructure, as well as valuable information for use in coastal area planning and management. An initial overview provides insight into the frequency, strength and location of tropical cyclones in conjunction with natural vegetation types, land-use patterns and coastal vulnerabilities. The effectiveness of coastal forests and trees in protecting population, infrastructure and natural resources from cyclones is discussed.

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2 TROPICAL CYCLONES

2.1 GENERATION

In tropical and some subtropical areas, organized cloud clusters form in response to perturbations in the atmosphere. If a cloud cluster forms in an area sufficiently removed from the Equator, then Coriolis accelerations are not negligible and an organized, closed circulation can form. A tropical system with a developed circulation, but with windspeeds of less than 17.4 metres/second (i.e. 63 kilometres/hour or 39 mph), is termed a tropical depression. Given that conditions are favourable for continued development (basically warm surface waters, little or no wind shear and a high pressure area aloft), this circulation can intensify to the point where sustained windspeeds exceed 17.4 metres/second, at which time it is termed a tropical storm. If development continues to the point where the maximum sustained windspeed equals or exceeds 33.5 metres/second (121 kilometres/hour or 75 mph), the storm is termed a cyclone (Indian Ocean), typhoon (Western Pacific) or hurricane (Atlantic and Eastern Pacific).

2.2 SAFFIR–SIMPSON SCALE AND ASSOCIATED CYCLONE HAZARDS

The Saffir–Simpson Scale is a guideline for the damage potential of a tropical cyclone based solely on sustained windspeed (Saffir and Simpson, 1969). Potential cyclone damages due to storm winds, storm surges and storm waves associated with the five Saffir–Simpson categories are shown in Figure 2.1, Table 2.1 and 2.2.

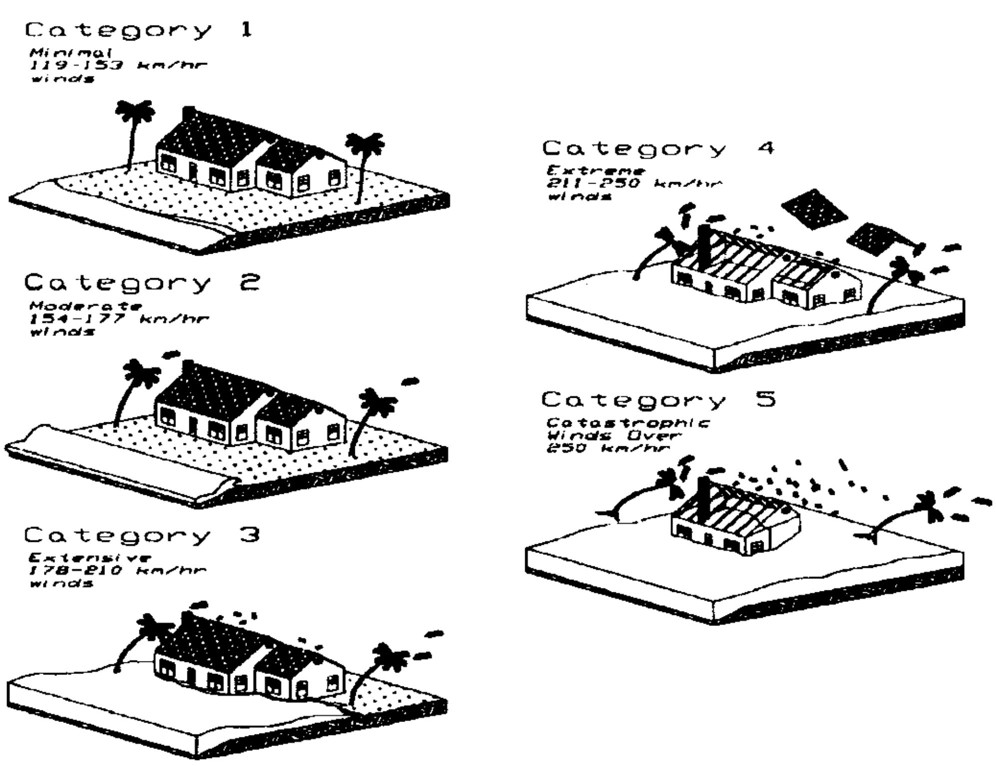

Figure 2.1 Windspeed based on the Saffir–Simpson Scale and associated cyclone damage levels (USACE, 2002)

Table 2.1 Amended Saffir–Simpson cyclone damage potential scale based on windspeed, storm surge heights and beach erosion volumes modified after Basillie (1998)

Cat	Central pressure [mb]	Wind speed [km/h]	Peak storm surge elevation above MSL [m]	Cyclone centre forward speed [km/h]	Storm surge rise time [hr]	Average beach erosion volume [m³/m shoreline]	Max. beach erosion volume [m³/m shoreline]	Damage potential
1	>980	119–153	1.2–1.7	50–88	2.5–4.5	3.0–8.3	6.3–17.6	Minimal
2	965–979	154–177	1.7–2.6	29–50	4.5–7.5	8.3–25	17.6–53	Moderate
3	945–964	178–210	2.6–3.8	19–29	7.5–11	25–63	53–133	Extensive
4	920–944	211–250	3.8–5.5	10–19	11–21	63–190	133–400	Extreme
5	<920	>250	>5.5	<10	>21	>190	>400	Catastrophic

Table 2.2 Local sea states with characteristic wave heights (H) and wave periods (T) generated by cyclones for the Saffir–Simpson categories (USACE, 2002)

Tropical Depression Weak circulating tropical system with winds under 73 km/hr	Squall lines superposed on background winds can produce confused, steep waves.	H 1 - 4 m T 4 - 8 sec
Tropical Storm Circulating tropical system with winds over 73 km/h and less than	Very steep seas. Highest waves in squall lines.	H 5 - 8 m T 5 - 9 sec
Hurricane Intense circulating storm of tropical origin with winds speeds over 126 km/hr Shape is usually roughly circular	Can produce large wave heights. Directions near storm center are very short-crested and confused. Highest waves are typically found in the right read quadrant of a storm. Wave conditions are primarily affected by storm instenisty, size, and forward speed, and in weaker storms by inteactions with other synoptic scale and large-scale features.	Saffir Simpson Hurricane Scale SS H (m) T (sec) 1 4 - 8 7 - 11 2 6 - 10 9 - 12 3 8 - 12 11 - 13 4 10 -14 12 - 15 5 12 -17 13 -17

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2.3 CYCLONE-AFFECTED AREAS AROUND THE WORLD

Tropical cyclones develop in the following ocean basins: North Atlantic (NATL: 90° to 20°west, 5° to 25° north), western North Pacific (WPAC: 120° to 180° east, 5° to 20° north), eastern North Pacific (EPAC: 90° to 120° west, 5° to 20° north), South Indian (SIO: 50° to 115° east, 5° to 20° south), North Indian (NIO: 55° to 90° east, 5° to 20° north) and Southwest Pacific (SPAC: 155° to 180° east, 5° to 20° south). Figure 2.2 shows the relative worldwide distribution of cyclones over these basins (Abbott, 2006). While cyclones occur within 15°-wide bands in the northern and southern hemisphere, a few areas account for the bulk of the casualties and damage including: the Bay of Bengal, the Gulf of Mexico, the South China Sea and the Mozambique Channel. Cyclone impacts are particularly catastrophic on these coasts due to the typically perpendicular cyclone tracks, converging bays and shallow bathymetries.

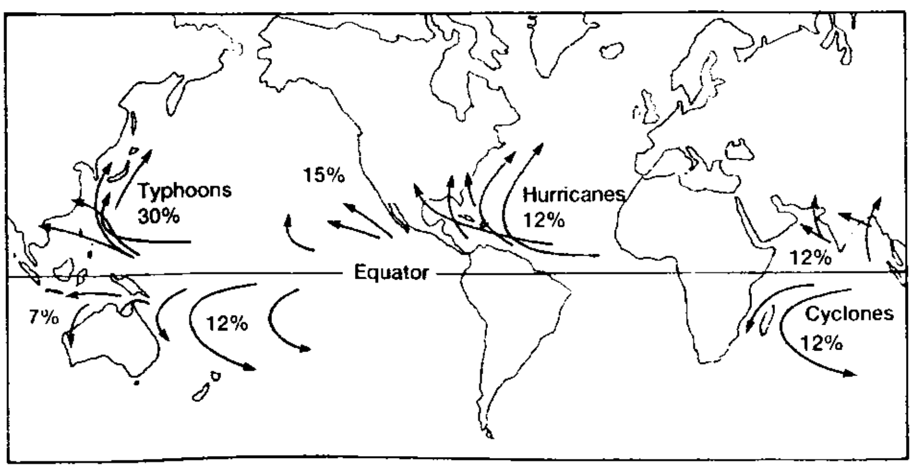


Figure 2.2 Typical tropical cyclone tracks with global distribution and local names (Abbott, 2006)

Webster *et al.* (2005) investigated the relationship between rising sea surface temperature (SST) and the frequency and intensity of tropical cyclones in each ocean basin. There has been much controversy over this issue, but the article outlines the relevant relationships between SST and tropical cyclones. Over the period of record from 1970 to 2004, the tropical ocean SST rose 0.5°C. The article indicates that there is no statistically significant trend in the total number of storms and the total number of storm days over that period with respect to the SST. There are apparent decadal-scale variations on the global scale that are similar to those in individual basins (Figure 2.3).

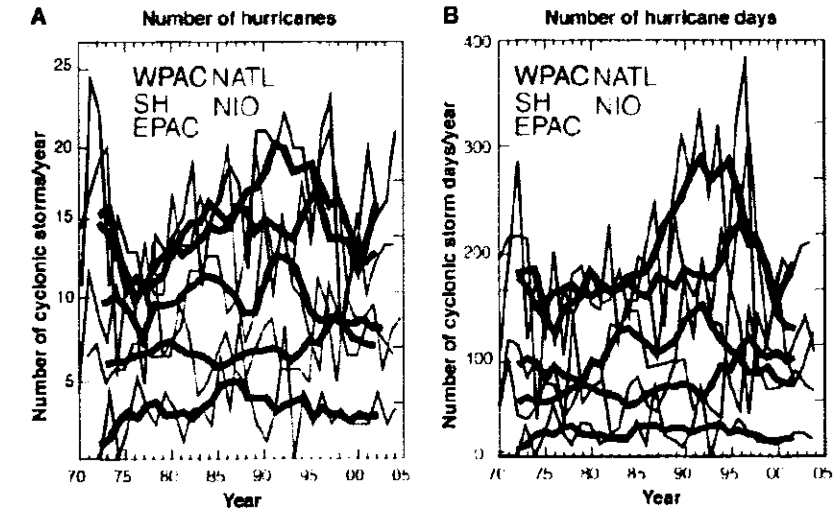


Figure 2.3 Regional time series for 1970 to 2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (A) total number of cyclones and (B) total number of cyclone days. Thin lines indicate the year-by-year statistics. Heavy lines show the 5-year running averages (Webster *et al.*, 2005)

Except for the North Atlantic, all of the basins have seen a decrease in the number of cyclones and cyclone days over the past decade; however, there has been a significant increase in the number and percentage of very intense (category 4 and 5) storms as shown in Figure 2.4. This increase in most hazardous and damaging cyclones occurs in all of the basins with the largest increases in the Indian, North Pacific and Southwest Pacific oceans and the smallest increase in the North Atlantic. The increase in category 4 and 5 cyclones is most disturbing with regard to the protective role of mangrove and coastal forests as their effectiveness in protecting coastlines declines with increasing storm intensity.

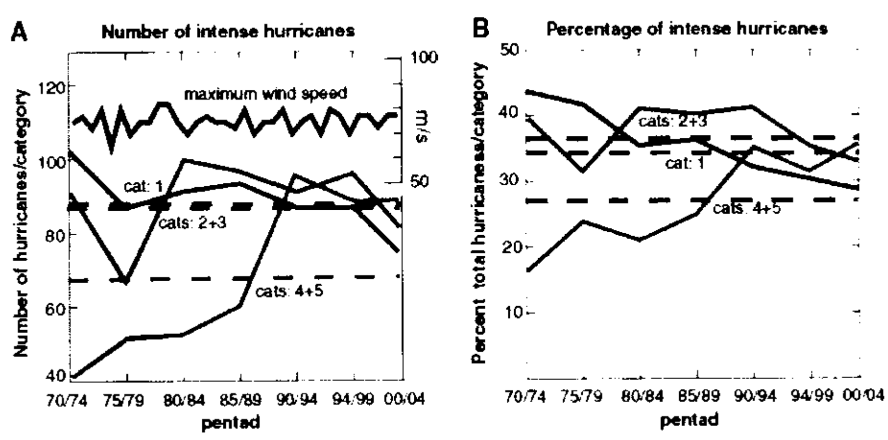


Figure 2.4 The number and percentage of intense cyclones from 1970 to 2004

These data correspond to the work done by Emanuel (2005), who created a power dissipation index (PDI) to measure the intensity and potential destructiveness of a cyclone. There is evidence that the SST is a major (but not the only) controlling factor of the PDI, and the report indicates there has been a near doubling of the PDI over the period of record. While Webster *et al.* (2005) reported stable upper bound limits on actual maximum intensity in the past, Emanuel proposed that potential and actual maximum intensities could increase with a continued increase in global warming.

2.4 NORTH INDIAN OCEAN TROPICAL CYCLONES

Singh *et al.* (2000) analysed 122 years (1877–1998) of tropical cyclone frequency in the North Indian Ocean. Approximately four times as many tropical cyclones occur in the Bay of Bengal compared to the Arabian Sea. Cyclones occur most often in May, October and November (Table 2.3), with an average of five to six tropical cyclones every year.

Table 2.3 Breakdown of cyclones by month, severity and sea in the North Indian Ocean

	Month				
	May	June	September	October	November
Bay of Bengal					
Cyclonic storms	59	35	40	89	114
Severe cyclonic storms	42	5	16	38	63
Arabian Sea					
Cyclonic storms	24	25	4	24	20
Severe cyclonic storms	19	17	2	11	15

Because of the heavy socio-economic impact suffered along the Bay of Bengal annually due to cyclones, it is important to track any change in frequencies. The highest number of severe cyclones occurs in November with an average of one per year. These cyclones usually hit the Andhra Pradesh or Tamil Nadu regions of the Indian coast, but the cyclones sometimes affect Bangladesh or Myanmar. Over the 122 years studied, the frequency of tropical cyclones in the Bay of Bengal during November has doubled. The second highest number of severe tropical cyclones occurs in May, and most of these cyclones strike Bangladesh or Myanmar.

Singh *et al.* (2000) concluded that cyclone frequency significantly increased in November and May (primarily in the Bay of Bengal), significantly decreased in June and September, and changed minimally during October. The overall frequency of tropical cyclones in the Bay of Bengal has a decreasing trend of 15 percent per hundred years, but November shows a 20 percent increase per 100 years *vis-à-vis* the rate of cyclones that reached severe cyclone stage.

Table 2.4 (De *et al.*, 2005) lists the most destructive cyclones to hit India and the surrounding area. Karim (2006) compiled a comprehensive list of cyclones to hit Bangladesh since 1960 (Table 2.5).

Table 2.4 Most destructive cyclones to hit India (modified after De *et al.* 2005)

Year	Name of Country	No. of Deaths	Storm surge (m)
1737	Hoogli, West Bengal (India)	300 000	12.2
1876	Bakerganj (Bangladesh)	25 000	3.0 - 12.2
1885	False point (Orissa)	5 000	6.7
1960	Bangladesh	5 490	5.8
1961	Bangladesh	11 468	4.9
1970	Bangladesh	200 000	4.0 - 5.2
1971	Paradeep, Orissa (India)	10 000	2.1 - 6.1
1977	Chirala, Andhra Pradesh (India)	10 000	4.9 - 5.5
1990	Andhra Pradesh (India)	990	4.0 - 5.2
1991	Bangladesh	138 000	2.1 - 6.1
1998	Porbander cyclone	1 173	
1999	Paradeep, Orissa (India)	9 885	9.1

Table 2.5 Most destructive cyclones to hit Bangladesh (modified after Karim, 2006)

Date	Year	Max. wind speed (km/hr)	Storm Surge (m)	Deaths		Date	Year	Max. wind speed (km/hr)	Storm Surge (m)	Deaths
9-Oct	1960	162	3.0	3 000		06-Nov	1971		2.4 - 5.5	-
30-Oct	1960	210	4.6 - 6.1	5 149		18-Nov	1971		2.4 - 4.0	-
09-May	1961	146	2.4 -3.0	11 466		09-Dec	1973	122	1.5 - 4.6	183
30-May	1961	146	6.1 - 8.8	-		15-Aug	1973	97	1.5 - 6.7	-
28-May	1963	203	4.3 - 5.2	11 520		28-Nov	1974	162	2.1 - 4.9	a few
11-Apr	1964	-	-	196		21-Oct	1976	105	2.4 - 4.9	-
11-May	1965	162	3.7	19 279		13-May	1977	122	-	-
31-May	1965	-	6.1 - 7.6	-		10-Dec	1981	97	1.8	2
14-Dec	1965	210	4.6 - 6.1	873		15-Oct	1983	97	-	-
01-Oct	1966	146	4.6 - 9.1	850		09-Nov	1983	122	-	-
11-Oct	1967	-	1.8 - 8.5	-		03-Jun	1984	89	-	-
24-Oct	1967	-	1.5 - 7.6	-		25-May	1985	154	3.0 - 4.6	11 069
10-May	1968	-	2.7 - 4.6	-		29-Nov	1988	162	1.5 - 3.0	2 000
17-Apr	1969	-	-	75		29-Apr	1991	225	6.1 - 7.6	138 000
10-Oct	1969	-	2.4 - 7.3	-		02-Jun	1991	100	1.8	-
07-May	1970	-	3.0 - 4.9	-		02-May	1994	200	-	170
23-Oct	1970	-	-	300		25-Nov	1995	100	-	6
12-Nov	1970	223	6.1 - 9.1	500 000		19-May	1997	225	4.6	126
08-May	1971	-	2.4 - 4.3	-		26-May	1997	150	3.0	70
30-Sep	1971	-	2.4 - 4.3	-						

The damage and destruction generated by these cyclones have not decreased. Loss of life, however, tends to show a decrease because of better weather forecasts and warnings, their dissemination, and disaster management strategies put in place by national weather services in conjunction with the significant role played by the World Meteorological Organization (WMO) through its regional meteorological centres (RMCs) that deal especially with tropical cyclones.

2.5 WESTERN PACIFIC OCEAN TROPICAL CYCLONES

Imamura and To (1997) compiled and summarized typhoon and flood data for 40 years and collected site information about the coastal problems by conducting field investigations along the coast of Viet Nam. Viet Nam continues to suffer from multiple human, economic and social damage owing to cyclones and flooding, even though an extensive flood control system has been developed. An increasing population with concentrations in hazardous coastal areas and the lack of funding for construction and maintenance of dykes and rivers are two of reasons for the continuing problem. Figure 2.6 shows the tracks of the two 1985 typhoons that successively devastated Viet Nam. Figure 2.7 shows the damage from human-induced and natural disasters in Viet Nam.

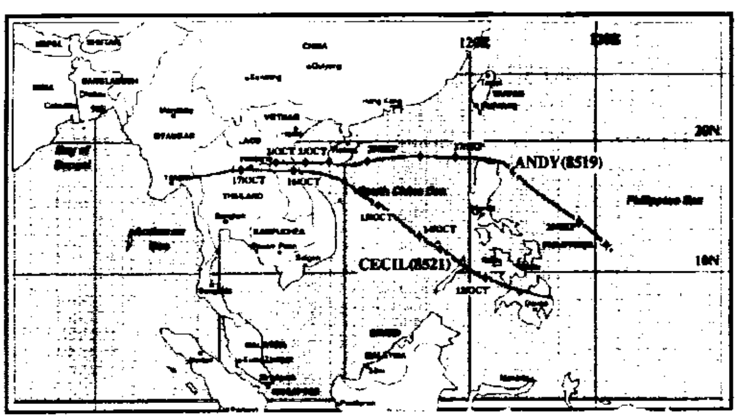


Figure 2.1 The tracks of typhoons Andy and Cecil that devastated central Viet Nam in 1985

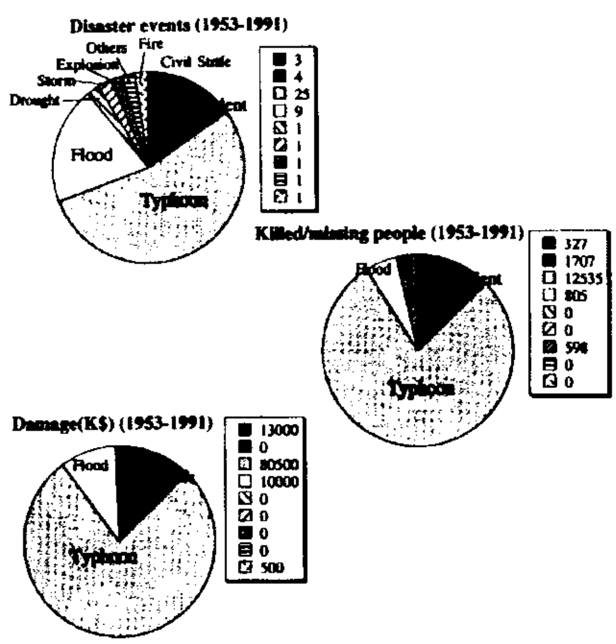


Figure 2.2 Estimated damage caused by human-induced and natural disasters in Viet Nam (1953–1991)

Statistical data for yearly frequency from 1954 to 1991, as well as numbers for submerged rice fields, deaths and calculations of losses from 1970 to 1990 (General Bureau of Hydro-Meteorology

[1980] and UN/DHA [1994]) indicate that during the 1960s and 1970s there were five years with more than eight typhoons, whereas only one occurred in the 1980s; this suggests that there was high typhoon activity from 1960 to 1980, which corresponds to the tendency recorded elsewhere in Southeast Asia, including Japan (Ohnishi, 1994). Typhoons start in March, peak in October and finally decrease at the end of the year. The period between June and November is considered to be the storm season.

Approximately one-third of the cyclones generated in the world occur in the Western North Pacific Ocean; consequently, Southeast Asia is always vulnerable. Table 2.6 summarizes 71 typhoons that caused damage to Southeast Asian countries from 1985 to 1989. Note that the totals each year do not add up, because each typhoon usually affected more than one country. China had the highest frequency at 46.5 percent; the Philippines and Japan were second (35.2 percent); the Republic of Korea, Viet Nam and Hong Kong Special Administrative Region were third (17.3 percent); and Thailand and Malaysia were fourth (5.6 percent). The number of typhoons hitting Viet Nam was almost half that of the Philippines, but higher than Thailand. The occurrence of typhoons decreases from the open sea to the coast. The report expected that Viet Nam would not be third but second in terms of losses because damage in Viet Nam has increased in spite of lower typhoon frequency. Financial losses in Japan and the Republic of Korea have decreased rapidly.

Table 2.6 Frequency of typhoons in Southeast Asian countries (1985–1989)

Country	1985	1986	1987	1988	1989	Total
China	8	6	4	4	11	33
Philippines	4	6	5	5	7	27
Japan	10	2	3	4	4	23
Rep. of Korea	8	3	2	0	1	14
Viet Nam	2	1	3	2	4	12
Hong Kong	2	3	1	3	2	11
Thailand	1	1	2	0	1	5
Malaysia	0	1	0	2	0	3
Total	17	11	12	12	19	71

3 CYCLONE IMPACT CHARACTERISTICS

3.1 RETURN PERIOD CALCULATIONS

The Indian state of Orissa on the Bay of Bengal coast has been hit by many tropical cyclones in the past 200 years. Chittibabu *et al.* (2004) compiled a comprehensive list of 128 tropical cyclones that struck Orissa from 1804 to 1999. Included in these strikes was the supercyclone of 29 to 30 October 1999, which killed approximately 10 000 people and had a 7.5-metre storm surge. Cyclonic flooding in the Bay of Bengal is associated with storm surges, high tides and high water levels due to the heavy rainfall. Chittibabu *et al.* (2004) calculated that the 1999 cyclone had a return period of approximately 50 years. Cyclones in 1831, 1885 and 1895 were also possible supercyclones. A location map of Orissa and an inundation map of Orissa districts caused by the aforementioned supercyclone in 1999 are given in Figure 2.8. Table 2.7 shows the India Meteorological Department (IMD) cyclone classification system.

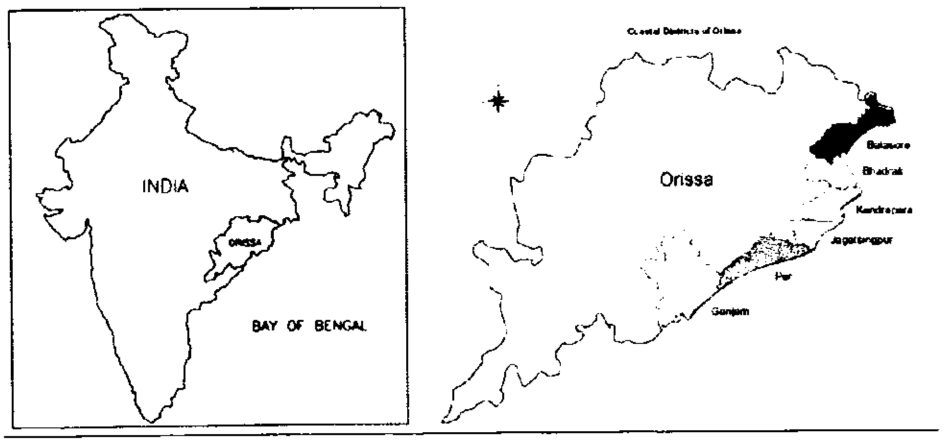


Figure 2.3 Location map of Orissa and the inundated areas of Orissa after the 1999 supercyclone

Table 2.7 IMD cyclone classification by sustained windspeed

Storm category	Abb.	Wind speed (knots)	Wind speed (kph)
Super cyclone	SC	> 120	> 221
Very severe cyclonic storm	VSCS	64 to 119	119 to 221
Severe cyclonic storm	SCS	48 to 63	88 to 118
Cyclonic storm	CS	34 to 47	63 to 87
Cyclonic depression	CDP	33 or less	62 or less
Cyclonic disturbance during monsoon	CD	(Not specified)	(Not specified)

Table 2.8 shows the individual tropical cyclones in Orissa as reported by the IMD. By sorting the historical data, the report shows the return periods for flooding in the nineteenth and twentieth centuries (Table 2.9). The report notes that minor events were eliminated in the twentieth century due to the construction of river embankments.

Table 2.8 Twentieth century cyclones in Orissa, India

Serial No.	Date	Wind speed (knots)	Classification
1	10 May 1903	51	SCS
2	30 June 1905	51	SCS
3	21 July 1906	49	SCS
4	29 August 1908	38	CS
5	3 July 1910	51	SCS
6	3 August 1910	51	SCS
7	10 June 1911	60	SCS
8	28 July 1912	47	CS
9	2 August 1912	45	CS
10	31 October 1912	51	SCS
11	17 July 1913	49	SCS
12	30 August 1913	45	CS
13	3 August 1915	45	CS
14	1 August 1919	51	SCS
11	4 August 1924	49	SCS
16	16 August 1926	51	SCS
17	16 September 1926	51	SCS
18	17 July 1927	59	SCS
19	25 July 1928	51	SCS
20	3 October 1928	49	SCS
21	23 August 1929	38	CS
22	3 August 1933	49	SCS
23	13 June 1936	51	SCS
24	4 October 1936	74	VSCS
25	24 July 1937	49	SCS
26	10 October 1938	92	VSCS
27	16 November 1942	91	VSCS
28	25 July 1943	49	SCS
29	25 July 1944	55	SCS
30	31 July 1944	55	SCS
31	27 June 1947	40	CS
32	14 August 1948	55	SCS
33	2 August 1953	62	SCS
34	22 August 1957	59	SCS
35	29 June 1959	60	SCS
36	2 October 1967	85	VSCS
37	12 September 1968	60	SCS
38	30 October 1971	100	VSCS
39	14 July 1972	55	SCS
40	11 October 1973	45	CS
41	9 November 1973	75	VSCS
42	8 August 1981	34 to 47	CS
43	25 September 1981	34 to 47	CS
44	3 June 1982	47 to 63	SCS
45	14 October 1984	47 to 63	SCS
46	20 September 1985	34 to 47	CS
47	16 October 1985	47 to 63	SCS
48	9 November 1995	70	VSCS
49	17 October 1999	64 to 100	VSCS
50	29 October 1999	140	SC

SC = Super Cyclone, VSCS = Very Severe Cyclonic Storm, SCS = Severe Cyclonic Storm, CS = Cyclonic Storm.

Table 2.9 Return periods for flooding in Orissa: (a) nineteenth century, (b) twentieth century

(a)

Event	Flood depth (m)	Return period (years)
Minor	<1.5	1.5
Moderate	1.5 to 3.0	3.5
Severe	>3.0	9

(a)

(b)

Event	Flood depth (m)	Return period (years)
Moderate	1.5 to 3.0	4
Severe	>3.0	10

Accurate methods to determine the maximum windspeed (and therefore intensity) have only been available since 1971. Hence, the 16 moderate to severe storms from 1971 to 2000 were used for the computer simulations by Chittibabu *et al.* (2004). These tracks were used to synthesize six tracks (one intersecting each coastal district) to provide more complete geographical coverage of the coastal area (Figure 2.9).

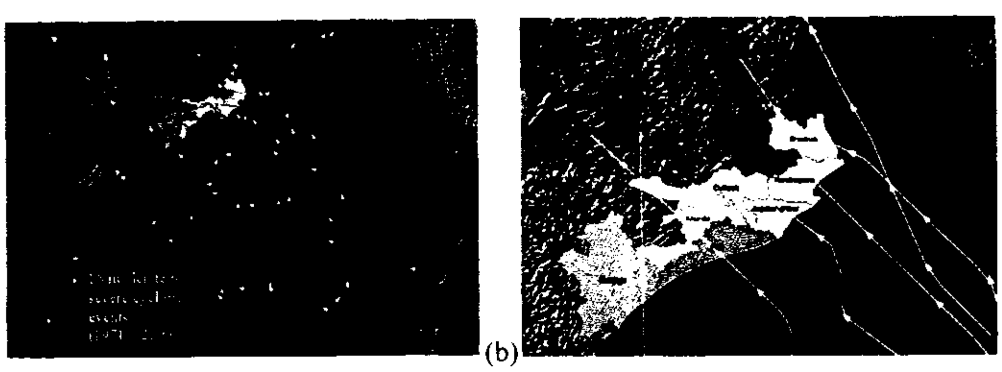
(a)  (b)

Figure 2.4 (a) Cyclone tracks impacting the coast of Orissa from 1971 to 2000 (b) six synthesized generic cyclone tracks (Chittibabu *et al.*, 2004)

These tracks were used with the Indian Institute of Technology (ITT-D) numerical storm surge model to calculate the storm surges along the Orissa coast. It should be noted that the surge values in the southern part of Orissa are almost half of those in the northern part due to the nearshore topography and orientation of the coastline with respect to the storm track. Combining these storm surge data with a tidal prediction model (WXTide) and wave setup, Chittibabu *et al.* predicted the total water level for a 50-year return period (Figure 2.10).

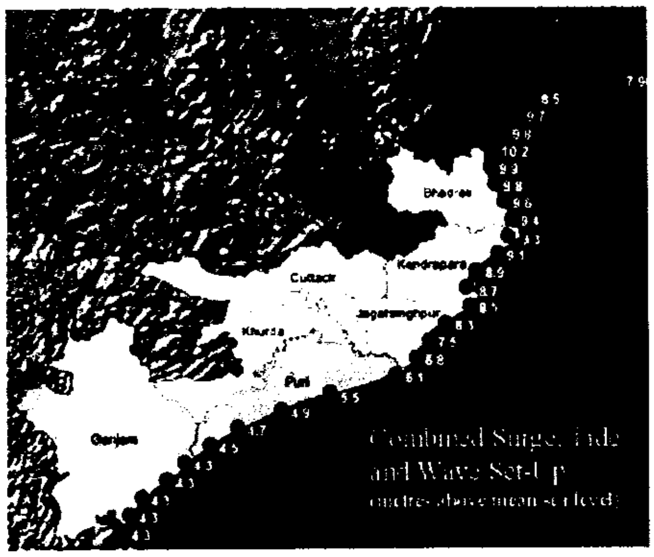


Figure 2.5 Total water level on a 50-year return basis (Chittibabu *et al.*, 2004)

A similar study was conducted for Bangladesh (Kabir *et al.*, 2006). The report discussed the creation, calibration and validation of hydrodynamic, cyclone and storm surge models using 17 major cyclones in Bangladesh from 1960 to 2000. Using a statistical analysis of the models, surge levels were calculated for the 10-, 20-, 50- and 100-year return periods. Figure 2.11b shows the calculated surges for the 100-year return periods. The analysis indicated that the areas around Sandwip Island and the Meghna River mouth have the highest storm surges. The computed storm surge levels match the areas affected by 1970, 1985 and 1991 cyclones (Figure 2.11a). The Sundarbans mangrove forests to the west of the Ganges River Delta are the largest in the world extending up to 80 kilometres into the Bay of Bengal; they reduce cyclone impacts significantly. This is the prime example of natural cyclone impact mitigation.

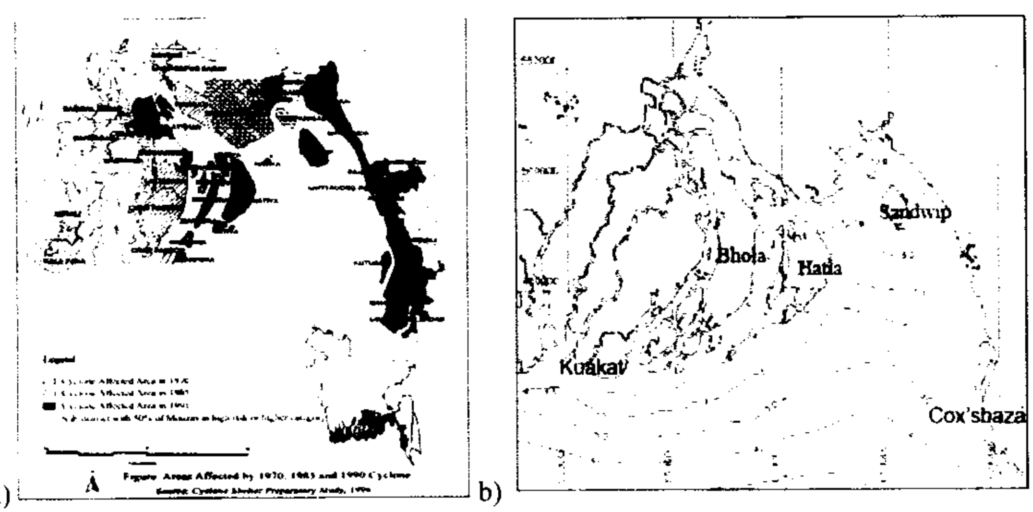
a)  b)

Figure 2.6 Bangladesh storm surges:
(a) Areas most affected by historic cyclones (Karim 2006)
(b) computed 100-year return period surge levels (Kabir *et al.*, 2006)

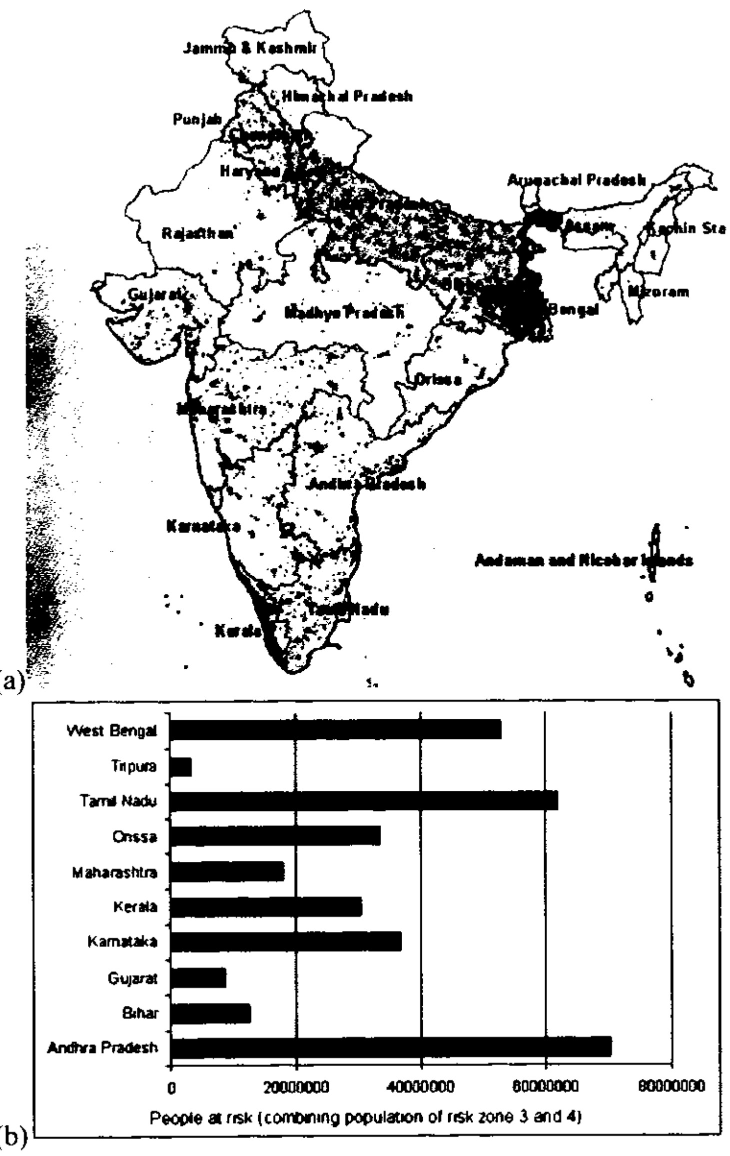
3.2 VULNERABILITY TO CYCLONES

Dube *et al.* (2004) created models to simulate the storm surgesfrom past cyclones in the head of the Bay of Bengal (Orissa, West Bengal and Bangladesh) and discussed how each of the storms that were modeled formed and how the storms affected the specific areas. Dube *et al.* (1997) also discussed storm surges in the Bay of Bengal and why the area is affected to such an extent by extreme sea levels. The reasons were summarized by Ali (1979) as follows:

- coastal waters (shallow bathymetry extending tens of kilometres offshore);
- convergence of the bay;
- high astronomical tides;
- thickly populated low-lying islands;
- favourable cyclone tracks impacting perpendicular to coastline; and
- innumerable inlets and river systems.

Hossain and Singh (2006), using a geographic information system, developed a method to assess the vulnerability of people in India. They conceptualized vulnerability as the exposure to hazard (cyclone) and the coping capacity of the people (for example, provision of an early warning system, capital) to adapt and reduce adverse impacts. This coping capacity also includes defense mechanisms and access to the resources (such as education, infrastructure). The report assigned risk levels from 1 (low) to 4 (high). Figure 2.12 shows the population density of India (darker purple indicates high density) and the populations in the high-risk states. Per capita income versus the assigned risk level is given in Figure 2.13, with the poorest people being the most vulnerable.

(a)



(b)

Figure 2.7 (a) Population density of India (b) population of high-risk states in India

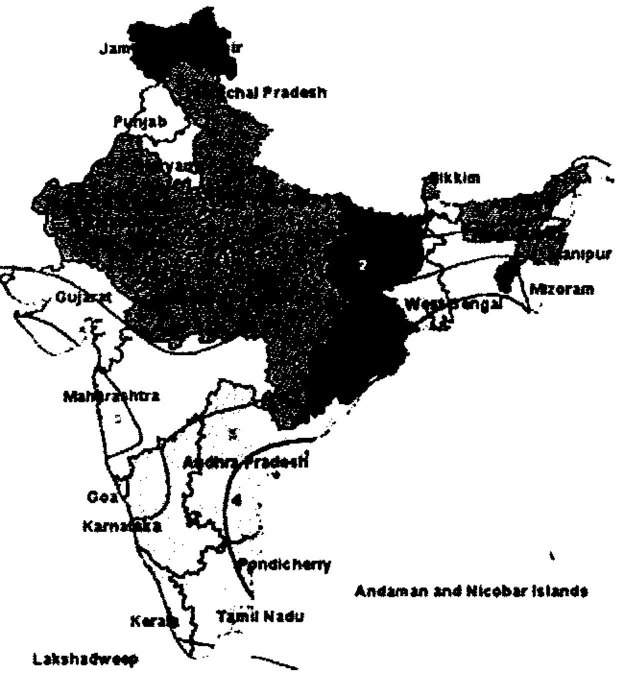


Figure 2.8 Per capita income of different states in India and risk level. Dark red areas equal low per capita income and yellow areas equal high per capita income

3.3 MANGROVE FOREST PROTECTION AGAINST CYCLONES

According to Kabir *et al.* (2006), forests are considered a low-cost and natural form of protection for lands subjected to strong currents and surges. For their study, development of mangrove forests was considered to be one measure for coastal protection in Bangladesh. A model based on the MIKE 21 numerical model was created to study the effect of mangrove forests on storm surges that hit Hatia Island in southeastern Bangladesh. For the model, mangrove forests were laid on the southern tip of Hatia (Figure 2.14a) in bands that ranged from 133 to 600 metres, and eight total simulations were conducted using the 1970 cyclone. Three fixed locations 600 metres from the shoreline were chosen. The variation of surge height with respect to forest band widths at the fixed locations 600 metres inland are shown in Figure 2.14b and the results are summarized in Table 2.10. The results show the reduction at fixed locations 600 metres inland and do not represent transects from the shoreline to the test locations.

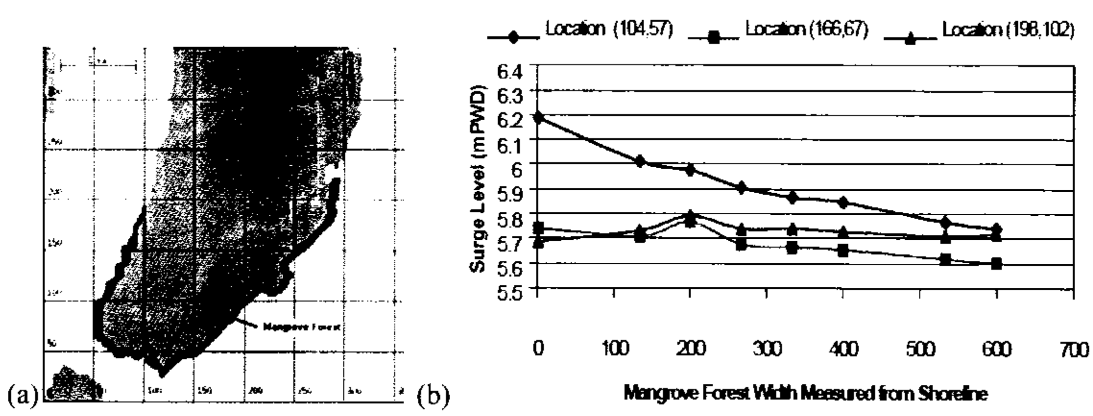


Figure 2.9 (a) Hatia Island locations of simulations (b) surge variations at fixed locations 600 m inland from the shoreline with different forest widths between the locations and the coastline (Kabir *et al.*, 2006)

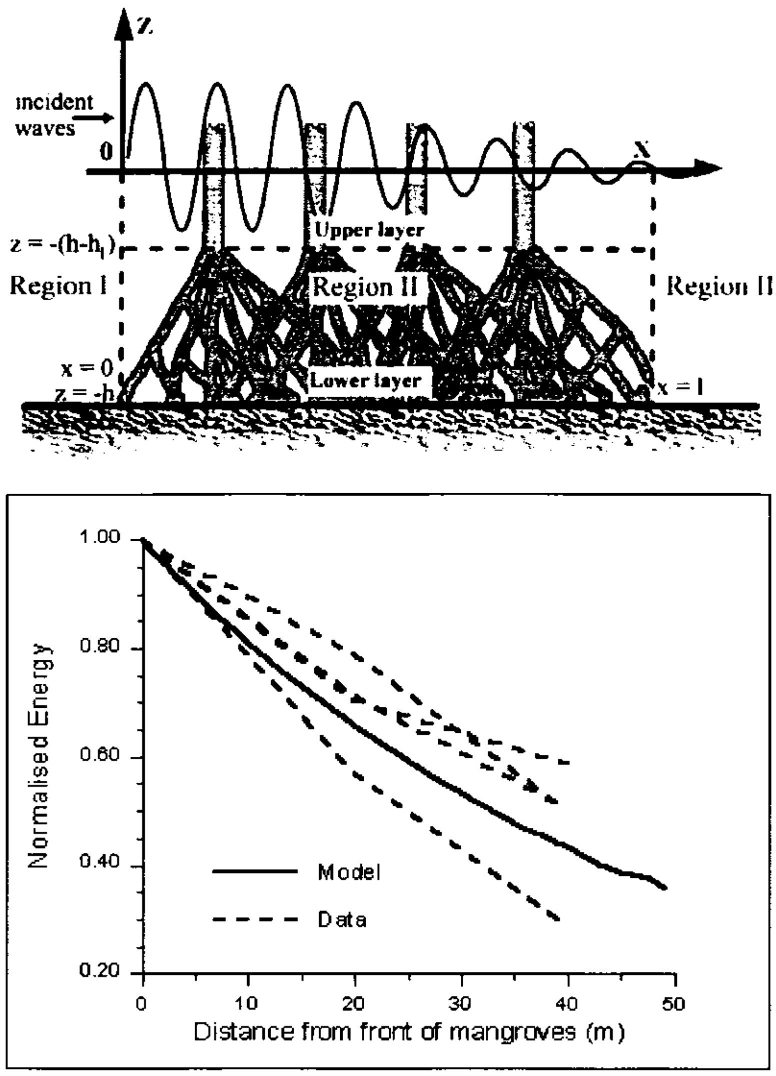
Table 2.10 Summary of computed storm surge reductions by mangrove bands of various widths (Kabir *et al.*, 2006)

Mangrove Forest			*Maximum Surge Level (m) at Locations (local co-ordinates)*		
Nota-tion	*No. of Rows*	*Total width (m)*	*(104, 57)*	*(166, 67)*	*(198, 102)*
Mg0	0	0	6.186	5.74	5.685
Mg2	2	133	6.01	5.708	5.73
Mg3	3	200	5.976	5.765	5.79
Mg4	4	267	5.906	5.674	5.737
Mg5	5	333	5.866	5.664	5.739
Mg6	6	400	5.846	5.653	5.727
Mg8	8	533	5.765	5.617	5.71
Mg9	9	600	5.738	5.599	5.717

According to the model, the most effective area of forest cover for the 1970 cyclone would have been along the southern tip of Hatia Island. This location would have seen a decrease in surge of 0.45 metre with a 600-metre strip of mangroves and a 0.18-metre decrease at the test location 600 metres inland for a 133-metre strip of mangroves. The site in the middle would have seen little decrease in surge height (0.15 metre with a 600-metre strip). The base flooding with no mangroves was 6.2 metres at this location 600 metres inland. Hence, a storm surge height reduction of seven percent was achieved by adding 600 metres of forest between the shoreline and the test location 600 metres inland. In the case of the northernmost site, the surge level would have increased slightly due to the forests' trapping of flow coming from other parts of the island. This illustrates the importance of site characteristics in determining that the effect of the forest will vary according to the site characteristics. Similarly, coastal forests can also funnel flows along creeks, thereby increasing surge heights in some cases. The main conclusion is that narrow coastal forests have minimal effects on the storm surge height and inland flooding. In order to significantly reduce the impact of the storm surge —usually the most devastating cyclone hazard — kilometres of coastal forests are required. Few other storm surge reductions by mangrove models were readily available to the authors.

However, there are many documented studies on the hydrodynamics within mangrove swamps and their wave attenuation properties. These include Mazda *et al.* (2005), Mazda *et al.* (1997), Liu *et al.* (2003), Wu *et al.* (2001), Brinkman (1997) and Massel *et al.* (1999). Mangroves trap and stabilize sediment and reduce the risk of shoreline erosion because they dissipate surface wave energy. It is this attribute that makes mangroves a potential natural solution for particular coastal protection problems. Field observations of surface wave attenuation in mangrove forests were undertaken in both Townsville, Australia and on Iriomote Island, Japan. High resolution wave gauges were deployed throughout the mangroves along transects in line with the dominant direction of wave propagation. Data were gathered to verify a numerical model of wave attenuation. The numerical model was based on the fact that surface waves propagating within a mangrove forest are subject to substantial energy loss due to two main energy dissipation mechanisms: (1) multiple interactions of wave motion with mangrove trunks and roots; and (2) bottom friction. The dissipative characteristics of the mangrove forest were estimated from physical parameters such as trunk diameter, spatial density and vegetation structure, which were not necessarily vertically and horizontally uniform. The resulting rate of wave energy attenuation depended strongly on the density of the mangrove forest, the diameter of the mangrove roots and trunks and on the spectral characteristics of the incident waves. The numerical model results were supported by field observations, which showed substantial attenuation of wave energy within the mangrove forest (Figure 2.15). Typically, wave energy is attenuated by a factor of 2 within 50 metres of the front of the mangrove forest. Hence, the wave heights are typically attenuated by a factor of square root 2 given that the wave energy is related to the square of the wave height. Both field and model results also indicated that longer period waves, such as swell waves, are subjected to less attenuation, while short period waves with frequencies typical of locally generated wind waves lose substantial energy due to interactions with the vegetation. Also, it is evident that as water level increases, wave energy is transmitted further into the forest. This is not only due to more of the forest being inundated, but also to the structure of the mangrove roots and trunks. The obstruction density caused by the mangrove wood structure decreases rapidly with height and, therefore, as the water level increases because of the storm surge there is proportionally less flow resistance and less reduction of wave energy. Unfortunately, this effect severely reduces wave attenuation with increasing cyclone intensity, storm surge height and wave period. All of the aforesaid studies analysed only wave attenuation at normal sea levels and not during cyclones with elevated storm tide levels.

(a)



(b)

Figure 2.10 Surface wave attenuation in mangrove forests:
(a) Schematic used in the analytical study by Massel *et al.* (1999)
(b) comparison between field data and numerical simulations
(http://www.aims.gov.au/ibm/pages/news/mangwave.html)

Badola and Hussain (2005) evaluated the protective function of mangroves in Bhitarkanika in the eastern state of Orissa, India. The Bhitarkanika mangrove ecosystem is the second largest mangrove forest of mainland India (Figure 2.16). Originally around 672 km^2, it is now limited to an area of 145 km^2 and is a wildlife sanctuary. This mangrove forest and the associated coast house the highest diversity of Indian mangrove flora and fauna. The mangrove forests of Bhitarkanika differ considerably from other mangroves because of the dominant tree species — *Sonneratia apetal, Heritiera fomes, H. littoralis* and several *Avicennia* species.

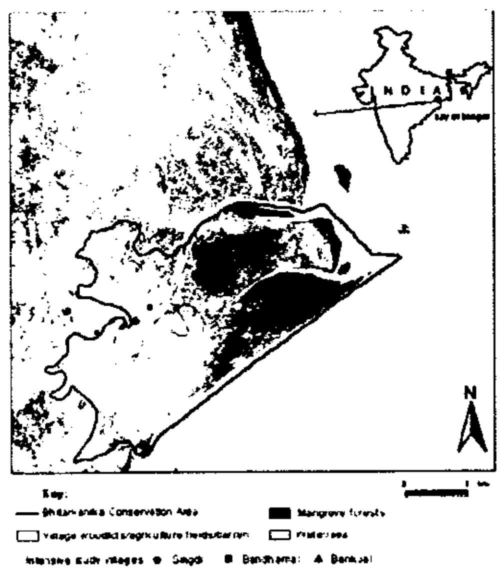


Figure 2.11 Kendarapara and Bhadrak districts of Orissa, India, with the location of Bhitarkanika Conservation Area and the extent of mangrove forests

The report aimed to measure the economic losses attributed to the 1999 supercyclone relative to the prevailing socio-economic conditions of the study villages. It evaluated the extent of damage caused in areas that were under the umbrella of mangrove forests and areas that were not, in the wake of this supercyclone. In 1971, an embankment was created along the entire Orissa coast to prevent seawater intrusion into reclaimed paddy fields. Therefore, the report also studied the effectiveness of such artificial structures in providing storm protection, as opposed to mangrove forests.

Hence, the following three situations were identified: (1) A village in the shadow of mangroves; (2) a village not in the shadow of mangroves and with no embankment; and (3) a village not in the shadow of mangroves, but with an embankment on the seaward side. Bankual village was in the shadow of a mangrove forest, Singidi village was neither in the shadow of mangroves nor protected by an embankment from storm surge and Bandhamal village was not in the shadow of mangroves, but had a seaward side embankment. The report indicated that the intensity of the impact of the 1999 cyclone on these villages should have been fairly uniform, as all the three selected villages were equidistant from the seashore and had similar aspects. The two villages outside mangrove cover were located close to each other, but both were far from the mangrove forest in order to eliminate any effect of mangrove forest presence.

Services provided by the Bhitarkanika mangrove ecosystem in India and estimated cyclone damage avoided in the three selected villages, taking the supercyclone of 1999 as a reference point, were evaluated by assessing the socio-economic status of the villages, the cyclone damage to houses, livestock, fisheries, trees and other assets owned by the people, and the level and duration of flooding. Eleven variables were used to compare damage in the villages (Table 2.11). Attitude surveys were carried out in 10 percent of the households in 35 villages located in the Bhitarkanika

Conservation Area to assess local people's perceptions regarding the storm protection function of mangroves and their attitudes towards mangrove forests in general. In the mangrove-protected village, variables had either the lowest values for adverse factors (such as damage to houses), or the highest values for positive factors (such as crop yield). The loss incurred per household was greatest (US$153.74) in the village that was not sheltered by mangroves but had an embankment, followed by the village that was neither in the shadow of mangroves or the embankment (US$44.02) and the village that was protected by mangrove forests (US$33.31). The local people were aware of and appreciated the functions performed by the mangrove forests in protecting their lives and property from cyclones and were willing to cooperate with the forest department with regard to mangrove restoration.

Table 2.11 Basic description and mean values of the variables (per household) in the three study villages in Bhitarkanika Conservation Area, India (US$1.00 = INR 45, August 2004)

		Villages		
Variables	*Description*	*Singdi*	*Bankual*	*Bandhamal*
DR	Damage to houses (0–19 scale)	9.40	5.34	10.44
PTD	Tree damage (%)	21.0	3.3	15.5
DPP	Damage to other personal property (INR)	108.11	0.00	2375.00
DL	Damage to livestock in money terms (INR)	54.05	127.63	1044.37
FP	Flooding in premises (m)	0.34	0.29	0.58
FF	Flooding in fields (m)	1.99	1.09	1.39
WLF	Water logging in fields (days)	9.46	5.63	12.87
CR	Cost of repair and reconstruction (INR)	996.97	682.86	973.21
Y99	Yield for the year 1999 (kg ha^{-1})	531	1479.5	335.9
LFS	Loss of fish seedlings (fingerlings) released prior to cyclone (INR)	310.81	69.74	260.94
TML	Total quantifiable variables (INR)	1983.3	61454.13	6918.62

Although only indicative, the report shows that the damage attributed to the cyclone was more extensive in the village further away from the mangrove shadow. The embankments constructed in 1971, after a previous cyclone, to prevent the intrusion of salt water into agricultural fields and villages were ineffective during the high storm surge; in fact, they acted as a barrier to runoff when the water was receding. The embankments suffered a number of breaches that resulted in the flooding of villages such as Bandhamal, which was surrounded on all sides by the embankment. Singdi village, with no mangrove cover and no embankment, suffered the highest level of field inundation; however, the seawater receded quickly, resulting in less damage to agricultural crops. Bankual village, which was in the shadow of mangrove forest and had minimal embankment around it, suffered the least. Although this study is not conclusive, the lack of breaches in the embankment closer to the forest is indicative of the protection provided by mangroves to the embankment. In areas far from the forest, several breaches in the embankment were observed. Water levels were higher and the flooding was of longer duration in Bandhamal.

Extensive *Casuarina* plantations established as a storm protection measure along the Orissa coast were ineffective in preventing damage; rather, they caused destruction to Olive Ridley sea turtle (*Lepidochelys olivacea*) nesting beaches. The cyclone uprooted almost all the trees in the immediate vicinity of the coast and caused much damage to trees several kilometres inland. However, mangrove forests and trees in the shadow of mangrove forests remained intact. The report contends that the vulnerability of many coastal communities to cyclones is heightened by the removal of mangroves for development, agriculture and habitation purposes. Mangrove forests are natural buffers against storm surges and protect tropical shores from erosion by tides and currents. Ecological functions such as storm protection may be very important components in the total economic value of a wetland and may constitute almost 80 percent of the estimated value. These major benefits are often the principal reasons for restoring mangrove forests along much of the low-lying deltaic coasts. In the aforementioned study in Orissa, there was a 20 to 30 percent reduction in repair and maintenance costs of sea dyke systems due to the presence of mangroves in front of the dyke. The report realized that the artificial sea defenses were not only expensive to build and repair, but they were also, in many cases, ineffective.

3.4 CYCLONE DAMAGE TO MANGROVE FORESTS

Hurricane Mitch (1998) was the second deadliest hurricane on record at the time. The eye of the storm passed directly over three countries (Honduras, Guatemala and Mexico). Damage to the region's coastal mangrove ecosystems resulted from three different mechanisms: winds, waves and sediment burial. Extreme winds (up to 287 kilometres/hour) defoliated and uprooted mangrove trees along the Caribbean coast, most notably in the Bay Island of Guanaja, which lost some 97 percent of its mangrove forest cover as shown in Plate 2.1 (Hensel and Proffitt, 2000). High wave activity eroded shorelines some 200 kilometres to the southwest, along the Caribbean coast of Guatemala (Punta de Manabique). Mangrove forests within the eroded zone were destroyed, and the remaining mangroves were buried with up to 1.2 metres of sand. Along the Pacific coast, damage was primarily attributable to the burial of mangrove forests by upland sediments, brought to the coastal area by massive flooding, upland erosion and mud and debris flows. These three mechanisms of hurricane damage had different impacts on coastal mangroves and led to different trajectories of recovery. The area of greatest damage was the Bay Island of Guanaja, where high mortality and the lack of natural regeneration made active restoration a priority. Over 27 months after the cyclone, severe chronic impacts remain evident, as recovery has not progressed to any significant degree. Wave-induced erosion and sedimentation some 200 kilometres away from the hurricane track also caused significant mangrove mortality.

(a) (b) (c)

Plate 2.1 Mangrove damage after Hurricane Mitch on the Bay Island of Guanaja, Honduras: (a) defoliation (b) uprooting (c) erosion of shallow roots (Hensel and Proffitt, 2000)

The negative example of the Bay Island of Guanaja shows that natural recovery is not always possible, even after several years in the aftermath of a cyclone. Unfortunately, cyclones tend to hit the most vulnerable coastlines with storms of various magnitudes within a few years. The possibility of multiple cyclone hits within a few years, or even within the same cyclone season prior to any significant recovery of mangrove forests, cannot be neglected when considering mangroves as protective shields.

Conclusions

The main conclusion is that narrow coastal forests have minimal effects on storm surge height and inland flooding. In order to significantly reduce the impact of the storm surge —usually the most devastating cyclone hazard — several kilometres of coastal forests are required. Mangroves are more efficient at attenuating surface waves and wind as well as providing protection against erosion. Typically, the wave energy is attenuated by a factor of two within 50 metres in front of the mangrove forest at normal sea level. The obstruction density caused by the mangrove wood structure decreases rapidly with height and, therefore, as the water level increases because of the storm surge there is proportionally less flow resistance and less reduction of wave energy. Unfortunately, this effect severely reduces wave attenuation with increasing cyclone intensity, storm surge height and wave period. Finally, the possibility of multiple cyclone hits prior to significant mangrove forest recovery needs to be considered.

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Field study presentation: Cyclone disaster mitigation in Bangladesh

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Bangladesh has witnessed many natural calamities. Between 1797 and 1998, 67 major cyclones occurred. The 1991 cyclone killed approximately 139 000 people and generated economic losses of US$2.07 billion. The coastal zone comprises 19 southern districts with 35 million inhabitants (28 percent of the country).

The Bangladesh Meteorological Department provides cyclone warnings. The Standing Orders for Cyclone constitute the basic plan for addressing cyclone disasters with guidelines for action at various stages during calamitous events. Elaborate institutional arrangements are in place to deal with disasters. The most dedicated agency is the Cyclone Preparedness Programme, which is an organization of 33 000 volunteers in the field who mobilize people at the community level to cope with cyclones. Structural mitigational measures such as cyclone shelters, coastal embankments and improved housing, as well as non-structural mitigation measures including coastal afforestation, public awareness, community preparedness, local level contingency planning and social mobilization are in place to a limited extent. Coastal afforestation activities were initiated in 1966. The protection afforded by natural mangrove forest has prompted afforestation in the five coastal districts. A coastal zone policy has been formulated with emphasis on sea dykes and afforestation, planned tree plantation, social forestry, plant care and maintenance, afforestation of new chars *(accreted land) and their conservation. A number of recommendations have been made to: improve storm surge forecasting; enhance public awareness; increase investment in warning presentation; promote information dissemination and comprehension; simplify warning contents; address knowledge and attitudes; carry out surveys on cyclones; and integrate disaster management in development planning.*

The conclusions pointed to the need for mainstreaming disaster management activities, increasing the interface between disaster and development, and conducting sustained awareness and advocacy programmes. All of these issues call for a higher level of investment in preparedness, shelter construction, afforestation, institutional arrangement, policy formulation and community involvement for improved cyclone disaster mitigation.

Field study presentation: Evaluation of storm protection functions — a case study of mangrove forest in Orissa, India and the 1999 super cyclone

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The research aimed at making a quantitative assessment of the storm protection functions of mangrove forests. In October 1999, the state of Orissa was battered by a super cyclone that caused tremendous loss of life and property in the coastal region. It was widely reported in the national as well as international press that areas with mangrove forest on their coastlines experienced comparatively less damage. Using village level human casualty data, cyclone damage (taking into account wind velocity, storm surge velocity and the socio-economic status of the villages separately) was estimated; an attempt was made to evaluate how many human lives had been saved by the presence of mangroves in some areas.

Key points and observations emphasized in the discussions

Cyclones are composite phenomena, consisting of winds, multiple storm waves, storm surges (which generally last from several hours up to a day) and inland flooding generated by heavy rainfall. This inland flooding often causes more fatalities than the wind. Cyclones generally cause massive erosion or deposition – both long- and cross-shore. In recent years important discussions on multihazard approaches for coastal protection have been ongoing; however, it should be noted that often coasts vulnerable to cyclone storm surges are less (or the least) vulnerable to tsunamis, and therefore require different protective measures.

Coastal forests and mangroves can help to mitigate cyclone damage, but are not effective against all hazards. Their mitigation effect is limited (or absent) during cyclones of categories exceeding 4 on the Saffir–Simpson Scale and super cyclones. Narrow belts of coastal forest do not reduce storm surges; several square kilometres of forests or coastal wetlands are required to significantly absorb massive inland inundation caused by cyclones of high intensity. Preliminary analysis of the 1999 Orissa super cyclone showed that the mitigation effects of *Casuarina* plantations were lower in comparison to mixed indigenous forests.

The following factors were identified:

1. Coastal forests are efficient in reducing wind and storm wave impacts up to a certain level.
2. Coastal forests and mangroves in narrow belts do not reduce storm surge efficiently; they can, however, help to decelerate flooding velocity and trap floating debris.
3. A dense forest can reduce 0.5 metres of surge for each kilometre of forest.
4. Extensive wetland systems are also important as mitigating measures and the loss of wetlands makes the coast more vulnerable. Mangroves and coastal wetlands must be preserved.

When planning a green belt for protective purposes, several factors should be taken into account.

1. Space availability: A very wide belt of forest is needed to ensure an appropriate reduction of cyclone strength. Because the coasts of several Asian countries (for example, Bangladesh) often have very high population densities, this space may not be available and consequently a green belt cannot be prepared to the required width. In this case environmental and hard engineering structures should be used in combination with – or as an alternative to – the green belt.
2. Social involvement in planning and management of protective forests is essential for the long-term success of the project. The green belt should also be a source of additional yield to local communities (for example, controlled harvesting of wood and non-wood forest products, ecotourism, etc.), which will avoid illegal felling and damage to the green belt.

Additional factors which would benefit the ultimate goal of saving lives and resources in cyclone-prone countries are as follows:

1. The creation or enhancement of an appropriate cyclone warning system (together with reliable storm forecasting) at the national level, which should be easily understood by rural people and which should also extend to remote areas and communities.
2. Investment in public awareness on cyclone mitigation, including the protective role of forests (knowledge–attitude–practice).

3. The encouragement of local community participation in prevention and rehabilitation activities (for example, volunteer groups).
4. Improvement or initiation of institutional arrangements (for example, collaboration between disaster managers and other government agencies).