

1 **Overview of the Monsoon-influenced Ayeyarwady River**  
2 **delta, and delta shoreline mobility in response to changing**  
3 **fluvial sediment supply**

4

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9

10 **Abstract**

11 A morpho-sedimentary analysis of the Ayeyarwady delta shoreline was conducted  
12 based on a field mission in Myanmar in November 2016 and interpretation of satellite  
13 images spanning the period 1974-2019. These analyses were complemented by data on  
14 land-to-water conversion and vice versa within a 2 km-wide coastal fringe, and on MERIS-  
15 derived seasonal and decadal-scale evolution of suspended particulate matter (SPM) off the  
16 delta. The objectives were to: (1) characterize the 450 km-long delta shoreline and coastal  
17 sediment transport pathways, (2) define the shoreline status (stability, erosion, accretion),  
18 and (3) identify potential causes of shoreline change and the future outcome of this status in  
19 terms of delta vulnerability. The delta shoreline was characterized on the basis of qualitative  
20 alongshore tidal, wave-energy, and sediment grain-size patterns (muddy, sandy or a mixture  
21 of both), and morphology (sandy beaches and mudflats). The deltaic coast exhibits a mixed  
22 wave-and-tide-dominated morphology and comprises a western sector characterized by four  
23 of the five main distributary mouths separating inter-distributary plains bounded by low

24 overwash-influenced beaches devoid of aeolian dunes. The eastern sector, in the Gulf of  
25 Martaban, is embayed, much less prograded and bounded by dominantly muddy shores.  
26 This simple shoreline dichotomy reflects the overarching alongshore sediment redistribution  
27 and storage patterns that have accompanied the growth of the delta, resulting in the two  
28 facies: sand dominantly retained in the western sector where the multiple distributary  
29 mouths have constrained potential alongshore sand transport by low- to moderate-energy  
30 monsoon-generated southwesterly waves, and mud transported by the regional monsoon-  
31 influenced coastal shelf circulation towards the eastern sector. The recent multi-decadal  
32 shoreline mobility in the Ayeyarwady delta points to the influence of fluvial sediment supply  
33 on these two facies. Between 1974 and 2019, 49% of the delta's shoreline underwent  
34 erosion, mainly affecting the sandy beaches in the western sector, whereas shoreline  
35 accretion is still prevalent along the large inter-distributary plain east of Yangon, where  
36 coastal mud preferentially accumulates in the Gulf of Martaban. We attribute erosion to  
37 reduced river sand supply generated by dams and by massive in-channel sand mining  
38 upstream of the delta, exacerbated by important channel dredging. Large-scale  
39 deforestation resulting from land-use changes (agriculture and mining) in the Ayeyarwady  
40 catchment are probably contributing to enhanced fine-grained sediment supply to the delta  
41 plain and the coast, as reflected by the relative stability of coastal SPM over a decade (2002-  
42 2012) and continued deposition in the accreting eastern sheltered part of the delta. The  
43 coastal sediment balance will be further impacted in the future if planned dams are  
44 constructed. Without proper sediment management, notably a significant reduction or  
45 prohibition of in-channel sand mining, the sandy beaches that armour the wave-exposed  
46 western sector of the delta will continue to erode, resulting in increased potential exposure  
47 of the delta to cyclones and sea-level rise.

48

49 **Keywords:** monsoon-influenced delta; delta erosion; river sediment supply; coastal  
50 suspended particulate matter; Ayeyarwady, Gulf of Martaban

51

## 52 **Highlights**

53 1. The monsoon-influenced Ayeyarwady delta shows prograded west and embayed east  
54 sectors

55 2. The sandy west sector eroded between 1974 and 2019 despite proximity of delta  
56 distributaries

57 3. In contrast, active mud-trapping in the eastern sector contributes to significant  
58 progradation

59 4. Contrast reflects influence of changing fluvial sand and mud supply induced by human  
60 activities

61 5. Sand supply is reduced by channel extraction and fine-grained supply enhanced by  
62 deforestation

63

64

## 65 **1. Introduction**

66 Many deltas are becoming economically and environmentally vulnerable and their  
67 physical and biological resilience declining as a result of human activities (Brondizio et al.,  
68 2016; Seijger et al., 2016; Hagenlocher et al., 2018). Increased vulnerability and loss of  
69 resilience occur as a result of reduced sediment flux from rivers and various other  
70 modifications caused by human interventions (Ericson et al., 2007; Syvitski and Saito, 2007;  
71 Syvitski et al., 2009; Evans, 2012; Besset et al., 2019; Grill et al., 2019). These conditions are  
72 aggravated by climate change and sea-level rise. The Ayeyarwady River, in Myanmar (Fig. 1),  
73 is increasingly affected by problems related to water and sediment management (WWF,  
74 2018) that are affecting the delta (Anthony et al., 2017). The Ayeyarwady delta is an  
75 important component of the developing economy of Myanmar, the largest country (676,600  
76 km<sup>2</sup>) in mainland Southeast Asia. Myanmar is heavily reliant on the economic advantages  
77 provided by the river and its delta, and is also among the 15 nations that, together, account  
78 for 80% of the world's population exposed to river (including delta) flood risk world-wide  
79 (Ward et al., 2013; Winsemius et al., 2013). This situation is of particular concern to the  
80 disproportionately large river delta (Fig. 2A). As in most developing countries, population  
81 growth in Myanmar has been extremely rapid, exacerbating exposure to the risks of river  
82 flooding, cyclones, and coastal erosion. The Ayeyarwady delta is particularly populous with  
83 over 15 million people, and registered an increase of nearly 150% in about 30 years  
84 (Brakenridge et al., 2017). The advantages provided by the delta as a home to millions of  
85 people and as Myanmar's food basket could be seriously offset by massive on-going in-  
86 channel aggregate extractions and, in the coming years, by the impacts of numerous

87 projected dams (Hennig, 2016; Taft and Evers, 2016) that could further stifle sediment  
88 supply (WWF, 2018).

89 Compared to most Asian and Pacific mega-deltas, the knowledge acquired on the  
90 Ayeyarwady system is quite sparse, and the morpho-sedimentary dynamics of the delta are  
91 still relatively understudied, notwithstanding a few recent efforts geared at shoreline  
92 changes (Hedley et al., 2010; Anthony et al., 2017), flood impact (Brakenridge et al., 2017),  
93 shoreline response to cyclone activity (Besset et al., 2017), and Holocene evolution (Giosan  
94 et al., 2018). Acquiring data on this large delta should be an important objective with high  
95 relevance for the future development of Myanmar. The delta, like the catchment of which it  
96 is a part, crystallizes factors related to environment and water management, climate,  
97 economic and social development, land-use changes (Taft and Evers, 2016), as well as the  
98 sediment issue, which is particularly pertinent to delta sustainability.

99 The aim of this paper is to characterize the 450 km-long delta shoreline and its  
100 coastal sediment transport pathways, define the recent to current shoreline status (stability,  
101 erosion, accretion), and identify potential causes of shoreline change and the future  
102 outcome of this status in terms of delta vulnerability. In particular, the link between  
103 changing fluvial sediment supply, increasingly influenced by a variety of drivers, notably  
104 anthropogenic, and shoreline mobility, forms the overarching discussion theme.

105

## 106 **2. The Ayeyarwady River and delta: a general overview**

107 The Ayeyarwady has its source in the eastern Himalaya and lies in a zone of active  
108 tectonics in the collision zone between the Indian and Eurasian Plates (Wang et al., 2014), a  
109 context favourable to large fluvial water and sediment discharges. The river's catchment  
110 covers 404,100 km<sup>2</sup> and comprises three large tributaries, the Chindwin, Shweli, and  
111 Myitnge rivers (Fig. 1), separated in the northern reaches by alluvial floodplains. The  
112 downstream end of this drainage system has formed a large delta (Fig. 2A) in the Andaman  
113 Sea that merges eastward with the mouth of the smaller catchment of the Sittaung River  
114 (48,100 km<sup>2</sup>). The Ayeyarwady delta and the contiguous coastal deposits of the Sittaung  
115 have formed 20,570 km<sup>2</sup> of low, fertile plain (Brakenridge et al., 2017). Although only 23<sup>rd</sup> in  
116 world catchment size rankings, the Ayeyarwady delta, with its Sittaung extension, ranks 11<sup>th</sup>  
117 in size among the deltas of the world (Coleman and Huh, 2004).



118           Overviews on the hydrology, geomorphology, sedimentology, and flood risks of the  
119 Ayeyarwady have been provided recently by van der Velden (2015), Brakenridge et al.  
120 (2017), and WWF (2018). The Ayeyarwady catchment experiences a tropical seasonal  
121 monsoon climate with rainfall concentrated in the hot humid months of May to October  
122 (Indian monsoon) as southwest winds blow northeastwards across the Bay of Bengal in the  
123 wake of the northward movement of the Intertropical Convergence Zone (ITCZ). In contrast,  
124 dry northwest winds blow from the continent during the cool months of December to March  
125 (Asian monsoon). The mean annual rainfall across the delta ranges from 2000 to 3000 mm,  
126 but other parts of the river's catchment experience up to 6000 mm of rainfall (Frenken,  
127 2012). Tropical cyclonic storms make landfall in Myanmar between May and October,  
128 generate heavy rainfall and severe flooding (Brakenridge et al., 2017), and their frequency  
129 seems to be affected by the Pacific Decadal Oscillation (PDO) (Haggag et al., 2010).

130           The present Ayeyarwady deltaic complex (Fig. 2A) developed in a confined setting  
131 between north-south-aligned bedrock ridges (Western Hills and Eastern Hills) as a bay-head  
132 delta (Fig. 1), a common development setting for many river deltas worldwide (Anthony,  
133 2015, 2016). Embayed settings are particularly favourable to the trapping of fluvial (and  
134 marine) sediments, as wave reworking, redistribution, and dispersal are commonly  
135 hampered. The delta coast, including the Gulf of Martaban (Gulf of Moutama), is adjacent to  
136 a relatively shallow shelf, and with a maximum depth of only about 50 m, composed of  
137 sediments deposited by the Ayeyarwady, the Sittaung, and the Salween (324,000 km<sup>2</sup>)  
138 (Ramaswamy et al., 2004). The shelf width is about 170 km off the Ayeyarwaddy delta and  
139 increases to more than 250 km in the centre of the Gulf of Martaban (Damodararao et al.,  
140 2016).

141           Coastal currents in the Andaman Sea off the delta are mainly governed by the  
142 monsoon winds, as well as by Rossby waves triggered by Ekman transport and by Equatorial  
143 Kelvin waves (Suwannathatsa et al., 2012). Current flows are dominantly alongshore from  
144 west to east, and this is important in the alongshore mobility of fine-grained sediment  
145 exiting from the multiple distributary mouths in the west, as discussed below. The wave  
146 regime is characterized by monsoon wind waves of moderate fetch (wave periods of 8-12 s  
147 with a mean of about 10 s) generated in the Andaman Sea by the southwesterly winds, and  
148 thus, almost exclusively from a southwest direction (Fig. 2B), but with a marked seasonal  
149 variability in height (Anthony et al., 2017). Waves are highest in July (mean values of up to 2

150 m) at the peak of the rainy Indian monsoon season. Their heights diminish during the dry  
151 season when the influence of southwest monsoon winds becomes attenuated due to the  
152 southward migration of the ITCZ. Maximum wave heights can reach 5 m during cyclones.  
153 Figure 2C shows a map of the dominant M2 tidal amplitude in the Andaman Sea and a 12-  
154 month extract of the tidal record from an offshore tide gauge in the delta (see location in  
155 Fig. 2A) for 2018. According to Kravtsova et al. (2009), the mean tidal range along the  
156 western shores of the delta is 3.0 m and about 3.2 m along the eastern shores. This data  
157 source further indicates that the tidal range during spring and neap tides along the western  
158 extremity of the delta are 2.2 m and 1.8 m, respectively, but up to 5.7 m and 4.0 m,  
159 respectively, along the eastern extremity of the delta off the mouth of the Sittaung. These  
160 values are similar to those of Volker (1966) who identified spring and neap tides at the  
161 eastern periphery of the Ayeyarwady delta amounting to 5.8 m and 4.0 m, respectively.  
162 These ranges attain 5.1 m and 3.5 m, respectively, in Yangon located 72 km from the sea.  
163 Spring-tide influence extends almost 300 km inland to the apex of the delta (Hedley et al.,  
164 2010). Tropical cyclones, thoroughly reviewed by Brakenridge et al. (2017), may generate  
165 strong coastal surges, resulting in significant damage periodically (Dube et al., 2010).  
166 Tropical Cyclone Nargis (2-4 May 2008), a category 5 event just prior to landfall in Myanmar,  
167 is the latest and strongest meteorological event to have affected the delta in historic times,  
168 causing the worst natural disaster in the recorded history of Myanmar (Fritz et al., 2009),  
169 and massive shoreline retreat (Besset et al., 2017).

170         According to data collated by Kravtsova et al. (2009), the mean fluctuation of sea  
171 level in the Andaman Sea within a year is about 8 cm. Sea level is slightly higher during the  
172 rainy season than the dry season due to the impact of river runoff. Seasonal sea-level  
173 fluctuations do not therefore play a significant role in the coastal hydrodynamic regime,  
174 which is dominated by winds, wind waves and moderately large tides.

175         In terms of the dominant marine processes acting to shape the delta's shoreline, the  
176 Ayeyarwady comes out as an example of a mixed wave-and-tide-dominated system in the  
177 commonly used classification system of Galloway (1975). Five main distributary mouths have  
178 developed downstream of the main-stem Chindwin and Ayeyarwady channels to convey the  
179 high water and sediment flux to the prograding delta in its western sector, where four main  
180 distributaries debouch (the fifth main one corresponds to the Yangon distributary in the  
181 eastern sector, Fig. 2A). The western sector is more significantly wave-influenced than the

182 less prograded embayed eastern sector which is more wave-sheltered and essentially  
183 composed of open-coast muddy-sandy tidal flats. Wave influence is reflected in the  
184 formation of beach-ridge sets in some of the inter-distributary plains, especially the large  
185 'promontory' between sites 7 and 10 (Fig. 2A), indicating that this western sector has  
186 formed a depocentre for sand supplied by the rivers (Anthony et al., 2017; Giosan et al.,  
187 2018; Kuehl et al., 2019). Wave influence in this sector is both a cause and consequence of a  
188 more prograded sector of coast (Fig. 1). Progradation has culminated in a more protruding  
189 delta lobe in this sector relative to the southwesterly monsoon waves, which enhances the  
190 efficacy of wave-reworking of the shoreline in the context of a moderate tidal range. As in  
191 other deltas, the progressive growth and seaward protrusion of the delta have been  
192 tantamount to increasing wave influence (Anthony, 2015). However, this influence has been  
193 moderated by the presence of the multiple distributary mouths, as well as by tidal  
194 amplification in the embayed eastern sector of the delta. Beach-ridge development has been  
195 both more recent (Giosan et al., 2018) and more limited in the eastern sector of the delta,  
196 probably sourced from the Yangon tributary.

197         The distributary mouths have remained relatively fixed in the western sector of the  
198 delta, as suggested by radiometric ages from beach-ridge deposits (Giosan et al., 2018). The  
199 inception and development of these distributaries appear to stem from channel bifurcations  
200 (Jerolmack, 2009) around distributary mouth bars, as has been proposed for the multiple  
201 mouths of the Mekong River delta (Tamura et al., 2012). The increase in tidal range eastward  
202 is the outcome of amplification of the tidal wave propagating over the shallow Andaman  
203 shelf and Gulf of Martaban embayment. The shallow shelf itself is a product of pronounced  
204 river, coastal and marine sedimentation through geological times that has produced the  
205 thick sedimentary deposits of the Central Burma Basin down to the Andaman shelf (Rodolfo,  
206 1969b).

207

### 208 **3. Fluvial water and sediment discharge to the coast and alongshore transport**

209         The disproportionately large size of the Ayeyarwady delta relative to the size of its  
210 river catchment reflects a favourable combination of a high river sediment supply related to  
211 an active tectonic context, a steep upper catchment topography, high monsoon rainfall, the  
212 confined bay-head morphological setting of delta growth between bedrock promontories,  
213 and the moderate hydrodynamic conditions of the Andaman Sea (Anthony et al., 2017). The

214 Ayeyarwady river catchment collects nearly 70% of the surface water volume of Myanmar  
215 (Kravtsova et al., 2009). The combined discharge of the Ayeyarwady and Chindwin Rivers at  
216 Chauk (Fig. 1) ranges from about 1500 m<sup>3</sup>/s to about 30,000 m<sup>3</sup>/s (van der Velden, 2015),  
217 and shows a strongly seasonal monsoon pattern (Stamp, 1940). Robinson et al. (2007)  
218 calculated, from data collected between 1969 and 1996 at Pyay (Fig. 1), an annual water  
219 discharge of 44,241 km<sup>3</sup> and a sediment discharge to the ocean of 226-364 Mt, concentrated  
220 in the rainy season, and among the highest in the world. Using these data, Furuichi et al.  
221 (2009) estimated the water discharge ( $379 \pm 47.10^9$  Mt/year) and suspended sediment load  
222 ( $325 \pm 57$ . Mt/year) for the river upstream of the delta head. These values are similar to  
223 those derived by WWF (2018) who also estimated a widely-ranging bedload volume of 7.2 to  
224 34 Mt/year (i.e., about 3 to 15% of the total load). A statistical comparison carried out by  
225 Furuichi et al. (2009) with earlier, 19<sup>th</sup> century data (1871 to 1879), shows a significant  
226 decrease in discharge in the last 100 years. Sediment discharge over the last few decades  
227 has been strongly affected by anthropogenic pressures in the catchment (WWF, 2018), as  
228 discussed later. Shorter-term fluctuations would also be expected from climatic variability.  
229 Precipitation in Myanmar is known to be affected by the inter-annual El Niño/Southern  
230 Oscillation (ENSO) (Krishnamurthy and Goswami, 2000; Furuichi et al., 2009), by the ENSO  
231 counterpart of El Niño (La Niña; equatorial Pacific cold water anomalies) (Rojas et al., 2014;  
232 Sein et al., 2015), by the intra-seasonal Madden–Julian Oscillation (Hendon and Salby, 1994),  
233 which is a tropical to near-global alternation in atmospheric and oceanic circulation patterns  
234 and rainfall, and finally by the Indian Ocean Dipole with which rainfall in Myanmar is  
235 negatively correlated, and which notably modulates monsoon rainfall (Ashok et al., 2001).  
236 Finally, rates of meltwater, and the frequency of the tropical cyclonic storms that make  
237 landfall in Myanmar between May and October, and which are accompanied by  
238 exceptionally heavy rainfall (Brakenridge et al., 2017), are deemed to be affected by the  
239 Pacific Decadal Oscillation (Haggag et al., 2010). Based on a sediment discharge at Chauk  
240 ranging from 165 kg/s in the dry season to 18,000 kg/s at the peak of the Indian monsoon,  
241 Kravtsova et al. (2009) calculated the mean water turbidity at the mouths of the Ayeyarwady  
242 at approximately 600 g/m<sup>3</sup>, which corresponds to relatively high values.

243         60 ±10% of the total sediment flux downstream is supplied by the Chindwin, the sub-  
244 catchment of which is characterized by more readily erodible rocks (Garzanti et al., 2016). It  
245 is not clear, however, how water and sediment are apportioned among the five major and

246 various smaller distributaries of the Ayeyarwady. Sand constitutes much of the shoreline in  
247 the western sector of the delta (Fig. 2A). There are no data on shoreline sand budgets for the  
248 individual beaches bounding the inter-distributary plains. It is clear, from the more advanced  
249 progradation of this western sector (Fig. 2A), that the sand supplied by the river to the  
250 deltaic shorelines has been sequestered in this sector, possibly throughout the development  
251 of the delta.

252 Figure 3A shows 10-year (2002-2012) averaged suspended particulate matter (SPM)  
253 concentrations offshore of the delta, compiled from the *GlobCoast* MERIS satellite  
254 (<http://sextant.ifremer.fr/en/geoportail/sextant>). The data were generated through a  
255 combination of the Polymer algorithm (Steinmetz et al., 2011) adapted for coastal waters  
256 (Loisel et al., 2016) and the SPM algorithm of Han et al. (2016). We assume that these  
257 concentrations dominantly reflect fine-grained terrestrial inputs to the coastal sea, an  
258 assumption supported by analysis of SPM concentrations for 2008 prior to, in the course of,  
259 and following Cyclone Nargis in May 2008 (Besset et al., 2017).

260 The pattern depicted by the *GlobCoast* data is very similar to that derived by  
261 Matamin et al. (2015). The seasonal SPM pattern does not strictly adhere to the seasonal  
262 rainfall regime, as depicted by water levels in the river close to the delta at Pyay and  
263 Hinthada (Fig. 3B), as one would expect a significant increase during the rainy Indian  
264 monsoon months (May–October) and a decrease in the dry-season Asian monsoon  
265 (December–March). The pattern is strongly influenced by lag effects, given the size of the  
266 Ayeyarwady catchment, and, in the offshore zone, by marked cross-shore and alongshore  
267 spatial variations. The Indian monsoon is characterized by offshore displacement of the SPM  
268 plume starting in May, with a clear banding from the coast to the offshore (Fig. 3A). This  
269 stronger offshore displacement, which largely reflects spread of mud under the strong  
270 outgoing fluvial jets at the distributary mouths, prevails until January, as the water discharge  
271 diminishes during the dry season. However, the strong offshore concentration zone appears  
272 to attain a peak in June before waning significantly in July and the remaining rainy season  
273 months. This could suggest that offshore SPM concentrations increase rapidly at the start of  
274 the rainy season under favorable conditions of coastal supply as river liquid discharge  
275 increases in the distributary channels, prior to overbank flooding of the river flood plain and  
276 the delta plain. The concentrations then diminish as these terrestrial units sequester a

277 significant part of the suspension-load supply with the rise in river level and widespread  
278 rainy-season flooding.

279 The alongshore spatial pattern shows that a significant fraction of the mud  
280 discharged by the Ayeyarwady into the sea in the western distributary-mouths sector during  
281 the Indian monsoon is transported by the regional coastal currents towards the Gulf of  
282 Martaban, where the SPM concentrations are highest (Fig. 3A). Here, further trapping of  
283 mud debouching from the Sittaung (Fig. 1) occurs. This eastward regional SPM transport  
284 pattern is in agreement with the finding of various authors who identified high mud  
285 concentrations in the Gulf of Martaban (Rodolfo, 1969a; Ramaswamy et al., 2004; Rao et al.,  
286 2005; Matamin et al., 2015; Damodararao et al., 2016; Kuehl et al., 2019). Matamin et al.  
287 (2015) and the *GlobCoast* data also show high dry-season concentrations in this eastern part  
288 of the delta (Fig. 3A), in agreement with the observations of these authors. These high dry-  
289 season concentrations may also reflect some degree of mud resuspension by the strong tidal  
290 currents in this macrotidal part of the gulf. The Andaman Sea has been described as highly  
291 turbid, and clastic mud is burying carbonate deposits consisting of molluscan fragments and  
292 foraminifera tests on the delta shelf, leading to a vertical depositional rate in that area of  
293 about 200 cm in 1000 years (Rodolfo, 1969a, 1969b). According to Rodolfo (1969a), and  
294 more recently Rao et al. (2005), a small amount of mud reaches the Andaman Basin through  
295 the Martaban Canyon, and river-derived mud is not accumulating in the western part of the  
296 shelf fronting the delta.

297

### 298 **3. Methodology**

#### 299 ***3.1. Field reconnaissance and alongshore sediment sampling***

300 A field mission aimed at ground-truthing shoreline characteristics (morphology,  
301 sedimentology, presence and type of vegetation, qualitative observations of bedforms, and  
302 shoreline dynamics), and collection of sand-rich samples for grain-size analysis was  
303 conducted in November 17-22, 2016. This mission consisted essentially of reconnaissance  
304 work and visits to 17 sites from east to west along the delta shoreline (Fig. 2A). The choice of  
305 the sites was based on access permission from the Myanmar administrative authorities and  
306 on accessibility. A total of 54 sediment samples were collected from 11 sites characterized  
307 by sandy beaches (sites 8 to 17 in the western sector of the delta, and sites 6 and 7  
308 transitional to the eastern sector). Four to five samples were collected on a cross-shore

309 transect from the lower to the upper beach, using observed bedforms or facies changes,  
310 where apparent, to delimit sampling zones. No samples were collected between sites 1 and  
311 5 where the foreshore was characterized by mud. All samples were initially homogeneously  
312 separated in the laboratory with a sediment inox splitter and dispersed using 0.3% sodium  
313 hexametaphosphate as a dispersing agent. The grain-size distribution was measured using a  
314 Beckman Coulter LS 13320 laser grain-sizer with a range of 0.04 to 2000  $\mu\text{m}$ . The calculation  
315 model uses the Fraunhofer and Mie theory. For the calculation model, water was used as  
316 the medium (RI = 1.33 at 20 °C), a refractive index in the range of that of kaolinite for the  
317 solid phase (RI = 1.56), and absorption coefficients of 0.15 for the 780-nm laser wavelength  
318 and 0.2 for the polarized wavelengths (Buurman et al., 1996).

319

### 320 **3.2. Multi-decadal shoreline changes**

321 Shoreline changes were analyzed using two metrics: (1) shoreline mobility and  
322 induced coastal area change over time, and (2) conversion of coastal land into water, or  
323 conversion of adjacent coastal water into land. Data on shoreline mobility and area change  
324 were obtained from 47 digitized LANDSAT satellite images (60-30 m pixel size) from 1974 to  
325 2019. Following work on similar delta shorelines, such as the Mekong (Anthony et al., 2015;  
326 Besset et al., 2019b), we used the mangrove fringe in the muddy mangrove-dominated  
327 sectors, and brush or plantation fringe in sandy, beach-dominated sectors as shoreline  
328 markers. These shoreline markers were confirmed in the course of the field observations at  
329 the 17 site stops covering over 300 km of the delta's shoreline in November 2016 (Fig. 2A). A  
330 specific focus was also set on the impact of Tropical Cyclone Nargis in May, 2008 (Besset et  
331 al., 2017), which will only be briefly evoked here insofar as it illustrates the increasing  
332 vulnerability of the delta.

333 Shoreline variations were calculated using the *ArcMap* extension module Digital  
334 Shoreline Analysis System (*DSAS*), version 5 (Himmelstoss et al., 2018), coupled with  
335 *ArcGIS*®10.2.2. Using a relevant cartographic frame (Projection UTM 48N), a baseline *B* was  
336 set about 1 km offshore of the delta shoreline. This baseline was regular enough to: (i)  
337 smooth any small-scale alongshore instabilities, and (ii) delineate large-scale geomorphic  
338 features such as distributary mouths, capes or bays. We then set up regularly spaced  
339 transects normal to the baseline and extending from offshore to 3 km inland. We set up a  
340 transect every 100 m alongshore from which shoreline variations between the changing

341 vegetation line and the inland base line were calculated between the successive sets of  
342 LANDSAT images. This distance, chosen as a compromise between quality of the  
343 interpretation and the important length of the Ayeyarwady delta shoreline (~ 450 km) was  
344 divided by the time in years between the two image dates to generate statistics of shoreline  
345 change in *DSAS 5*. Using *ArcGIS®10.2.2*, we further determined surface area differentials  
346 between shorelines of different dates to obtain annual area gains and losses. We retained a  
347 relatively large uncertainty shoreline change band of  $\pm 20$  m, which is much more than  
348 commonly used in the literature. The reader is referred to Besset et al. (2019a, 2019b) for  
349 the complete error computation methodology.

350 Data downloaded from the global database of Pekel et al. (2016) were used to  
351 identify coastal areas converted from land into water and vice versa in the Ayeyarwady  
352 delta. The rationale for examining these transformations is that they are a complementary  
353 input on multi-decadal shoreline mobility. Land-to-water conversion generally denotes  
354 erosion (but also back-shore land-use changes such as the installation of shrimp farms and  
355 rice cultivation), whereas water-to-land conversion implies land gain resulting from  
356 shoreline accretion (and less commonly from land reclamation, which is non-existent in the  
357 coastal fringe of the Ayeyarwady delta). The data from Pekel et al. (2016) are derived for  
358 each pixel (30 x 30 m) of LANDSAT satellite images covering a long-trend of 32 years (1984-  
359 2015) that smooths out the impact, on land or water extent, of exceptional events such as  
360 droughts or floods. In addition to producing a map covering the delta, we calculated the  
361 land-to-water and water-to-land changes in a 2 km-wide coastal fringe relative to the 1984  
362 shoreline. This 2-km fringe is well within the bandwidth of change liable to be caused by  
363 shoreline erosion (delta land conversion into coastal water) or accretion (coastal water  
364 conversion into delta land). The data also show seasonal patterns of conversion for each  
365 pixel. Overall, we retained four conversion categories over the 32-year period of  
366 observation, following Besset et al. (2019a): (1) new permanent water surfaces (land into  
367 permanent water), (2) loss of permanent water (permanent water into land), (3) permanent  
368 water into seasonal water, and (4) seasonal water into permanent water. A single category  
369 suffices to validate the presence of water. The category representing the year a change is  
370 identified is then considered as the first year of change. The category of the last year is  
371 always attributed to the last year of observation (October 2014 to October 2015).

372



## 373 **4. Results**

### 374 **4.1. Shoreline morphological and grain-size variations**

375 The November 2016 field reconnaissance enabled the identification of a clear west-  
376 to-east change in shoreline morphology and sedimentology (summarized in Fig. 2A in terms  
377 of two sectors), and embedded in a transition from a wave-and-tide-dominated system in  
378 the western, to a more tide-dominated eastern sector. This difference is reflected in both  
379 the pattern of long-term delta development and the coastal landforms, briefly summarized  
380 in section 2, and grain-size gradients.

381 The multiple distributary channels in the western sector (sites 7 to 17, Fig. 4)  
382 alternate alongshore with inter-distributary plains and their beach-ridge sets, bounded  
383 seaward by low sandy beaches (Fig. 5A) that exhibit, in places, a morphology of multiple bars  
384 and troughs. The upper beach is commonly characterized by washovers, and the backshore  
385 devoid of foredunes. The beaches front wide back-barrier depressions that are bounded  
386 landwards by the most recent sets of beach ridges. Generally, in this sand-rich western  
387 sector, the low-tide beach exhibits a grain-size fining trend (Fig. 5A1) and is characterized by  
388 an abrupt transition to a muddy foreshore (Fig. 5A2) that commonly exhibits mangrove root  
389 remains, indicating erosion associated with barrier translation landwards. Between sites 8  
390 and 6, the  $D_{50}$  grain-size values decrease significantly, and the percentage of mud increases,  
391 indicating the transition towards the mud-dominant foreshores of the eastern sector (sites 1  
392 to 5). East of the mouth of the Yangon distributary, foreshore mud dominates throughout  
393 (Fig. 5B1), colonized by mangroves and, in places, tropical salt marshes (Fig. 5B2).

394

### 395 **4.2. Multi-decadal shoreline changes**

396 The 450 km of delta shoreline showed a mean overall advance of  $9.5 \text{ m/yr} \pm 3.9 \text{ m}$   
397 between 1974 and 2019, up from  $7.5 \text{ m/yr}$  for the period 1974-2015 (Anthony et al., 2017),  
398 thus suggesting a mild gain in accretion. This mean rate masks, however, a strong  
399 alongshore variability (Fig. 6). Areas of shoreline advance indeed show high rates: a mean of  
400  $+26 \text{ m/year}$  overall, and exceeding  $50 \text{ m/yr}$  along large stretches and even  $100 \text{ m/year}$   
401 locally, in the muddy northeast corner of the delta on either side of the mouth of the Yangon  
402 tributary where patches of bare low-tide foreshore mud are also visible (Fig. 6). The analysis  
403 has not been carried out beyond this accretion zone. Observations of satellite images show  
404 that the shoreline in the approaches to the large macrotidal mouth of the Sittaung is

405 characterized by rapidly changing muddy foreshores that probably correspond to the mud  
406 pool accumulating in this corner of the Gulf of Martaban. Shimozono et al. (2019) have  
407 highlighted significant morphological changes in the mouth of the Sittaung associated with  
408 rapid bank erosion under tidal and fluvial forces.

409 The overall net retreat rate has been -8 m/yr. Although this rate is well below that of  
410 the net advance rate, erosion over the observation period affected, nevertheless, a  
411 significant stretch of the delta's shoreline, notably in the western sector of multiple  
412 distributary mouths, which are, paradoxically, the delta's main arteries for sediment supply  
413 to the coast. Net erosion has prevailed, over the 45-year period of analysis, along 220 km of  
414 delta shoreline, i.e., nearly 49%. Erosion has particularly affected the western, distributary-  
415 mouth sector (Fig. 6). In order to highlight the temporal trends, an analysis was carried out  
416 of shoreline gains and losses in km<sup>2</sup>/yr on a time-slice basis (Fig. 7). The western sector has  
417 been largely in erosion since 1988, albeit with a progressively attenuated trend. Although  
418 this sector has registered very mild gains since 2010, much of this is accounted for by the  
419 sandy-muddy transitional zone (between sites 6 and 8, Fig. 2A) to the eastern sector, where  
420 one of the two branches of the Yangon distributary debouches (Fig. 6). In this critical  
421 western sector, where the delta has prograded most, the current status of the beaches over  
422 the latest 2015-2019 period is one of rampant erosion. In contrast to the western sector, the  
423 presently accreting northeast sector showed retreat prior to 1988, losing up to 3.35  
424 km<sup>2</sup>/year, followed by fluctuations and important advance between 1992 and 2000 related  
425 to the formation of a large mud bank that was partially colonized by mangroves and, locally,  
426 tropical salt marshes. Shoreline changes since 2000 in the extreme northeast corner of the  
427 delta have not been included in the analysis as they show an anomalous erosion hotspot  
428 that, in fact, corresponds to in-situ reworking of this mud bank close to the mouth of the  
429 Sittaung (Fig. 8). It is important to stress the net coastal land gain of > 25 km<sup>2</sup>/yr in this  
430 eastern sector since 2015 (Fig. 7).

431 The land-water (water-land) conversion of the delta is depicted in Fig. 9, together  
432 with changes in the 2 km-wide coastal fringe. Conversion of land into water has occurred in  
433 large areas of the delta plain, and this pattern also prevails along the 2 km-wide coastal  
434 fringe where land-to-water (all categories considered) dominated between 1984 and 2015 (>  
435 70%). This figure largely exceeds that of the shoreline stretch in erosion, but this apparent  
436 discrepancy may be due to the choice of a 2 km-wide band. Large stretches of the eroding

437 western sector of the delta comprise narrow beaches behind which wetlands have appeared  
438 that correspond to areas of rice cultivation, but several small areas of water-to-land  
439 conversion also appear, and correspond to accreting spits, further discussed below.  
440 Conversion of land to water is particularly prominent in the eastern sector (Fig. 9),  
441 highlighting some apparent disagreement with the dominant shoreline accretion in this  
442 sector (Fig. 6). This inconsistency may, in fact be explained by the tendency for the  
443 conversion to include areas that correspond to intertidal shore-detached mud, which may  
444 fluctuate considerably in shape and size over time, and with the macrotidal frame. The  
445 shoreline is, in contrast, dominated by water-to-land conversion in this sector, reflecting the  
446 multi-decadal accretion trend (Fig. 6).

447

## 448 **5. Discussion**

449 Delta shorelines are dependent on fluvial sediment supply to balance marine forces  
450 of sediment dispersal, subsidence and sea-level rise. There is no simple straightforward  
451 relationship between fluvial sediment supply and shoreline mobility, since the latter can also  
452 be influenced by various other drivers acting at a variety of timescales (Besset et al., 2019a).  
453 However, fluvial sediment supply is the overarching driver of the shoreline mobility of the  
454 Ayeyarwady delta, complemented by sediment redistribution processes by monsoon-  
455 generated waves and currents along the coast, including regional trapping in the Gulf of  
456 Martaban. The simple shoreline dichotomy adopted in this study reflects the overarching  
457 alongshore sediment redistribution and storage patterns that have accompanied the growth  
458 of the delta and the two resultant facies. Sand is dominantly retained in the western sector,  
459 where the multiple distributary mouths have constrained potential alongshore sand  
460 transport by low- to moderate-energy monsoon-generated southwesterly waves, and mud  
461 transported by the regional monsoon-influenced coastal shelf circulation towards the  
462 eastern sector. The recent multi-decadal shoreline mobility in the Ayeyarwady delta points  
463 to the influence of fluvial sediment supply on these two facies. According to Rodolfo  
464 (1969a), the Ayeyarwady delta prograded at an average rate of 2.5 km in 100 years into the  
465 Andaman Sea up to the start of the last quarter of the 20<sup>th</sup> century. The shoreline erosion  
466 pattern drawn out of the satellite data thus shows a significant slow-down in progradation  
467 (Figs. 6, 7). These results are in agreement with those of Hedley et al. (2010) who identified a  
468 turnaround to erosion starting from 1989.

469           Although the Ayeyarwady is a high-sediment load river relative to the size of its basin,  
470 the erosion that affects the western sector (Fig. 6) is striking, inasmuch as the main sediment  
471 sourcing of the delta occurs in this sector of active distributary mouths. Attempting to  
472 explain this situation needs taking into account complex mechanisms of catchment-scale  
473 sediment release, storage and redistribution strongly mediated by human activities in the  
474 last three to four decades, and the propensity for transport of sand and suspension load to  
475 the delta's shoreline. To summarize, the western sandy shoreline undergoes erosion  
476 whereas the muddy eastern shoreline is accreting more or less strongly, thus calling for an  
477 explanation that takes into account the impact, on shoreline mobility, of: (1) the segregation  
478 of fine-grained sediment and bedload supplied by the river, (2) the preponderance of sand in  
479 the western sector of the delta where the multiple distributary mouths refract waves,  
480 leading to immobilization of this fraction in this sector, and (3) the regional-scale transfer, by  
481 the hydrodynamic regime, of mud exiting from these distributary mouths towards the Gulf  
482 of Martaban.

483           Fluvial sediment supply in the Ayeyarwady River is influenced by dams, aggregate  
484 mining in channels, channel dredging, deforestation, and climate change. Gauging the  
485 magnitude of each of these factors at this stage is an impossible task, and the issue is further  
486 complicated by differential impacts on bedload and suspended load that can only be grossly  
487 outlined, and by the fact that activities that lead to deforestation, such as agriculture and  
488 mining on catchment slopes, but also climate change, could actually enhance catchment  
489 sediment supply. A 30% drop in sediment supply generated by trapping of the fluvial load  
490 behind reservoirs in the Ayeyarwady catchment was calculated by Syvitski and Saito (2007).  
491 This is a significant amount. Between 1988 and 2004, for instance the storage capacity of  
492 reservoirs on the small tributaries of the Ayeyarwady and Chindwin grew from 2.34 to over  
493 18 km<sup>3</sup> (Myanmar Irrigation Works Department, 2004). Many dams have recently been  
494 constructed along the smaller rivers and tributaries, and more are planned for the larger  
495 ones (Kattelus et al., 2014; Hennig, 2016; Taft and Evers, 2016; Brakenridge et al., 2017).  
496 Assessment of the energy potential of Myanmar identified 92 new large hydropower  
497 projects (ADB, 2012), including the controversial Myitsone dam (with a projected potential  
498 of 3,600 kW). The project has been suspended by the Government, a decision taken in the  
499 broader interests of Myanmar. Data collected by Brakenridge et al. (2017) show that there  
500 are currently almost 200 large dams in Myanmar. The impacts of trapping of bedload (sand

501 and gravel) by dams are further aggravated by channel dredging and in-channel mining. The  
502 massive scale at which aggregate mining in the Ayeyarwady river channels is practiced has  
503 been considered as being more pernicious on the river's bedload supply to the delta than  
504 river dams (WWF, 2018). Current volumes of aggregate mining in the river, to the tune of 9  
505 Mt (5-6 Mm<sup>3</sup> of sand) and nearly 0.5 Mt (about 0.3 Mm<sup>3</sup> of gravel a year (Fig. 10A), and  
506 considered as conservative estimates by WWF (2018), must constitute a significant  
507 proportion of the annual bedload supply by the fluvial system, and the true values, are, in  
508 fact, likely to be much higher. In addition to aggregate mining, dredging has also been  
509 carried out on a large scale in the river channels. Data collated by WWF (2018) show an  
510 estimated 24 Mm<sup>3</sup> of sediment dredged in the Ayeyarwady between 1989 and 2017, the  
511 total volume of dredged material between 2012 and 2017 being 7.72 Mm<sup>3</sup> (about 12.4 Mt),  
512 i.e., about one-third of the total volume dredged since 1989. Most of the dredging has  
513 occurred since 2015 (78%), a year when 2.5 Mm<sup>3</sup> of material were removed from the river.  
514 The dredging volumes are considerably lower than the estimated volumes of material  
515 removed through sand and gravel mining, which are at least ten-fold higher, but they also  
516 contribute to the aggravation of the sediment balance of the river. Although quantified  
517 changes in the fluvial sediment load other than estimations of potential reservoir trapping,  
518 aggregate extractions and dredging are still lacking (WWF, 2018), several activities in the  
519 river catchment, notably mining (Fig. 10B) and agriculture, are currently generating massive  
520 deforestation (Fig. 10C), which has been important in Myanmar in the recent decades  
521 (Leimgruber et al., 2005; Hansen et al., 2013; Webb, 2013). Erosion of the bare slopes  
522 generated by mining and deforestation is contributing to an increase in sediment supply to  
523 the river system (WWF, 2018), thus counter-balancing the sediment reduction generated by  
524 dams, in-channel mining and dredging.

525 Deltas need to keep up with sea-level rise and marine forcing. The chronic erosion  
526 that affects the western sector of the delta (Fig. 6, 7) indicates, thus, that the sand supply to  
527 the Ayeyarwady delta's shoreline is no longer sufficient to balance forcing. The shoreline is  
528 deprived of sand needed to maintain its beaches by massive aggregate mining in the river  
529 reaches (Fig. 10A) as well as by dams. The ensuing beach erosion occurs through both the  
530 well acknowledged mechanism of diminished sand supply to inter-distributary beaches, and  
531 the less well acknowledged effect of reversed (towards upstream) bedload transport in the  
532 distributary mouths caused by salt intrusion resulting from artificial channel deepening

533 generated by aggregate extraction, as has been postulated for the Mekong delta (Anthony et  
534 al., 2015). In addition, the considerable amount of sediment stored in the river bed and  
535 fluvial floodplain as a result of rampant deforestation (Fig. 10C), could also be affected by  
536 the buffering of peak flows by reservoirs, causing reduction of the capacity for bedload  
537 mobilization towards the delta (WWF, 2018).

538         The narrowing beaches in the Ayeyarwady delta are being reworked, with landward  
539 migration through abundant washovers along the central sectors of beaches bounding the  
540 inter-distributary plains, accompanied by bi-directional drift that results in sand being stored  
541 in peripheral accreting spits (Anthony et al., 2017). This weakening of the delta's sandy  
542 'armour' and the absence of aeolian dunes potentially favour massive landward translation  
543 of the high-water line during cyclones, as happened under the strong surge conditions  
544 generated by Cyclone Nargis in May 2008. The shoreline was translated landwards by  
545 hundreds of metres in places, resulting in weakening of, and lengthening of the time of,  
546 delta shoreline resilience as beach erosion became aggravated in the months following this  
547 event (Besset et al., 2017). This event was followed by slow recovery that has never been  
548 totally achieved in the dominantly erosional multi-decadal context in which these beaches  
549 now evolve.

550         An additional contributor to the erosion that affects the western sector of the delta  
551 could be sediment redistribution modulated by the numerous embankments built upstream  
552 in the fluvial reaches. The transport of sediment to the sea should, theoretically, be aided by  
553 river embankments, as such structures confine sediment within the channels and, thus,  
554 lower the spill-over of fluvial load onto the delta plain during the flood season (Woodroffe,  
555 2000). Recognition of the loss of sediment from flooding for land in the delta led to a call for  
556 non-rebuilding of such embankments as early as 1939 (Kravtsova et al., 2009). However,  
557 while inhibiting lateral channel migration and deposition in the protected floodplain areas,  
558 these structures also enhance channel-bed aggradation, which exacerbates local flood  
559 hazard (Brakenridge et al., 2017) and reduces delivery of sediment to the coast. Over time,  
560 channel-bed sedimentation induces higher river levels for the same discharge (Pinter, 2005),  
561 with overbank flooding resulting in spillover of sediment onto the delta plain rather than  
562 sediment transport to the coast. The flood hazard and potential sequestering of bedload in  
563 the channel reaches are also exacerbated by the marked difference in slope between the  
564 main-stem Ayeyarwady and its various distributaries, all of which exhibit much steeper

565 slopes (WWF, 2018). This difference is deemed to be contributing to a glut in sediment in the  
566 middle reaches well upstream of the delta, and the ensuing accumulation of sediment and  
567 the river-bed aggradation exacerbate rainy season flooding (WWF, 2018).

568         The more sheltered eastern sector is, in contrast, the current main depocentre for  
569 mud transported by coastal currents from the multiple mouths towards the Gulf of  
570 Martaban (Fig. 3A). The overall trend indicated by the 10-year coastal SPM data (2002-2012)  
571 from *GlobCoast* suggests that the fluvial fine-grained sediment supply exiting at the mouths  
572 of the Ayeyarwady has been relatively stable overall (max  $\pm$  5%) (Fig. 11), assuming, of  
573 course that these concentrations are a faithful reflection of fine-grained fluvial sediment  
574 supply, which, as indicated earlier, seems to be the case. By balancing losses generated by  
575 fine-grained sediment retention behind reservoirs, sediment released by deforestation could  
576 explain the relative stability of the coastal SPM concentrations between 2002 and 2012 (Fig.  
577 10), given the propensity for easier mobilization and transport of suspension load from the  
578 fluvial reaches to the sea. This load largely dominates the sediment supply of the  
579 Ayeyarwady (WWF, 2018), and has been dominant in the construction of the delta (Rodolfo,  
580 1975). Another issue in the Ayeyarwady delta is that of aggravated subsidence (Syvitiski et  
581 al., 2009), but the areal pattern of this process is not known. van der Horst et al. (2018) have  
582 monitored very high local subsidence rates in Yangon (Fig. 1), Myanmar's capital city (5  
583 million inhabitants), aggravated by urban development needs in terms of buildings,  
584 infrastructure and ground-water abstraction. Tidal gauge data for the delta indicate a 3.4–6  
585 mm/y relative sea-level rise (Syvitski et al., 2009). Aggravated subsidence and sea-level rise  
586 can only be balanced by the trapping of more fine-grained sediment by the deltaic plain. An  
587 increased supply of suspension load resulting from deforestation may essentially be  
588 compensating for delta-plain subsidence, while also contributing to the current progradation  
589 of the relatively sheltered eastern sector of the delta where sediment is trapped.

590         Significant losses of mangrove forests in the Ayeyarwady delta to shrimp farms and  
591 rice fields, notably in the decade prior to Cyclone Nargis, have been identified (Hedley et al.,  
592 2010; Frenken, 2012; Veetil et al., 2018; Chatagno et al., 2019). According to Hedley et al.  
593 (2010), the total mangrove forest area decreased from 2345 km<sup>2</sup> to 1786 km<sup>2</sup> between 1924  
594 and 1995 from clearance for agriculture and aquaculture. It is projected that unprotected  
595 Ayeyarwady delta mangrove forests could be completely deforested by 2026 (Webb, 2013).  
596 Chatagno (2019) mapped a loss of 636 km<sup>2</sup> of mangroves but also a much lower gain of 279

597 km<sup>2</sup> between 1998 and 2018, yielding a net loss of 29%. The contribution of mangrove loss  
598 to shoreline change is hard to identify, since much of the erosion of the delta's shoreline  
599 concerns the sandy beach sector in the west, where mangroves essentially occur in back-  
600 barrier plains and fringe the delta distributary channels. If not controlled, mangrove removal  
601 in the mud-dominated eastern sector of the delta could contribute to the local exacerbation  
602 of erosion.

603

## 604 **6. Conclusion and perspectives**

605 Like many deltas worldwide, the Ayeyarwady delta is faced with increasing  
606 urbanization and investments in agriculture, fisheries and aquaculture, transport and  
607 industry. But the river is also part of a large catchment in which issues of environment,  
608 water management, climate change, economic and social development, and land use are  
609 driving significant change (Taft and Evers, 2016), with strong implications for the sediment  
610 balance of the delta. Irrigation and hydropower are going to be key elements of this  
611 development (IFC, MOEE and MONREC, 2017), but could also pose a threat to the stability of  
612 the Ayeyarwady delta. A considerable amount of sediment is reported to be stored in the  
613 river bed and fluvial floodplain as a result of deforestation, such that the combined impact of  
614 hydropower and irrigation dams will be more important, in the short term, in buffering peak  
615 flows and thus reducing the capacity to move sediment to the delta, notably bedload, while  
616 exacerbating the flood hazard (WWF, 2018). Future dams could only compound the  
617 deleterious effects of existing reservoirs and of the current massive fluvial aggregate mining,  
618 which, by curtailing sand supply to the coast, are the most important threat to the stability  
619 of the delta's shoreline. In the future, the distributary mouths could be increasingly affected  
620 by upstream bedload transport, and salt intrusion if aggregate extractions (and attendant  
621 channel deepening) in the tidally-influenced reaches of the Ayeyarwady are maintained at  
622 current levels. Unless such mining is regulated towards much more reasonable and less  
623 damaging levels, and alternative solutions found to compensate for such regulation, the  
624 sandy beaches of the delta will continue to recede, leading to impairing of their energy-  
625 buffering capacity and their ability to protect large fronts of the delta. This could, in turn,  
626 exacerbate the lowering of resilience to cyclones, thus increasing risks to humans and to the  
627 delta ecosystem.

628



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633

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838 FIGURE CAPTIONS

839 Figure 1. Shaded-relief map showing the setting and main tributaries of the Ayeyarwady  
840 River delta.

841

842 Figure 2. 2016 Google earth image of the Ayeyarwady delta (A), and wave (B) and tidal (C)  
843 characteristics. The delta has been divided into two main sectors, eastern and western. Red  
844 dots along the shoreline show field sites visited during a reconnaissance survey in  
845 November, 2016. The wave climate was culled from the ERA-Interim hindcast wave database  
846 (1978-2016) generated by the ECMWF (European Centre for Medium-Range Weather  
847 Forecasting) Wave Atmospheric Model, the M2 tidal amplitude map derived from the tide  
848 and current prediction programme *WXTide32*© (Version 4.6), and the one-year tidal record  
849 from the nearshore tide gauge the location of which is shown in Fig. 2A.

850 Figure 3. Monthly mean values of suspended particulate matter (2002-2012) off the mouths  
851 of the Ayeyarwady delta and along the Andaman coast culled from the *GlobCoast* database  
852 and obtained from MERIS sensor with POLYMER atmospheric corrections (Han et al., 2016)  
853 (A), and monsoon-influenced water levels in the river at Pyay and Hinthada (Fig. 1) at the  
854 apex of the delta (B). The SPM show high concentrations in June (start of the rainy season)  
855 and December (dry season, reflecting, probably, a lag in terrestrial fine-grained sediment  
856 supply to the coast following overbank sedimentation in the river flood plain and delta plain  
857 during the rainy season which lasts till October).

858

859 Figure 4. Examples of mid-beach sand samples depicting alongshore variations in shoreline  
860 sedimentology in the sandy, western sector of the Ayeyarwady delta (sites 8-17) and  
861 transitional sandy-muddy shoreline (sites 6, 7) towards the mud-dominated eastern sector  
862 (not shown here).

863

864 Figure 5. Ground photographs (November, 2016) of the two dominant shoreline types in the  
865 Ayeyarwady: sandy beaches with muddy low-tide foreshores (A), and dominantly muddy  
866 mangrove shorelines with local concentrations of sand (B), and sometimes colonized by  
867 shore-front saltmarshes (foreground in B1).

868



869 Figure 6. Net shoreline mobility along the Ayeyarwady delta between April 1974 and April  
870 2019. Erosion has dominated in the sandy western sector of the delta, whereas accretion  
871 has been preponderant in the eastern sector, with increased rates east of Yangon.

872

873 Figure 7. Coastal area change at different time frames between April 1974 and April 2019,  
874 highlighting both the accretion in the eastern sector that has gained momentum in 2015-  
875 2019, and the decreasing erosion trend in the western sector since 1988 and turnaround to  
876 very mild accretion since 2010, much of it explained by the area gains in the northeast  
877 portion of this sector between sites 7 and 10.

878

879 Figure 8. Massive local reworking of muddy foreshore deposits in the eastern sector of the  
880 delta close to the mouth of the Sittaung, where several mud banks have accumulated,  
881 reflecting the important mud storage and mud remobilisation in this part of the delta.

882

883 Figure 9. Map of land-water and water-land conversion of the coastal Ayeyarwady delta  
884 between 1984 and 2015 generated from data downloaded from Pekel et al. (2016), and  
885 percentages of various categories of conversion within a 2 km-wide coastal band. The  
886 coastal band shows the dominance (78%) of conversion of land into permanent or seasonal  
887 water, and of seasonal water into permanent water, largely indicative of shoreline erosion.  
888 Wetlands behind narrow beaches in this 2 km-wide band probably correspond to areas  
889 converted to rice cultivation, whereas small areas of water-to-land conversion correspond to  
890 accreting spits.

891

892 Figure 10. Summary of river-use and land-use pressures in the Ayeyarwady catchment that  
893 are affecting the sediment discharge (adapted from WWF, 2018), with impacts on sediment  
894 supply to the delta shoreline and its mobility. Massive aggregate extraction in the lower  
895 fluvial reaches of the Ayeyarwady and upper delta distributary channels is deemed to be  
896 leading to chronic erosion of the delta's sandy beaches in the western sector, whereas new  
897 sediment releases from deforestation caused by agriculture and mining may be contributing  
898 to the maintenance of sustained levels of suspended sediments that are mainly contributing  
899 to progradation of the muddy eastern sector of the delta.

900

901 Figure 11. Map of 10-year (2002-2012) overall evolution pattern of SPM concentrations (A),  
902 and monthly seasonal evolution trends (B) over the same period in the nearshore zone and  
903 over the continental shelf of the Ayeyarwady delta (data from *GlobCoast*,  
904 <http://sextant.ifremer.fr/en/geoportail/sextant>). The data show relatively stable  
905 concentrations over the ten-year period.

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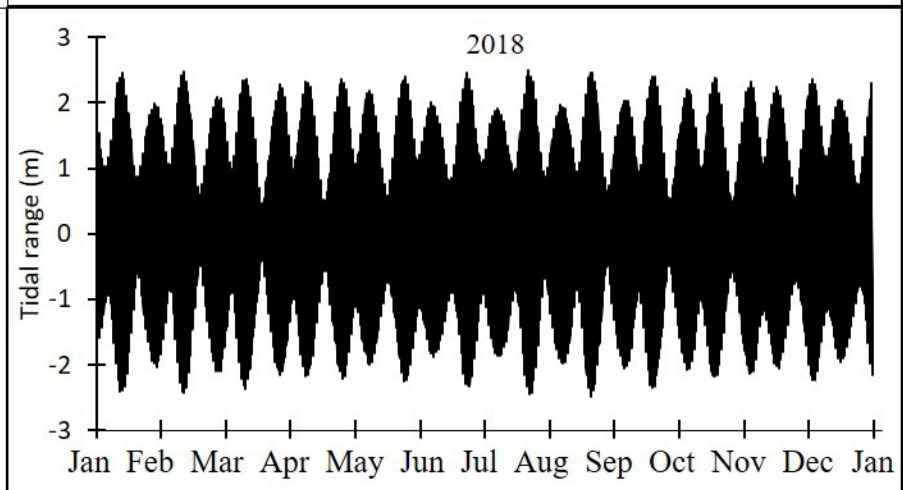
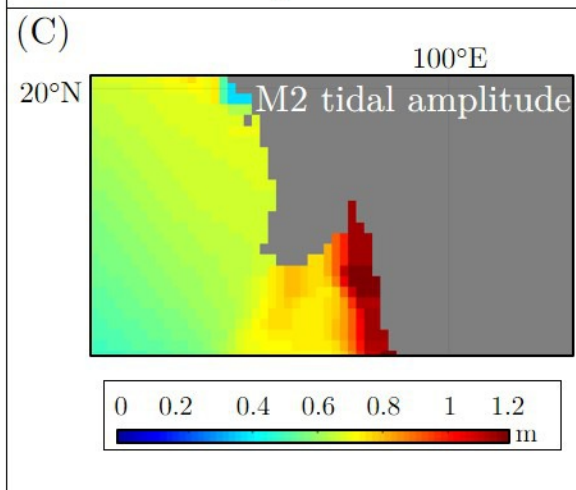
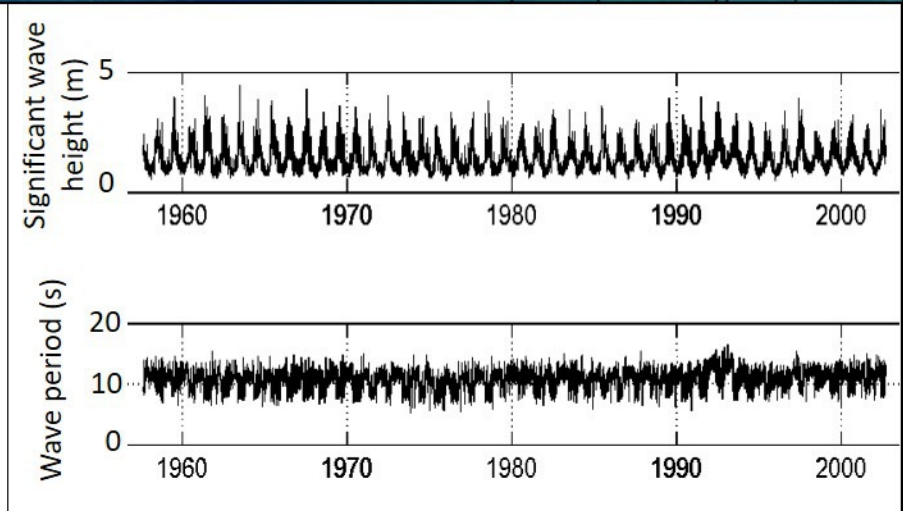
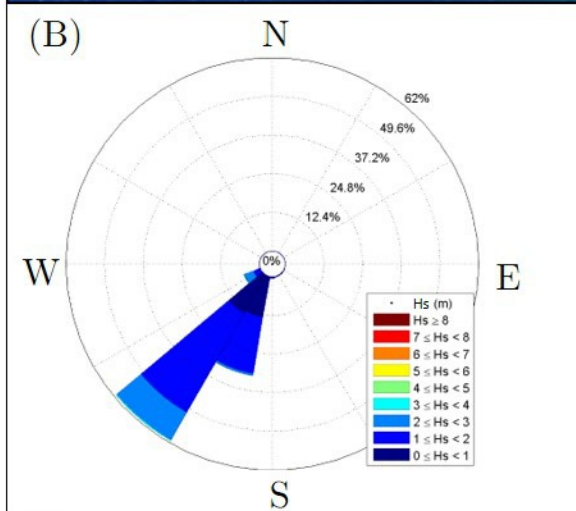
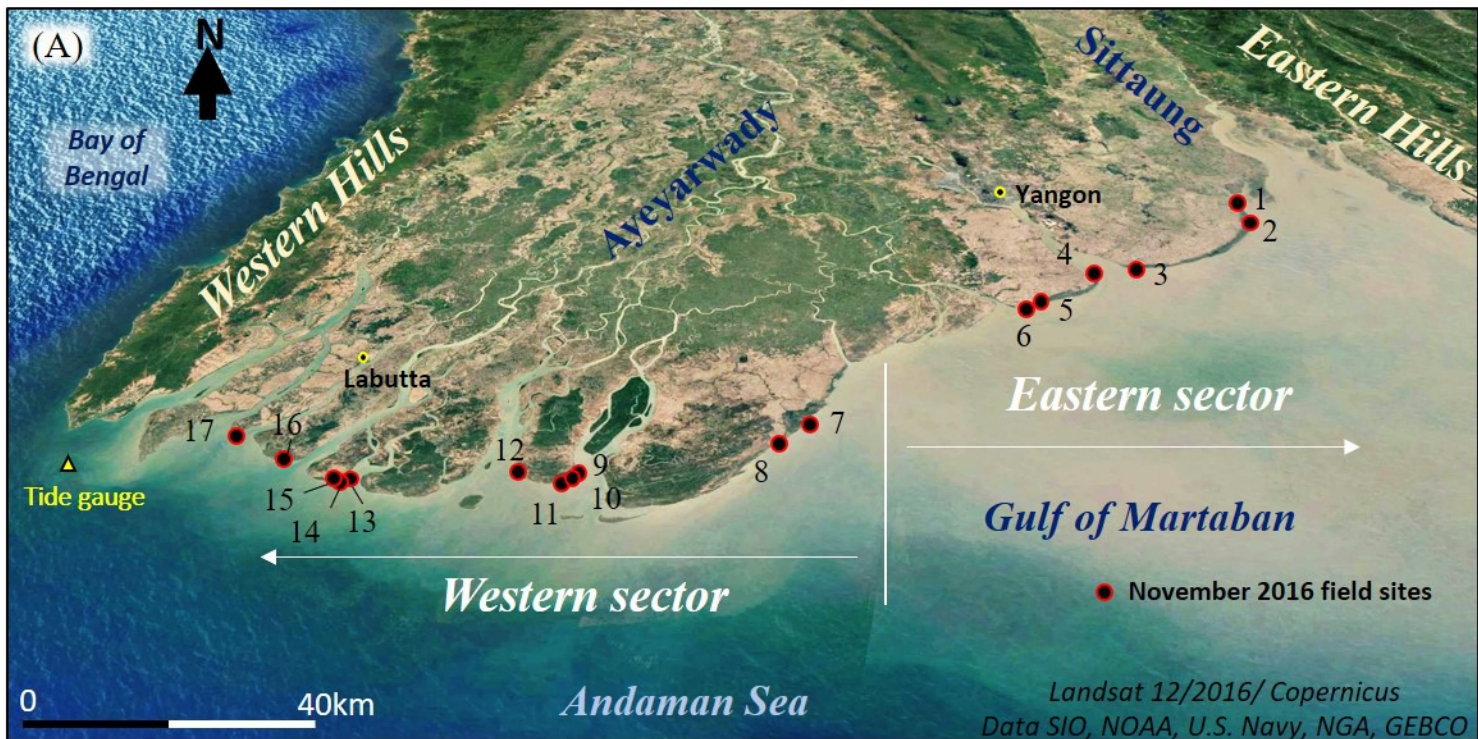
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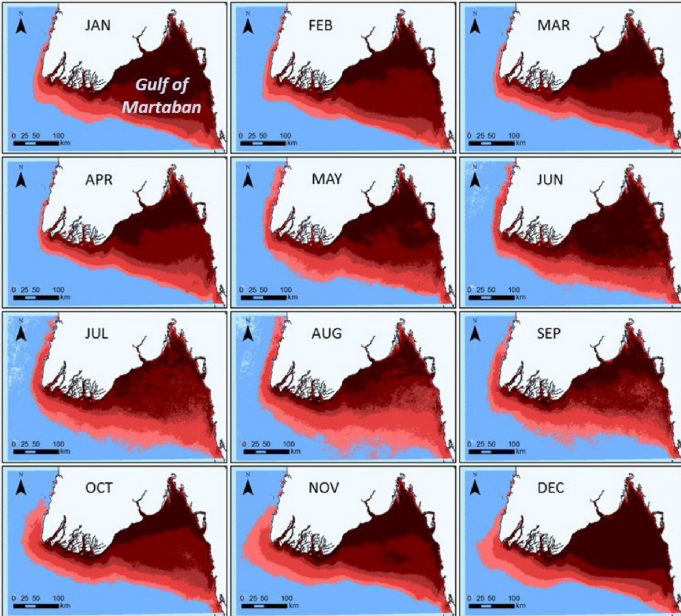
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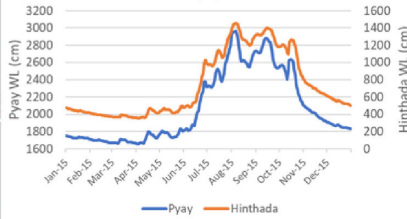


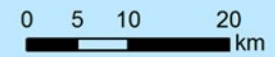
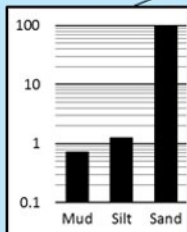
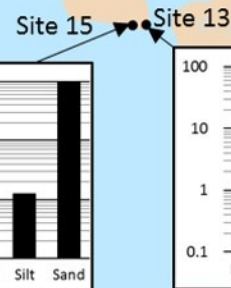
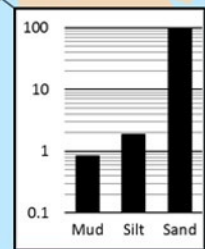
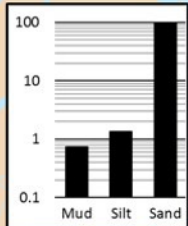
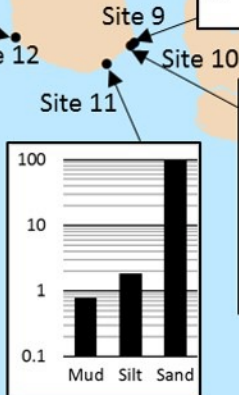
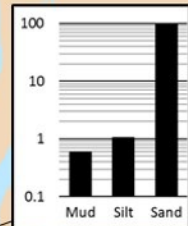
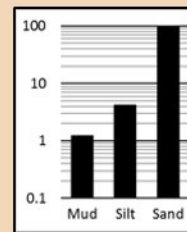
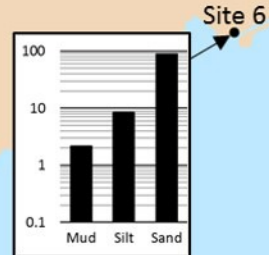
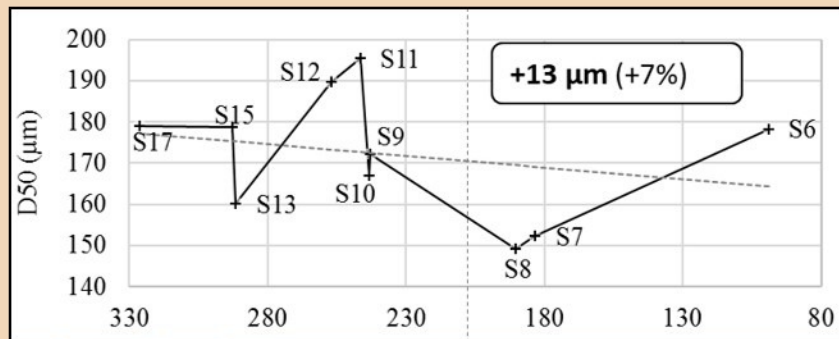


**(A) - Concentrations in suspended particulate matter (g/m<sup>3</sup>)**



**(B) - Water levels at Pyay and Hinthada, 2015**

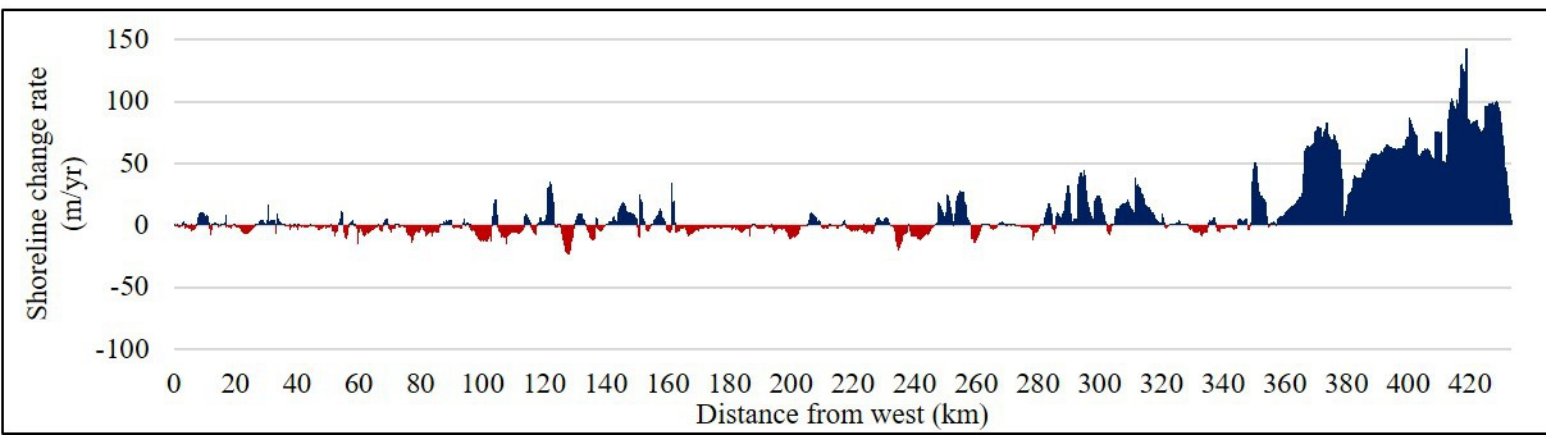
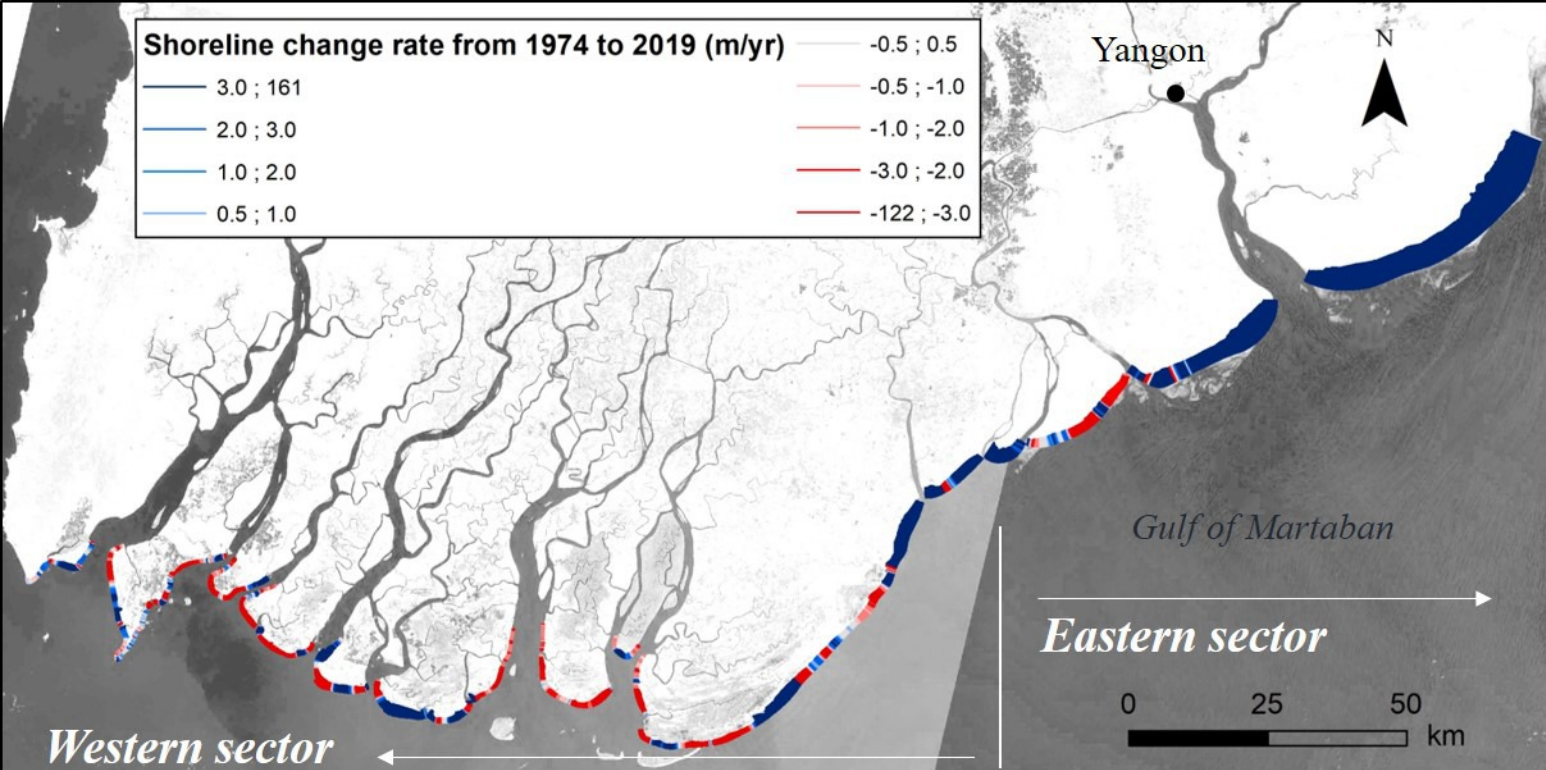




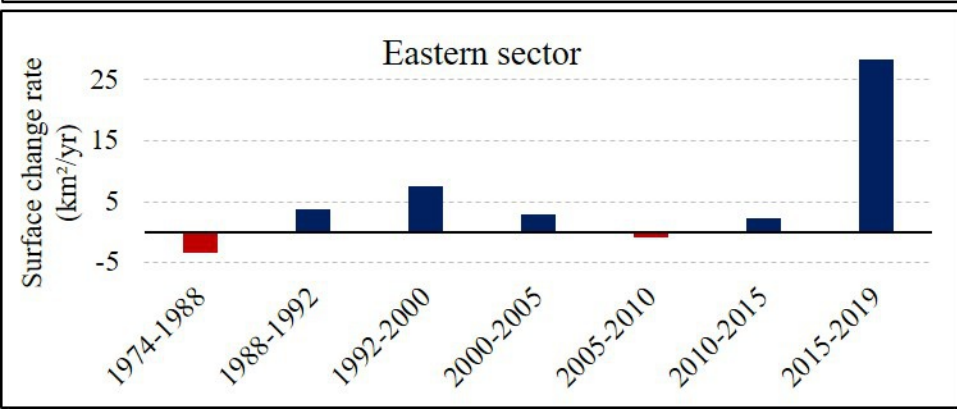
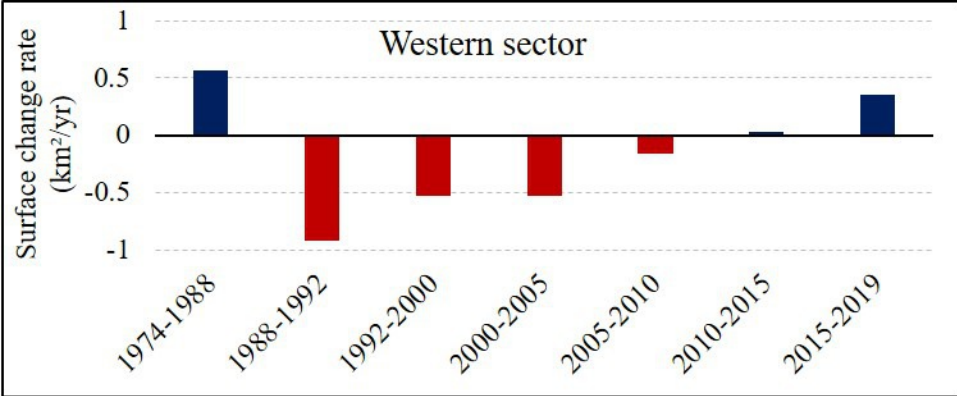












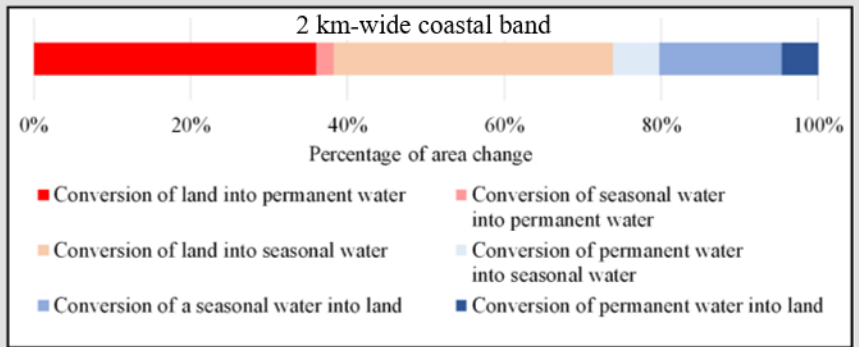
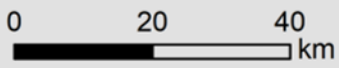


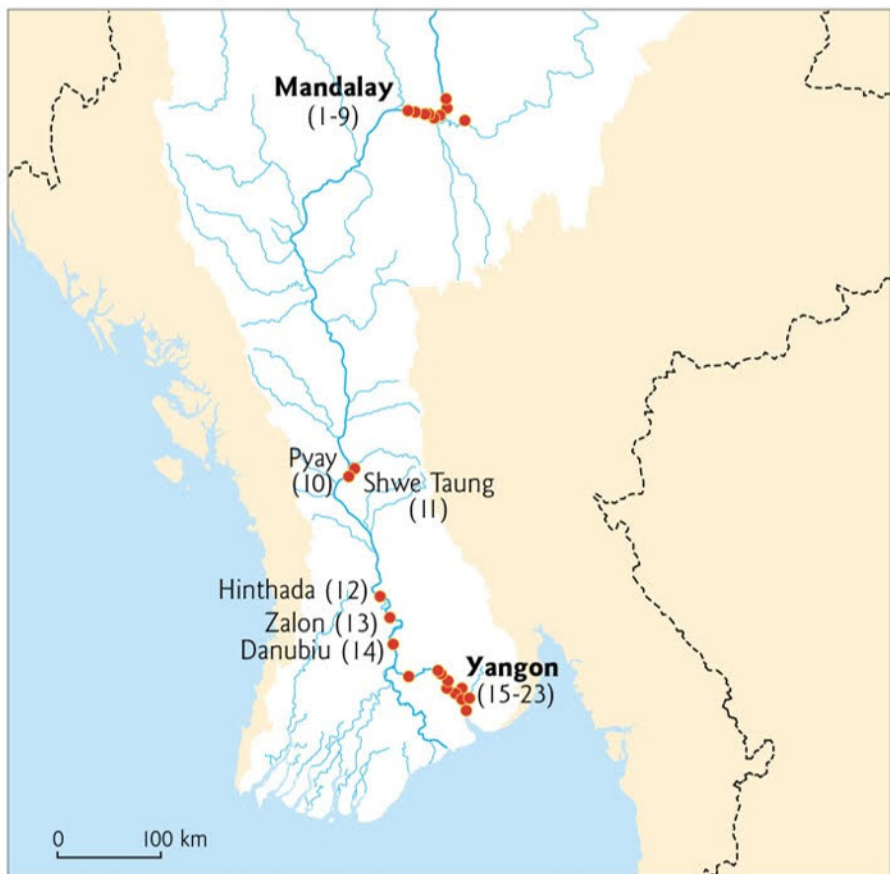
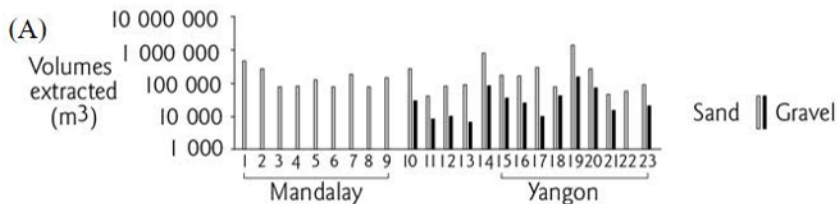




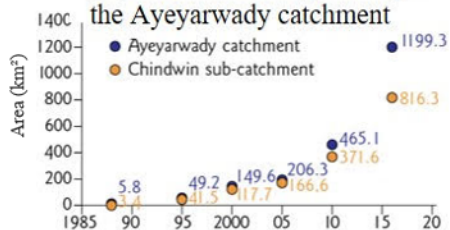
**Land to water / water to land conversion (1984-2015)**

-  Not water
-  New permanent
-  Lost permanent
-  New seasonal
-  Lost seasonal
-  Seasonal to permanent
-  Permanent to seasonal





(B) Area affected by mining in the Ayeyarwady catchment



(C) Deforestation in the Ayeyarwady catchment

