

1 A review of current and possible future human-water dynamics in
2 Myanmar's river basins

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6

7 **Abstract**

8 Rivers provide a large number of ecosystem services and riparian people depend directly and
9 indirectly on water availability, quality and quantity of the river waters. The country's economy, the
10 people's well-being and income particularly in agriculturally dominated countries is strongly
11 determined by the availability of sufficient water. This is particularly true for the country of Myanmar
12 in Southeast Asia, where more than 65% of the population live in rural areas, working in the
13 agricultural sector. Only few studies exist on river basins in Myanmar at all and detailed knowledge
14 providing the base for human-water research is very limited. A deeper understanding on human-water
15 system dynamics in the country is required because Myanmar's society, economy, ecosystems and
16 water resources are facing major challenges due to political and economic reforms and massive and
17 rapid investments from neighbouring countries. However, not only policy and economy modify the
18 need for water. Climate variability and change is another essential driver within human-water systems.
19 Myanmar's climate is influenced by the Indian Monsoon circulation which is subject to interannual
20 and also regional variability. Particularly the central dry zone and the Ayeyarwady delta are prone to
21 extreme events such as serious drought periods and extreme floods. On the one hand, the farmers
22 depend on the natural fertilizer brought by regular river inundations and high groundwater level for
23 irrigation; on the other hand, they suffer from these water-related extreme events. It is expected that
24 these climatic extreme events will likely increase in frequency and magnitude in the future as a result
25 of global climate change. Different national and international interests in the abundant water resources
26 may provide opportunities and risks at the same time for Myanmar. Several dam projects along the
27 main courses of the rivers are currently in the planning phase. Dams will most likely modify the river
28 flows, the sediment loads and also the still rich biodiversity in the river basins, in an unknown
29 dimension. Probably, these natural and anthropogenic induced developments will also impact a special
30 type of farming, we call it alluvial farming, in the river floodplains and on sandbars in the
31 Ayeyarwady River basin in Myanmar, which is called Kaing and Kyun, respectively.

32 Relevant aspects for future development of Myanmar's river basins combine environment-water-
33 related factors, climate, economic and social development, water management and land use changes.
34 Research on this interplays need to capture the spatial and temporal dynamics of this drivers. Yet, it is
35 only possible to gain a full understanding of all these complex interrelationships, if multi-scale
36 spatiotemporal information will be analysed in an inter- and transdisciplinary approach. This paper
37 gives a structured overview on the current scientific knowledge available and reveals the relevance of
38 this information with regard to human-environment and particularly to human-water interactions in
39 Myanmar's river basins. By applying the eDPSIR framework, it identifies key indicators in the
40 Myanmar human-water system, which has been shown exemplary by giving an example of use related
41 to alluvial farming in the central dry zone.

42 **Keywords**

43 Human-water dynamics; River basins; Myanmar; Southeast Asia, Climate Change, eDPSIR, Alluvial
44 farming

45 **1 Introduction**

46 Rivers provide a large number of ecosystem services, e.g. water supplies, food source, biodiversity
47 conservation or drought mitigation, and river basins are home to almost one billion people worldwide
48 (Postel and Richter, 2003; Allen et al., 2010; Di Baldassarre et al., 2013). Riparian people depend
49 directly and indirectly on water availability, quality and quantity of the river waters, which is, in turn,
50 influenced by precipitation, evaporation, glacial meltwater in the river source areas, and increasing
51 human impact. For example, pollution, increasing water use for irrigation and dam building alter the
52 quality and availability of river waters. Additionally, anthropogenic climate change will possibly
53 impact flow regimes and the water demand. Rivers worldwide are under pressure due to multiple uses
54 which often have severe impacts on ecosystems, or water quality and flow. Vörösmarty et al. (2010)
55 stated that 65% of global river discharge, and the aquatic habitats supported by this water, are under
56 moderate to high threat of biodiversity loss.

57 The country's economy, the people's well-being and income particularly in agriculturally dominated
58 countries strongly depend on the availability of sufficient water. This is particularly true for the
59 country of Myanmar in Southeast Asia, where more than 65% of the population live in rural areas,
60 working in the agricultural sector (FAO, 2014). The Ayeyarwady River (also referred to as Irrawaddy
61 River) catchment covers 413,700 km² which represents about 61% of the country. Thus it is the most
62 important river system in Myanmar. The mighty Ayeyarwady River is called the life line of the nation
63 because it serves for transportation, domestic and industrial water supply, irrigation, a high
64 biodiversity and fishing. This river is highly important for Myanmar but is the least known among the

65 large Asian rivers (Furuichi et al., 2009). Since the end of Myanmar's political and economic isolation
66 in 2011, the country's abundant water resources are now facing major changes. It is assumed that the
67 current and future progressive socio-economic development of the country have and will have a
68 significant impact on the water resources (Kattelus et al., 2014). However, not only political,
69 economic and demographic changes have and will have major effects on the natural water resources.
70 The headwaters of the Ayeyarwady River are fed by glacier melt in the Himalayan Mountains and the
71 river discharge is likely to change due to climate change impacts. Myanmar's climate is directly
72 influenced by the Indian summer monsoon (ISM; Sen Roy and Kaur, 2000; Sein et al., 2015) which is
73 the second basic source of Myanmar's rivers. It is currently still not predictable if the complex Asian
74 monsoon circulation will strengthen, weaken or become more variable as a result of global warming
75 (Turner and Annamalai, 2012; IPCC, 2014). Already now, there seems to be a trend to a delay and an
76 earlier ending of the monsoon rains of 2 weeks in Myanmar respectively (The Irrawaddy, 2015). On
77 the one hand, the Burmese riparian people depend on frequent river floods for agriculture, particularly
78 rice production in the river delta regions. On the other hand, extreme flood events can cause
79 destructing effects. Just recently, the western part of the country was affected by very heavy monsoon
80 rains in August 2015. Thousands of people had to be evacuated and more than 100 people died (Burki,
81 2015). The occurrence of extreme weather events like floods, cyclones and severe droughts has
82 shown an increasing trend over the last six decades in Myanmar, most likely as a result of climate
83 change (GCCA, 2012).

84 Only few research exist on river basins in Myanmar at all and detailed knowledge is very limited (e.g.
85 Varis et al., 2012; Salmivaara et al., 2013). However, more research on human-water dynamics in the
86 country is strongly required because Myanmar's society, economy, ecosystems and water resources
87 are facing major challenges due to political and economic reforms, massive and rapid investments
88 from neighbouring countries (particularly from China and Thailand; Webb et al., 2012) and climate
89 change impacts. There is a large number of grey literature such as reports and workshop presentations
90 from NGOs, political institutions and Burmese and international organizations, dealing with human
91 and climate impacts and the water resources in Myanmar. However, systematically compiled English
92 scientific publications on this topic have not been published yet. Hence, English grey literature and
93 peer-review publications on current and likely future impacts from human activities and climate
94 change on Myanmar's river basins have been reviewed by the authors in order to gain an overview on
95 the key drivers in these human-water dynamics.

96 Following a socio-ecological understanding we hypothesise that all components (e.g. stakeholders,
97 water resource, climate, aquatic fauna) within the Burmese river basins interact and that the degree of
98 interactions between driving forces (e.g. foreign investments, water demand, water management
99 measures, regional climate change) and feedbacks permanently change. If, for example, the demand

100 for domestic water increases due to a dry spell, the riparian people will increasingly extract river water
101 as well as ground water. This higher water extraction in turn, will probably impact the aquatic
102 ecosystem which has potential negative effects on the fisheries and therefore also on the economic
103 income of the people.

104 The major aim of this review was to compile the natural given physical conditions and the socio-
105 economical features in terms of land and water use in order to make this information internationally
106 accessible in a scientific status-quo review paper. The first part of the paper provides general
107 information on physical features with focus on the river basins, followed by socio-economical
108 features. Chapter 4 concentrates on possible future impacts with focus on climate change. Based on
109 the reviewed literature we attempt to structure the information on human-water dynamics by means of
110 the eDPSIR (enhanced driving force-pressure-state-impact-response) framework by Niemeijer & de
111 Groot (2008a, b). We applied this framework by using a concrete example in order identify important
112 key nodes within a causal network of various driving forces, feedback mechanisms, impacts and
113 responses on the societal and the physical-environmental side. Open research gaps concerning human-
114 water dynamics in Myanmar and recommendations for research approaches have been identified and
115 elaborated in the end.

116 **2 Physical features**

117 The Republic of the Union of Myanmar (9°55' - 28°15' N, 92°10' - 101°11' E) is a Southeast Asian
118 country located between Bangladesh and India to the west, China to the north and northeast, Laos and
119 Thailand to the east and the Bay of Bengal and the Andaman Sea to the southwest and south (Fig. 1).
120 The maximum north-south extent is about 2,500 km and the maximum west-east extent is ca. 900 km.
121 With 676.578 km² Myanmar (Department of Population, 2015) is the second largest country in
122 Southeast Asia after Indonesia.

123 **2.1 Geology and geomorphology**

124 The country slopes downward in elevation from north to south and the central lowlands are
125 surrounded by steep mountain ranges (Fig.1). Three mountain ranges trending from north to south,
126 namely the Rakhine Yoma (the term Yoma means mountain range), the Bago Yoma and the Shan
127 Plateau (from west to east), divide the country (Fig. 1). The Rakhine and the Bago mountain ranges
128 have been thrust up through the collision of the Indian-Australian and the Eurasian plate since the
129 past 50 million years (Bender, 1983). The Shan Plateau was already formed during the Mesozoic era
130 and it has an average elevation of about 900 m a.s.l. (Hadden, 2008). The topography can be divided
131 into five sub-regions: 1) the northern mountains including the highest point of Myanmar Mount
132 Hkakabo Razi (5,881 m a.s.l.); 2) the western Rakhine ranges; 3) the eastern Shan Plateau; 4) the

133 central basins and lowlands and 5) the coastal plains including the wide Ayeyarwady delta. The Mount
134 Hkakabo Razi is part of a geological complex where the Indian-Australian plate has been colliding
135 with the southern edge of the Eurasian plate since the Eocene (Hadden, 2008). This northern mountain
136 region is the source area of several of Asian's great rivers, including the Irrawaddy. The central basin
137 lies between the western Rakhine ranges and the eastern Shan Plateau in the rain shadow of the
138 monsoon precipitations. The Ayeyarwaddy, Chindwin and Sittaung rivers cover soft sandstones,
139 shales and clays with their fertile alluvial deposits in the central basin (Bender, 1983). The coastline
140 has a length of about 3,000 km and there are numerous islands of varying sizes (Oo, 2002).

141 2.2 Hydrogeography

142 Major rivers are the Ayeyarwady, the Salween, the Chindwin and the Sittaung. All these rivers are
143 understudied river basins (Salmivaara et al., 2013), despite their great importance for the Burmese
144 people's life and the nation's economy. The north-south trending courses of most of the Burmese
145 rivers are geologically predetermined following the mountain ranges Rakhine, Bago and the Shan
146 Plateau. For about 230 km, the transnational Mekong River forms the border between Myanmar and
147 Laos (Fig. 1).

148 The Ayeyarwady River is Myanmar's most important commercial waterway (Salween Watch and
149 SEARIN, 2004). It is about 2,170 km long and originates at the confluence of the Mali Hka and N'Mai
150 Hka rivers in the northern Kachin state (Fig. 1). The headwaters of both rivers originate in the eastern
151 syntaxis of the Himalayas and the Tibetan Plateau in Yunnan Province, China. The river basin of the
152 Ayeyarwady covers around 413,700 km² of which 95% is located in Myanmar (Salween Watch and
153 SEARIN, 2004; Bird et al., 2008). The broad fertile lowland floodplain is extensively used for
154 agriculture. The river is fed by glacial meltwater in the source areas of the Mali Hka and N'Mai Hka
155 rivers as well as by precipitation. Based on data collection between 1969-1996 by Furuichi et al.
156 (2009), the average annual discharge is $379 \pm 47 \times 10^9$ m³/year and around 70% of it occurs between
157 July and October (Robinson et al., 2007). The Ayeyarwady has the fifth highest sediment load of any
158 major river worldwide (Furuichi et al., 2009; The World Bank, 2014). Furuichi et al. (2009) estimated
159 the suspended sediment load to be $325 \pm 57 \times 10^6$ t annually. However, the river is navigable year-
160 round for approximately 1,500 km from Yangon, but sandbanks and shallow sections make it often
161 difficult to navigate during the dry season (Lwin, 2014). The basin's ecosystem is very rich and
162 dynamic and the river is home to the endangered 'Irrawaddy dolphin' (Smith et al., 2009; Aung et al.,
163 2013).

164 With a total length of about 2,800 km the transboundary (China, Thailand, Myanmar) Salween River
165 is one of the longest rivers in Southeast Asia. However, it is navigable for only 150 km from its delta
166 due to its rapids and deep gorges (Salween Watch and SEARIN, 2004). Annual runoff is

167 approximately 210 km³ (Robinson et al., 2007). The source of the river is located on the Tibetan
168 Plateau and subsequently the water flows through Yunnan Province in China to the eastern part of
169 Myanmar where the Salween drains the Shan Plateau. For approximately 120 km, the river forms the
170 border between Myanmar and Thailand until it flows to the Andaman Sea in the Gulf of Martaban
171 (Salween Watch and SEARIN, 2004; Fig. 1). The river basin covers 320,000 km² and has one of the
172 most diverse ethnic concentrations worldwide (Salween Watch and SEARIN, 2014). Furthermore, the
173 basin is very rich in natural resources including surface and groundwater, forest, wildlife, fisheries and
174 minerals (FAO, 2011).

175 The Chindwin River exists since at least the Eocene and is the largest tributary of the Ayeyarwady
176 (Hedley et al., 2010). It has a length of about 1,200 km (Salween Watch and SEARIN, 2014). The
177 Chindwin rises in the Kumon Range in northern Myanmar and reaches the Ayeyarwady near
178 Mandalay in the central dry zone. For about 600 km the river is navigable from its confluence with the
179 Ayeyarwady River (Ministry of Forestry, 2005). Most of its course has not been studied yet due to the
180 difficulty of access (Salween Watch and SEARIN, 2004).

181 The Sittaung River originates at the southern edge of the Shan Plateau and drains after 420 km into the
182 Gulf of Martaban of the Andaman Sea (Salween Watch and SEARIN, 2004). Year-round, the Sittaung
183 River is navigable only for 40 km and for 90km during the rainy season. It is mainly used for floating
184 teak wood for export to the souths. At its lower course, the river is linked by a canal to the Bago River,
185 located in Yangon (Fig. 1).

186 The Ayeyarwady delta is one of the major tropical deltas worldwide (Hedley et al., 2010). Its current
187 extensive wedge-shape originated around 7,000-8,000 years ago and it comprises >20,500 km² of flat,
188 low-lying fertile delta plain with five major tributaries (Hedley et al., 2010; Woodroffe, 2000). The
189 delta area continues upriver at sea-level for more than 200 km (Webster, 2008). The delta plain hosts a
190 fragile and complex ecosystem of mangrove swamps and tidal estuaries (Salween Watch and
191 SEARIN, 2004). Mangrove forests play an important role in delta evolutions because they act as
192 sediment traps, primary colonisers and bio shields against impacts of cyclones and tsunamis. However,
193 the ecological status of the Ayeyarwady mangroves is continuously declining due to increasing rice
194 production, land use changes and population growth (Ministry of Forestry, 2005; Webb et al., 2014).
195 The Ayeyarwady delta is under intensive land use and the population density is the second highest
196 (177/km²) in the entire country, after Yangon (716/km²) (Salmivaara et al., 2013; Department of
197 Population, 2015). Saline water penetrates up to 100 km upstream due to tidal influences (Aung, 2003
198 in Hedley et al., 2010). Drainage, flood protection and salt intrusion are major concerns in the
199 Ayeyarwady delta (FAO, 2015). The Salween River has rather a river mouth than a clearly developed

200 delta and is less populated. However, the Salween river mouth area is facing similar environmental
201 pressures, only on a smaller scale (Salmivaara et al., 2013).

202 2.3 Soil types

203 Due to the wide range of climatic and geologic conditions, soil types in Myanmar vary accordingly.
204 Fertile alluvial soils are predominantly located in the river basins of the Ayeyarwady, the lower
205 Salween and the Chindwin Rivers (MOAI, 2001). These soils are of high importance for farming (see
206 3.1). Red-brown and yellow-brown forest soils (cambisols following the FAO soil classification or
207 inceptisols following the USDA soil classification) are found in the hilly areas of the mountains ranges
208 and its forelands. These soils are suitable for forest plantation (Ministry of Forestry, 2005). The central
209 part of the country is covered with red-brown and dark compact savanna soils which are susceptible
210 for soil erosion and dryland salinity. The humus content of red earths is relatively high (< 8%) and
211 thus this soil type is very suitable for diversified agriculture which can be found from the eastern
212 Mandalay division to large parts of the Shan Plateau (Ministry of Forestry, 2005).

213 2.4 Climate

214 Few regional studies exist on modern climate conditions in Myanmar. In general, large parts of the
215 country have a tropical monsoon climate. Due to the diverse orography of the country ranging from
216 low-lying delta regions to high mountainous terrain, the climate can be divided into the following five
217 sub-types according to the Köppen-Geiger climate classification (Peel et al., 2007): 1) Tropical,
218 monsoon climate (Am) along the coastlines and the western part; 2) Tropical, savannah climate (Aw)
219 in the central and eastern part; 3) Temperate, dry winter, hot summer climate (Cwa) in the north-
220 eastern mountainous area; 4) Temperate, dry winter, warm summer climate (Cwb) in the northern part,
221 a small area subsequent to the Cwa climate region and 5) Temperate, without dry season, warm
222 summer (Cfb) in the most north-eastern high mountain area.

223 Palaeoclimate research in Myanmar is very scarce, although findings about past monsoon variabilities
224 in this region would definitely contribute to a deeper understanding of this atmospheric circulation.
225 There are teak tree ring chronologies covering the last three centuries in Myanmar (D'Arrigo et al.,
226 2011; D'Arrigo and Ummenhofer, 2015). Following these studies, the tree-ring records show monsoon
227 rainfall variabilities consistent with results from surrounding countries, indicating that Myanmar is
228 influenced by the same atmospheric circulation system. Sen Roy and Kaur (2000) noted that even
229 though India and Myanmar are geographical neighbours and are influenced by the same monsoon
230 system, Myanmar's rainfall seems to have no significant relationship with the rainfall of Northern
231 India. This pattern might be due to the fact that the Rakhine Mountains (< 3,800 m a.s.l.) located in the
232 western part of Myanmar (Fig. 1) redirect the wind flows. In contrast, D'Arrigo et al. (2011) detected

233 a positive correlation of monsoon variability in Myanmar with the monsoon larger scale indices over
234 northeastern India based on teak tree ring chronology for the last three centuries. These contrary
235 findings highlight the urgent need for more climate research in Myanmar.

236 2.4.1 Precipitation

237 Myanmar's climate is largely influenced by the Indian summer monsoon as well as from convective
238 rainfall from the Bay of Bengal (Sen Roy and Kaur, 2000; D'Arrigo et al., 2011; Htway and
239 Matsumoto, 2011; Sein et al., 2015). The patterns of rainfall indicate considerable complexity,
240 particularly in summer, when Indian and East Asian monsoon circulations interact (D'Arrigo et al.,
241 2011). Already Maung (1945) studied the forecasting of coastal monsoon rainfalls in Myanmar;
242 however, his study does not include a detailed description of the general climatology. Sen Roy and
243 Kaur (2000) gave an overview on the climatology of monsoon rains of Myanmar using 33 years
244 (1947-1979) of station level monthly data. After this study, about 75% of the country's annual average
245 rainfall is from June to September (Sen Roy and Kaur, 2000). Sein et al. (2015) concluded that the
246 summer monsoon accounts for almost 90% of Myanmar's observed rainfall. The monsoon rains reach
247 the southern part of Myanmar by around the third week of May and cover the entire country by the
248 beginning of June (Sen Roy and Kaur, 2000). Results of a study by Sen Roy and Sen Roy (2011)
249 showed the existence of five homogenous precipitation regions, namely, north, west, central, east and
250 south Myanmar. Thereby, the amount of annual precipitation varies between 500-1.000 mm in the
251 central dry zone (Johnston et al., 2013; FAO, 2015) and up to 4.000-6.000 mm at the western coast
252 (MOAI, 2001; FAO, 2015). The central dry zone lies in the rain shadow of the Rakhine Mountains
253 located along the western coastline (Fig. 2). This area receives only 3.2% of the country's total rainfall
254 (Ministry of Forestry, 2005). Easterly winds and local depressions in the Gulf of Thailand can cause
255 post-monsoon rains from mid-October to end-November (MOAI, 2001; Sein et al., 2015). A
256 correlation between El Niño-Southern Oscillation (ENSO) and the variability of Asian monsoon
257 intensity has been discussed elaborately during the last decades (e.g. Kumar et al., 1999; Torrence and
258 Webster, 1999; Xavier et al., 2007; Li and Ting, 2015). All these studies conclude a significant
259 correlation between both atmospheric circulations. Current research from Sein et al. (2015) indicated
260 that El Niño events can result in drought periods in Myanmar, while La Niña events can result in more
261 extreme floods due to intensified monsoon rains. Temperature

262 The average temperature varies from 21-34°C in the hot season and from 11°C-23°C in the cool
263 season, depending on location and elevation. The mean relative humidity ranges between 58 and 79%
264 (Ministry of Forestry, 2005). Average diurnal temperatures show little variation across the country
265 ranging from 26°C-28°C between Sittwe in the western region, Yangon near the southern coast and
266 Mandalay in the central dry zone. During the rainy season, the diurnal temperatures range between 25-

267 33°C and from 10-25°C during the cold season. Between mid-April and mid-May, the maximum
268 temperatures rise continuously in the whole country (Htway and Matsumoto, 2011). The maximum
269 diurnal temperatures in the central dry zone can reach >43°C in the hot season prior to the monsoon
270 season (Aung, 2002). In this area, the mean monthly potential evapotranspiration exceeds the mean
271 monthly rainfall.

272 2.5 Hydro-meteorological extreme events and climate variability

273 Myanmar is considerable prone to risks from weather extremes and climate variability. According to
274 the Germanwatch Global Climate Risk Index, Myanmar is one of the countries worldwide affected
275 most by extreme weather events between 1993 and 2012 (Kreft and Eckstein, 2014). The coast, the
276 river delta zones and the central dry zone are the most vulnerable areas for weather extreme events
277 like cyclones, river floods, storm surges and drought periods. Climate variability is a major concern
278 for the country since the majority of Myanmar's economy and people's income and wellbeing are
279 depending on the right timing and amount of monsoon rains. Myanmar's farmers strongly depend on
280 monsoon precipitation since they use the water for irrigating rain-fed rice paddies and storing the rain
281 water for the dry season. However, extreme amounts of monsoon rains have the potential to destroy
282 their livelihoods. Extreme and long-lasting dry periods or extreme low amounts of monsoon rains
283 cause water scarcity and threaten the food security of the country.

284 2.5.1 Floods

285 Floods can represent both a basic asset for people's well-being, income and cultures, but also a
286 drawback for a societal and economic development. Myanmar is regularly affected by severe floods
287 comprising river floods, flash floods, pluvial floods and coastal floods. Catastrophic flash floods
288 associated with high rainfall occurred in the central dry zone e.g. in the year 2011 (Rao et al., 2013).
289 Just recently, the western part of the country was affected by very heavy monsoon rains in August
290 2015. Particularly, the Ayeyarwady delta zone and the central dry zone are extremely vulnerable to
291 impacts from floods due to associated crop loss and the relatively dense population. In hilly and
292 mountainous rural areas, heavy rainfalls often trigger disastrous landslides with severe consequences
293 for the Burmese people who normally live in small wooden huts. The flood risk of Myanmar is
294 assessed very high due to high vulnerability and low capacity to cope with floods. For the future, the
295 frequency of 100-year floods in Myanmar is likely to increase (Hirabayashi et al., 2013).

296 2.5.2 Droughts

297 Increasing pressure on water resources and water scarcity is becoming a worldwide problem in most
298 arid and semi-arid regions (Kahil et al., 2015). Particularly in the central dry zone of Myanmar,
299 rainfall is associated with high heterogeneity across space and time (McCartney et al., 2013).

300 Precipitation amounts in the dry zone are generally less compared to other regions in Myanmar (see
301 chapter 2.2.1). In the here presented context, a drought is considered as a temporary extreme dry
302 period characterized by below-normal precipitation over a period of months or even years (Dai, 2011).
303 Severe drought periods in e.g. the years 1997-98, 2010 and 2014 led to crop failures and water
304 shortage in the central dry zone where more than 14 million people predominantly practice agriculture.
305 Most of the wells dried up due to the sinking of groundwater levels (Department of Meteorology and
306 Hydrology Myanmar DMH, n.d.). Due to a strong El-Niño impact since 2015, the country, and
307 particularly the dry zone and the Ayeyarwady delta, is severely affected by drier than average
308 conditions associated with risks such as fire hazards, drought, disease and food insecurity (FAO,
309 2016). The sources of income are affected by drought periods as well as the quality and availability of
310 domestic and drinking water which can have severe effects on people's health. Droughts can also have
311 negative impacts on the river basin's ecosystem (Kahil et al., 2015). During drought periods the
312 navigability of the rivers is a severe problem for national and international companies as well as for
313 the people living in this area (The World Bank, 2014; Ministry of Transport, Htun Lwin Oo, personal
314 communication, 2015). Most likely, water demand in Myanmar will increase in the future due to
315 enhanced production and trade in agricultural products, the expansion of transport systems via rivers
316 and ports, and the anticipated growth of cities and industries (The World Bank, 2014). This increasing
317 water demand and the high rainfall variability in the dry zone will probably cause the construction of
318 more pumping stations for both groundwater and river water as well as the building of more reservoirs
319 and dams.

320 2.5.3 Cyclones

321 The coast and the delta zones of the Ayeyarwady and Chindwin River are extremely exposed to
322 impacts from cyclones associated with winds, storm surges and salt water intrusion into groundwater
323 (Rao et al., 2013). The Ayeyarwady Division is, compared to other regions in Myanmar, densely
324 populated (177/km²; Department of Population, 2015)) and the extensive and shallow continental shelf
325 of the Andaman Sea allows cyclones and storm surges to inundate the delta and some inbound areas
326 (Webster, 2008). Tropical cyclone formation in the northern Indian Ocean occur preferentially before
327 (April-May) and directly after (October-November) the Asian summer monsoon season (Webster,
328 2008). During the cyclone Nargis in the year 2008, which was the most devastating cyclone to strike
329 Asia since 1991, the Ayeyarwady River delta region was flooded by a 3.5 meter wall of water
330 (Thomson Reuters, 2009). Wind speed was in excess of 65 ms⁻¹ (Webster, 2008). More than 130,000
331 people died and 2.4 mio people were severely affected (van Driel and Nauta, 2013; Thomson Reuters,
332 2009). Nargis caused severe harm to the winter rice crop and loss of rice seed and Myanmar faced
333 food shortages after the event (Webster, 2008). Seawater inundated large areas of the Ayeyarwady
334 delta posing challenges to future rice production (Webster, 2008). Lin et al. (2009) detected a pre-

335 existing warm ocean anomaly in the Bay of Bengal which was probably the cause why a weak
336 category-1 storm could rapidly intensify to an intense category-4 storm within only 24 hours.
337 Mangrove clearance for shrimp farms and rice paddies was probably a major factor in aggravating the
338 impacts of cyclone Nargis (Nature News, 2008). Historically seen, Myanmar has only infrequent
339 tropical cyclone landfalls but since 2006, there has been an apparent increased activity in the Indian
340 Ocean. Whether this development is part of a continuing trend due to climate change is difficult to
341 assess because data quality and length of the records are limited (Webster, 2008).

342 2.6 Flora and fauna

343 Myanmar is one of the few countries in Southeast Asia with relatively high levels of biodiversity and
344 intact forest areas (Rao et al., 2013). About 48%, or 317,730 km² of Myanmar's surface is covered
345 with closed tropical forest; however, according to the FAO, both quantity and quality are decreasing
346 (Htun, 2009). In the early 1990s, Myanmar had still a total forest cover of about 442 000 km², which is
347 67% of the total surface area (Leimgruber et al., 2005). The forest flora ranges from sub-alpine to
348 tropical formations (Aung, 2002). The forest along the Salween River on the Thai-Burmese border lies
349 on a bio-geographic border that is rich in biodiversity, in wildlife and fish populations, and this area is
350 one of the most fertile areas for teak in the world (Salween Watch and SEARIN, 2004). Tropical
351 evergreen rainforests occur in areas receiving >2,000 mm of rain annually and they are home to many
352 birds species. Many wild animals which were once plentiful, are now reduced in number and are
353 protected, e.g. the 'Irrawaddy dolphin', the Asian two-horned rhinoceros, the wild water buffalo, the
354 gaur and other deer species (Hadden, 2008; Smith et al., 2009; Aung et al., 2013).

355 All species play an important role in maintaining balance in and supporting ecosystems. If these
356 significant values and benefits are lost, humans will respond with additional inputs to maintain the
357 system's functionality (Allen et al., 2010). The majority of threats to Myanmar's biodiversity are in
358 general linked to human population growth and economic development, and the corresponding
359 increasing demand for natural resources and space (Allen et al., 2010). Overexploitation of fishes is a
360 major concern for the country's inland fisheries which are likely to increase due to political and
361 economic transitions (Rao et al., 2013). However, little is known about species-ecosystem interactions
362 to be sure of human (e.g. dam projects, mining) or climate impacts (e.g. temperature changes may lead
363 to alien species invasions). Following Allen et al. (2010), alien species invasions, pollution from
364 mining activities, river flow modifications and overexploitation of fishes are the major threats to the
365 biodiversity of freshwater systems in Myanmar.

366 **3 Social and economic features**

367 3.1 Agricultural land use

368 Agriculture is the main pillar of the country's economy and contributes ~37% to the GDP (Ministry of
369 Forestry, 2005; CIA, 2015). The estimated cultivated area in Myanmar is 18.27 million ha which is
370 equivalent to 55 % of the cultivable area (FAO, 2015). More than 65% of the population live in rural
371 areas, working in the agricultural sector (FAO, 2014). The major agricultural products are rice, pulses,
372 beans, sesame, groundnuts, sugarcane and hardwood. 42% of Myanmar's cropland is cultivated with
373 paddy rice, particularly in the Ayeyarwady delta region (FAO, 2004). The delta areas and river mouths
374 are the most populated sections within the river basins. Here, cultivation of rice in flooded paddies
375 predominates (FAO, 2004). In general, the agricultural practices are still very low tech, and usually
376 water buffalos are used for ploughing (van Driel and Nauta, 2013). The majority of the farmers there
377 are small-scale landholders with an average lot size of 2.27 ha cultivating paddy fields during the
378 monsoon season and vegetable gardens on the river banks in the dry season (Salween Watch and
379 SEARIN, 2004). All-the-year, they cast for fish in the rivers and along the coasts. The country has the
380 largest estimated population of small-scale fisheries in the world (SEAFDEC, 2012). The government
381 is the ultimate owner of all land in Myanmar and the farmers are only allowed to cultivate the land
382 with the government's prescription. One third of the rural residents are landless labourers (Hiebert,
383 2012). Land-grabbing and confiscation by the military, government and international investors are a
384 huge problem, particularly in the Tanintharyi Region, followed by Kachin State (Farmlandgrab, 2014).

385 The mangrove forests in the delta and coastal areas supply firework and bark for tanning which has
386 already led to critical degradation of the ecologically important mangrove forests (Webb et al., 2014).
387 The Ministry of Forestry in Myanmar (2005) estimated that the mangrove forest area decreased to
388 about almost half of its size between 1990 and 2002. This development is likely going on due to the
389 increasing number of fish and prawn ponds, salt evaporation ponds for commercial purposes and the
390 expansion of agriculture land for food security (Ministry of Forestry, 2005).

391 Following categories of farmland exist in the country (JICA 2013, p.9): 1. Paddy field or wet land
392 which can be used for paddy farming (so called Le), 2. Upland farming (Yar), 3. Farmland which
393 appears in the floodplain in the Ayeyarwady River as the water recedes (Kaing), and 4. Farmland
394 which appears on the sandbars in the Ayeyarwady River as the water recedes (Kyun) (Fig.2). Farming
395 on flood plains and sandbars of the Ayeyarwady River is of interest due to the relatively good
396 conditions of fertility and access to water for irrigation either directly from the river or from shallow
397 groundwater aquifers. In contrast to the rainfed upland farms, where the groundwater aquifer is drawn
398 out by tube-wells, exploitation of water for irrigation is much easier and less costly.

399 We identified via remote sense analysis that in 2016 roughly 8 % of the area in the central dry zone is
400 alluvial farming land. The amount of farmland used for alluvial farming increased slightly from 1988
401 (3,855 km²) to 2016 (5,511 km²) from 5,6 to 8% of the total farmland. The alluvial land can be used as
402 farmland only during and after the raining season, thus there is only a short cultivation period.

403 About 22% of the annual paddy production of Myanmar is generated within the central dry zone
404 (McCartney et al., 2013). Furthermore, 89% of Myanmar's sesame production, 69% of the groundnut
405 production and 70% of the country's sunflower production are generated within this area (McCartney
406 et al., 2013). Pulses and cotton are other important crops in this region.

407 3.2 Water use and management

408 Myanmar has abundant water resources including both surface and groundwater. The potential water
409 resources volume is estimated to be about 1,000 km³ for surface water and about 500 km³ for
410 groundwater (WEPA, 2014; Oo, 2015). The country's total renewable water resources are 24,352
411 m³/year per inhabitant but only 5% of its physical water resources are used at present (WEPA, 2014).
412 Water utilization for the agricultural sector is about 90% while industry and domestic use is only about
413 10% of the total water use. Due to ongoing and expected future economic development and population
414 growth, it is obvious that the physical potential for further development of water resources is
415 substantial (WEPA, 2014).

416 Several national ministerial departments are responsible for the coordination of water-related issues in
417 Myanmar. There is the Department of Irrigation, the Water Resources Utilisation Department, the
418 Ministry of Rural Development (domestic water), the Ministry of Environmental Conservation and
419 Forestry (MOECAF), and the Department of Meteorology and Hydrology and the Directorate of
420 Water Resources and River Improvement, both associated with the Ministry of Transport.

421 *Central dry zone*

422 Farming in the central dry zone is only possible with irrigation due to the high variability of rain falls.
423 Irrigation in the dry zone has its beginning in the 11th century when weirs and tanks were constructed.
424 The first groundwater and surface water pumped systems were initiated in 1962 and they significantly
425 contribute to increased food security in the central dry zone (McCartney et al., 2013). The annual
426 recharge of groundwater in the dry zone is estimated around 4,770 Mm³ and the annual total use is
427 >770 Mm³ (data from 2000; Johnston et al., 2013). In this region, irrigation is mainly conducted by
428 canal systems from the rivers to the arable land while groundwater withdrawal still plays a minor role.
429 However, the number of pumping systems is increasing, particularly through Chinese investments
430 (Johnston, R., 2015, personal communication). Rainwater harvesting and storage is another simple and
431 common method for domestic and livestock purposes in the villages. During the dry season, village

432 ponds dry out frequently. This problem is often solved by groundwater or river water pumping to the
433 ponds (Johnston et al., 2013), which is in some regions conducted by the local government who sells
434 the water to the villagers (personal communication from a resident in Bagan, 2016).

435 *Ayeyarwady delta area*

436 Embankments, sluice gates and drainage systems have been constructed to protect the agricultural land
437 in the lower delta against saltwater intrusion (van Driel and Nauta, 2013). During the monsoon season,
438 rainwater is stored in drainage canals for the dry period. The gates of the sluices are kept open from
439 mid-May to mid-September in order to control the water level of the drainage canal. Old river courses
440 are functioning as major drainage canals but there are also smaller artificial drainage channels (van
441 Driel and Nauta, 2013). Although these drainage systems are quite proven for a long time, intrusion of
442 saline water is a major concern in this area because of leakages, dam failures or natural hazards such
443 as storm surges and cyclones. During the dry season, irrigation is practiced in the delta by pumping the
444 water from the channels to the paddy fields. In the middle part of the delta, tidal irrigation is
445 extensively practiced and possible due to sufficient flow of river water to the ocean (van Driel and
446 Nauta, 2013).

447 3.3 Hydropower and river flow modifications

448 Myanmar's major rivers are still less regulated compared to other Asian rivers (Hedley et al., 2010).
449 There are currently no dams on the mainstream of the Ayeyarwady River. However, about 1,300 km
450 of embankments were built during the late nineteenth and early twentieth century (Hedley et al.,
451 2010). Between 1988 and 2003, the government of Myanmar has constructed about 150 smaller dams
452 and reservoirs and 265 river water pumping stations along the tributaries (Ministry of Forestry, 2005).
453 The Ayeyarwady River is subject to numerous potential dam projects and seven dams are currently in
454 the planning stage (Allen et al., 2010). Several dams are also planned along the Salween River which
455 likely will impact both the hydrodynamic and the sediment load (Salmivaara et al., 2013). In 2011,
456 planned hydropower dam constructions by the China Power Investment Corporation near Myitsone at
457 the confluence of the Mali and the N'Mai Rivers (Fig.2) were halted due to peaceful public protests as
458 well as armed resistance (Burma Rivers Network, 2014). The dam was intended to build 152 m high
459 and it was envisaged to inundate 47 villages and to displace ca. 10,000 people in the Kachin State
460 (Burma Rivers Network, 2014). Another critical point is that the northern part of the country is prone
461 to earthquakes and a broken dam would have catastrophic impacts on downstream areas and the city of
462 Myitkyina, the capital of the Kachin State (Burma Rivers Network, 2014). It is expected that building
463 larger dams will come along with social impacts like displacements, food security, health concerns,
464 and the loss of culture (Smakhtin and Anputhas, 2006; Burma Rivers Network, 2014). Myanmar has
465 experienced a rapid growth of hydropower capacity with a potential of almost 40,000 MW, of which

466 only 6% have been developed. Hydropower supplies the majority of the electric exports supported by
467 foreign investments (ADB, 2012; Kattelus et al., 2014).

468 River flow modifications lead to changes in the composition and diversity of aquatic communities.
469 Aquatic species have evolved life history strategies primarily in response to the natural flow regimes.
470 Therefore, flow regime alterations can lead to loss of biodiversity of native species (Smakhtin and
471 Anputhas, 2006). Dam building results in a range of upstream and downstream impacts, not least
472 disruption of migratory routes and of breeding patterns (Nilsson et al., 2005). Water abstraction and
473 damming are one of the major threats to freshwater biodiversity (Allen et al., 2010). In the deltas,
474 mangrove forests rely on the non-saline water from rivers. Any reduction in the volume of sweet-water
475 to their roots causes mangroves to dry up, resulting in salt-water intrusion, and subsequent soil-
476 erosion. It is further assumed that the construction of dams would accelerate the deforestation in the
477 Salween River basin, with severe negative effects on biodiversity and the dense dry deciduous forests
478 also called teak forest, which is crucial for the livelihood function of local ethnic people (Salween
479 Watch and SEARIN, 2014). In general, the full scope and scales of potential environmental and
480 ecological impacts from dams is largely uncertain due to the complexity of feedback mechanisms and
481 system response (Fan et al., 2015), particularly in regions where the rivers play such an important role
482 like in Myanmar. Dams will alter the river flows as well as the sediment load, which will impact the
483 further development of the Ayeyarwady delta. For the navigability of the rivers and the canals, a
484 decrease of the sediment load would be a favourable effect of dam building.

485 China has an increasing interest in covering its energy demand, forced by the international community
486 to get out of CO₂-emission intensive power generation. Making investments in hydropower in
487 Myanmar in order to provide energy for the western part of China solve these challenges for now. At
488 first glance, both nations benefit from this energy trade. Building dams could potentially increase the
489 irrigation opportunities, particularly in the central dry zone of Myanmar. It would enhance navigation
490 possibilities and provide flood control (Lu et al., 2014). On the one hand, the energy trade is an
491 economic and political opportunity because it must be based on cooperation between Myanmar and its
492 neighbouring countries and counters the isolation status which is partly still existent (Kattelus et al.,
493 2015). On the other hand, damming Myanmar's rivers could have very serious negative effects on the
494 river biodiversity and the stability of the deltas (Hedley et al., 2010). A decreasing supply of the fertile
495 alluvial sediments would modify the availability of agricultural land in an unknown dimension. It is
496 expected that deforestation would further increase in the dam building areas as a result of
497 infrastructure plans, with severe impacts on local biodiversity, local people, hydrology and on regional
498 and even global climate.

499 India, Bangladesh, China and Thailand have different interests in Myanmar's water resources and all
500 of them are involved in diverse hydropower project plans. These natural resources as well as
501 Myanmar's convenient geographical and strategic geopolitical location will possibly strengthen the
502 country's economic and politic role in Southeast Asia. Negative aspects of hydropower development
503 are the risk of rising conflicts between ethnic minorities and the military (Burma Rivers Network,
504 2014) and also between Myanmar and neighbouring countries due to differing interest and needs of
505 the water resources.

506 3.4 River ecology protection

507 All aspects of water resources conservation are unified in the Conservation of Water Resources and
508 Rivers Law, enacted in 2006. It aims to conserve and protect all water resources and river systems for
509 beneficial utilization by the public, to protect the environment, to smooth and safety waterways
510 navigation along rivers and creeks and to contribute to the development of State economy through
511 improving water resources and the river system (The Union of Myanmar, 2006). Mining within 100 m
512 of the Ayeyarwady, the Salween, the Chindwin and the Sittaung rivers is banned by the Ministry of
513 Mines (Schmidt, 2012). However, despite these ambitious laws, freshwater diversity, including inland
514 wetlands, estuaries and mangroves, appear to be limitedly protected in Myanmar (Salmivaara et al.,
515 2013).

516 In 2013, a National Water Resources Committee (NWRC) has been established by a Presidential
517 decree. The NWRC stated that the weak cooperation between the water-related agencies in Myanmar
518 is the major problem (Win, 2014). The committee follows the vision "*In 2020 Myanmar will become*
519 *water efficient nation with well developed and sustainable water resources based on fully functional*
520 *integrated water resources management system*" (Win, 2014). The NWRC concludes that more
521 research is needed to solve the problems in Myanmar's river basins (Win, 2014).

522 4 Climate change impacts and future perspectives

523 Only very few studies on climate change impact assessments in Myanmar have been conducted so far
524 (Shrestha et al., 2014). During the past decades, inter-seasonal, interannual and spatial variability in
525 rainfall has been observed across all Southeast Asian countries (IPCC, 2014). However, detailed
526 studies for Myanmar in particular are lacking, but a similar pattern can be assumed due to the
527 influence of the same monsoonal atmospheric circulation system. A substantial inter-decadal
528 variability exists in the Indian monsoon circulation which is particularly crucial for the central dry
529 zone (IPCC, 2014). Extreme weather events have become more frequent and intense during the last
530 decades related to their direct impacts on socio-economy what could also be detected for Myanmar
531 (GCCA, 2012). Most likely, the intensity and frequency of droughts in the dry zone particularly during

532 ENSO events will increase (IPCC, 2014). Variability of river runoff and changes in seasonality are
533 expected for Southeast Asia as a result of climate change (IPCC, 2014). Sea level rise, decreasing river
534 runoff and increasing intensity and frequency of droughts will lead to even more increased saltwater
535 intrusion into river deltas. In the medium term, enhanced glacier and snow melt in the source areas of
536 rivers will cause generally higher discharges and potential floods. However, individual glaciers are
537 currently advancing or stable in Asia depending on their particular features (Scherer et al., 2011).
538 Studies on the glaciers feeding the Ayeyarwady have not been conducted yet. The low-lying
539 Ayeyarwady delta is particularly exposed to sea-level rise and vulnerable due to its high food
540 productivity and population density. It is assumed that a 0.5 m sea-level rise would advance the
541 shoreline along the Ayeyarwady delta by 10 km inland (NAPA, 2012). Changes in river flow will
542 likely increase the risk of flash floods and lowland regions will be regularly inundated (NAPA, 2012).
543 Furuichi et al. (2009) showed a decrease of the annual discharge of the Ayeyarwady River over the
544 last 100 years based on a statistical comparison with data collected in the 19th century, but the driving
545 forces remain unclear. The central dry zone experienced higher maximum temperatures and lesser
546 rainfall in the 1990s compared to other regions in Myanmar (Ministry of Forestry, 2005). This is
547 hypothesized as a result of anthropogenic climate change and global warming (Ministry of Forestry,
548 2005). Increasing temperatures in this region will raise the concentration of dissolved salts in the
549 ponds, channels and other storage systems resulting in a reduction of drinking water (NAPA, 2012).

550 Climate change is expected to exacerbate existing threats to biodiversity in Myanmar through its
551 impacts on humans and their dependence on products and services produced by freshwater ecosystems
552 (Rao et al., 2013). Changes of rainfall regimes, air and water temperature and evapotranspiration will
553 affect distribution and abundance of freshwater species in unknown ways (Rao et al., 2013).
554 Particularly the Ayeyarwady River basin will most likely be affected by population growth,
555 urbanization, land use change and climate change in the future (Bates et al., 2008; Salmivaara et al.,
556 2013). Rao et al. (2013) concluded, based on findings from Iwamura et al. (2010), that the
557 Ayeyarwady dry forest located in the central river basin is particularly prone to future changing
558 rainfall and temperature conditions. The authors expect that the seasonal amount of rainfall will
559 decrease which will exacerbate the already water-stressed region (Rao et al., 2013).

560 Continuing loss of natural forest cover and mangrove habitats can influence processes affecting
561 climate change by release of CO₂ to the atmosphere (Van der Werf et al., 2009). It can be summarized
562 that climate change most likely will impact the river basin ecosystems in Myanmar in a so far
563 unknown dimension through modification of seasonal flow regimes and the timing, extent and
564 duration of floods and droughts. Climate change projections and scenarios have not yet been
565 developed for Myanmar in particular. There are numerous assumptions and expectations but no

566 detailed data for the country. This lack of future assessments is also a result of the nonexistence of
567 paleoclimate data.

568 Due to the lack of scientific research in the country, often uncertain or incomplete data bases and rapid
569 political and economic changes, future perspectives for human-water dynamics in Myanmar's river
570 basins can only be assessed with high uncertainties. However, it should be possible to indicate the
571 major drivers of future changes. Undoubtedly, the availability and quality of freshwater is and will be
572 the core of the country's future development but increasing conflicts on water may arise due to
573 growing foreign investments and various international and national interests.

574 Findings from Salmivaara et al. (2013) indicate that the Ayeyarwady delta, the Salween river mouth
575 and the central lowlands in the Ayeyarwady River basin are under the highest pressure as a result of
576 intensive land use, high population density and vulnerability to water pollution. These regions are
577 most likely to be exposed to further pressures such as urbanization, land use change and climate
578 change (Bates et al., 2008). Major challenges for the Salween river basin will be linked to extensive
579 dam projects (Burma River Networks, 2014; Kattelus et al., 2014). The major challenges for Myanmar
580 are seen in covering the balance between national societal, economic and political development and
581 the urgent need to protect and conserve its water resources and biodiversity.

582 **5 Selection and identification of human-water dynamic key indicators**

583 Human-water dynamics include one-way causal chains as well as complex feedback mechanisms.
584 Particularly in a country like Myanmar where water plays such a major role in people's life, detailed
585 knowledge and understanding of human-water interactions is essential in order to evaluate possible
586 future developments. This knowledge is crucial for a proper and sustainable water management that
587 meets the social, the environmental, economic and the political interests. Our first step for future
588 human-water dynamic studies in Myanmar is therefore the selection and identification of
589 environmental key indicators based on the reviewed literature within the here presented paper and
590 based on own observations during field studies. Environmental key indicators provide information on
591 complex issues in a simplified manner and characterize major causal impact-response chains. They
592 can be used for future development assessments and current state analyses.

593 For the here presented study, the eDPSIR (enhanced driving force-pressure-state-impact-response)
594 concept by Niemeijer & de Groot (2008a, b) is seen as a suitable framework to structure the selection
595 of relevant environmental indicators. This framework is an enhancement of the DPSIR (driving force-
596 pressure-state-impact-response) approach which has been applied to several water-related
597 environmental studies in order to identify causal chains (e.g. Pirrone et al., 2005; Kagalou et al., 2012;
598 Pinto et al., 2013; Geng et al., 2014). The advantage of an enhanced DPSIR application is that this

599 framework is causal network based and includes the interrelations and feedbacks between various
600 causal chains within a system. First, we follow the steps to build a causal network proposed by
601 Niemeijer & de Groot (2008):

602 *Step 1: Broadly define the domain of interest:* Human-water interactions in Myanmar's river basins

603 *Step 2: Determine boundary conditions:* Socio-hydrological system in the humid tropics, monsoon
604 influenced

605 *Step 3: Determine the boundaries of the system:* In situ situation in the river basins with particular
606 focus on the Ayeyarwady River basin

607 *Step 4: Identification of abstract indicators for the main factors and processes:* (Table 1). Energy
608 needs, land use intensification, increase of atmospheric CO₂, global warming, expansion of industrial
609 zones and demand for wood are examples for driving forces in Myanmar's river basins. These drivers
610 create pressures which in turn modify the state of e.g. river discharge, soil degradation, water quality,
611 and so on. Changes in the state of e.g. water quality impact aquatic biodiversity and the availability of
612 drinking water. The last row, responses, has been omitted since this aspect is not in the focus of this
613 paper and particular responses of the society or government have to be studied in the future more in
614 detail.

615 *Step 5: Iteratively mapping the indicators in a direction graph:* Fig. 3 shows a causal network of
616 selective indicators for human-water interactions in Myanmar. There is no claim for completeness
617 regarding the specific links and feedbacks. It is a first attempt to structure the relationships between
618 and within water-related social and physical-environmental indicators in Myanmar's river basins.

619 Fig. 3 demonstrates the complexity of a causal network of indicators for human-water dynamics in
620 Myanmar. Mapping this network helps to identify important nodes and to structure further study
621 approaches. Runoff for example seems to be an important end-of-chain node (cf. Niemeijer & de
622 Groot, 2008a, b) as well as fish population, which is indicated by many incoming arrows, whereas
623 dam and reservoir building and deforestation represent a central node with several incoming and
624 outgoing arrows. It is challenging to identify a typical root-node indicated by many outgoing arrows.
625 Climate change might be a root-node within this network. It is undoubtedly triggered by human
626 activities, though rather on a larger spatial scale and the impact of the Burmese people on global
627 climate change is comparatively small at least at the current state.

628 Furthermore, Fig.3 clearly exhibits that studying human-water interactions essentially need the input
629 from social as well as from natural science and it is indispensable that experts from both disciplines
630 exchange their knowledge and work together on the same research questions.

631 *Alluvial framing as an example for human-water dynamics within the Ayeyarwady River basin*

632 Alluvial farming can be seen as a demonstrative example for human-water dynamics in the dry zone of
633 Myanmar. Assuming that climate variability in terms of (monsoon) precipitation variability is one of
634 the root-node indicators of human-water dynamics in Myanmar, changes of precipitation amounts or
635 timing cause high hydromorphological and sedimentation dynamics in the Ayeyarwady River. Lower
636 rainfall amounts or dry periods result in lower river discharge and foster the accumulation of sandbars
637 in the river bed. Moreover, land use changes and forest logging have an additional influence on
638 sedimentation loads in the river and creates new fertile floodplains. Most likely, these processes have a
639 visible impact on alluvial farming in the dry zone because more fertile arable land with good access to
640 irrigation water is available. This is of even higher importance in the light of increase of dry spells and
641 changed timing of the monsoon rain in the dry zone. Our remote sensing analysis shows an increase of
642 alluvial farming by 1,656 km² (almost 70%) since 1988. Most of the alluvial farmers grow crops like
643 onions because of market prices, suitability to alluvial land, and short term benefits (personal
644 communication with citizen of the dry zone). Concurrently small scale alluvial farming implies a
645 potential higher flood risk and related crop failure and loss of yields for the farmers and livelihoods of
646 their families and communities. However, if and how these observations are actually an impact-chain ,
647 has to be investigated and is subject for further research.

648 **6 Conclusions**

649 Myanmar's economy and the people's income and well-being strongly depend on the quality and
650 availability of sufficient water resources. The delta region of the Ayeyarwady River and the central
651 dry zone are the areas most populated and most intensely used by agriculture in the country. On the
652 one hand, the farmers depend on frequent river flood events because the river provides fertile alluvial
653 soils; on the other hand, they suffer from water-related extreme events such as floods or drought
654 periods. It is expected that these climatic extreme events will likely increase in frequency and
655 magnitude in the future as a result of climate change. Different national and international interests in
656 the abundant water resources may provide opportunities and risks at the same time for Myanmar.
657 Several dam projects along the main courses of the major rivers are currently in the planning phase.
658 Dams will most likely modify the river flows, the sediment loads and also the still rich biodiversity in
659 the river basins, in a still unknown dimension. On the other hand, these foreign investments allow the
660 development of infrastructure and probably stabilize the political relations between Myanmar and its
661 neighbouring countries and strengthen its role in Southeast Asia and even globally.

662 All authors of the reviewed literature agree that Myanmar is facing big water-related challenges.
663 However, future perspectives and developments are mostly still intangible due to the large gap of
664 research in the country and the limited detailed knowledge about the status-quo. More in-depth
665 qualitative and especially quantitative analyses on human and climate impacts on Myanmar's water

666 resources are strongly required in order to adapt water and land management to current and future
667 climate change. The year 2008 was a kind of turning point when cyclone *Nargis* made landfall in the
668 Ayeyarwady delta region. Since then, a number of action plans have been established with the aim to
669 call attention on extreme weather events. Furthermore, the vulnerability of the Burmese people is
670 increasing because population pressure is forcing more people to live and work in coastal zones and
671 river basins. The central dry zone and the delta zone are the most vulnerable parts of the river basin
672 related to climate change and also to human impact.

673 Relevant aspects for future development of Myanmar's river basins combine environment-water-
674 related indicators, climate, economic and social development, water management and land use
675 changes. Research on this interplays need to capture the spatial and temporal dynamics of this drivers.
676 Yet, it is only possible to gain a full understanding of all these complex interrelationships, when multi-
677 scale spatiotemporal information will be analysed in an inter- and transdisciplinary approach. The
678 eDPSIR approach is considered to be a suitable starting point for human-water research in Myanmar.
679 The here presented indicator scheme (Fig.3) was a first attempt to structure the reviewed information
680 and to provide a first assessment on relevant indicators and key nodes on the socio-economic as well
681 as on the physical side. Alluvial farming is a suitable example for human-water dynamics in
682 Myanmar's central dry zone and it could be demonstrated that the share of alluvial farmland increased
683 by 70% since 1988 in this region. We hypothesize that the increase of alluvial farming is an effect of
684 hydromorphological impacts (potentially enhanced by human interventions like forest clearing).
685 Concurrently this land is largely used because of relatively good farming conditions (fertile soils and
686 good access to water for irrigation) compared to upland farmland in the central dry zone especially in
687 light of the difficult climate conditions. However, increased alluvial farming increases the potential
688 flood risk for the farmers' livelihoods. Yet, this hypothesis has to be investigated in further studies.

689

690 **Acknowledgements**

691 The authors are grateful to Stephan Opitz (University of Cologne) and Henrik Bours (University of
692 Bonn), whose critical comments helped to improve the manuscript. Adrian Almoradie (University of
693 Bonn) assisted the preparation of the overview map. Furthermore, we thank Mukesh Boori (Samara
694 State Aerospace University Russia) for the remote sensing analysis on alluvial farmland. The research
695 was funded by the German Science Foundation (DFG). The authors would like to thank three
696 anonymous reviewers for their useful comments on earlier versions of this manuscript.

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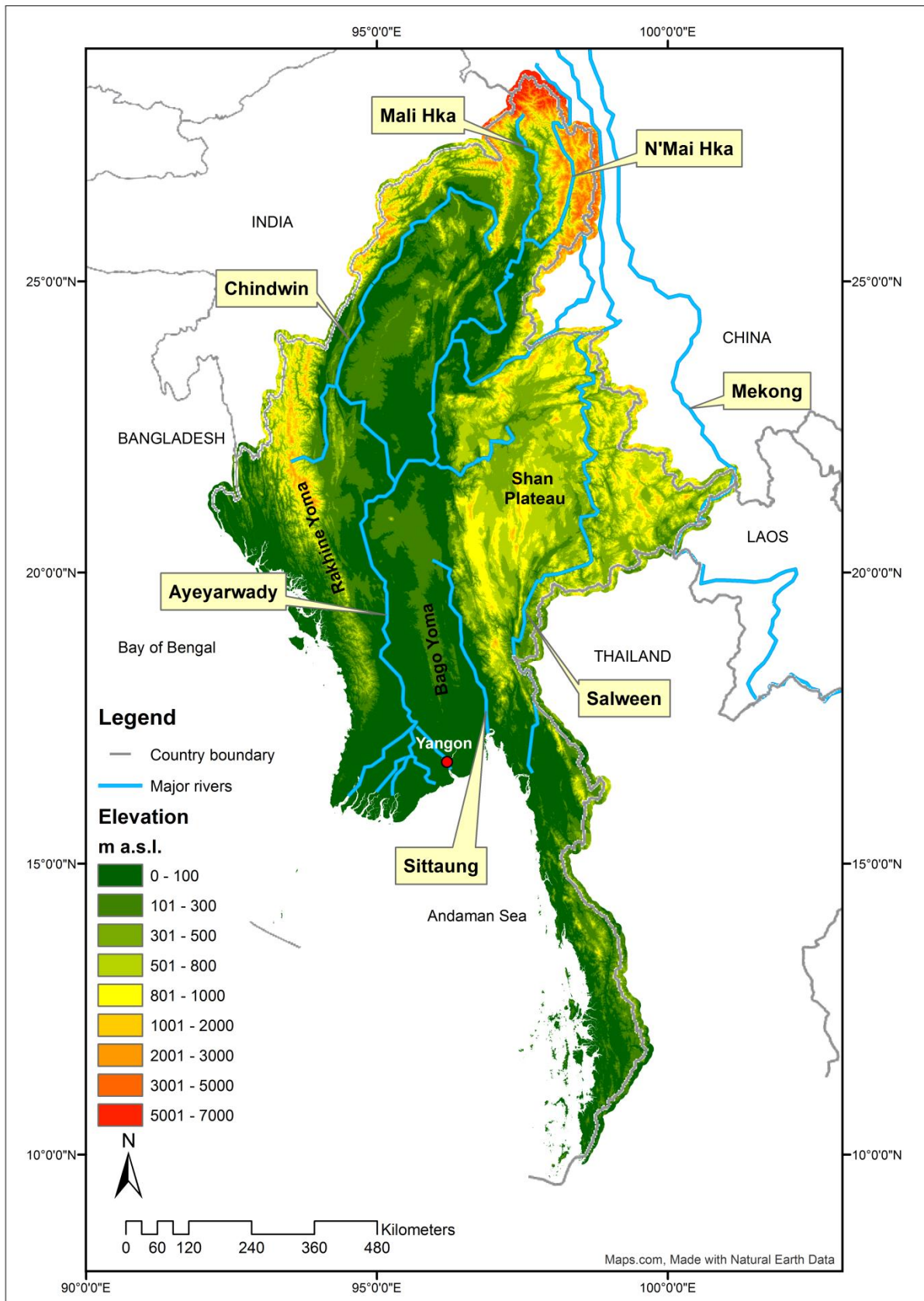
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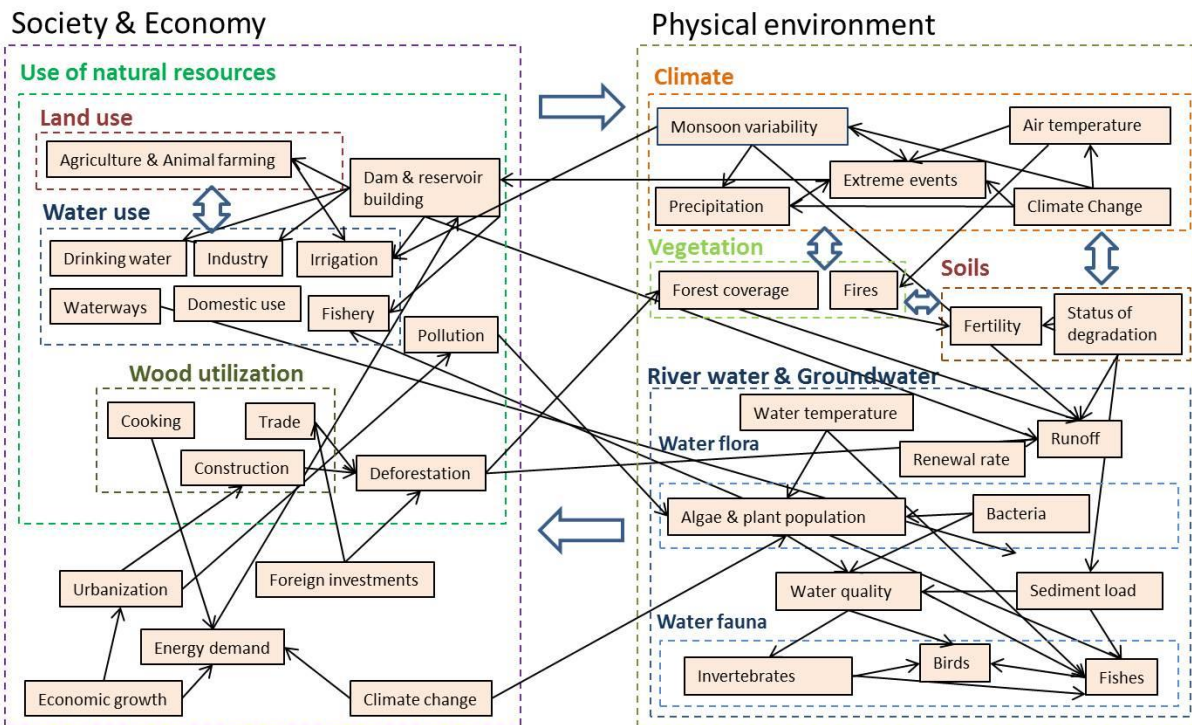
946 **Figure 2**



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949 **Figure 3**



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956 **Figure captions**

957 Fig.1: Physical overview map of Myanmar including state border lines, major rivers and mountain
 958 ranges.

959 Fig.2: Left: Example of Kaing farming (farmlands which appear in the flood plain in Ayeyarwady
 960 River) in Magway district (Chauk). Right: Example of Kyun farming (farmlands which appear on
 961 sandbars in Ayeyarwady River) in Pakkoku township. Pictures taken by M. Evers

962 Fig. 3: A causal network to demonstrate specific (thin black arrows) and general (large blue arrows)
 963 links between and within water-related social and physical-environmental indicators in Myanmar's
 964 river basins.

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966 **Table 1: Selection of general indicators within the DPSIR framework. Respective responses are not listed**
 967 **because they are subject of our future research and will be studied more in detail.**

Driving force	Energy demand	Land use intensification	Increase of atmospheric CO ₂		Industrialisation	Demand for wood /wood trade
Pressure	Building hydropower dams	Increase of water withdrawal and groundwater pumping	Increase of temperature and evaporation		Polluted sewage release	Deforestation
State	Change of river flow	Decrease of groundwater level	Change of precipitation (monsoon) patterns	Increase of glacier melt	Deteriorating of water quality	Soil degradation
Impact	Biodiversity Fish migration	Shortage of groundwater	Longer dry periods, droughts, higher maximum temperatures	Seasonal shift in river discharge Agriculture, biodiversity	Availability of water in good quality for humans and agricultural use, biodiversity	Increase of erosion processes and sediment load in the rivers

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