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

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Abstract

Rivers provide a large number of ecosystem services and riparian people depend directly and indirectly on water availability, quality and quantity of the river waters. The country's economy, the people's well-being and income particularly in agriculturally dominated countries is strongly determined by the availability of sufficient water. This is particularly true for the country of Myanmar in Southeast Asia, where more than 65 % of the population live in rural areas, working in the agricultural sector. Only few research exist on river basins in Myanmar at all and sound knowledge is very limited. Though detailed knowledge and understanding on human-water dynamics in the country is required because Myanmar's society, economy, ecosystems and water resources are facing major challenges due to political and economic reforms and massive and rapid investments from neighbouring countries. However, not only policy and economy modify the need for water. Climate variability and change is another essential driver within human-water systems. Myanmar's climate is influenced by the Indian Monsoon circulation which is subject to interannual and also regional variability. Particularly the central dry zone and the Ayeyarwady delta are prone to extreme events such as serious drought periods and extreme floods. On the one hand, the farmers depend on frequent river flood events for irrigation; on the other hand, they suffer from these water-related extreme events. It is expected that theses climatic extreme events will likely increase in frequency and magnitude in the future as a result of climate change. Different national and international interests in the abundant water resources may provide opportunities and risks at the same time for Myanmar. Several dam projects along the main courses of the rivers are currently in the planning phase. Dams will most likely modify the river flows, the sediment loads and also the still rich biodiversity in the river basins, in a still unknown dimension.

Relevant aspects for future development of Myanmar's river basins combine environment-water-related factors, climate, economic and social development, water management and land use changes. Research on this interplays need to capture the

spatial and temporal dynamics of this drivers. Yet, it is only possible to gain a full understanding of all these complex interrelationships, when multi-scale spatiotemporal information will be analysed in an inter- and transdisciplinary approach. This paper gives a structured overview on the current scientific knowledge available and reveals the relevance of this information with regard to human-water/human-environment interactions in Myanmar's river basins.

1 Introduction

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

The country's economy, the people's well-being and income particularly in agriculturally dominated countries strongly depend on the availability of sufficient water. This is particularly true for the country of Myanmar in Southeast Asia, where more than 65 % of the population live in rural areas, working in the agricultural sector (FAO, 2014). The Ayeyarwady River catchment covers 413 700 km^2 which represents about 61 % of the country. Thus it is the most important river system in Myanmar. The mighty Ayeyarwady River is called the life line of the nation because it serves for transportation, domestic

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

Only few research exist on river basins in Myanmar at all and sound knowledge is very limited (e.g. Varis et al., 2012; Salmivaara et al., 2013). However, more research on human-water dynamics in the country is strongly required because Myanmar's society, economy, ecosystems and water resources are facing major challenges due to political and economic reforms, massive and rapid investments from neighbouring countries (particularly from China and Thailand; Webb et al., 2012) and climate change

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impacts. There is a large number of grey literature such as reports and workshop presentations from NGOs, political institutions and Burmese and international organizations, dealing with human and climate impacts and the water resources in Myanmar. However, systematically compiled English scientific publications on this topic have not been published yet. Hence, English grey literature and peer-review publications on current and likely future impacts from human activities and climate change on Myanmar's river basins have been reviewed in order to gain an overview on the key drivers in these human-water dynamics.

To better understand the dynamics, feedbacks and interactions of coupled human-water systems, Sivapalan et al. (2011, 2014) have proposed the socio-hydrology as a new science of people and water. This concept accounts for the dynamics of interactions between water and people and focuses on observing, understanding and predicting future conditions of the co-evolution of coupled human-water systems (Sivapalan et al., 2011). The conceptual framework of this approach (Fig. 1) is organized along three aspects, namely (a) multiscale water system structure and dynamics; (b) water-related human well-being outcomes and c) normative goals, values and norms of individuals and whole societies with respect to water use (Sivapalan et al., 2014). This framework has been adopted to structure the review on human-water dynamics in Myanmar's river basins because this concept appears to be suitable to cope with gradients of climate, socioeconomic status, water management and ecological aspects (Sivapalan et al., 2014). We hypothesise that all components within the Burmese river basins interact and that the degree of interactions between driving forces and feedbacks permanently change. The socio-hydrologic approach has the potential to be the appropriate framework to structure current available knowledge on major components in the river basins as a first step for better understanding the system. A future detailed study in the "real-world system" (Sivapalan et al., 2014) of Myanmar is planned to be conducted in order to test this approach.

A further aim of this review was to compile the natural given physical conditions in order to make this information internationally accessible in a scientific status-quo re-

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view paper. The review starts with the water system structure and dynamics including physical features, current climate conditions and the description of the biodiversity in Myanmar, followed by the physical characters of the river basins with focus on the Ayeyarwady River. Furthermore, human impacts on the river basin comprising water and land use, water resources management and deviating interests related to river waters and possible climate change impacts on Myanmar's rivers have been reviewed. Open research gaps concerning human-water dynamics in Myanmar and recommendations for research approaches are elaborated in the end. The question if the socio-hydrology approach is well applicable to Myanmar's river basins or if and what kind of adaptions are required will be answered.

2 Structure and dynamics

The first aspect of the socio-hydrological framework is related to multiscale water system structures and dynamics across sectors, scales and biophysical, socio-economical and institutional sub-systems (Sivapalan et al., 2014). For the case of Myanmar, these aspects include the basic physical features of the country, climatic conditions and hydrologic information on the river basins.

2.1 Physical features

The Republic of the Union of Myanmar (9°55′–28°15′ N, 92°10′–101°11′ E) is the largest Southeast Asian country located between Bangladesh and India to the west, China to the north and northeast, Lao and Thailand to the east and the Bay of Bengal and the Andaman Sea to the south and southeast. The maximum north-south extent is about 2500 km and the maximum west-east extent is ca. 900 km. The country slopes downward in elevation from north to south and the central lowlands are surrounded by steep mountain ranges (Fig. 2). Three mountain ranges trending from north to south, namely the Rakhine Yoma (the term Yoma means mountain range), the Bago Yoma

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and the Shan Plateau (from west to east), divide the country (Fig. 2). The Rakhine and the Bago mountain ranges have been thrusted up through the collision of the Indian-Australian and the Eurasian plate since the past 50 million years (Bender, 1983). The Shan Plateau was already formed during the Mesozoic Era. The topography can be divided into five sub-regions: (1) the northern mountains including the highest point of Myanmar Mount Hkakabo Razi (5881 m a.s.l.); (2) the western Rakhine ranges; (3) the eastern Shan Plateau; (4) the central basins and lowlands and (5) the coastal plains including the wide Ayeyarwady delta. The central basin lies between the western Rakhine ranges and the eastern Shan Plateau in the rain shadow of the monsoon precipitations. The coastline has a length of about 3000 km and there are numerous islands of varying sizes along (Oo, 2002).

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

2.2 Climate

The naturally given climate conditions, in terms of precipitation, temperature, evaporation and general atmospheric circulation, largely influence anthropogenic use and human behaviour like land use, urbanisation, resources management, societal development. On the other hand, anthropogenic activities influence the natural conditions such as emission of greenhouse gases or forest clearance and land use change. Climate includes variabilities of short- and long-term atmospheric conditions as well as trends and weather extreme events in the here presented context.

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

Palaeoclimate research in Myanmar is very scarce, although findings about past monsoon variabilities in this region would definitely contribute to a deeper understanding of this atmospheric circulation which is not only significant for the people's lives in Myanmar but also in SE-Asia and even worldwide. There are teak tree ring chronologies covering the last three centuries in Myanmar (D'Arrigo et al., 2011; D'Arrigo and Ummenhofer, 2015). Following these studies, the tree-ring records show monsoon rainfall variabilities consistent with results from surrounding countries, indicating that Myanmar is influenced by the same circulation system.

2.2.1 Precipitation

Myanmar's climate is largely influenced by the Indian summer monsoon as well as from convective rainfall from the Bay of Bengal (Sen Roy and Kaur, 2000; D'Arrigo et al., 2011; Htway and Matsumoto, 2011; Sein et al., 2015). The patterns of rainfall indicate considerable complexity, particularly in summer, when Indian and East Asian monsoon circulations interact (D'Arrigo et al., 2011). Already Maung (1945) researched on forecasting the coastal monsoon rainfalls in Myanmar; however, his study does not include a detailed description of the general climatology. Sen Roy and Kaur (2000)

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gave an overview on the climatology of monsoon rains of Myanmar using 33 years (1947–1979) of station level monthly data. After this study, about 75 % of the country's annual average rainfall is from June to September (Sen Roy and Kaur, 2000). Sein et al. (2015) concluded that the summer monsoon accounts for almost 90 % of Myanmar's observed rainfall. The monsoon rains reach the southern part of Myanmar by around the third week of May and cover the entire country by the beginning of June (Sen Roy and Kaur, 2000). Results of a study by Sen Roy and Sen Roy (2011) showed the existence of five homogenous precipitation regions, namely, north, west, central, east and south Myanmar. Thereby, the amount of annual precipitation varies between 500–1000 mm in the central dry zone (Johnston et al., 2013; FAO, 2015) and up to 4000–6000 mm at the western coast (MOAI, 2001; FAO, 2015). The central dry zone lies in the rain shadow of the Rakhine Mountains located along the western coastline (Fig. 2). This area receives only 3.2 % of the country's total rainfall (Ministry of Forestry, 2005). Easterly winds and local depressions in the Gulf of Thailand can cause post-monsoon rains from mid-October to end-November (MOAI, 2001; Sein et al., 2015).

A correlation between El Niño-Southern Oscillation (ENSO) and the variability of Asian monsoon intensity has been discussed elaborately during the last decades (e.g. Kumar et al., 1999; Torrence and Webster, 1999; Xavier et al., 2007; Li and Ting, 2015). All these studies conclude a significant correlation between both atmospheric circulations. Current research from Sein et al. (2015) indicated that El Niño events result in drought periods in Myanmar, while La Niña events result in floods due to intensified monsoon rains. Sen Roy and Kaur (2000) noted that even though India and Myanmar are geographical neighbours and are influenced by the same monsoon system, Myanmar's rainfall seems to have no significant relationship with the rainfall of Northern India. This pattern might be due to the fact that the Rakhine Mountains (< 3800 m a.s.l.) located in the western part of Myanmar redirect the wind flows. In contrast, D'Arrigo et al. (2011) detected a positive correlation of monsoon variability in Myanmar with the monsoon larger scale indices over northeastern India based on teak tree ring chronology for the last three centuries. These contrary findings highlight the urgent need for more climate research in Myanmar.

2.2.2 Temperature

The average temperature varies from 21–34 °C in summer and from 11–23 °C in the cool season, depending on location and elevation. The mean relative humidity ranges between 58 and 79 % (Ministry of Forestry, 2005). Average diurnal temperatures show little variation across the country ranging from 26–28 °C between Sittwe in the western region, Yangon near the southern coast and Mandalay in the central dry zone. During the rainy season, the diurnal temperatures range between 25–33°C and from 10–25 °C during the cooler winter season. Between mid-April and mid-May, the maximum temperatures rise continuously in the whole country (Htway and Matsumoto, 2011). The maximum diurnal temperatures in the central dry zone can reach > 43°C in the hot season prior to the monsoon season (Aung, 2002). In this area, the mean monthly potential evapotranspiration exceeds the mean monthly rainfall.

2.3 Hydrogeography

Major rivers are the Ayeyarwady, the Thanlwin, the Chindwin and the Sittaung. All these rivers are understudied river basins (Salmivaara et al., 2013), despite their great importance for the Burmese people's life and the nation's economy. The north-south trending courses of most of the Burmese rivers are geologically predetermined following the mountain ranges Rakhine, Bago and the Shan Plateau (Fig. 2). For about 230 km, the transnational Mekong River forms the border between Burma and Laos.

The Ayeyarwady River (also referred to as Irrawaddy River) is Myanmar's most important commercial waterway (Thanlwin Watch and SEARIN, 2004). It is about 2170 km long and originates at the confluence of the Mali Hka and N'Mai Hka rivers in the northern Katchin state (Fig. 2). The headwaters of both rivers originate in the eastern syntaxis of the Himalayas and the Tibetan Plateau in Yunnan Province, China. The river

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basin of the Ayeyarwady covers around 413 700 km^2 of which 95 % is located in Myanmar (Salween Watch and SEARIN, 2004; Bird et al., 2008). The broad fertile lowland floodplain is extensively used for agriculture. The river is fed by glacial meltwater in the source areas of the Mali Hka and N'Mai Hka rivers as well as by precipitation. The average annual discharge is > 420 km^3 and 71 % of it occurs between July and October (Robinson et al., 2007; Furuichi et al., 2009). The Ayeyarwady has the fifth highest sediment load of any major river worldwide (Furuichi et al., 2009; The World Bank, 2014). Furuichi et al. (2009) estimated the suspended sediment load to be 325 ± 57 × 106 t annually. However, the river is navigable year-round for ca. 1500 km from Yangon, but sandbanks and shallow sections make it often difficult to navigate during the dry season (Lwin, 2014). The basin's ecosystem is very rich and dynamic and the river is home to the endangered "Irrawaddy dolphin" (Smith et al., 2009; Aung et al., 2013).

With a total length of about 2800 km the transboundary Thanlwin River is one of the longest rivers in Southeast Asia. However, it is navigable for only ca. 150 km from its delta due to its rapids and deep gorges (Salween Watch and SEARIN, 2004). Annual runoff is ca. 210 km^3 (Robinson et al., 2007). The source of the river is located on the Tibetan Plateau and subsequently the water flows through Yunnan Province in China to the eastern part of Myanmar where the Salween drains the Shan Plateau. For ca. 120 km, the river forms the border between Myanmar and Thailand until it flows to the Andaman Sea in the Gulf of Martaban (Salween Watch and SEARIN, 2004; Fig. 2). The river basin covers 320 000 km^2 and has one of the most diverse ethnic concentrations worldwide (Salween Watch and SEARIN, 2014). Furthermore, the basin is very rich in natural resources including surface and groundwater, forest, wildlife, fisheries and minerals (FAO, 2011).

The Chindwin River exists since at least the Eocene and is the largest tributary of the Ayeyarwady (Hedley et al., 2010). It has a length of about 1200 km (Salween Watch and SEARIN, 2014). The Chindwin rises in the Kumon Range in northern Myanmar and reaches the Ayeyarwady near Mandalay in the central dry zone. For about 600 km the river is navigable from its confluence with the Ayeyarwady River (Ministry of Forestry, 2005). Most of its course has not been studied yet due to the difficulty of access (Salween Watch and SEARIN, 2004).

The Sittaung River originates at the southern edge of the Shan Plateau and drains after 420 km into the Gulf of Martaban of the Andaman Sea (Salween Watch and SEARIN, 2004). Year-round, the Sittaung River is navigable only for 40 km and for 90 km during the rainy season. It is mainly used for floating teak wood for export to the souths. At its lower course, the river is linked by a canal to the Bago River, located in Yangon (Fig. 2).

The Ayeyarwady delta is one of the major tropical deltas worldwide (Hedley et al., 2010). Its modern extensive wedge-shape originated around 7000–8000 years ago and it comprises >20 500 km^2 of flat, low-lying fertile delta plain with five major tributaries (Hedley et al., 2010; Woodroffe, 2000). The delta area is densely populated and continues upriver at sea-level for more than 200 km (Webster, 2008). The delta plain hosts a fragile and complex ecosystem of mangrove swamps and tidal estuaries (Salween Watch and SEARIN, 2004). Mangrove forests play an important role in delta evolutions because they act as sediment traps, primary colonisers and bio shields against impacts of cyclones and tsunamis. However, the ecological status of the Ayeyarwady mangroves is continuously declining due to increasing rice production, land use changes and population growth (Ministry of Forestry, 2005; Webb et al., 2014). The Ayeyarwady delta is under intensive land use and the population density is the highest in the entire country (Salmivaara et al., 2013). Saline water penetrates up to 100 km upstream due to tidal influences (Aung, 2003 in Hedley et al., 2010). Drainage, flood protection and salt intrusion are major concerns in the Ayeyarwady delta (FAO, 2015). The Salween River has rather a river mouth than a clearly developed delta and is less populated. However, the Thanlwin river mouth area is facing similar environmental pressures, only on a smaller scale (Salmivaara et al., 2013).

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3 Status in terms of well-being

The second aspect is linked to water-related human well-being effects that emerge across physical scales and governance levels (Sivapalan et al., 2014). Due to the fact that Myanmar is an agricultural country, water is at the core of human well-being. Thereby, water is essential for the livelihoods of millions of Burmese people. However, extreme events such as floods and droughts can have severe destructing impacts. A very diverse and rich flora and fauna have been developed, particularly within the river basins (Rao et al., 2013). The high biodiversity provides various ecosystem services because people benefit from e.g. fishing and wood trading.

3.1 Weather extreme events and climate variability

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

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3.1.1 Floods

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

3.1.2 Droughts

Increasing pressure on water resources and water scarcity is becoming a worldwide problem in most arid and semi-arid regions (Kahil et al., 2015). Particularly in the central dry zone of Myanmar, rainfall is associated with high heterogeneity across space and time (McCartney et al., 2013). Precipitation amounts in the dry zone are generally less compared to other regions in Myanmar (see Sect. 2.2.1). In the here presented context, a drought is considered as a temporary extreme dry period characterized by below-normal precipitation over a period of months or even years (Dai, 2011). Severe drought periods in e.g. the years 1997–1998, 2010 and 2014 led to crop failures and water shortage in the central dry zone where more than 14 mio people predominantly practice agriculture. Most of the wells dried up due to the sinking of groundwater levels (Department of Meteorology and Hydrology Myanmar DMH, n.d.). The sources of income are affected by drought periods as well as the quality and availability of domestic

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and drinking water which can have severe effects on people's health. Droughts can also have negative impacts on the river basin's ecosystem (Kahil et al., 2015). During drought periods the navigability of the rivers is a huge problem for national and international companies as well as for the people living in this area (The World Bank, 2014; Ministry of Transport, Htun Lwin Oo, personal communication, 2015). Most likely, water demand in Myanmar will increase in the future due to enhanced production and trade in agricultural products, the expansion of transport systems via rivers and ports, and the anticipated growth of cities and industries (The World Bank, 2014). This increasing water demand and the high rainfall variability in the dry zone will cause the construction of more pumping stations for both groundwater and river water as well as the building of more reservoirs and dams.

3.1.3 Cyclones

The coast and the delta zones of the Ayeyarwady and Chindwin Rivers are extremely exposed to impacts from cyclones associated with winds, storm surges and salt water intrusion into groundwater (Rao et al., 2013). The Ayeyarwady delta is densely populated and the extensive and shallow continental shelf of the Andaman Sea allows cyclones and storm surges to inundate the delta and some inbound areas (Webster, 2008). Tropical cyclone formation in the northern Indian Ocean occur preferentially before (April–May) and directly after (October–November) the Asian summer monsoon season (Webster, 2008). During the cyclone *Nargis* in the year 2008, which was the most devastating cyclone to strike Asia since 1991, the Ayeyarwady River delta region was flooded by a 3.5 m wall of water (Thomson Reuters, 2009). Wind speed was in excess of 65 $\mathrm{m\,s^{-1}}$ (Webster, 2008). More than 130 000 people died and 2.4 mio people were severely affected (van Driel and Nauta, 2013; Thomson Reuters, 2009). *Nargis* caused severe harm to the winter rice crop and loss of rice seed and Myanmar faced food shortages after the event (Webster, 2008). Seawater inundated large areas of the Ayeyarwady delta posing challenges to future rice production (Webster, 2008). Lin et al. (2009) detected a pre-existing warm ocean anomaly in the Bay of Bengal which was

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

4 Flora and fauna

Myanmar is one of the few countries in Southeast Asia with relatively high levels of biodiversity and intact forest areas (Rao et al., 2013). About 40–50 % (Aung, 2002; Htun, 2009) of Myanmar's surface is covered with closed tropical forest; however, according to the FAO, both quantity and quality are decreasing (Htun, 2009). The forest flora ranges from sub-alpine to tropical formations (Aung, 2002). The forest along the Thanlwin River on the Thai-Burmese border lies on a bio-geographic border that is rich in biodiversity, in wildlife and fish populations, and this area is one of the most fertile areas for teak in the world (Salween Watch and SEARIN, 2004). Tropical evergreen rainforests occur in areas receiving > 2000 mm of rain annually and they are home to many birds species. Many wild animals which were once plentiful, are now reduced in number and are protected, e.g. the "Irrawaddy dolphin", the Asian two-horned rhinoceros, the wild water buffalo, the gaur and other deer species (Hadden, 2008; Smith et al., 2009; Aung et al., 2013).

All species play an important role in maintaining balance in and supporting ecosystems. If these significant values and benefits are lost, humans will response with additional inputs to maintain the system's functionality (Allen et al., 2010). The majority of threats to Myanmar's biodiversity are in general linked to human population growth and economic development, and the corresponding increasing demand for natural resources and space (Allen et al., 2010). Overexploitation of fishes is a major concern for

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the country's inland fisheries which are likely to increase due to political and economic transitions (Rao et al., 2013). However, little is known about species-ecosystem interactions to be sure of human (e.g. dam projects, mining) or climate impacts (e.g. temperature changes may lead to alien species invasions). Following Allen et al. (2010), alien species invasions, pollution from mining activities, river flow modifications and overexploitation of fishes are the major threats to the biodiversity of freshwater systems in Myanmar.

5 Values and norms

Values and norms in the socio-hydrology framework refer to normative goals of individuals and whole societies with respect to water use, conservation and sustainability (Sivapalan et al., 2014). This aspect includes various interests from stakeholders and different perspectives on the water resources.

5.1 Agricultural land use

Agriculture is the main pillar of the country's economy and contributes ∼ 37 % to the GDP (Ministry of Forestry, 2005; CIA, 2015). The estimated cultivated area in Myanmar is 18.27 million ha which is equivalent to 55 % of the cultivable area (FAO, 2015). More than 65 % of the population live in rural areas, working in the agricultural sector (FAO, 2014). The major agricultural products are rice, pulses, beans, sesame, groundnuts, sugarcane and hardwood. 42 % of Myanmar's cropland is cultivated with paddy rice, particularly in the Ayeyarwady delta region (FAO, 2004). The delta areas and river mouths are the most populated sections within the river basins. Here, cultivation of rice in flooded paddies predominates (FAO, 2004). In general, the agricultural practices are still very low tech, and usually water buffalos are used for ploughing (van Driel and Nauta, 2013). The majority of the farmers there are small-scale landholders with an average lot size of 2.27 ha cultivating paddy fields during the monsoon season and

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vegetable gardens on the river banks in the dry season (Salween Watch and SEARIN, 2004). All-the-year, they cast for fish in the rivers and along the coasts. The country has the largest estimated population of small-scale fisheries in the world (SEAFDEC, 2012). The government is the ultimate owner of all land in Myanmar and the farmers are only allowed to cultivate the land with the government's prescription. One third of the rural residents are landless labourers (Hiebert, 2012). Land-grabbing and confiscation are a huge problem, particularly in the Tanintharyi Region, followed by Kachin State (Farmlandgrab, 2014).

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

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

5.2 Water use and management

Myanmar has abundant water resources including both surface and groundwater. The potential water resources volume is estimated to be about 1,000 km^3 for surface water and about 500 km^3 for groundwater (WEPA, 2014; Oo, 2015). The country's total renewable water resources are 24 352 $m^3 yr^{-1}$ per inhabitant but only 5 % of its physical water resources are used at present (WEPA, 2014). Water utilization for the agricultural sector is about 90 % while industry and domestic use is only about 10 % of the total water use. Due to ongoing and expected future economic development and pop-

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ulation growth, it is obviuos that the physical potential for further development of water resources is substantial (WEPA, 2014).

5.2.1 Central dry zone

Farming in the central dry zone is only possible with irrigation due to the high variability of rain falls. Irrigation in the dry zone has its beginning in the 11th century when weirs and tanks were constructed. The first groundwater and surface water pumped systems were initiated in 1962 and they significantly contribute to increased food security in the central dry zone (McCartney et al., 2013). The annual recharge of groundwater in the dry zone is estimated around 4770 Mm^3 and the annual total use is > 770 Mm^3 (data from 2000; Johnston et al., 2013). In this region, irrigation is mainly conducted by canal systems from the rivers to the arable land while groundwater withdrawal still plays a minor role. However, the number of pumping systems is increasing, particularly through Chinese investments (Johnston, R., 2015, personal communication). Rainwater harvesting and storage is a simple and common method for domestic and livestock purposes in the villages. During the dry season, village ponds dry out frequently. This problem is often solved by groundwater or river water pumping to the ponds (Johnston et al., 2013).

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

5.2.2 Ayeyarwady delta area

Embankments, sluice gates and drainage systems have been constructed to protect the agricultural land in the lower delta against saltwater intrusion (van Driel and Nauta,

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

5.3 Hydropower and river flow modifications

Myanmar's major rivers are still less regulated compared to other Asian rivers (Hedley et al., 2010). There are currently no dams on the mainstream of the Ayeyarwady River. However, about 1300 km of embankments were built during the late nineteenth and early twentieth century (Hedley et al., 2010). Between 1988 and 2003, the government of Myanmar has constructed about 150 smaller dams and reservoirs and 265 river water pumping stations along the tributaries (Ministry of Forestry, 2005). The Ayeyarwady River is subject to numerous potential dam projects and seven dams are currently in the planning stage (Allen et al., 2010). Several dams are also planned along the Thanlwin River which likely will impact both the hydrodynamic and the sediment load (Salmivaara et al., 2013). In 2011, Chinese constructions of a large storage-backed hydropower dam near Myitsone at the confluence of the Mali and the N'Mai Rivers (Fig. 2) were halted due to peaceful public protests as well as armed resistance (Burma Rivers Network, 2014). The dam was intended to build 152 m high and it was envisaged to inundate 47 villages and to displace ca. 10 000 people in the Kachin State (Burma Rivers Network, 2014). Another critical point is that the northern part of the country is prone to earthquakes and a broken dam would have catastrophic impacts on down-

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stream areas and the city of Myitkyina, the capital of the Kachin State (Burma Rivers Network, 2014). It is suggested that building larger dams will come along with social impacts like displacements, food security, health concerns, impacts on women and the loss of culture (Smakhtin and Anputhas, 2006; Burma Rivers Network, 2014). Myanmar has experienced a rapid growth of hydropower capacity with a potential of almost 40 000 MW, of which only 6 % have been developed. Hydropower supplies the majority of the electric exports supported by foreign investments (ADB, 2012; Kattelus et al., 2014).

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

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

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

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5.4 River ecology protection

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

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

6 Climate change impacts and future perspectives

Only very few studies on climate change impact assessments in Myanmar have been conducted so far (Shrestha et al., 2014). During the past decades, inter-seasonal, inter-annual and spatial variability in rainfall has been observed across all Southeast Asian countries (IPCC, 2014). However, detailed studies for Myanmar in particular are lacking, but a similar pattern can be assumed due to the influence of the same monsoonal atmospheric circulation system. A substantial inter-decadal variability exists in the Indian monsoon circulation which is particularly crucial for the central dry zone (IPCC,

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2014). Extreme weather events have become more frequent and intense during the last decades related to their direct impacts on socio-economy what could also be detected for Myanmar (GCCA, 2012). Most likely, the intensity and frequency of droughts in the dry zone particularly during ENSO events will increase (IPCC, 2014). Variability of river runoff and changes in seasonality are expected for Southeast Asia as a result of climate change (IPCC, 2014). Sea level rises, decreasing river runoff and increasing intensity and frequency of droughts will lead to saltwater intrusion into river deltas. In the medium term, enhanced glacier and snow melt in the source areas of rivers will cause generally higher discharges and floods. However, individual glaciers are currently advancing or thickening in Asia most likely due to enhanced precipitation (Referenz, Hewitt, 2005?). Studies on the glaciers feeding the Ayeyarwady have not been conducted yet. The low-lying Ayeyarwady delta is particularly exposed to sea-level rise and vulnerable due to its high food productivity and population density. It is assumed that a 0.5 m sea-level rise would advance the shoreline along the Ayeyarwady delta by 10 km inland (NAPA, 2012). Changes in river flow will likely increase the risk of flash floods and lowland regions will be regularly inundated (NAPA, 2012). Furuichi et al. (2009) showed a decrease of the annual discharge of the Ayeyarwady River over the last 100 years based on a statistical comparison with data collected in the 19th century, but the driving forces remain unclear. The central dry zone experienced higher maximum temperatures and lesser rainfall in the 1990s compared to other regions in Myanmar (Ministry of Forestry, 2005). This is hypothesized as a result of anthropogenic climate change and global warming (Ministry of Forestry, 2005). Increasing temperatures in this region will raise the concentration of dissolved salts in the ponds, channels and other storage systems resulting in a reduction of drinking water (NAPA, 2012). Simulations by Neupane et al. (2015) indicate generally higher stream discharges during monsoon season in Nepalese rivers in the future as a response to climate change and land use change, particularly deforestation. However, they estimate decreasing discharges during the pre- and post-monsoon seasons which might affect seasonal water availability influencing crop production and hydropower generation. This hydrologic response to

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climate and land use changes is also likely for Myanmar, however, detailed studies are still lacking.

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

Continuing loss of natural forest cover and mangrove habitats can influence processes affecting climate change by release of CO_2 to the atmosphere (Van der Werf et al., 2009). It can be summarized that climate change most likely will impact the river basin ecosystems in Myanmar in a so far unknown dimension through modification of seasonal flow regimes and the timing, extent and duration of floods and droughts. Climate change projections and scenarios have not yet been developed for Myanmar in particular. There are numerous assumptions and expectations but no detailed data for the country. This lack of future assessments is also a result of the nonexistence of paleoclimate data.

Due to the lack of scientific research in the country, often uncertain or incomplete data bases and rapid political and economic changes, future perspectives for human-water dynamics in Myanmar's river basins can only be assessed. However, it should be possible to indicate the major drivers of future changes. Undoubtedly, the availability and quality of freshwater is and will be the core of the country's future development but

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increasing conflicts on water may arise due to growing foreign investments and various international and national interests.

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

7 Conclusions

Myanmar's economy and the people's income and well-being strongly depend on the quality and availability of sufficient water resources. The delta region of the Ayeyarwady River and the central dry zone are the areas most populated and most intensely used by agriculture in the country. On the one hand, the farmers depend on frequent river flood events for irrigation; on the other hand, they suffer from water-related extreme events such as floods or drought periods. It is expected that theses climatic extreme events will likely increase in frequency and magnitude in the future as a result of climate change. Different national and international interests in the abundant water resources may provide opportunities and risks at the same time for Myanmar. Several dam projects along the main courses of the major rivers are currently in the planning phase. Dams will most likely modify the river flows, the sediment loads and also the still rich biodiversity in the river basins, in a still unknown dimension. On the other hand, these foreign investments allow the development of infrastructure and probably

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stabilize the political relations between Myanmar and its neighbouring countries and strengthen its role in Southeast Asia and even globally.

All authors of the reviewed literature agree that Myanmar is facing big water-related challenges. However, future perspectives and developments are mostly still intangible due to the large gap of research in the country and the limited detailed knowledge about the status-quo. More in-depth qualitative and especially quantitative analyses on human and climate impacts on Myanmar's water resources are strongly required in order to adapt water and land management to current and future climate change. The year 2008 was a kind of turning point when cyclone *Nargis* made landfall in the Ayeyarwady delta region. Since then, a number of action plans have been established with the aim to call attention on extreme weather events. Furthermore, the vulnerability of the Burmese people is increasing because population pressure is forcing more people to live and work in coastal zones and river basins. The central dry zone and the delta zone are the most vulnerable parts of the river basin related to climate change and also to human impact.

Relevant aspects for future development of Myanmar's river basins combine environment-water-related indicators, climate, economic and social development, water management and land use changes. Research on this interplays need to capture the spatial and temporal dynamics of this drivers. Yet, it is only possible to gain a full understanding of all these complex interrelationships, when multi-scale spatiotemporal information will be analysed in an inter- and transdisciplinary approach. Applying the concept of socio-hydrology to this real-world case study can be a promising first step to increase the understanding and knowledge on these complex systems. We suggest applying the process socio-hydrology to study human-water systems in Myanmar in more detail and to indicate causal relationships, feedback processes, and spatial as well as temporal dynamics.

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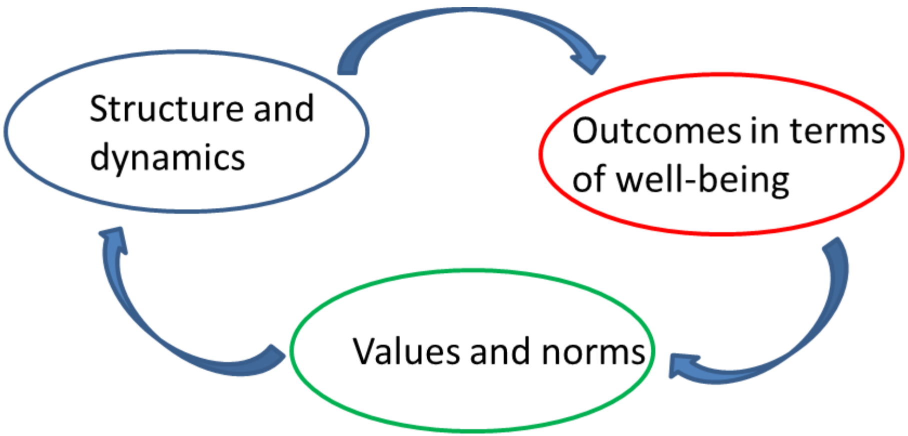

Figure 1. Conceptual framework for the socio-hydrology approach adopted from Sivapalan et al. (2014).

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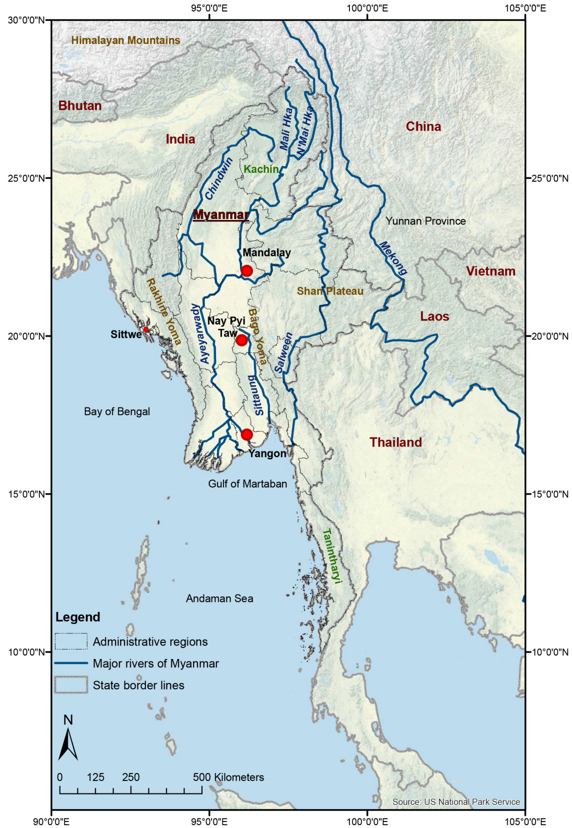

Figure 2. Physical overview map of Myanmar including state border lines, major rivers, major cities and places being referred to in the text.

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