SOBA 1.4: ECOHYDROLOGY ASSESSMENT

AYEYARWADY STATE OF THE BASIN ASSESSMENT (SOBA)

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Disclaimer
"The Ayeyarwady State of the Basin Assessment (SOBA) study is conducted within the political boundary of Myanmar, where more than 93% of the Basin is situated."

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LIST OF ABBREVIATIONS

CD	current development
DCI	Dendritic Connectivity Index
HEZ	hydro-ecological zone
IUCN	International Union for Conservation of Nature
KBA	key biodiversity area
km^2	square kilometres
m	metres
MCM	million cubic metres
MCM/y	million cubic metres per year
NWRC	National Water Resources Committee
PD	pre-development
RFI	River Fragmentation Index
SOBA	State of the Basin Assessment

EXECUTIVE SUMMARY

BACKGROUND

This ecohydrological assessment, based on the analysis and synthesis of readily available information, aims to characterise the status and trends of the key attributes of the Ayeyarwady Basin's flow regime that are likely to be of importance to biodiversity, fisheries, and the ecological processes that sustain them. It also explores the associated risks to these environmental assets from water infrastructure development, including hydrologic alteration, river impoundment, and longitudinal fragmentation by large dams. This report is not a comprehensive assessment of environmental flow needs. It makes no attempt to recommend sustainable water extraction and diversion limits or to provide assessments of critical flow needs for specific species. Such an effort would require more detailed environmental flow assessments and was well beyond the scope and timing of this study.

REVIEW OF KEY PRINCIPLES AND EXISTING KNOWLEDGE

The ecology of aquatic ecosystems in the Ayeyarwady Basin is fundamentally linked to the seasonality of the climate and the natural flow regime. The Ayeyarwady River can be described as having a highly rhythmic flood pulse (Jardine et al., 2015). Tropical floodplain rivers with these features are associated with higher fish species richness, more stable avian populations, and elevated rates of riparian forest production compared with those river systems with arrhythmic flood pulses. Water resource and hydropower development that alters the hydrologic rhythmicity is likely to have significant long-term consequences for both biodiversity and productivity.

The movement of water and associated nutrients, carbon, energy, and aquatic biota between different habitats of the river are essential to sustain biodiversity, productive fisheries, and other essential ecosystem services. Maintenance of connectivity between these components, both longitudinal and lateral, is vital for natural ecosystem function. In-channel or floodplain development in the Ayeyarwady Basin that diminishes or severs these links is likely to diminish these values.

APPROACH

This ecohydrological assessment of the Ayeyarwady Basin was based on a rapid assessment approach to achieve the following:

- Collate relevant literature, including State of the Basin Assessment (SOBA) Draft package reports, and undertake a mini-review of key freshwater biodiversity assets, ecosystem values, and ecological processes of the Ayeyarwady Basin.
- Review and conceptualise the critical ecohydrological mechanisms that link hydrology with maintenance of biodiversity, ecosystem values, and ecological processes.
- Collate available, observed, and measured hydrological data – liaising with eWater Solutions (SOBA 1.2 report team) to provide hydrologic data (modelled) to represent pre- and post-water resource development scenarios to allow a hydrologic assessment.
- Based on these data, develop and apply a method to quantitatively characterise spatio-temporal variation in natural hydrologic regimes throughout the Ayeyarwady Basin. This included the calculation of a series of hydrologic metrics describing ecologically-relevant components of the flow regime (e.g., magnitude, frequency, timing, duration, seasonality, and temporal variability of flow events).
- Using the modelled data from SOBA 1.2 and other information sources, characterise the spatial extent and intensity of hydrologic alteration of these key components of the flow regime as well as river impoundment and longitudinal fragmentation caused by water resource developments.
- Assess the likely risks to biodiversity, ecosystem values, and ecological processes caused by these water-related threats in the Ayeyarwady Basin. This includes a semi-quantitative risk ranking of each ecological response attribute (i.e., biodiversity, ecosystem values, and ecological processes) to hydrologic alteration, river impoundment, and longitudinal fragmentation in each sub-basin.

- Develop recommendations for more detailed investigations, including assessment and implementation of environmental flows and other management interventions, to mitigate these risks and identify future research priorities that address critical knowledge gaps.

ASSESSMENT OF HYDROLOGIC ALTERATION & EXPOSURE TO OTHER WATER-RELATED THREATS

Detailed analyses of long-term modelled daily flow data for pre-development and current development scenarios allowed an assessment of the nature and extent of hydrologic alteration in the Ayeyarwady Basin. The Upper Ayeyarwady (Hydro-Ecological Zone [HEZ] 1) has experienced relatively minor hydrological changes from water resource development and extraction. Similarly, the Chindwin Basin (HEZ 2) has had relatively minor hydrological changes overall. The most notable change is the 15% increase in the duration of low flow spells. Upstream, sub-basins within the Chindwin Basin have experienced more pronounced changes in flows, particularly the Manipur Sub-basin in which low flow magnitude has decreased by 10% and the duration of low flow spells has increased by 42%.

The Middle Ayeyarwady (HEZ 3) shows some major alterations in hydrology, with a 3% decrease in mean annual flow and <10% decreases in the magnitude, frequency, duration, and variability in timing of high flows, respectively. Major changes in the mean duration (16% increase) and number (25% decrease) of low flow spells occurred, and minor changes (<5% absolute difference) in the timing and variability of low flow spells was evident. Upstream sub-basins within the Middle Ayeyarwady experienced more dramatic changes in flow, particularly the Mu, Panlaung, Myitnge and Shweli Sub-basins, which had a 29%, 22%, 7% and 2%, respectively, decrease in mean annual flow volume. The magnitude and frequency of high flow spells has decreased substantially across these sub-basins (e.g., 38% reduction in high spell frequency in the Panlaung Sub-basin). Low flows have also changed considerably, with a maximum decrease in low flow magnitude of 39% (Mu Sub-basin), a maximum increase in low flow spell duration of 106% (Panlaung), and a maximum increase in low flow spell frequency of 104% (Mu Sub-basin). The timing and variability of high and low flow spells have also changed considerably in these sub-basins (up to 42% difference from pre-development flows).

The Lower Ayeyarwady (HEZ 4) shows an overall decline of 2% flow volume, an 8% decline in the average duration of high flow spells, and a >20.0% difference in the mean duration and frequency of low spells.

The relative exposure of each sub-basin to ecological threats, posed by river impoundment and longitudinal fragmentation caused by water resource developments, was also calculated. River impoundment was highest in the Ayeyarwady (Upper), Mu, and Panlaung Sub-basins. The Ayeyarwady (Middle), the Ayeyarwady (Lower), and the Manipur Sub-basins had lower exposure to river impoundment, and the remaining sub-basins had little or no impoundment of riverine habitat. The Shweli, Panlaung, and Mu Sub-basins were severely affected by longitudinal fragmentation. The Ayeyarwady (Upper), the Ayeyarwady (Middle), the Ayeyarwady (Lower), and the Myitnge Sub-basins were also affected, to a lesser degree, by fragmentation.

ECOLOGICAL RISKS FROM HYDROLOGIC ALTERATION, RIVER IMPOUNDMENT, AND LONGITUDINAL FRAGMENTATION

Ecological assets in the Ayeyarwady Basin are facing increasing threats from a range of processes related to water resource development, including hydrologic alteration, river impoundment, and longitudinal fragmentation. The cumulative impacts from these threats are unknown but may pose severe risks in the long term. An ecological risk assessment was undertaken, using available information and expert knowledge, to estimate the cumulative impacts of current threats to ecological assets in the Ayeyarwady Basin, including risks to aquatic biodiversity, ecological processes, and ecosystem values. The risk assessment was based on a widely accepted approach to ecological risk assessment that combines spatially-explicit information on threat exposure; the occurrence and relative importance of aquatic biodiversity assets, ecological processes, and ecosystem values; and their potential vulnerability to threats. These analyses allowed areas (e.g., sub-basins) to be ranked on their overall risk to each threat. The assessment, in turn, can be used to identify areas where more detailed investigations may be required to better understand the magnitude of potential impacts on ecological integrity and inform biodiversity conservation, threat mitigation, and spatial planning of decision-making. Key findings from the risk assessment are summarised as follows:

- *Hydrologic alteration* – The assessment of risks posed by hydrologic alteration revealed that the sub-basins in HEZ 3, particularly the Panlaung and Mu Sub-basins, were at highest cumulative risk. Overall, ecological assets/processes/values assessed as being at highest cumulative risk from hydrologic alteration included flowing rivers and streams, floodplain wetlands, floodplain primary productivity, lateral connectivity, and migratory species. Hydrologic alteration from current development poses a lower, but still substantial, risk to rare and endemic species, longitudinal connectivity, and fisheries production.

- *River impoundment* – The loss of riverine habitat and the associated effects on biodiversity and ecosystem processes is not offset by the creation of lentic habitat through construction of impoundments (see Section 2.3.4). Assessment of cumulative risks from river impoundment, revealed that the Upper Ayeyarwady and, to a lesser extent, the Mu Sub-basin in HEZ 3 were at substantially higher risk than all other sub-basins. These sub-basins contained the highest proportion of impounded area and a relatively high number of assets that were all highly vulnerable to this threat. Ecological assets/processes/values assessed as being at highest cumulative risk from river impoundment included rare and endemic species, flowing rivers and streams, Key Biodiversity Areas (KBAs), and fisheries production.

- *Longitudinal fragmentation* – Assessment of cumulative risks from longitudinal fragmentation revealed that all sub-basins in HEZ 3 were at high risk, particularly the Shweli, Panlaung, Mu, and Ayeyarwady (Upper) Sub-basins. Other sub-basins at relatively lower risk included the Ayeyarwady (Middle), Ayeyarwady (Lower), and the Myitnge Sub-basins. Ecological assets, processes and values assessed as being at highest cumulative risk from longitudinal fragmentation included migratory species, longitudinal connectivity, and fisheries production. KBAs and rare and endemic species were assessed as being at moderate risk, with all other assets of relatively low risk.

MANAGEMENT OPTIONS TO MITIGATE RISKS

In lieu of detailed, on-the-ground assessments of threat management and risk mitigation options, we outline key strategies and general principles to minimise the negative ecological impacts of water resource development and associated flow regime changes in the Ayeyarwady Basin. These strategies and principles related to environmental flow management, water infrastructure management, and strategic water resource planning and adaptive management.

LIMITATIONS, CRITICAL KNOWLEDGE GAPS, AND FUTURE PRIORITIES

We identified several limitations and assumptions of the cumulative risk assessment approach used here that are common to most spatially explicit cumulative risk assessments (largely related to data and knowledge limitations for the Ayeyarwady Basin). Notwithstanding these assumptions, our assessment of the cumulative risks posed by hydrologic alteration and other threats to the aquatic ecological integrity of the Ayeyarwady Basin is the most up-to-date; comprehensive (in terms of spatial extent, number of threatening processes, and number of ecological responses assessed); ecologically relevant; quantitative (e.g., uses continuous data to estimate exposure and risk instead of qualitative and discretised risk ratings); and scientifically robust evaluation yet undertaken.

KNOWLEDGE PRIORITIES FOR MANAGEMENT

The prospect of dramatic environmental changes over the coming years underscores the need for informed and efficient conservation management of freshwater ecosystems in Myanmar. Improved capacity of natural resource managers to implement effective mitigation and adaptation programs should aid greatly in the environmentally sustainable economic and social development of Myanmar. In particular, there is a compelling need to apply spatially explicit scenario evaluation tools for Myanmar's river catchments to evaluate trade-offs of different development and climate scenarios. These would be underpinned by gathering new knowledge of the following:

1. Some sub-basins and their ecological assets and values are already at high risk – strategic, coordinated, and inclusive management is required to address current and future threats.
2. Information on the environmental flow requirements of freshwater biota and ecological processes is urgently required to inform planning and management.
3. Targeted assessment is required on ecological responses to development and the benefits of management actions.
4. A geophysical representation that quantifies changes in floodplain inundation and sediment is required

1 BACKGROUND AND INTRODUCTION

1.1 Background to This Study

Myanmar's Hydro-Informatics Centre has designed and is managing the implementation of the Ayeyarwady State of the Basin Assessment (SOBA) – a multi-disciplinary, integrated environmental, social, and economic assessment of the Ayeyarwady Basin. With inputs from 25 international and Myanmar organisations, companies, universities, and institutes, SOBA will be a major milestone in the river basin planning process that the National Water Resources Committee (NWRC) has initiated for the Ayeyarwady Basin through the Ayeyarwady Integrated River Basin Management Project.

SOBA was conducted, as a coordinated program of six technical packages, between May through October 2017 and included the following:

- SOBA 1: Surface water resources and use;
- SOBA 2: Groundwater resources, use and water information system for data management;
- SOBA 3: Geomorphology and sediments;
- SOBA 4: Biodiversity and fisheries;
- SOBA 5: Socio-economics; and
- SOBA 6: Participatory 3D mapping and local consultations.

The Ayeyarwady Basin is recognized as a global hotspot of freshwater fish biodiversity and endemism (Abell et al., 2008), and supports a productive fishery (SOBA 4.1 report). These freshwater ecological assets and values are sustained by critical flow-related ecological processes that can be affected by flow alteration, habitat transformation through impoundment of riverine habitat, fragmentation of longitudinal connectivity associated with water infrastructure developments (dams and weirs), and habitat degradation and pollution associated with intensified land use.

The purpose of this ecohydrology assessment is to characterise the status and trends of the key attributes of the Ayeyarwady Basin's flow regime that are likely to be of importance to biodiversity and fisheries. In addition, the assessment explores the associated risks to these environmental assets from water infrastructure (e.g., through the loss of connectivity due to in-stream barriers or the impoundment of key habitats). The intent is that key concepts and information on the interactions between water and ecosystems (*viz*. ecohydrology) are featured in future planning and management initiatives in the Ayeyarwady Basin.

1.2 Objectives and Scope

This report is not expected to be a comprehensive assessment of ecohydrology, rather an initial synthesis and integration of the information provided from the other SOBA packages. Importantly, this study makes no attempt to recommend sustainable water extraction and diversion limits or to provide assessments of critical flow needs for specific species. Such an effort would require more-detailed environmental flow assessments that are well beyond the scope and timing of this study.

Specifically, the objectives are as follows:

1. Describe in clear, simple, and visual terms the key ecohydrological concepts, principles, and features of the Ayeyarwady system, including environmental flows to maintain biodiversity, species populations, and river ecosystem and geomorphological functioning.

2. Characterise qualitatively (and, where possible, quantitatively) the key flow regime features of the Ayeyarwady for each hydro-ecological zone (HEZ) and for the river as a whole.

3. Undertake a rapid, qualitative assessment of existing and past flow regime disturbances due to human development (e.g., reservoir development, mining, land use change) that are likely to be of ecological relevance.

4. Articulate how such changes may affect biodiversity and fisheries production in the basin (drawing, where necessary, on examples from elsewhere) and provide recommendations for possible mitigation.

The following sections review the key principles and existing knowledge of the Ayeyarwady Basin and then focus on the biodiversity and ecological assets under threat from water resource development. The subsequent sections describe the methodology and application of a risk assessment to evaluate ecological risks associated with hydrologic alteration and other water-related threats. We conclude by summarising key findings; synthesising candidate management options to mitigate ecological risks; and outlining limitations, critical knowledge gaps, and future priorities.

2 ECOHYDROLOGY OF THE AYEYARWADY BASIN – REVIEW OF KEY PRINCIPLES AND EXISTING KNOWLEDGE

2.1 Hydrological Regimes and Ecological Responses

The flow regime is regarded, by many aquatic ecologists, to be the key driver of river and floodplain wetland ecosystems (Poff et al., 1997; Bunn and Arthington, 2002). High flows interact with the surrounding landform and geology to shape the channel form (e.g., width and depth, pools and riffles) and to disturb the substrate of the river bed and banks. This creates a high level of physical habitat complexity which, in turn, is known to be a major determinant of aquatic biodiversity (Figure 1; Principle 1). Many features of the flow regime influence life history patterns of aquatic and riparian species – not only the seasonality and predictability of the overall pattern, but also the timing of particular flow events (Figure 1; Principle 2). Critical life events of many aquatic species are linked to these flow patterns. For example, spawning behavior of fish may be synchronized to take advantage of predictable stable base-flows or triggered by high flow events to enhance larval dispersal.

The long-term viability of populations of many riverine species also depends on the natural patterns of connectivity along the channel network and, in some migratory species, to the sea (longitudinal connectivity). Populations of many riverine species are also sustained by the massive subsidy of resources available during periods of floodplain inundation and connection of associated lowland wetlands. Larger flow events trigger and facilitate longitudinal dispersal of migratory aquatic species and allow access to otherwise disconnected floodplain and wetland habitats (Figure 1; Principle 3).

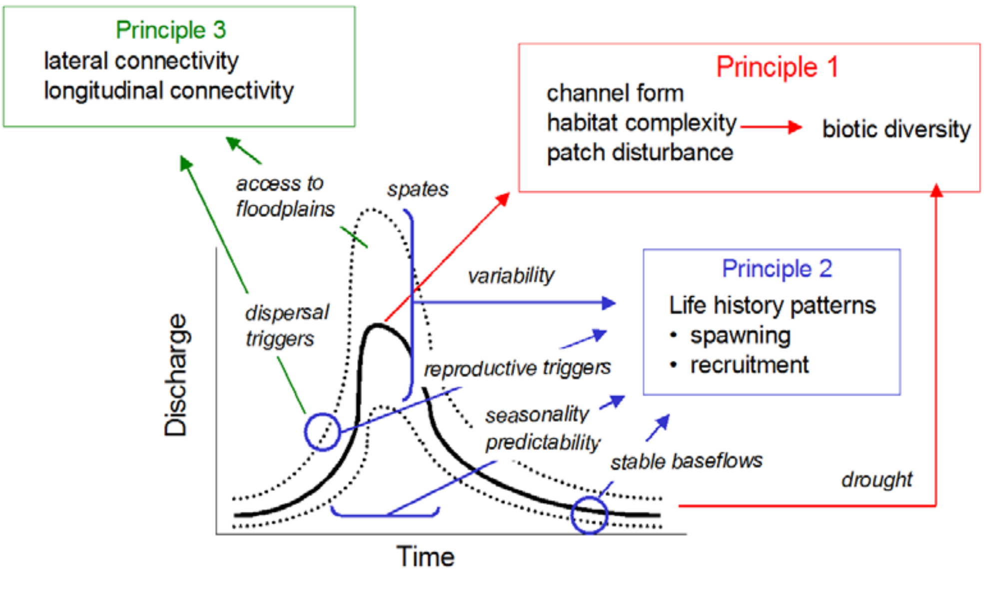

Figure 1 - Three of the guiding principles on the influence of flow regimes on aquatic biodiversity *(Bunn and Arthington, 2002)*

This simple conceptual view of a hydrograph and its influence on aquatic biodiversity and key ecological processes (Figure 1) understates the complexity of intra- and inter-annual variation in hydrology (see Figure 2). It is important to be able to quantify these key components of the flow regime across these temporal scales (see Section 3.3.2). It is worth noting that several attributes of the flow regime, particularly the low-flow characteristics and the timing of smaller flow events, may be of critical ecological importance (Rolls et al., 2012), even though they are of little importance from a water resource development perspective. Our ability to measure and model low flows and the connections between groundwater and surface water remains a major technical challenge for environmental flow management (Bunn, 2017).

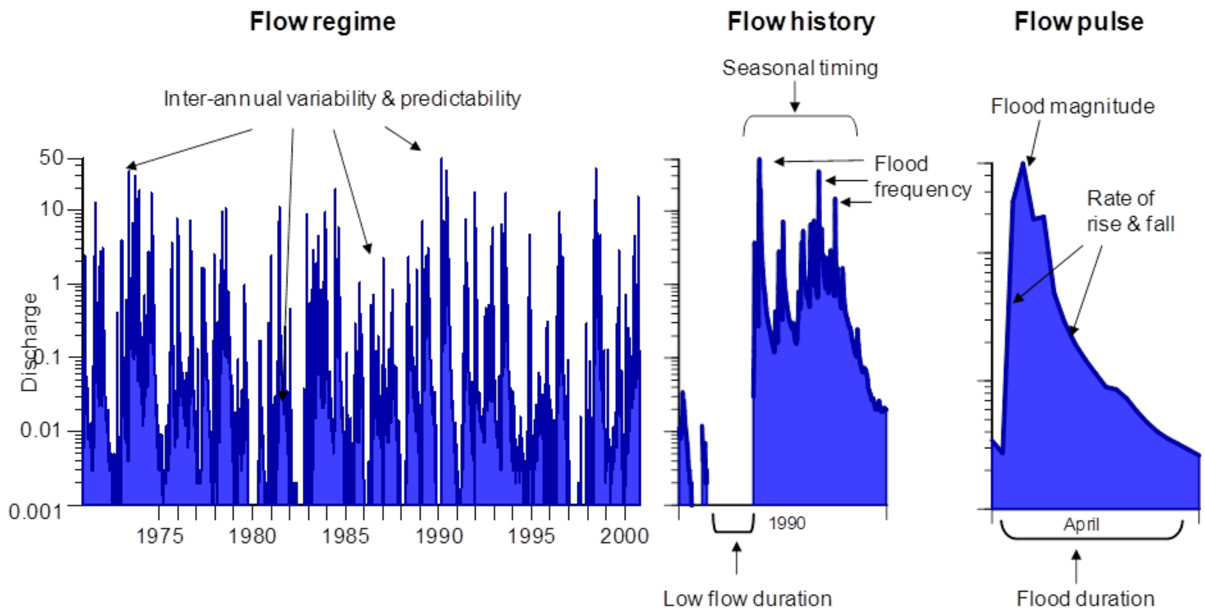

Figure 2 - Components of flow variability may be characterized over various temporal scales including the long-term flow regime, the short-term history of flow events, and individual flow pulses
(Olden et al., 2012)

2.2 Aquatic Biodiversity Assets, Ecological Processes, Ecosystem Values, and Critical Links to Flow

An important first step in any ecohydrological assessment is to identify the important environmental assets and values that need to be considered. These include essential goods and services, such as fisheries production, but also specific conservation and biodiversity objectives. This approach typically requires extensive consultation and engagement with stakeholders to derive a shared understanding of important environmental assets and values and their relationships to flow. Some such consultations were undertaken by other SOBA package teams, and we have drawn on relevant information provided in the SOBA 4 reports as well as published studies on the Ayeyarwady and other tropical floodplain rivers.

Based on our review of available information and in the absence of specific flow-ecology information on key species, we have focussed this assessment on the following:

Five groups of 'biodiversity' assets:

- Migratory species
- Rare and endemic species
- Critical habitat - floodplain wetlands
- Critical habitat - rivers and streams
- Key Biodiversity Areas (KBAs)

One provisioning ecosystem service:

- Fisheries production

And three ecological processes that underpin the above assets and values:

- Floodplain primary productivity
- Lateral connectivity (floodplain inundation)
- Longitudinal connectivity

Although groundwater dependent ecosystems are widespread (SOBA 2 report) and likely critical habitats in the Ayeyarwady Basin, we did not include these as biodiversity assets in our analyses, because we could not obtain reliable threat exposure data for this critical habitat (e.g., groundwater drawdown intensity).

2.2.1 Migratory species

The life cycles of some important riverine species involve extensive migrations through the channel network. These species include catadromous species (e.g., barramundi, *Lates calcarifer*; and shrimps) (Wowor et al., 2009) that inhabit freshwater regions as adults but need to return to the ocean to reproduce; anadromous species (e.g., hilsa, *Tenualosa ilisha*) that spend their adult life at sea but return to freshwaters to spawn and spend their juvenile life stages; and potamodromous species (e.g., migratory carps) (Hortle, 2009) that can make long migratory movements within the freshwater system to reproduce. Many undergo these longitudinal movements in response to flow-driven cues. Upstream migrations can be particularly challenging, and many species require specific (and predictable) hydrologic conditions to move against the current or to locate spawning beds with the requisite hydraulic conditions.

Many migratory species are of importance from a fisheries perspective (Hortle, 2009) or have high conservation significance (Dudgeon, 2011). Large migratory macroinvertebrates, such as shrimps and crabs, are also an important component of the biota of many tropical streams and rivers because of their direct influence on ecosystem level processes (e.g., primary production, organic matter processing (Pringle et al., 1993; Moulton et al., 2004). There are 135 migratory fish species in the Mekong River, many of which are important to the fishery or have conservation significance (Baran, 2006). Similarly, many species of commercial and subsistence importance in the Ayeyarwady are migratory (see Section 3.2 in SOBA 4.1 report).

2.2.2 Rare and endemic species

In contrast to migratory species, many freshwater species have specialized habitat requirements, restricted distributions, and often small population sizes, making them vulnerable to localized disturbance. Among the 388 fish species recorded in the Ayeyarwady, there is a high degree of endemism, especially in the Upper Ayeyarwady Sub-basin and the upper part of the Chindwin Sub-basin, where the upstream fauna are characterized by a number of genera and species typical of high gradient, fast flowing rivers (SOBA 4.5 report).

Only 254 species in the basin have been assessed by the International Union for Conservation of Nature (IUCN), with 28 (11%) included in the Red List as threatened (2 critical, 6 endangered, 20 vulnerable) and 20 (8%) near threatened. The Ayeyarwady and Chindwin Basins are considered to have between 85 to 101 freshwater mollusc species, with greater richness and endemicity in the Upper Chindwin and northern Rakhine (Buddha et al., 2010, cited in SOBA 4.5 report).

2.2.3 Critical habitat – floodplain wetlands

Many species of river fish, crustaceans, and other biota move into seasonally connected floodplain wetlands during the flood season (Pettit et al., 2017). These represent important nursery habitats and places of high production of food resources (Davies et al., 2008; Ward et al., 2016). Wetlands also provide important feeding and breeding habitat for waterbirds. For example, the wetlands in the Ayeyarwady Basin are known to be important for the survival of the critically endangered Baer's pochard (*Aythya baeri*), and several are identified as KBAs (SOBA 4.5 report).

2.2.4 Critical habitat – rivers and streams

During the dry season, most aquatic species are confined to the river channels. The deeper pools become major aquatic refuges during this time, and sufficient base-flows are required to sustain water depth and maintain water quality. Irrawaddy dolphins (*Orcaella brevirostris*) are known to prefer areas of slow moving water and, during the dry season, reside in deep pools >8 to 10 metres (m), which provide critical shelter from swift river currents and support high prey fish populations (Beasley, 2007; Smith and Reeves, 2012). These deep channel pools are maintained by regular scouring flows during the wet season, preventing a build-up of fine sediment.

Stable base flows also provide aquatic biota with access to fringing riparian vegetation and submerged logs along the river banks, which provide important habitat and food resources. Shallow, fast-flowing riffle areas are also important in smaller rivers and streams as sites of high primary and secondary production. These productive areas can be drowned out during high flow periods and, in turbid systems, remain below the photic zone. During extreme low flows, productive riffle areas can be greatly reduced in surface area, and their role, as a productive habitat for consumers downstream and in re-aerating water, is greatly diminished.

2.2.5 *Key biodiversity areas*

KBAs are defined under an international agreed set of criteria, initially developed for birds but now expanded to include all species (IUCN, 2016). In this study, we have used the KBAs identified in SOBA 4.5 report. Using criteria based on globally threatened and range-restricted species, this study identified 83 KBAs in in the Ayeyarwady. Another six sites were proposed, based on new information gathered through their assessment (SOBA 4.5 report).

2.2.6 *Fisheries production*

As in the Mekong (Hortle, 2009), fish comprise the major source of animal protein for communities in the Ayeyarwady Basin (SOBA 4.1 report), representing a substantial provisioning ecosystem service sustained by freshwater flows. The relationship between large flood flows and estuarine fisheries production is well established for shrimp (e.g., Loneragan and Bunn, 1999) and fish species of commercial and recreational significance (e.g., Robins et al., 2006). Similarly, there is strong evidence of substantial subsidies from tropical river floodplains and wetlands to riverine food webs associated with the flood pulse (e.g. Hortle, 2009; Pettit et al., 2017). The Ayeyarwady fishery is characterized, like in the Mekong system, by huge yields and large-scale fish migrations (SOBA 4.1 report).

2.2.7 *Floodplain primary production*

River floodplains and associated wetlands sustain high levels of primary production compared to the main channels, even though they may be inundated on a seasonal basis (Davies et al., 2008). Variation in annual flood magnitude, combined with local topography, determines the area and duration of inundation, which, in turn, are key factors influencing annual primary production. Riparian forest production is also related to flood rhythmicity in tropical rivers with ‘rhythmic’ systems (like the Ayeyarwady) supporting elevated production (Jardine et al., 2015).

Although macrophytes appear to be the major primary producers within floodplains, epiphytic algae also can represent a significant component of the total production (Davies et al., 2008; Adame et al., 2017). The latter are particularly important because of their high quality as a food source for primary and secondary consumers. They represent a major source of carbon and essential nutrients for freshwater food webs in tropical river systems (Pettit et al., 2017; Brett et al., 2017). Recent studies in tropical floodplain rivers have shown that some locations are ‘hotspots’ for algal primary production because of a combination of macrophyte habitat structure, light environment, and a pattern of floodplain inundation (Ward et al., 2016).

2.2.8 *Lateral connectivity (floodplain inundation)*

As noted above (Section 2.2.7), floods are essential to connect river channels to their floodplains. Many species of fish, crustaceans, and other biota move on and off seasonally inundated floodplains (Pettit et al., 2017). Such movements are necessary to complete life-cycles and are vital for maintaining population sizes and genetic integrity. The extent and duration of river flooding during the wet season, and rate of rise and fall of the flood peak, can determine whether and for how long fish can gain access to nursery habitats and food, and whether they will remain trapped in isolated floodplain waterbodies or be released back into the river system (Bunn and Arthington, 2002).

2.2.9 *Longitudinal connectivity*

As noted above (Section 2.2.1), many species of fish, crustaceans, and other aquatic biota move extensively throughout river networks and between freshwater and marine ecosystems (Pringle, 2003). Such movements are necessary to complete life-cycles and are vital for maintaining population sizes and genetic integrity. For example, over 33% of fish species in Australia's tropical rivers migrate to the estuary during their life history. Another 33% are "estuarine vagrants" often found hundreds of kilometres upstream, and many remaining use the periods of hydrological reconnection to move into tributaries and spawn (Pusey et al., 2011).

2.3 Ecological Responses to Hydrological Alteration, Habitat Transformation, and Fragmentation Associated with Water Resource Development

The alteration of flow regimes is regarded as one of the most serious and ongoing threats to ecological sustainability of rivers and their associated floodplain wetlands (Bunn and Arthington, 2002; Dudgeon et al., 2006; Vörösmarty et al., 2010). It is important to understand how attributes of the flow regime are affected by water resource development and the likely risks to ecological assets and values associated with these changes. This information is also needed to identify appropriate ecohydrological indicators for assessing these risks.

2.3.1 Changes to low flows

Flow regulation and other anthropogenic disturbances (e.g., land clearing, climate change) can alter the ecologically relevant attributes of low-flow hydrology (Rolls et al., 2012). Perennial rivers often have permanent baseflows due to significant shallow groundwater inputs during the dry season. Reductions in low flow magnitude downstream of dams or from groundwater extraction that reduces groundwater contributions to surface flow, can reduce the availability and quality of important flow-sensitive habitats, such as shallow, fast-flowing riffles and refugial pools. Reductions in water depth can also affect longitudinal connectivity, as increasingly shallow areas become barriers to migration for a range of biota, including turtles, fish, and crustaceans (Rolls et al., 2012).

Ecologically important low flows can also be impacted by flow supplementation, when water stored in impoundments in the wet season is delivered down the stream channel during the dry season. This form of supplementation often occurs in storages delivering water for irrigation, when water is released in the dry season when it is most needed by irrigators. However, elevated flows during the dry season can also occur downstream of large-storage hydropower dams. Although elevated base flows in the dry season may increase longitudinal connectivity and reduce the risk of poor water quality in isolated river pools, there are associated negative effects. Elevated flows during the dry season may inundate key habitats for biota (e.g., nesting sand banks for turtles or productive littoral habitats). This is a particular problem in naturally turbid systems, where key habitats (e.g., submerged logs, riffle zones) are submerged below the photic zone and no longer function as highly productive food resources (Bunn et al., 2006).

2.3.2 Changes to high flows

Large dams typically dampen flood peaks, reducing the frequency, extent, and often the duration of floodplain inundation. Reduction in the size, number, and duration of floods decreases the area and depth of floodplains, the period in which biota may freely move between the main channel and the floodplain, and the duration of floodplain waterhole persistence throughout the dry season (Bunn and Arthington, 2002). Given the strong positive relationships between wet season flows and fisheries production (Loneragan and Bunn, 1999), a reduction in the magnitude and frequency of flood events is likely to have a marked impact on this important ecosystem service.

A reduction in the magnitude and frequency of smaller, channel-forming flows (i.e., those with a return frequency of 1:1 to 1:2 years) can result in sediment accumulation in river pools, encroachment of riparian vegetation, accumulation of aquatic weeds, and a contraction in river channel size and overall habitat for biota. This can also lead to changes in the pattern of channel migration, lowering habitat diversification on floodplains and, ultimately, reduce the biological diversity and ecological integrity of floodplain rivers (Ward and Stanford, 1995).

Smaller dams and weirs may not have a great effect on flood dynamics but may be sufficiently large to trap smaller flood events particularly those that occur late in the dry season when water levels are low. These flow 'pulses' may be critical in maintaining water quality and, hence, the survival of biota, in pools late in the dry season (Bunn et al., 2006).

2.3.3 Changes to timing and variability

Although temperature regimes influence the life cycles of many stream and river animals, the timing of particular flow events is also important (Bunn and Arthington, 2002). The operation of large storages, especially for irrigation supply but also hydropower, can lead to the dampening and, in some cases, complete reversal of seasonal flow pulses (Young, 2001; Lytle and Poff, 2004). This can disrupt life cycles of aquatic species, where reproductive or migration flow cues are linked to seasonal differences in temperature and food availability. The operation of some hydropower dams can also lead to erratic changes in flow variability, completely masking natural flow cues. Extreme daily variations below peaking power hydroelectric dams have no natural analogue in freshwater systems (Poff et al., 1997). In addition to stranding of aquatic organisms in floodplain habitats, dam operations that lead to rapid draw down of flood events can lead to mass failure of saturated river banks and increased erosion.

2.3.4 River impoundment and loss of flowing riverine habit

It is often perceived that the loss of flowing riverine habitat, due to inundation from impoundments, is balanced by the creation of non-flowing lake habitat. This can be quite misleading, because natural lakes and wetlands often function in a very different way to river storages. Much of the productivity of lakes and wetlands is associated with the littoral margins (Davies et al., 2008; Adame et al., 2017). Large impoundments are generally not operated at a constant water level, and productive littoral areas are rarely sustained. In addition, water levels are usually significantly elevated above natural stream levels, flooding part of the terrestrial-aquatic interface and creating a new littoral zone with steeper banks, less complex aquatic habitat, and different physicochemical conditions for aquatic plants. Moreover, the simple transformation of previously flowing riverine to non-flowing lake habitat in impoundments has major implications for species with an obligate need for flowing riverine habitats (e.g., for spawning, juvenile recruitment, foraging and refuge). Water quality in impoundments is often very different from that in rivers, due to the absence of continual physical mixing. Stratification of the water column may develop as deeper waters become colder and more oxygen-deficient than surface waters. This can result in much of the reservoir becoming unsuitable habitat for all but the most tolerant of species

2.3.5 Fragmentation and loss of connectivity

In addition to the way in which they alter natural flow regimes, dams form barriers to the longitudinal movement of biota and materials (e.g., sediments, nutrients, carbon) along river channels (Wohl, 2017). The disappearance or decline of important migratory fish species often follows river impoundment and the blocking of passage in the system (Bunn and Arthington, 2002). In the Mekong, extensive studies all conclude that mainstream hydropower developments will have a major negative impact on fisheries resources through two main mechanisms: 1) river fragmentation and disruption of fish migrations (in particular loss of access to breeding sites), and 2) a significant loss of nutrients due to sediment retention by dams, resulting in an overall loss of water productivity (Baran et al., 2015).

Water abstraction and the construction of dams can also have a major impact on the migration of large shrimp. For example, damming of the lower reaches of one of the main drainages of the Caribbean National Forest in Puerto Rico has had a major impact on shrimp recruitment. More than 50% of migrating larvae were drawn into water intakes for municipal supplies, and juvenile shrimps returning upstream faced severe predation below the dam (Pringle and Scatena, 1999). Cascading impacts throughout the riverine ecosystem can occur, because many such species are top predators and have an important role in structuring natural communities and the way that carbon and energy move through aquatic food webs.

Large dams may also act as barriers to the movement of materials other than biota. For example, fine sediment may be trapped and no longer available for downstream and lateral transport in floodwaters, thus preventing the annual replenishment of floodplain habitats and deltas, vital for natural communities as well as agricultural production (see Section 2.4.3). Disruption of floodplain connections (through levee construction, blocking of distributary channels, and converting wetlands for aquaculture) are also big issues in many Asian floodplain rivers (Dudgeon, 2011).

2.4 Ecological Responses to Other (Non-Flow) Stressors

Alterations to the flow regime and the associated effects of water resource development, through loss of habitat from impoundment or loss of longitudinal and lateral connectivity, are not the only stressors affecting environmental assets and values associated with rivers and their floodplains (Dudgeon et al., 2006; Vörösmarty et al., 2010). The following sections (2.4.1 through 2.4.4) provide a brief summary of some of these issues, noting that these were not considered in our assessment of ecological risk.

2.4.1 *Thermal pollution*

Water temperature directly influences the metabolic rates, physiology, and life-history traits of aquatic species and helps determine rates of important ecological processes, such as nutrient cycling and productivity (Olden and Naiman, 2010). Deep impoundments are prone to thermal stratification, and water released from the lower strata of dams is often much colder (and poorer in water quality - including lower oxygen) than ambient surface waters (Bobat, 2015). Reservoirs tend to moderate downstream thermal regimes, with lower temperatures in the spring and summer months, higher temperatures in winter, and a dampened seasonal signal (Olden and Naiman, 2010). Such releases can make many kilometres of river downstream unsuitable habitat for riverine plants and animals.

2.4.2 *Climate change*

In developing Asian countries, climate change is having negative impacts across the water, agriculture, and environment sectors (Dudgeon, 2011; Wong et al., 2014). This is especially so in the low-lying river basins, such as the Mekong (Keskinen et al., 2010; Kano et al., 2016) and Ganges Deltas (Gray and Mueller, 2012), which have been affected by extremes of temperature, rainfall, and rising sea levels. Myanmar is also one of the countries most vulnerable to climate change on a global basis (SOBA 4.1 report). In terms of fishery resources, climate effects are likely to lead to: 1) reduced availability of wild fish stocks due to degraded water quality, new predators and pathogens, and changed abundance of food available to the fishery species; 2) changes in fish migration and recruitment patterns and success; 3) reduced wild fish stocks, intensified competition for fishing areas, and more migration by fisherfolks; 4) alteration to freshwater capture fisheries due to saline influence (SOBA 4.1 report). People consulted for this study observed that the late arrival of the monsoon was already affecting fish migration and spawning.

2.4.3 *Changes in sediment regime*

The role of dams in sediment sequestration is well established (Vörösmarty et al., 2003). However, the implication of this observed in major rivers across Asia has been profound, with recent delta shrinkage and reductions in the rate of aggradation (Syvitski and Kettner, 2011; Dudgeon, 2011). This is likely to compound the effects of sea-level rise on river deltas and alter the spatial and temporal patterns inundation on floodplains (SOBA 3 report). It is not clear how sediment sequestration by dams and associated nutrient reduction will interact with the other effects of dams (e.g., flow alteration, barriers to connectivity) and influence aquatic biodiversity and fisheries production.

2.4.4 *Water pollution*

Flow regulation seldom occurs in isolation from changes in catchment land use, with intensive agriculture and urbanisation, mining, and industry also having wide-ranging and cascading effects on river ecosystems (Allan, 2004; Vörösmarty et al., 2010). Thermal pollution and the associated water quality issues associated with stratification of reservoirs are briefly noted in Section 2.4.1. Water pollution issues in the Ayeyarwady Basin are considered more comprehensively in the SOBA 1.3 report. The impact of pollutant loading to river systems (e.g., from industrial or urban sources) can be ameliorated by flow – '*dilution being the solution to pollution.*' As noted above (Section 2.3.1), reduction in base flows can be associated with water quality problems, and this is, undoubtedly, compounded by diffuse and non-point source pollution.

3 ECOHYDROLOGICAL RISK ASSESSMENT APPROACH AND METHODOLOGY

3.1 Overview of the Approach

This ecohydrological assessment of the Ayeyarwady Basin is based on a rapid assessment approach to achieve the following:

- Collate relevant literature (including SOBA Draft Package reports) and undertake a mini-review of key freshwater biodiversity assets, ecosystem values, and ecological processes of the Ayeyarwady Basin.
- Review and conceptualise the critical ecohydrological mechanisms that link hydrology with the maintenance of biodiversity, ecosystem values, and ecological processes.
- Collate available observed and measured hydrological data – liaising with eWater Solutions (SOBA 1.2 report team) to provide hydrologic data (modelled) to represent pre- and post- water resource development scenarios to allow a hydrologic assessment.
- Based on these data, develop and apply a method to quantitatively characterise spatio-temporal variation in natural hydrologic regimes throughout the Ayeyarwady Basin. This includes the calculation of a series of hydrologic metrics describing ecologically-relevant components of the flow regime (i.e., magnitude, frequency, timing, duration, seasonality, and temporal variability of flows).
- Using the modelled data from SOBA 1.2 and other information sources, characterise the spatial extent and intensity of hydrologic alteration of these key components of the flow regime as well exposure to other threats caused by water resource developments (including the spatial extent of river impoundment and the degree of longitudinal fragmentation).
- Assess the likely risks to biodiversity, ecosystem values, and ecological processes caused by these water-related threats to the Ayeyarwady Basin. This includes a semi-quantitative risk ranking of each ecological response attribute (i.e., biodiversity, ecosystem values, and ecological processes) to hydrologic alteration, river impoundment, and longitudinal fragmentation in each sub-basin.
- Develop recommendations for a more detailed investigation (including assessment and implementation of environmental flows and other management interventions) to mitigate these risks and to identify future research priorities to address critical knowledge gaps.

3.2 Characterising Riverine Flow Regimes and Quantifying Hydrologic Alteration

3.2.1 *Data availability and SOURCE Model*

For this analysis, we used modelled daily discharge data (from SOURCE model outputs developed for the SOBA 1.2 report) for each of the 12 sub-basins in the Ayeyarwady Basin (Figure 3). The modelled flow covers the period from 1981 to 2016. The two flow scenarios available are the "without development" approach (referred to here as pre-development [PD]) and "current level of development" (referred to here as current development [CD]). These two flow scenarios are identical in all aspects (climate, hydrological calibration) except for the anthropogenic water resource development and extraction activities. For this reason, the comparison of the modelled PD (as reference) and CD (as test) flow series presents a good basis for considering the effects of water resource development on the flow regime. See SOBA 1.2 report for more details on the SOURCE model and flow scenarios.

It is difficult to develop a well-calibrated hydrological model with limited input data. By comparing the relative difference between model scenarios (rather than comparing model output to observed data), the effect of any model calibration deficiencies on the ecohydrological assessment are minimised, because they apply to both of the series used in the comparison.

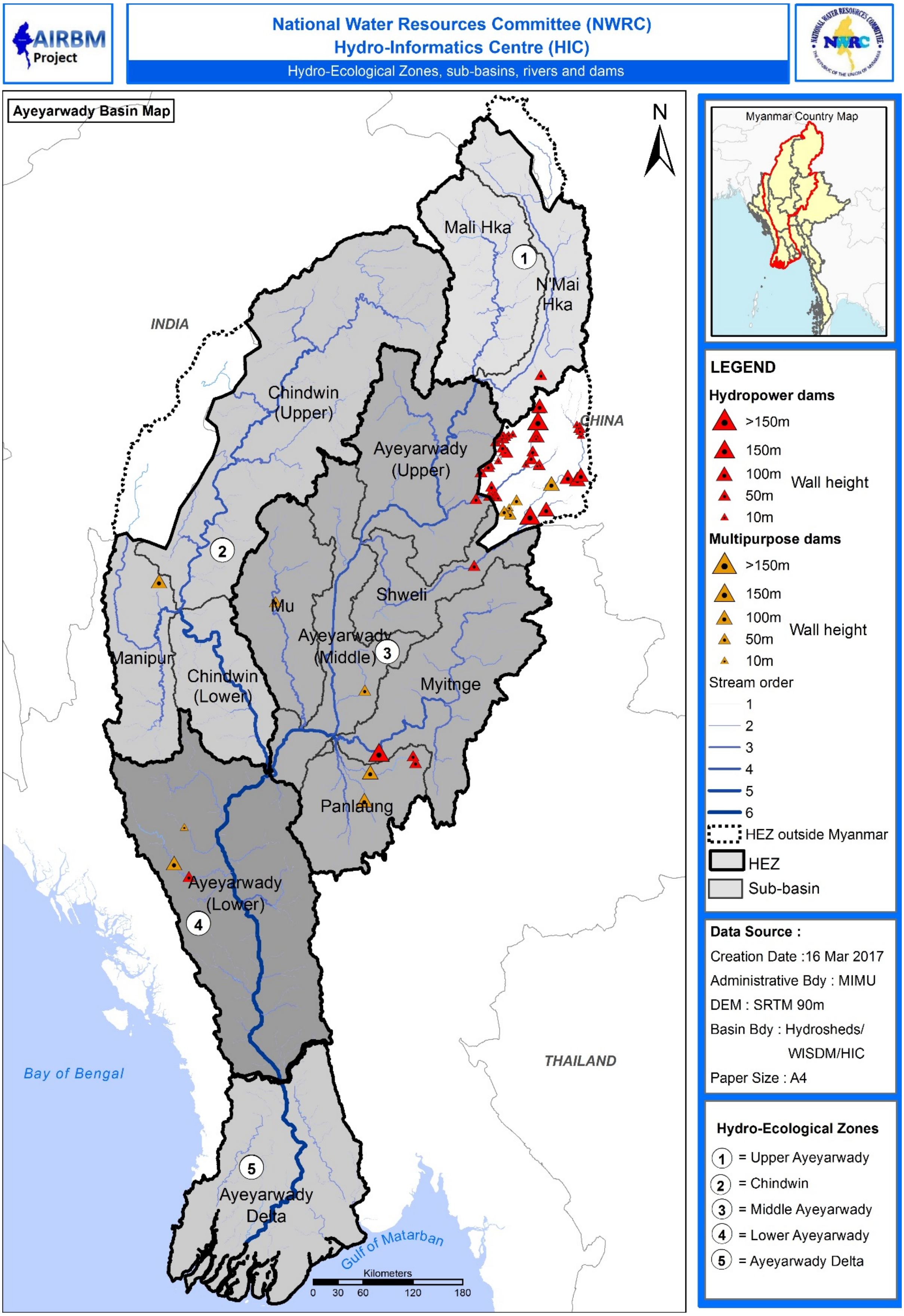

Figure 3 - Hydro-ecological zones, sub-basins, rivers, and dams in the Ayeyarwady Basin

3.2.2 *Ecologically-relevant hydrologic metrics*

A range of hydrologic metrics are routinely used to characterize ecologically-relevant components of the flow regime of rivers. Collectively, they describe variation in the magnitude, frequency, duration, timing, and rates of change of a range of different flows (e.g., high flows, low flows) as well as temporal variability in these metrics (Kennard et al., 2010; Olden and Poff, 2003; Bond and Kennard, 2017). For this report, we focused on 12 metrics that describe the key aspects of the flow regime based on measures of central tendency, high-flows, low-flows, timing, and variability (Table 1). These metrics also describe facets of the flow regime known to be sensitive to hydrologic alterations caused by human activities (Richter et al., 1996; Bunn and Arthington, 2002) and are potentially amenable to management through ecologically-sensitive dam operations and constraints on abstraction (Mackay et al., 2014). Hydrologic metrics were calculated using the Time Series Analysis module of the River Analysis Package (www.toolkit.net.au).

Table 1 - Description of the 12-hydrologic metrics used to characterise riverine flow regimes and quantify hydrologic alteration

Flow component	Metric	Method
Flow volume	Mean annual flow	Mean total annual flow for entire modelled period (1981 to 2016)
High flows	High flow magnitude	Flow exceeded on 10% of days (10th percentile flow)
	Mean duration of high spells	Mean duration of all spells above the PD 10th percentile flow
	Mean annual number of high spells	Mean of annual count of spells above the PD 10th percentile flow
Low flows	Low flow magnitude	Flow exceeded on 90% of days (90th percentile flow)
	Mean duration of low spells	Mean duration of all spells below the PD 90th percentile flow
	Mean annual number of low spells	Mean of annual count of spells below the PD 90th percentile flow
Timing and variability	Timing of high flow	Mean of annual day of year of maximum flow (based on Julian date determination using circular statistics)
	Variability in timing of high flow	Standard deviation/mean of Julian date of annual maximum flow
	Timing of low flow	Mean of annual day of year of minimum flow (based on Julian date determination using circular statistics)
	Variability in timing of low flow	Standard deviation/mean of Julian date of annual minimum flow
Seasonality	Proportion flow driest 6 months	Mean annual dry season flow (Dec to May)/mean total annual flow

3.2.3 *Quantifying hydrologic alteration*

We quantified the extent of hydrologic alteration in each sub-basin by comparing PD and CD flow characteristics following the general approach of Richter et al. (1996). For each hydrologic metric, we calculated the percentage difference between PD and CD flow characteristics (i.e., % difference = (CD - PD)/PD*100). Here, we assumed that both negative and positive differences represent deviations from the natural flow regime and would pose equivalent ecological risks. We also calculated an overall measure of flow alteration (i.e., combining information from all 12 metrics) using the Gower dissimilarity metric (Gower, 1971). We used this to quantify overall differences in PD and CD flow regimes for each sub-basin based on the 12-flow metrics described in Table 1. The Gower metric accommodates mixed data types and ranges from 0 to 1 (i.e., proportional), where higher values indicate greater divergence of the CD flow regime from the PD flow regime.

3.3 Semi-Quantitative Ecological Risk Assessment - Background

Ecological assets, processes and values in the Ayeyarwady Basin are facing increasing threats from a range of factors (Section 2), including hydrologic alteration, river impoundment, and longitudinal fragmentation. Cumulative impacts from these potentially interacting threats are unknown but may pose severe risks to these assets and values over the long term.

The spatial distributions of threats are varied but, in many places, little is known about which stressors are having the biggest impacts or cumulative effects (i.e., combined effects of multiple, potentially interacting threats). Mapping where threats occur is important for management, but it does not explicitly account for differences in the extent and nature of ecological responses to threats (Halpern et al., 2007; 2015). Understanding these differences in ecological responses is critical to identifying which threats have the biggest impacts on river-floodplain ecosystems as a whole (i.e., incorporates the cumulative effect of each threat on multiple ecosystem components in the area) and how to best address them at different scales. Quantifying these differences allows threats to be ranked on the severity of their potential impact on ecological integrity as well as allowing areas (e.g., sub-basins) to be ranked on their overall risk (by combining threat exposure and relative vulnerability). Such assessments, in turn, can inform identification of areas where more detailed investigations may be required to better understand the magnitude of potential impacts on ecological integrity and inform biodiversity conservation, threat mitigation, and spatial planning of decision-making.

This section outlines the development and application of a semi-quantitative risk assessment framework to estimate the cumulative impacts of current threats to ecological assets in the Ayeyarwady Basin. The term 'cumulative risk assessment' is defined as an analysis, characterization, and quantification of the combined (additive or interactive) risks to the environment from multiple anthropogenic threats over time (U.S. Environmental Protection Agency [USEPA], 2003). Our approach follows most elements of this definition, except that we do not assess the effects of interacting threats due to insufficient knowledge, and we assess present-day, not future, changes in threats. The assessment accommodates data paucity; integrates multiple threats and ecological and habitat processes; and considers the species-specific attributes that confer resistance and resilience to disturbance. The assessment uses best available data to quantify threat exposure and uses literature, unpublished data, ecological theory, and expert knowledge (from the report authors) to estimate species vulnerability to threats.

3.4 Risk Assessment Approach

The approach used to assess risks to aquatic biodiversity assets, ecological processes, and values from cumulative risks of flow alteration, impoundments, and fragmentation (described in Table 3) is modified from Halpern et al. (2007; 2008; 2015). Cumulative impacts (I_C) are calculated for each sub-basin as follows:

$$I_C = \sum_{i=1}^{n} \frac{1}{m} \sum_{j=1}^{m} T_i * S_j * \mu_{i,j}$$

- Where T_i is the value (scaled between 0 and 1) of a threat at sub-basin *i*;
- S_j is the occurrence/importance of asset, process or value *j* in each sub-basin (scored as 3, 2, or 1 for high, medium, or low, respectively – see Section 3.6); and
- μ_{ij} is the vulnerability weight for the threat *i* and asset, process or value *j* (scored as 3, 2, 1 or 0 for high, medium, low, or no threat, respectively – see Section 3.7), given *n* = 3 threats and *m* = 9 assets/processes/values.

The cumulative impact of a particular threat (I_D) across all assets, processes and values is calculated as follows:

$$I_T = \sum_{j=1}^{m} T_i * S_j * \mu_{i,j}$$

and the cumulative impact of all threats on a particular asset/process/value (I_S) is calculated as follows:

$$I_S = \sum_{i=1}^{n} T_i * S_j * \mu_{i,j}$$

By combining information on weighted vulnerabilities to threats of assets, processes and values, the spatial occurrence/importance of these assets, processes and values and the relative threat intensities across sub-basins, the sum of these vulnerability-weighted threat-by-asset, process or value combinations then represents the relative cumulative impact of threats on all assets, processes and values in a particular sub-basin.

From these data, we can evaluate:

1) Which sub-basins are exposed to the greatest number and intensity of threats.
2) How vulnerability to threats varies among assets/processes/values.
3) Which sub-basins are at the highest risk (i.e., contain a high number/importance of vulnerable assets, processes and values and are exposed to the highest threat intensities).

3.5 Quantifying Ecohydrological Threat Exposure

We calculated the relative exposure of each sub-basin to each of three ecohydrological threats (flow alteration, river impoundment, longitudinal fragmentation) identified and reviewed in Section 2.

Exposure to each threat was calculated as follows:

1. *Flow alteration* – The Gower dissimilarity coefficient (Gower, 1971) was used to quantify differences in PD and CD flow regimes for each sub-basin based on the 12-flow metrics described previously. The Gower metric accommodates mixed data types and ranges from 0 to 1, where higher values indicate greater divergence of the CD flow regime from the PD flow regime.
2. *River impoundment* – We estimated the spatial extent of impounded rivers and streams (in square kilometres [km^2]) in each sub-basin, using the HydroLAKES dataset (Lehner and Messager, 2016) and Arc GIS. The relative degree of impoundment for each sub-basin was expressed as the proportion of total sub-basin area covered by reservoirs. We acknowledge there are limitations in this dataset concerning the spatial accuracy, temporal currency, and appropriate identity of artificial versus natural waterbodies, but it represented the best and most spatially comprehensive information available to us at the time of analysis.
3. *Longitudinal fragmentation* – We used a modification of the River Fragmentation Index (RFI) (Grill et al., 2015) to quantify the degree of fragmentation caused by large dams in each sub-basin. This index is a modification of the original Dendritic Connectivity Index (DCI) developed by Cote et al. (2009) and quantifies the cumulative impact of the number, permeability, and location of barriers to longitudinal connectivity of a river network. RFI was calculated as follows:

$$\mathrm{RFI} = 1 - \left(\sum_{i=1}^{n} \frac{l_i^2}{L^2{}_i} \right)$$

- Where n is the number of fragments;
- l_i is the total river length of the contiguous network fragment i that is disconnected by one or more dams (i.e., the fragment can be up- or downstream of a dam or in-between dams); and
- L is the total length of the entire river network.

The RFI of an unfragmented river network is 0, whereas each subsequent dam increases the RFI to a maximum of 1, depending on the size distribution of the fragments. A single dam in a previously undisturbed network leads to greatest fragmentation if it splits the network into two equal volume fragments, in which case the RFI increases to 0.5. Note that modifications to this basic index (e.g., using river volume instead of segment length) (Grill et al., 2014; 2015) could not be applied due to data limitations. Moreover, we assumed all barriers were impassable (i.e., permeability set to zero, which we considered appropriate for large dams, such as those assessed in this study; see also Grill et al., 2014).

3.6 Estimating Spatial Variation in Occurrence or Importance of Biodiversity Assets, Ecological Processes and Ecosystem Values

We estimated the relative occurrence/importance of biodiversity assets, ecological processes, and ecosystem values in each sub-basins using expert opinion with reference to available information for the Ayeyarwady Basin. Ideally, we would use empirical data on the spatial distribution of biodiversity assets (e.g., species occurrences), the relative important of ecological processes in sustaining biodiversity, and the actual fisheries production (based on catch data); however, much of this information for the Ayeyarwady Basin is lacking, could not be accessed, or could not be collated in time for use in this study. Practitioners often rely on expert knowledge in such situations (Burgman 2005; Runge et al., 2011; Martin et al., 2012). The relative occurrence or importance among sub-basins of each biodiversity asset, ecological process, and ecosystem value was scored as 3, 2, or 1 for high, medium, or low, respectively.

Biodiversity assets included:

- Migratory species
- Rare and endemic species
- Critical habitat - floodplain wetlands
- Critical habitat - flowing rivers and streams
- KBAs

Ecological processes included:

- Floodplain primary productivity
- Lateral connectivity (floodplain inundation)
- Longitudinal connectivity

Ecosystem values included:

- Fisheries production

3.7 Estimating Vulnerability of Assets, Processes and Values to Threats

Vulnerability weights were estimated using expert judgement (by the report authors) with reference to available information, and they represented (in relative terms) how vulnerable a given asset, process or value is to a given threat. We used expert judgment to estimate the vulnerability weights (μ_{ij}) because empirical data on ecological responses to threats in the Ayeyarwady Basin are lacking. The relative vulnerability of each biodiversity asset, ecological process, and ecosystem value was scored as 3, 2, 1, or 0 for high, medium, low, or no threat, respectively. We assumed all assets/processes/values were highly vulnerable to overall flow alteration. It would be desirable, in future work, to estimate relative vulnerability to flow alteration for different ecologically relevant components of the flow regime (e.g., vulnerability to alteration of high and low flow spell magnitude, frequency, duration, timing, variability).

4 ASSESSMENT OF HYDROLOGIC ALTERATION AND EXPOSURE TO OTHER WATER-RELATED THREATS

4.1 Summary of Hydrological Alteration for Each HEZ

We have applied 12 hydrologic metrics across each sub-basin to consistently characterise changes to hydrology through the effects of modelled water resource development. Each of the 12 metrics was calculated for both the modelled PD scenario and the modelled CD scenario. Table 2 shows the percentage change in each of the 12-flow metrics for each of the sub-basins in the Ayeyarwady Basin. A negative or positive percentage change indicates that the metric has decreased or increased, respectively, when comparing the CD scenario to the pre-development scenario. The raw values for each flow metric for each scenario are presented in Annex 1.

The Upper Ayeyarwady (HEZ 1) has experienced no detectable hydrological changes from water resource development and extraction (Table 2). Similarly, the Chindwin Basin (HEZ 2) has had relatively minor hydrological changes overall. The most notable change is the 15% increase in the duration of low flow spells (Table 2). Upstream, sub-basins within the Chindwin Basin have experienced more pronounced changes in flows, particularly the Manipur Sub-basin in which low flow magnitude has decreased by 9.78% and the duration of low flow spells has increased by 42% (see Section 4.3).

The Middle Ayeyarwady (HEZ 3) shows some major alterations in hydrology, with a 3% decrease in mean annual flow and <10% decreases in the magnitude, frequency and duration, and variability in timing of high flows, respectively (Table 2). Major changes in the mean duration (16% increase) and number (25% decrease) of low flow spells occurred, and minor changes (<5% absolute difference) in the timing and variability of low flow spells was evident. Upstream, sub-basins within the Middle Ayeyarwady experienced more dramatic changes in most flow regime characteristics, particularly the Mu, Panlaung, Myitnge, and Shweli Sub-basins, which have had a 29%, 22%, 7%, and 2%, respectively, decrease in mean annual flow volume. The magnitude and frequency of high flow spells has decreased substantially across these sub-basins (e.g., 38% reduction in high spell frequency in the Panlaung Sub-basin). Low flows have also changed considerably, with a maximum 39% decrease in low flow magnitude (Mu Sub-basin), a maximum increase in low flow spell duration of 106% (Panlaung), and a maximum increase in low flow spell frequency of 104% (Mu Sub-basin). The timing and variability of high and low flow spells have also changed considerably in these sub-basins (up to 42% difference from PD flows).

The Lower Ayeyarwady (HEZ 4) shows an overall decline of 2% flow volume, 8% decline in the average duration of high flow spells, and a >20% difference in the mean duration and frequency of low spells.

The hydrological alteration of each sub-basin is described in more detail in Section 4.2 with reference to the values in Table 2. Figure 4 shows a spatial summary of key hydrologic metrics across all sub-basins.

Table 2 - Percentage change in hydrologic metrics between CD and PD modelled flow scenarios for each sub-basin
Negative value indicates that the metric has decreased for the CD compared to PD scenario.

		HEZ 1		HEZ 2			HEZ 3						HEZ 4
Flow class	**Metric**	N'Mai Hka	Mali Hka	Upper Chindwin	Manipur	Lower Chindwin	Upper Ayeyarwady	Shweli	Myitnge	Panlaung	Mu	Middle Ayeyarwady	Lower Ayeyarwady
Flow volume	Mean annual flow	0%	0%	0%	-1%	0%	0%	-2%	-7%	-22%	-29%	-3%	-2%
High flows	High flow magnitude	0%	0%	0%	0%	0%	-1%	0%	-7%	-31%	-25%	-2%	-2%
	Mean duration of high spells	0%	0%	0%	0%	0%	-0%	2%	4%	-4%	-22%	-1%	-8%
	Mean annual number of high spells	0%	0%	0%	0%	0%	-4%	-2%	-20%	-38%	-29%	-9%	-1%
Low flows	Low flow magnitude	0%	0%	0%	-10%	-2%	5%	-30%	-21%	-23%	-39%	2%	1%
	Mean duration of low spells	0%	0%	4%	42%	15%	-21%	90%	56%	106%	-9%	16%	21%
	Mean annual number of low spells	0%	0%	0%	13%	-1%	-38%	13%	0%	-8%	104%	-25%	-20%
Timing and variability	Timing of high flow	0%	0%	0%	0%	0%	1%	1%	4%	12%	21%	0%	0%
	Variability in timing of high flow	0%	0%	0%	0%	0%	-2%	-9%	-26%	-42%	-16%	-5%	-1%
	Timing of low flow	0%	0%	0%	-3%	-1%	5%	-9%	-7%	-12%	29%	4%	2.6%
	Variability in timing of low flow	0%	0%	1%	2%	1%	14%	-9%	27%	37%	-6%	-5%	-6%
Seasonality	Proportion flow driest 6 months	0%	0%	0%	-3%	-1%	4%	-7%	-5%	-1%	19%	1%	0%
Overall flow alteration	Gower dissimilarity*	0.00	0.00	0.02	0.02	0.01	0.05	0.05	0.09	0.18	0.19	0.03	0.04

*Gower dissimilarity reflects the overall degree of hydrologic alteration for each sub-basin (calculated using the Gower dissimilarity between hydrologic metrics calculated for PD and CD flow regimes). The Gower metric ranges from 0 to 1, where higher values indicate greater divergence of the CD flow regime from the PD flow regime.

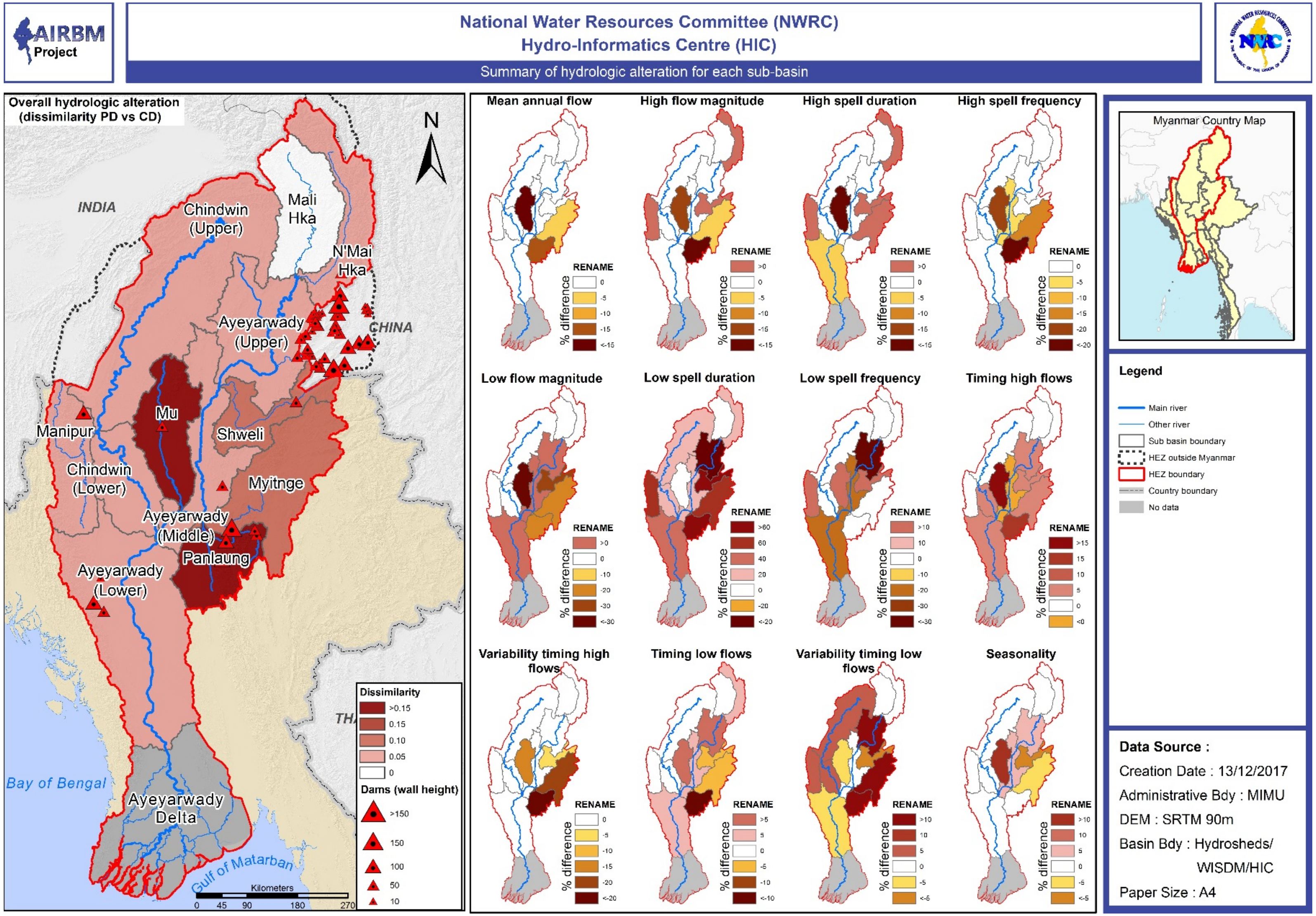

Figure 4 - Summary of hydrologic alteration for each sub-basin

Main map shows overall hydrologic alteration (Gower proportional dissimilarity between PD and CD modelled flow scenarios); inset maps show percent difference between PD and CD modelled flow scenarios for each metric.

4.2 Detailed Assessment of Hydrological Alteration for Sub-basins Within Each HEZ

4.2.1 *HEZ 1: Upper Basin*

HEZ 1 encompasses the upper basin with two major sub-basins, N'Mai Hka and Mali Hka. There were no hydrological changes detected for these sub-basins.

4.2.1.1 N'Mai Hka

The N'Mai Hka Sub-basin (mean annual flow 52,280 million cubic metres [MCM]) had no hydrological change across the metrics considered.

4.2.1.2 Mali Hka

There were no detectable differences between the two modelled scenarios for the Mali Hka Sub-basin. The mean annual flow for the modelled period was 89,412 MCM.

4.2.2 *HEZ 2: Chindwin Basin*

4.2.2.1 Chindwin (Upper)

Water resource development has had little effect on the hydrological metrics for the Chindwin (Upper) Sub-basin. The mean annual flow of 131,070 MCM is largely unchanged, and the timing of flows has not changed significantly under CD conditions. The main hydrological impact is that the mean duration of low flow spells has increased by 4 (Table 2).

4.2.2.2 Manipur

The Manipur Sub-basin flow volume has decreased slightly (1% from 29,250 million cubic metres per year [MCM/y]). The decrease in flow volume has occurred in the form of a lowering of the end of dry season low flow (Figure 5). Low flow magnitude has decreased by 10%, and the duration and frequency of low flow spells has increased by 42% and 13%, respectively (Table 2).

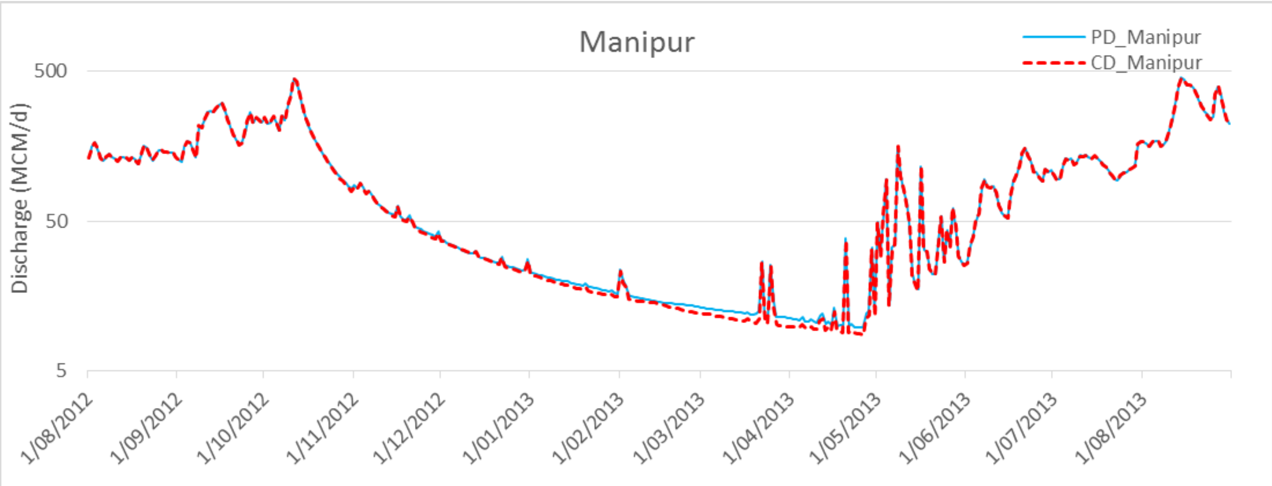

Figure 5 - Manipur Sub-basin example hydrographs for each modelled flow scenario
This shows the lowering of the end of dry season low flows for CD versus PD.

4.2.2.3 Chindwin (Lower)

The mean annual discharge from the Chindwin (Lower) Sub-basin (170,003 MCM) has not changed discernibly due to water resource development, but there has been a 15% increase in the duration of low flow spells (Table 2). It is likely that the changes to low flow in the Chindwin (Lower) Sub-basin are a flow through effect from the upstream Manipur Sub-basin.

4.2.3 HEZ 3: Middle Ayeyarwady

4.2.3.1 Ayeyarwady (Upper)

The Ayeyarwady (Upper) Sub-basin has a large number of hydropower dams; however there is no change to the total flow volume due to water resource development. However, there is a moderate change to the low flow regime. There is an overall increase in low flow magnitude (5%), which is most noticeable at the end of the dry season (Figure 6). The elevated dry season flows have resulted in a 21% decrease in the mean duration of low flow spells (from 25 days to 20 days) and a decline in the mean annual number of low spells (38%). Inter-annual variability in the timing of low flows has also increased by 14%.

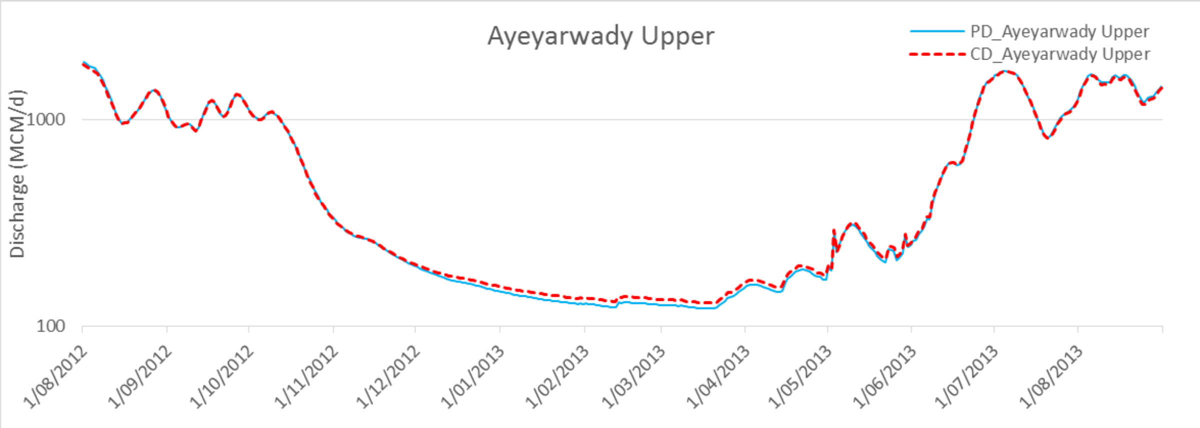

Figure 6 - Upper Ayeyarwady Sub-basin example hydrographs for each modelled flow scenario
This shows the elevated dry season low flows for CD versus PD.

4.2.3.2 Shweli

The Shweli Sub-basin has had a small decrease in overall flow volume (2% from 18,456 MCM/y). This has mostly occurred toward the end of the dry season, resulting in a reduction in low flow magnitude (30%), and an increase in the duration and frequency (90% and 13%, respectively) of low flow spells (Table 2, Figure 7).

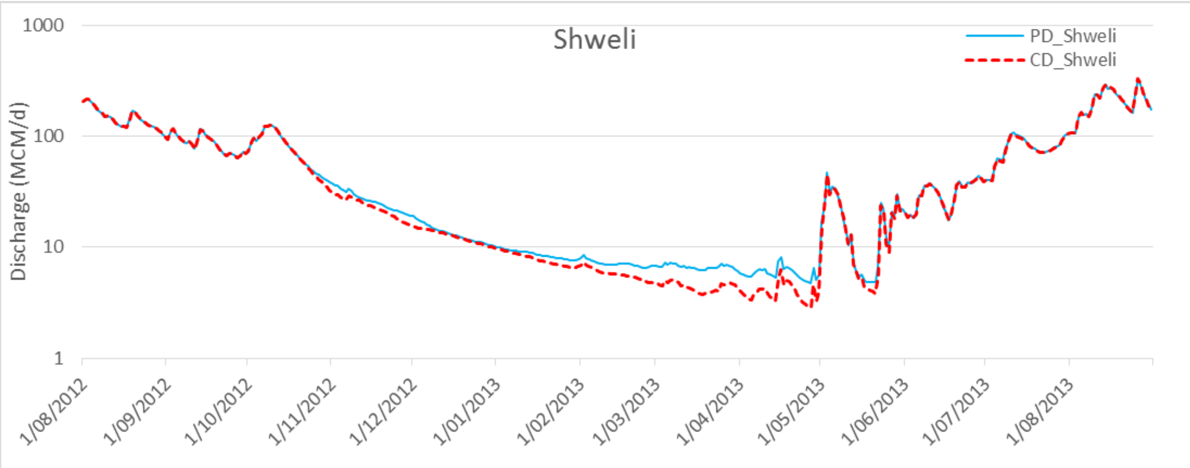

Figure 7 - Shweli Sub-basin example hydrographs for each modelled flow scenario
This shows the reduced end of dry season discharge for CD versus PD.

4.2.3.3 Myitnge

Water resource development in the Myitnge Sub-basin has reduced the overall flow volume by 7% (from 29,489 MCM/y). The hydrologic alteration is in the form of a reduction in the magnitude (-7%), frequency (-20%), and inter-annual variability in timing (-26%) of high flow spells (Table 2). Major changes in low flows are also evident (Table 2, Figure 8), with a 21% reduction in low flow magnitude and 56% increase in duration of low flow spells (average low spell duration has increased from approximately 6 to 10 days). Inter-annual variability in the timing of high flows has decreased by 26% (i.e., the timing of the high flow period is more predictable from year to year). Low flows occur slightly earlier in the year on average (7% difference), but inter-annual variability in the timing of low flows has increased by 27% (i.e., the timing of the low flow period is more variable).

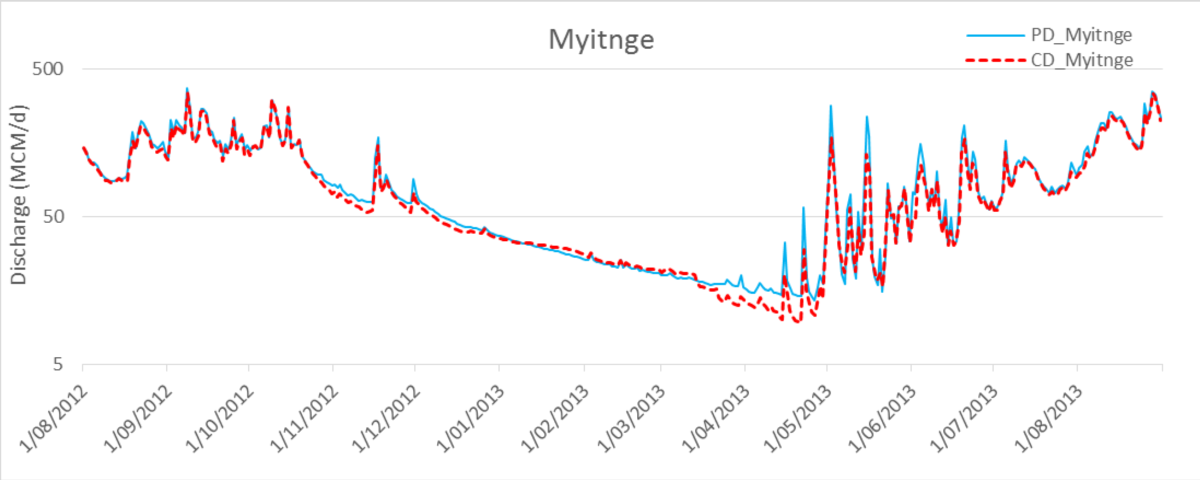

Figure 8 - Myitnge Sub-basin example hydrographs for each modelled flow scenario
This shows the reduced peak flow in early wet season and reduced late dry season flow for CD versus PD.

4.2.3.4 Panlaung

Water resource development has substantially reduced the mean annual discharge in the Panlaung Sub-basin by 22% (from 6,511 MCM/y). This has resulted in a 31% reduction in high flow magnitude, particularly at the start of the wet season and presumably as reservoirs fill (Figure 9). Low flows have also been affected with a 23% reduction in low flow magnitude and a 106% increase in the duration of low flow spells. Note, in Figure 9, the dramatic difference in the dry season recession – from a smooth continuous decline under the pre-development regime to a more variable regime under CD. This is reflected in a 37% increase in inter-annual variability of timing of low flows. In contrast, there has been a 42% reduction in inter-annual variability of the timing of high flows.

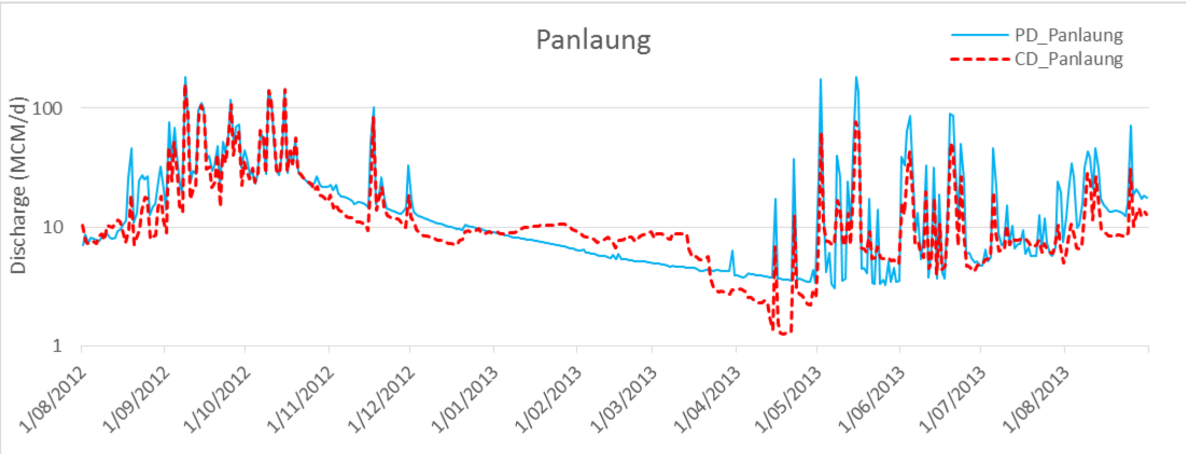

Figure 9 - Panlaung Sub-basin example hydrographs for each modelled flow scenario
This shows the differences in high flow magnitude and post-wet season recession flows between CD and PD.

4.2.3.5 Mu

Water resource development in the Mu Sub-basin has reduced discharge by 29% (from 8,578 MCM/y to 6,133 MCM/y). Water resource development in the sub-basin appears to be capturing large wet season flow events, with the magnitude of high flows being reduced by 25% (Table 2, Figure 10). Dry season flows are also affected, with early dry season flows being lower, and late dry season flows being higher (Figure 10). This potentially reflects storage and use of water for irrigation and a subsequent return of this water to the main river channel by the late dry season. These changes are reflected in the timing and variability measures, with high and low flows occurring later in the year (increased values in Table 2) and inter-annual variability in these flows decreasing, indicating a less variable flow regime. Overall, the magnitude and duration of low flow spells has decreased (by 39% and 9%, respectively) and the frequency of low flow spells has doubled (by 104%).

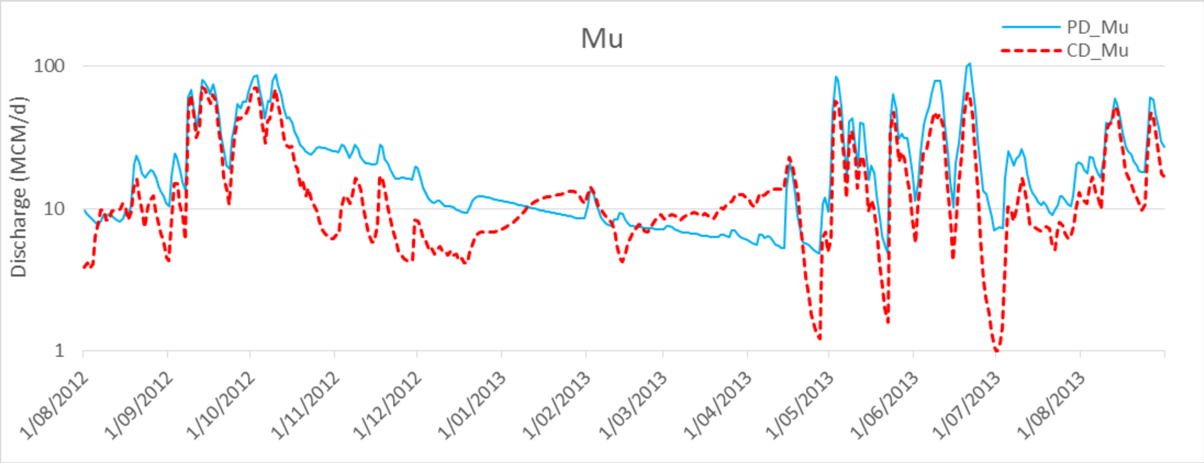

Figure 10 - Mu Sub-basin example hydrographs for each modelled flow scenario
This shows the reduced wet season peaks and elevated end of dry season flows for CD versus PD.

4.2.3.6 Ayeyarwady (Middle)

The Ayeyarwady (Middle) Sub-basin is downstream from the other HEZ 3 sub-basins and the HEZ basin. Consequently, the more dramatic effects in the smaller basins are diluted by the inputs from other basins further upstream. The Ayeyarwady (Middle) Sub-basin shows some major alterations in hydrology, with a 3% decrease in mean annual flow (from 259,019 MCM/y) and <10% decreases in the magnitude, frequency, duration, and variability in timing of high flows, respectively (Table 2, Figure 11). Major changes in the mean duration (16% increase) and number (25% decrease) of low flow spells occurred, and minor changes (<5% absolute difference) in the timing and variability of low flow spells were evident.

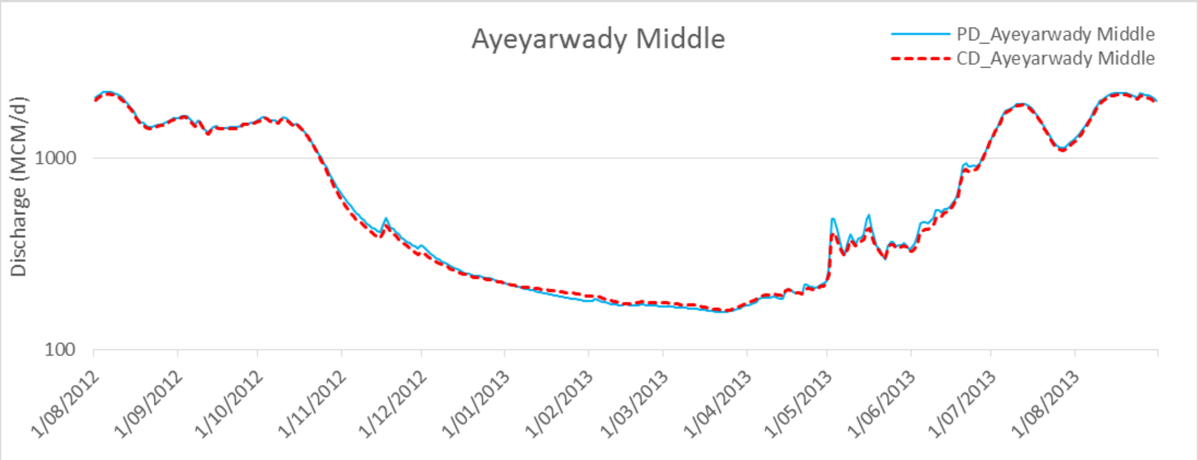

Figure 11 - Middle Ayeyarwady Sub-basin example hydrographs for each modelled flow scenario
This shows the slightly reduced early wet season high flows for CD versus PD.

4.2.4 *HEZ 4: Lower Ayeyarwady*

Collectively, water resource development in the upstream basins results in a small overall volumetric decrease in discharge from the Lower Ayeyarwady (2% reduction from 466,401 MCM/y) (Table 2). The Lower Ayeyarwady also has an 8% decline in the average duration of high flow spells and major changes in the duration (21% increase) and frequency (20.0% decrease) of low flow spells (Figure 12). Relatively small changes in the timing (3% increase) and inter-annual variability (6% decrease) of low flows were also evident (Table 2).

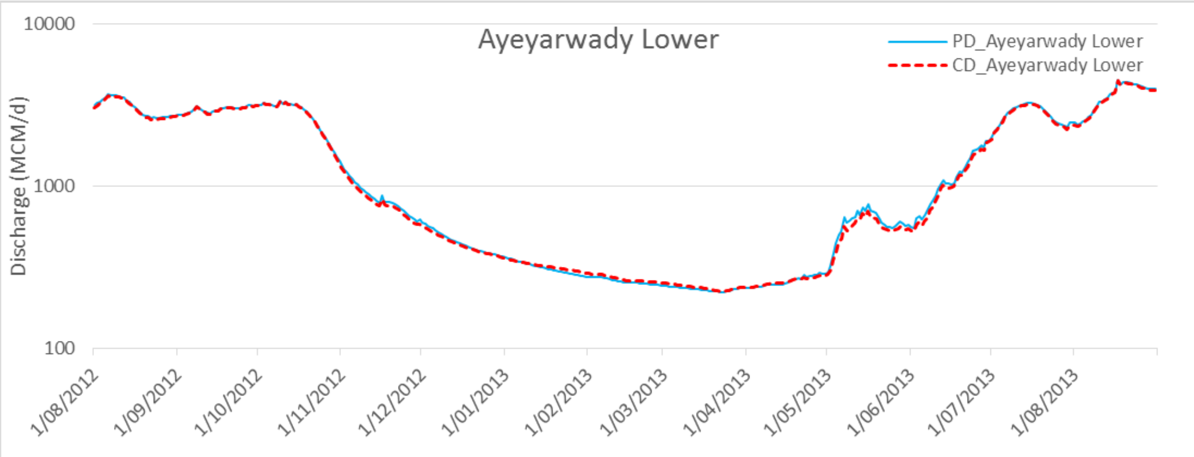

Figure 12 - Lower Ayeyarwady example hydrographs for each modelled flow scenario
This shows the slightly reduced early wet season high flows for CD versus PD.

4.3 Exposure to Other Water-Related Threats

4.3.1 *River impoundment*

The relative exposure of each sub-basin to the threat of river impoundment is presented in Table 3 and Figure 13. River impoundment was highest in the Ayeyarwady (Upper), Mu, and Panlaung Sub-basins. The Ayeyarwady (Middle), Ayeyarwady (Lower), and the Manipur Sub-basins had lower exposure to river impoundment, and the remaining sub-basins had little or no impoundment of riverine habitat.

4.3.2 *Longitudinal fragmentation*

The relative exposure to longitudinal fragmentation of each sub-basin is presented in Table 3 and Figure 13. The Shweli, Panlaung, and Mu Sub-basins were severely affected by longitudinal fragmentation (RFI scores $\geq$ 0.5). The Ayeyarwady (Upper), Ayeyarwady (Middle), Ayeyarwady (Lower), and Myitnge Sub-basins were also affected by fragmentation, with RFI scores between 0.1 and 0.5.

Table 3 - Relative exposure in each sub-basin to threats posed by river impoundment (proportion of sub-basin area) and longitudinal fragmentation (RFI)
Each threat can have a maximum exposure score of 1 at a given sub-basin.

HEZ	Sub-basin	Ecohydrological threat	
		River impoundment	Longitudinal fragmentation
Upper Basin (1)	N'Mai Hka	0.0000	0.0324
Upper Basin (1)	Mali Hka	0.0002	0.0000
Chindwin Basin (2)	Upper Chindwin	0.0002	0.0000
Chindwin Basin (2)	Manipur	0.0032	0.0155
Chindwin Basin (2)	Lower Chindwin	0.0007	0.0000
Middle Basin (3)	Upper Ayeyarwady	0.0457	0.3640
Middle Basin (3)	Shweli	0.0004	0.7298
Middle Basin (3)	Myitnge	0.0002	0.1320
Middle Basin (3)	Panlaung	0.0076	0.5816
Middle Basin (3)	Mu	0.0184	0.4996
Middle Basin (3)	Middle Ayeyarwady	0.0038	0.2665
Lower Basin (4)	Lower Ayeyarwady	0.0032	0.1878

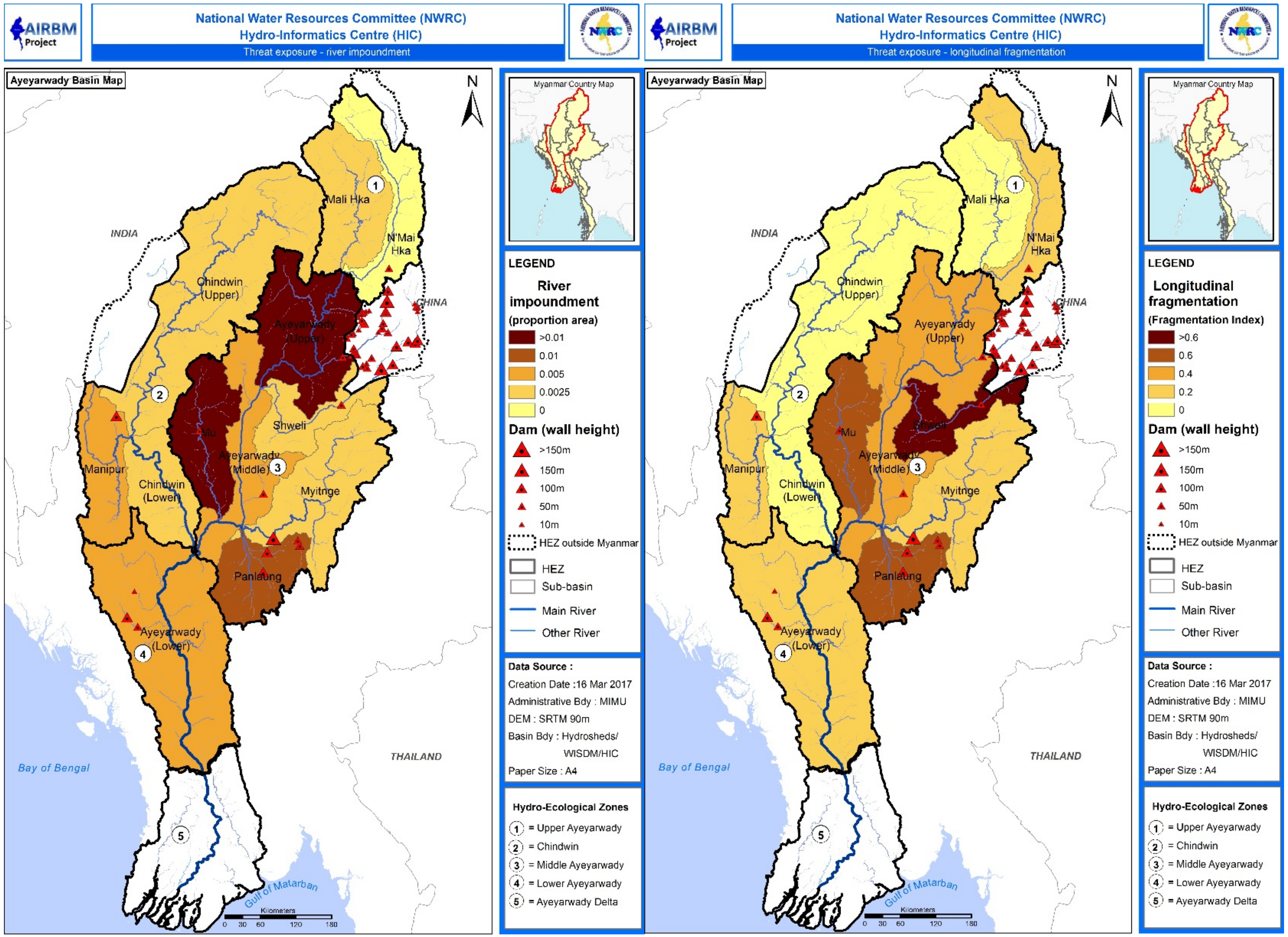

Figure 13 - Spatial variation in relative exposure to threats posed by (a) river impoundment (proportion of sub-basin area) and (b) longitudinal fragmentation (RFI), for each sub-basin

Each threat can have a maximum exposure score of 1 at a given sub-basin.

5 ECOLOGICAL RISKS FROM HYDROLOGIC ALTERATION AND OTHER WATER-RELATED THREATS

5.1 Spatial Variation in Occurrence or Importance of Assets, Processes and Values

The estimated relative occurrence or importance of biodiversity assets, ecological processes, and ecosystem values in each sub-basin of the Ayeyarwady Basin is presented in Table 4.

Table 4 - Estimated relative occurrence or importance of biodiversity assets, ecological processes, and ecosystem values across all sub-basins

Relative occurrence or importance among sub-basins was scored as 3, 2, or 1 for high, medium, or low, respectively.

HEZ	Sub-basin	Biodiversity assets					Ecological processes			Values
		Migratory species	Rare/endemic species	Floodplain wetlands	Flowing rivers and streams	Key Biodiversity Areas	Floodplain primary productivity	Lateral connectivity	Longitudinal connectivity	Fisheries production
Upper Basin (1)	N'Mai Hka	1	3	1	3	3	1	1	1	1
Upper Basin (1)	Mali Hka	1	3	1	3	3	1	1	1	1
Chindwin Basin (2)	Upper Chindwin	1	3	2	3	3	2	2	2	1
Chindwin Basin (2)	Manipur	2	3	2	3	1	2	2	2	1
Chindwin Basin (2)	Lower Chindwin	2	2	2	3	2	2	2	3	2
Middle Basin (3)	Upper Ayeyarwady	2	3	3	3	2	3	3	2	2
Middle Basin (3)	Shweli	2	2	2	3	2	2	2	2	2
Middle Basin (3)	Myitnge	3	2	2	3	1	2	2	2	2
Middle Basin (3)	Panlaung	2	2	3	3	1	3	3	2	2
Middle Basin (3)	Mu	3	2	3	3	1	3	3	2	2
Middle Basin (3)	Middle Ayeyarwady	3	2	3	3	2	3	3	3	3
Lower Basin (4)	Lower Ayeyarwady	3	1	3	2	2	3	3	3	3

5.2 Vulnerability of Assets, Processes and Values to Threats

Expert elicited scores for vulnerability to each threat for each biodiversity asset, ecosystem process, and ecosystem value are presented in Table 5.

Table 5 - Expert elicited scores for vulnerability to each threat for each biodiversity asset, ecosystem process, and ecosystem value, respectively

Vulnerability to each threat ranges from 0 (no threat) to 3 (high), respectively.

	Ecohydrological threat		
	Flow alteration	River impoundment	Longitudinal fragmentation
Biodiversity assets			
Migratory species	3	0	3
Rare/endemic species	3	3	2
Floodplain wetlands	3	1	1
Flowing rivers and streams	3	3	1
Key Biodiversity Areas	3	3	3
Ecological processes			
Floodplain primary productivity	3	1	1
Lateral connectivity	3	1	1
Longitudinal connectivity	3	0	3
Ecosystem value			
Fisheries production	3	2	3

5.3 Ecological Risks from Hydrologic Alteration

Assessment of cumulative risks from hydrological alteration, revealed that the Panlaung and Mu Sub-basins in HEZ 3 were at substantially higher risk than all other sub-basins (Figure 14a, Figure 15). These sub-basins were exposed to flow alteration with the highest cumulative intensity (Table 3) and contained a relatively high number of assets that were all highly vulnerable to this threat (Table 4, Table 5). Thus, the Panlaung and Mu Sub-basins can be considered of relatively high conservation concern. Other sub-basins in HEZ 3 were at moderate risk from hydrologic alteration compared with elsewhere, including the Myitnge, Ayeyarwady (Upper), Shweli, and Ayeyarwady (Middle) Sub-basins (Figure 14a, Figure 15). The Ayeyarwady (Lower) Sub-basin (HEZ 4) was also assessed as being at moderate risk, whereas sub-basins in HEZ 1 and HEZ 2 were at relatively low risk from hydrologic alteration compared with elsewhere (Figure 14a, Figure 15).

Ecological assets/processes/values assessed as being at highest cumulative risk from hydrologic alteration (Figure 14b) included flowing rivers and streams, floodplain wetlands, floodplain primary productivity, lateral connectivity, and migratory species. Rare and endemic species, longitudinal connectivity, and fisheries production were of lower, but still substantial, risk; whereas KBAs were at lowest risk, because there were largely not exposed to the threat of hydrologic alteration (being concentrated in HEZs with comparatively little flow regulation by dams).

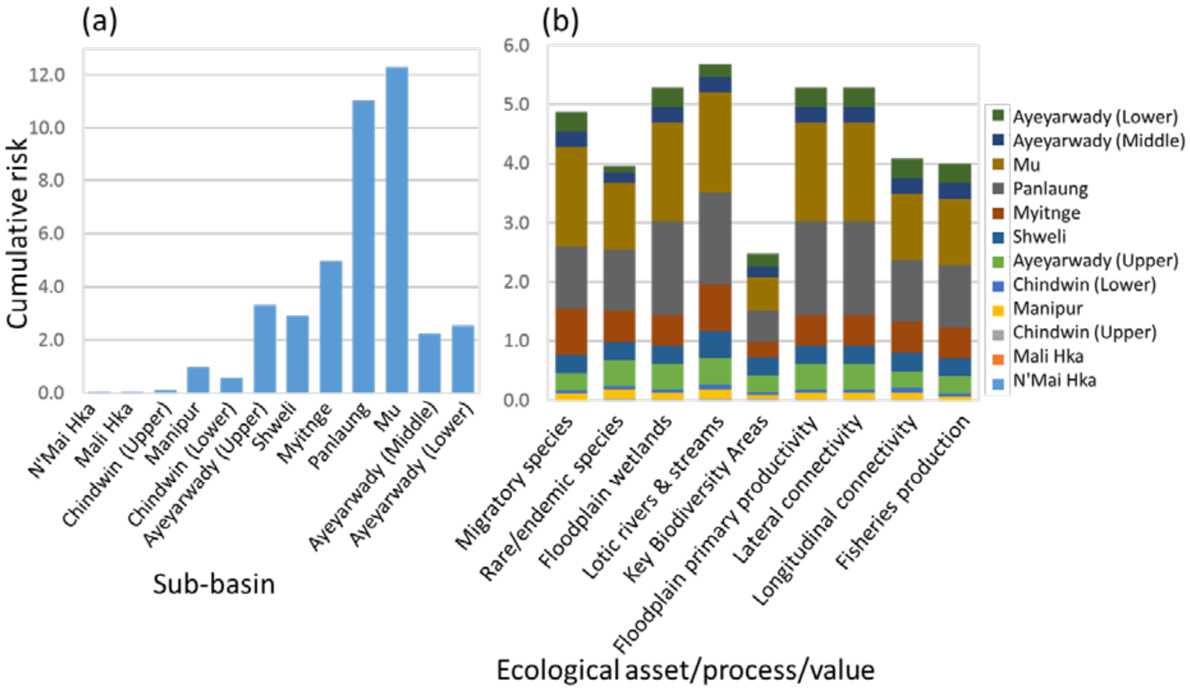

Figure 14 - Cumulative ecological risks from hydrologic alteration across (a) all assets, processes and values in each sub-basin and (b) each asset, process and value in each sub-basin (indicated by colours)
Cumulative impact combines threat exposure data with the occurrence or importance of each asset, process and value and their vulnerability to threats for each sub-basin. A high-risk score for a given sub-basin could be attained by that sub-basin having high exposure to a threat and containing a high occurrence or importance of highly vulnerable assets, processes and values.

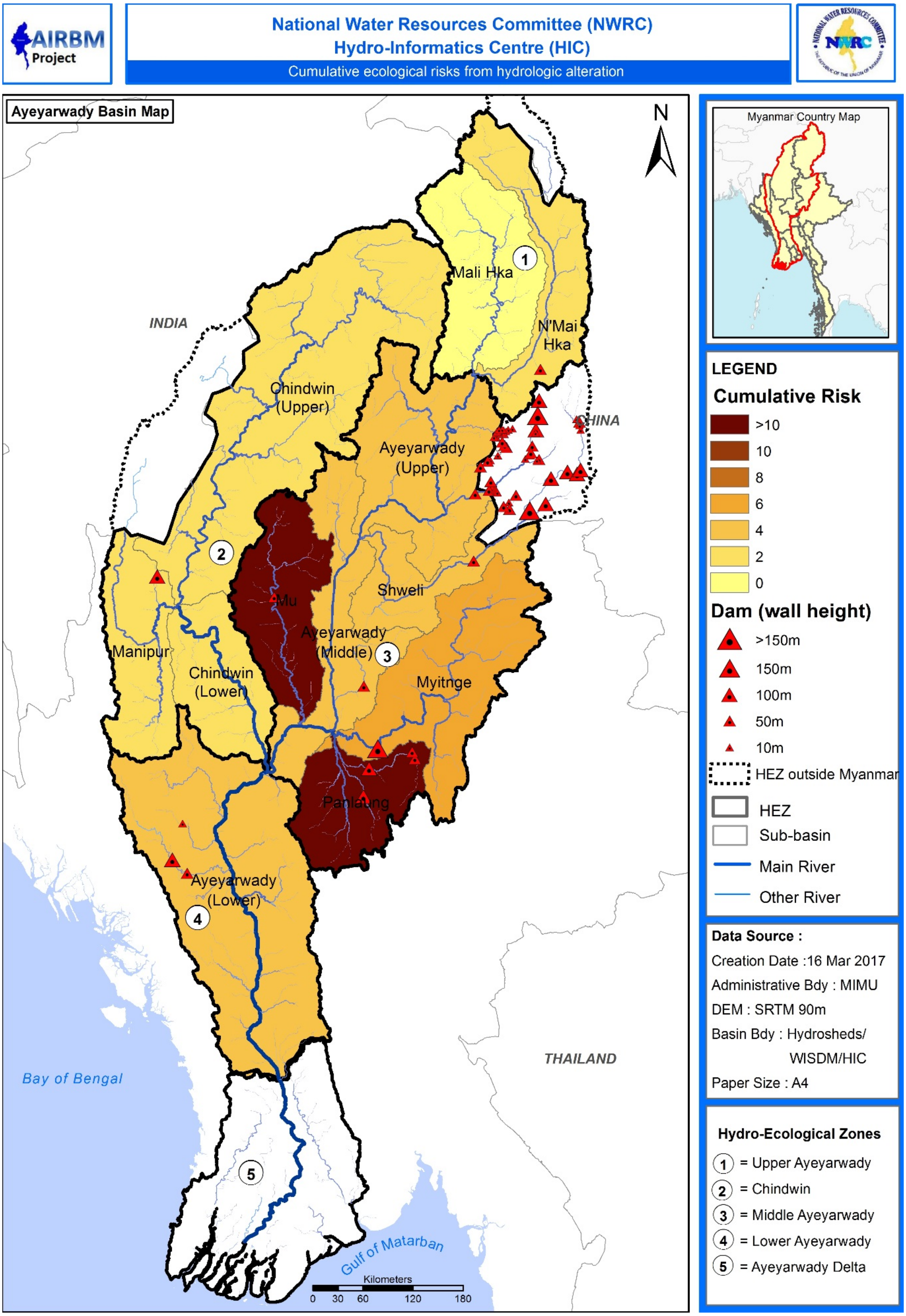

Figure 15 - Spatial variation in cumulative risks from flow alteration across all assets, processes and values in each sub-basin

5.4 Ecological Risks from River Impoundment

Assessment of cumulative risks from river impoundment, revealed that the Ayeyarwady (Upper) and, to a lesser extent, Mu Sub-basins in HEZ 3 were at substantially higher risk than all other sub-basins (Figure 16a, Figure 17). These sub-basins contained the highest proportion of impounded area (Table 3) and contained a relatively high number of assets that were all highly vulnerable to this threat (Table 4, Table 5). Other sub-basins, at relatively minor risk, included the Panlaung, Ayeyarwady (Middle), Manipur, and Ayeyarwady (Lower) Sub-basins. Although the Shweli Sub-basin contains a relatively high number of dams (Figure 17), they are of comparatively small size (area), so this sub-basin was assessed as being of low risk.

Ecological assets, processes and values assessed as being at highest cumulative risk from river impoundment (Figure 16b) included rare and endemic species, flowing rivers and streams, KBAs, and fisheries production. Floodplain wetlands, floodplain primary productivity, and lateral connectivity were assessed as being at relatively lower cumulative risk.

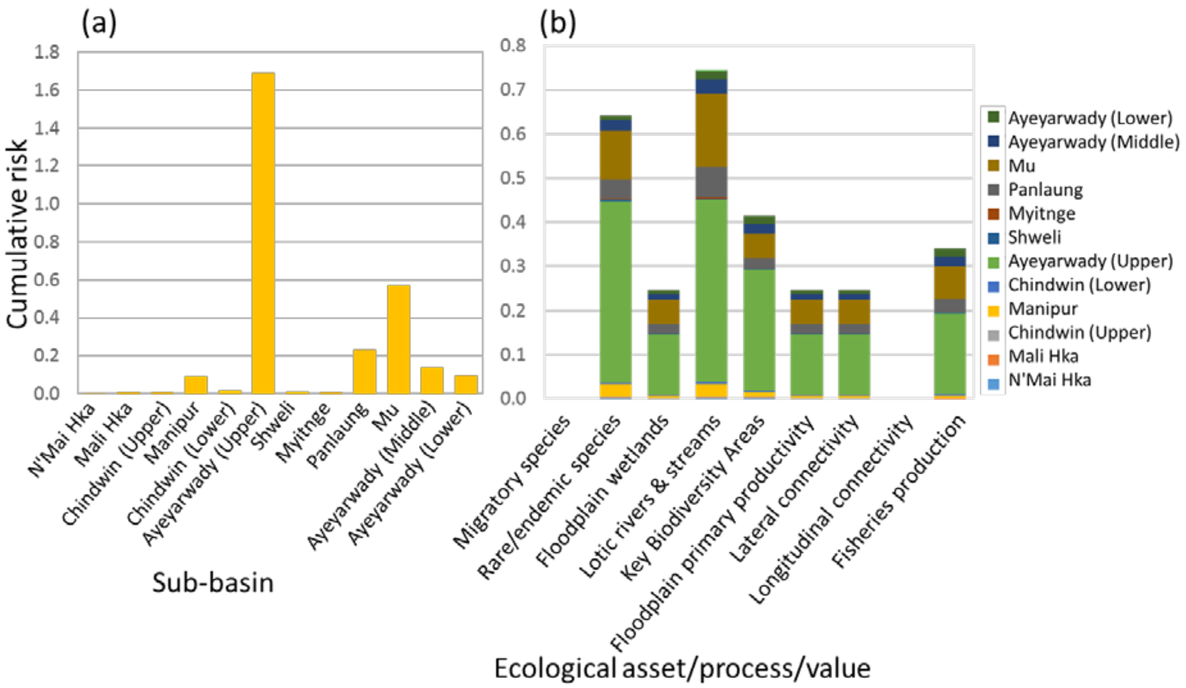

Figure 16 - Cumulative ecological risks from river impoundment across (a) all assets, processes and values in each sub-basin and (b) each asset, process and value in each sub-basin (indicated by colours)

Cumulative impact combines threat exposure data with the occurrence or importance of each asset, process and value and their vulnerability to threats for each sub-basin. A high-risk score for a given sub-basin could be attained by that sub-basin having high exposure to a threat and containing a high occurrence or importance of highly vulnerable assets, processes and values.

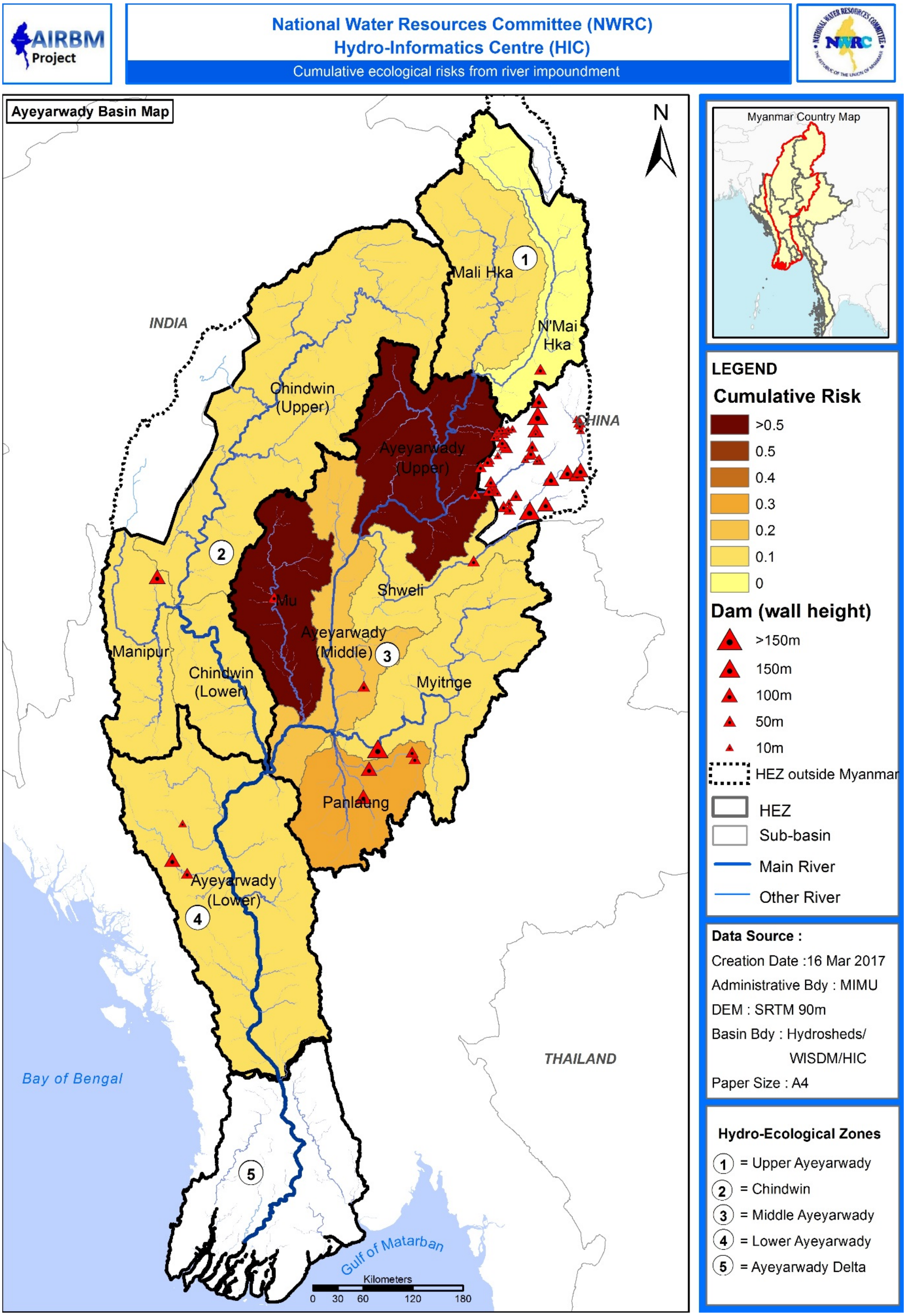

Figure 17 - Spatial variation in cumulative risks from river impoundment across all assets, processes and values in each sub-basin

5.5 Ecological Risks from Longitudinal Fragmentation

Assessment of cumulative risks from longitudinal fragmentation revealed that all sub-basins in HEZ 3 were at high risk, particularly the Shweli, Panlaung, Mu, and Ayeyarwady (Upper) Sub-basins (Figure 18a, Figure 19). Other sub-basins at comparatively lower risk included the Ayeyarwady (Middle), Ayeyarwady (Lower), and Myitnge Sub-basins.

Ecological assets/processes/values assessed as being at highest cumulative risk from longitudinal fragmentation (Figure 18b) included migratory species, longitudinal connectivity, and fisheries production. KBAs and rare and endemic species were assessed as being at moderate risk, with all other assets at relatively low risk.

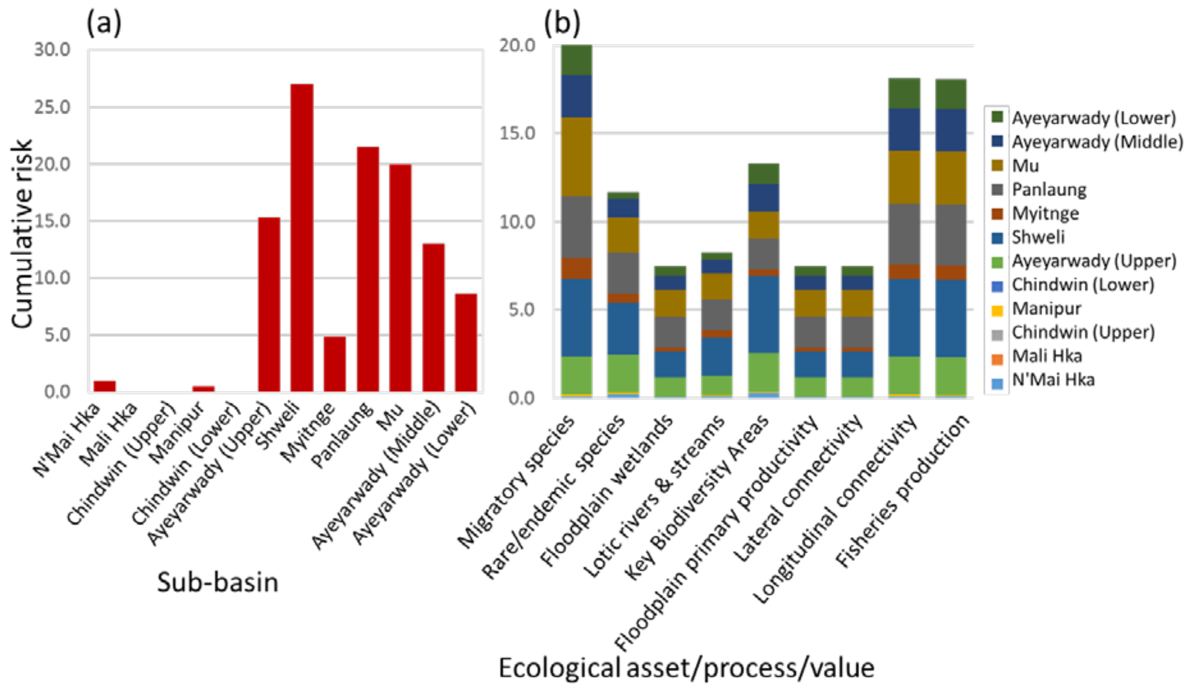

Figure 18 - Cumulative ecological risks from longitudinal fragmentation across(a) all assets, processes and values in each sub-basin and (b) each asset, process and value in each sub-basin (indicated by colours)

Cumulative impact combines threat exposure data with the occurrence or importance of each asset, process and value and their vulnerability to threats for each sub-basin. A high-risk score for a given sub-basin could be attained by that sub-basin having high exposure to a threat and containing a high occurrence or importance of highly vulnerable assets, processes and values.

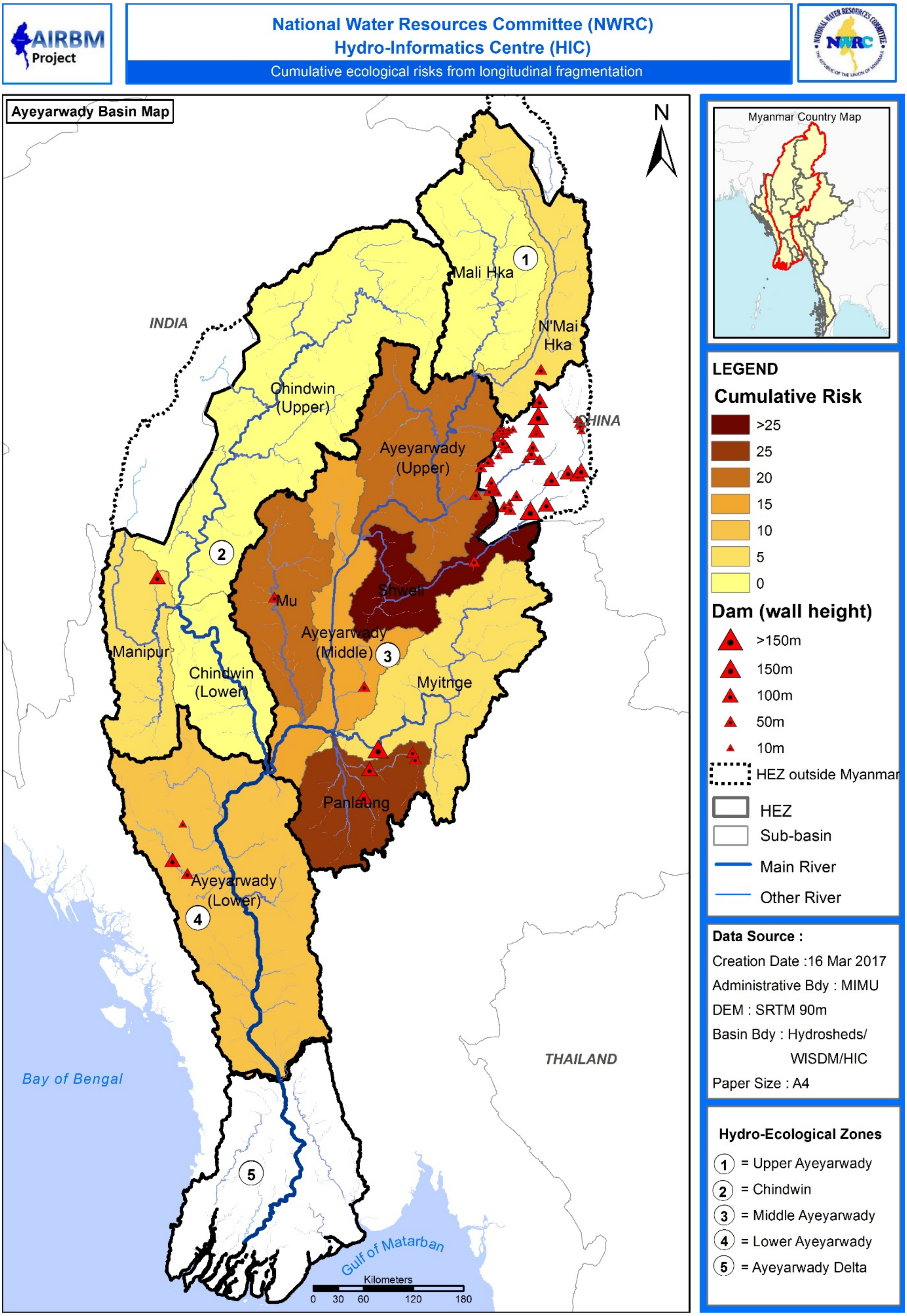

Figure 19 - Spatial variation in cumulative risks from longitudinal fragmentation across all assets/processes/values in each sub-basin

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Key Findings

This ecohydrological assessment, based on analysis and synthesis of readily available information, aims to characterise the status and trends of the key attributes of the Ayeyarwady Basin's flow regime that are likely to be of importance to biodiversity, fisheries, and the ecological processes that sustain them. It also explores the associated risks to these environmental assets from water infrastructure development (including hydrologic alteration, river impoundment, and longitudinal fragmentation by large dams). This report is not a comprehensive assessment of environmental flow needs and makes no attempt to recommend sustainable water extraction and diversion limits or to provide assessments of critical flow needs for specific species. Such an effort will require more detailed environmental flow assessments (see Section 6.2.1) that are beyond the scope and timing of this study. The key findings of the ecohydrological assessment outlined below.

6.1.1 Review of key principles and existing knowledge

The ecology of the aquatic ecosystems in the Ayeyarwady Basin is fundamentally linked to the seasonality of the climate and the natural flow regime. The Ayeyarwady River can be described as having a highly rhythmic flood pulse (Jardine et al., 2015), and the tropical floodplain rivers with these features are associated with higher fish species richness, more stable avian populations, and elevated rates of riparian forest production compared with those river systems with arrhythmic flood pulses. Water resource and hydropower development that alters the hydrologic rhythmicity is likely to have significant long-term consequences for both biodiversity and productivity.

The movement of water and associated nutrients, carbon and energy, and aquatic biota, between different habitats of the river, are essential to sustain biodiversity, productive fisheries, and other essential ecosystem services. Maintenance of connectivity between these components, both longitudinal and lateral, is vital for natural ecosystem function. In-channel or floodplain development in the Ayeyarwady Basin that diminishes or severs these links is likely to diminish these values.

6.1.2 Assessment of hydrologic alteration

The Upper Ayeyarwady (HEZ 1) has experienced relatively minor hydrological changes from water resource development and extraction. Similarly, the Chindwin Basin (HEZ 2) has had relatively minor hydrological changes overall. The most notable change is the 15% increase in the duration of low flow spells. Upstream sub-basins within the Chindwin Basin have experienced more pronounced changes in flows, particularly the Manipur Sub-basin in which low flow magnitude has decreased by 10% and the duration of low flow spells has increased by 42%.

The Middle Ayeyarwady (HEZ 3) shows some major alterations in hydrology, with a 3% decrease in mean annual flow and <10% decreases in the magnitude, frequency and duration, and variability in timing of high flows, respectively. Major changes in the mean duration (16% increase) and number (25% decrease) of low flow spells occurred, and minor changes (<5% absolute difference) in the timing and variability of low flow spells was evident. Upstream sub-basins within the Middle Ayeyarwady experienced more dramatic changes in flow and most flow regime characteristics, particularly the Mu, Panlaung, Myitnge, and Shweli Sub-basins, which have had a 29%, 22%, 7%, and 2% decrease in, respectively, mean annual flow volume. The magnitude and frequency of high flow spells has decreased substantially across these sub-basins (e.g., 38% reduction in high spell frequency in the Panlaung Sub-basin). Low flows have also changed considerably, with a maximum decrease in low flow magnitude of 39% (Mu Sub-basin), a maximum increase in low flow spell duration of 106% (Panlaung), and a maximum increase in low flow spell frequency of 104% (Mu Sub-basin). The timing and variability of high and low flow spells have changed considerably in these sub-basins (up to 42% difference from PD flows).

The Lower Ayeyarwady (HEZ 4) shows an overall decline of 2% flow volume, an 8% decline in the average duration of high flow spells, and a >20.0% difference in the mean duration and frequency of low spells.

6.1.3 Ecological risks from hydrologic alteration, river impoundment, and longitudinal fragmentation

The aquatic ecosystems of the Ayeyarwady Basin are clearly of high national and global significance. Although the results of our rapid ecological risk assessment should be treated with caution due to data limitations and knowledge uncertainties (see Section 6.3.1), it is clear that current flow alteration and associated threats from river impoundment and fragmentation are already posing serious risks to aquatic ecosystems in some parts of the basin. These areas could be prioritised for a more detailed, on-the-ground assessment of potential ecological impacts and options for threat management and risk mitigation. Key findings from the risk assessment are summarised below:

- *Hydrologic alteration* – The assessment of risks posed by hydrologic alteration revealed that the sub-basins in HEZ 3, particularly the Panlaung and Mu Sub-basins, were at highest cumulative risk. Overall, ecological assets, processes and values assessed as being at highest cumulative risk from hydrologic alteration included flowing rivers and streams, floodplain wetlands, floodplain primary productivity, lateral connectivity, and migratory species. Hydrologic alteration from CD poses a lower, but still substantial, risk to rare and endemic species, longitudinal connectivity, and fisheries production.

- *River impoundment* – The loss of riverine habitat and associated effects on biodiversity and ecosystem processes are not offset by the creation of lentic habitat through construction of impoundments (see Section 2.3.4). An assessment of the cumulative risks from river impoundment revealed that the Ayeyarwady (Upper) and, to a lesser extent, the Mu Sub-basins in HEZ 3 were at substantially higher risk than all other sub-basins. These sub-basins contained the highest proportion of impounded area and contained a relatively high number of assets that were all highly vulnerable to this threat. Ecological assets/processes/values assessed as being at highest cumulative risk from river impoundment included rare and endemic species, flowing rivers and streams, KBAs, and fisheries production.

- *Longitudinal fragmentation* – Assessment of cumulative risks from longitudinal fragmentation revealed that all sub-basins in HEZ 3 were at high risk, particularly the Shweli, Panlaung, Mu, and Ayeyarwady (Upper) Sub-basins. Other sub-basins, at relatively lower risk, included the Ayeyarwady (Middle), Ayeyarwady (Lower), and Myitnge Sub-basins. Ecological assets, processes and values assessed as being at highest cumulative risk from longitudinal fragmentation included migratory species, longitudinal connectivity, and fisheries production. KBAs and rare and endemic species were assessed as being at moderate risk, with all other assets of relatively low risk.

6.2 Management Options to Mitigate Risks

As human activities continue to alter aquatic ecosystems globally, a critical conservation goal is to predict how aquatic biota and ecosystem processes will respond to changing environmental conditions. This will allow development of mitigation, restoration, and conservation strategies to address these anthropogenic threats (Bunn, 2016). These include the development of robust tools to guide the determination of environmental flow requirements (Arthington et al., 2006; Poff et al., 2010); reduce diffuse pollution (Sheldon et al., 2012); minimise barrier effects to connectivity through improved spatial planning (Branco et al., 2014; Hermoso et al., 2016); and design and operation of infrastructure (Arthington, 2012). A broad conceptual understanding, informed by evidence from specific case studies and research conducted elsewhere (Arthington et al., 2006), does allow articulation of key strategies and general principles to minimise the negative ecological impacts of water resource development and associated flow regime changes in the Ayeyarwady Basin. These strategies are outlined in Sections 6.2.1 through 6.2.3.

6.2.1 Environmental flow management

Environmental flows can be defined as: "*… the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems*" (International Rivers Foundation, 2007). This includes managing flows to sustain the physical integrity of river-floodplains, water-dependent species (e.g., fish, birds, riparian trees), ecological processes (nutrient and energy flow), ecosystem goods and services from which people benefit (e.g., water purification, fisheries production, tourism values), and cultural and spiritual values. Environmental flow assessments evaluate how much water the river needs, to sustain natural values and processes, recognizing that the environment is a legitimate and essential user of water. Importantly, an environmental flow is not simply a fixed allocation delivered, for example, as a minimum daily flow, but acknowledges that key attributes of the flow regime (e.g., magnitude, frequency, timing, and duration of particular flow events) are also ecologically important (Poff et al., 1997; Bunn and Arthington, 2002). Environmental flow assessments are, therefore, an important step for decision-makers to evaluate tradeoffs among other, often competing, users of water (e.g., for agriculture, hydropower, urban supply, and industry) (Arthington, 2012). Following is a series of general principles for environmental flow management (modified from Pusey and Kennard, 2009) that may be appropriate for consideration in the Ayeyarwady Basin:

- Ideally, detailed environmental flow assessments should be undertaken for all existing and future water resource developments so that the flow requirements of important aquatic biota andrisks of hydrological change for aquatic ecosystem services can be evaluated and mitigated. This would guide the choice of appropriate mitigation strategies (listed in the following dot points).
- Water infrastructure (dams and weirs) can be designed and operated to be hydrologically transparent (bounded by infrastructure constraints and reductions in yield). This means that ecologically important flow events (e.g., floods, flow pulses, baseflows, low flow spells) from upstream can be delivered downstream. This would help to mimic ecologically important components of the flow regime for downstream aquatic ecosystems.
- Dry season flow releases from dams (e.g., for delivery of water for irrigation purposes) that result in artificially elevated low flows that may drown out important habitats (e.g., nesting banks for turtles) can be avoided by delivering the water through off-stream pipelines, instead of along the river channel, and off-stream storage at the destination.
- Flow releases from dams that result in unnaturally rapid rises and falls in water levels, downstream and within impoundments, should be avoided due to the risk of strandingaquatic organisms, nesting areas and other ecological assets.
- Flood harvesting (capture and use of water flowing across a floodplain) and off-stream storage could be used to mitigate the requirement for in-channel storages. Harvesting of floodwaters should only be considered in circumstances where changes to ecologically important components of the natural flood hydrograph (e.g., rates of rise and fall, peak magnitude) can be minimised, and the location of off-stream storages can be situated in areas that avoid habitat for important terrestrial and aquatic biota (e.g., important floodplain wetlands or hotspots of aquatic primary production).
- Groundwater extraction should be carefully assessed to ensure protection of groundwater-dependentecosystems, especially during the dry season. Over extraction of groundwater can lead to land subsidence on floodplains and alter the pattern of flood inundation.
- The cumulative effects of riparian extraction of water from streams and rivers (i.e., through direct pumping) can lead to major reductions in low flows and increases in the frequency and duration of dry spells. Similarly, water extraction from isolated waterholes can reduce the duration of persistence and quality of these important dry season refugial habitats. These impacts could be mitigated by setting minimum thresholds for dry season water extraction by riparian users and adequately policing these regulations. Pump offtakes should be positioned well below the water surface to minimise the possibility of removing high-quality surface waters from deep, stratified waterholes. For high-priority aquatic habitats (e.g., those known to be critical dry season refugia and/or supporting species of conservation significance), individual site-specific management rules should be established to protect their ecological values, including specification of permissible drawdown depths and rates. Ecological impacts could also be minimised, if riparian extraction was undertaken during high flow conditions rather than during low flow periods. However, this would require suitable storage capacity to be provided off-stream, given that the greatest demand for water is usually at times of low flow (i.e., during the dryseason).

6.2.2 *Water infrastructure management*

Associated with the general principles for environmental flow management described in Section 6.2.1, the following general principles for water infrastructure management (modified from Pusey and Kennard, 2009) may be appropriate for consideration to minimise ecological impacts in the Ayeyarwady Basin:

- Dams should be fitted with multi-level offtakes to minimise the release of poor quality water downstream (e.g., release of bottom waters of low temperature and dissolved oxygen). Cold water pollution from reservoirs can pose significant barriers to migration for some fish species and affect reproduction and recruitment.
- Sediment bypass measures may be used to mitigate clearwater-erosion and substrate changes caused by sediment load deficits downstream of dams and larger weirs. Such measures could include installation of gates on water infrastructure to minimise impedance to sediment transport or removal of accumulated bedload from impoundments and reintroduction downstream.
- Some impoundments provide ideal habitat for growth of aquatic invasive weeds. In situations where the problem is severe, it may be feasible to reduce such plant growth by manual harvesting or biological control.
- Installation of effective fish passage devices (e.g., rock-ramp fishways, fish ladders, fish locks, fish lifts) on some existing and new water infrastructure may be required. Provisions of specific environmental flow allocations, to render these fish passage devices effective, should also be ensured. However, it should be noted that fish passage devices can never fully restore natural fish passages and can, at best, only allow movement of a subset of the fish. Dams and weirs may also impede passage of other aquatic and water-dependent biota (e.g., crustaceans, turtles, dolphins). It is, therefore, critical that their passage requirements (i.e., in terms of depths, velocity, and turbulence in fishways) also be provided for.
- Interbasin transfers of water increase the risk of translocation of non-native organisms between catchments. Installation and regular maintenance of effective screens can help prevent such translocations.
- Maintenance of the integrity of riparian zones, upstream and downstream of impoundments, is critical.

6.2.3 Strategic water resource planning and adaptive management

In addition to the general principles for environmental flow management (Section 6.2.1) and water infrastructure management (Section 6.2.2), the following general principles for strategic water resource planning and management (modified from Pusey and Kennard, 2009; Kennard et al., 2016) may be appropriate for consideration to minimise ecological impacts in the Ayeyarwady Basin:

- Future water infrastructure developments should be strategically located to avoid upstream and downstream impacts on aquatic ecosystems of high conservation value. For example, smaller structures in tributaries may have less impact on connectivity than a single large barrier on the main channel.
- Collection of long-term baseline environmental and ecological data for key ecosystem assets should be undertaken prior to any water resource development and/or implementation of threat mitigation strategies (such as environmental flow releases and fish passage devices). Thereafter, ongoing monitoring of the ecological impacts or efficacy of the threat mitigation strategies should be performed, and these strategies should be revised and implemented within an adaptive management context.
- Different management actions will likely be needed to achieve the conservation goals (e.g., protection, threat mitigation, rehabilitation); therefore, monetary estimates of management costs should ideally be linked to decision-making, concerning which management actions to implement in which places. The incorporation of realistic and spatially explicit cost estimates for different management actions would allow cost-benefit tradeoffs to identify the most efficient combination of actions, and where they should be spatially prioritised to achieve the conservation goals (Carwardine et al., 2012). However, the cost of each management action must include an estimate of each action's efficacy, which usually relies on expert knowledge and information regarding the ecology of the species in question (e.g., Cattarino et al., 2016). More objectively derived estimates of conservation benefits that are gained through monitoring programs could help increase the efficacy of a management plan. Adaptive management plans, where information is gained through well-defined monitoring programs in the early stages of the plan or from previous experiences, can be incorporated in the decision-making process and would greatly improve the cost-efficiency of conservation management.

6.3 Limitations, Critical Knowledge Gaps, and Future Priorities

6.3.1 *Limitations and assumptions*

There are several limitations and assumptions of the cumulative risk assessment approach used in this report that are common to most spatially explicit cumulative risk assessments (reviewed in Halpern and Fujita, 2013). The most relevant to our study include the following:

- *Appropriate characterisation of threat exposure* – This is dependent on such factors as the accuracy, currency, and spatial grain size of the individual threat data layers and the methods used for integration of individual data layers within each threat type and their subsequent transformation.
- *Accurate estimation of distributions and importance of assets, processes, and values* – Our rapid assessment of the distribution and relative importance of assets, processes, and values was based primarily on expert opinion, with reference to the literature. Ideally, future assessments could be improved by more quantitative, spatially-explicit, and spatially comprehensive data on species distributions, fisheries, and production – at least some of which is already available or could be modelled.
- *Linear response of species to threats* – Our cumulative risk assessment relied on assumptions of linear and additive responses of assets, processes, and values to increasing intensity of threats. However, threshold or non-linear responses to intense or cumulative stress are also possible but are difficult to quantify.
- *Vulnerability weights are sufficiently accurate* – Extremely limited, available knowledge required that we used expert judgement to estimate vulnerability assets, processes, and values to threats. We assumed our estimates to be representative and accurate, but the estimates could certainly be refined and improved through surveying a broader pool of experts and by estimating and representing uncertainty in assessment (McBride et al., 2012).

The assumptions described in the dot points above were necessary due to the challenges arising from data limitations and knowledge uncertainties. Many additional challenges remain that are common to most cumulative risk assessment approaches. For example, characterising some of the major threatening processes were challenging in our study because of missing or imperfect data and/or a lack of access to it in the limited time available.

Notwithstanding these assumptions, our assessment of the cumulative risks posed by hydrologic alteration and other threats to the aquatic ecological integrity of the Ayeyarwady Basin is the most up-to-date; comprehensive (in terms of spatial extent, number of threatening processes, and number of ecological responses assessed); ecologically relevant; quantitative (i.e., uses continuous data to estimate exposure and risk instead of qualitative and discretised risk ratings); and scientifically robust evaluation yet undertaken.

6.3.2 *Knowledge priorities for management*

The prospect of dramatic environmental changes over the coming years underscores the need for informed and efficient conservation management of freshwater ecosystems in Myanmar. Improved capacity of natural resource managers to implement effective mitigation and adaptation programs should aid greatly in the environmentally sustainable economic and social development of Myanmar. In particular, there is a compelling need to develop spatially explicit scenario evaluation tools for Myanmar's river catchments to evaluate tradeoffs of different development and climate scenarios. These would be underpinned by gathering new knowledge on the following:

1. Some sub-basins, their ecological assets, and values are already at high risk – strategic, coordinated, and inclusive management is required to address current and future threats.

Threat management is usually required at different tiers and with different stakeholders. However, the three key ecohydrological threats addressed in this report (flow alteration, impoundments, and fragmentation by large dams) is a large-scale problem that requires a basin-scale approach to complement state-based and regional initiatives, because impacts in one area are likely to be propagated far upstream and downstream.

2. More information on the environmental flow requirements of freshwater biota and ecological processes is urgently required to inform planning and management.

The life history and flow requirements of native fish species in the study area, even those that are important for the fishery, are generally poorly known. Consequently, predicting the ecological responses of native fish to flow alteration and habitat disturbance is difficult. Research, aimed at determining reproductive schedules, larval and juvenile flow and habitat requirements, trophic dynamics, and movement patterns, will be required to diagnose the potential effects of such impacts and, hence, develop strategies to minimise them.

The environmental flow requirements of floodplain systems that underpin the productive fishery and sustain key wetland species of conservation significance remain virtually unstudied. Quantification of the subsidy provided by floodplain processes to the fishery and the food webs, which sustain populations of fish, birds, and crustaceans, is needed. Key floodplain areas that represent hotspots of production and their critical connections with the river also need to be identified. With this information, the effect of reductions in the magnitude, duration, and area of floodplain inundation on the fishery and wetlands of significance can be determined. Much of this work can be undertaken through a combination of remote sensing and campaign-style field measurements.

Links between the river ecosystems and the estuarine and coastal zone (in both directions) need to be better understood. In particular, the role of fauna (e.g., fish and crustaceans), in maintaining connections between components of the river-floodplain system and the environmental triggers for movement of different species and life stages, is an important knowledge gap. We also need to better understand the connectivity to estuarine and coastal processes and the implications of more intensive land use for these ecosystems and the assets they support, such as commercial and recreational fisheries (see Point 4 below).

3. Targeted assessment is required on ecological responses to threats and the benefits of management actions to mitigate threats.

This project has identified that quantitative data are lacking concerning population trends, responses to threats, and the benefits of management actions to mitigate those threats for most ecological assets and values in the Ayeyarwady Basin. Targeted monitoring of population trends can build understanding of key drivers of natural temporal variation. Targeted monitoring can, in turn, inform managers on how species are or are likely to be responding to environmental changes, and highlight conservation concerns that would require management actions. Our expert elicitation revealed that many ecological assets and values species are highly vulnerable to the threats considered in this report. However, we lack precise evidence of actual species responses and how cumulative interacting threats may exacerbate vulnerability.

4. A geophysical representation that quantifies changes in floodplain inundation and sediment regimes is required.

This review has identified significant changes to the frequency and duration of high flows in some sub-basins (particularly in the HEZ 3 region). Changes to the high flow component of the flow regime can have significant consequences, through a breakdown of the lateral connectivity between the floodplain and stream. We recommend the development of a floodplain inundation model for at-risk sub-basins to better quantify the ecological risks posed by reduced floodplain wetting extent, duration, and frequency. Associated with this, an improved understanding of the likely changes in sediment regime (from upstream impoundments) is required to predict changes in floodplain, delta extent, and response to inundation.

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8 ANNEX

Annex 1 - Raw hydrologic metric values for pre-development and current development modelled flow scenarios at each sub-basin (MCM refers to million cubic metres)

Hydrologic metric			HEZ 1		HEZ 2			HEZ 3						HEZ 4
Description	Units	Flow scenario	N'Mai Hka	Mali Hka	Upper Chindwin	Manipur	Lower Chindwin	Upper Ayeyarwady	Shweli	Myitnge	Panlaung	Mu	Middle Ayeyarwady	Lower Ayeyarwady
Mean annual flow	MCM	PD	52,280	89,413	131,070	29,250	170,003	189,798	18,456	29,489	6,511	8,578	25,9019	466,401
		CD	52,298	89,412	131,027	29,069	169,436	189,408	18,104	27,349	5,064	6,133	25,2404	456,477
High flow magnitude	MCM	PD	298	629	1026	196	1250	1277	136	179	41	53	1,657	3,097
		CD	298	629	1026	196	1250	1260	136	167	28	40	1,619	3,045
Mean duration of high spells	days	PD	6	5	14	6	18	12	12	4	2	5	16	17
		CD	6	5	14	6	18	12	12	4	2	4	16	15
Mean annual number of high spells	count	PD	5	7	3	5	2	3	3	7	12	6	2	2
		CD	5	7	3	5	2	3	3	5	8	5	2	2
Low flow magnitude	MCM	PD	60	58	37	12	57	135	7	18	3	6	180	259
		CD	60	58	37	11	56	142	5	15	3	4	183	260
Mean duration of low spells	days	PD	24	27	9	4	14	25	8	6	4	8	20	29
		CD	24	27	9	6	17	20	16	10	8	7	23	35
Mean annual number of low spells	count	PD	2	1	3	6	2	1	4	5	6	4	2	1
		CD	2	1	3	6	2	1	4	5	6	9	1	1
Timing of high flow	Julian day	PD	235	217	217	254	228	218	246	258	243	192	234	231
		CD	235	217	217	254	228	220	248	268	272	234	233	231
Variability in timing of high flow (CV Julian day)	dimensionless	PD	0.16	0.16	0.10	0.14	0.11	0.11	0.11	0.22	0.27	0.29	0.11	0.09
		CD	0.16	0.16	0.10	0.14	0.11	0.11	0.10	0.16	0.15	0.24	0.10	0.08
Timing of low flow	Julian day	PD	64	65	101	124	98	70	126	117	142	134	82	88
		CD	64	65	101	121	96	73	115	109	125	172	85	90
Variability in timing of high flow (CV Julian day)	dimensionless	PD	0.42	0.35	0.26	0.20	0.24	0.32	0.20	0.21	0.22	0.25	0.27	0.25
		CD	0.42	0.35	0.26	0.20	0.24	0.36	0.18	0.26	0.30	0.24	0.26	0.24
Proportion flow driest 6 months	proportion	PD	0.25	0.16	0.08	0.14	0.10	0.16	0.11	0.22	0.28	0.28	0.17	0.14
		CD	0.25	0.16	0.08	0.13	0.10	0.17	0.10	0.21	0.28	0.33	0.17	0.14