SOBA 1.2: SURFACE WATER RESOURCES

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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Disclaimer

This report provides a basin scale assessment of the water resources of the Ayeyarwady River Basin upstream of the delta. The report was prepared based on analysis using the best available data. The analysis can be improved as more accurate and detailed data become available.

LIST OF ABBREVIATIONS

°C	Degrees Celsius
ARB	Ayeyarwady River Basin
AWP	Australian Water Partnership
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CSIRO	Commonwealth Scientific and Industry Research Organisation
DEM	Digital Elevation Model
DMH	Department of Meteorology and Hydrology
DWIR	Directorate of Water Resources and Improvement of River Systems
ENSO	El Niño Southern Oscillation
FAO	Food and Agriculture Organisation of the United Nations
FSC	Full Supply Capacity
GLORIC	Global River Classification
HEZ	Hydro-Ecological Zones
HP	Hydropower
IADS	Integrated Ayeyarwady Delta Strategy
ICEM	International Centre for Environmental Management
IW	Irrigation Works
IWMI	International Water Management Institute
km	kilometres
m	meters
m amsl	metres above mean sea level
MCM	million cubic metres
MDBA	Murray Darling Basin Authority
mm	millimetres
MHRI	Myanmar Healthy Rivers Initiative
MP	Multi-purpose
MW	Megawatts
NWRC	National Water Resources Committee
PET	Potential Evapotranspiration
SOBA	State of the Basin Assessment
WWF	World Wildlife Fund

EXECUTIVE SUMMARY

There has previously been no integrated assessment available for the Ayeyarwady River Basin, nor an integrated water system model to support such assessment. This has been identified in Myanmar as key to supporting understanding and future planning in the river basin.
This Surface Water Resources Assessment of the Ayeyarwady River Basin:

- provides a preliminary Baseline Source water system model which can be used to facilitate the ongoing assessment of the Ayeyarwady Basin, and scenario building to evaluate future options and implications
- contributes to the credible, evidence base that SOBA is developing for the Ayeyarwady River Basin planning process
- facilitates an understanding of any gaps in data collection as required for effective model building
- provides a description of the hydrology of the Ayeyarwady River Basin according to five identified hydro-ecological zones (HEZ) and thirteen identified sub-basins, with a focus on water availability and water use in the Ayeyarwady River Basin

With its source in the Himalayan regions of Myanmar the Ayeyarwady River Basin is the second largest river basin in South East Asia, after the Mekong. It has a drainage basin area[1] of 413,700 km^2. The morphology of the river is controlled by the north-south orientation of the regional geology where the Indian-Australian Plate collides with the Eurasian Plate. The largest tributary of the Ayeyarwady River is the Chindwin River, which joins the right bank of the Ayeyarwady River upstream of Pakokku. Other major tributaries include the N'Mai Hka, Mali Hka, Tarpein River, Shweli River, the Myitnge River, the Panlaung River, the Mu River and the Myittha River (which is a tributary of the Chindwin River). In the south, the Ayeyarwady River enters the Andaman Sea through a large delta, where there Ayeyarwady main stem divides into nine distributaries.

A surface water resources baseline assessment of the Ayeyarwady Basin is conducted at three spatial scales:

- Whole of Basin scale
- Hydro-ecological zone scale
- Sub-basin scale

There are five hydro-ecological zones, and thirteen identified sub-basins.

Five hydro-ecological zones:

1. Upper Basin - incorporating the upper reaches of the Ayeyarwady River and the N'Mai Hka and Mali Hka Rivers, the Upper Basin extends from the most northern sections of the Ayeyarwady River Basin to approximately 50km downstream of Myitkyina
2. Chindwin Basin - this zone incorporates the entire basin of the Chindwin River to its confluence with the Ayeyarwady River upstream of Pakokku
3. Middle Basin - the Middle Ayeyarwady Basin is defined as the section of the Ayeyarwady River Basin between the Upper Ayeyarwady (near Myitkyina) and the Ayeyarwady/Chindwin River confluence. The largest tributaries in this zone include the Tarpein River, Shweli River, Myitnge River and Mu River.
4. Lower Basin – this zone extends from the Chindwin/Ayeyarwady confluence in the north to Myanaung Township in the south – approximately 100km downstream of Pyay. This is the point in

[1] 95% of the basin is within Myanmar.

the Ayeyarwady River where tidal influences have been noted to influence channel hydrology (Volker, 1966).

5. Ayeyarwady Delta - the Delta is characterised by a division of the Ayeyarwady main stem into a complex of nine low gradient streams

The Chindwin River Basin is divided into three sub-basins

- Chindwin Upper – upstream of the Chindwin/Myittha confluence at Kalewa, includes the Uyu River which joins the Chindwin River from the east at Homalin
- Chindwin Lower – downstream of the Chindwin/Myittha confluence at Kalewa extending to the Ayeyarwady River confluence, and
- Manipur - the basin of the Manipur River and the Myittha River, which rise in the Arakan Mountains and includes the Loktak Lake.

The main stem Ayeyarwady River is associated with a further ten sub-basins:

- the N'Mai Hka and Mali Hka sub-basins are the highest and most upstream river basins. They form the source of the Ayeyarwady River. The N'Mai Hka and Mali Hka sub-basins in the Upper Basin HEZ have the highest average elevation and average slope.
- the Ayeyarwady River main stem is divided into four sub-basins:
    - the Ayeyarwady (Upper) which extends from the N'Mai Hka/Mali Hka confluence to the confluence with Shweli River, and includes the Tarpein River tributary
    - the Ayeyarwady (Middle) which extends from the confluence with Shweli River to the Ayeyarwady/Chindwin confluence
    - the Ayeyarwady (Lower) which extends from the Ayeyarwady/Chindwin confluence to Myanaung Township, considered to be the most upstream point of tidal influences (and also the most downstream extent of the Lower Basin hydro-ecological zone)
    - the Ayeyarwady River Delta, downstream of Myanaung Township. Downsteam of this point the Ayeyarwady River divides into several distributaries.
- also included are the four main tributaries to the Ayeyarwady River main stem:
    - the Mu River sub-basin located in the central regions of the Ayeyarwady Basin. The Mu River flows in a north-south direction, entering the Ayeyarwady River between Mandalay and the Ayeyarwady/Chindwin confluence
    - the Shweli River sub-basin. The Shweli River has its source in the Chinese regions of the Ayeyarwady River Basin. It flows into the Ayeyarwady River from the east, downstream of Katha
    - the Myitnge River sub-basin. Also, an eastern tributary of the Ayeyarwady River, the Myitnge River flows into the Ayeyarwady at Sagaing
    - the Panlaung River sub-basin. The Panlaung River is a tributary of the Myitnge River. It flows into the Myitnge River from the south east, joining it just before the Ayeyarwady/Myitnge confluence at Sagaing

The climate of the Ayeyarwady River Basin is dominated by a monsoonal rainfall regime associated with the south western Indian monsoon and also affected by convectional systems and cyclones from the Bay of Bengal. Under the influence of the south-west monsoon the wet season generally starts around mid-May and extends till the end of October. Mean annual rainfall in the Ayeyarwady River Basin varies from less than 1,000 mm in the Central Dry Zone to more than 4,000 mm in the north-western parts of the Basin and in the Ayeyarwady Delta. Temperatures are generally high with a low diurnal range. However, this varies across the Basin, impacted by latitude and elevation, as well as localised rain shadow effects. In the northern mountains daily temperatures can fall to below 0°C, while in the Central Dry Zone in the rain shadow of the Arakan Mountains they can rise to the mid-forties and typically average around 32°C during the warm season.

While annual floods are common in the Ayeyarwady River Basin, nine years have been identified as representing particularly high flows: 2015, 2008, 2009, 2004, 2002, 2001, 1991, 1997 and 1988. High flow events as a result of extreme weather or cumulated monsoonal flows in the upper reaches of the Ayeyarwady and Chindwin rivers can lead to concentrated flows and flooding downstream of the Ayeyarwady/Chindwin confluence.

A hydrological model of the Ayeyarwady River Basin has been developed to produce a baseline assessment of the hydrology of the basin, using the Source Water System modelling package (ewater.org.au). This model includes representations of agricultural (crop), domestic, urban and hydropower water use. All major storages supplying these water requirements are included in the model. The model represents all hydro-ecological zones upstream of the Ayeyarwady River Delta. The baseline represents a 'current' level of development at 2014–2016, in terms of storages, land use, irrigation areas and population. This baseline model is run with historic climate data for 1981–2016. Only areas upstream of the Delta are considered in the model and are represented in model outputs.

The observed average annual discharge at Pyay above the Delta is estimated at 375,000 MCM/year. Most of the mean annual flow in the Ayeyarwady River comes from the northern higher elevation sections of the river basin. The Mali Hka and N'Mai Hka together (Upper Basin HEZ) contribute 35 % of the mean annual flow volume at Pyay, with another 32 % coming from the northern parts of the Chindwin River.

The coefficients of variation measures the variation of annual flows across the basin. It is calculated at Myitkyina, Katha, Sagaing, Magway, Pyay, Hkamti, Mawlaik and Monywa. It is generally less than 0.2, indicting a fairly stable inter-annual flow regime. Pyay is the most downstream site considered on the Ayeyarwady River and is taken to represent river discharge upstream of the Ayeyarwady River Delta. The coefficient of variation of flow at Pyay is 0.12 – comparable with that of the Mekong River.

The monsoonal nature of rainfall in the Ayeyarwady River Basin results in a wet season that typically is identified as occurring between mid-May to the end of October, and a dry season extending from November to April. However, there is a spatial as well as annual variability in the onset of this wet season. Identifying a high flow period, where flows exceed mean annual flow values at a site, can be used to examine this variability. It is found that, while there is some annual variation in the length of the high flow period, dates typically lie within a narrow range, generally lasting from mid-June until late October. However, considering spatial comparisons, the high flow season starts much earlier in the upper part of the Ayeyarwady River Basin (based on the Myitkyina site) than at the lower parts of the Basin. This is in part due to snow melt during the latter part of the dry season. At Myitkyina the high flow period can already start in April, while for the remaining catchments the calculated high flow period starts in June or July.

The Ayeyarwady River Basin is still a relatively undeveloped basin. Forestry and agriculture are the dominant land use. Sixty-two percent of the basin is under forest. Shrub lands and grass lands account for another eight percent of land use, meaning that seventy percent of the Ayeyarwady River Basin can be classified as being under 'natural' cover. The remaining thirty percent is mostly agriculture, with rain-fed agriculture dominating. Twenty-one percent of the basin is rain-fed agriculture and six percent is irrigated agriculture. Although the total area being used for irrigated agriculture is relatively small, agriculture is the main consumptive use of water in the Ayeyarwady River Basin. The impacts of this use can be noticeable, particularly in those sub-basins where large storages have been built to support irrigation.

By 2016 214 storages could be identified in the Ayeyarwady River Basin within Myanmar, built to support hydropower and irrigation supply. Twenty-seven major storages were commissioned in the period 1980-2016. While most of the irrigation works and multi-purpose storages are situated within Myanmar, as of 2016 most of the hydropower storages are situated in the Chinese sections of the Basin. The Middle Basin hydro-ecological zone has the highest volume of storage capacity within the Ayeyarwady River Basin. This HEZ contains the Mu River, Myitnge River and Panlaung River sub-basins, which have the highest volumes of storage capacity in the Ayeyarwady River Basin.

At scale of the whole Ayeyarwady River Basin upstream of the Delta 1.6 % of mean annual flows are extracted for irrigation. However, the impact of water use on the hydrological regime is more evident during the dry season. During the dry season an amount equivalent to 7 % of total dry season flow in the Ayeyarwady River Basin is estimated to be extracted. These calculations assume all water, including that in the main stream of the Ayeyarwady and Chindwin rivers, is available for extraction and should not be considered as a quantification of sustainable exploitation potential.

These impacts become even more evident as spatial scale decreases, being more noticeable at sub-basin scale that it is at whole basin scale. While water supplies from the main stream of the Ayeyarwady (subject to access) should be reliable year-round, tributaries show greater stress in the dry season. For example, in the heavily cropped Mu River sub-basin where only flows from upstream of Thapanseik 2 reservoir are available to the local beneficial area, it is estimated that on an annual basis 21% of available surface water is extracted, with an amount equivalent to 111 % of dry season runoff extracted during the dry season. These dry season extractions are made possible only by releases from the Thapanseik 2 reservoir.

The surface water resource baseline model which has been built to underpin this assessment is a first cut at drawing together the information required to adequately understand and simulate the complexities of the Ayeyarwady River Basin. The task of producing a basin wide water system model has highlighted a number of issues around the availability and quality of water resources-related information required to undertake a comprehensive assessment. The uncertainties surrounding these input data increases the uncertainty in modelled outputs. Limited spatial distribution of rainfall and evaporation data meant that global satellite products were used as surrogate. Errors in the estimated rainfall resulted in poor representation of the highest flows. Adequate instream measurements are also important to understanding other processes such as groundwater interactions, extractions and local inflows. Uncertainty in water use and storage operations impact on the understanding and simulation of patterns of use at a sub-basin level. These findings can inform the focus of long term efforts, with the baseline model providing the opportunity to not only identify gaps in understanding but also form a framework for continued updating as these gaps are addressed.

1 AYEYARWADY RIVER BASIN – HYDROLOGICAL REGIME

1.1 Ayeyarwady River Basin overview

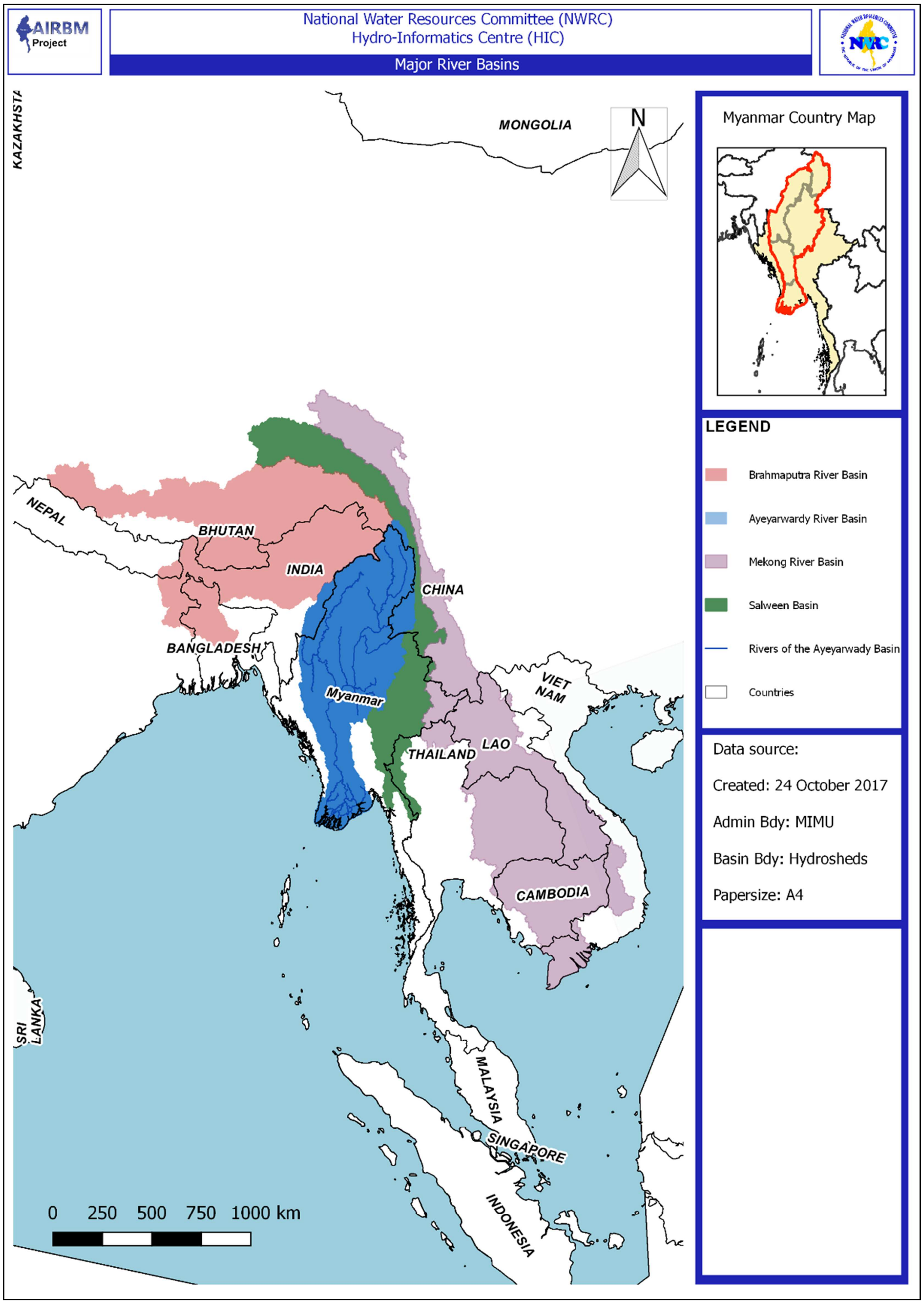


Figure 1 Regional location of the Ayeyarwady River Basin

1.1.1 *Catchment area and physical characteristics*

1.1.1.1 Location

The Republic of the Union of Myanmar is an agriculturally dominated country in south-east Asia bordered by Bangladesh and India to the west, China to the north, Laos and Thailand to the east, the Bay of Bengal to the south-west and Andaman Sea to the south (Figure 1). With an area of 676,578 km^2, Myanmar is the second largest country in South-East Asia after Indonesia.

The Ayeyarwady River flows in a north-south direction through Central Myanmar. Similar to its larger neighbours, the Mekong (795,000 km^2) and Brahmaputra (712,000 km^2) basins, the Ayeyarwady River Basin originates in the Himalayan regions. The Ayeyarwady River drops steeply from the Himalayan foothills and flows through the lower-lying Central Myanmar Basin, ending at a large effluent delta in the Andaman Sea (Figure 2). The Ayeyarwady River Basin is bounded by the Arakan Mountains to the west and the Shan highlands to the east, and has a drainage basin area of 413,700 km^2, which represents about 61% of the country (Taft and Evers, 2016). While 95% of the Ayeyarwady River Basin is situated within the Myanmar borders, approximately 5% of the Basin extends into the neighbouring countries of India (in the west) and China (in the east). The Ayeyarwady River Basin has a length of approximately 2,000 km and is the longest and most important river basin system in Myanmar (Rocha, 2017). The Ayeyarwady Delta in the south of the Ayeyarwady River Basin has an area of 35,000 km ^{2} which is relatively large compared to the size of the drainage basin, covering 9% of the Ayeyarwady River Basin area within Myanmar.

1.1.1.2 Topography and physiography

The topography of Myanmar is characterised by large changes in elevation ranging from the foothills of the Himalayan Mountains in the north, where elevations range from 5,881 m amsl at Hkakabo Razi - the country's highest peak, down to sea level in the south and southeast of the country along the coast (Rocha, 2017) (Figure 2). Three north-south trending mountain ranges, the Arakan Mountains, Bago Yoma and Shan Plateau divide the length of the country (Taft and Evers, 2017). The geography of the Ayeyarwady River Basin can be divided into four physiographic regions:

1) ***Mountain ranges***

- **Northern mountains:** The northern mountain region and Tibetan Plateau is the source area for several of Asia's great rivers, including the Ayeyarwady, Chindwin, Sittaung and Salween rivers in Myanmar, and other greats such as the Mekong River, the Brahmaputra River and the Ganges River (Taft and Evers, 2016) (Figure 2, after Taft and Evers, 2016). The N'Mai Hka and Mali Hka Rivers flow as the headwaters of the Ayeyarwady River Basin from the foothills of the Himalayan Mountains in Kachin state, and their confluence marks the beginning of the Ayeyarwady River.
- **Western mountains:** described as the Arakan Mountains (also Rakhine Yoma) comprising the Naga Hills, the Chin Hills and the Patkai Range, extending about 400 km in length and occupying an area of approximately 53 000 km^2 (Simmance, 2013). The highest point at Mount Victoria has an elevation of 3,094 m. Notable, is that this mountain range: (a) forms an orographic barrier to Bay of Bengal precipitation dynamics; and (b) separates the basin from the short, wet catchments of Rakhine State to the west.
- **Bago Yoma:** the mountain range located in the central-south of the basin, extending 270 km in length and occupying an area of approximately 17,800 km^2 (Simmance, 2013). The range averages 600 m in elevation, with the highest point in the north at Popa Hill (1,518 m), which is an extinct volcano. A notable feature of this range is that it separates the Ayeyarwady and Bago-Sittaung river basins; although, a low elevation spur to the south allows hydrological connectivity during high flow conditions.
- **Shan Plateau:** a deeply dissected, crystalline massive located in the east of the Ayeyarwady River Basin. The average elevation of the plateau is 900 m, with interspersed mountain peaks reaching from 1,800 to 2,600 m. Notable is that the Shan Plateau separates the Ayeyarwady River Basin from the Salween Basin.

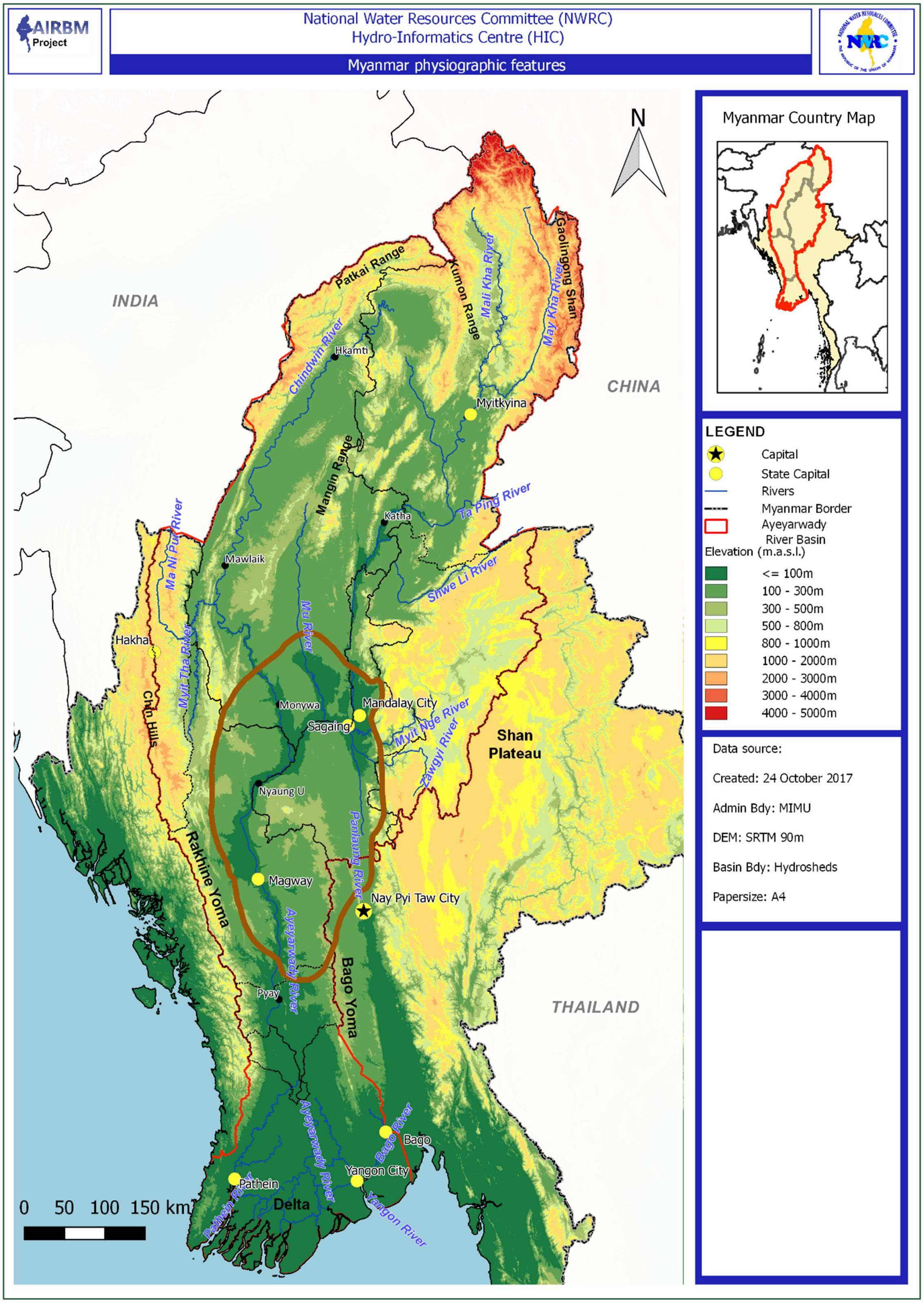


Figure 2 Physiographic features of the Ayeyarwady River Basin (Central Dry Zone outlined in brown)

2) Central Dry Zone

A central climatic zone lying between the western Rakhine Yoma; the south-central Bago Yoma; and the eastern Shan Plateau. It has a maximum length of 560 kilometres and width of 270 kilometres, with a total area of approximately 75,700 km^2. According to Voissanges et al (2017), the Dry Zone is a climatic boundary defined as the area where rainfall is less than 1,000 millimetres (mm) per year as a consequence of being situated within the rain shadow of the Rakhine Yoma. The Ayeyarwady River and two of its major tributaries (Chindwin and Mu rivers) traverse roughly north-south through this region. Most villages, towns and cities in the Dry Zone use groundwater as their primary source for domestic and potable water, and it is used extensively for industrial purposes.

3) Riverine floodplain

Due to flat topography the Ayeyarwady River Basin has a vast floodplain, with major floodplain areas found along the length of Ayeyarwady River Basin and at most major confluences with the Ayeyarwady. Floodplain areas are especially predominant in the upper river basin area between Myitkyina and Sinbo where the river gradient is low (Lee and Zöckler, 2017). In these areas, slow flowing water has formed extensive sand, silt and gravel bars with semi-permanent river banks. During the wet season, extensive areas of wetlands are created where the river banks are overtopped, creating seasonal marshes and wetland lakes. The Ayeyarwady River is generally wide (700-800 m or more) along the floodplain sections of the river with depths of approximately 12-18 m during the wet season. Water levels drop by 2 to 3 m during the dry season. The continuous erosion and meandering of the river channel results in numerous cut-off channels and oxbow lakes. In recent years there has been a decrease in floodplains thought to be attributed to dam and infrastructure development (Lee and Zöckler, 2017).

4) Ayeyarwady Delta

The Ayeyarwady Delta covers an area of 54,700 km^2, and begins where the Central Dry Zone terminates, spreading outwards towards the Andaman Sea as a maze of distributary channels. The delta formed during the Holocene when the Ayeyarwady outlet was near the Chindwin confluence. Its initial formation was constrained by the Rakhine Yoma mountain ranges and later by tidal currents in the Bay of Bengal. Voissanges et al (2017) describes the region as a densely settled area, which includes Yangon city and the right bank of the Yangon River. The delta divides into three zones: tidal/coastal; brackish estuarine and a freshwater plain, and the boundaries of these zones shift with the seasons and tides. The Ayeyarwady River transports large amounts of sediment, particulate and dissolved organic carbon, and it has been identified that the delta is historically pro-grading at an estimated average rate of 2.5 km per 100 years into the Andaman Sea (Rocha, 2017). The delta is an extremely fertile and productive area because of the large volume of river-borne silt regularly deposited, and the upper and central portions of the delta are almost entirely under cultivation, principally for rice.

1.1.1.3 Tributary Basins

The Ayeyarwady River has five major tributaries, which have not been well studied despite their importance. These tributaries are, from north to south (Figure 2):

- Tarpein River: the first left bank tributary with its headwaters originating on the Tibetan Plateau in the Yunnan Province of China. It drains the Shan Plateau to the east and enters the Ayeyarwady near Bhamo.
- Shweli River: the second left bank tributary with its headwaters originating on the Tibetan Plateau in the Yunnan Province of China. It also drains the Shan Plateau and enters the Ayeyarwady 60 km north of Tagaung at Inywa.
- Myitnge River: the third left bank tributary with its headwaters originating from the Tibetan Plateau of the Yunnan Province of China, and draining the Shan Plateau and enters the Ayeyarwady at Amarapura. Its tributaries include the Zawgyi and Panlaung Rivers.
- Mu River: the first right bank tributary flowing from north to south between the narrow Ayeyarwady to the east and the broad Chindwin River to the west. The Mu River drains the central basin and is situated within the Dry Zone. The Mu River enters the Ayeyarwady River downstream of Mandalay near Myinmu.

- Chindwin River: the second right bank and the largest tributary of the Ayeyarwady River. The broad, flat western valley of the Chindwin is predominantly fed by easterly flowing rivers arising from the Rakhine Yoma. Its tributaries include the Manipur, with its source in India, and the Myittha rivers.

Downstream of the confluence of the Chindwin and Ayeyarwady rivers, the Ayeyarwady River continues to flow in a southerly direction through low hills before emerging onto alluvial flats that grade into the delta (WWF, 2017).

1.1.1.4 Wetlands and lakes

Eighty-three key biodiversity areas have been internationally identified within the Basin Figure 3, including nine stretches of the Ayeyarwady River between Magway and Myitkyina identified for the protection of the Irrawaddy Dolphin.

Viossanges et al (2017) listed five wetland types in the Ayeyarwady River Basin which support important ecosystem functions. These include:

1) coastal mangroves and mudflats in the Ayeyarwady Delta,
2) freshwater marshes in the Delta beyond the saline zone and along the river in the middle Ayeyarwady in southern Kachin State and northern Sagaing Region,
3) freshwater lakes and related wetlands that very in size from Lake Indawgyi, which is over 20 km in length, through to small lakes and wetlands along the Ayeyarwady and its tributaries,
4) river channels and associated wetlands in the floodplain zones where the gradient to the river is low, including swamp forests in the Delta and the floodplains of the Chindwin, and
5) Intermittent wetlands in the Dry Zone, including riverine wetlands and chaungs, intermittently flooded forest in the upper Mu valley and spring fed marshes, such as those found at Yinmabin.

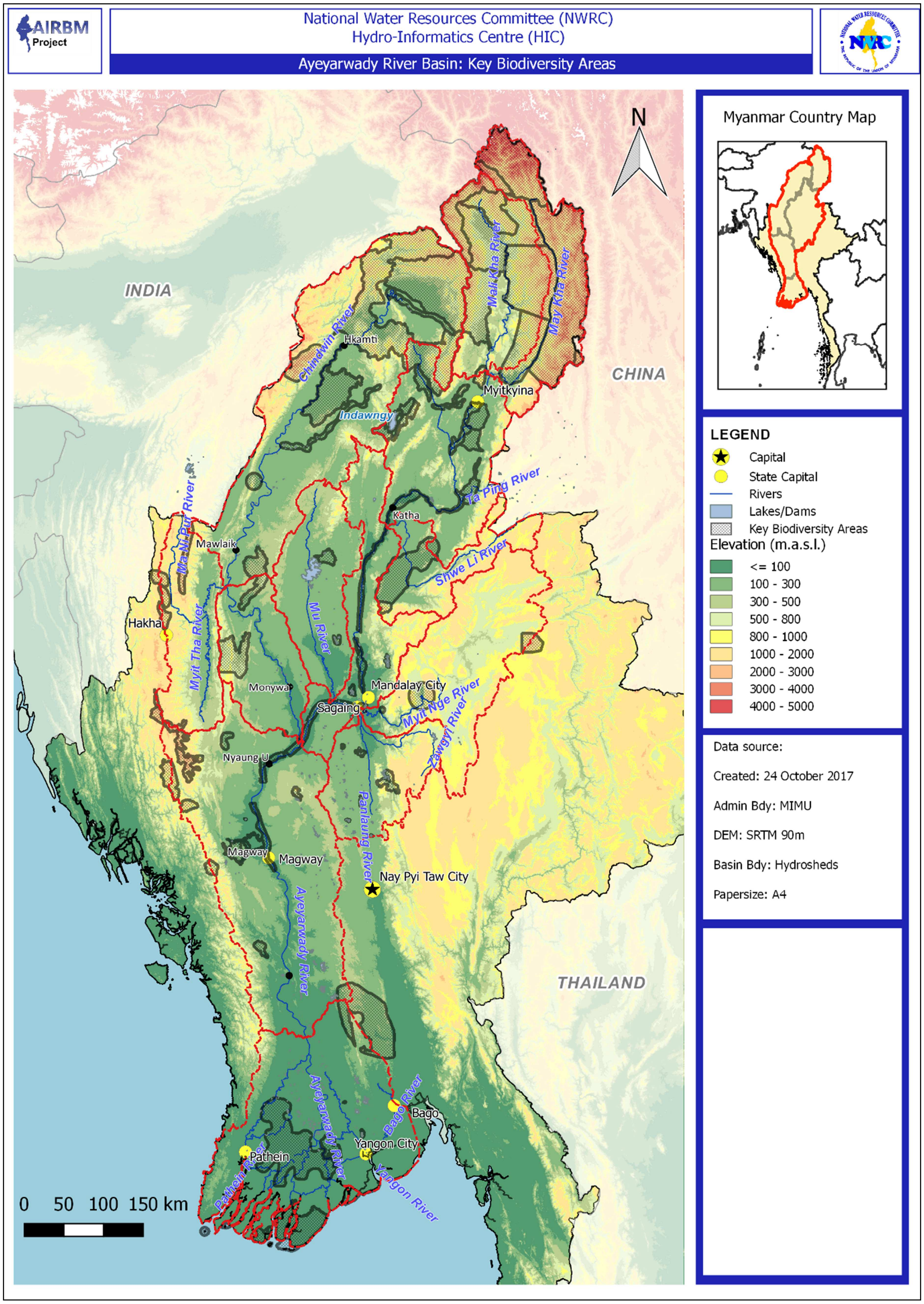


Figure 3 Key biodiversity areas of the Ayeyarwady River Basin

1.1.2 Geological context

Myanmar is situated within an active tectonic setting, with the country occupying the collision zone between the Indian-Australian and Eurasian Plates that formed the Himalayan Mountain ranges, and which has resulted in a series of north-south oriented anticlines, synclines and associated faults described in detail by Bender (1983) (Viossanges et al, 2017). The collision zone between the Indian-Australian and Eurasian Plates is delineated by the north-south trending Sagaing fault which approximately cuts Myanmar in half (Figure 4, after Viossanges et al, 2017). On the western side of the fault the Indian Plate is moving northward, whilst on the eastern side the Eurasian Plate is moving southward, with additional east-west movement along ancillary faults to accommodate plate movements (WWF, 2017). Adding to the complexity of the geological setting is the active subduction and thrust faulting occurring along western Myanmar, which is responsible for the north-west trending parallel thrust faults found in the Arakan mountain range (WWF, 2017).

Key tectonic structures are briefly described by Viossanges et al (2017). From west to east they include (after Viossanges et al, 2017): The Outer Arc (Indo-Burma Range); the Inter-arc Trough (Western Trough); the Inner Volcanic Arc (central Volcanic Line) and the Back-arc Basin (Eastern Trough). The Eastern Trough is located along the Sagaing Fault. According to Viossanges et al (2017), these structures can be described as follow:

- The Outer Arc/Indo Burma Ranges includes the Rakhine Yoma in the southwest and Chin Hills further north. The highest altitude is above 3000 m and declines towards the south. Geologically this area consists of mainly sedimentary and meta-sedimentary units.
- The Inner Burman Tertiary Basin is located between the Indo-Burma and Sino-Burma ranges, and is a complex basin that is often sub-divided. It contains extensive Tertiary Sediments, estimated to be more than 10,000 m thick, which have been metamorphosed and intruded by igneous rocks of the Central Volcanic Line.
- The Sino-Burma range area is located east of the Sagaing Fault system, where tectonic activity has led to an uplift of the eastern block by more than 1000 m, resulting the current topography. The main structure is the Shan Plateau, consisting of older meta-sedimentary rocks and thick limestone units. Further north in heavily faulted metamorphic and igneous rocks have formed the hills and high mountains of Kachin state, with recent alluvium found along the rivers and between the valleys.

The hydrological and physical characteristics of the Ayeyarwady River Basin have been strongly influenced by these geological and tectonic features, with the river basin having developed along the active collision zone. Accordingly, the course of the river, sediment types and input rates are all influenced by this setting, and a strong regional variability is exhibited (WWF, 2017).

In the north of Ayeyarwady River Basin, east of this collision zone marked by the Sagaing Fault, the geology is dominated by the older, resistant crystalline igneous and metamorphic rocks that form the Shan Plateau, and the northern sedimentary, metamorphic and volcanic rocks that form the southernmost extent of the Tibetan Plateau (Figure 4, after Viossanges et al, 2017). The headwaters and tributaries of the Ayeyarwady River that drain from these steeply sloping areas tend to produce higher proportions of sands and gravels since the underlying rocks are relatively resistant to physical weathering. In contrast, to the west of the Sagaing fault, the geology comprises relatively young thrusted and faulted, and mainly sedimentary and meta-sedimentary rocks where high rainfall has led to deep weathering of the tectonically weakened strata. The flysch deposits, such as those that occur in the Arakan Mountains in the west, tend to erode quickly and produce abundant silts, muds and sands. This area is drained predominantly by the Chindwin River, which as previously mentioned is the largest tributary of the Ayeyarwady, and is a major contributor to the suspended sediment load of clay and fine sands in the basin. Downstream of the confluence with the Chindwin River, the Ayeyarwady River continues to flow through this geologically younger material before reaching the wedge-shaped, flat laying depositional Ayeyarwady delta (WWF, 2017).

WWF (2017) describes a number of broad basins that have developed within the Ayeyarwady River Basin as a result of the complex faulting. The largest basin, the Central Dry Zone (previously outlined above in section 3.1.1), is located between the Arakan Yoma and the Sagaing fault zone, and contains the lower Chindwin and Mu Rivers. Other smaller basins occur within the upper Ayeyarwady between the Sagaing fault zone and the western edge of the Shan Plateau, between Myitkyina and where the river enters the

Sagaing fault zone at Tagaung. Faulting at the northern extent of the Sagaing zone has also been responsible for the development of the Lake Indawgyi. All of these basins are areas of sediment deposition and reworking and are sensitive to changes in hydrology and sediment supply.

Five marked defiles have influenced the position of the river: three upstream of Mandalay and two between Mandalay and Magway. Stamp (1940) describes the three defiles occurring upstream of Mandalay:

- the first defile is about 65 kilometres downstream from Myitkyina
- the second is below Bhamo, where the river makes a sharp westward swing, leaving the Bhamo alluvial basin to cut through the limestone rocks of the second defile. This defile is about 90 metres wide at its narrowest and is flanked by vertical cliffs about 60 to 90 metres high.
- the third defile is about 100 kilometres north of Mandalay, at Mogok
- the fourth and fifth defiles are downstream of the Chindwin/Ayeyarwady river confluence, where there are two geological constrictions on channel planform

The occurrence of groundwater resources in the Ayeyarwady River Basin is directly related to the geology, with most of the potential occurring in the intra montane deposits, mainly from Plio-Quaternary sand, gravel and silt deposits in the lowland plains (Viossanges et al, 2017). Groundwater flow direction throughout the basin is generally north to south broadly following the topography, and towards the rivers and streams, which form major discharge zones, particularly where there are structural constrictions, such as occur at the junction with faults and uplift zones. Groundwater discharges contribute considerably to dry season flows both in the intermittent chaungs[2] of the Central Dry Zone, and in the Ayeyarwady mainstream. Viossanges et al (2017) reported that in the Central Dry Zone at Magway (Figure 2), groundwater flows contribute around 20% of the total dry season flow in the river. Baseflows are also expected to play an important role in supporting many of the wetlands in the basin, particularly during the dry season.

In addition to the unconsolidated sedimentary and alluvial aquifers, there are also numerous other minor hard rock aquifer groups that are locally important within the basin. Groundwater-fed springs occur in the limestone terrain on the Shan Plateau, which in some areas form permanent ponds and lakes, in volcanic aquifers around Mount Popa at Kyaukpadaung, and along regional faults (Mahlaing, Sagaing and Shinmatuaung Fault zones) and artesian zones along the edge of the Shan Plateau (Viossanges et al, 2017).

[2] Watercourses, regardless of whether they contain water or not, are called "*chaung*" in Burmese (Stamp, 1940)

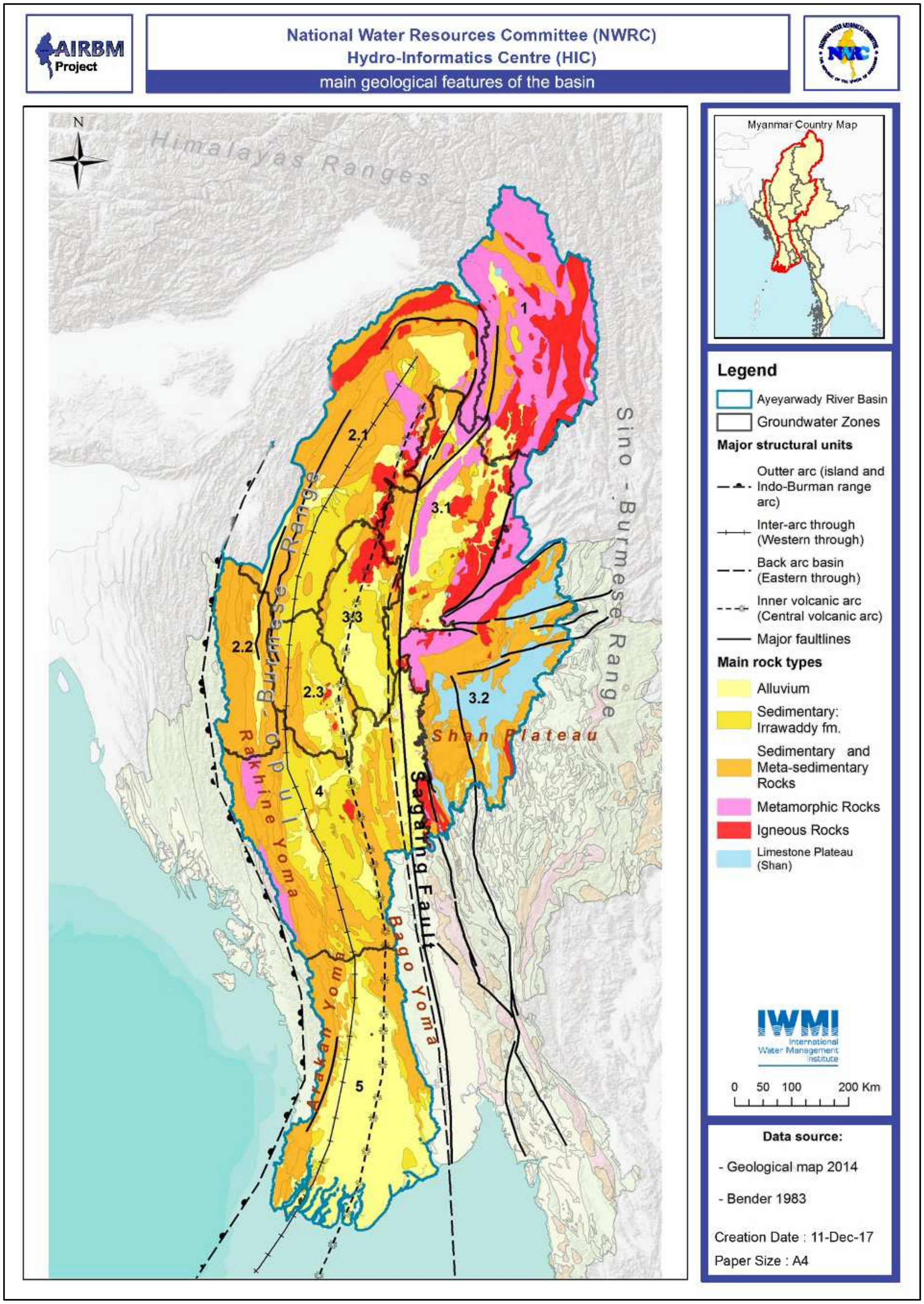


Figure 4 Main geological features of the Ayeyarwady River Basin (from Viossanges et al, 2017)

1.1.3 Land cover

Lehner and Dallaire (2014) combined terrestrial biomes, elevation and features such as karst, swamps and deltas, to produce a physio-climatic classification of the river basins of the Greater Mekong Region, represented here in Figure 5. According to this classification, the Ayeyarwady River Basin is characterized mostly by moist broadleaf forest at medium to low elevations. The Central Dry Zone is identifiable as an area of dry broadleaf forest at medium to low elevations and the Ayeyarwady River Delta is described as having coastal zone of mangroves. The far northern and north-western upland sections of the Ayeyarwady River basin are characterized by areas of coniferous forest and high elevation broadleaf forest, with a small zone of montane grassland extending into the Himalayas.

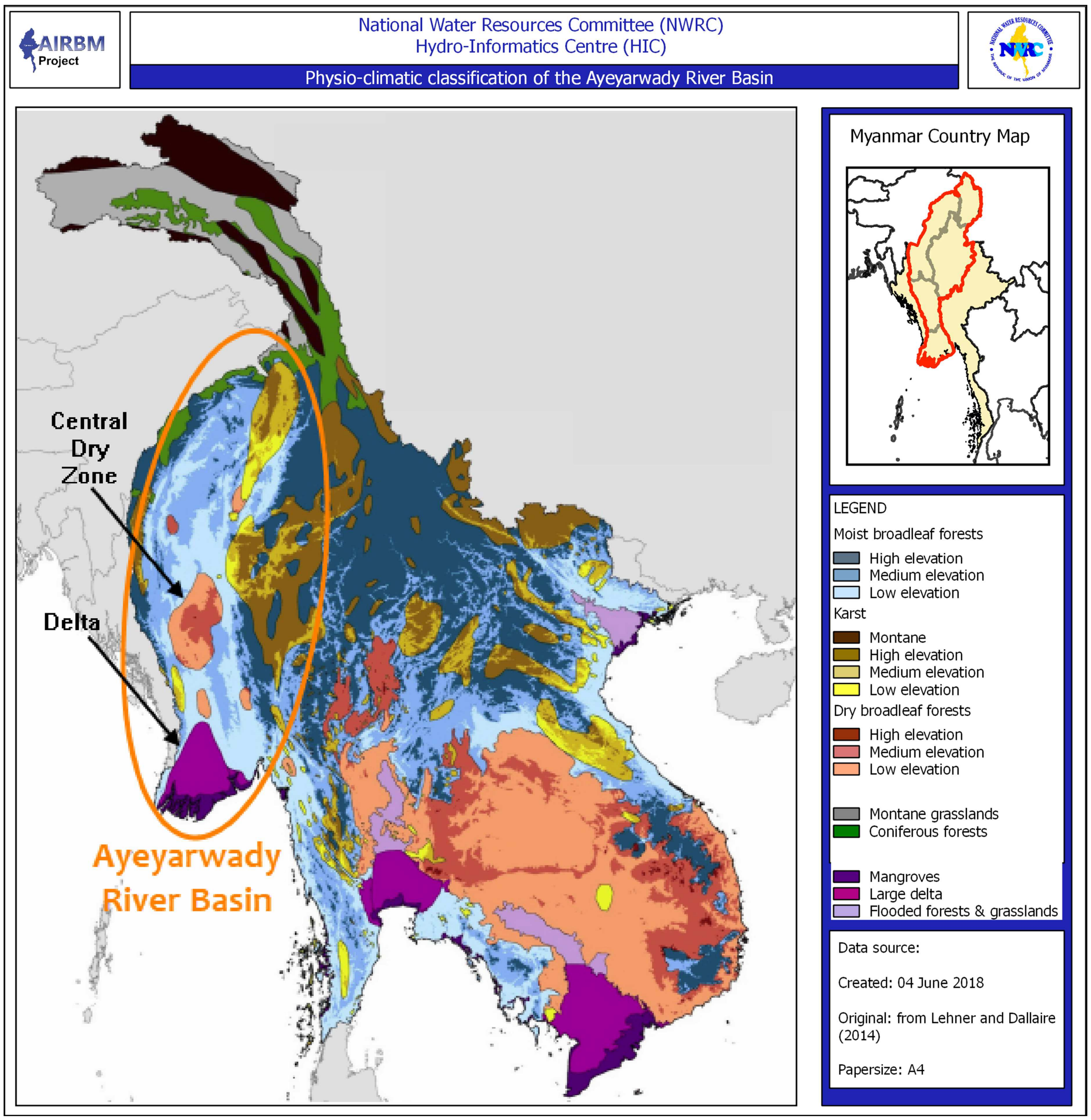


Figure 5 Physio-climatic classification of the Greater Mekong Region (from Lehner and Dallaire, 2014)

Considering land use, the Ayeyarwady River Basin is a relatively undisturbed basin. According to the IWMI (2014) land cover classification, applied here to represent land use[3] and shown in Figure 6 and Figure 7, more than 60 % of the Ayeyarwady River Basin is classified as forested, largely in the upland areas. Twenty-seven percent is classified as being used as agricultural land and is largely limited to the lower lying, flatter, parts of the basin extending along river valleys and into the flat lands of the Central Dry Zone and the Delta. According to the IWMI land cover classification irrigated land is defined as that which showed signs of cropping during both wet and dry periods of the year. About ¼ of the agricultural land is classed as irrigated, and about ¾ exclusively rain fed. It can also be assumed that lands which are irrigated in the dry periods are available to be planted and rain fed in the wet season.

Urban development is minimal. Mandalay, the second largest city on Myanmar with a population of 1.5 million, is located in the central Ayeyarwady River Basin. Yangon, the largest city in Myanmar, is situated on the lower south-eastern boundary of the Delta, and in terms of water resources, generally has a limited impact on the basin when considered as a whole.

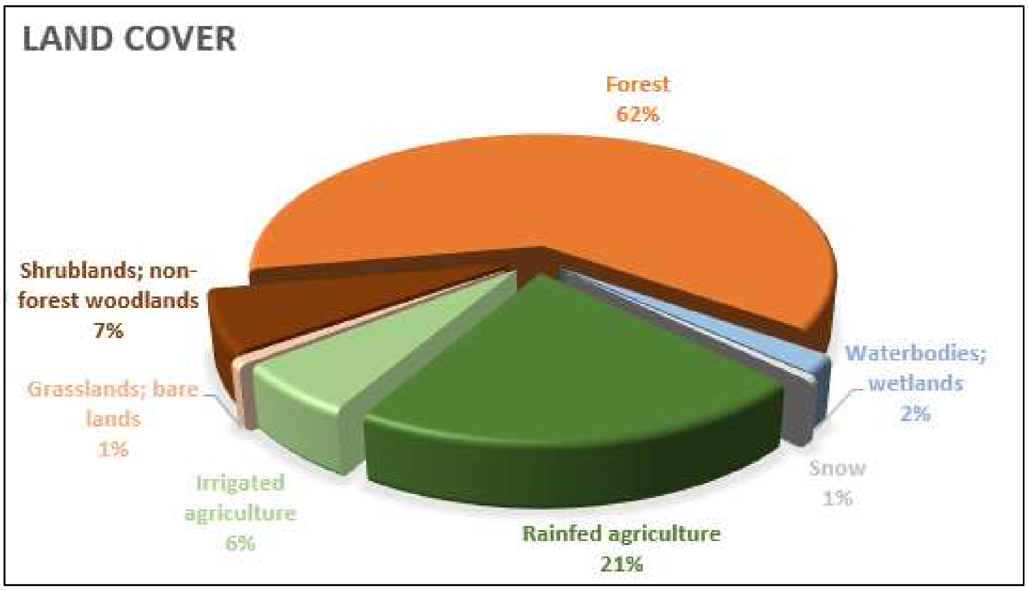


Figure 6 Distribution of land cover in the Ayeyarwady River Basin (after IWMI, 2014)

[3] While there may be overlaps, land cover and land use are not the same. FAO classifies land cover as the description of the observed (bio) physical cover on the earth's surface, while land use describes the arrangements, activities and inputs undertaken in a land cover type to produce, change or maintain it (FAO, 2017)

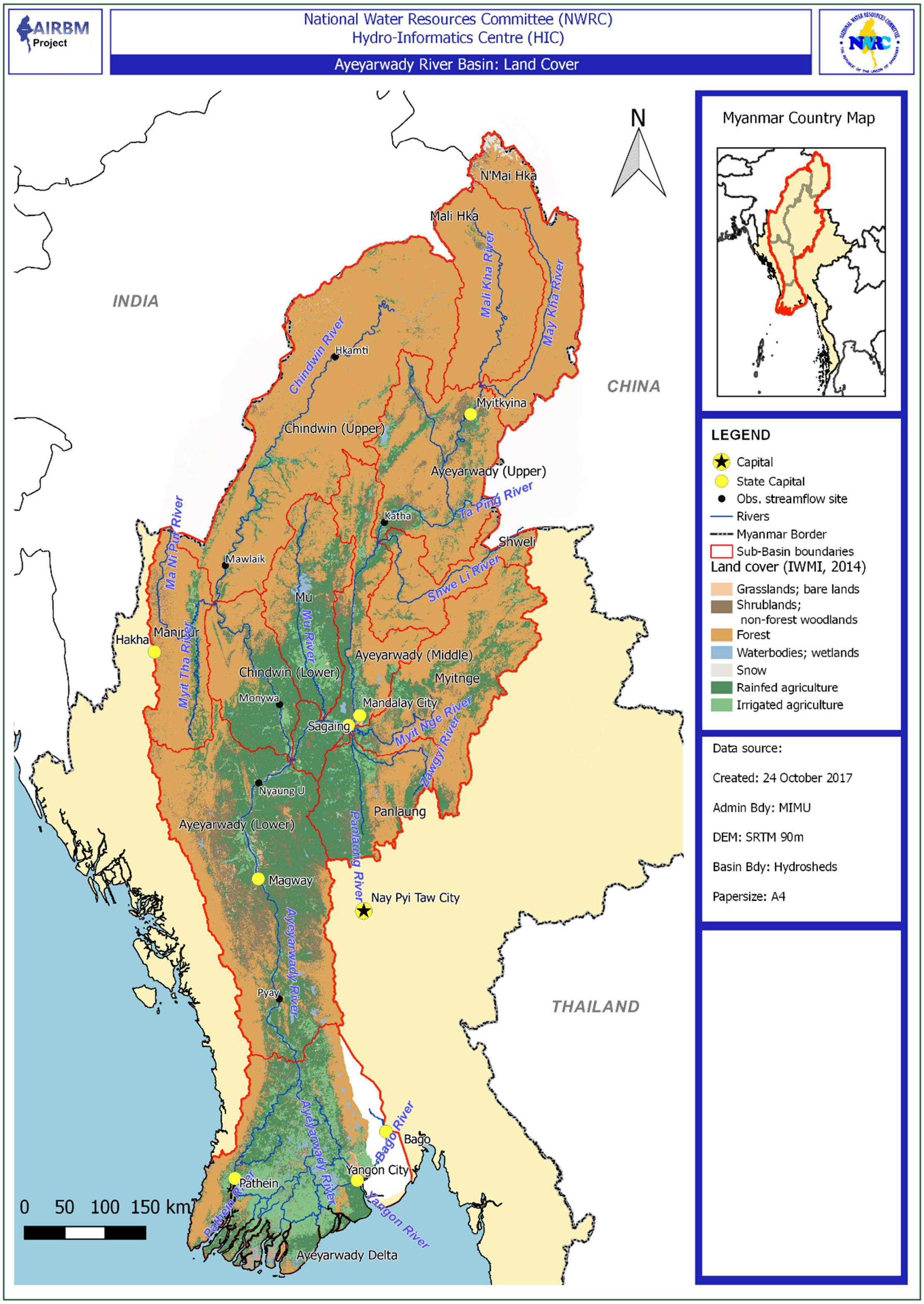


Figure 7 Land Cover of the Ayeyarwady River Basin (after IWMI, 2014)*

*available land cover layer did not include whole Delta

1.1.4 River network, hydro-ecological zones and sub-basins

The Ayeyarwady River originates in the Kachin State, its tributaries sourced from high mountain glaciers in the north. The river flows southward for about 2,000 km ending in an effluent delta with nine main distributaries flowing into the Andaman Sea. The Ayeyarwady Basin spans a complex of diverse landscapes and ecosystems. The Myanmar Healthy Rivers Initiative (MHRI) (ICEM, 2017) consolidated these into areas of similar hydro-ecology features, resulting in the definition of five Hydro-ecological Zones.

The largest tributary of the Ayeyarwady River is the Chindwin River, which has its confluence with the Ayeyarwady River upstream of Pakokku. The Chindwin River has a catchment area of about 114,500 km^2, approximately one quarter of the total Ayeyarwady River Basin area. Thirteen sub-basins can be identified within the Ayeyarwady River Basin, encompassing all the major tributaries of the Ayeyarwady and Chindwin Rivers. These sub-basins can be classified into the five Hydro-Ecological Zones (HEZ). Figure 8 illustrates the major tributaries (and sub-basins) of the Ayeyarwady River, together with their associated Hydro-Ecological Zones. Table 1 summarises the hydro-physical characteristics of each sub-basin.

The Chindwin River Basin is divided into three sub-basins:

- Chindwin Upper – upstream of the Chindwin/Myittha confluence at Kalewa, includes the Uyu River which joins the Chindwin River from the east at Homalin
- Chindwin Lower – downstream of the Chindwin/Myittha confluence at Kalewa extending to the Ayeyarwady River confluence, and
- Manipur - the basin of the Manipur River and the Myittha River, which rise in the Arakan Mountains and includes the Loktak Lake.

The main stem Ayeyarwady River is associated with ten sub-basins:

- the N'Mai Hka and Mali Hka sub-basins are the highest and most upstream river basins. They form the source of the Ayeyarwady River. The N'Mai Hka and Mali Hka sub-basins in the Upper Basin HEZ have the highest average elevation and average slope.
- the Ayeyarwady River main stem is divided into four sub-basins:
    - the Ayeyarwady (Upper) which extends from the N'Mai Hka/Mali Hka confluence to the confluence with Shweli River
    - the Ayeyarwady (Middle) which extends from the confluence with Shweli River to the Ayeyarwady/Chindwin confluence
    - the Ayeyarwady (Lower) which extends from the Ayeyarwady/Chindwin confluence to the Myanaung Township, considered to be the most upstream point of tidal influences (and also the most downstream extent of the Lower Basin hydro-ecological zone)
    - the Ayeyarwady River Delta, downstream of Myanaung Township. Downstream of this point the Ayeyarwady River divides into several distributaries.
- also included are the four main tributaries to the Ayeyarwady River main stem:
    - the Mu River sub-basin located in the central regions of the Ayeyarwady Basin. The Mu River flows in a north-south direction, entering the Ayeyarwady River between Mandalay and the Ayeyarwady/Chindwin confluence
    - the Shweli River sub-basin. The Shweli River has its source in the Chinese regions of the Ayeyarwady River Basin. It flows into the Ayeyarwady River from the east, downstream of Katha
    - the Myitnge River sub-basin. Also, an eastern tributary of the Ayeyarwady River, the Myitnge River flows into the Ayeyarwady at Sagaing
    - the Panlaung River sub-basin. The Panlaung River is a tributary of the Myitnge River. It flows into the Myitnge River from the south east, joining it just before the Ayeyarwady/Myitnge confluence at Sagaing

Table 1 Hydro-physical characteristics of each sub-basin

SUB-BASIN	HEZ#	AREA	MAIN RIVER *		ELEVATION **	SLOPE **
		km^2	Name	km	Mean (m amsl)	Mean (%)
Mali Hka	1	23309	Mali Hka	312	1,093	32
n' Mai Hka	1	24388	n' Mai Hka	469	2512	52
Chindwin (Upper)	2	73497	Chindwin River	818	686	23
Chindwin (Lower)	2	16601	Chindwin River	318	253	6
Manipur	2	24369	Manipur River ****	329	902	27
Ayeyarwady (Upper)	3	37162	Ayeyarwady River	397	600	15
Ayeyarwady (Middle)	3	22250	Ayeyarwady River	385	308	10
Mu	3	19459	Mu River	376	227	5
Myitnge	3	30682	Myitnge River	477	878	17
Panlaung	3	16316	Panlaung River	139	501	11
Shweli	3	22924	Shweli River ***	567	1,047	20
Ayeyarwady (Lower)	4	59238	Ayeyarwady River	469	313	10
Delta	5	43826	Ayeyarwady River	285	27	3

HEZs (Hydro-ecological zones) are depicted in Figure 8 below
* River length based on Hydrosheds DEM stream basin threshold of 1350 km^2
** Zone elevation based on Hydrosheds DEM
*** Tributary originates in China
**** Tributary originates in India

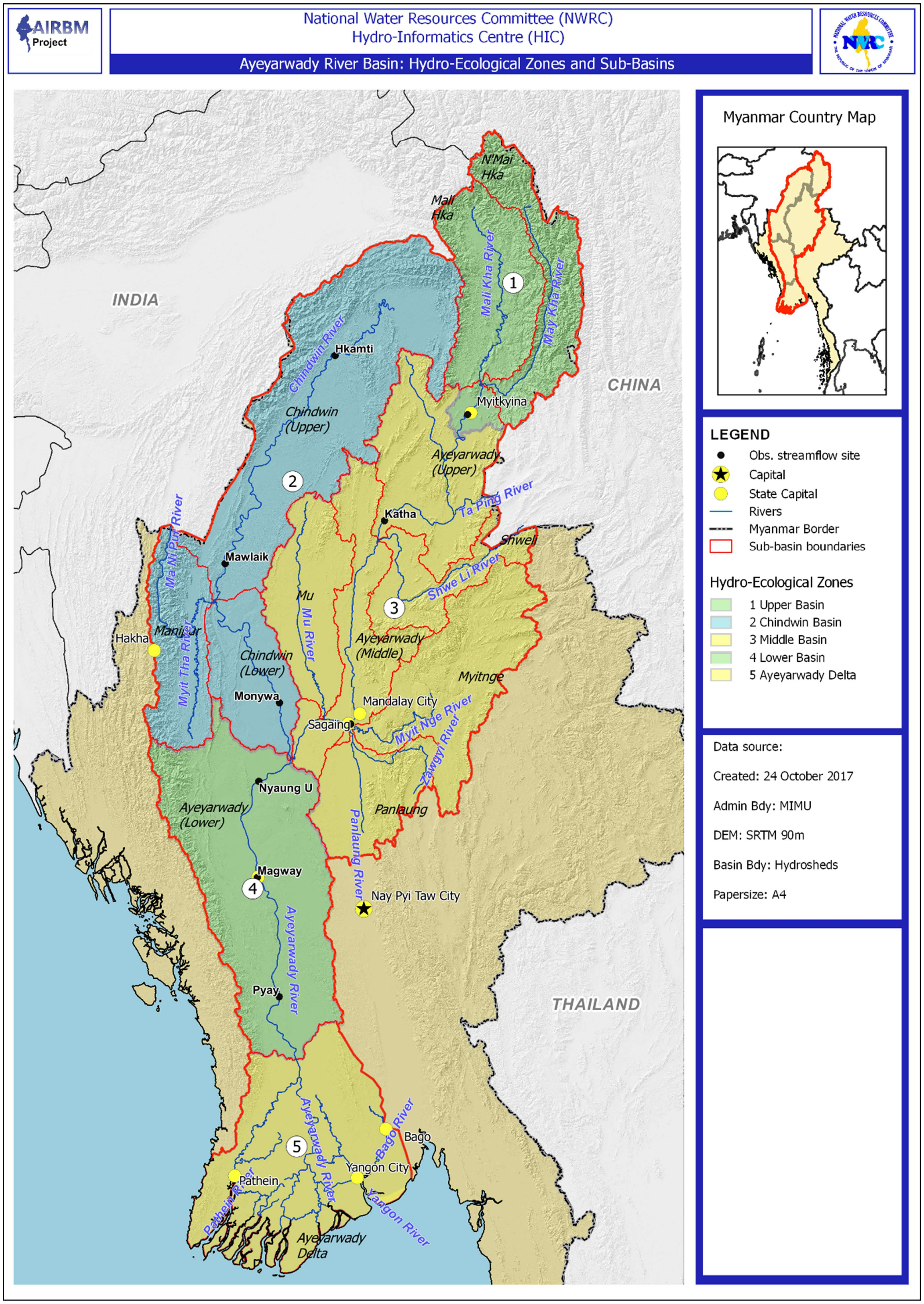


Figure 8 Major tributaries and sub-basins of the Ayeyarwady River Basin

The hydro-ecological zones were developed by MHRI as a synthesised summary on the river classification assessment of the Greater Mekong undertaken by McGill University for the WWF (Lehner and Dallaire, 2014). The river classification process utilised the GLORIC developed by McGill University, which disaggregates sub-classifications according to indices and characteristics from different disciplines (hydrologic, physio-climatic, geomorphologic, chemical, biological, and human alteration) (Dallaire, 2012). These indices and characteristics were spatially overlaid using GIS software to group areas of similar characteristics into distinct river reaches. In the Greater Mekong exercise, disciplines were limited to hydrological, physio-climatic, geomorphology and habitats due to data availability (Lehner and Dallaire, 2014). Under the MHRI project the 29 river classes (shown here in Figure 9) were further constrained into the five HEZs outlined in Figure 8 and described below, based primarily on the geomorphology of the main-stem in the basin.

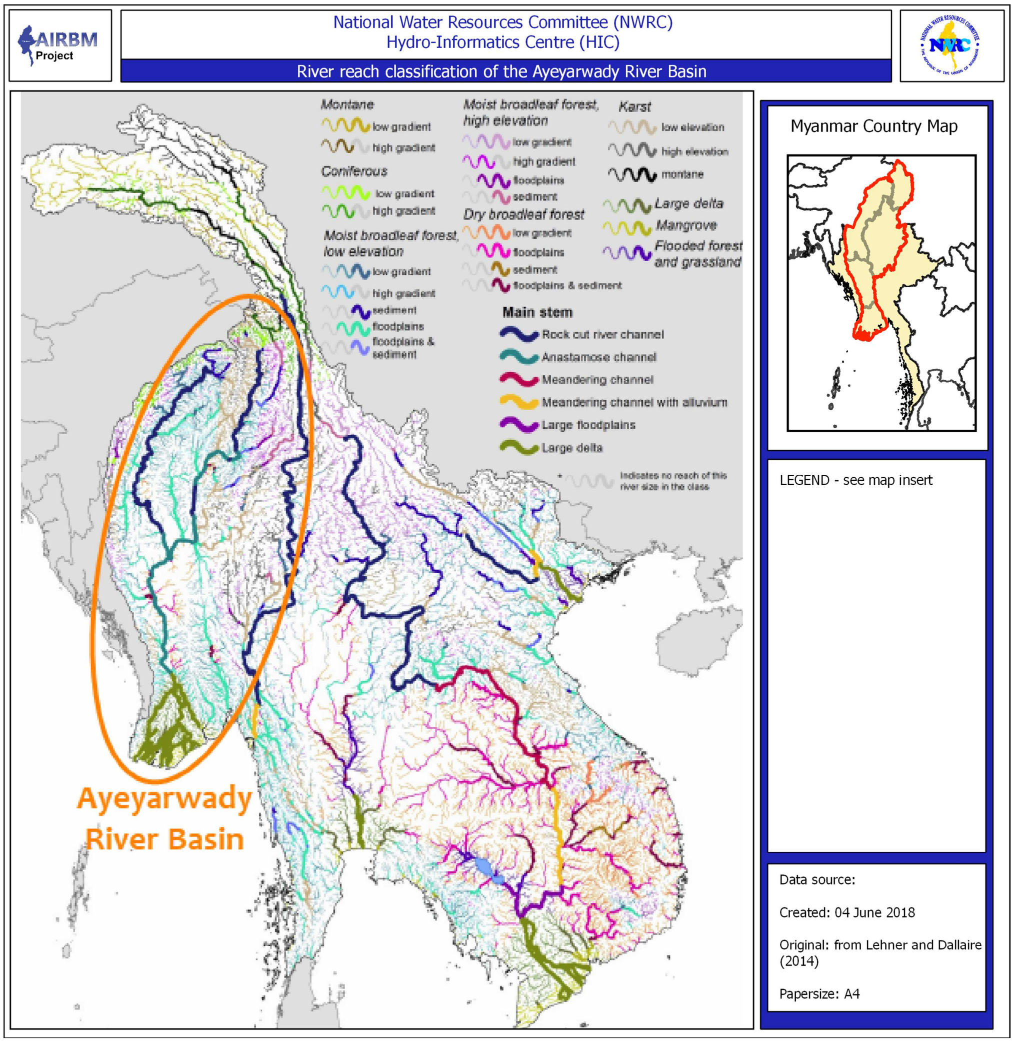


Figure 9 River reach combination for the Greater Mekong region (from Lehner and Dallaire, 2014)

- ***Hydro-Ecological Zone (HEZ) 1 - Upper Basin***

Incorporating the upper reaches of the Ayeyarwady River and the N'Mai Hka and Mali Hka Rivers, the Upper Basin extends from the most northern sections of the Ayeyarwady River Basin to approximately 50km downstream of Myitkyina. It is dominated by a river cut rock channel, incised into the steep terrain associated with this section of the Ayeyarwady River Basin. The headwaters rise in steep-sloped coniferous forests, karst and moist broad-leaved forest. Most of the drop in elevation of the Ayeyarwady River occurs within HEZ 1 - Upper Basin (Figure 10).

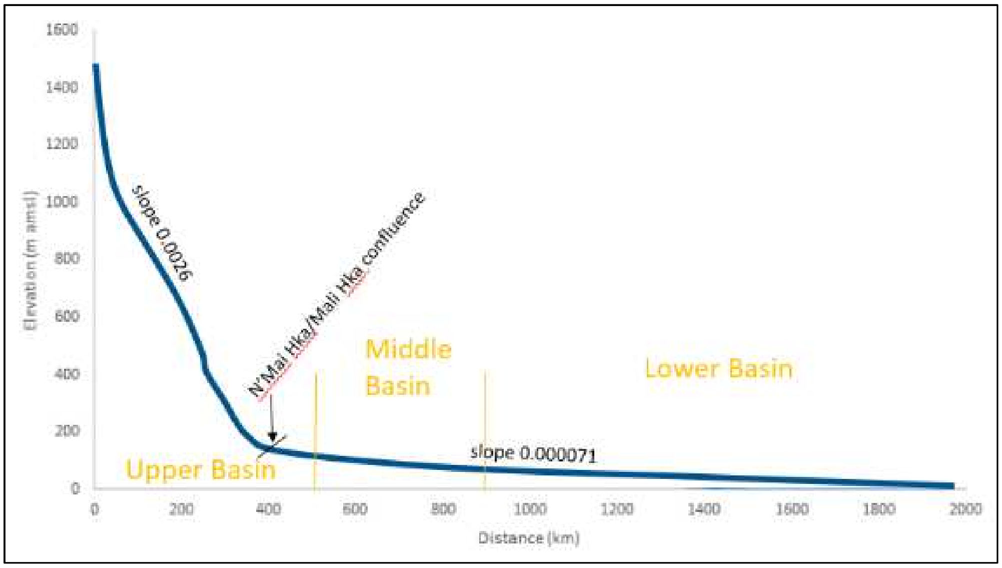


Figure 10 Longitudinal profile of the Ayeyarwady River

- ***Hydro-Ecological Zone (HEZ)*2 – Chindwin Basin**

This zone incorporates the entire basin of the Chindwin River to its confluence with the Ayeyarwady River upstream of Pakokku. The Chindwin River main stem has a predominantly rock cut channel, flattening into a complex anastomosing channel with both significant meandering in planform and multiple highly mobile braided channels. These anastomosing channels are also characteristic of the adjacent Middle Basin and Lower Basin zones. They display some of the most complex and dynamic morphology found in the rivers of the Greater Mekong Sub-region, and are unique to the Ayeyarwady River Basin. The zone is a complex of low gradient coniferous and moist broad leaf forest and smaller areas of karst formations. A number of medium-sized tributaries including the Myittha River and Uyu River form significant floodplains at their confluences with the Chindwin River.

Although the upper reaches are not as steep (or as high) as those of the Ayeyarwady River, the Chindwin River has an average slope steeper than the Ayeyarwady River (Figure 11). Upstream of Hkamti, the river passes through a sharp defile forming the Taron valley (labelled 6 on Figure 14 below).

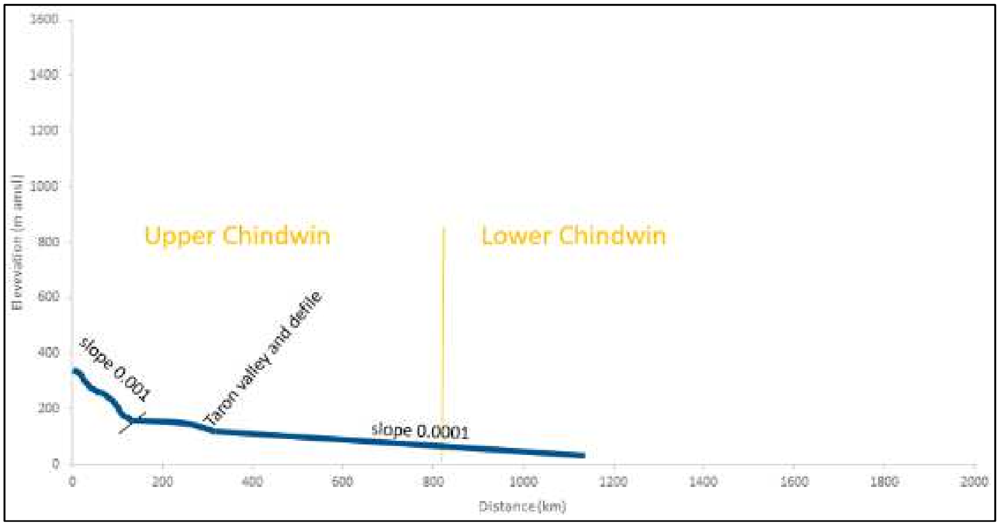


Figure 11 Longitudinal profile of the Chindwin River

- ***Hydro-Ecological Zone (HEZ)3 – Middle Basin***

The Middle Basin is defined as the section of the Ayeyarwady River Basin between the Upper Ayeyarwady (near Myitkyina) and the Ayeyarwady/Chindwin River confluence. The largest tributaries in this zone include the Tarpein River, Shweli River, Myitnge River and Mu River. The zone represents a largely flat reach, with the southern parts of the zone entering into the 'Dry Zone' climatic area. The main stem channel is a predominantly anastomosing channel interspersed by short reaches of confined rock-cut river channel that partially constrains meandering and mobility of the channel planform.

Lee and Zöckler (2017) describe the three most well-known defiles (gorges) which occur in the Middle Basin (in a downstream direction) as follows:

- The first river defile begins approximately 12 km downstream of Sinbo and continues for 45 km. Here the river width narrows from approximately 1 km down to 200 – 300 m at the mouth of the gorge, with river depths ranging from 30 to 40 m. The river banks are steep with heavily forested ridges rising to 900 m above sea level. This gorge has fast moving water, and the surrounding rock outcroppings have led to the creation of rapids and eddies.
- The second defile is located approximately 30 km downstream of Bhamo where the river width narrows from approximately 1km down to 400 m. The banks of the gorge are very steep, with vertical limestone cliffs rising up to 100 m above the river. The river ranges from 25 – 30 m in depth and is confined by rocky banks with little floodplain habitat. After about 12 km, the gorge opens up into outwash floodplain.
- The third river defile is located approximately 55 km downstream of Tagaung. Here the river narrows to about 500 m in width and becomes 15 to 25 m deeper with a faster current speed. The gorge remains straight for approximately 30 km before turning abruptly to the west, as a result of a large lava sheet which has caused the river to bend, it follows along another fault line for 8 km, and then turns towards the southeast for 20 km, ending near the town of Singu. The floodplain habitat is confined to the flooded margins along the river bank.

Between Katha and Mandalay, the course of the river is remarkably straight, flowing almost southwards, except near Kabwet, where a sheet of lava has caused the river to bend sharply westward (Stamp, 1940). The geomorphological classification of the river undertaken by Lehner and Dallaire (2014) clearly illustrates the location of rock cut river channels and hence the location of the defiles referred to above, as shown in Figure 12 and in Figure 14 below. These defiles are labelled 1 – 3 in Figure 14.

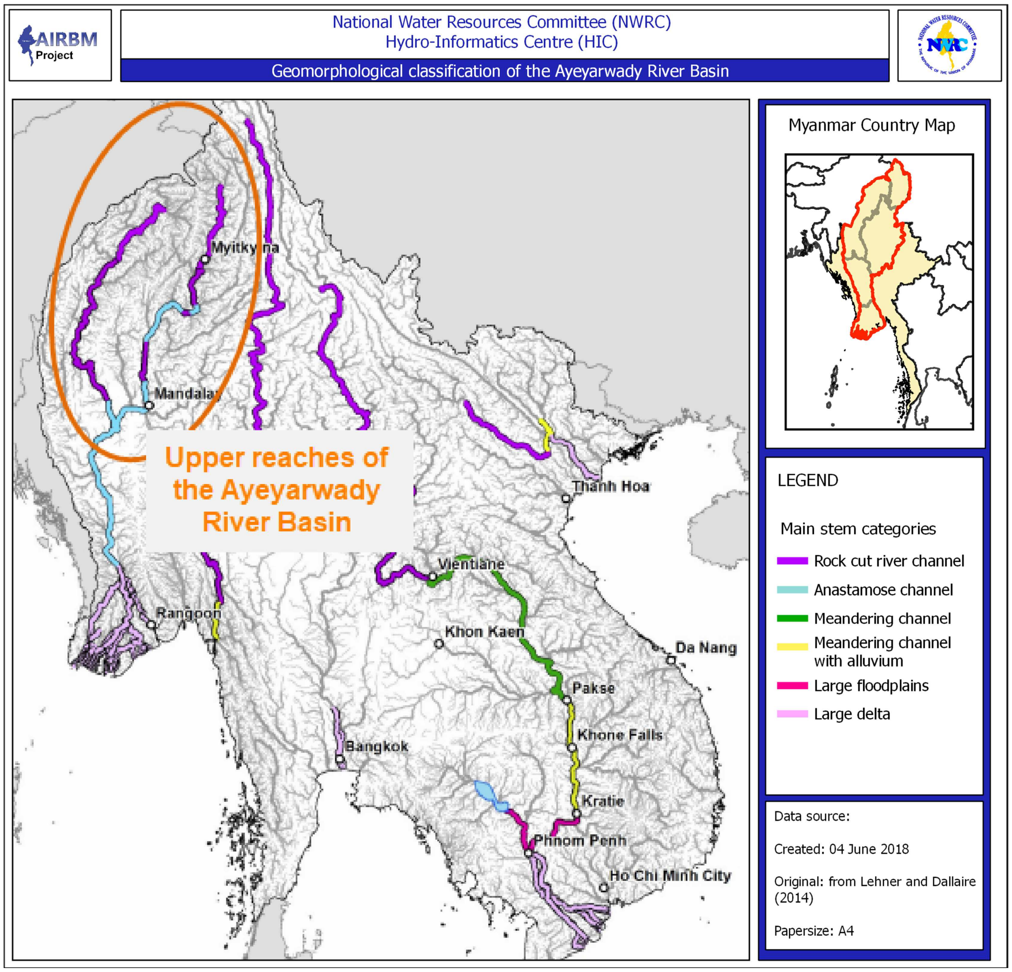


Figure 12 Geomorphological classification of the Upper Ayeyarwady River Basin rivers (from Lehner and Dallaire, 2014)

The right bank tributaries of the Middle Basin generally comprise of low gradient moist-broadleaf forests with large floodplains. Left bank tributaries consist of higher elevation moist-broadleaf forests as well as karst formations and generally smaller floodplains.

Hydro-Ecological Zone (HEZ)4 – Lower Basin

The Lower Basin hydro-ecological zone extends from the Chindwin/Ayeyarwady confluence in the north to Myanaung Township in the south – approximately 100km downstream of Pyay. This is the point in the Ayeyarwady River downstream of which tidal influences have been noted to influence channel hydrology (Volker, 1966). Lehner and Dallaire (2014) classified the variability of rivers of the Greater Mekong Region using the ratio of maximum monthly discharge over long-term average discharge thereby illustrating the higher variability and intermittent nature of tributary streams in the lower zones of the Ayeyarwady River Basin.

The Yin and Narwin rivers are the only major rivers in this zone which enter from the left bank of the channel, with the majority of rivers draining the Arakan Mountains to enter the right back of the Ayeyarwady River. This includes the Yaw Chaung and the Pin, Mon and Pani Rivers. The Ayeyarwady main stream is an anastomosed channel. There are two geological constrictions on channel planform at two defiles downstream of the Chindwin confluence. The location of these defiles is shown in Figure 14 below, labelled 4 and 5 on Figure 14 below.

- ***Hydro-Ecological Zone (HEZ)5 – Delta***

The southernmost zone comprises the Ayeyarwady River Delta, an area of approximately 51,000 km^2. As described by Lehner and Dallaire (2014) the Delta is characterised by a division of the main stem into a complex of nine low gradient streams. The Delta can be described as having three zones (see Figure 13):

  - a largely marine influenced, tidal coastal front with mangroves along the southern edges (lower delta)
  - a brackish water estuarine zone (middle delta), and
  - a freshwater floodplain (upper delta)

The delineation of these Delta zones shifts with seasons and tides. High spring tides in the summer season can lead to a strong seasonal intrusion of saline waters.

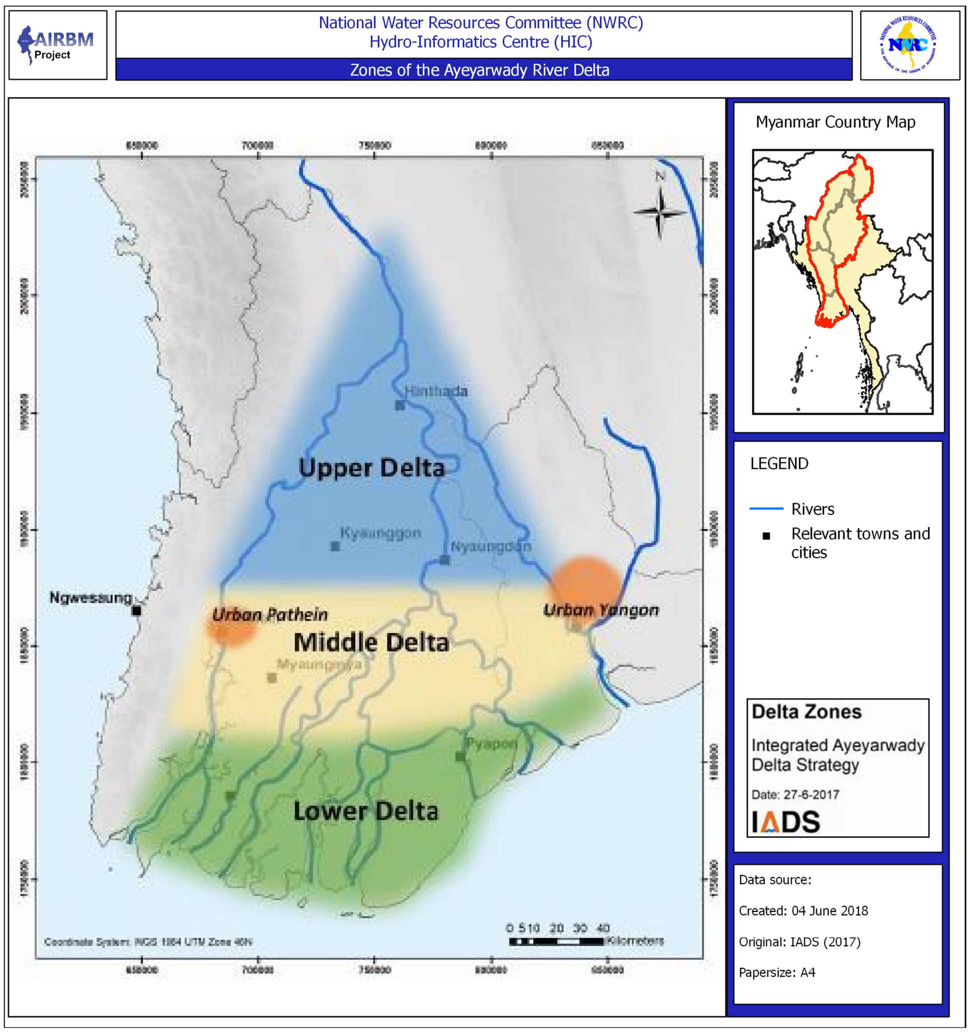


Figure 13 Zones of the Ayeyarwady River Delta (from IADS, 2017)

1.1.5 The Ayeyarwady River floodplain and Delta

Most of the length Ayeyarwady and Chindwin rivers downstream of the high-elevation mountains of their headwaters, is flat and anastomosing, with alternating major floodplain areas and rock-cut channels through gorges (defiles) found along the length of these rivers. Figure 14 illustrates the locations of low-lying areas and gorges, based on a DEM assessment of potential flood-susceptible surface area.[4] The figure shows extensive floodplains in all HEZs – a characteristic unique to the Ayeyarwady which reflects the strong influence of the basin flat, low slope topography.

The Ayeyarwady Delta spans approximately 51,000 km^2 and represents a shelf composed of sediments deposited by the branches of the Ayeyarwady River system. The delta was formed by alluvial activities during the Holocene era. The soil layer is thick but relatively young. The landscape of the Ayeyarwady Delta region is very flat and monotone, with only a few blocks of erosion-resistant rocks that are never more than 18 meters in height.

Fertile alluvial material from the river basins make the Ayeyarwady Delta very suitable for agricultural practice. The Delta is also rich in minerals, including metal ores, petroleum, and natural gas. It was once home to extensive tracts of mangrove forests along the southern coastal front, but it is suggested the delta lost 1685 km^2 of mangrove forest from 1978 to 2011 (https://earthshots.usgs.gov/earthshots/node/67#ad-image-8). The water salinity in the southern part of the Delta depends strongly on the inflow of fresh water of the Ayeyarwady River and changes from season to season.

At the maritime boundary of the delta, the Ayeyarwady River discharges through three main distributaries: Pathein River, Ayeyarwady River and the Hlaing River fanning out into a complex network of river channels further downstream (Figure 15). These rivers are only connected to the Ayeyarwady River during flood season.

[4] This is a first cut at identifying possible floodplain areas and may require further refinement in some areas, such as the northern Chindwin.
DEM analysis could not extend beyond the derived streamlines in the Delta. Potential floodplain area should be extended to the coastline.

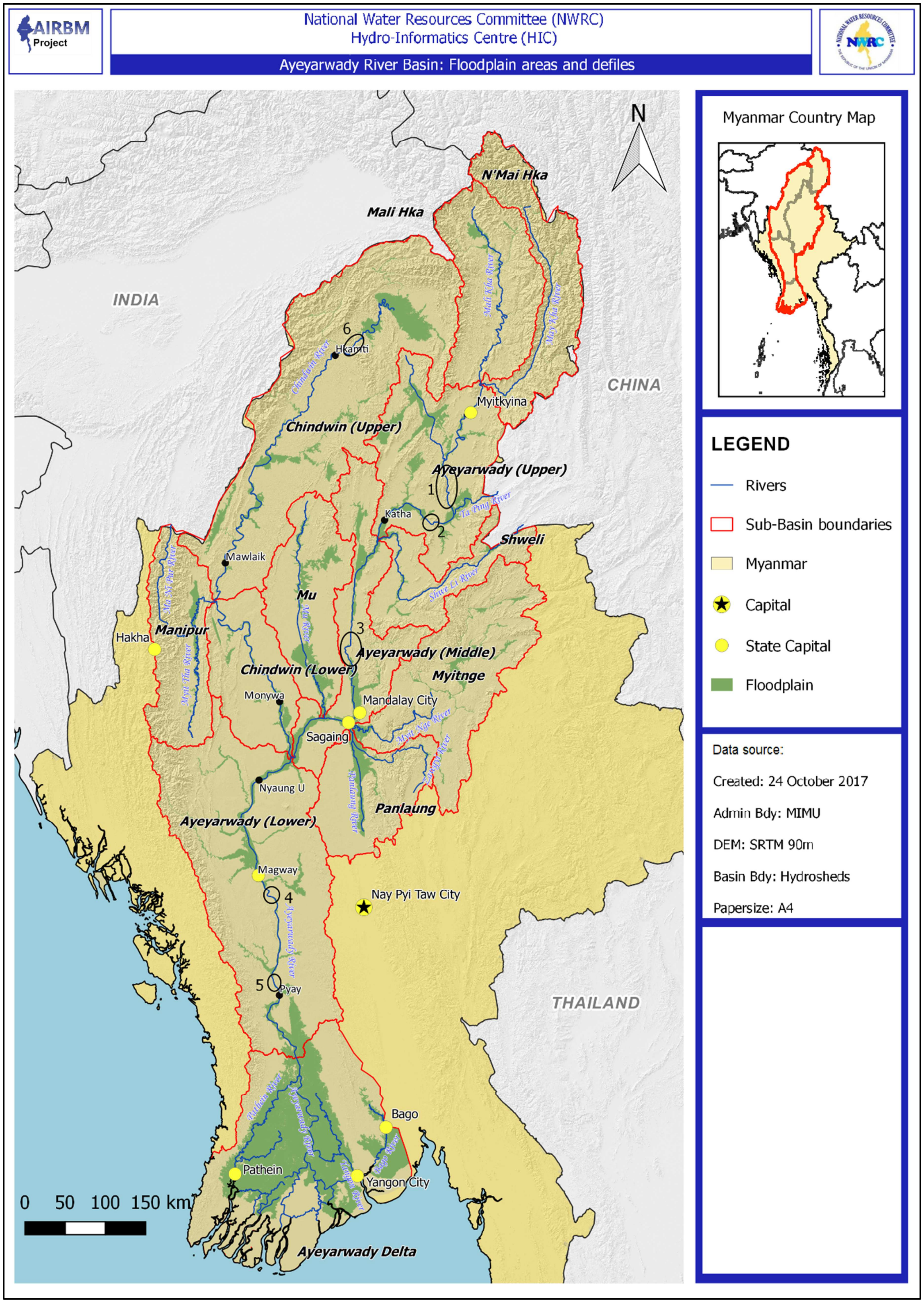


Figure 14 Flood-susceptible areas and defiles of the Ayeyarwady River Basin: *Defiles are numbered 1 – 6.*

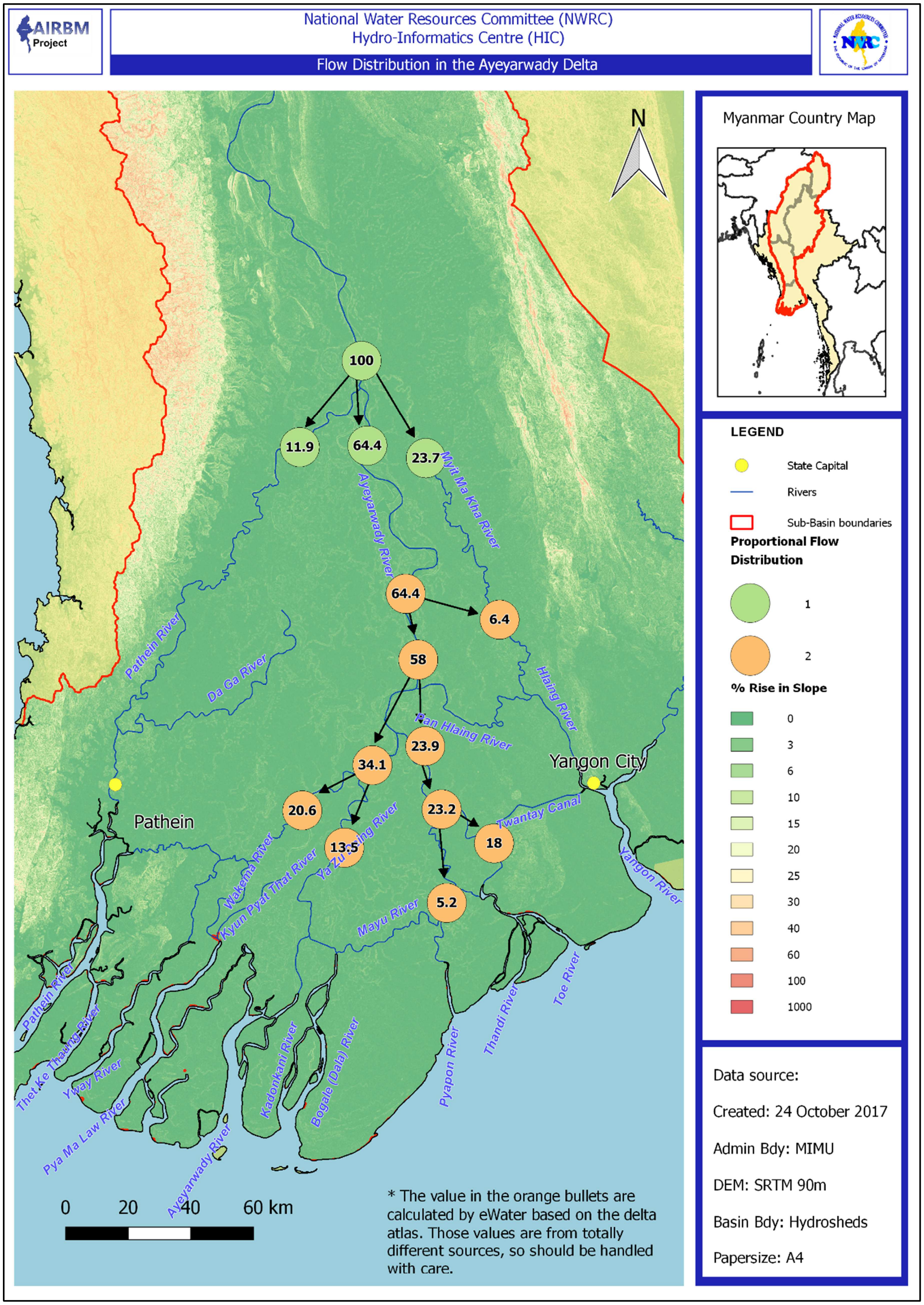


Figure 15 Main distributaries of the Ayeyarwady Delta

1.2 Climate characteristics

1.2.1 Drivers of climate in the Ayeyarwady River Basin

The climate of the Ayeyarwady River Basin is dominated by a monsoonal rainfall regime associated with the south western Indian monsoon and also affected by convectional systems and cyclones from the Bay of Bengal. Temperatures are generally high with a low diurnal range. However, this varies across the Basin, impacted by latitude and elevation, as well as localised rain shadow effects. In the northern mountains daily temperatures can fall to below 0°C, while in the Central Dry Zone in the rain shadow of the Arakan Mountains they can rise to the mid-forties and typically average around 32 degrees Celsius during the dry season. According to D'Arrigo et al (2011) there is a correlation between Myanmar rainfall and the El Niño Southern Oscillation (ENSO).

The southern parts of the Ayeyarwady River Delta are particularly prone to cyclones and accompanying storm surges, typically occurring in the pre-monsoon months of April and May and the post-monsoon October to December (IADS, 2017), although there is some variability in this timing. Furthermore, while most of the cyclones originate in the Bay of Bengal and approach Myanmar from the south-west, this pattern is not distinct, adding more uncertainty which increases local vulnerability. Figure 16 shows the paths of cyclones observed during the period 1980 – 2010, illustrating the variability in directions.

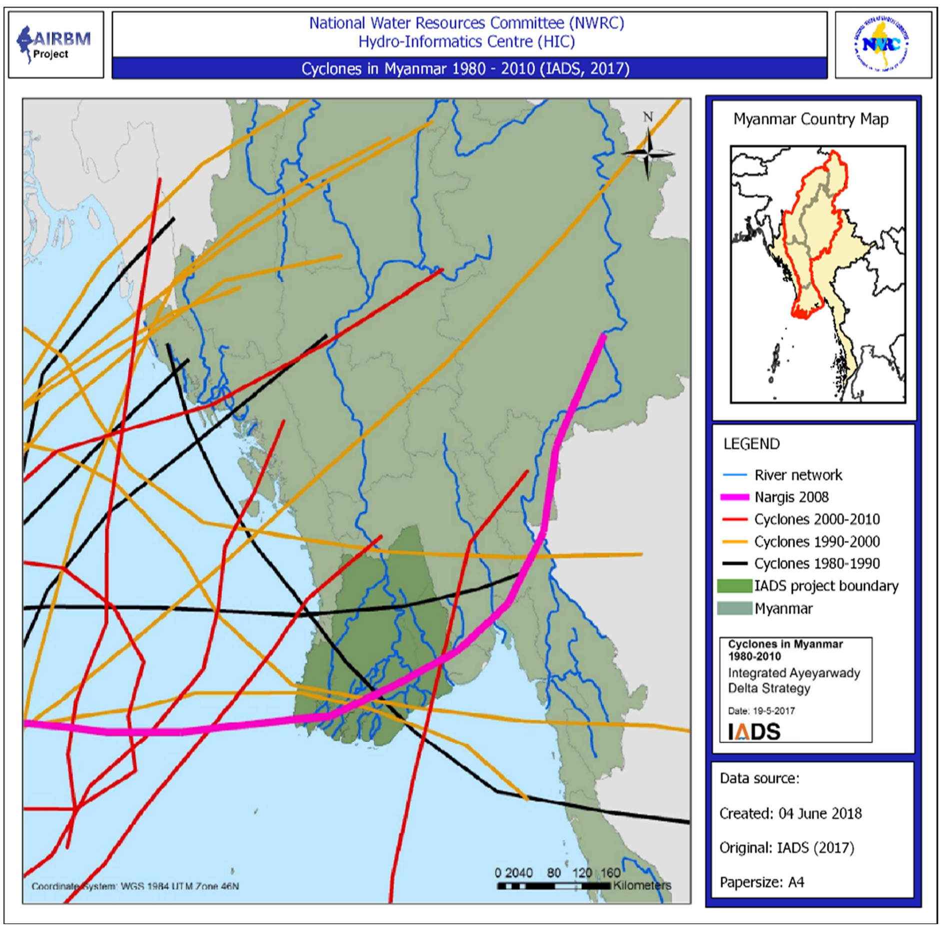


Figure 16 Observed cyclone paths (1980 – 2010)* (from IADS, 2017)

* Naval research Lab, Monterey and JTWC http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/ioindex.php

Although the Ayeyarwady Delta is frequently subjected to cyclones - the worst being Cyclone Nargis in 2008 which killed more than 100,000 people and affected approximately 2.4 million people - the impact of cyclones is not limited to only the Delta and to only pre and post -monsoon periods. Cyclones can lead to high rainfall and associated flooding in more inland areas, particularly if combined with existing wet season flooding.

1.2.2 Rainfall

The Ayeyarwady River Basin has a strongly monsoonal climate, with definite wet and dry seasons. Under the influence of the South-West Monsoon the wet season starts in mid-May and extends till the end of October, while dry season months (November to mid-May) are divided into a winter (December – February) and hot (March – mid May) period. Mean annual rainfall in the Ayeyarwady River Basin varies from less than 1,000 mm in the Central Dry Zone to more than 4000 mm in the north-western parts of the Basin and in the Ayeyarwady Delta (Figure 18). A view of the seasonal rainfall patterns across the Basin gives an indication of these seasonal variations (Figure 19). During the winter months of December, January and February rainfall across the whole basin is very low. In June, July and August rainfall increases, although remains lower in the Central Dry Zone, in the rain shadow of the Arakan Mountains.

At all times, the Central Dry Zone receives less rainfall than any other part of the Basin. Figure 17 shows mean monthly total rainfall at Hkamti in the far Upper Chindwin Basin against that at Nyaung U in the Central Dry Zone for 1981 - 2017. Total volume of rainfall at Nyaung U is 27% of the total rainfall at Hkamti.

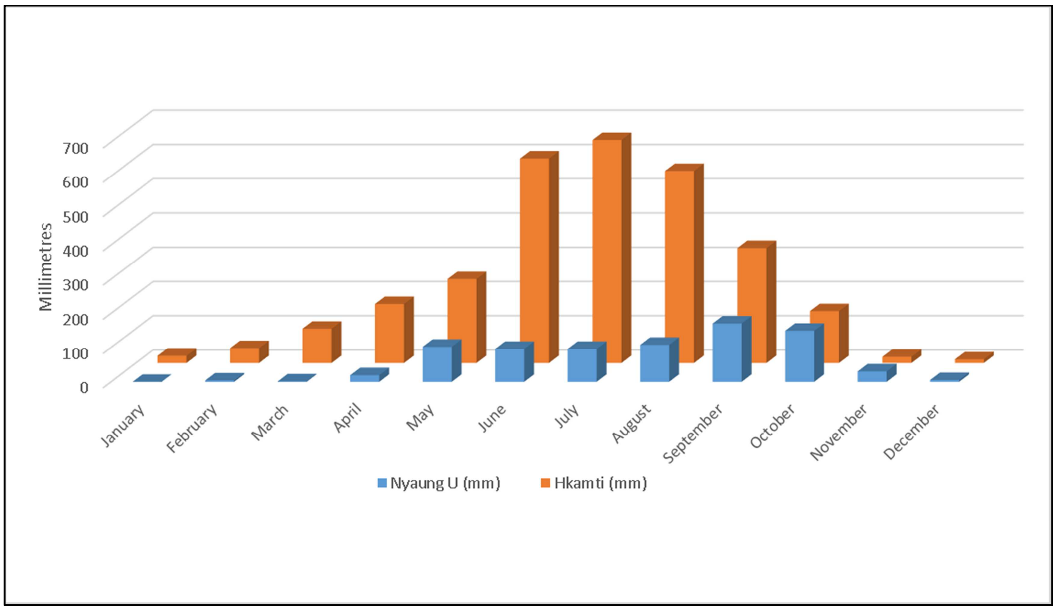


Figure 17 Mean monthly rainfall (mm) at Hkamti and Nyaung U (1981 – 2017) (derived from CHIRPS global rainfall)

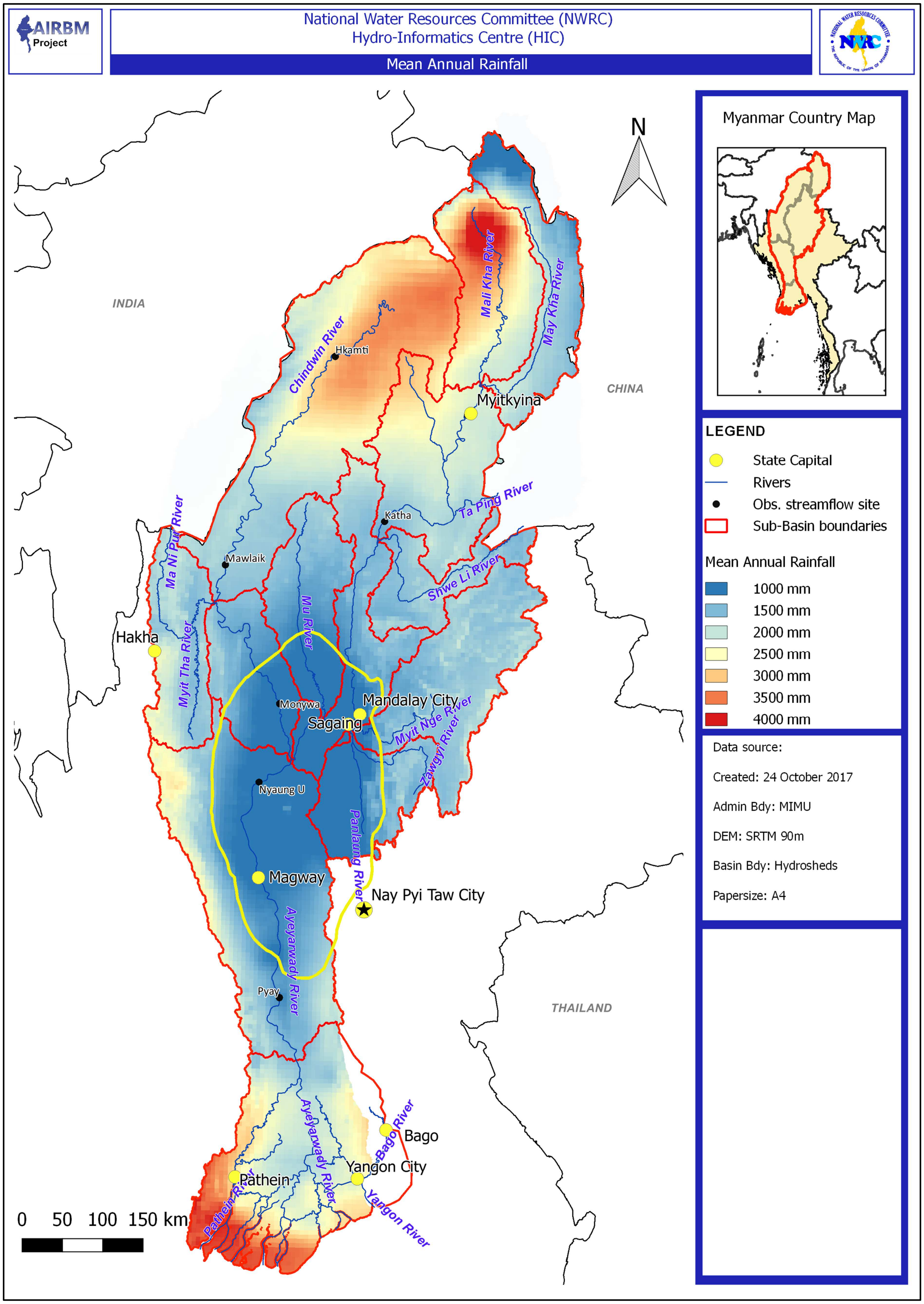


Figure 18 Mean Annual Rainfall of the Ayeyarwady River Basin (mm) (derived from CHIRPS global rainfall), with the Central Dry Zone (yellow circle)

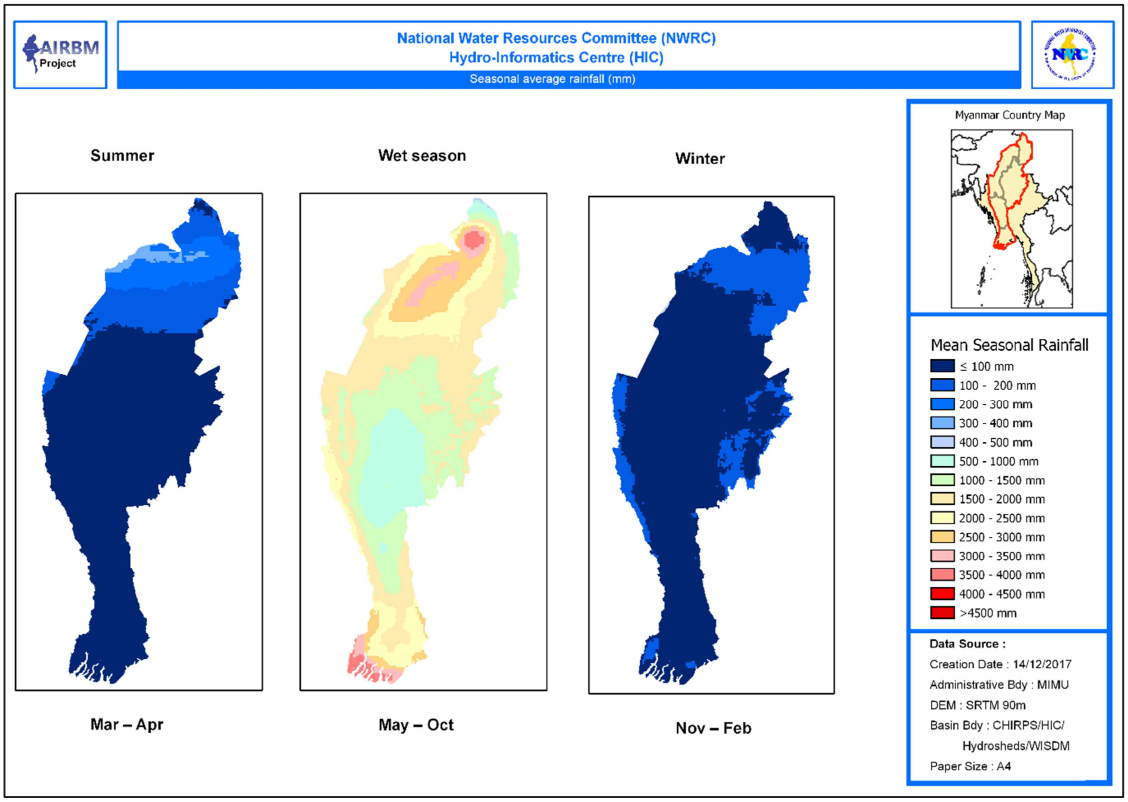


Figure 19 Seasonal average rainfall (mm) (derived from CHIRPS global rainfall)

In Figure 20, average annual discharge and total annual rainfall is graphed at eight sites across the Basin: Hkamti, Mawlaik and Monywa in the Chindwin Basin; Myitkyina, Katha and Sagaing in the Upper and Middle Basin; Magway in the Lower Basin and downstream of Pyay, at the point where flows enter the Ayeyarwady Delta. As average discharge increases downstream through the Ayeyarwady Basin, total rainfall is seen to decrease towards Monywa and Sagaing as the river approaches the Central Dry Zone and gradually increases again towards the Delta. This pattern emphasises that the availability of water in the lower parts of the basin is strongly dependent on surface water network connectivity with the high rainfall, high-elevation areas in the headwaters of the basin.

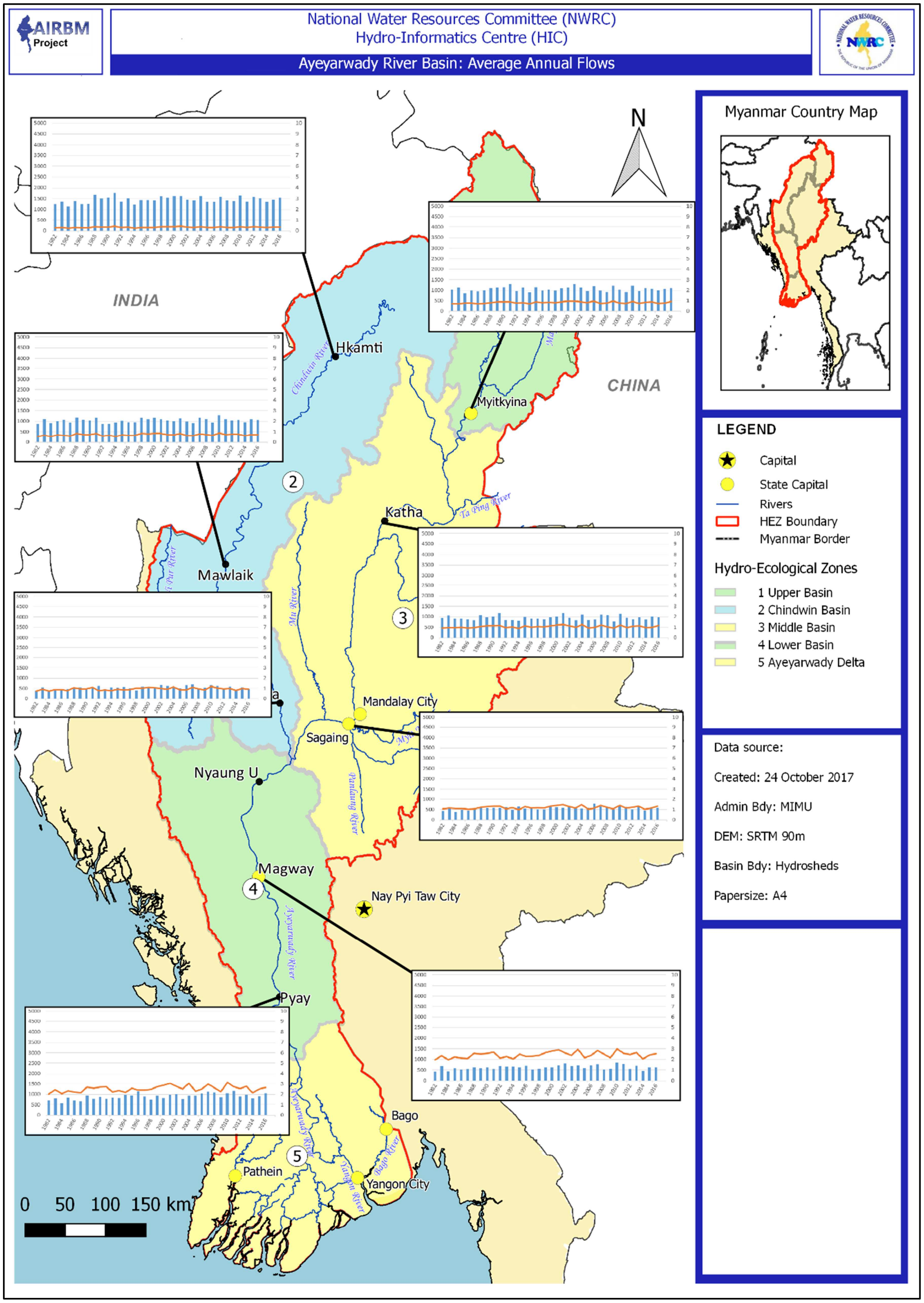


Figure 20 Average annual discharge (orange) (MCM) and Total Annual Rainfall (blue) (m) at various sites in the Ayeyarwady River Basin

1.2.3 Temperature and Evapotranspiration

Temperatures across the Ayeyarwady River Basin decrease from the northern mountain regions southwards to the Central Dry Zone and Delta. Although hot across most of the lowland parts of the basin, they are generally highest in the Central Dry Zone. Figure 21 shows average monthly temperatures from Myitkyina and Hkamti in the north to Hinthada in the south, calculated from observed daily values for 1986 – 2015. Highest temperatures are experienced in April at all sites, except for Hkamti, where temperatures are highest in May. The location of these sites and the average diurnal range in temperature for each month is illustrated in Figure 22. The daily range in temperature is typically least during the wet season months, and greatest in the pre-monsoon months. Also evident is a decrease in maximum temperatures after the onset of the wet season, with a slight rise in temperature again in the latter half of the wet season. Minimum temperatures do not show this dip in the wet season, steadily increasing from winter across the summer months into the wet season, and then decreasing again into winter.

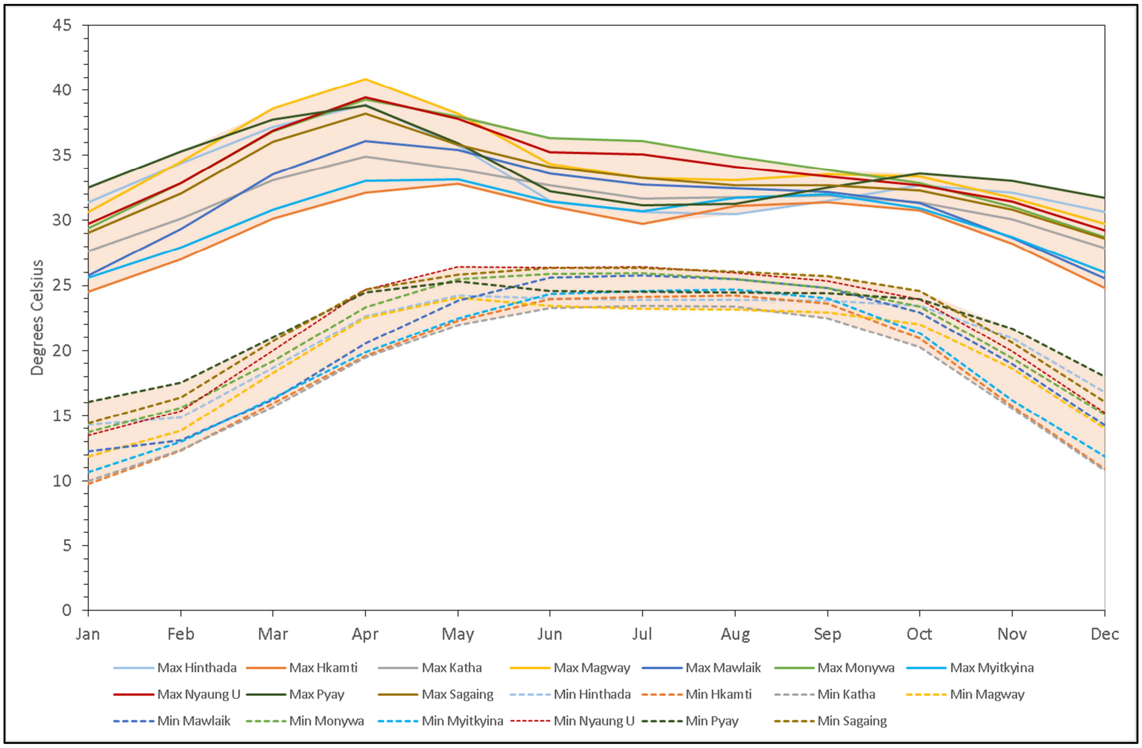


Figure 21 Mean maximum and minimum monthly temperatures

There is a relationship between temperature and evaporation. The Hargreaves method calculates potential evapotranspiration (PET) from daily temperature values. In the absence of observed data, the Hargreaves method has been used here to generate evapotranspiration values for the Ayeyarwady River Basin from remotely sensed temperature data (see 'ANNEX II - Climate data review'). Figure 23 shows the distribution of average annual PET across the basin. This distribution directly reflects the distribution of temperature across the basin. The trend in PET is generally higher in the southern parts, decreasing northwards as altitude increases and temperature decreases, but with the highest values in the Central Dry Zone. Like temperature, potential evapotranspiration is highest at the end of the dry season in the months including March and April and preceding the onset of the monsoon.

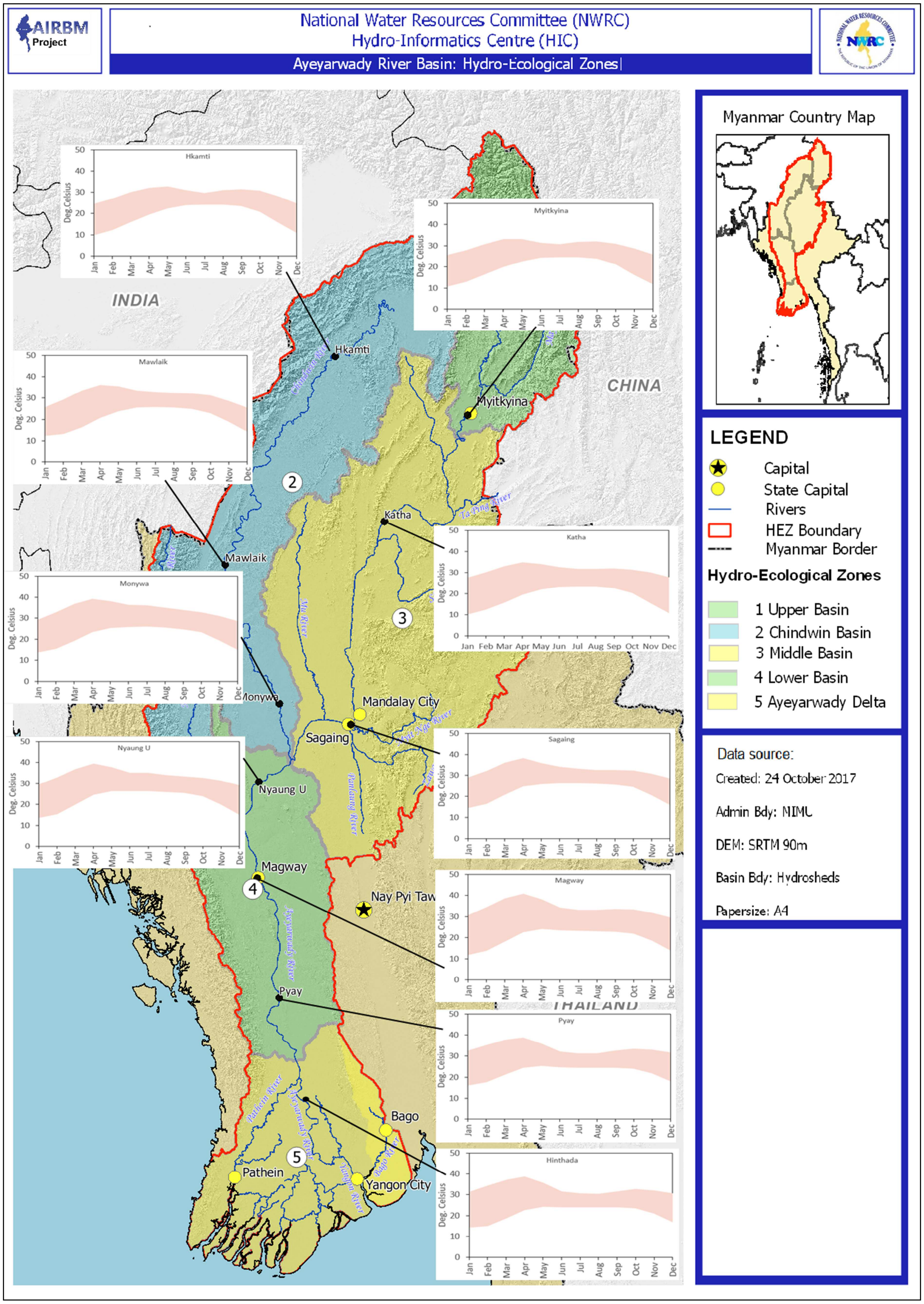


Figure 22 Spatial and temporal distribution of temperature in the Ayeyarwady River Basin.

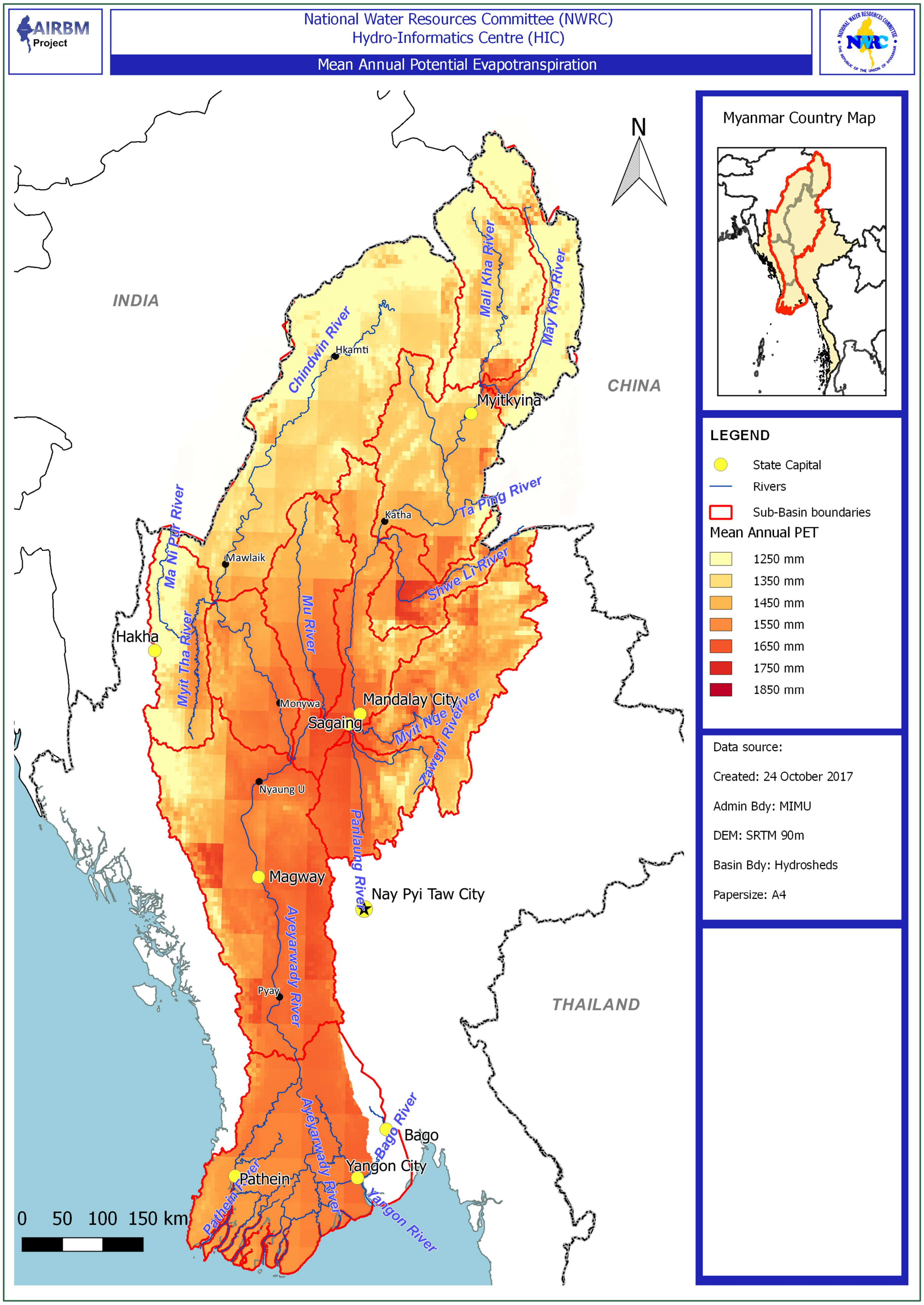


Figure 23 Mean Annual PET of the Ayeyarwady River Basin (mm)

1.2.4 Snowmelt

The Ayeyarwady River originates in the south-eastern Himalayas and is fed by glacier and snow melt off the high mountains (Figure 24). The highest peak in Myanmar, Hkakabo Razi (5,881 m amsl), is situated in the Himalayan peaks of the upper N'Mai Hka sub-basin. Snowfalls have been reported totalling around 5 m per year in this area. Despite some melting in spring, snow remains in place in some parts all year round, and several smaller glaciers can be found. The pattern of runoff from the Himalayas, its timing and intensity, is governed by the quantity and distribution of precipitation, its form - whether solid or liquid - and seasonality (Bandyopadhyay et al, 1994). The hydrological processes differ in high-altitude areas where snow and glacier melt processes dominate (Immerzeel et al, 2013). The snow melt runoff from high-altitude areas, including glacial areas, can potentially sustain streamflow even during the dry season.

The melting process depends on several energy fluxes that either deliver heat to or remove heat from the snowpack. Data to support these complex hydrological processes and energy fluxes are difficult to obtain due to harsh terrain, remoteness and inaccessibility. Therefore, lumped rainfall-runoff models are often used to estimate meltwater.

The main snow melt season extends from June to September, largely coinciding with the wet season and rising temperatures. However, the evidence of snow melt contributions can be seen in the hydrograph at Myitkyina as early as April, particularly when compared to other downstream sites. This is illustrated in Figure 25 where observed wet season flows at Myitkyina for 2010 and 2011 are plotted together with downstream sites in the Ayeyarwady River. The meltwater brings about a sharp rise in flow at Myitkyina during April to May, and a further steep rise in May to June with the onset of the monsoon. The enlargement of a single season in 'Inset A' of Figure 25 shows that flows from Myitkyina (the red line) dominate in the months prior to the wet season, but any snowmelt occurring after the onset of the wet season will be lost in the magnitude of the monsoon flows.

There are no observed data quantifying snowmelt contributions, but hydrological simulation (from 2000 to 2012) estimates that seasonal snowmelt contribution to monthly runoff varies between 1-5 percent during the months of April to August. However, overall annual snowmelt contribution to total runoff is low - in the order of 0.1%.

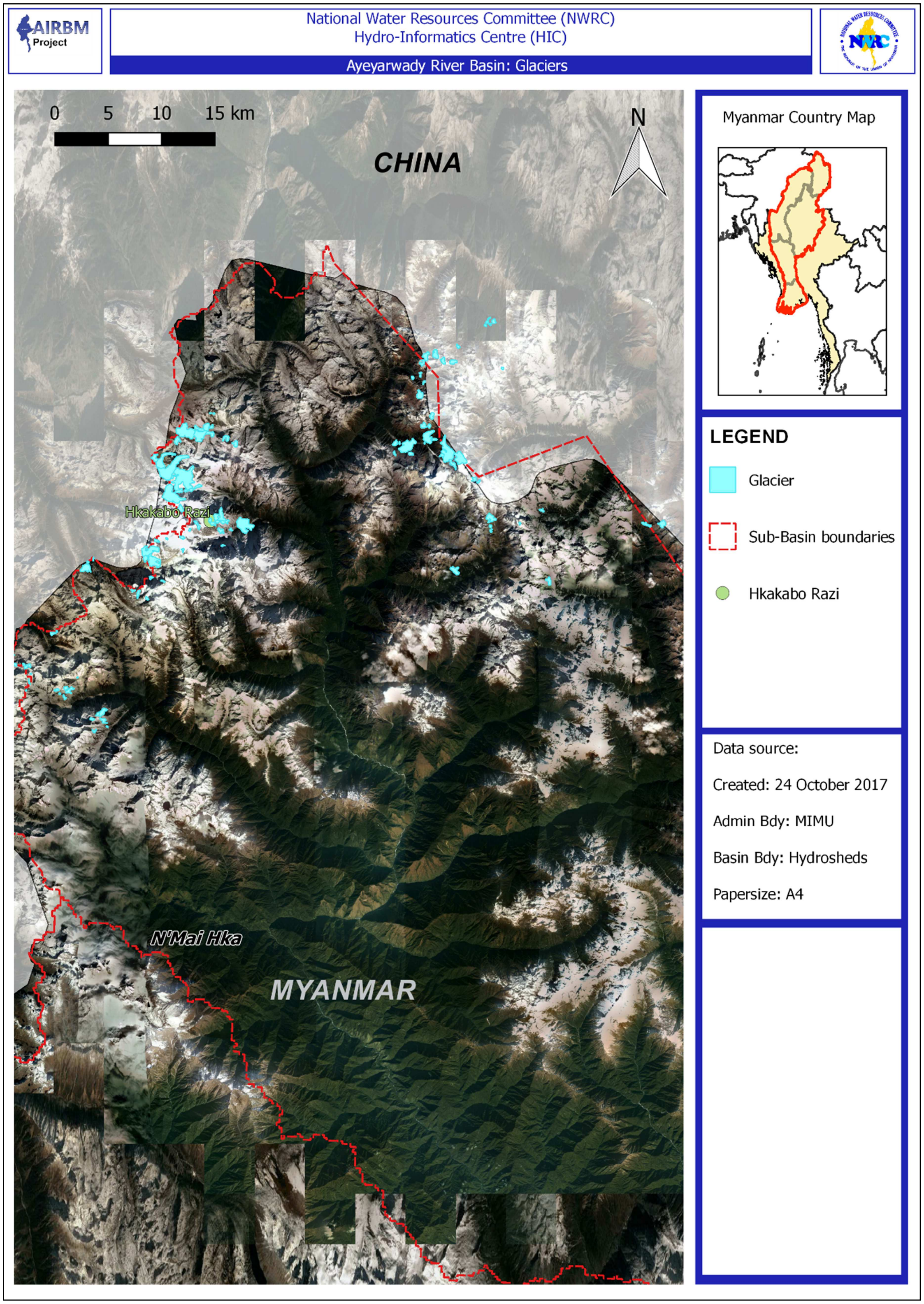


Figure 24 Upper N'Mai Hka sub-basin with glaciers

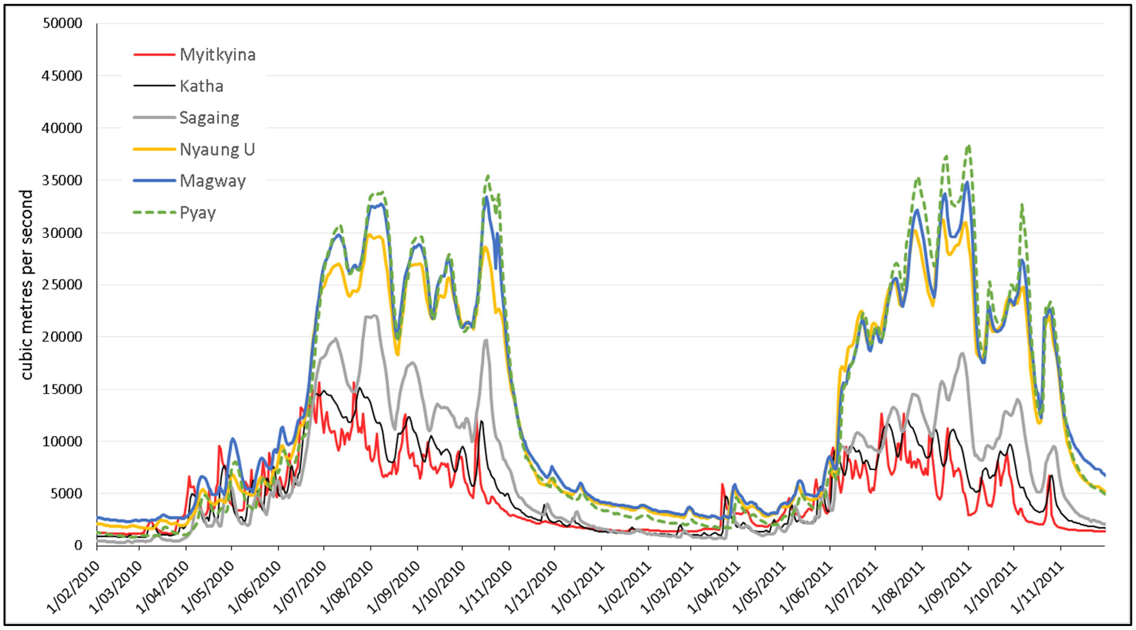


Figure 25 Indication of snow melt contribution at Myitkyina (2010 and 2011)

1.3 Hydrology

1.3.1 A Source Water System Model

A hydrological model of the Ayeyarwady River Basin has been developed to produce a baseline assessment of the hydrology of the basin, using the Source Water System modelling package (ewater.org.au). A detailed description of the model and the assumptions made is available in Annex I.

This model includes representations of agricultural (crop), domestic, urban and hydropower water use. Major storages supplying these water requirements are included in the model. Agricultural areas in the model are based on a 2014 IWMI land cover classification (IWMI, 2014). Rainfall-runoff generation is driven by layers of gridded rainfall and evaporation. The model is calibrated to observed flow volumes at 6 sites, and represents all Hydro-Ecological Zones upstream of the Ayeyarwady River Delta. The baseline represents a 'current' level of development at 2014–2016, in terms of storages, land use, irrigation areas and population. The model is run with historic climate data for 1981–2016.

The Delta regions of the Ayeyarwady River Basin are not modelled as part of the SOURCE model of the basin. The IADS Atlas (Atlas - Ayeyarwady Delta. Towards a safe, sustainable and prosperous delta) (2017) was used as a primary source of information on the Delta. Figure 26 shows the areas covered by the SOURCE model and the IADS Atlas(2017). In the future IADS will develop a hydraulic model of the Delta.

Having this water system model of the basin makes it possible to:

- simulate components of the hydrological cycle at points in the Ayeyarwady River Basin where observed values are not available,
- combine outputs from the model together with observed values, to provide an overall assessment of water availability and uses across the Ayeyarwady River Basin north of the Delta
- have a baseline for comparison which can be used in subsequent studies,
- have a baseline which can be used in other studies to examine possible future scenarios

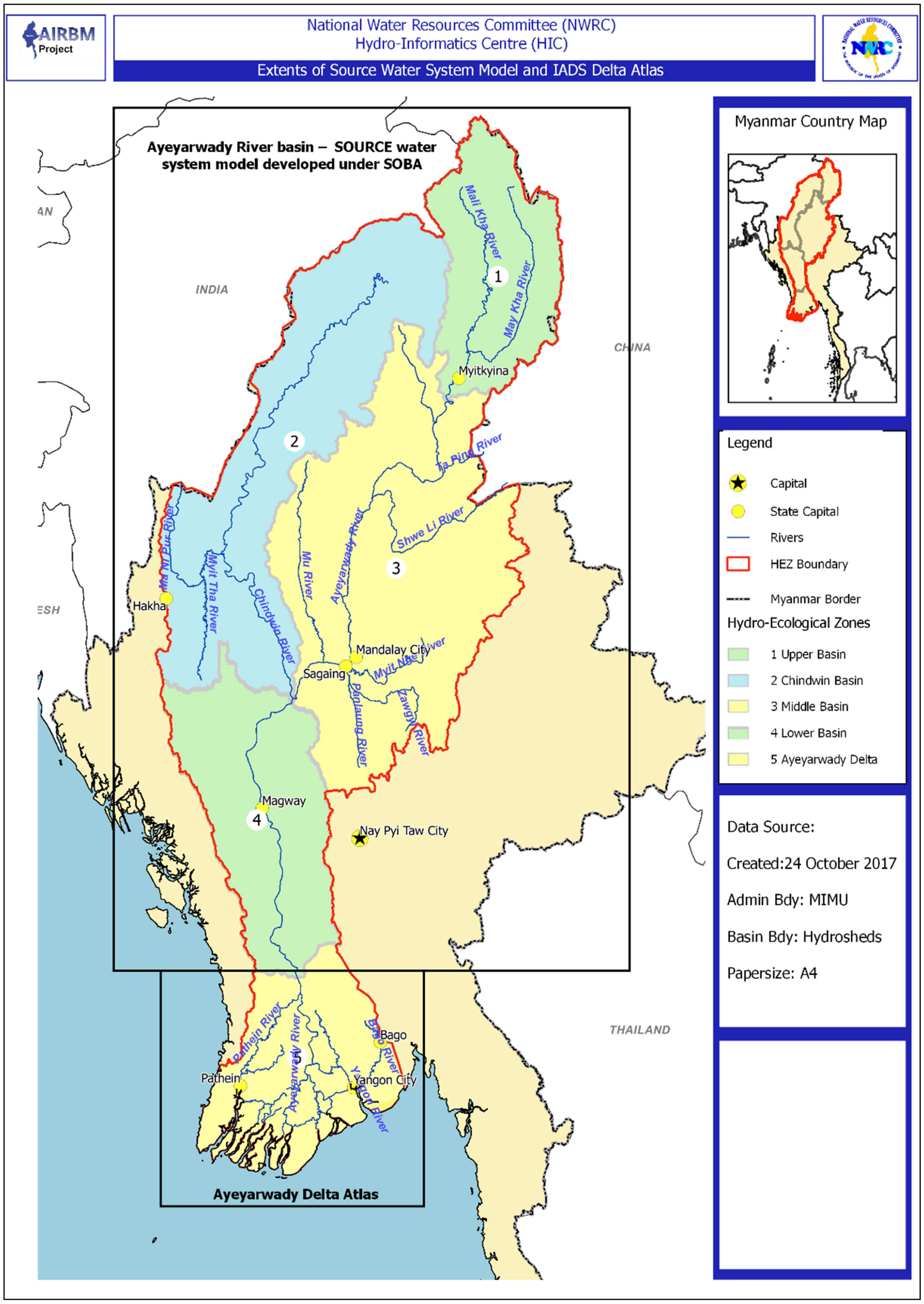


Figure 26 Extents of the Source Water System Model of the Ayeyarwady River Basin and the future IADS Delta hydraulic model

1.3.2 Flow Provenance

A diagrammatic view of the sub-basins showing the proportion of total modelled flow contributed by each sub-basin summarises the source of flows. Approximately 67 % of total flows upstream of the Delta are generated from the headwater catchments of the Chindwin, Mali Hka and N'Mai Hka. Figure 27 describes the proportion of basin outflow downstream of Pyay contributed by each sub-basin, as derived from the baseline Source model including all extractions and storage.

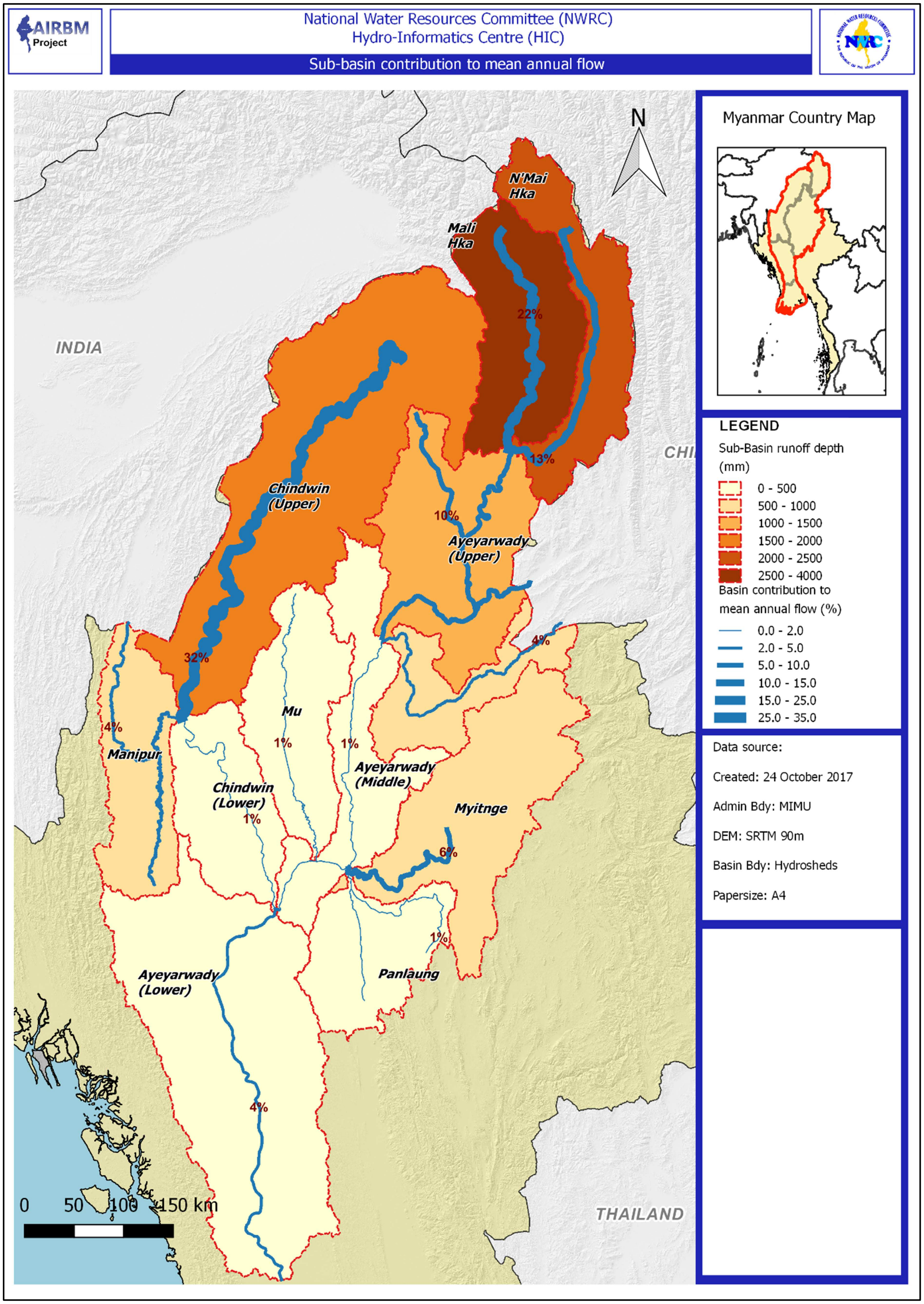


Figure 27 Flow contribution per sub-basin

Two aspects of flow contribution are represented: the contribution to mean annual flow volume by each sub-basin as a percent, and the actual depth[5] of the sub-basin runoff which is associated with the sub-basin flow volumes. The highest contributions are from the Himalayan regions of the Upper Basin HEZ and the mountains of the Chindwin Basin, where rainfall is the highest. Only considering proportion of flow volume, the Chindwin (Upper) contributes the largest (32 %) proportion of the flow leaving the Basin downstream of Pyay. However, in terms of area the Chindwin (Upper) is also the largest sub-basin in the Ayeyarwady River Basin. Expressing flow contribution as a depth in mm takes into consideration the effect of sub-basin area. According to the volume of mean annual flow produced per area, the Mali Hka and N'Mai Hka are the highest contributors to mean annual flows. The lower basin regions are dominated by the Central Dry Zone which is in the rain shadow of the Arakan Mountains and also has high rates of evaporation, therefore contributing the least flow. Furthermore, as a result of this rain shadow, many of the smaller tributaries of HEZ3 and HEZ4 are ephemeral in character. Annual Flow Volumes

Observed total annual flows together with Mean Annual Flow at nine sites across the Ayeyarwady River Basin are shown in Figure 28. Mean annual flows increase in a downstream direction. Table 2 lists the Mean Annual Flow volume at each site, together with the period of data availability. It is interesting to note that mean annual observed flows at Myitkyina are comparable to those at Monywa. There is a slight decrease in observed mean annual flow volume at Pyay when compared to upstream Magway – this is likely explained by issues of measurement, which are addressed in Annex I below.

The coefficient of variation of the annual available observed values at each site is also included in Table 2. With low coefficients of variation, the annual variation in flows across the basin is generally fairly stable. Pyay is the most downstream site considered on the Ayeyarwady River and is taken to represent river discharge upstream of the Ayeyarwady River Delta. The coefficient of variation of flow at Pyay is 0.12 – comparable with that of the Mekong also cited as 0.12 in McMahon and Mein (1986). Sagaing and Hkamti indicate higher annual variations, but, at Sagaing in particular, this could also be related to measurement uncertainty.

Table 2 Observed mean annual flows

Site	HEZ no	Start date	End date	Mean Annual Flow volume (MCM)	Coefficient of Variation
Myitkyina	1	1/1/1999	31/12/2015	146,561	0.14
Hkamti	2	1/01/1986	31/12/2015	64,876	0.32
Mawlaik	2	1/01/1986	31/12/2015	129,193	0.17
Monywa	2	1/01/1986	31/12/2015	145,366	0.17
Katha	3	1/1/1981	31/12/2015	159,672	0.13
Sagaing	3	1/01/1986	31/12/2015	215,384	0.22
Magway	4	1/03/1993	31/12/2015	380,436	0.11
Pyay	4	1/01/1986	31/12/2015	375,783	0.12

[5] Depth (mm) calculated as flow divided by area

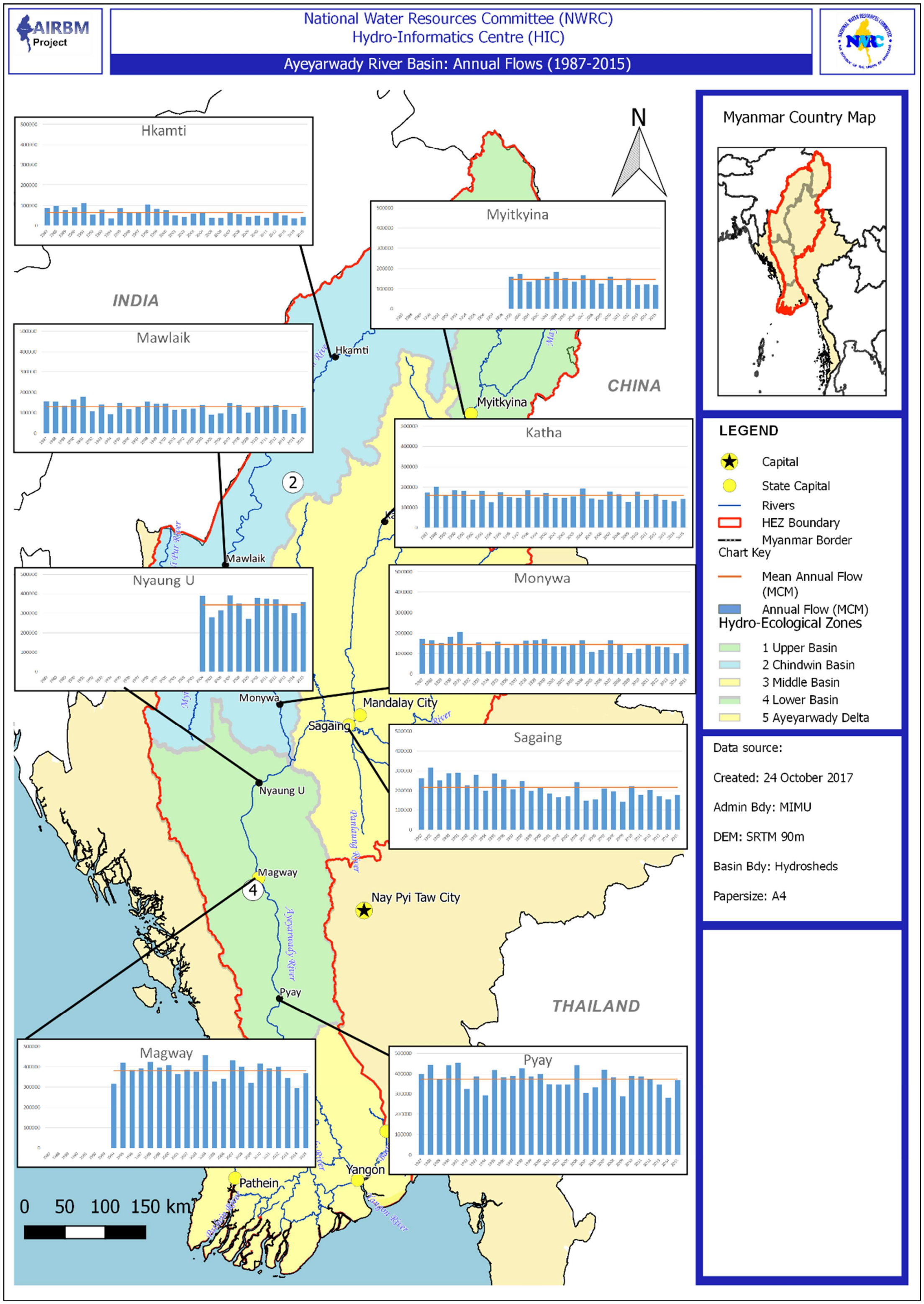


Figure 28 Annual flows at various sites across the Ayeyarwady River Basin

1.3.3 Low and high flow conditions

As noted already, the annual hydrological regime of the Ayeyarwady River Basin is driven by a tropical monsoon climate. This results in a rainy season that typically occurs between mid-May to the end of October, and a dry season extending from November to April.

The high flow season of the Ayeyarwady varies from year to year, for the purpose of this analysis, the high flow season is defined as starting when the flows rise above the mean annual discharge and finishing when the flows fall below the mean annual discharge. Mean annual discharge is based on the period of available data at each gauging site (Table 3). For the purposes of identifying low flow periods the 75th percentile flow has been used. Not all sites are used in the analysis. The data used are summarised in Table 3.

Table 3 Observed flow data used for high flow/low flow analyses

Site	HEZ no	Start date	End date	Mean annual flow (m^3/s)	75th percentile flow (m^3/s)
Myitkyina	1	1/1/1999	31/12/2015	4,644	1,660
Hkamti	2	1/01/1986	31/12/2015	2,054	128
Monywa	2	1/01/1986	31/12/2015	4,588	872
Sagaing	3	1/01/1986	31/12/2015	6,830	1,852
Magway	4	1/03/1993	31/12/2015	12,211	3,850
Pyay	4	1/01/1986	31/12/2015	11,845	3,167

Typically flows cross this threshold once at the commencement of the high flow season and once and the end of the high flow season. However, where the flow crosses the threshold multiple times at the start or end of the season the first and last crossing has been used to define the high flow season. Based on this definition the annual high flow seasons defined for the key gauging sites are shown in Figure 29, for the period of record.

The dates for the high flow season lie within a very narrow range and generally lasts from mid-June until late October. However, in general, at the upper part of the Ayeyarwady (based on the Myitkyina site) the high flow season starts earlier than at the lower parts of the Basin. This is in part due to snow melt during the latter part of the dry season. This variation in temporal extent of the high flow season is illustrated by the 2010 calendar year in Figure 30. This plot clearly shows the commencement of the high flow season in the Myitkyina starting in April, while for the remaining catchments the flood or high flow season starts in June/July.

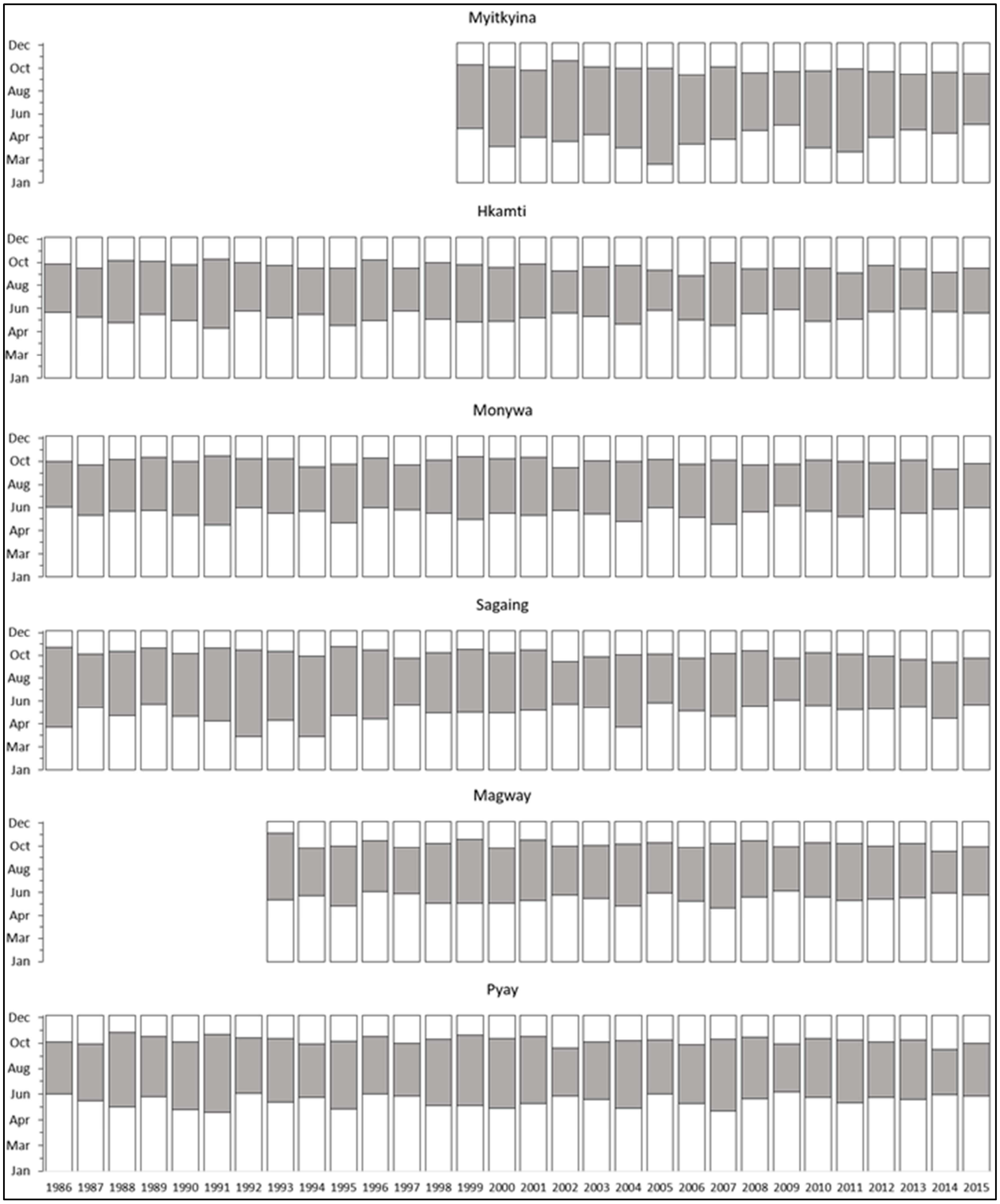


Figure 29 Extent of high flow season* at selected sites

*High flow season is shaded

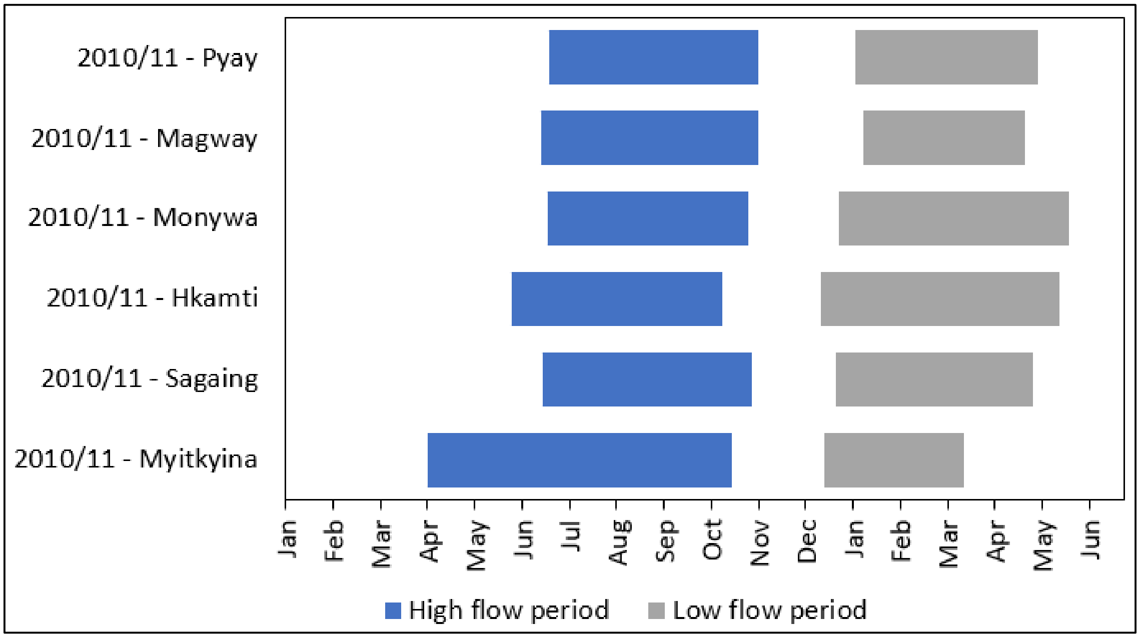


Figure 30 High and low flow periods for the 2010/2011 calendar years

A low flow period can be defined as containing all flows below the 75th percentile, i.e. the lower 25% of flows. The temporal extent of a low flow period shows a much greater variability than the high flow season. This is depicted in Figure 31, with the low flow season for the 2010-11 dry season also included in Figure 30. These figures illustrate that in dry years, the low flow season starts towards the end of the calendar year and finishes before the onset of the monsoon. Figure 30 suggests that the Chindwin sub-basin (Hkamti and Monywa sites) has a longer period of low season flows than other parts in the Ayeyarwady. It is possible that the longer high flow season upstream of Myitkyina as a result of snow melt in the upper catchment reduces the low flow period along the Ayeyarwady.

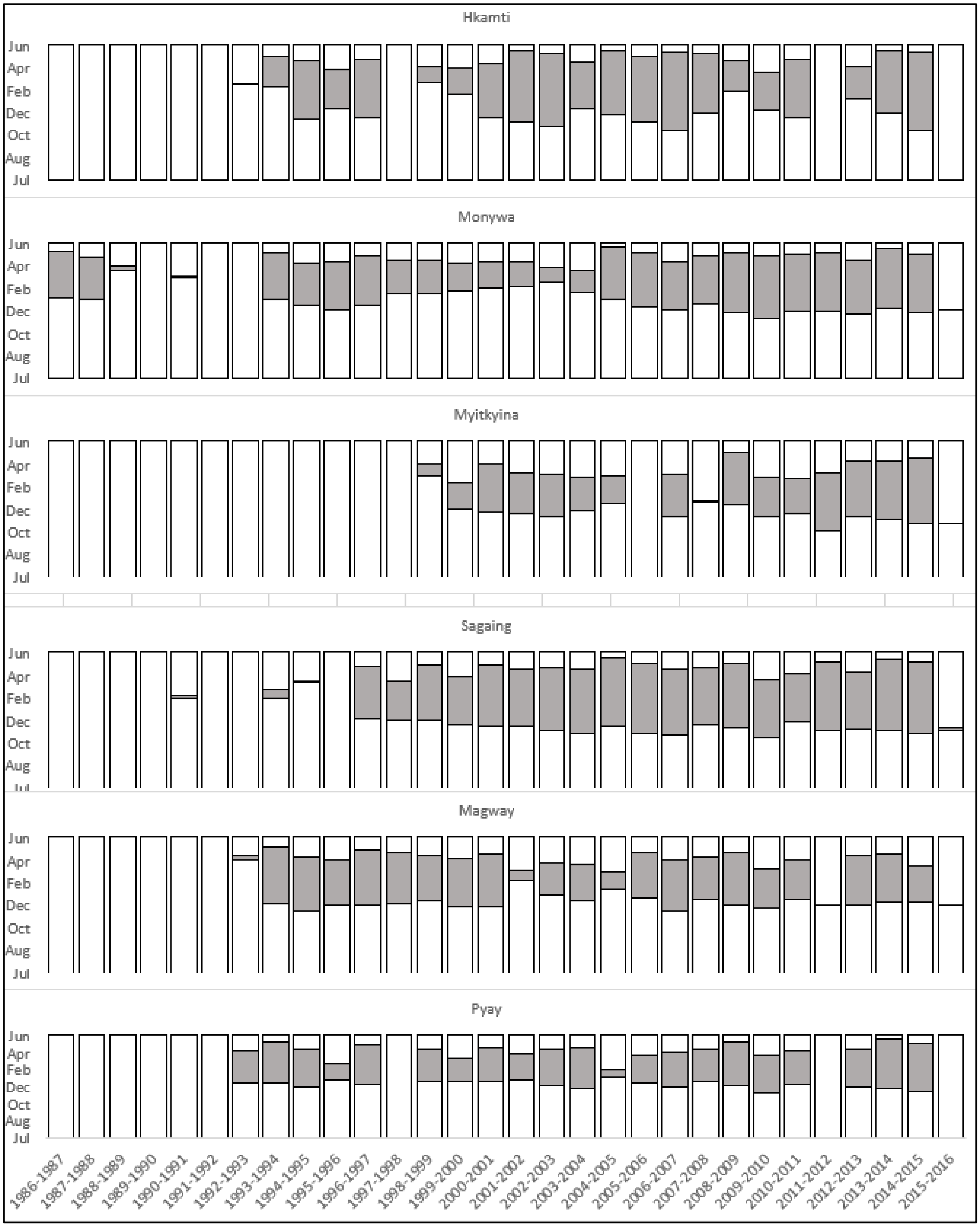


Figure 31 Extent of low flow season

1.3.4 The Ayeyarwady flood pulse and downstream attenuation

The highly seasonal nature of the rainfall in the Ayeyarwady River Basin gives rise to a rhythmic flood pulse which moves through the basin at regular intervals. Despite damage that occurs every year, these seasonal floods are relied on by natural ecosystems and humans alike. The flood pulse is a highly predictable phenomenon of the basin's hydrology with only slight variations in its arrival each year. Figure 32 indicates this predictable arrival of the wet season along the length of the Ayeyarwady River (in brown) and the Chindwin River (in blue). On average flows begin to rise after May, but peak at different times. Upstream flows at Hkamti and Myitkyina, in the Upper Chindwin and Upper Ayeyarwady respectively, generally peak around early July, while downstream flows peak around early August, as the flood pulse is attenuated through the basin. Figure 33 shows an example of observed flows during the wet season of 2010 at six sites along the length of the Ayeyarwady River, from Myitkyina in the north to Pyay in the south. Clearly illustrated is the movement of the flood pulse in a downstream direction.

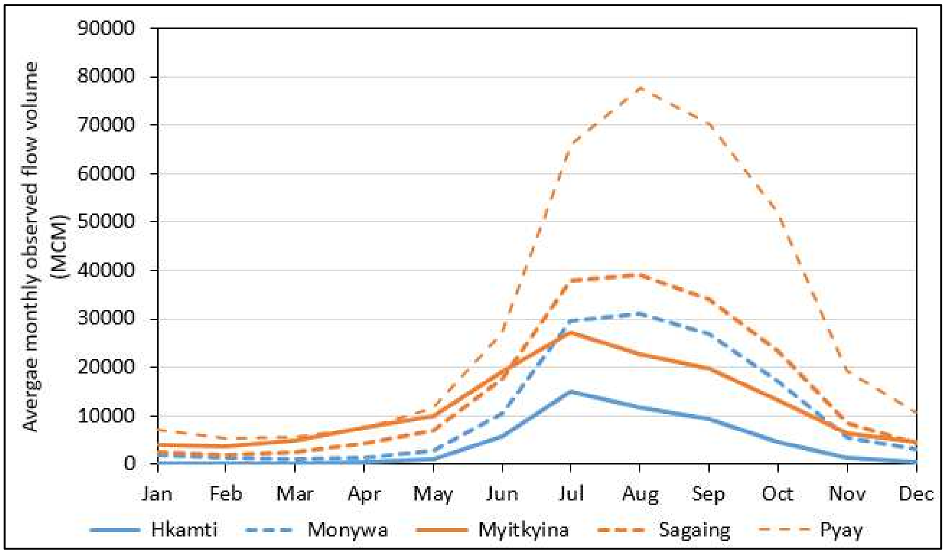


Figure 32 Average monthly flows along the length of the Ayeyarwady River

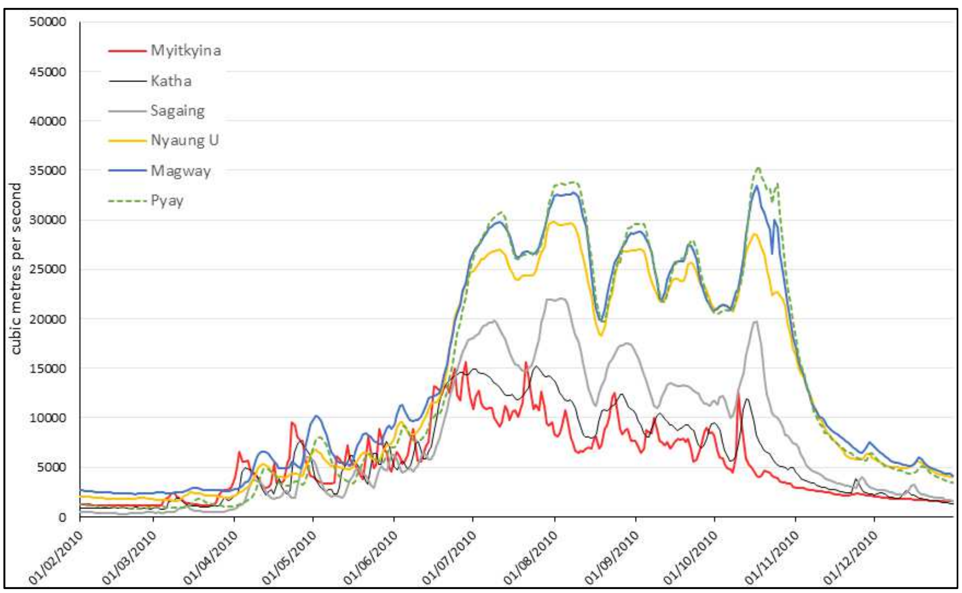


Figure 33 Progression of flood peaks down the length of the Ayeyarwady River

In order to better understand the flood attenuation, the number of days spent above the 1 in 2 year ARI has been determined for flood events in 1997, 2002, 2004 and for two events in 2015. The 1 in 2 year ARI is typically considered to represent 'bank-full' conditions. This is depicted in Figure 34 which shows that the duration of events increases in a downstream direction - primarily due to flood attenuation. The amount of attenuation will be dependent on the location of the rainfall causing the flood event. As can been seen in

Figure 34 not all floods exceeding the 1 in 2 year ARI at the downstream gauges are present in the flow record at the upstream gauging station.

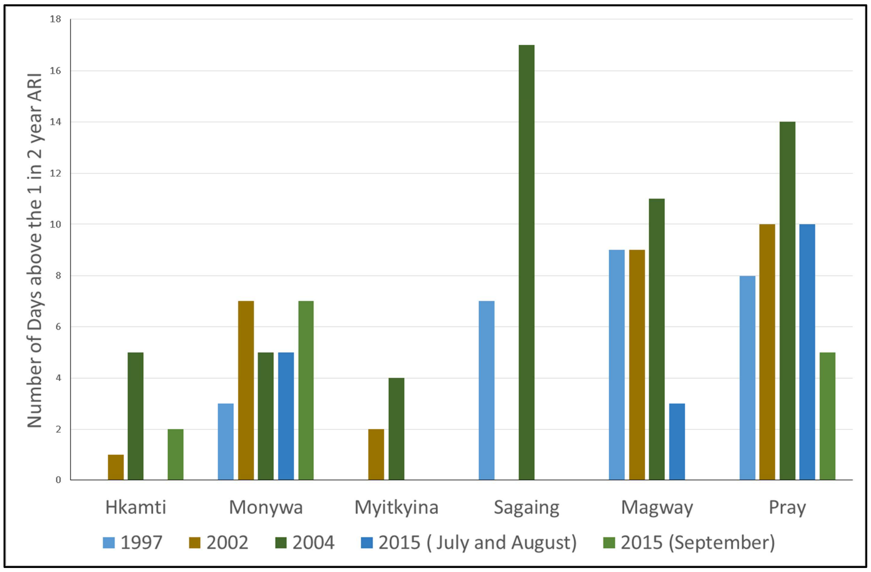


Figure 34 Duration of flood events at various sites

1.3.5 Extreme events – flood occurrence

During the heavy monsoon season, rainfall in the north causes rivers to exceed maximum levels and can result in destructive flooding of adjacent and downstream towns and villages. The Chindwin River floods several times in a year from the onset of the rainy season to the end of the monsoon. Most of the floods in the Lower Ayeyarwady sub-basin and the Ayeyarwady Delta area are due to the Chindwin River and when these coincide with upper Ayeyarwady floods, severe flooding occurs in the downstream sub-basins. The Ayeyarwady Delta is particularly vulnerable to flooding when the high tide and the high river flows occur at the same time. The upper delta region, though relatively well protected against flooding, mostly gets impacted by monsoon high flows. The central delta area lacks dyke protection and often gets inundated. The lower parts of the delta get inundated due to tides and storm surges. (IADS, 2017)

While annual floods are common in the Ayeyarwady River Basin, nine years have been identified as representing particularly high flows: 2015, 2008, 2009, 2004, 2002, 2001, 1991, 1997 and 1988.

For each of the observed gauging station sites shown previously in Figure 34, the annual recurrence intervals (ARI) for floods have been determined for the 1 in 1 year, 1 in 2 year, 1 in 5 year, 1 in 10 year and 1 in 20 year annual recurrence intervals (ARI). The 1 in 2 year ARI is typically considered to represent bank full conditions. Therefore, anything beyond the 1 in 2 year ARI can be considered to be moving towards the potential for flooding. The 1, 2 and 5 year ARI are determined using a partial series analysis while the 1 in 10 and 1 in 20 year ARIs were determined using annual series analysis. The ARI for the six sites shown before in Figure 34 are listed in Table 4.

Table 4 ARI for observed gauging sites (m^3/s)

ARI	Hkamti	Monywa	Myitkyina	Sagaing	Magway	Pyay
1 in 1 year	10,960	17,932	16,527	21,824	34,786	35,032
1 in 2 Year	12,886	19,782	19,060	25,163	39,865	41,299
1 in 5 year	14,554	21,293	21,102	27,351	42,211	44,579
1 in 10 year	16,263	21,637	23,775	28,868	42,849	45,284
1 in 20 year	17,543	22,423	26,111	30,273	44,654	46,598

Based on the nine individual years that have been identified as representing high flow years: 2015, 2008, 2009, 2004, 2002, 2001, 1991, 1997 and 1988, figures have been created to show where the peaks in these years fall in terms of annual recurrence intervals (Figure 35 and Figure 36). These figures also illustrate the attenuation of flood peaks in a downstream direction.

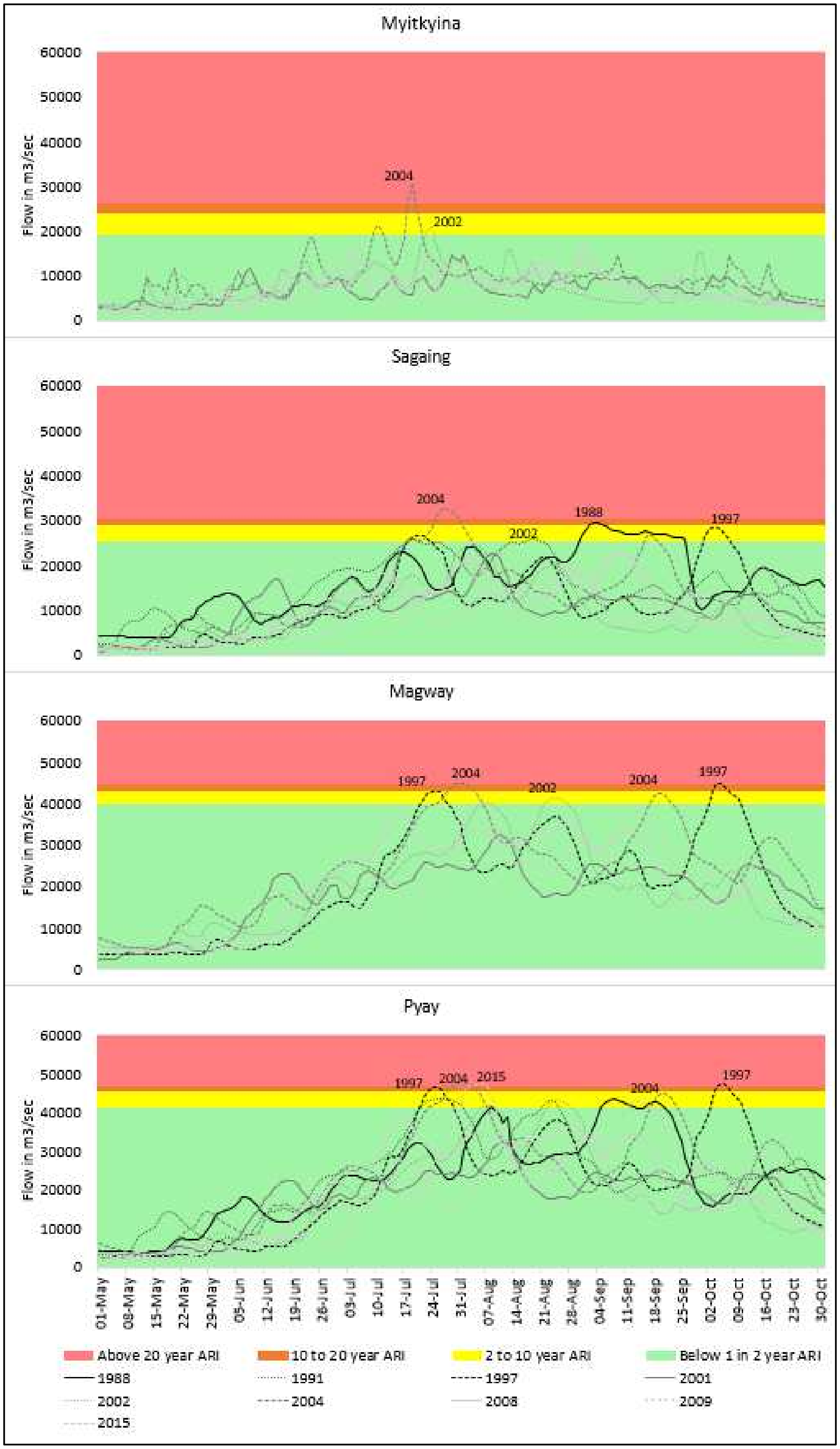


Figure 35 Wet season flows for selected years in the Ayeyarwady River Basin

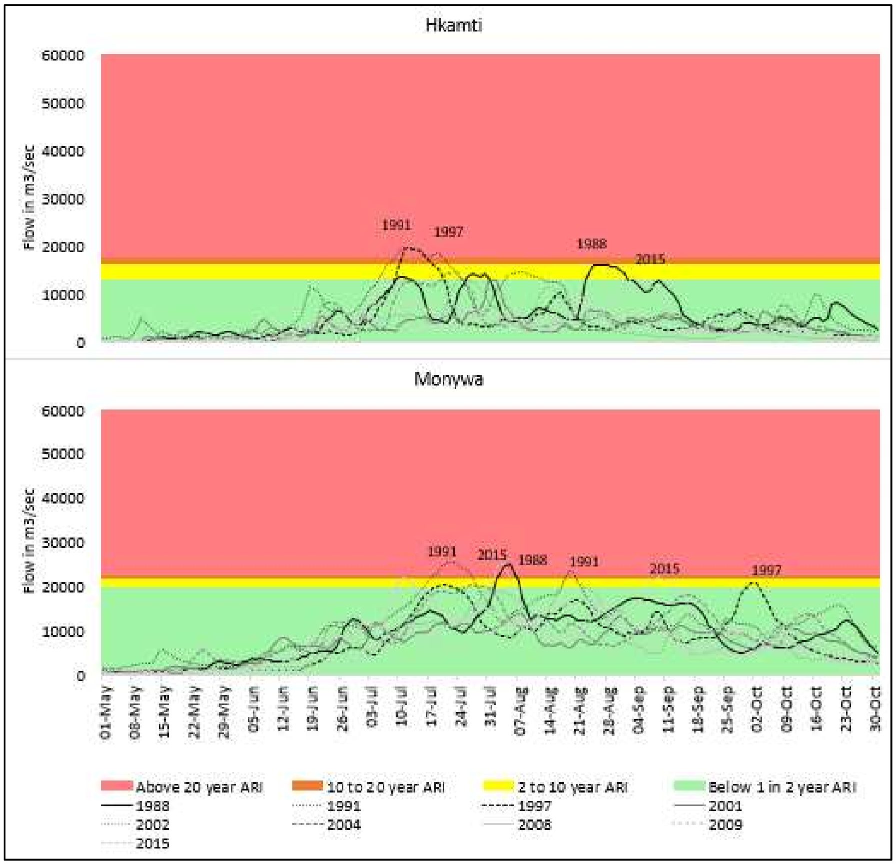


Figure 36 Wet season flows for selected years in the Chindwin River Basin

Table 5 lists the highest water levels measured at the six analysis sites for the years 1988 – 2015. Several years stand out as experiencing flood events at various sites in the basin: 1991, 1997, 2004 and 2015. Where possible, the events associated with these observed high flows have been identified.

Table 5 ARI of highest annual flows at selected sites (m^3/s)

Year	Myitkyina	Sagaing	Magway	Pyay	Hkamti	Mawlaik	Monywa	Events
1988		29,493		43,450	16,067	21,900	25,050	
1989		25,100		40,827	16,907	22,440	22,413	
1990		26,440		43,753	14,117	19,873	20,430	
1991		25,867		43,590	19,613	24,323	25,500	
1992		21,053		30,837	11,077	13,310	14,277	
1993		25,883		41,740	12,740	20,067	21,027	
1994		14,990	29,723	26,080	7,358	10,817	12,967	
1995		26,133	40,150	41,320	14,990	21,263	20,427	
1996		26,980	38,047	40,720	12,957	15,830	16,007	
1997		28,483	44,907**	47,533**	19,400*	25,083*	20,700	*BOB 02 ** BOB 07
1998		26,390	42,593	43,217	16,290	21,220	20,000	
1999	17,693	24,080	40,173	40,283	14,740	24,093	21,127	
2000	18,550	20,270	33,080	32,413	11,107	16,590	18,603	
2001	14,590	22,583	32,333	32,573	12,927	12,290	13,897	
2002	20,700	24,680	41,387	43,500	13,043	26,443	22,020	
2003	20,263	21,907	36,047	37,890	14,630	20,343	18,447	
2004	30,853*	32,613*	44,973*	47,697*	14,617*	22,337*	20,280*	Early July
2005	15,320	18,820	32,893	34,930	11,760	17,100	16,200	
2006	20,490	16,513	32,227	33,920	8,172	13,820	16,440	
2007	18,953	28,100	41,293	44,903	13,150	21,403	19,647	
2008	16,260	22,780	37,193	38,440	13,457	24,410	21,880	
2009	15,673	19,100	33,790	34,840	8,880	16,073	16,067	
2010	15,667	22,077	33,450	35,403	7,180	13,920	13,787	
2011	12,660	18,447	34,800	38,400	7,927	20,120	19,673	
2012	23,260	23,567	33,540	37,100	9,805	15,963	16,600	
2013	19,953	27,360	38,077	42,780	10,357	16,450	16,560	
2014	14,706	21,877	33,583	38,060	9,565	17,083	17,853	
2015	17,143	22,490	40,987*	47,483*	13,403	24,543	25,510*	*Cyclone Komen

Key:

< 1 in 2 year ARI	2 - 10 year ARI	10 - 20 year ARI	> 1 in 20 year ARI

In 1997, two very high flow events occurred in the Lower Ayeyarwady in mid-July and early October. Both these events were the result of the combined impact of high rainfall in the upper parts of both the Ayeyarwady and Chindwin rivers:

- Figure 37 shows several events of high rainfall at Hkamti and Myitkyina in early July 1997, associated with a deep depression (BOB 02 of 1997) moving across the northern parts of the basin. The cumulative impact of these events is observed in high flows exceeding the 10 year ARI at Magway in late July (Figure 35). According to Figure 35 events exceeding the 1 in 10 year ARI were also recorded at this time at Pyay, while the flows at Hkamti exceeded the 1 in 20 year ARI. While observed flow is not available at Myitkyina for this date, a peak in flow is evident at Sagaing.
- In early October 1997 flows at Magway and Pyay exceeded the 1 in 20 year ARI (and Figure 35). These were associated with high rainfall measured in the central Chindwin (e.g. Mawlaik) and central Ayeyarwady (e.g. Mandalay) as a result of a severe cyclonic storm moving into Myanmar from the south-west in late September (BOB 07 of 1997) bringing rain to already wet basins.

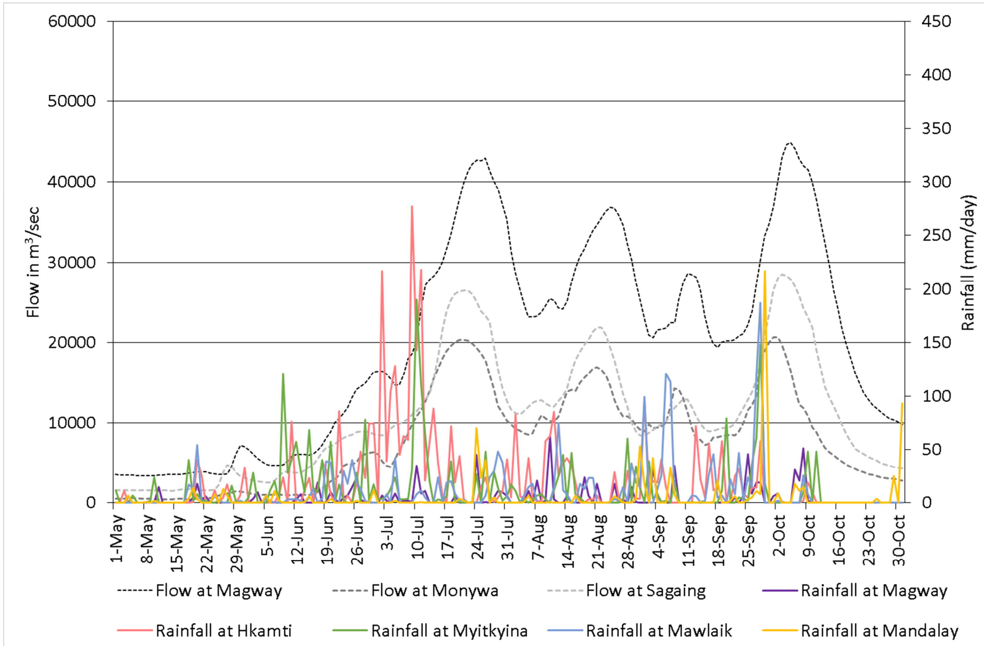


Figure 37 Observed rainfall and flow at selected sites in the Ayeyarwady River Basin - 1997

While no specific extreme weather event could be identified during July 2004, extreme rainfall exceeding 400 mm led to the highest flows of the season at Hkamti in the northern Chindwin (Figure 38). While particularly high rainfall was not recorded at Myitkyina, it can be assumed that the upstream sub-basins received high amounts of rain since flows at Myitkyina exceeded the 1 in 20 year threshold. These combined high flows from the upper Chindwin and Ayeyarwady River headwaters resulted in flows exceeding the 20 year ARI downstream at Magway and Pyay (Figure 38).

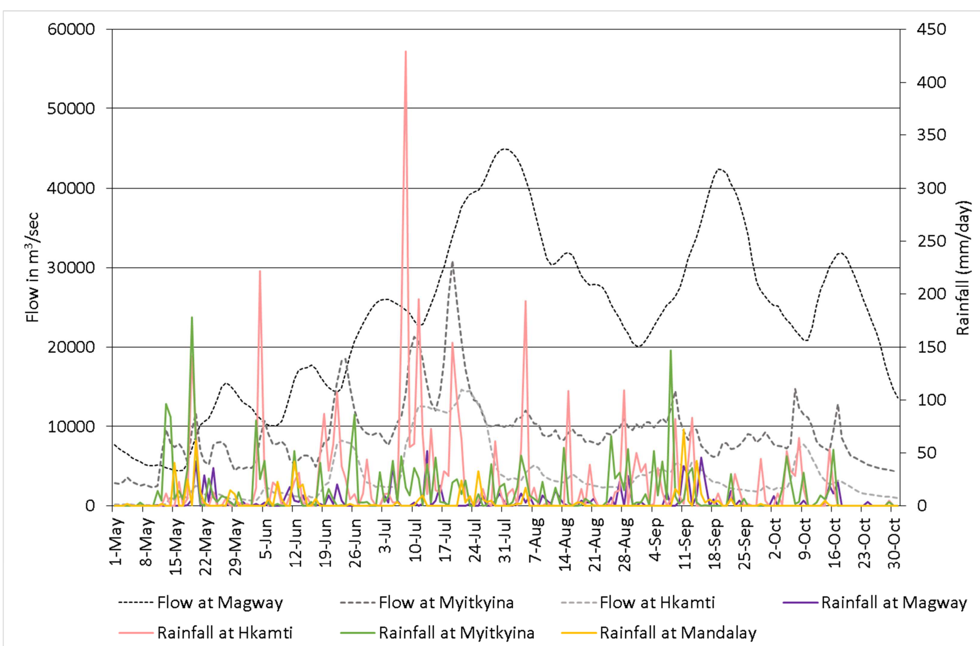


Figure 38 Observed rainfall and flow at selected sites in the Ayeyarwady River Basin – 2004

High flows and riverine flooding in early August 2015 were associated with the rainfall accompanying Cyclone Komen at the end of July 2015. Moving in a northerly direction towards the Ganges Delta (Figure 39 inset), Cyclone Komen crossed western Myanmar in late July 2015, at a time when parts of the country were already seeing the impact of annual monsoon flooding. In Figure 39 an infra-red image made available by the United States Naval Research Laboratory shows the extent of the associated wide band of cloud across Myanmar on 30 July 2015. While measured rainfall was not unusually high (Figure 40) and the cyclone path was not directly over Myanmar, the extensive rainfall associated with the wide cyclone band, in already wet areas, increased river flows and brought flooding and landslides to much of western Myanmar. The highest rainfalls were measured at Hinthada and Pyay. Most of the flow originated from the western and southern parts of the Ayeyarwady River Basin, and the highest flows of the season were measured at Monywa, Magway and Pyay (Figure 40). An estimated 1.6 million people were displaced, and 132 lives were lost (Government of Myanmar, 2015).

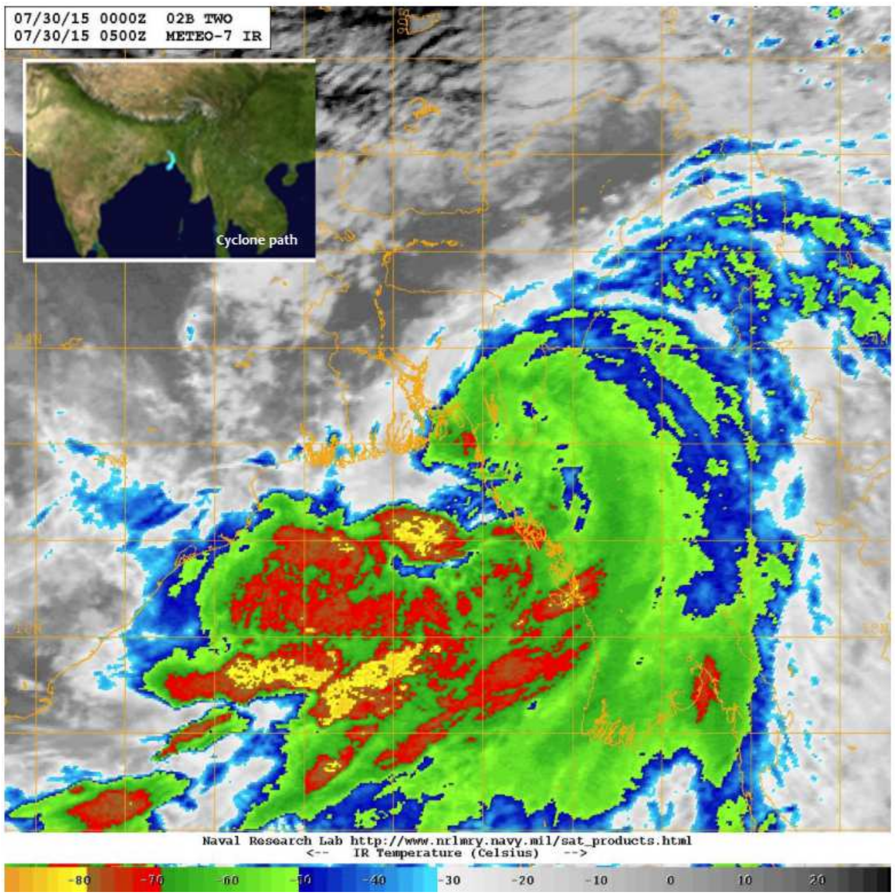


Figure 39 Infra-red image of Cyclone Komen (30 July 0215)

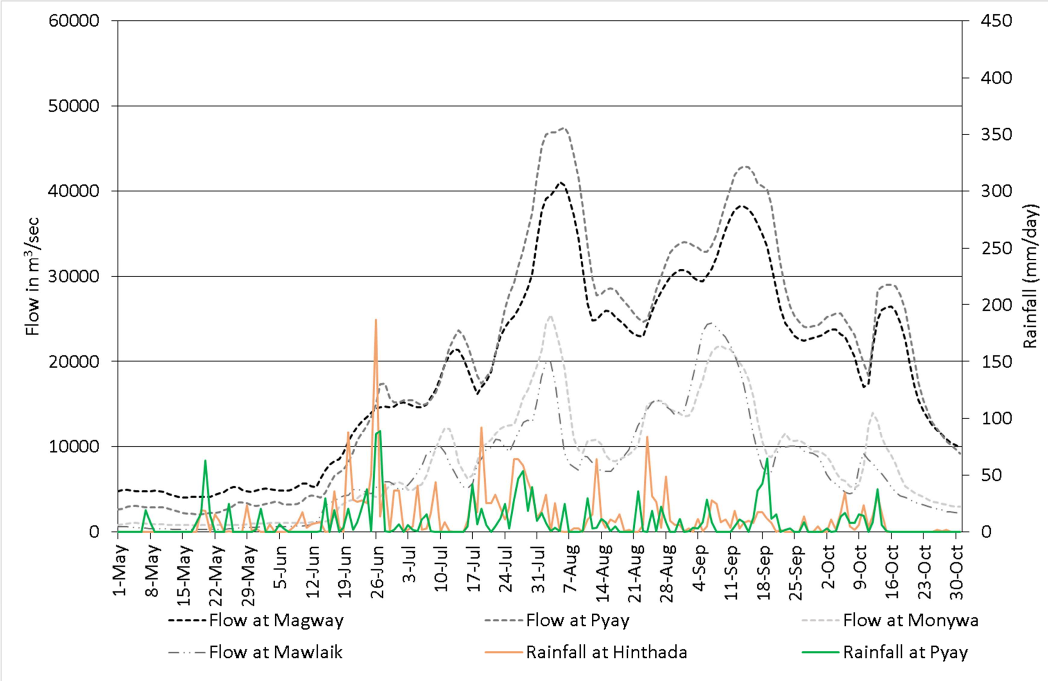


Figure 40 Observed rainfall and flow at selected sites in the Ayeyarwady River Basin – 2015

1.3.6 Extreme events – flood extent and damage

Flood extent can be evaluated using satellite imagery. The SERVIR-Mekong project is a geospatial data-for-development program aimed at using satellite and geospatial technologies to facilitate the management of climate risk in the Mekong countries. To achieve this the United States Agency for International Development (USAID) and the United States National Aeronautics and Space Agency (NASA) have partnered with leading organisations from Myanmar, Thailand, Cambodia, Laos and Vietnam. The online Surface Water Tool (http://surface-water-servir.adpc.net) has been created by SERVIR-Mekong and partners to provide spatial coverage of inundated areas across the region. These data can be downloaded for a particular period or season and is categorised according to areas which are either temporarily (shows water for a part of the period) or permanently (shows water for the entire period) inundated during the download period. For a particular wet season areas of temporary inundation can be considered an indicator of flood during that season and provides a view of the extent of this flood.

Using this SERVIR-Mekong data, an examination of wet season flooded extent representing the selected years 2015, 2008, 2009, 2004, 2002, 2001, 1991, 1997 and 1988 makes it possible to get an indication of areas most often subjected to flooding in these years, by considering areas most often temporarily inundated during the wet season. While some areas of temporary paddy rice can be confused with riverine flooding, it is possible to combine all areas inundated for these years during the wet season months of June to October to produce a map illustrating these frequently flooded areas (Figure 41). Floodplain areas which are more frequently flooded appear as areas of more dense shading along the river lines, highlighting sections such as the Chindwin/Ayeyarwady River confluence and a section of the Ayeyarwady River upstream of Magway.

In more detail, the Chindwin/Ayeyarwady confluence and sections downstream in the Lower Ayeyarwady and the Delta indicate as being temporarily inundated during the wet season for five or more years out of the nine years examined. Figure 42 shows the total extent of this inundation at the Chindwin/Ayeyarwady confluence and in the Lower Ayeyarwady upstream of Magway.

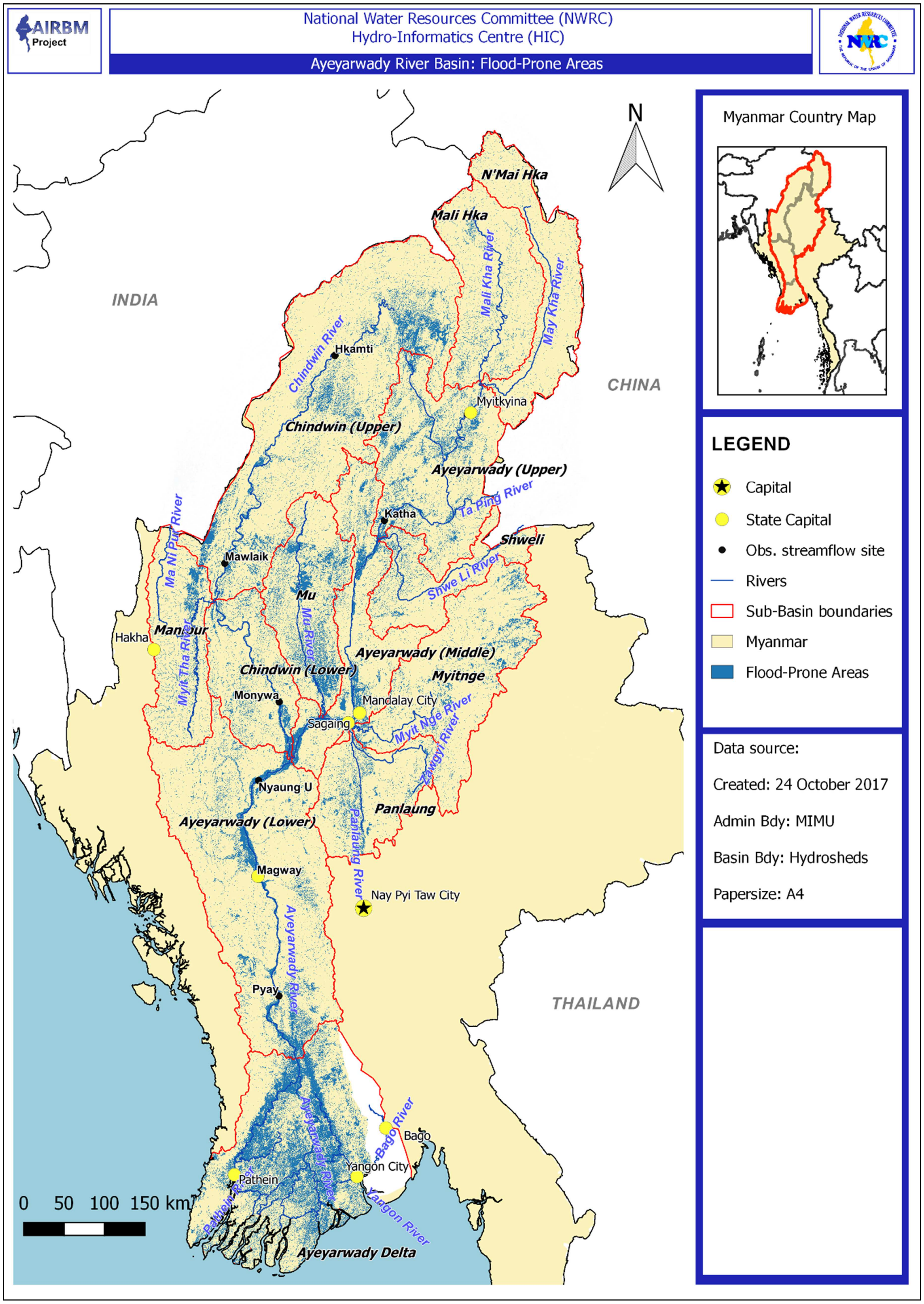


Figure 41 Flood prone areas of the Ayeyarwady River Basin

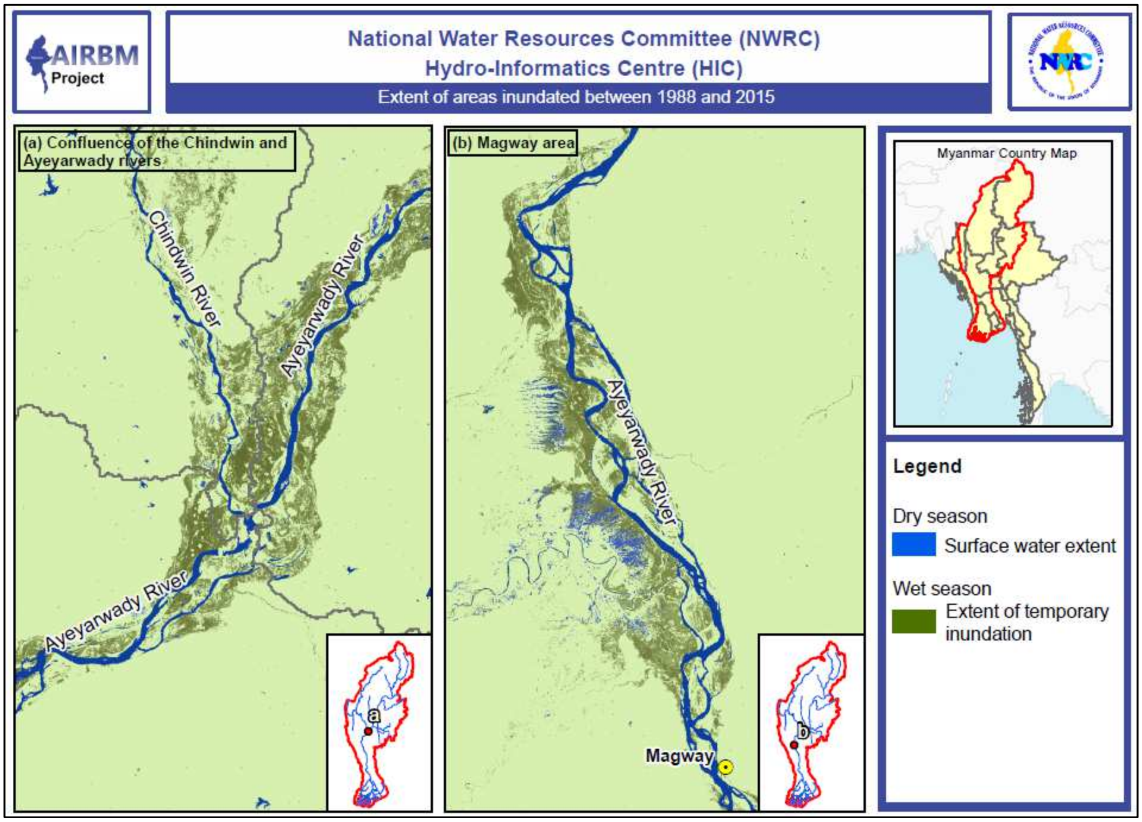


Figure 42 Extent of areas inundated in at least five of the years 1988, 1991, 1997, 2001, 2002, 2004, 2008, 2009, 2015 and 2015. Chindwin/Ayeyarwady confluence (left); upstream Magway (right)

The international Emergency Events database (EM-DAT, 2017) provides flood-related damage information for Myanmar. Table 6 lists identified events from 2001 to Jun 2017 including the cause of flooding, the population numbers affected and, where possible, the associated costs.

Table 6 Myanmar disaster impacts 2001 - 2017 (EM-DAT, 2017)

Month Year	Disaster	Pop. affected	Total damage ('000 US$)	Total deaths	Province
Jun 2001	Riverine flood	3,750		51	Mandalay province
Aug 2002	Riverine flood	50,000		21	Kyain, Kayin, Min, Mon province Yangon, Mandalay, Kayin, Kachin province, Shan (E)
May 2004	Tropical cyclone	25,000	688	236	Rakhine
Aug 2004	Riverine flood	35,400		0	Ayeyarwady, Bago (E), Bago (W), Kayin, Kachin, Magway, Rakhine, Shan (E), Shan (N), Shan (S), Tanintharyi, Yangon
May 2006	Tropical cyclone	60,106		34	Yangon, Ayeyarwady, Rakhine
Oct 2006	Riverine flood	10,000		25	Mandalay
May 2007	Riverine flood	3,000		5	Yangon
Jun 2007	Riverine flood	-		0	Rakhine

Month Year	Disaster	Pop. affected	Total damage ('000 US$)	Total deaths	Province
Jul 2007	Riverine flood	101,920		0	Arakan, Yangon
Aug 2007	Riverine flood	61,744		0	Ayeyarwady, Kachin
May 2008	Tropical cyclone	2,420,000	4,000,000	138,366	Ayeyarwady, Yangon, Bago (E), Bago (W), Kayin, Kayah, Mon provinces
Oct 2010	Tropical cyclone	260,049	57,000	45	Rakhine province, Rakhine, Magway
Oct 2011	Flash flood	35,734	1,700	151	Magway, Sagaing, Mandalay
Aug 2012	Riverine flood	85,000		2	Kayin
Aug 2013	Riverine flood	73,300		7	Kayin, Mon, Rakhine, Tanintharyi, Ayeyarwady
Sep 2014	Riverine flood	4,600		0	Shan (E) province
Apr 2015	Convective storm	-		3	Chin, Kachin, Sagaing, Shan (N)
Jun 2015	Riverine flood	14,000		7	Rakhine, Tanintharyi, Kayin, Ayeyarwady, Bago (E), Bago (W)
Aug 2015	Riverine flood	1,621,703	119,000	149	Mandalay, Rakhine, Chin, Sagaing, Kachin, Kayin, Shan (E), Magway, Mon, Ayeyarwady, Bago (West)
Oct 2015	Flash flood	-	-	16	Sagaing
Apr 2016	Convective storm	12,012	2,000	14	Sagaing, Mandalay, Magway, Shan, Shin
May 2016	Convective storm	87,944	2,600	18	Mandalay
Jun 2016	Flood	377,667	-	14	Sagaing, Bago (E), Bago (W), Rakhine, Mandalay, Ayeyarwady, Magway, Yangon, Kachin, Mon
Aug 2016	Flood	474,560	2,000	5	Sagaing, Mandalay, Bago, Ayeyarwady, Magway, Yangon, Kachin
Jun 2017	Tropical cyclone	22,420	-	0	Arakan (Maungdaw), China, Irrawaddy Division

According to ECLAC (2003) floods impact assets (direct damages) and the production of goods and services (indirect losses). In this way socio-economic and environmental aspects can suffer both direct and indirect damages. Direct damages are mostly linked to particular location or region while indirect damages can impact wider regions.

Flood damage can be assessed through a combination of fractional flood depth-damage functions and maximum damage values. Damage functions describe the share of an asset that is damaged at a given flood depth, while the maximum damage values describe the associated maximum damage value for the given asset. When combined together, these yield the monetary value of the damage. Curves expressing the relationship between flood depth and damage based on these values, make it possible to evaluate the potential impact of events at a site.

The derivation of flood depth-damage curves for the Ayeyarwady River Basin are limited by:

- the availability of detailed data on the spatial distribution of residential, commercial and industrial buildings, road infrastructure and transport
- the availability of river bathymetry information to enable the calculation of changes in water level and related flood depths and spatial extent

In the absence of this information, only agricultural damage was considered in developing depth-damage curves and flood depths were only computed at river reaches where sufficient bathymetry data was available.

Where specific information is not available, fractional flood depth-damage functions and maximum damage values can be estimated for various assets using existing information in similar regions. Huizinga et al (2017) provide global fractional flood depth-damage functions developed for Asia by the Joint Research Centre of the European Commission. Table 7 presents these values for agriculture. Table 8 summarises maximum damage values for agriculture, adjusted for 2010 price levels. The maximum damage for agriculture is estimated based on agricultural land area (km^2) and agriculture value added (current US$) data available from the World Development Indicators. An average of the five years (2008-2012) is computed to minimise single-year deviations.

In the calculation of damage values only the 2015 flood year is considered since damage data from secondary sources (EM-DAT, 2017) are available for this year.

Table 7 Fractional flood depth-damage functions for Asia (Huizinga et al, 2017)

Flood depth (m)	Agriculture (proportion)
0	0.00
0.5	0.14
1	0.37
1.5	0.52
2	0.56
3	0.66
4	0.83
5	0.99
6	1.00

In accordance with the availability of bathymetry data five reaches representing the Chindwin and Ayeyarwady River main stems were identified for the calculation of flood depths required to compute the relationship between flood depth and damage. These are shown in Figure 43. They represent the Upper Chindwin, Lower Chindwin, Upper Ayeyarwady, Middle Ayeyarwady and Lower Ayeyarwady. Flood levels at these reaches are converted to depths based on careful scrutiny of level-extent data for each river reach. Figure 44 shows the final flood depth-damage curves calculated for each reach.

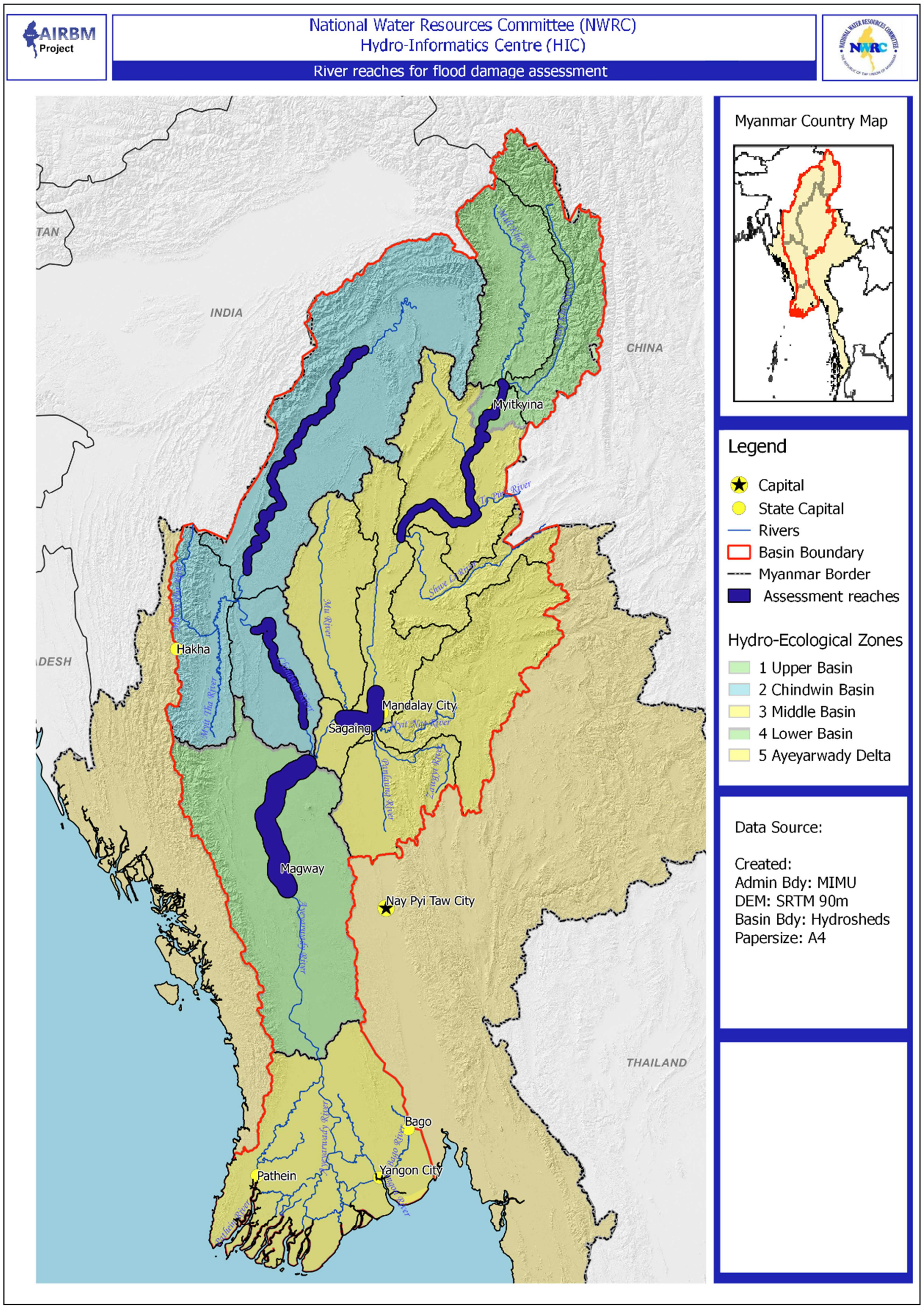


Figure 43 Location of Ayeyarwady River Basin reaches for flood damage assessment

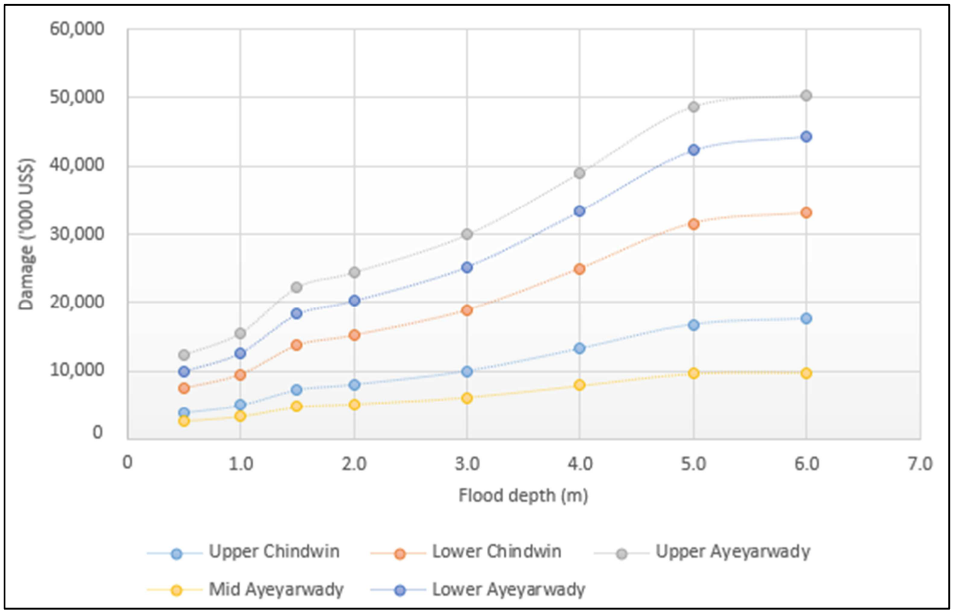


Figure 44 Flood depth vs damage along selected river reaches

1.3.7 Drainage to the Delta

According to Volker (1966) the most upstream edge of tidal influence is approximately 100km downstream of Pyay. This point defines the northernmost boundary of the Delta HEZ (and therefore the southern-most boundary of the Lower Basin HEZ). Approximately 375,000 million cubic meters flows towards the Delta from Pyay, to be divided between the various distributaries of the Delta. The apex of the Delta is considered to be about 40km north of Hinthada. From here the Ayeyarwady splits into 3 branches: the main Ayeyarwady River, with the Pathein River and Hlaing River branching in a south-westerly and south-easterly direction, respectively.

According to IADS (2017) most of the dry season flows will generally continue in the main stem of the Ayeyarwady, with the Pathein and Hlaing distributaries only being connected during the flood season. Halcrow and Partners (1982) (cited in IADS, 2017), calculated that 64.4% of the volume during flood season continues down the main stem of the Ayeyarwady River, while 11.9 % and 23.7 % flow down the Pathein and Hlaing rivers, respectively (Figure 45). These values were based on measurements undertaken in 1979 – 1980.

A comparison of more recent observed data undertaken for 2003 – 2004 by IADS (2017) indicated that the discharge to the Pathein River varies annually between 10 % and 17 %, and that even during the dry season there is some discharge to the Pathein River. They suggest that dredging of the Pathein River could be allowing water to enter this distributary during the dry season too.

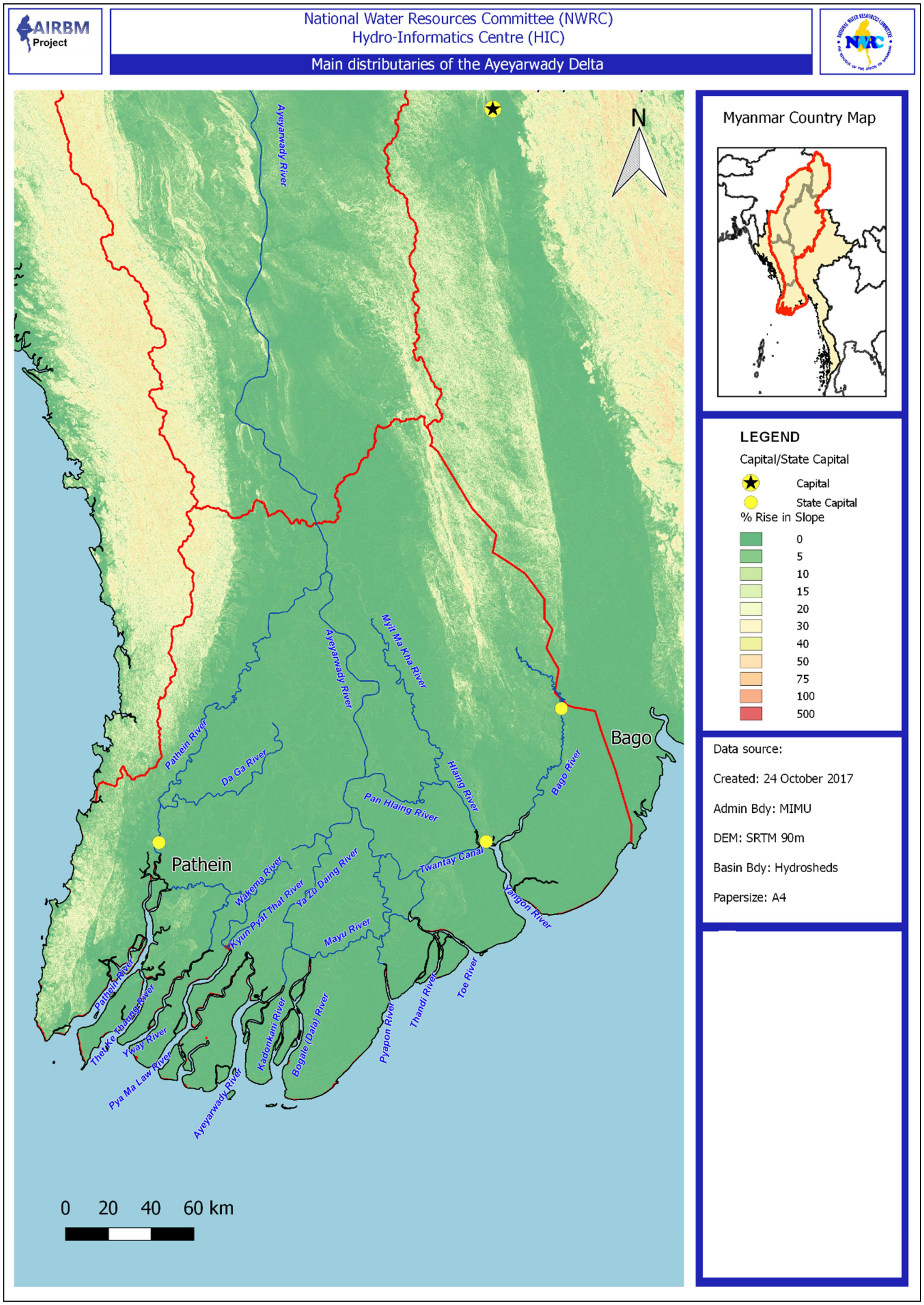


Figure 45 Distribution of wet season flow in the Delta (from IADS, 2017)

2 SURFACE WATER RESOURCES

2.1 Water Storage

2.1.1 *Storages of the Ayeyarwady River Basin*

By the end of 2016, nearly 285 man-made storages could be identified in the Ayeyarwady River Basin, based on available data. These storages have been built to provide for irrigation supply and hydropower. While many are single purpose, providing for hydropower or irrigation only, some are multi-purpose used for both hydropower and irrigation supply. Table 9 and Figure 46 provide a breakdown of the number of storages in each type, in the Ayeyarwady River Basin. Figure 46 only includes the storages within Myanmar. While most of the irrigation works and multi-purpose storages are situated within Myanmar, as of 2016 most of the hydropower storages are situated in the Chinese sections of the Basin. The distribution and relative capacity of these storages, across the Basin, is illustrated in Figure 47.

Table 8 Breakdown of storages by type, constructed in the Ayeyarwady River Basin by 2016

Storage type	Total no of storages	No in Myanmar	No in China
Hydropower	57	8	49
Multi-purpose	14	9	5
Irrigation works	214	214	-

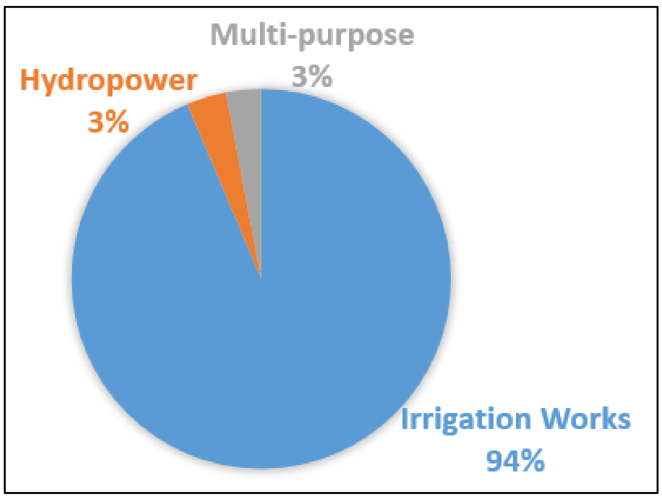


Figure 46 Breakdown of storage by type, in the Ayeyarwady River Basin (Myanmar only)

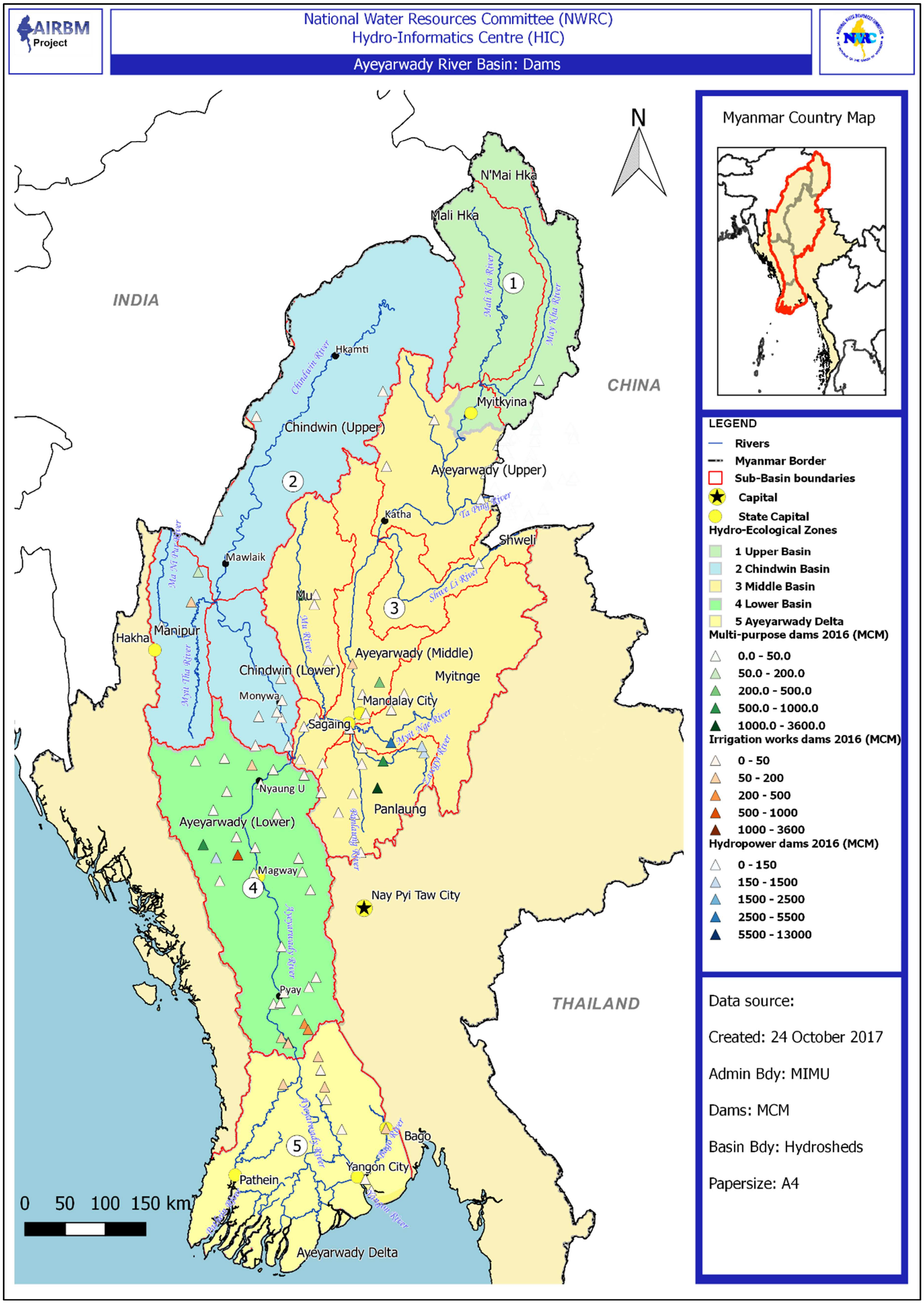


Figure 47 Surface Water Storages of the Ayeyarwady River Basin in 2016

For the purposes of analysis, the storages are classified into major and minor storages according to volume, crest height and, where relevant, hydropower production capacity. Major storages are classified as those with:

- volume greater than 250 x 10^6 m^3, or
- dam height greater than 40m, or
- installed capacity > 100MW (if hydropower)

Using available information on known storage volumes, the total storage capacity of these major reservoirs in the Ayeyarwady River Basin has increased from approximately 1,000 MCM to approximately 12,000 MCM between 1985 and 2016 (Figure 48), with 27 major reservoirs being built. Including major and minor storages, there was a total of approximately 28,800 MCM of known storage volume in the Ayeyarwady River Basin by 2016.

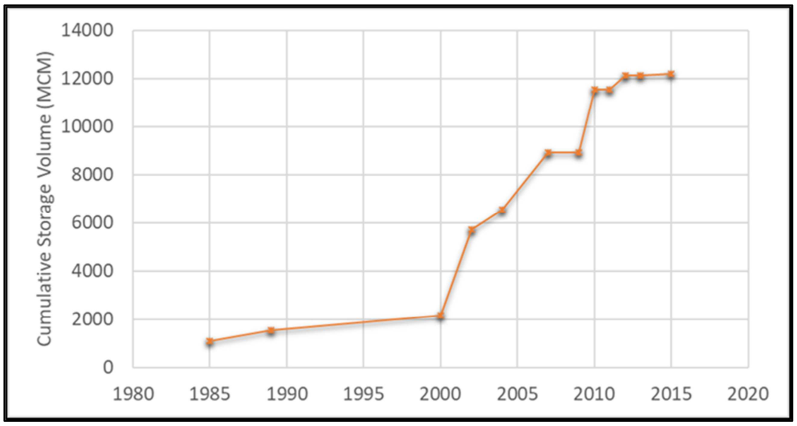


Figure 48 Growth in total storage volume of major reservoirs in the ARB

Figure 49 shows the total volume of all storages according to each Hydro-Ecological Zone and Figure 50 breaks these down according to each storage type. The Middle Basin HEZ has the highest volume of storage. A number of the upstream tributaries of the Middle Basin HEZ rise in China. There are 49 hydropower dams in this Chinese section of the Basin, but the storage capacity of many of these dams is unknown and total storage capacity for the Middle Basin HEZ is underestimated. Using known values, 22% of the total storage volume in the Middle Basin HEZ is in parts of the Shweli sub-basin and upstream sections of the Tarpein River Basin in China – all upstream of Myanmar borders.

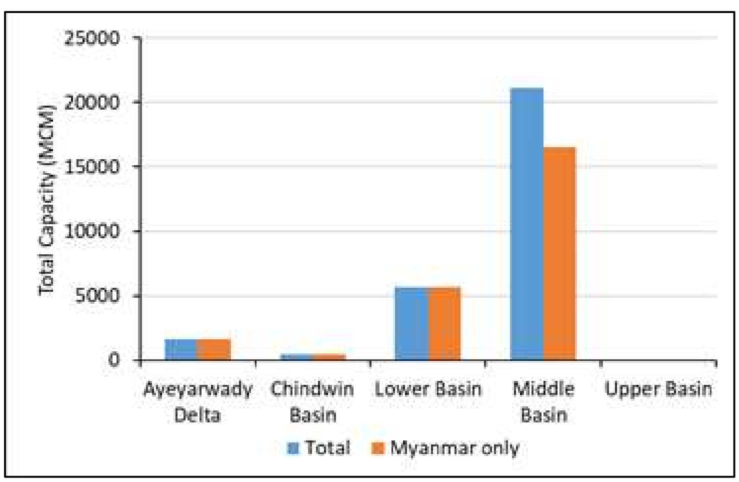


Figure 49 Total storage capacity in each Hydro-Ecological Zone

Figure 50 shows the total storage volume per storage type, per HEZ. Only storages within Myanmar are included. The Middle Basin is the most impacted by storages – with large volumes stored for all purposes, but hydropower (in the form of both single purpose hydropower and combined multi-purpose storages) being dominant. As of 2016 the Upper Basin is the least impacted by storages. There is only 1 major storage in the Upper Basin: Chibwe Nge, which is used to generate hydropower. However, this could change in the future with several new dams planned in the N'Mai Hka River basin.

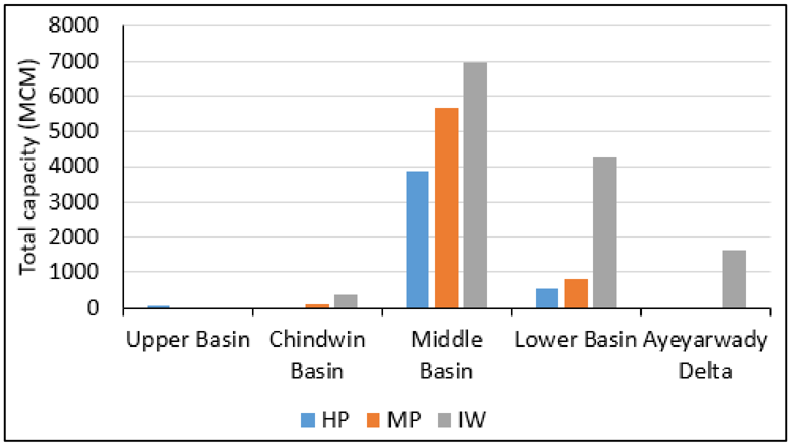


Figure 50 Total capacity of irrigation works (IW), hydropower (HP) and multi-purpose (MP) storages per HEZ, within Myanmar

Figure 51 shows a breakdown of these storage volumes according to sub-basin. Most of the storage volume is in the Middle Basin HEZ. With a full supply capacity of 3,552 MCM Thapanseik 2 multi-purpose storage in the Mu River sub-basin comprises 63% of all multi-purpose storage in the Middle Basin HEZ, and 22% of total storage in the Middle Basin HEZ (Figure 50).

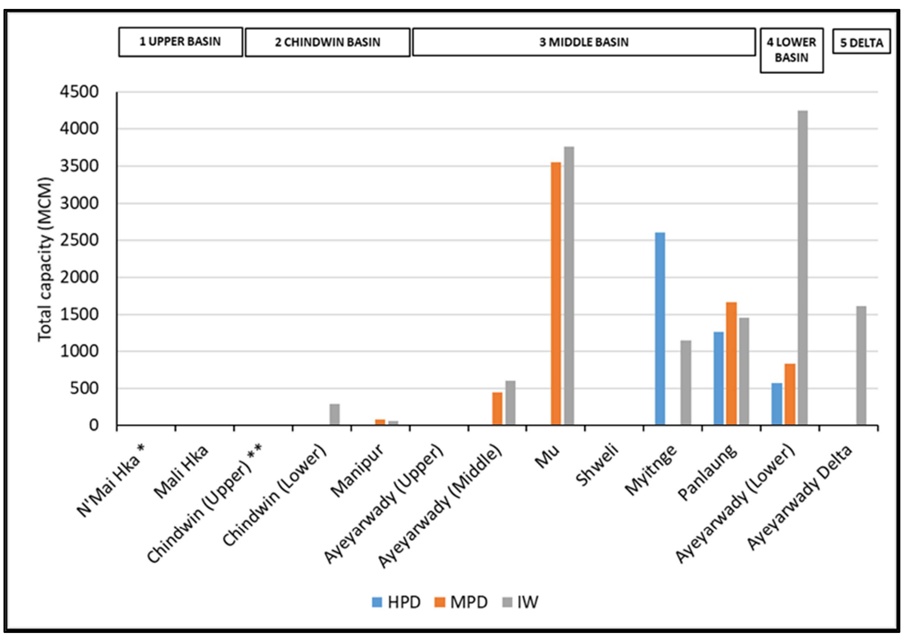


Figure 51 Total storage capacity per sub-basin, within Myanmar

** Total storage capacity is very small*
***Actual full supply capacity of storages in the Chindwin Upper sub-basin could not be ascertained*

Not all sub-basin runoff is available to the storages in a sub-basin. Only the sections of a sub-basin upstream of each storage are available to contribute flow to that storage. Figure 52 shows the total storage full supply capacity of all storage in each sub-basin as a proportion of the average annual sub-basin runoff which flows into each storage from upstream. The Mu River sub-basin is the most heavily impacted by storages in terms of total storage volume as a proportion of available upstream sub-basin runoff. In the Mu River sub-basin, Thapanseik 2 reservoir has a total storage volume of more than 3,552 MCM. Mean annual inflows into the Thapanseik 2 reservoir are 1,615 MCM. Storage volume is therefore more than 200% of available average annual sub-basin runoff.

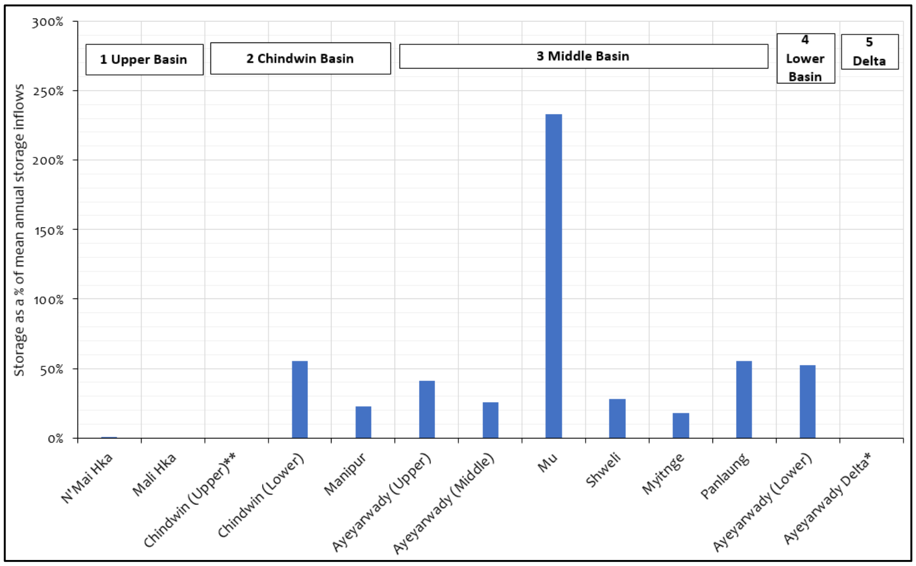


Figure 52 Storage volume as a % of average annual sub-basin runoff

** Sub-Basin runoff in the Ayeyarwady Delta could not be ascertained*
***Actual full supply capacity of storages in the Chindwin Upper sub-basin could not be ascertained*

2.2 Consumptive Water Use

Much of the Ayeyarwady River Basin is characterised as rural with agriculture being the major consumptive use of water and domestic water use very much secondary. Discussion of consumptive water use in the Basin therefore focusses on agricultural water requirements as these have the biggest impact on local water balance within sub-basins. Only surface water resources are considered. The use of groundwater is covered in detail in Viossanges *et al* (2017). Also, agricultural water requirements in the Ayeyarwady Delta are not discussed here. These are elaborated on in IADS (2017).

2.2.1 Agricultural Water Requirements

While extensive cropping information is collected in Myanmar, much of this is not yet in an electronically available form at an appropriate scale. The distribution and proportions of crops planted in the Ayeyarwady River Basin (Ayeyarwady River Basin) are based on 2002 District-level data available in the FAO Agricultural Atlas (FAO, 2002), up-scaled according to cropped areas available from the 2014 land cover classification undertaken by IWMI (2014). Irrigated agriculture in the IWMI land cover layer is defined as areas which have evidence of cropping all year round. This distinguishes it from rain fed agriculture which is defined as areas which show evidence of cropping only during wet (monsoon) months. Figure 53 illustrates the proportion of land cover in each sub-basin which is associated with irrigated and rain fed agriculture. While the amount of agriculture varies across the basin, rain fed agriculture is most common. In the upland areas where slopes are steep, and populations numbers are low, the proportion under agriculture of any type is small. However, this increases downstream towards the flatter areas of the Central Dry Zone and the Ayeyarwady Delta.

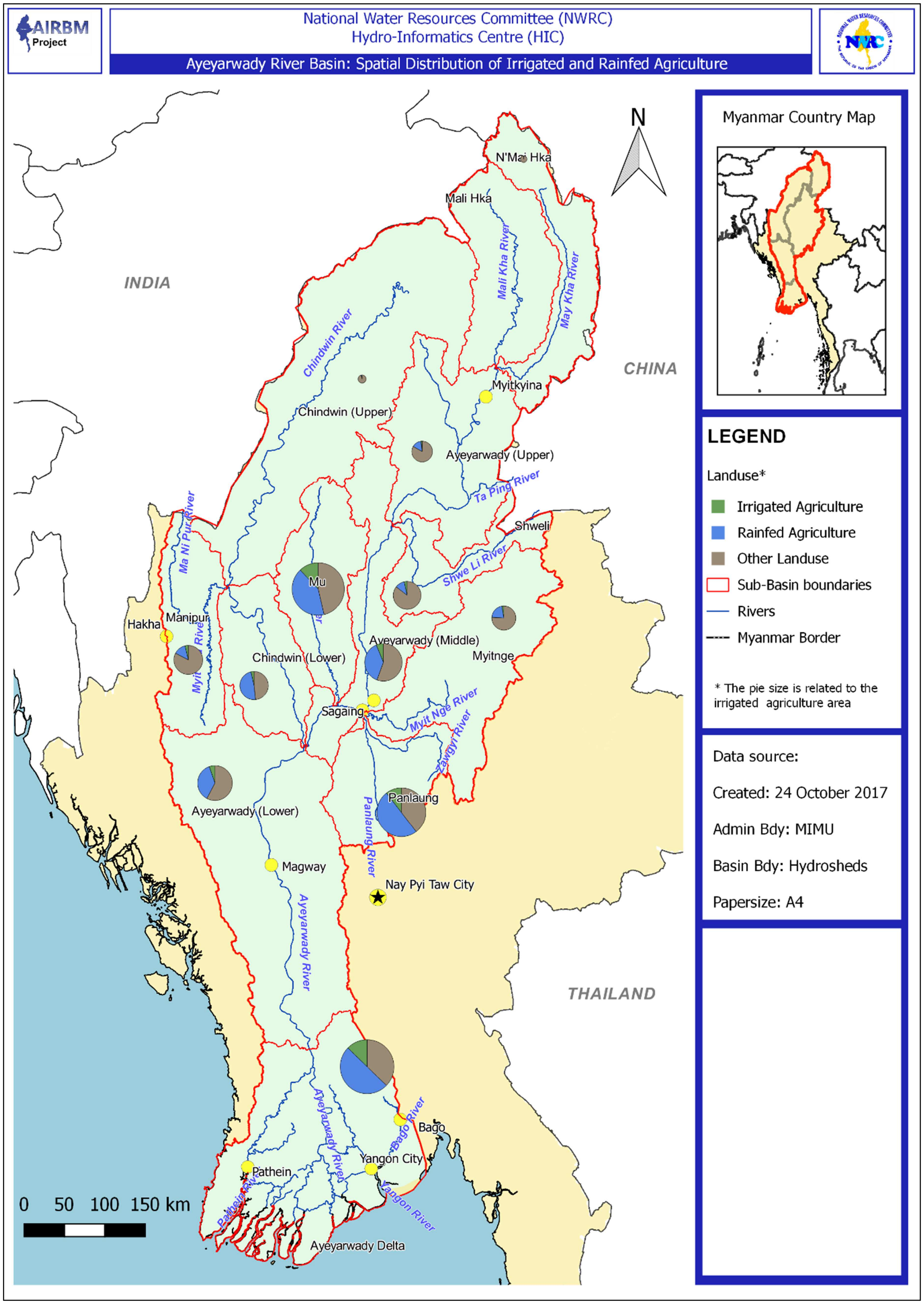


Figure 53 Proportion of irrigated and rain fed agriculture per sub-basin

Areas planted during the dry season will depend on the supply of irrigated water, either from storages or directly from rivers (or groundwater). The volume of water extracted during the dry season becomes an indicator of water required to sustain sown areas during that period. Figure 54 represents irrigation extraction requirements as a percent of the average flow volume available per year in each HEZ upstream of the Ayeyarwady Delta, compared to dry season only extractions as a percent of available dry season flows. However, not all sub-basin runoff is available to the extractions in a sub-basin. Only the sections of a sub-basin upstream of each extraction point are available to contribute flow to that extraction. Figure 54 also compares the annual and dry season net extractions per HEZ as a proportion of these available upstream contributions to each extraction point. If all local[6] sub-basin runoff is considered as available to extraction points, then the Lower Basin HEZ appears to use the largest proportion of available water. However, only allowing extraction points to access flows from upstream of their location – a more realistic option – indicates that Middle Basin is more impacted by extractions, both annually and in the dry season only.

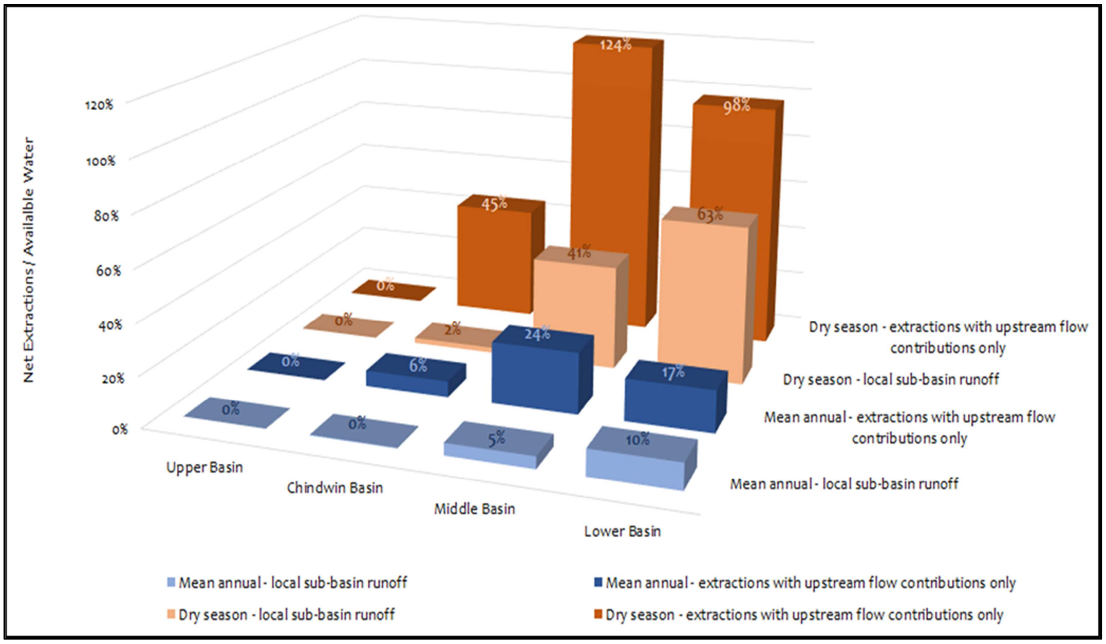


Figure 54 Irrigation requirements as a percent of average annual flow volume and dry season flow volume per HEZ

A breakdown of net water extracted per month per hydro-ecological zone is shown in Figure 55. Net extraction is defined as the total volume of water extracted minus any return flows to the river system. Figure 55 shows the increase in water used for agriculture during the dry season months (October to mid-May). The most water is extracted in the Middle Basin and the least in the Upper Basin.

[6] 'local' sub-basin runoff is defined as runoff which is produced only from within the sub-basin, excluding any upstream inflows

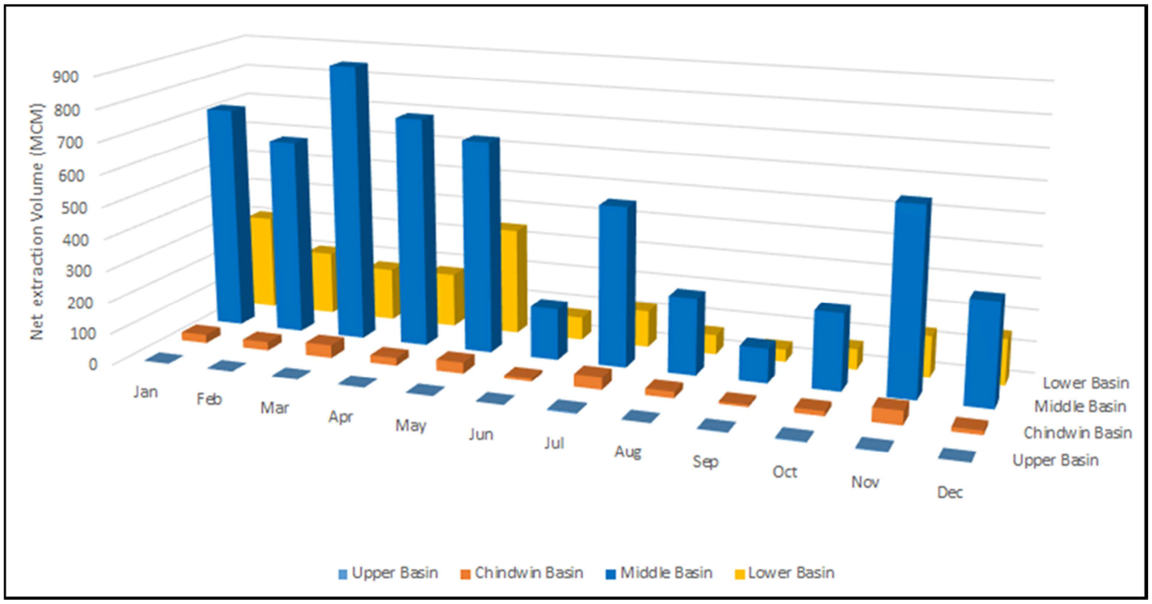


Figure 55 Monthly net volume extracted for irrigation requirements per HEZ

There is an increase in extractions in July, most noticeable in the Chindwin Basin and the Middle and Lower HEZs of the Ayeyarwady River. This increase in irrigation requirement is related to a decrease in rainfall in that month, clearly evidenced by examining monthly observed rainfall at Monywa, Sagaing and Magway (Figure 56).

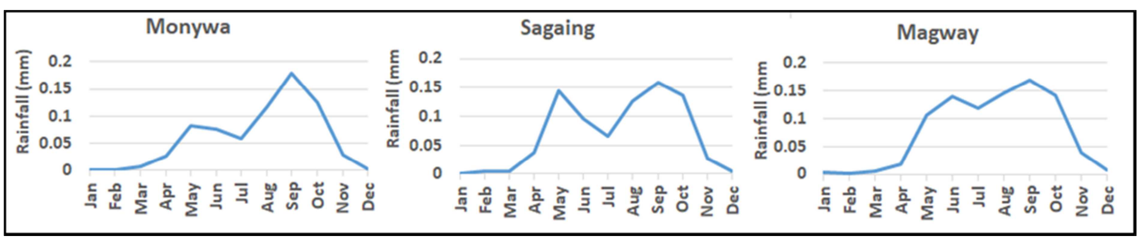


Figure 56 Average monthly observed rainfall at sites in the Chindwin Basin and Middle and Lower Ayeyarwady Basin

Although seasonal patterns remain similar, considering average monthly net irrigation extractions at the sub-basin scale, provides more detail on the distribution of irrigation extractions across the Ayeyarwady River Basin. The upland sub-basins of the Chindwin River HEZ and the Upper Basin HEZ have the lowest volume of net irrigation extractions, while the Central Dry Zone sub-basins of the Mu River, Ayeyarwady (Lower), Ayeyarwady (Middle) and Panlaung River are the biggest users of irrigation water (Figure 57).

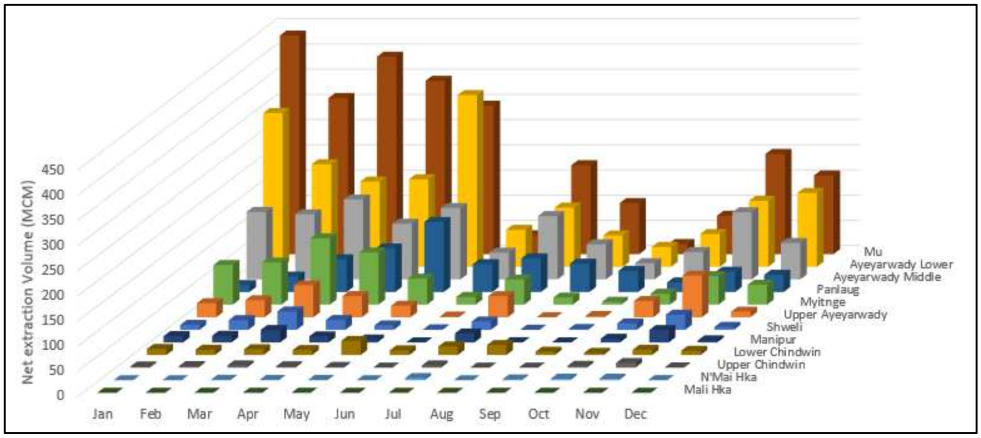


Figure 57 Monthly net volume extracted for irrigation requirements per sub-basin

Summarising per sub-basin, Figure 58 represents irrigation extraction requirements as a percentage of the average sub-basin runoff per year, compared to dry season only extractions as a percentage of available dry season flows. However, not all sub-basin runoff is available to the extractions in a sub-basin. Also shown in Figure 58 is the percentage extraction only considering the inflows contributing from upstream of each extraction point as being available to that extraction. The Mu River and Chindwin (Lower) sub-basins extract the highest proportion of available upstream contributing flows. During the dry season extractions can greatly exceed available inflows, and are only supported by the water released from storages.

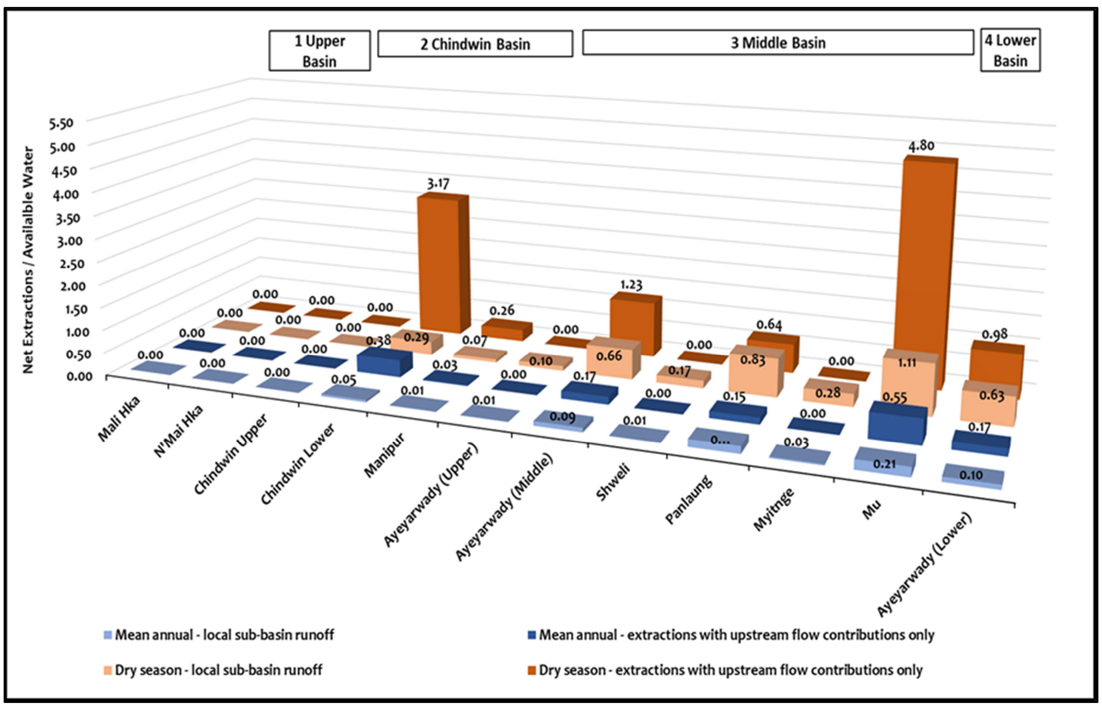


Figure 58 Irrigation requirements as % of annual flow volume and dry season flow volume per sub-basin

2.2.2 Domestic Water Requirements

Most of the Ayeyarwady River Basin has less than 250 persons per square kilometre (Figure 60). The largest urban areas within the Basin are Yangon, with a population exceeding 5 million people, and Mandalay, with a population of 1.2 million.

Domestic water requirements in the Ayeyarwady River Basin upstream of the Ayeyarwady Delta are small by comparison to the available flows. Total annual surface water demand is calculated as 303 MCM for the Ayeyarwady River Basin upstream of the Ayeyarwady Delta. This amounts to 0.07% of total average annual flows in the Basin. Even considering these requirements on a more localised spatial and temporal scale, per HEZ and per season, they remain comparatively small.

The Ayeyarwady (Middle) sub-basin, located in the Middle Basin HEZ, is the most densely populated sub-basin outside of the Ayeyarwady Delta. Fifty-six percent of domestic surface water demand in the Ayeyarwady River Basin upstream of the Delta occurs in the Middle Basin HEZ, where Mandalay alone extracts 25% of the total demand in this HEZ.

Figure 59 considers these requirements as a percent of the total[7] average flow volume available per year and per dry season in each HEZ upstream of the Ayeyarwady Delta. As of 2016 total domestic water requirements in all Hydro-Ecological Zones are less than 1% of total available water. Even during the dry season, the proportion of dry season flows required for domestic consumption are less than 1% of the dry season flows in each HEZ.

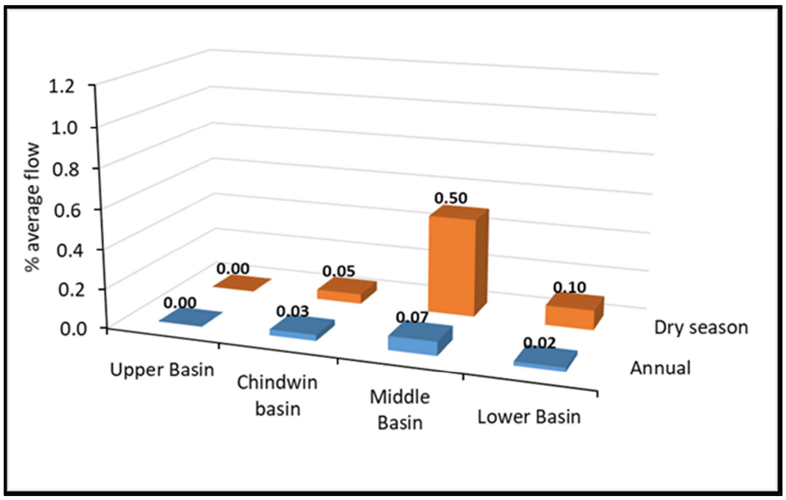


Figure 59 Domestic requirements as % of total flow volume

[7] Upstream inflows are included in the calculation of HEZ flow since many domestic users (particularly including Mandalay) would extract from the Chindwin or Ayeyarwady main streams flowing through the HEZ, or from groundwater wells located on the edge of the main rivers. Even if only local sub-basin runoff was considered, the proportion of domestic use would remain very small.

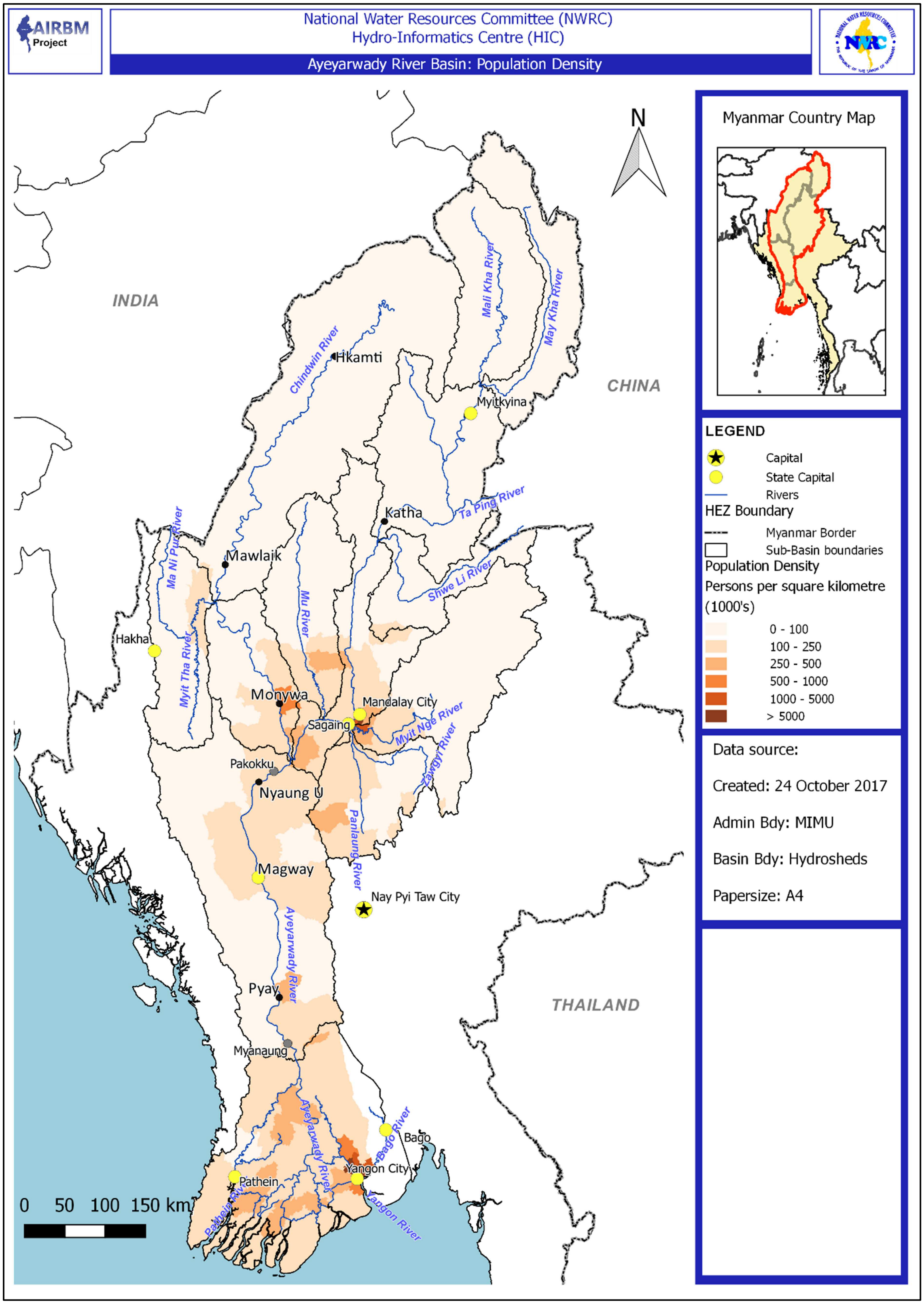


Figure 60 Population Density in the Ayeyarwady River Basin per Township

2.3 Non-consumptive water use

Both human and environmental life in the Ayeyarwady River Basin has long been supported by the presence of these large waterways. The waters of the Ayeyarwady River Basin support a wide diversity of fish as well as other aquatic life. These become a source of food as well as livelihood through commercial fishing and fish farming (Baran et al, 2017 and Zöckler, 2017).

With about 3,800 km of navigable waterways (IWT, 2017), the rivers of the Ayeyarwady Basin are a major mode of transportation. Most of the waterways are natural. There is commercial transportation on the Ayeyarwady River for about 1,300 km: between Hinthada and Bhamo (1080 km) throughout the year and further upstream between Bhamo and Myitkyina (200 km) for only seven months of the year (Britannica, 2017). Transport through these rivers to the sea is challenging during the monsoon season. The Twante Canal – which connects the Ayeyarwady River and the Hlaing/Yangon River – is used for transport from the Delta to Yangon. A critical issue related to river transportation is sedimentation and lack of water depth especially during the dry months of November to May.

As the source of livelihood, much of religious and cultural life is also centred on the river, with shrines and prayers for ongoing provision of food from the waters and also festivals to honour Buddhist history and traditions. Arcadis (2017) describes some spiritual and cultural uses of the rivers of the Ayeyarwady Basin.

Although non-consumptive water uses don't consume water they do require specific flow volumes at certain times of the year which can require trade-offs in areas of high consumption.

3 SURFACE WATER RESOURCES PER SUB-BASIN

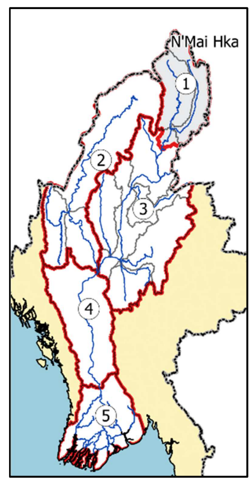
This chapter discusses the key issues in each sub-basin in terms of its physical and climate characteristics, water availability and water use. Overall water use and availability in each sub-basin is summarised in a water balance for each sub-basin. Rather than providing detailed data within each sub-basin, the main goal is to emphasise key issues around the water resources, highlighted in specific tables and graphics.

What's in the Water Balance?

A baseline run of the SOURCE model makes it possible to calculate a water balance for the whole basin, and also parts of the Ayeyarwady River Basin, including un-monitored areas. A water balance shows how water is accounted for within a basin and provides an overview of where and when water is most or least available in the context of existing water requirements. The water balance takes into consideration catchment runoff, net evaporation, change in storage volume, and total extractions. Net evaporation is defined as rainfall minus evaporation, with a 'loss to net evaporation' when evaporation exceeds rainfall, such as happens during the dry season.

3.1 Mali Hka and N'Mai Hka sub-basins

3.1.1 *Physical and climate description*



Physical and climate characteristics of the Mali Hka and N'Mai Hka sub-basins are represented in Figure 61. Together they are the most upstream sub-basins of the Ayeyarwady River basin, forming the source of the Ayeyarwady River. Table 10 lists the physical characteristics of these two sub-basins. Together they have a catchment area of approximately 47,700 km^2 and are located in HEZ 1 (the Upper Basin). Elevations range from Hkakabo Razi at more than 5800 m above mean sea level in the Himalayas, to as low as 135 m above mean sea level at the downstream junction of the two rivers. The N'Mai Hka sub-basin has the highest elevations with a median elevation of 2,466 m. Hkakabo Razi, the highest point in Myanmar at 5,881 m, is located in the northern parts of this sub-basin. The highest point in the neighbouring Mali Hka sub-basin is more than 4,700 m above mean sea level, but the median elevation is 870 m above mean sea level. The upper reaches of these basins are characterised by very steep slopes in the Himalayan regions. Median slope for the N'Mai Hka sub-basin is above 50%.

Rainfall in these sub-basin ranges from less than 10 mm in December and January to almost 500 mm in July, as measured at Myitkyina in the downstream section of these sub-basins (Figure 63). Remotely-sensed derived rainfall makes it possible to examine rainfall in the upper reaches of this sub-basin, where observed data is not available. There is an indication that maximum monthly rainfall in the upper Mali Hka sub-basin, which contributes most flow to the Ayeyarwady River, could be in the region of 700 mm in July.

The land cover of both the Mali Hka and N'Mai Hka sub-basins is dominated by mountains with forested uplands (Figure 62).

Table 9 Physical characteristics of the N'Mai Hka and Mali Hka sub-basins

Sub-basin	HEZ	Area	Main river *		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Mali Hka	1	23,309	Mali Hka	312	135	4,759	1,093	870	0	185	29
n' Mai Hka	1	24,388	n' Mai Hka	469	136	5,881	2,512	2,489	0	231	53

* River length based on Hydrosheds DEM stream basin threshold of 1,350 km^2

** Zone elevation and slope based on Hydrosheds DEM

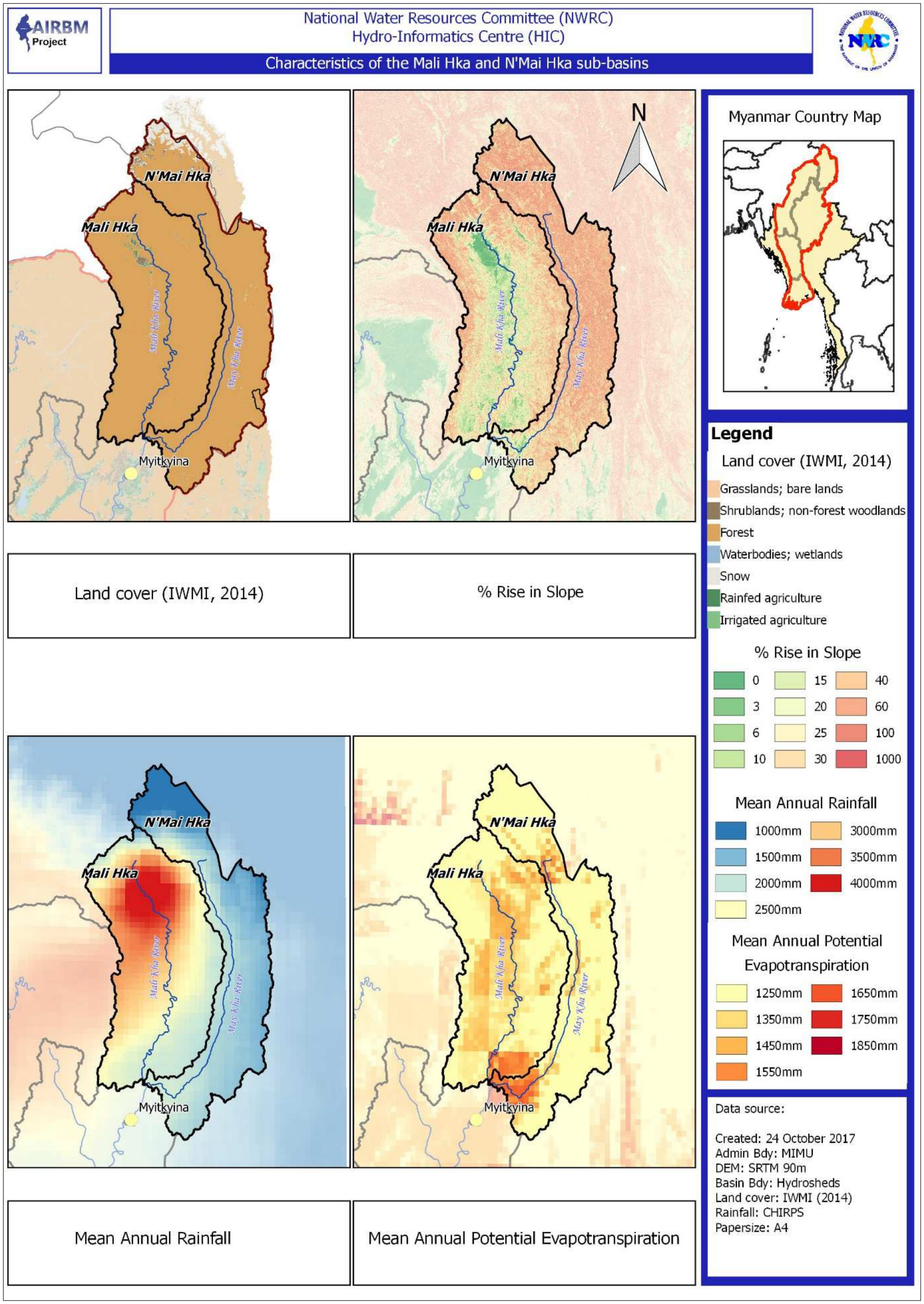


Figure 61 Characteristics of the Mali Hka and N'Mai Hka sub-basins

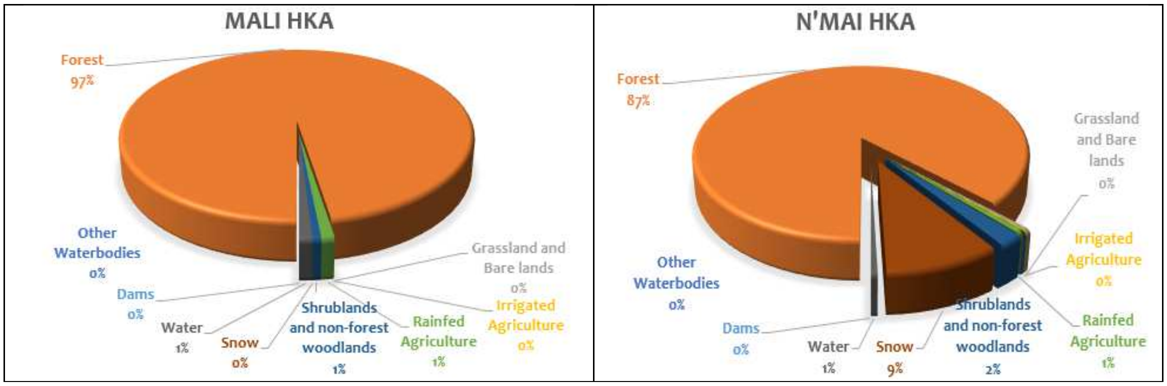


Figure 62 Land cover classes in the Mali Hka and N'Mai Hka sub-basins (IWMI, 2014)

3.1.2 Water Availability

FLOWS

The N'Mai Hka and Mali Hka sub-basins contribute 35% of the total flow volume in the Ayeyarwady River Basin, with 22 % of flow generated from the Mali Hka sub-basin and 13 % produced from the N'Mai Hka sub-basin. Figure 63 shows monthly rainfall and flows in the N'Mai Hka and Mali Hka sub-basins. 75 % to 80 % of sub-basin annual flows occur during the wet season May to October. As temperatures increase and the rain season starts, snow melt also contributes to early wet season flows from the N'Mai Hka sub-basin. In the N'Mai Hka sub-basin approximately 0.12 % of total annual flow is from snow melt, and approximately 0.1 % of dry season flows are from snow melt.

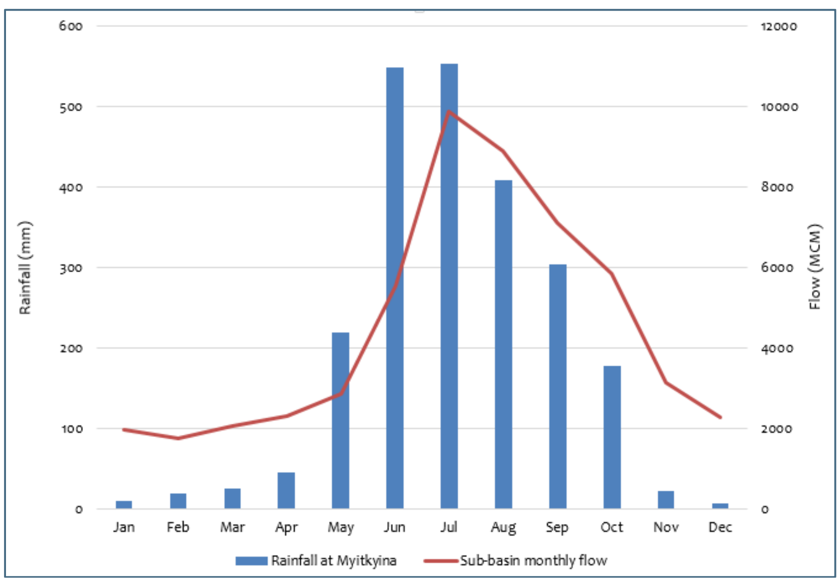


Figure 63 Monthly rainfall and flows in the N'Mai Hka and Mali Hka sub-basins

STORAGES

The Mali Hka River and N'Mai Hka River sub-basins are largely un-impacted by storages. The Chibwe Nge hydropower storage, in the N'Mai Hka sub-basin, was commissioned in 2013 and as of 2016 is the only major storage in these sub-basins. Salient features of the Chibwe Nge reservoir are listed in Table 11. With a full supply capacity of 1.23 MCM, storage volume is 0.1% of upstream inflows to the storage and currently has very little impact on total sub-basin flows.

Table 10 Reservoir salient features

Name	Purpose	FSC * (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Chibwe Nge	HP	1.23	47.5	-	-	99	2013	0.1%

**Full Supply Capacity*

***the ratio of total FSC and runoff upstream of all storages*

WATER USE

The Mali Hka and N'Mai Hka sub-basins are sparsely populated, and all agriculture is rain fed, with no extra irrigation being supported by storages.

3.1.3 Water Balance

According to Figure 64 and Figure 65 most of the flow generated in these sub-basins leaves at the outlets. Taking the average of the two sub-basins, dry season outflows are approximately 20 % of wet season outflows

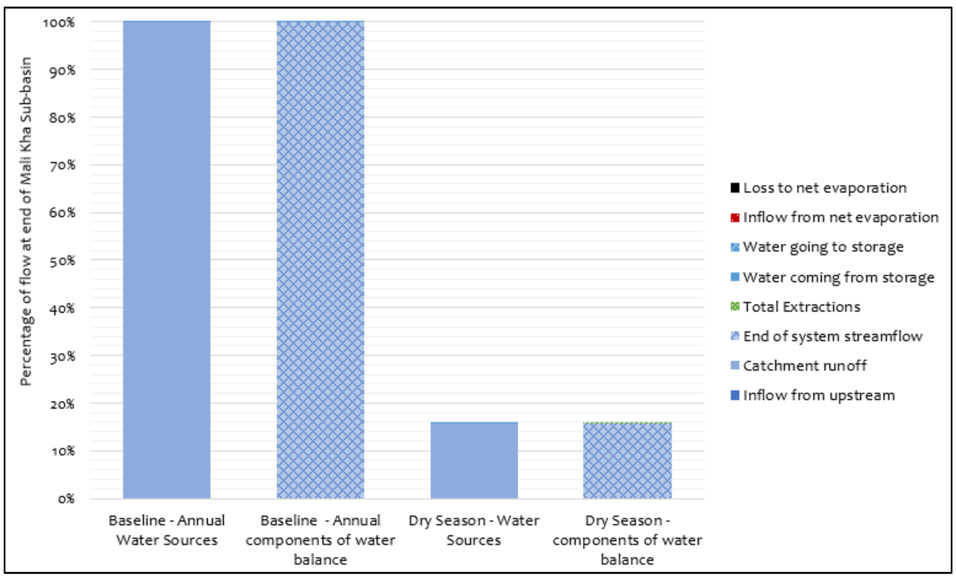


Figure 64 Water balance in the Mali Hka sub-basin

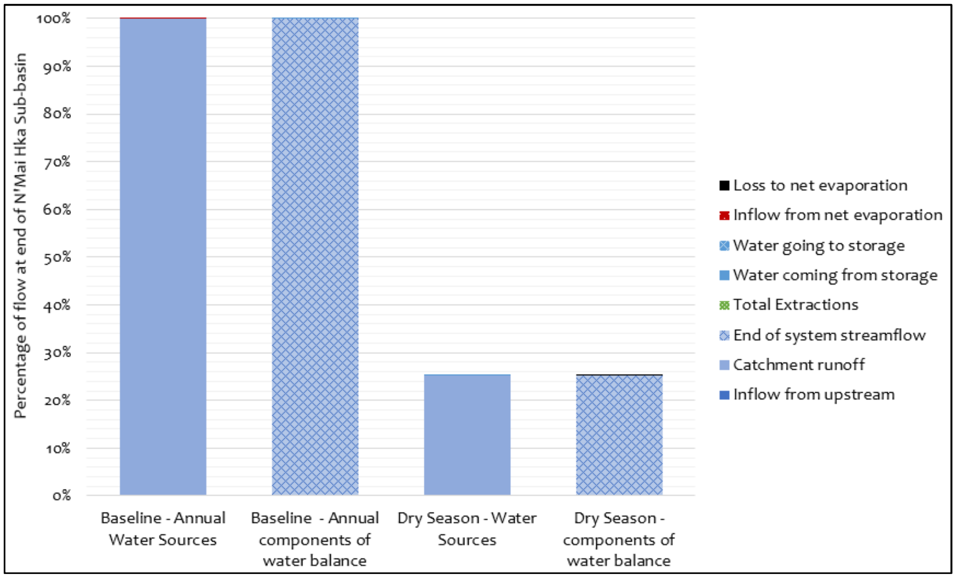
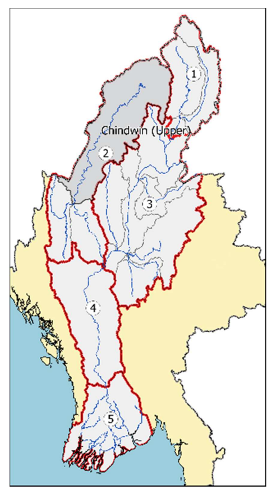


Figure 65 Water balance in the N'Mai Hka sub-basin

3.2 Chindwin (Upper) sub-basin



3.2.1 *Physical and climate description*

Physical and climate characteristics of the Chindwin (Upper) sub-basin are represented in Figure 67. The Chindwin (Upper) sub-basin is the most upstream sub-basin in the Chindwin Basin (HEZ 2). Table 12 lists the physical characteristics of this sub-basin. It has a catchment area of approximately 73,500 km^2 and is the largest sub-basin in the Ayeyarwady River Basin. Elevations range from more than 3,814 m above mean sea level to as low as 34 m above the mean sea level, but the median elevation is 431 m above mean sea level. The reaches in the northern and western Chindwin (Upper) sub-basin are steep, including the Patkai Range and the Naga Hills. Median slope for the Chindwin (Upper) River sub-basin is about 19%.

The land cover of the Chindwin Upper sub-basin is dominated by forest (93%). Figure 66 shows the percentage of each land cover class in the Chindwin (Upper) sub-basin.

Rainfall in the Chindwin (Upper) sub-basin is highly seasonal, ranging from 9 mm in December to more than 1,200 mm in July, as measured at Hkamti (Figure 68).

Table 11 Physical characteristics of the Chindwin (Upper) sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Chindwin (Upper)	2	73497	Chindwin River	818	34	3,814	686	431	0	236	19

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

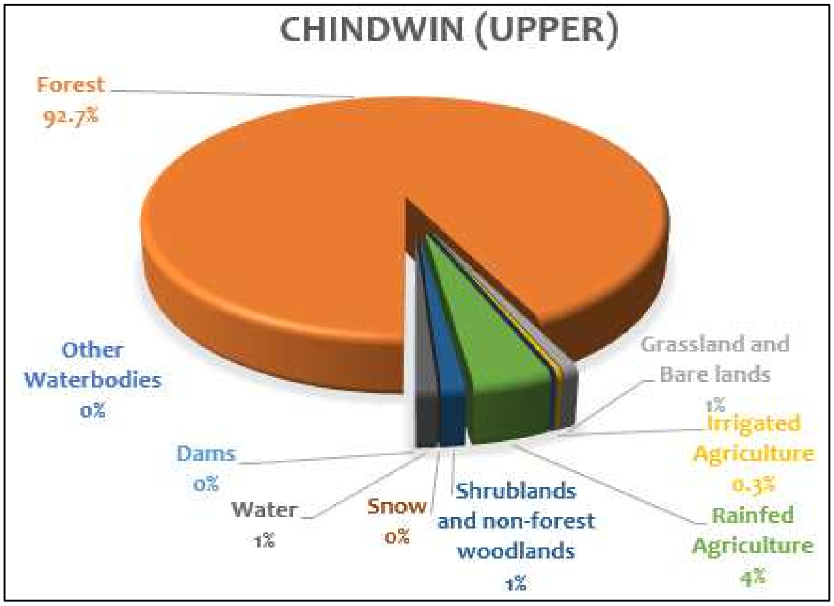


Figure 66 Land cover classes of the Chindwin (Upper) sub-basin (IWMI, 2014)

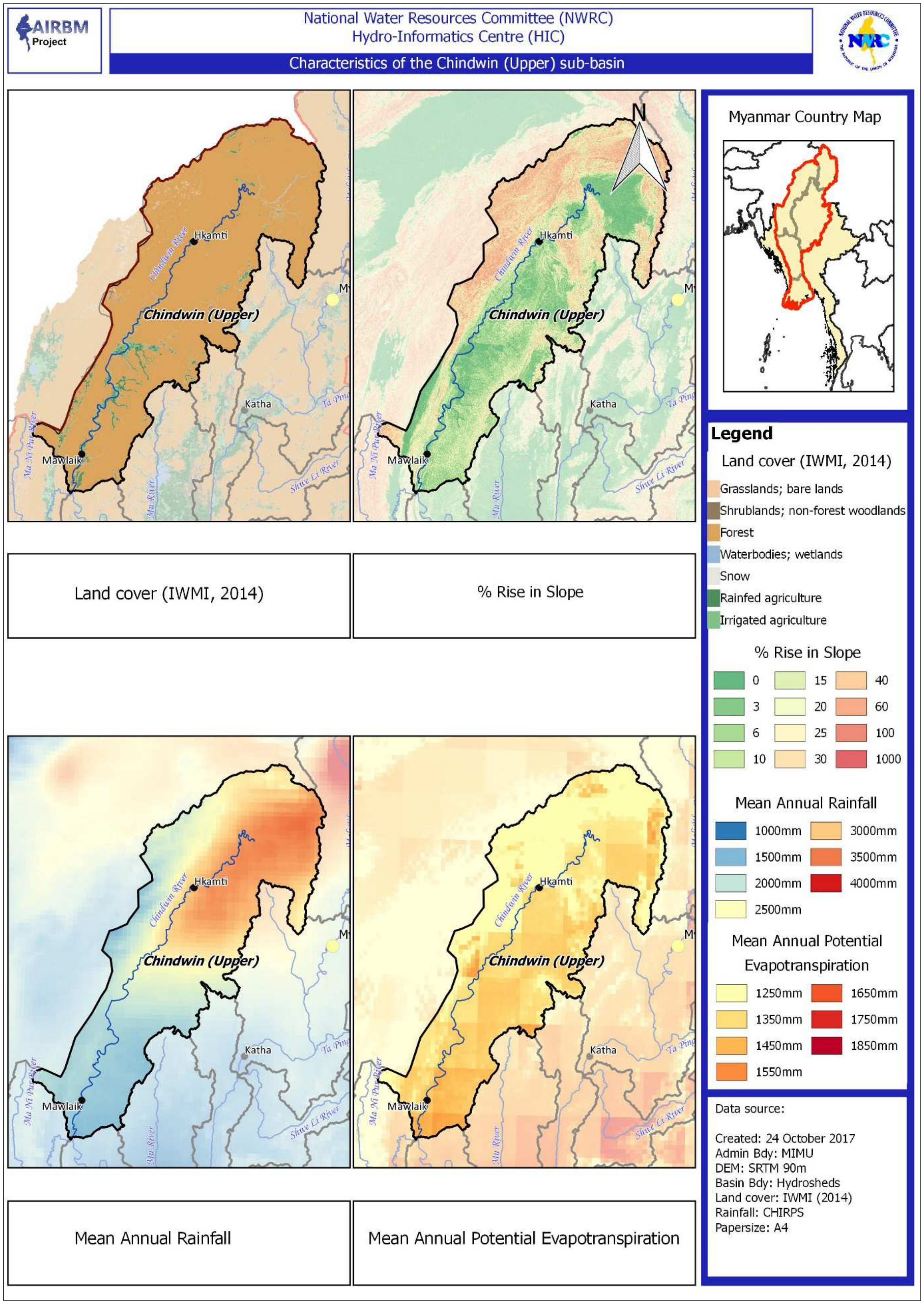


Figure 67 Characteristics of the Chindwin (Upper) sub-basin

3.2.2 *Water availability*

FLOWS

The Chindwin (Upper) sub-basin contributes 12% of the total flows in the Ayeyarwady River Basin. After the Mali Hka and N'Mai Hka sub-basins, it is the second biggest contributor to flows in the Basin. 90% of sub-basin annual flows occur during the wet season May to October. Figure 68 shows monthly rainfall and flows in the Chindwin (Upper) sub-basin.

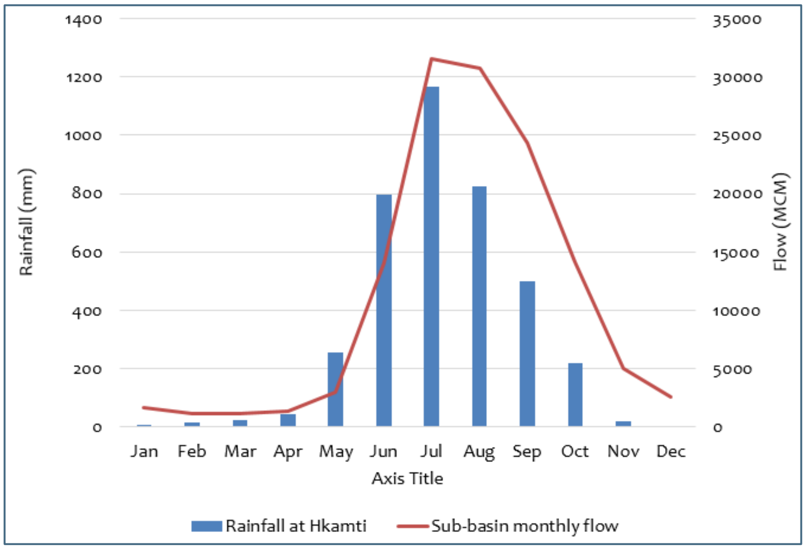


Figure 68 Monthly rainfall and flows in the Chindwin (Upper) sub-basin

STORAGES

The largest storage is Warshaung Weir near the town of Waingmaw, built in 1967 to provide for irrigation. The full supply capacity of the Weir could not be ascertained, but it is known that it serves a beneficial area of 46.32 km^2 (Table 13). There are also at least 6 more smaller storages (full supply capacity unknown) which together serve a total beneficial area of 23.5 km^2. These are combined in Table 13. Since full supply capacity information for the storages in the Chindwin (Upper) sub-basin was not available, the volume/inflow ratio could not be calculated with any certainty.

Table 12 Reservoir salient features

Name	Purpose	FSC * (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Warshaung Weir	IW	-	7.6	-	46.32		1967	-
Other (6)	IW	-	3.1***		23.55		-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*

WATER USE

Agriculture accounts for less than 5% of the land use in the Chindwin (Upper) sub-basin with most of it being rain fed. Irrigation water use is small with a total known beneficial area of 69.87 km^2. Both mean annual and dry season extractions (domestic plus irrigation) are currently negligible.

3.2.3 Water balance summary

According to Figure 69 most of the flow generated in this sub-basin leaves at the outlet. Amounts lost due to evaporation, extractions or retained in storage are too small to reflect in the total water balance. Dry season outflows are approximately 10 % of wet season outflows

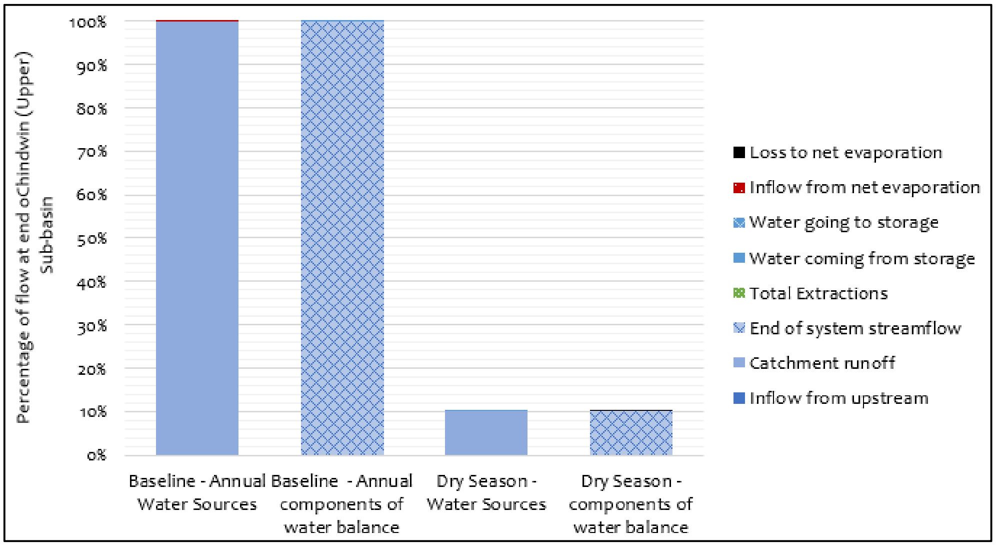
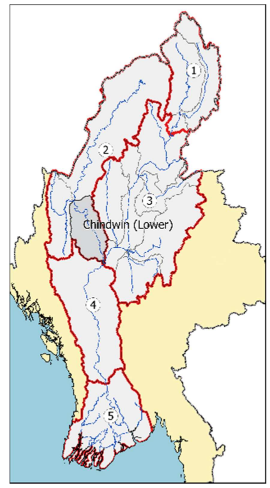


Figure 69 Water balance in the Chindwin (Upper) sub-basin

3.3 Chindwin (Lower) sub-basin



3.3.1 Physical and climate description

Physical and climate characteristics of the Chindwin (Lower) sub-basin are represented in Figure 71. The Chindwin (Lower) sub-basin is located in the lower Chindwin River basin, extending downstream from the Myittha/Chindwin River confluence to the Chindwin/Ayeyarwady River confluence. Table 14 lists the physical characteristics of this sub-basin. It has a catchment area of approximately 16 600 km^2 and is in HEZ No. 2 (Chindwin Basin). Elevations range from more than 1315 m above mean sea level to as low as 14 m above the mean sea level, but median elevation is 193 m above mean sea level. The Chindwin Lower river sub-basin is very flat. Median slope for the Chindwin (Lower) sub-basin is about 3%.

The land cover of the Chindwin (Lower) sub-basin is dominated by agriculture (52%) and forest (41%). Figure 70 shows the percentage of each land cover class in the Chindwin (Lower) sub-basin.

The Chindwin (Lower) sub-basin is located in the Central Dry Zone and rainfall is lower than that of the Chindwin (Upper) sub-basin. Average monthly rainfall at Monywa ranges from 1 mm in January to approximately 180 mm in September (Figure 72). Also evident is a bi-modal monsoon, with rainfall noticeably lower in July.

Table 13 Physical characteristics of the Chindwin (Lower) sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Chindwin (Lower)	2	16,601	Chindwin River	318	14	1,315	253	193	0	111	3

* River length based on Hydrosheds DEM stream basin threshold of 1350 km^2
** Zone elevation and slope based on Hydrosheds DEM

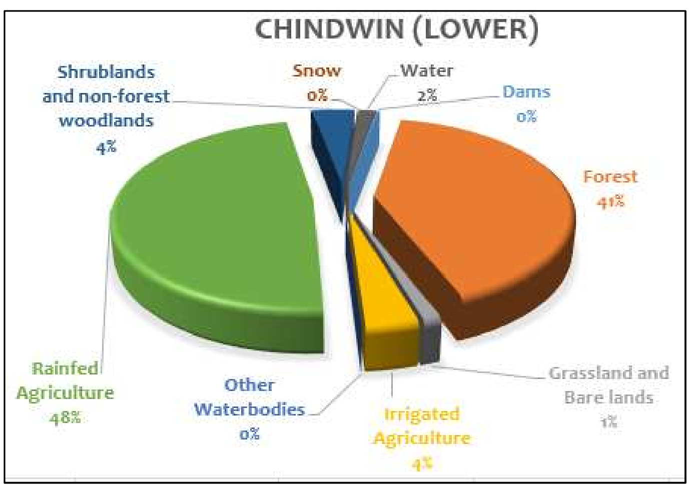


Figure 70 Land cover classes of the Chindwin (Lower) sub-basin (IWMI, 2014)

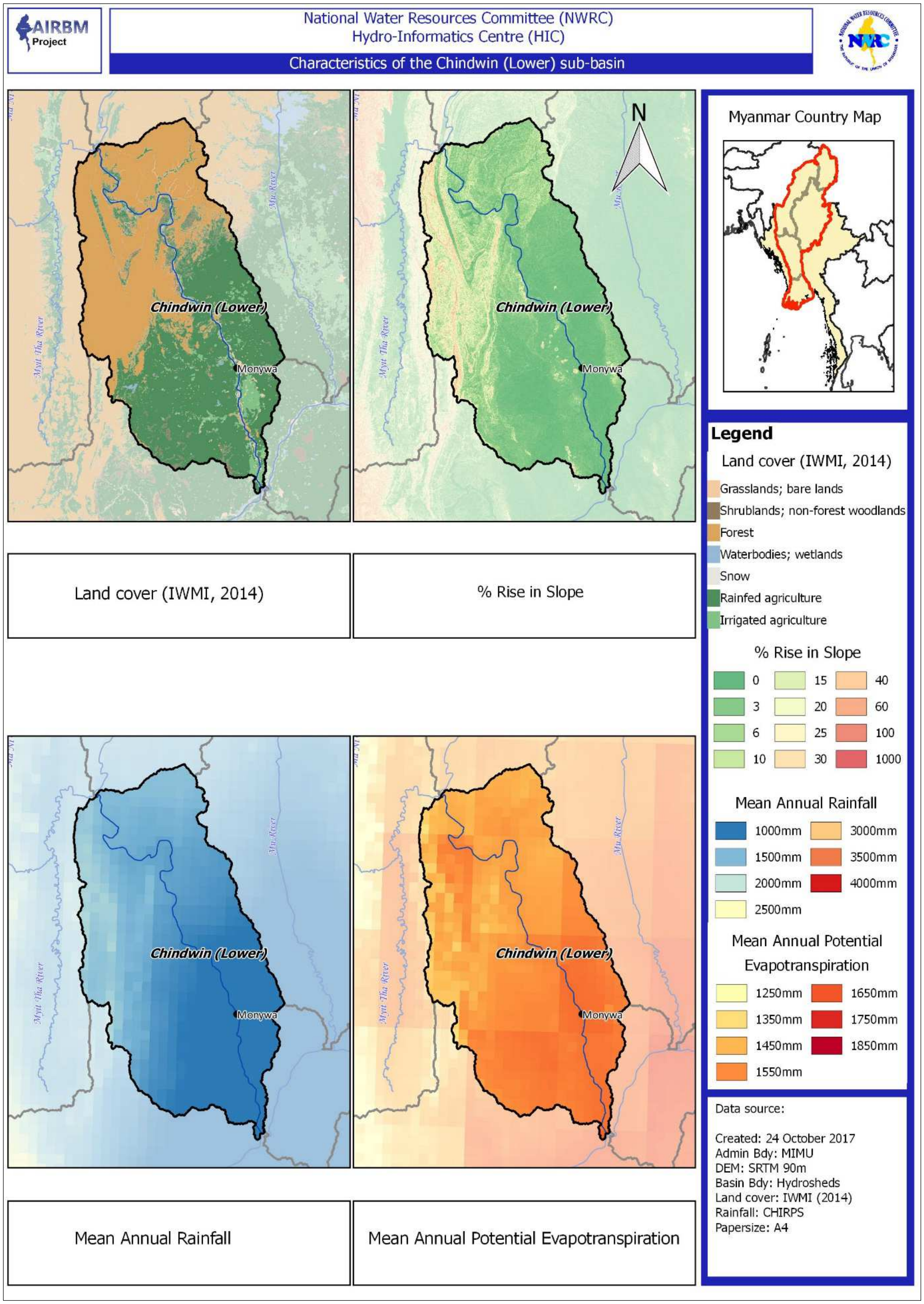


Figure 71 Characteristics of the Chindwin (Lower) sub-basin

3.3.2 Water availability

FLOWS

The Chindwin (Lower) sub-basin contributes 1% of the total flows in the Ayeyarwady River Basin. 89% of sub-basin annual flows occur during the wet season May to October. Figure 72 shows monthly rainfall and flows in the Chindwin (Lower) sub-basin.

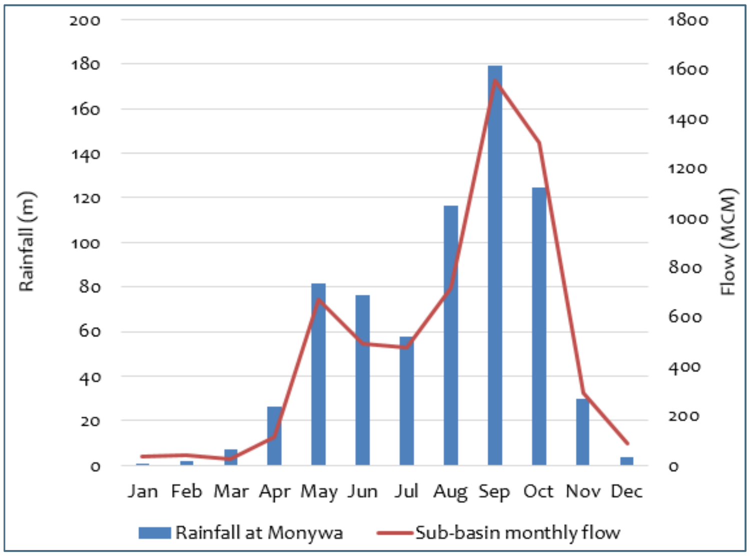


Figure 72 Monthly rainfall and flows in the Chindwin (Lower) sub-basin

STORAGES

The largest storage is Northyamar Dam near the town of Pale, built in 2004 to provide for irrigation. It has a full supply capacity of 151 MCM and serves a beneficial area of 117.69 km² (Table 15). Southyamar Dam is the second largest storage, with full supply capacity of 20.27 MCM and a beneficial area of 22.26 km². Twenty-eight smaller storages also provide for irrigation in this sub-basin, together serving a total beneficial area of 70.33 km². These are combined in Table 13. Total storage volume in the Chindwin (Lower) sub-basin is 56 % of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 14 Reservoir salient features

Name	Purpose	FSC *(MCM)	Height (m)	Surface Area (km²)	Beneficial Area (km²)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Northyamar Dam	IW	151.6	43	-	117.69	-	2004	56
Southyamar	IW	20.27	27.4	-	22.26		2000	
Other (28)	IW	142.84****	17***	-	70.33		-	

*Full Supply Capacity
** the ratio of total FSC and runoff upstream of all storages
***average height
****total volume

WATER USE

Agriculture accounts for 52 % of the land use in the Chindwin (Lower) sub-basin with most of it being rain fed. Four percent of agriculture in the sub-basin is irrigated with a total known beneficial area of 210.28 km^2. According to Table 16, 38 % of the average annual flow available upstream of major beneficial areas is extracted. Considering only the dry season, when extractions will be highest, 317 % of average dry season flow upstream of all extraction points is extracted. The extremely high extraction/inflow ratio during the dry season occurs because during the dry season months of January to April, the required extractions exceed the available inflows from local runoff. Extra water from Northyamar Dam and other irrigation works make it possible to support the extent of crops under irrigation. This is illustrated in Figure 73 using Northyamar Dam as an example. During the wet season months, the dam volume increases, filled by inflows from upstream. However, there is hardly any inflow during the dry season months, and the ratio between water required for extraction and available upstream inflow will increase dramatically. These extraction requirements are then supplemented by releases from Northyamar Dam, causing storage levels to drop, and also resulting in flows downstream of the dam being higher than those upstream.

Table 15 Extraction/inflow ratio*

Annual (%)	Dry season (%)
38	317

*the ratio of total extractions and runoff upstream of all extraction points

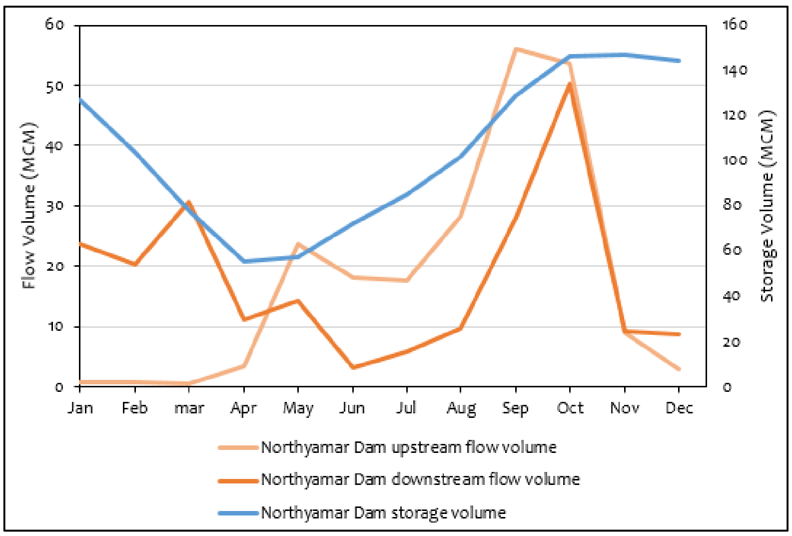


Figure 73 Relationship between seasonal inflows and average monthly storage volume at the Northyamar Dam

3.3.3 *Water balance summary*

According to Figure 74, 96 % of the average annual outflows from this sub-basin are as a result of inflows from upstream – passing through the sub-basin in the main stem of the Chindwin River. Only 4 % of average annual flow is generated by local sub-catchment runoff from within the sub-basin. On average releases from the irrigation storages to support irrigation extractions make up about 0.8 % of average annual outflows, but 7 % of dry season outflows. Dry season outflows are approximately 11 % of wet season outflows.

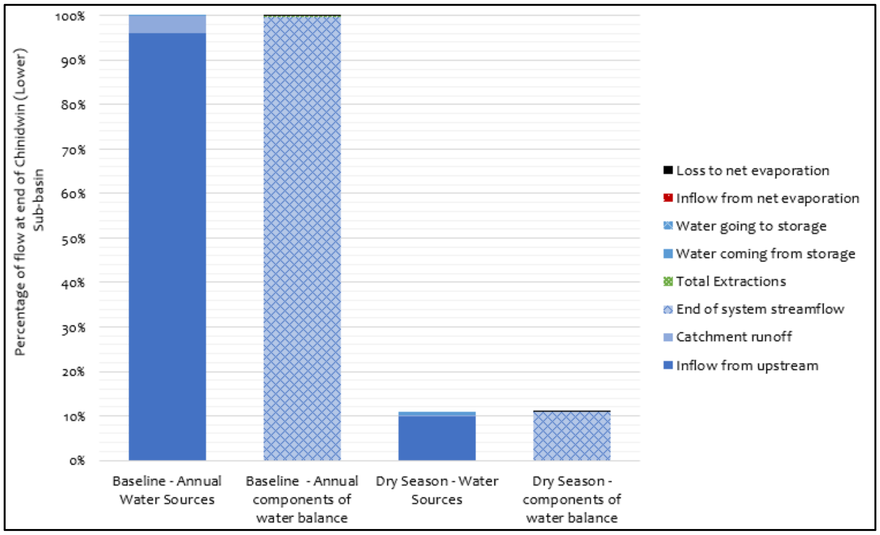
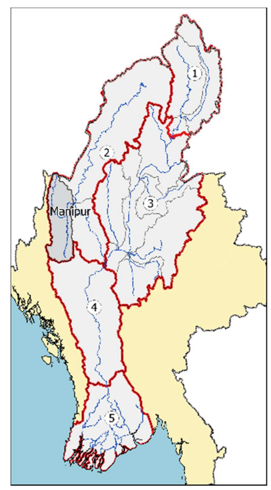


Figure 74 Water balance in the Chindwin (Lower) sub-basin

3.4 Manipur River sub-basin



3.4.1 *Physical and climate description*

Physical and climate characteristics of the Manipur sub-basin are represented in Figure 76. The Manipur River sub-basin is located in the western Chindwin River basin. It includes the Myittha River and its tributary, the Manipur River, extending upstream of the Myittha/Chindwin confluence at the town of Kalewa. The Myittha and Manipur rivers flow in a north/south direction. The Manipur River rises in the Naga Hills, in the Indian section of the Ayeyarwady River Basin and flows southwards to meet the Myittha River west of Kalewa. The Myittha River rises in the south in the Chin Hills in the Chin State of Myanmar and flows northwards. Table 17 lists the physical characteristics of this sub-basin. It has a catchment area of approximately 24,400 km^2 and is in HEZ 2 (Chindwin Basin). Elevations range from 2,730 m above mean sea level to as low as 83 m above the mean sea level, but it is a mostly steep, upland area with a median elevation of 800 m above mean sea level and median slope of 27 %.

The land cover of the Manipur River sub-basin is dominated by forest (76 %), with some agriculture occurring in the flatter river floodplain areas. Figure 75 shows the percentage of each land cover class in the Manipur sub-basin.

Rainfall in the Manipur sub-basin is highly seasonal. Average monthly rainfall at measured Gangaw ranges from 2 mm in January to approximately 240 mm in August (Figure 77).

Table 16 Physical characteristics of the Manipur River sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Manipur	2	24,369	Manipur River	329	83	2,730	902	864	0	161	27

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

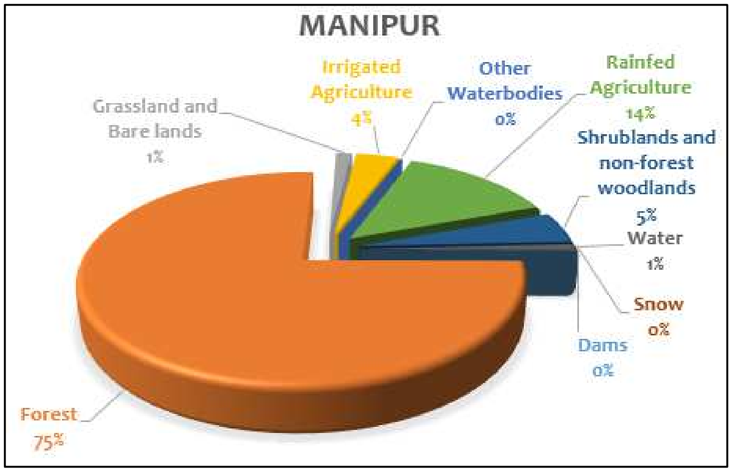


Figure 75 Land cover classes of the Manipur River sub-basin (IWMI, 2014)

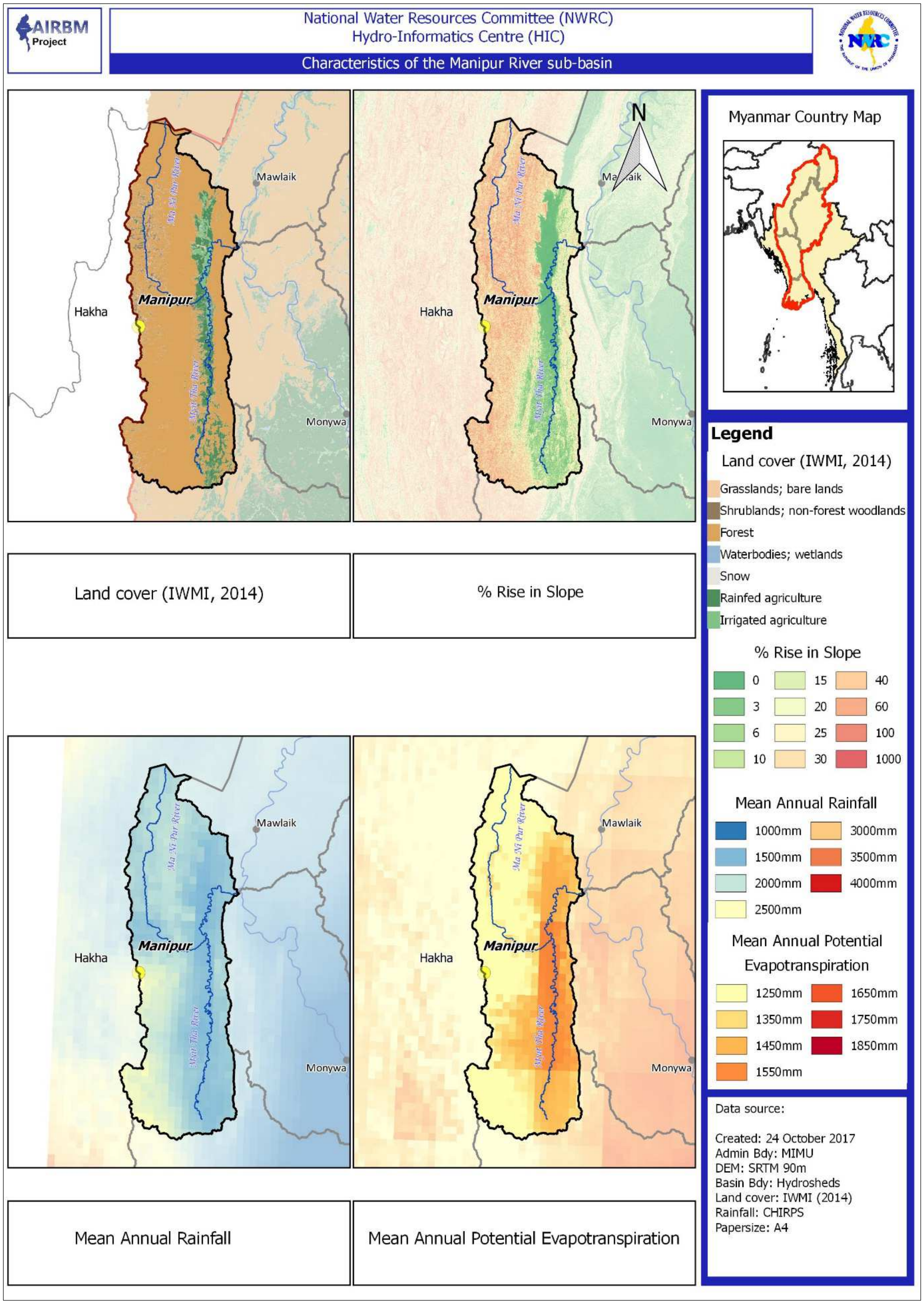


Figure 76 Characteristics of the Manipur River sub-basin (within Myanmar)

3.4.2 *Water availability*

FLOWS

The Manipur sub-basin contributes 4 % of the total flows in the Ayeyarwady River Basin. 89% of sub-basin annual flows occur during the wet season May to October. Figure 77 shows monthly rainfall and flows in the Manipur sub-basin.

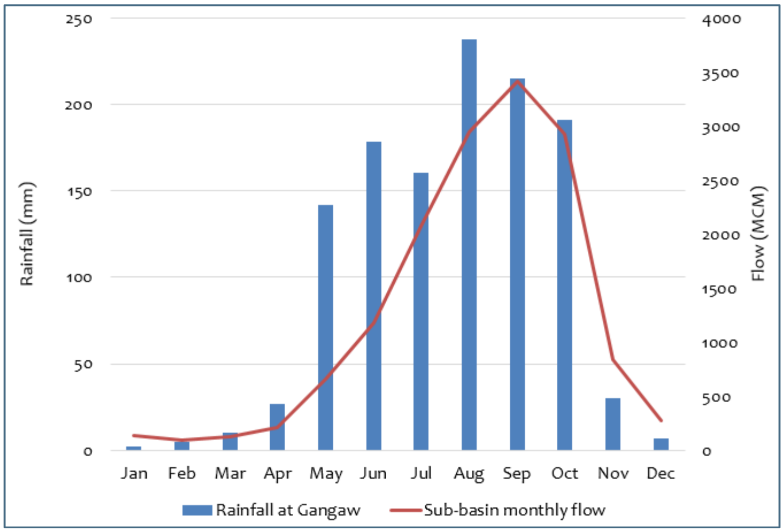


Figure 77 Monthly rainfall and flows in the Manipur sub-basin

STORAGES

As far as could be established total storage volume in the Manipur sub-basin is 532 MCM. The largest storage is the multi-purpose Myittha Dam on the Myittha River, built in 1981 to provide both irrigation water and hydropower. It has a full supply capacity of 465.76 MCM (Table 18). The size of the beneficial area served by this dam could not be established. Yazagyo Dam, located north-west of Kalewa and completed in 2015, is the second largest storage, with a full supply capacity of 64.14 MCM and a beneficial area of 34.4 km^2. Three smaller storages also provide for irrigation in this sub-basin, together serving a total beneficial area of 8.2 km^2. These are combined in Table 18. Total storage volume in the Manipur sub-basin is 23 % of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 17 Reservoir salient features

Name	Purpose	FSC * (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Myittha Dam	MP	465.76	62.5	12.2	-	-	1981	23
Yazagyo	IW	64.14	50.3	-	34.4	-	2015	
Other (3)	IW	2.15****	11***	-	8.2	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume – the FSC of two of the three storages could not be established*

WATER USE

Agriculture accounts for 18 % of the land use in the Manipur sub-basin with most of it being rain fed. Four percent of agriculture in the sub-basin is irrigated with a total known beneficial area of 42.6 km². According to Table 19, 3 % of the average annual runoff available upstream of all extraction points is extracted. Considering only the dry season, when extractions will be highest, 26 % of average dry season runoff upstream of all extraction points is extracted.

Table 18 Extraction/inflow ratio*

Annual (%)	Dry season (%)
3	26

*the ratio of total extractions and runoff upstream of all extraction points

3.4.3 Water balance summary

According to Figure 78 most of the flow generated in this sub-basin leaves at the outlet with a small amount being extracted. Dry season outflows are approximately 11 % of wet season outflows.

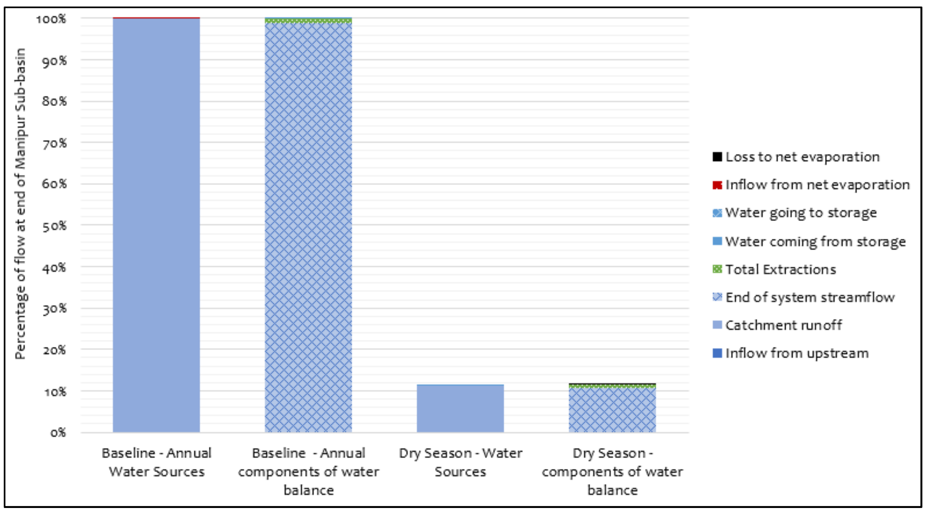
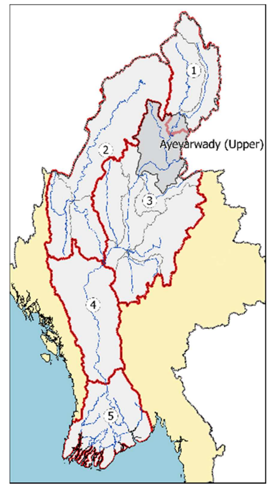


Figure 78 Water balance in the Manipur sub-basin

3.5 Ayeyarwady (Upper) sub-basin

3.5.1 *Physical and climate descriptions*



Physical and climate characteristics of the Ayeyarwady (Upper) sub-basin are represented in Figure 80. The Ayeyarwady (Upper) sub-basin is an upstream sub-basin of the Ayeyarwady River Basin. It extends from the confluence of the N'Mai Hka and Mali Hka Rivers in the north to the confluence of the Ayeyarwady River and the Shweli River in the south. The largest river is the Ayeyarwady main stem. The Tarpein River has its source in the mountains to the east in China and is the largest tributary of the Ayeyarwady River in this sub-basin. Table 20 lists the physical characteristics of this sub-basin. It has a catchment area of approximately 3,066 km^2 and is located in HEZ 3 (Middle Basin). Elevations range from 3,715 m above mean sea level to as low as 20m above mean sea level, and the median elevation is 270 m above mean sea level. The reaches in the north-western and north-eastern Ayeyarwady (Upper) sub-basin are relatively steep. Median slope is about 11 %.

The land cover of the Ayeyarwady (Upper) River sub-basin is dominated by mountains and forested uplands (72 %) and agriculture (17 %). Figure 79 shows the percentage of each land cover class in the Ayeyarwady (Upper) sub-basin.

Rainfall in the Ayeyarwady (Upper) River sub-basin ranges from less than 10 mm in December and January to nearly 500 mm in July, as measured at Myitkyina in the upstream section of these sub-basins (Figure 81).

Table 19 Physical characteristics of the Ayeyarwady (Upper) sub-basin

Sub-basin	HEZ	Area	Main river *		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Ayeyarwady (Upper)	1	3,066	Ayeyarwady River	397	20	3715	600	270	0	145	11

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

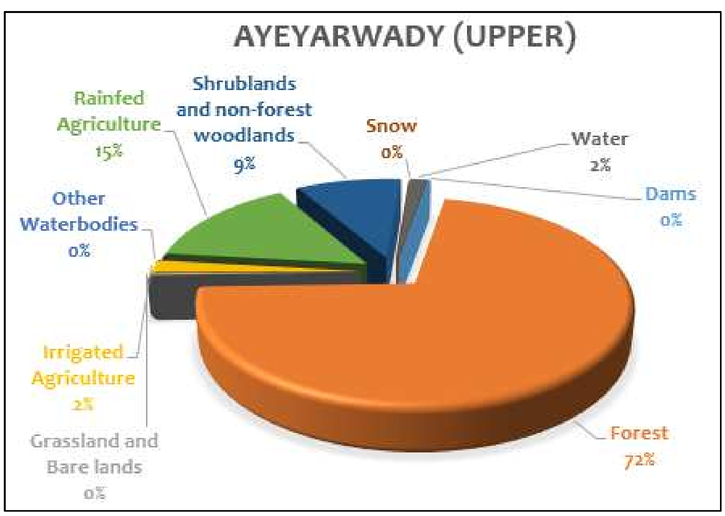


Figure 79 Land cover classes of the Ayeyarwady (Upper) sub-basin (IWMI, 2014)

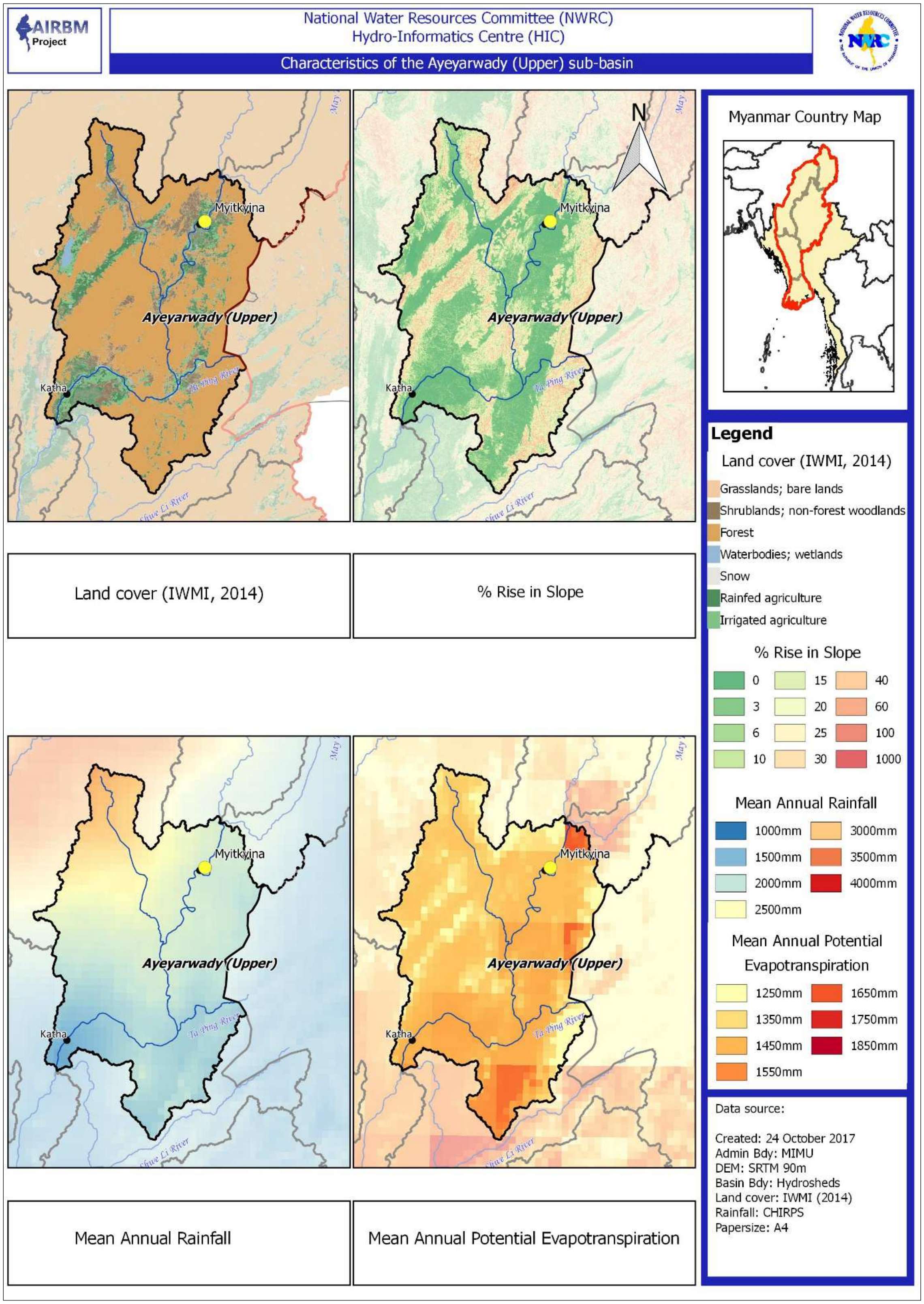


Figure 80 Characteristics of the Ayeyarwady (Upper) sub-basin

3.5.2 *Water availability*

FLOWS

The Ayeyarwady (Upper) sub-basin contributes 10 % of the total flows in the Ayeyarwady River Basin. 83% of sub-basin annual flow occurs during the wet season May to October. Figure 68 shows monthly rainfall and flows in the Ayeyarwady (Upper) sub-basin.

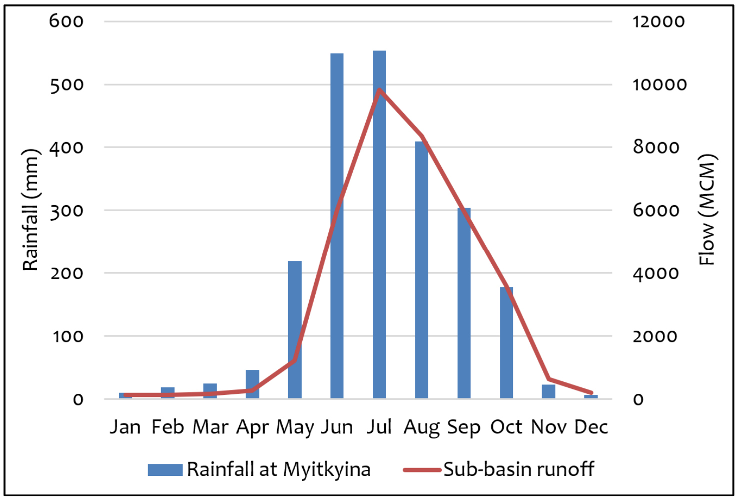


Figure 81 Monthly rainfall and flows in the Ayeyarwady (Upper) sub-basin

STORAGES

Forty-one hydropower dams have been built in the upstream section of the Tarpein River in China. The total storage capacity and operations of these is unknown. Tarpein I (Table 21) is the largest storage in the Ayeyarwady (Upper) sub-basin within Myanmar borders. It was built in 2011 to provide electricity. There are 3 smaller storages in the sub-basin built to provide for irrigation requirements. The FSC of these storages could not be ascertained, but they have an average height of only 1.7 m and together they serve a total beneficial area of 33.71 km^2. These are combined in Table 21. Total storage volume in the Ayeyarwady (Upper) sub-basin is 24 % of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages. Although this volume/inflow ratio for this sub-basin appears small, it should be noted that this is only taking into account the single storage within Myanmar borders. Due to lack of information, the impact on inflows from upstream of Myanmar could not be reported with confidence, and inflows could be much less.

Table 20 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Tarpein I	HP	22.0	46	-	-	240	2011	-
Other (3)	IW	- ****	1.7***	-	33.71	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume*

WATER USE

Agriculture accounts for 17 % of the land use in the Ayeyarwady (Upper) sub-basin with most of it being rain fed. Only two percent of agriculture in the sub-basin is irrigated with a total known beneficial area of 33.71 km^2. Both mean annual and dry season extractions (domestic plus irrigation) are currently negligible.

3.5.3 Water Balance

According to Figure 82, 78 % of the average annual outflows from this sub-basin are as a result of inflows from upstream – passing through the sub-basin in the main stem of the Ayeyarwady River. The remaining 22 % of average annual flow is generated by local sub-catchment runoff from within the sub-basin. Although the storages are small, during the dry season releases from the irrigation storages to support irrigation extractions make up about 7 % of dry season outflows. Dry season outflows are approximately 17.5 % of wet season outflows.

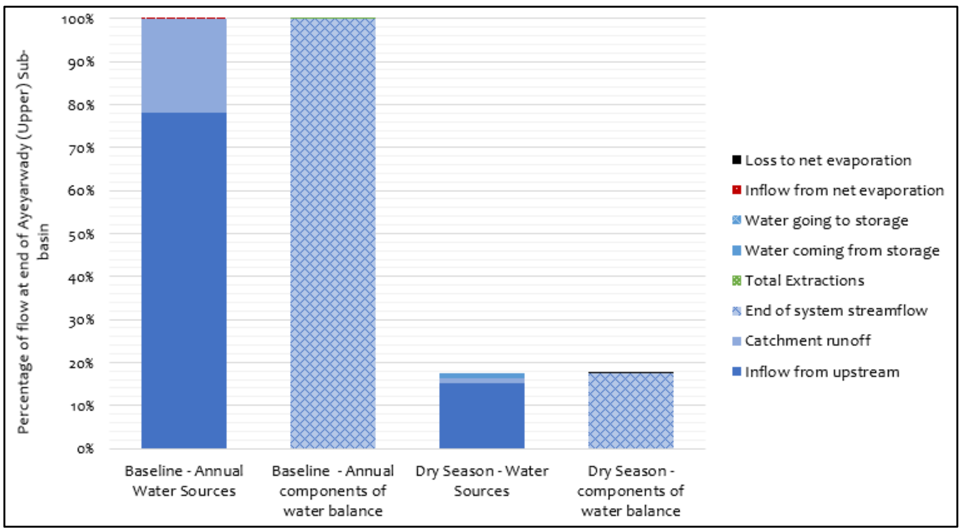
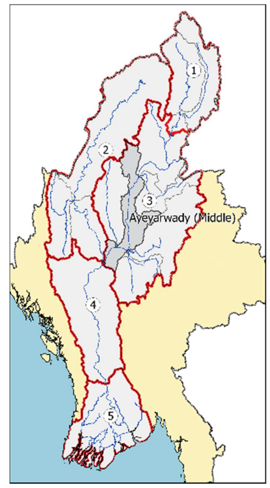


Figure 82 Water balance in the Ayeyarwady (Upper) sub-basin

3.6 Ayeyarwady (Middle) sub-basin



3.6.1 Physical and climate description

Physical and climate characteristics of the Ayeyarwady (Middle) sub-basin are represented in Figure 84. Table 22 lists the physical characteristics of this sub-basin. It has a catchment area of 22,250 km^2 and is located in HEZ 3 (Middle Basin). Elevations range 2117 m above mean sea level to 33 m above mean sea level, and the median elevation is 181 m above mean sea level. The Shweli and Myitnge river sub-basins flow into the Ayeyarwady sub-basin from the east. This is a predominantly flat sub-basin, including the central floodplain area of the Ayeyarwady River main stem extending from the confluence of the Ayeyarwady River and the Shweli River in the north to the confluence of the Chindwin and Ayeyarwady rivers in the south. The median slope of the Ayeyarwady (Middle) sub-basin is about 4 %.

According to Figure 83 and Figure 84 the land cover of the Ayeyarwady (Middle) sub-basin is dominated by forest (45 %), in the steeper higher-lying areas, and agriculture (44 %) in the floodplain areas.

The southern parts of this sub-basin fall within the Central Dry Zone. Rainfall in the Ayeyarwady (Middle) River sub-basin decreases from north to south and is lower than that of the Ayeyarwady (Upper) sub-basin just north of it, ranging from 1 mm in January to 170 mm in September if measured at Mandalay near the southernmost point of this sub-basin (Figure 85). Also evident is a bi-modal monsoon, with rainfall noticeably lower in July.

Table 21 Physical characteristics of the Ayeyarwady (Middle) sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Ayeyarwady (Middle)	3	22,250	Ayeyarwady River	385	33	2117	308	181	0	159	4

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

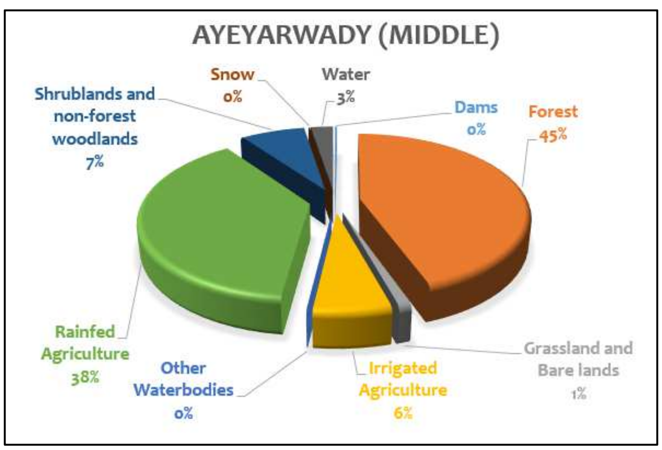


Figure 83 Land cover classes of the Ayeyarwady (Middle) sub-basin (IWMI, 2014)

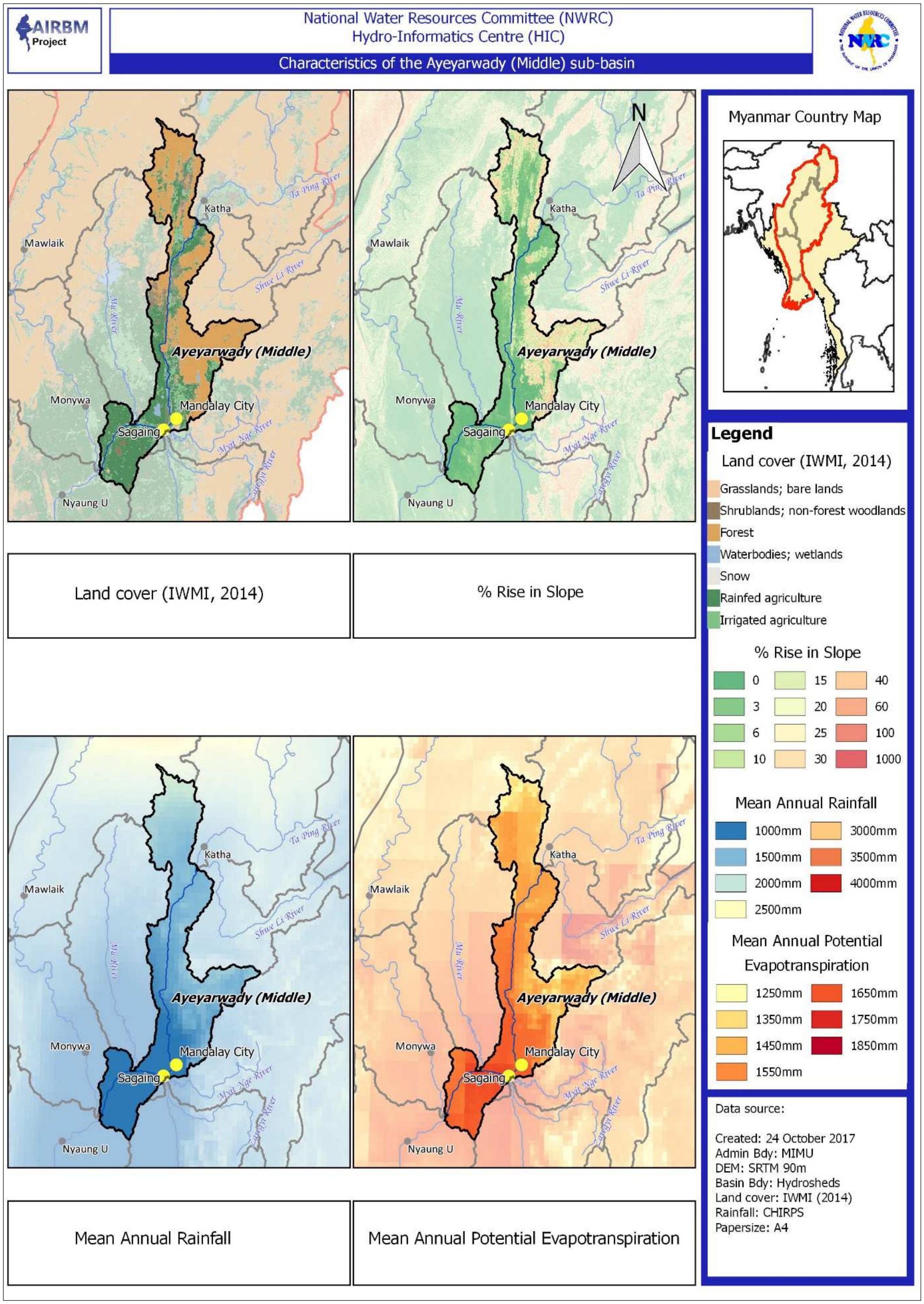


Figure 84 Characteristics of the Ayeyarwady (Middle) sub-basin

3.6.2 *Water Availability*

FLOWS

A relatively dry sub-basin, the Ayeyarwady (Middle) sub-basin contributes 1% of the total flows in the Ayeyarwady River Basin. 84% of sub-basin annual flow occurs during the wet season May to October. Figure 85 shows monthly rainfall and local sub-basin flows from the Ayeyarwady (Lower) sub-basin.

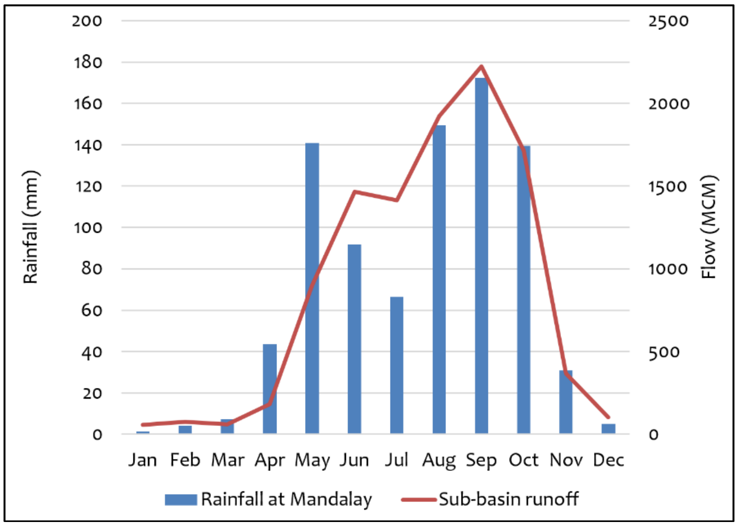


Figure 85 Monthly rainfall and flows in the Ayeyarwady (Lower) sub-basin

STORAGES

Storage in the Ayeyarwady (Middle) sub-basin is focussed on providing for irrigation requirements. Total available storage in the sub-basin is 600 MCM. The largest reservoir in this sub-basin is the multi-purpose Sedawgyi Dam which was built in 1,989, located north of Mandalay on the Chaunginagyi River. The Sedawgyi Dam has a Full Supply Capacity of 446 MCM and serves a beneficial irrigation area of 377 km^2 (Table 23). The dam also has a small hydropower station. The remaining storage capacity in the sub-basin is contained in thirteen smaller irrigation works. The salient features of the storages in the Ayeyarwady (Middle) sub-basin are listed in Table 23. Total storage volume in the Ayeyarwady (Middle) sub-basin is 26 % of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 22 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Sedawgyi	MP	446.5	40.5	-	377.92	25	1989	26
Other (13)	IW	154.1 ****	17.5***	-	114.14	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume*

WATER USE

Mandalay is the second largest urban area in the Ayeyarwady River Basin and located in the south of the Ayeyarwady (Middle) sub-basin. Water requirements in Mandalay are largely provided from tube wells many of which are located along the edge of the Ayeyarwady River, and can effectively be considered as extracting from the river. Known water requirements for the city are about 75 MCM per year, but it should be noted value excludes industrial water use which is largely from private tube wells and is not measured. Hydropower is also produced from the Sedawgyi multi-purpose storage. Beyond this irrigation is the major use of water in the sub-basin, largely provided from the Sedawgyi Dam.

According to Table 24, 17 % of the average annual runoff available upstream of all extraction points is extracted. Considering only the dry season, when extractions will be highest, 123 % of average dry season runoff upstream of all extraction points is extracted, supported by releases from storages.

Table 23 Extraction/inflow ratio*

Annual (%)	Dry season (%)
17	123

**the ratio of total extractions and runoff upstream of all extraction points*

3.6.3 Water Balance Summary

According to Figure 86, 96 % of the average annual outflows from this sub-basin are as a result of inflows from upstream – passing through the sub-basin in the main stem of the Ayeyarwady River. Only 4 % of average annual flow is generated by local sub-catchment runoff from within the sub-basin. Similarly, during the dry season 93 % of outflows from the sub-basin are as a result of inflows from upstream. Also, during the dry season releases from the irrigation storages to support irrigation extractions make up about 6 % of dry season outflows. Dry season outflows are approximately 15 % of wet season outflows.

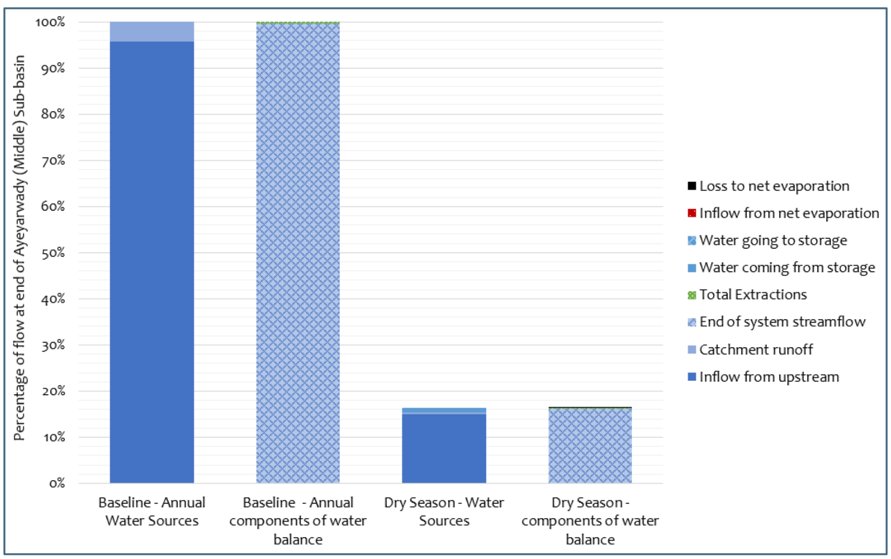
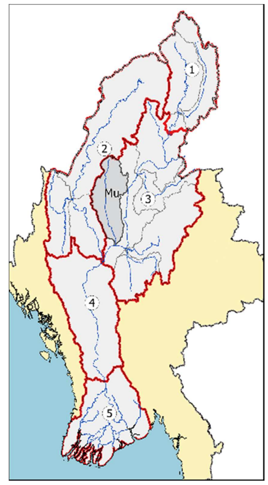


Figure 86 Water balance in the Ayeyarwady (Middle) sub-basin

3.7 Mu River sub-basin

3.7.1 Physical and climate description



Physical and climate characteristics of the Mu River sub-basin are represented in Figure 88. Table 25 lists the physical characteristics of this sub-basin. The Mu River sub-basin is located in the central Ayeyarwady River Basin. It has a catchment area of 19,456 km² and is located in HEZ3 (the Middle Basin). Elevations range from 1,678 m to 52 m above mean sea level, with most of the basin below 200 m in elevation. It is a largely flat sub-basin with a large floodplain and a median slope of 2%.

The Mu River sub-basin is a predominantly agricultural sub-basin, with agriculture making up 54% of land use in the sub-basin (Figure 87). Thapanseik 2 reservoir provides a large amount of water for irrigation, and the third most common land use is irrigated agriculture (12%).

The southern parts of this sub-basin fall within the Central Dry Zone, and rainfall is generally low. Monthly rainfall ranges from 0 mm in January to 160 mm in August, measured at Ywatha in the south-eastern edge of the sub-basin (Figure 89). Also evident is a bi-modal monsoon, with rainfall lower in July.

Table 24 Physical characteristics of the Mu River sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km²	name	km	min	max	mean	med	min	max	med
Mu	3	19,456	Mu River	139	52	1,678	231	195	0	90	2

** River length based on Hydrosheds DEM stream basin threshold of 1350 km²*
*** Zone elevation and slope based on Hydrosheds DEM*

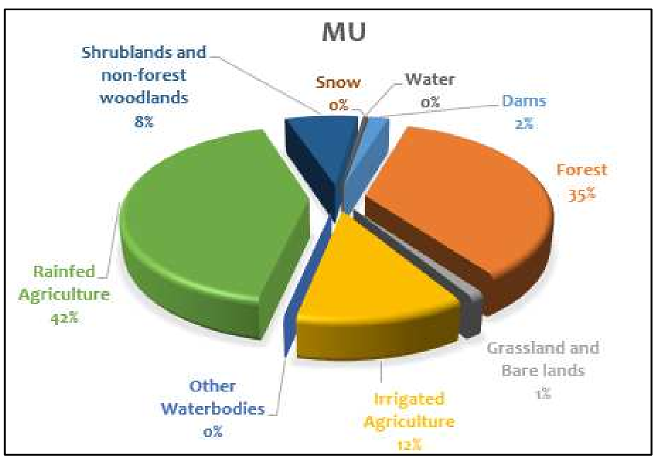


Figure 87 Land cover classes of the Mu River sub-basin (IWMI, 2014)

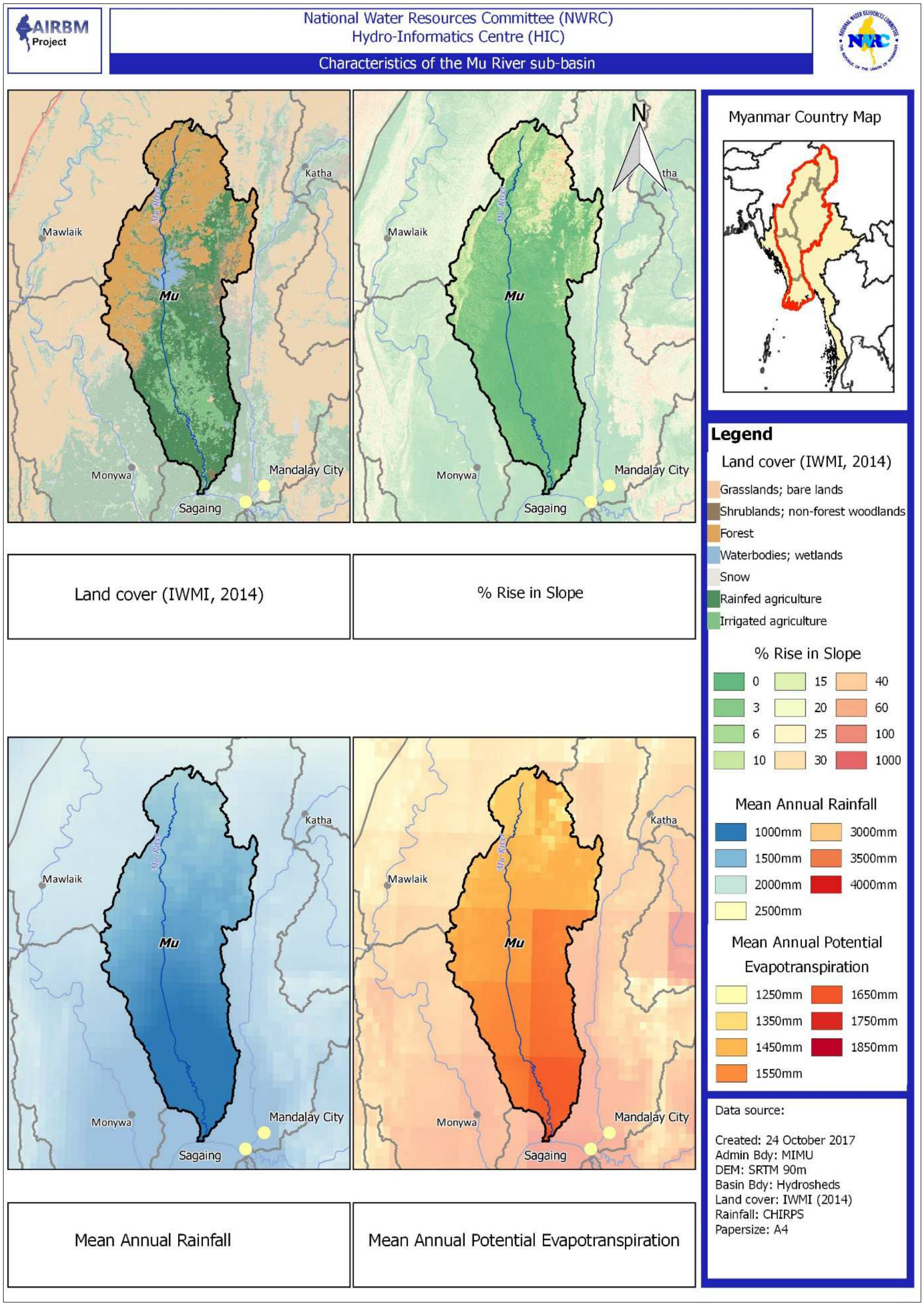


Figure 88 Characteristics of the Mu River sub-basin

3.7.2 Water Availability

FLOWS

The Mu sub-basin contributes 1 % of the total flows in the Ayeyarwady River Basin. Flows are highly seasonal, with 70% of annual flows occurring during the wet season May to October. Figure 89 shows monthly rainfall and local sub-basin flows from the Mu River sub-basin. The flows in particular illustrate the bi-modal monsoon which is typical of the central parts of the Ayeyarwady River Basin.

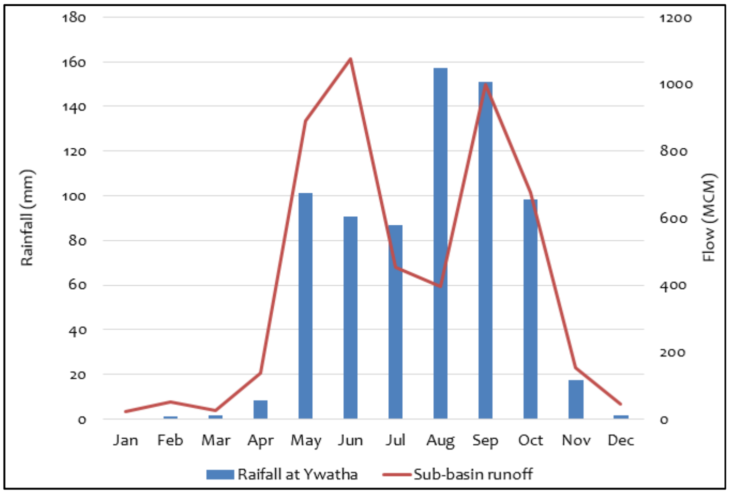


Figure 89 Monthly rainfall and flows in the Mu River sub-basin

STORAGES

Total available storage in the sub-basin is 3,800 MCM. The largest reservoir in the Mu River sub-basin is Thapanseik 2 reservoir which has a full supply capacity of 3,552 MCM (about 50 % of Mean Annual Runoff) and came into operation in 2002. It accounts for 92% of total available storage in the basin, and can store twice the mean annual inflow into the storage. The Thapanseik 2 reservoir provides for both irrigation and hydropower water use (Table 26). The dam also has a small hydropower station. The remaining storage capacity in the sub-basin is contained in ten smaller irrigation works. The salient features of the storages in the Mu River sub-basin are listed in Table 26. Total storage volume in the Mu River sub-basin is 232 % of average annual storage inflows – mostly because of the storage size of the Thapanseik 2 reservoir.

Table 25 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Thapanseik 2	MP	3,552	33	397.1	1,989.79	30	2002	233
Other (10)	IW	209 ****	12.9***	-	5,683	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume*

WATER USE

Irrigation is the dominant use of water in the Mu River sub-basin, with irrigated agriculture mostly located downstream of the Thapanseik 2 reservoir. According toTable 27, 55 % of the average annual runoff available upstream of all extraction points is extracted. Considering only the dry season, when extractions will be highest, 480 % of average dry season runoff upstream of all extraction points is extracted. During the dry season months of January to April, extra water from Thapanseik Reservoir makes it possible to support the extent of crops under irrigation. This is illustrated in Figure 90. During the wet season months, the storage volume increases, filled by inflows from upstream. However, inflows are low during the dry season months, and the ratio between water required for extraction and available upstream inflow will increase. These extraction requirements are then supplemented by releases from Thapanseik 2 reservoir, causing storage levels to drop, and resulting in flows downstream of the storage being higher than those upstream.

Table 26 Extraction/inflow ratio*

Annual (%)	Dry season (%)
55	480

**the ratio of total extractions and runoff upstream of all extraction points*

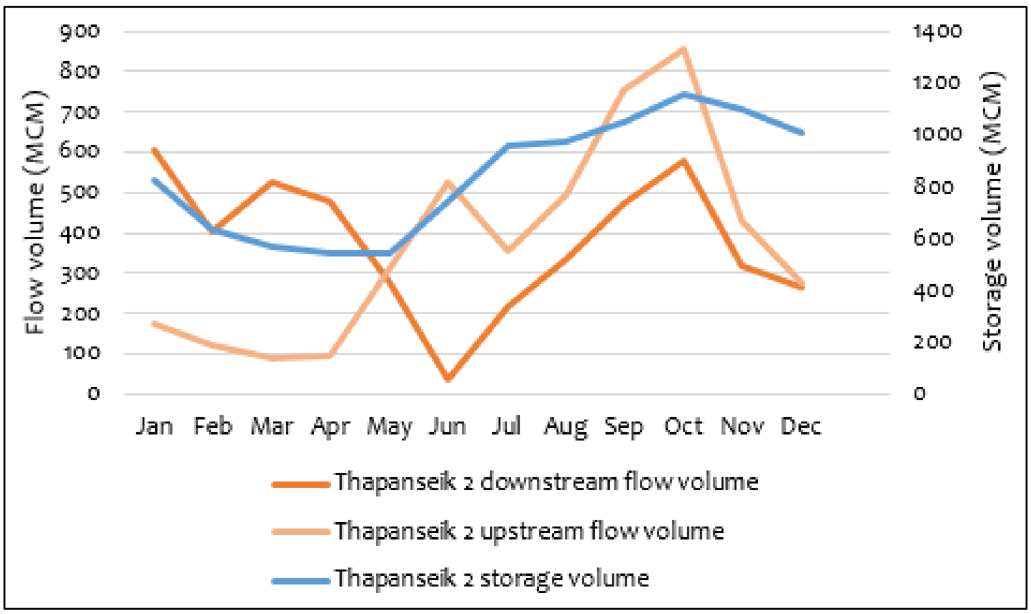


Figure 90 Relationship between seasonal inflows and average monthly storage volume at Thapanseik 2

3.7.3 Water balance summary

According to Figure 91 only 80 % of the mean annual flow generated in this sub-basin leaves at the outlet. Most of the remaining 20% is extracted. Dry season outflows are approximately 22 % of wet season outflows, but 60 % of these outflows can be accounted for by releases from Thapanseik 2 reservoir. There is also a noticeable loss to evaporation during the dry season – most likely from the surface area of Thapanseik 2 reservoir.

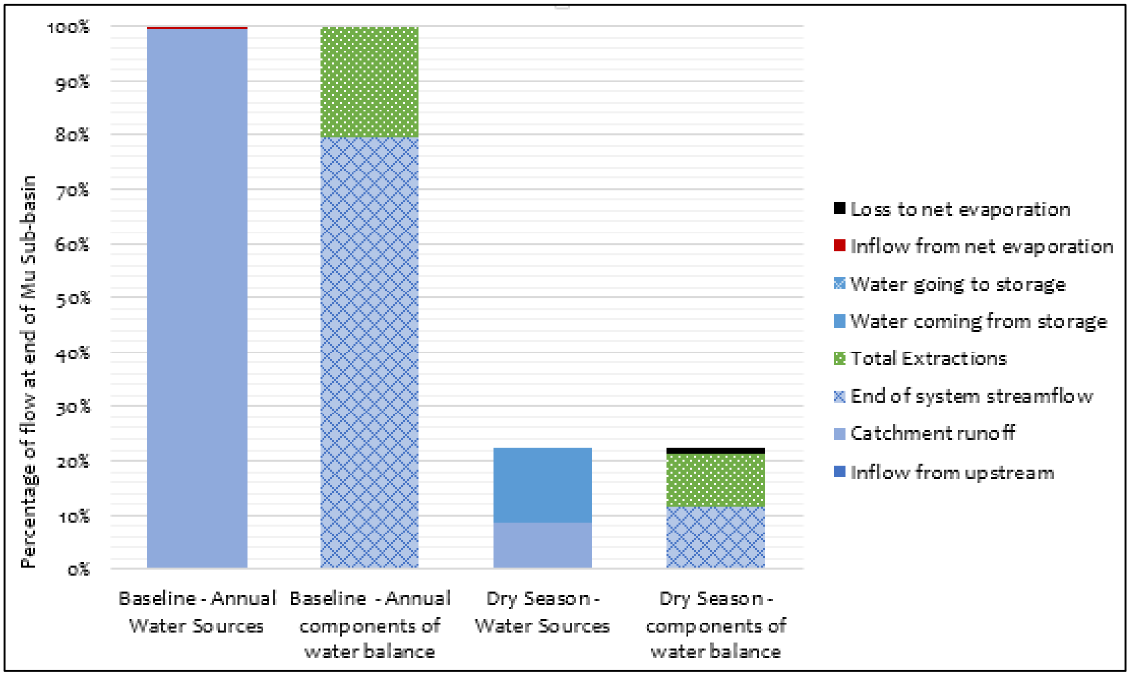
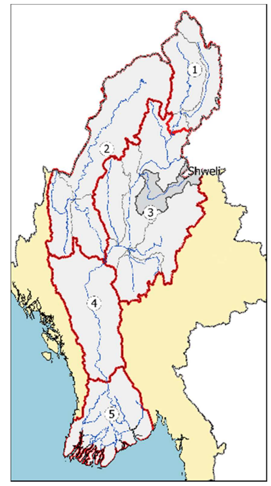


Figure 91 Water balance in the Mu River sub-basin

3.8 Shweli River sub-basin

3.8.1 Physical and climate description



Physical and climate characteristics of the Shweli River sub-basin are represented in Figure 93. Table 28 lists the physical characteristics of this sub-basin. The Shweli River sub-basin is located in the eastern Ayeyarwady River Basin. It has a catchment area of approximately 23,000 km² and is in HEZ 3 (Middle Basin). The Shweli River joins the Ayeyarwady River downstream of Katha. Much of the sub-basin is steep and high, with a median elevation of 1,045m above mean sea level. The Shweli River has its source in China, and forty-two percent of the Shweli River sub-basin is located within China (excluded in Figure 93).

The land cover classes of the Shweli River sub-basin and their percentages are shown in Figure 92. The land cover of the Shweli River sub-basin is dominated by forest (82%). Agriculture is the second largest land use, at only 14 %, mostly in the floodplain area of the Ayeyarwady/Shweli River confluence.

Although generally drier than its northern neighbours, total monthly rainfall in the Shweli River sub-basin ranges from 7 mm in January to 400 mm in July, as measured at Bhamo in the western part of the sub-basin (Figure 94).

Table 27 Physical characteristics of the Shweli River sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km²	name	km	min	max	mean	med	min	max	med
Shweli	3	22,924	Shweli River	567	67	3,754	1,047	1,045	0	154	18

** River length based on Hydrosheds DEM stream basin threshold of 1350 km²*
*** Zone elevation and slope based on Hydrosheds DEM*

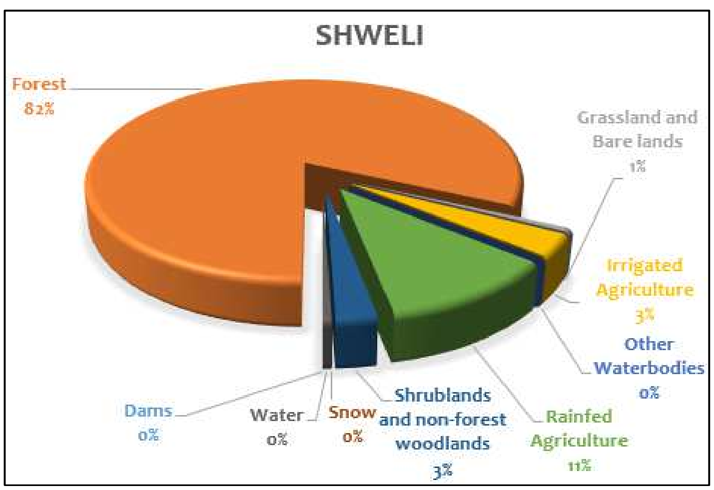


Figure 92 Land cover classes in the Shweli River sub-basin (IWMI, 2014)

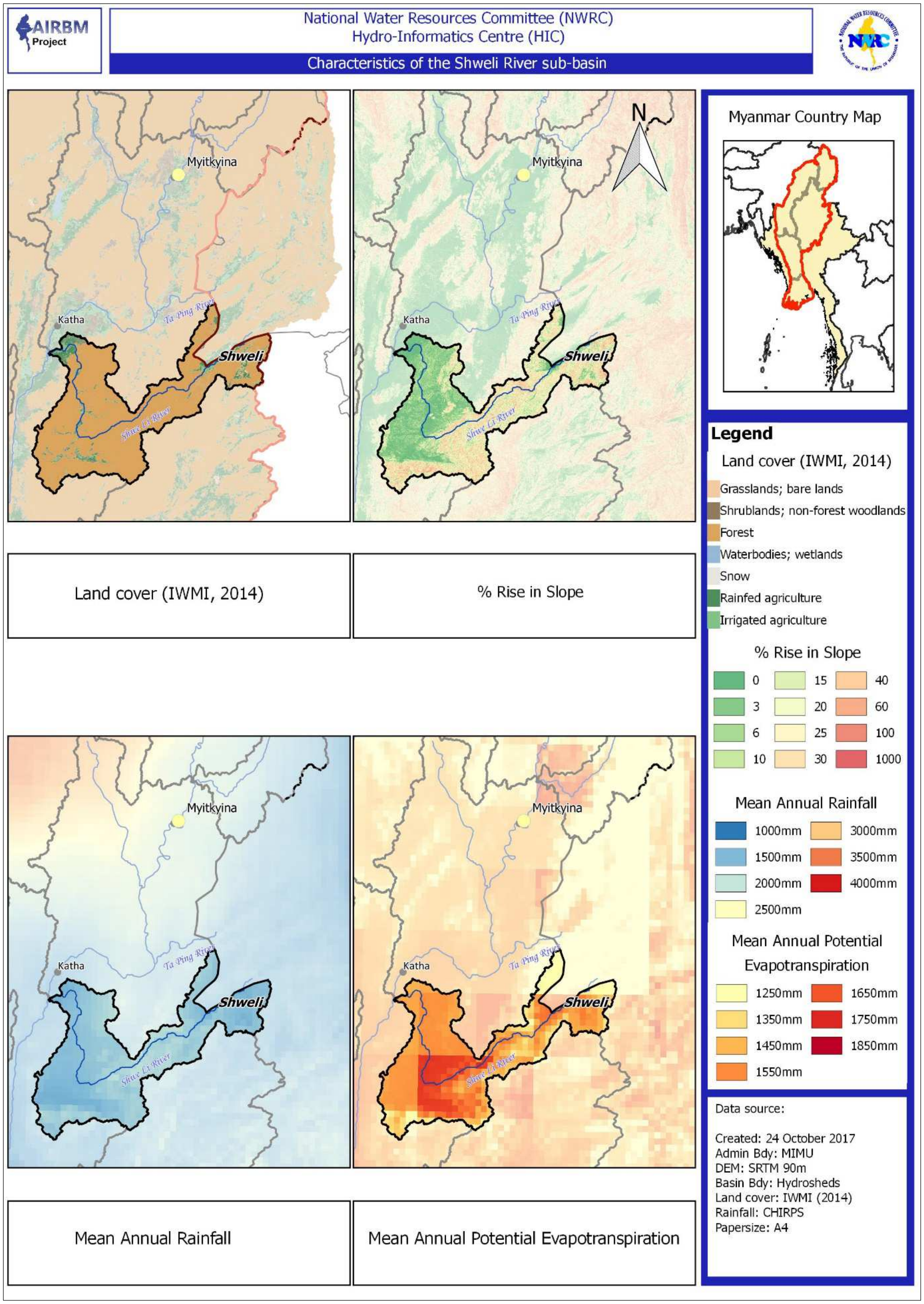


Figure 93 Characteristics of the Shweli River sub-basin

3.8.2 *Water availability*

FLOWS

The Shweli River sub-basin contributes 4% of the total flows in the Ayeyarwady River Basin. Flows are highly seasonal, with 94% of annual flows occurring during the wet season May to October. Figure 94 shows monthly rainfall and local sub-basin flows from the Shweli River sub-basin.

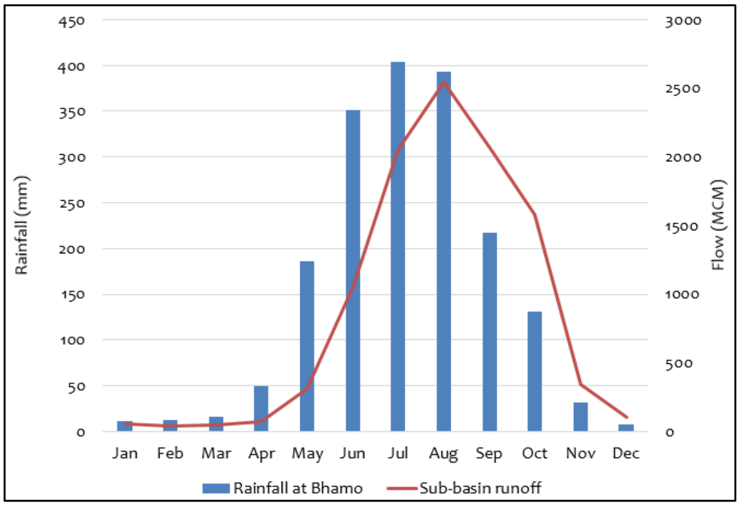


Figure 94 Monthly rainfall and flows in the Shweli River sub-basin

STORAGES

Total available storage in the sub-basin is 2,240 MCM.
Nine hydropower dams have been built in the upstream sections of the Shweli River in China. The total storage capacity and operations of these is unknown. Shweli I (Table 29) is the only storage in the Shweli River sub-basin within Myanmar borders. It was built in 2009 to provide hydropower, with an installed capacity of 600 MW. There are no storages in the sub-basin built to provide for irrigation requirements. Total storage volume in the Shweli sub-basin is 17% of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 28 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km²)	Beneficial Area (km²)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Shweli I	HP	11.4	47	1.2	-	600	2009	17
Other (0)	-	- ****	-***	-	-	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume*

WATER USE

Hydropower generation is the dominant use of water in this sub-basin. Irrigated agriculture accounts for 3 % of the area of Shweli River sub-basin, and is most likely provided from groundwater and pumped irrigation from rivers. Water use for irrigation is negligible.

3.8.3 Water Balance summary

According to Figure 95 most of the mean annual flow generated in this sub-basin leaves at the outlet. Very little is extracted. Thirty percent of the Shweli River mean annual outflows are upstream inflows from the sections in China. Dry season outflows are approximately 6 % of wet season outflows.

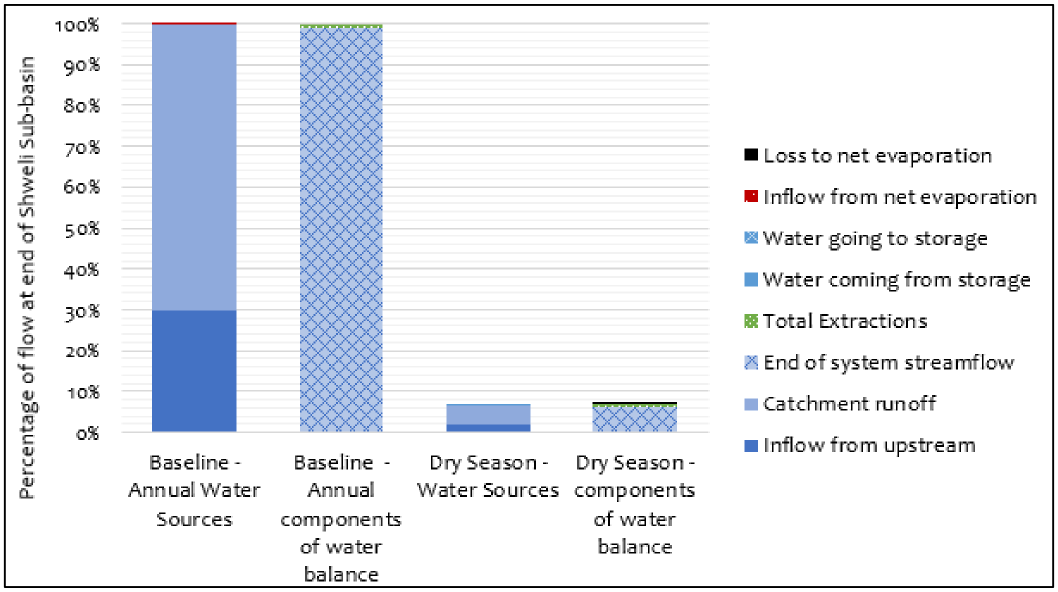
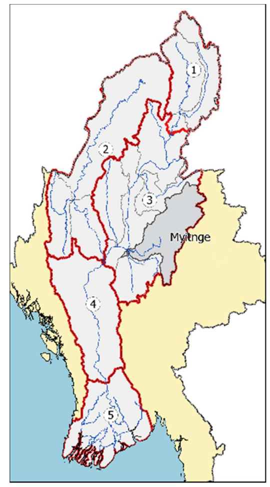


Figure 95 Water balance in the Shweli River sub-basin

3.9 Myitnge River sub-basin



3.9.1 Physical and climate description

Physical and climate characteristics of the Myitnge River sub-basin are represented in Figure 97. Table 30 lists the physical characteristics of this sub-basin. The Myitnge River sub-basin is located in the eastern Ayeyarwady River basin. It has a catchment area of 30,682 km² and is located in HEZ 3 (Middle Basin). The Myitnge River flows westwards through the Shan Plateau and joins the Ayeyarwady River at Sagaing. Elevations of the Myitnge River sub-basin range from 2,625m above mean sea level to as low as 53m above the mean sea level. A generally high sub-basin, it has a median elevation of 850 m above mean sea level. Median slope is 13%.

The largest tributary of the Myitnge River is the Panlaung River. For this assessment, the Panlaung River considered separately and is not included in the identification of the Myitnge River sub-basin.

The land cover of the Myitnge River sub-basin is dominated by forest (69%). Agriculture makes up 25 % of land use in the sub-basin. Land cover classes and their percentages in this sub basin are shown in Figure 96.

Although generally dry, total monthly rainfall in the Myitnge River sub-basin is highly seasonal, ranging from 1 mm in January to 170 mm in September (Figure 98). This rainfall is measured at Mandalay in the most south-western part of the Myitnge River sub-basin and is not necessarily representative of the whole basin. Satellite-derived rainfall makes it possible to examine rainfall in the upper reaches of this sub-basin, where observed data is not available. There is an indication that maximum monthly rainfall in the eastern Myitnge River sub-basin, could exceed 350 mm in July.

Table 29 Physical characteristics of the Myitnge River sub-basin

Sub-basin	HEZ	Area *	Main river		Elevation (m amsl) **				Slope (% rise)**		
		km²	name	km	min	max	mean	med	min	max	med
Myitnge	3	30,682	Myitnge River	477	53	2625	878	850	0	202	13

** River length based on Hydrosheds DEM stream basin threshold of 1350 km²*
*** Zone elevation and slope based on Hydrosheds DEM*

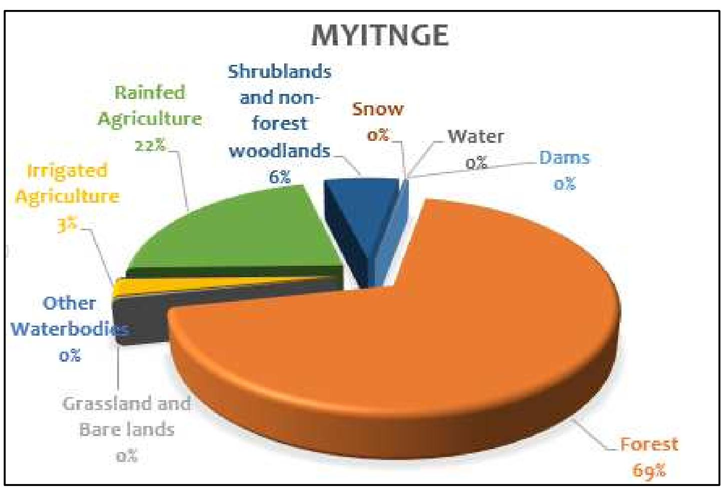


Figure 96 Land cover classes of the Myitnge River sub-basin (IWMI, 2014)

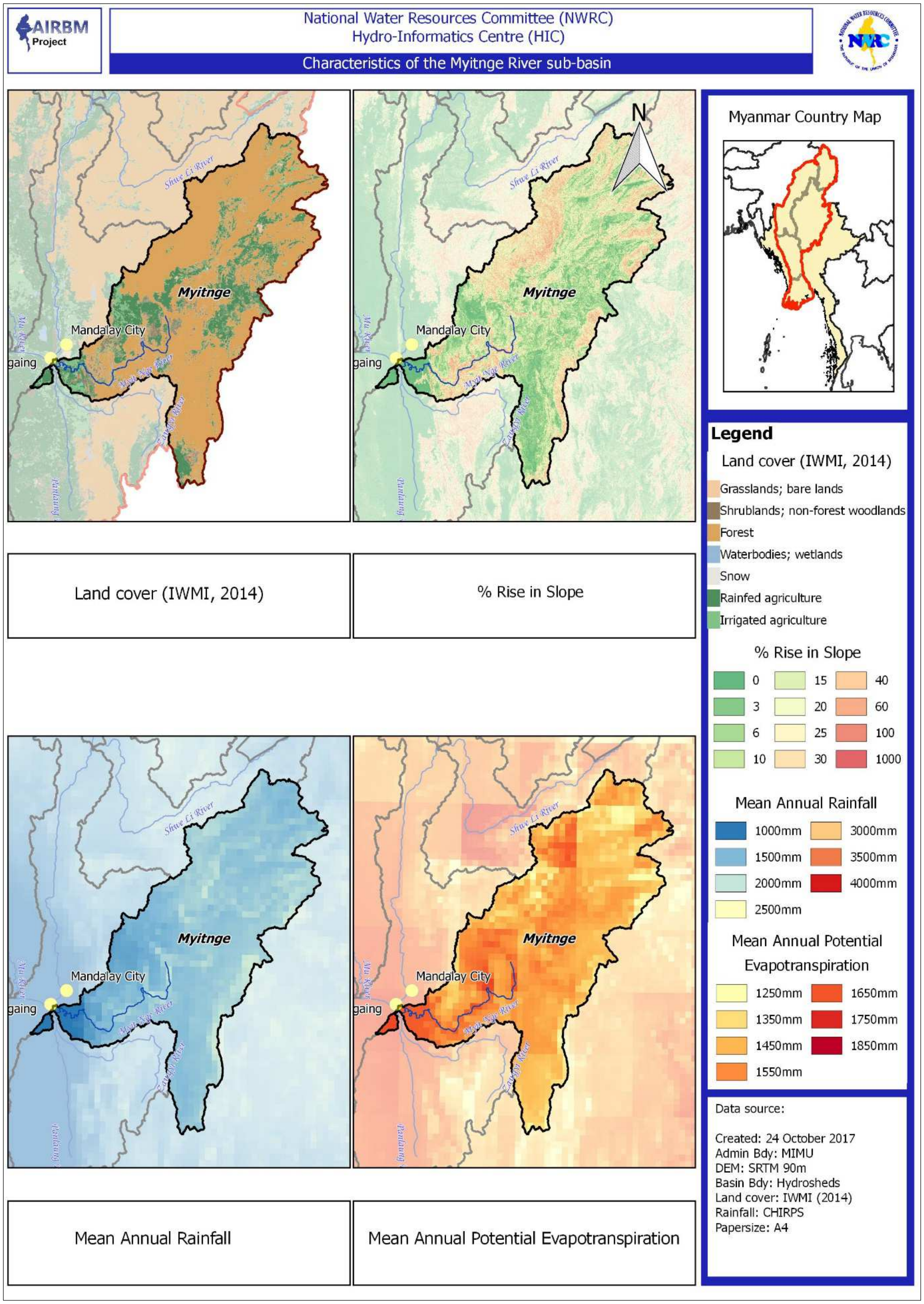


Figure 97 Characteristics of the Myitnge River sub-basin

3.9.2 Water availability

FLOWS

The Myitnge River sub-basin (excluding the Panlaung River) contributes 6% of the total flows in the Ayeyarwady River Basin. Eighty-nine percent of sub-basin mean annual flows occur during the wet season May to October. Figure 98 shows monthly rainfall and local sub-basin flows from the Myitnge River sub-basin.

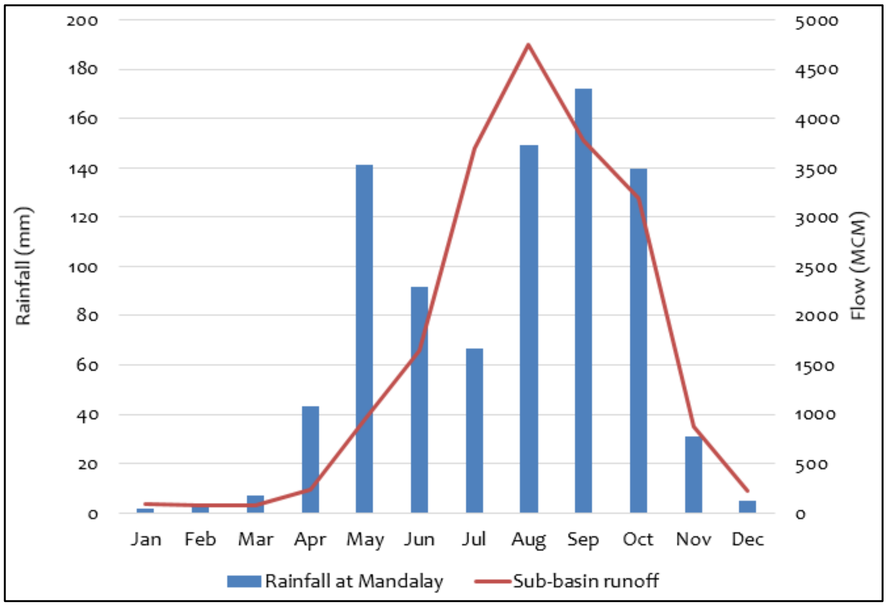


Figure 98 Monthly rainfall and flows in the Myitnge River sub-basin

STORAGES

Total storage in the Myitnge River sub-basin is 3,286.3 MCM. The largest reservoir in this sub-basin is the Yeywa Dam which was built in 2010 to provide hydropower (Table 31). The remaining storage capacity in the sub-basin is contained in eleven irrigation works, serving a beneficial area of 229 km². The salient features of the storages in the Myitnge River sub-basin are listed in Table 31. Total storage volume in the Myitnge River sub-basin is 17 % of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 30 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km²)	Beneficial Area (km²)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Yeywa	HP	2,607.83	132	59	-	790	2010	17
Other (11)	IW	678.5 ****	21***	-	229.2	-	-	

*Full Supply Capacity
** the ratio of total FSC and runoff upstream of all storages
***average height
****total volume

WATER USE

Irrigation and hydropower generation is the dominant use of water in the sub-basin. However, only 3% of the sub-basin area is under irrigated agriculture and the use of surface water for irrigation is negligible.

3.9.3 Water balance summary

According to Figure 99 most of the mean annual flow generated in the Myitnge sub-basin leaves at the outlet. Average annual extractions account for 2.2 % of sub-basin mean annual flows. Although the Panlaung River is considered separately in this assessment, inflows from the Panlaung River sub-basin account for 22.5 % of mean annual outflows from the Myitnge River sub-basin. Dry season outflows are approximately 11 % of wet season outflows. Approximately 9 % of dry season flows come from storage releases to support irrigated agriculture and hydropower.

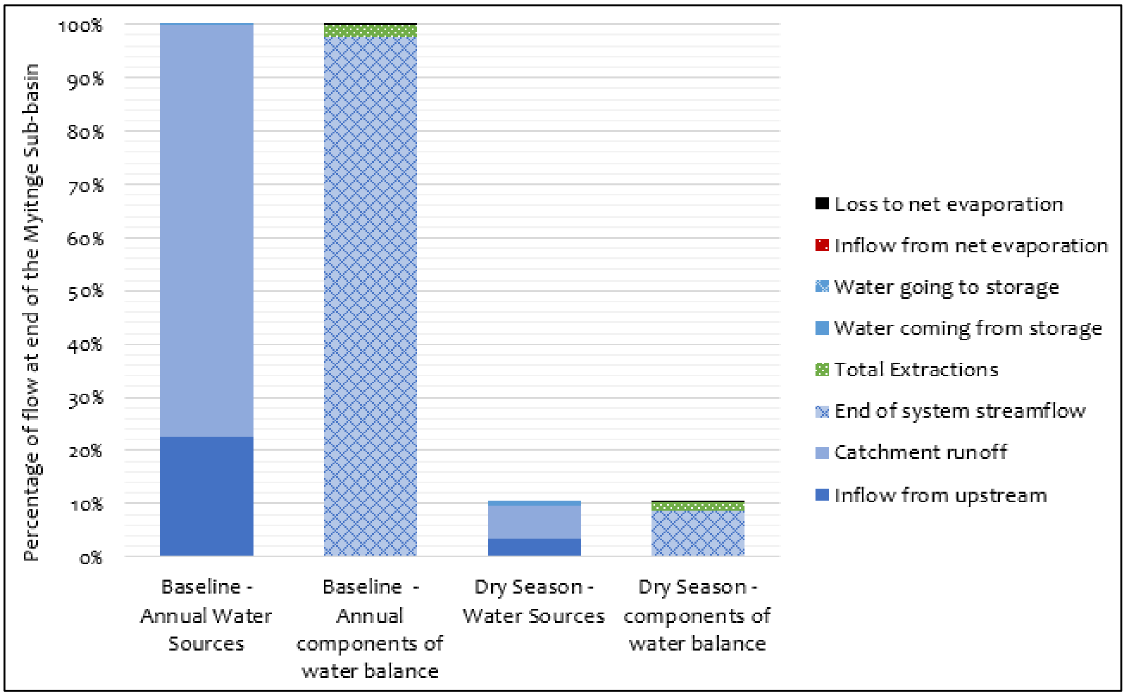
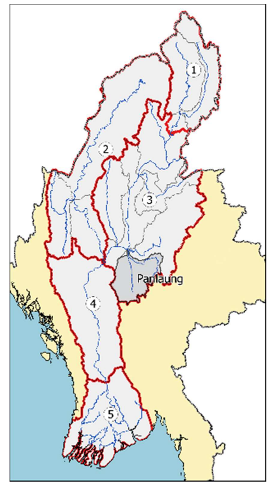


Figure 99 Water balance in the Myitnge River sub-basin

3.10 Panlaung River sub-basin



3.10.1 Physical and climate characteristics

Physical and climate characteristics of the Panlaung River sub-basin are represented in Figure 101. Table 32 lists the physical characteristics of this sub-basin. The Panlaung River is the largest tributary of the Myitnge River. It has a catchment area of 16,316 km^2 and is located in HEZ 3 (Middle Basin). The Myitnge/Panlaung confluence is situated just upstream of the Myitnge/Ayeyarwady River confluence at Sagaing. The Zawgyi River is the largest tributary of the Panlaung River, joining it just upstream of the Myitnge/Panlaung River confluence. Elevations of this sub-basin range from 2,357 m above mean sea level to as low as 67 m above mean sea level. The steeper, higher parts of the Panlaung River sub-basin are in the eastern parts of the sub-basin, which form the Zawgyi River catchment. Generally, it is a low and flat sub-basin, with a median elevation of 293 m above mean sea level and median slope of 3%.

The land cover of the Panlaung River sub-basin is dominated by agriculture (60%). Figure 100 displays the land cover classes and their percentages for the Panlaung River sub-basin.

This sub-basin falls within the Central Dry Zone, and rainfall is generally low. Monthly rainfall ranges from 1 mm in January to 170 mm in September, as measured at Mandalay at the northern corner of the sub-basin (Figure 102). Also evident is a bi-modal monsoon, with rainfall lower in July.

Table 31 Physical characteristics of the Panlaung River sub-basin

sub-basin	HEZ	Area	Main river *		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Panlaung	3	16,316	Panlaung River	139	67	2,357	501	293	0	191	3

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

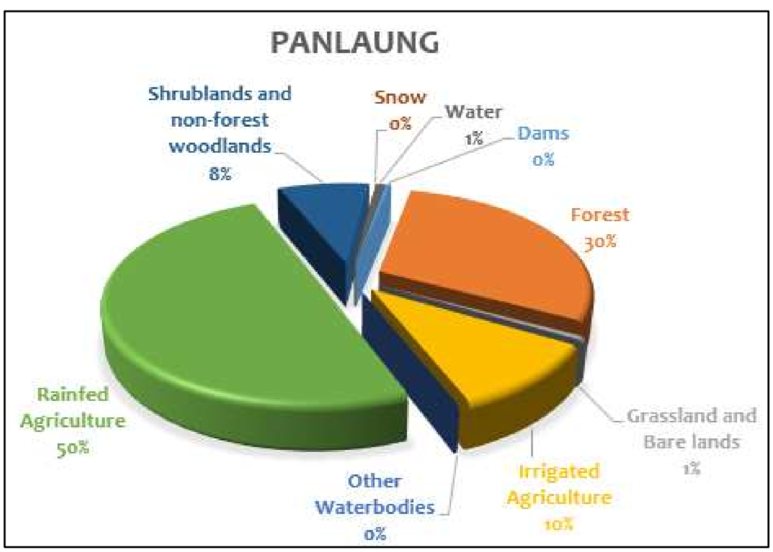


Figure 100 Land cover classes of the Panlaung sub-basin (IWMI, 2014)

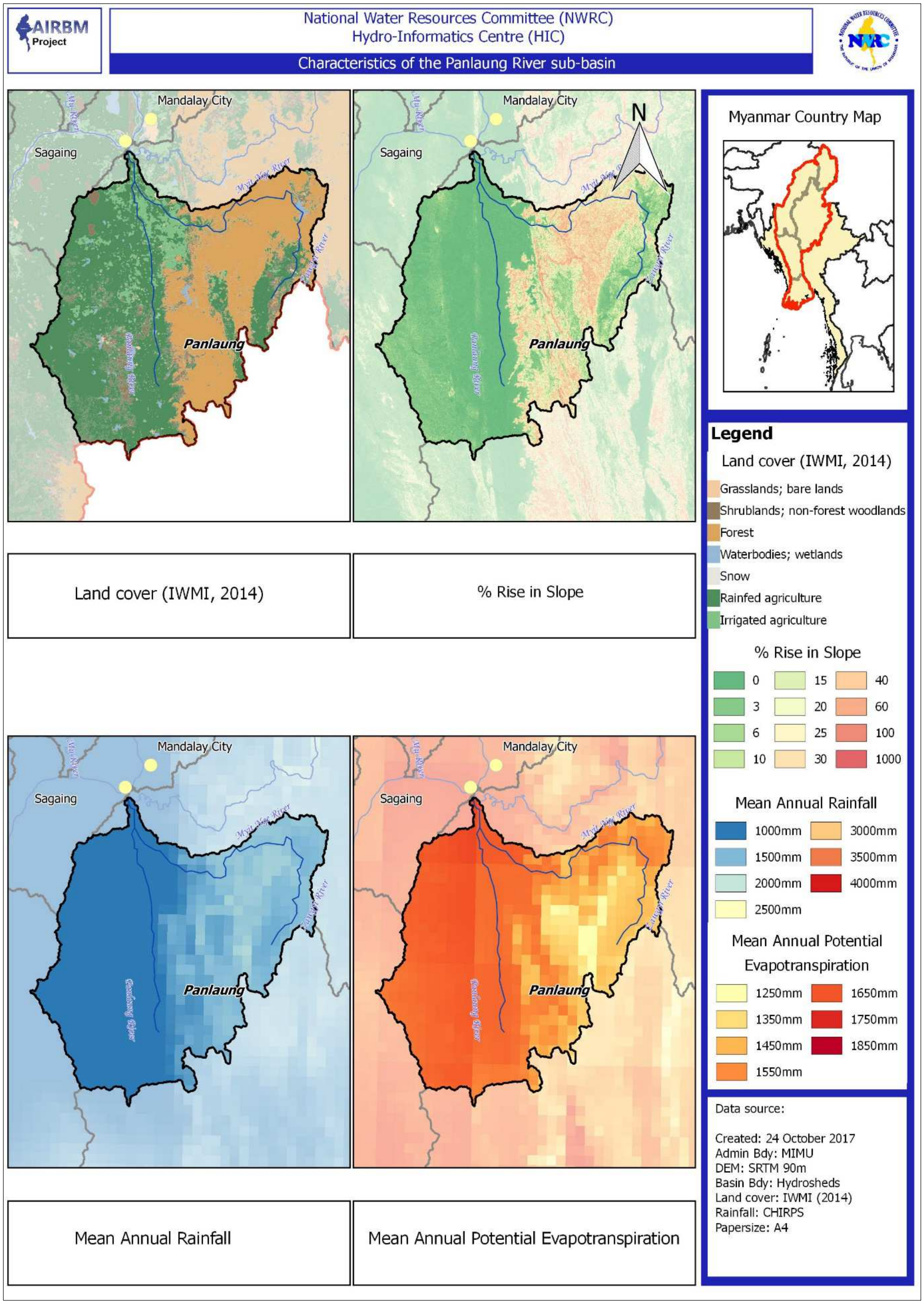


Figure 101 Characteristics of the Panlaung River sub-basin

3.10.2 Water availability

FLOWS

The Panlaung River sub-basin contributes 1% of the total flows in the Ayeyarwady River Basin. Twenty three percent of sub-basin mean annual flows occur during the wet season May to October. Figure 102 shows monthly rainfall and local sub-basin flows from the Panlaung River sub-basin. Flows from the Panlaung sub-basin echo the bi-modal monsoon distribution of rainfall.

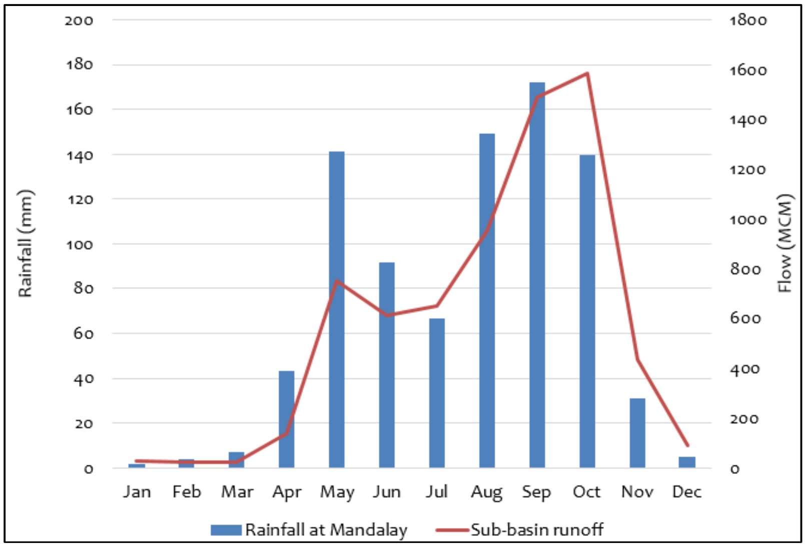


Figure 102 Monthly rainfall and flows in the Panlaung River sub-basin

STORAGES

The salient features of the storages in the Panlaung River sub-basin are listed in Table 33. Panlaung River sub-basin contains 2 storages built for hydropower, 38 storages built for irrigation exclusively, and also 2 multi-purpose storages (Table 33). The full supply capacity of 13 smaller irrigation works could not be established, but including known values, total available storage in the sub-basin is 2,719 MCM. The largest reservoir in this sub-basin is the multi-purpose Kinda reservoir which was built in 1985. It has a full supply capacity of 1,077 MCM and serves a beneficial irrigation area of 815 km^2. The capacity of the Kinda reservoir is 91% of mean annual inflows to the reservoir. The Myogyi multi-purpose reservoir was completed in 2016. It is located on the Zawgyi River, downstream of Zawgyi I and Zawgyi II hydropower reservoirs. The remaining storage capacity in the sub-basin is contained in 38 smaller irrigation works. Total storage volume in the Panlaung River sub-basin is 44% of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 32 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Kinda	MP	1077	72	28.6	815	56	1985	44
Myogyi	MP	593	86	9.7	121	24	2016	
Zawgyi I	HP	639	44	43.5	-	18	1995	
Zawgyi II	HP	619.5	40.5	38.5	-	12	2000	
Other (38)	IW	383.5 ****	12.7***	-	456	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*

****average height*
*****total volume – only includes FSC of 25 storages – FSC of 13 storages is unknown*

WATER USE

The dominant water uses in the Panlaung River sub-basin are hydropower and irrigation. Ten percent of the Panlaung River sub-basin is under irrigated agriculture. According toTable 27 Table 34, 15 % of the average annual runoff available upstream of all extraction points is extracted. Considering only the dry season, when extractions will be highest, 64 % of average dry season runoff upstream of all extraction points is extracted. Thirty-nine percent of sub-basin extractions are from the Kinda reservoir and 11 % from the Myogyi reservoir.

Table 33 Extraction/inflow ratio*

Annual (%)	Dry season (%)
15	64

**the ratio of total extractions and runoff upstream of all extraction points*

3.10.3 Water balance summary

According to Figure 103, 84 % of the mean annual flow generated in the Panlaung River sub-basin leaves at the outlet. The remaining 16% is extracted. Dry season outflows are approximately 22 % of wet season outflows, but 55 % of these outflows can be accounted for by storage releases to support irrigated agriculture and hydropower. There is also a noticeable loss to evaporation during the dry season – most likely from the surface area of the various storages.

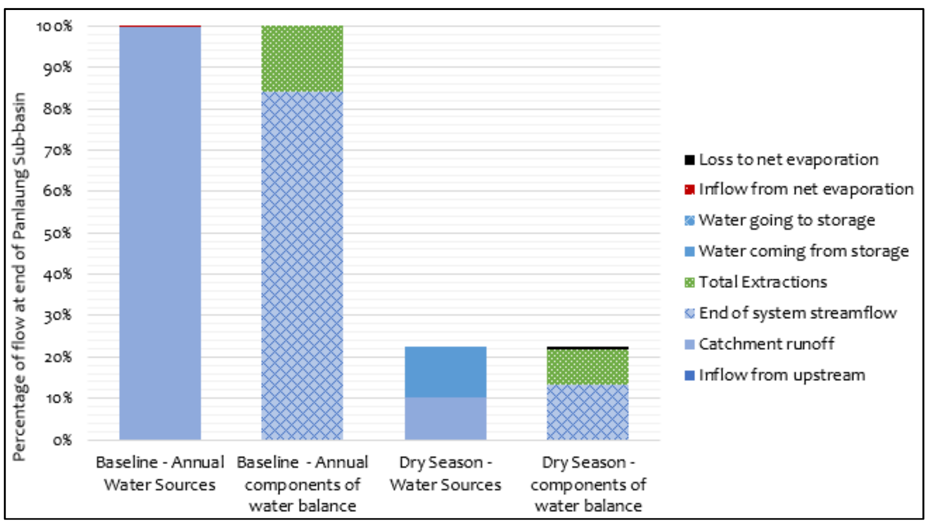
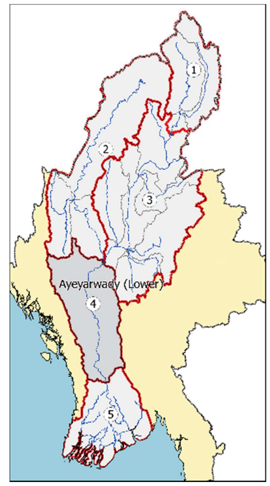


Figure 103 Water balance in the Panlaung River sub-basin

3.11 Ayeyarwady (Lower) sub-basin



3.11.1 *Physical and climate description*

Physical and climate characteristics of the Ayeyarwady (Lower) sub-basin are represented in Figure 105. Table 35 lists the physical characteristics of this sub-basin. The Ayeyarwady (Lower) sub-basin is the most downstream non-delta sub-basin of the Ayeyarwady River Basin. It has a catchment area of 59,238 km^2 and is located in HEZ 4 (Lower Basin). Although elevations range from more than 3,065 m above mean sea level to as low as 0 m above mean sea level (0 meter). Although the western reaches in the Arakan Mountains are steep and high, it is on average a relatively flat and low sub-basin, with a median elevation of 203 m above mean sea level and an average slope of 4%. Median slope for the Ayeyarwady Lower River sub-basin is above 4%.

Forty-two percent of the Ayeyarwady (Lower) sub-basin contains agriculture, with most of the rest of the sub-basin being a mix of forest and shrublands. Figure 104 displays the land cover classes and their percentages in the Ayeyarwady (Lower) sub-basin.

This sub-basin falls within the Central Dry Zone, and rainfall is generally low. Monthly rainfall ranges from 2 mm in January to nearly 170 mm in September, as measured at Magway in the centre of the sub-basin (Figure 106). Also evident is a bi-modal monsoon, with rainfall lower in July.

Table 34 Physical characteristics of the Ayeyarwady (Lower) sub-basin

Sub-basin	HEZ	Area *	Main river		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Ayeyarwady (Lower)	4	59,238	Ayeyarwady River	469	0	3,065	313	203	0	114	4

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

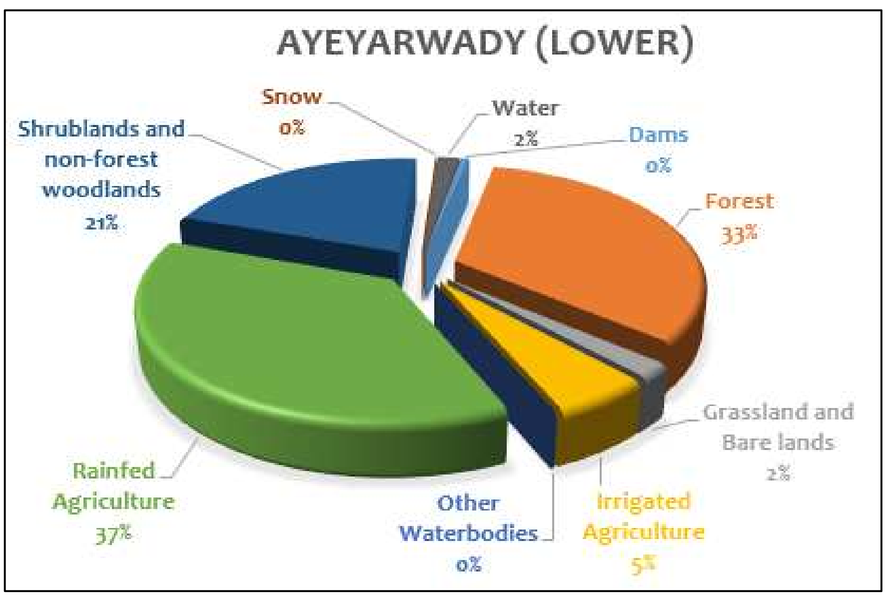


Figure 104 Land cover classes of the Ayeyarwady (Lower) sub-basin (IWMI, 2014)

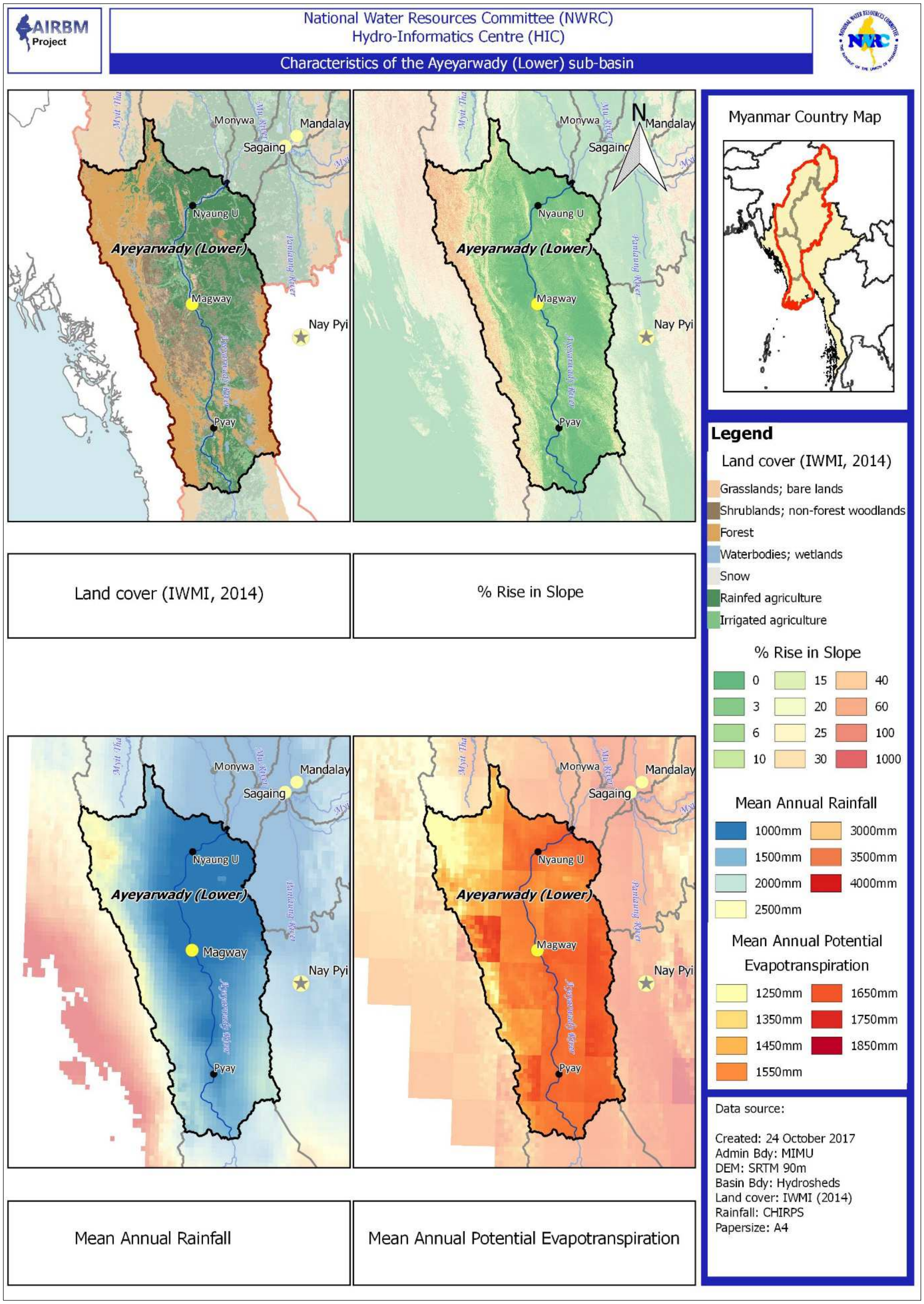


Figure 105 Characteristics of the Ayeyarwady (Lower) sub-basin

3.11.2 *Water Availability*

FLOWS

The Ayeyarwady (Lower) sub-basin contributes 4% of the total flows in the Ayeyarwady River Basin. Eighty-five percent of sub-basin mean annual flow occurs during the wet season May to October. Figure 106 shows monthly rainfall and local sub-basin flows from the Ayeyarwady (Lower) sub-basin. Flows from the sub-basin echo the bi-modal monsoon distribution of rainfall.

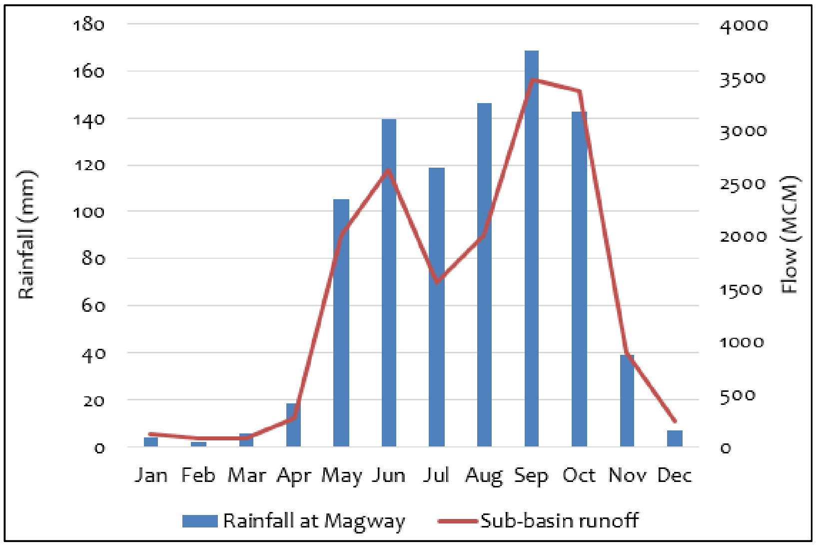


Figure 106 Monthly rainfall and flows in the Ayeyarwady (Lower) sub-basin

STORAGES

With a total of 76, this sub–basin has the largest number of built storages in the Ayeyarwady River Basin. Total available storage in the sub-basin is 4,254.7 MCM. The largest storage in the sub-basin is the Mone multi-purpose reservoir on the Mone Chaung, commissioned in 2004 and with a full supply capacity of 832 MCM. The second largest storage is the Kyeeon Kyeewa hydropower dam, commissioned in 2012. Together, these two storages make up about one third of the total storage capacity in the Ayeyarwady (Lower) sub-basin. The remaining storage capacity in the sub-basin is contained in 73 irrigation works built to support agriculture in this generally dry sub-basin. Table 36 lists the salient features of these storages. Total storage volume in the Ayeyarwady (Lower) sub-basin is 43% of average annual storage inflows, considering only flow available from the sub-catchments upstream of the storages.

Table 35 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Mone	MP	832	61	41.5	43,700	75	2004	43
Kyeeon Kyeewa	HP	571	50	32.8	-	74	20012	
Other (73)	IW	2,851.6 ****	20.1***	-	456	-	-	

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume*

WATER USE

Irrigation is the dominant use of water in the Ayeyarwady (Lower) sub-basin. With the main stem of the Ayeyarwady River passing through this sub-basin, it can appear that there is a large amount of water available to support irrigation. However, agricultural areas are not necessarily close to the main stem and access to this water is limited. Agricultural activity during the dry season is supported largely through releases from the various storages in the sub-basin. According to Table 37, 17 % of the average annual runoff available upstream of all extraction points is extracted. Considering only the dry season, when extractions will be highest, 98 % of average dry season runoff upstream of all extraction points is extracted.

Table 36 Extraction/inflow ratio*

Annual (%)	Dry season (%)
17	98

**the ratio of total extractions and runoff upstream of all extraction points*

3.11.3 Water Balance Summary

According to Figure 107, 96% of the average annual outflows from this sub-basin are as a result of inflows from upstream – passing through the sub-basin in the main stem of the Ayeyarwady River. Only 4% of average annual flow is generated by local sub-catchment runoff from within the sub-basin. Similarly, during the dry season 90 % of outflows from the sub-basin are as a result of inflows from upstream. Three percent of dry season outflows are generated from within the Ayeyarwady (lower) sub-basin and dry season releases from the irrigation storages to support irrigation extractions make up about 7% of dry season outflows. Dry season outflows are approximately 15% of wet season outflows.

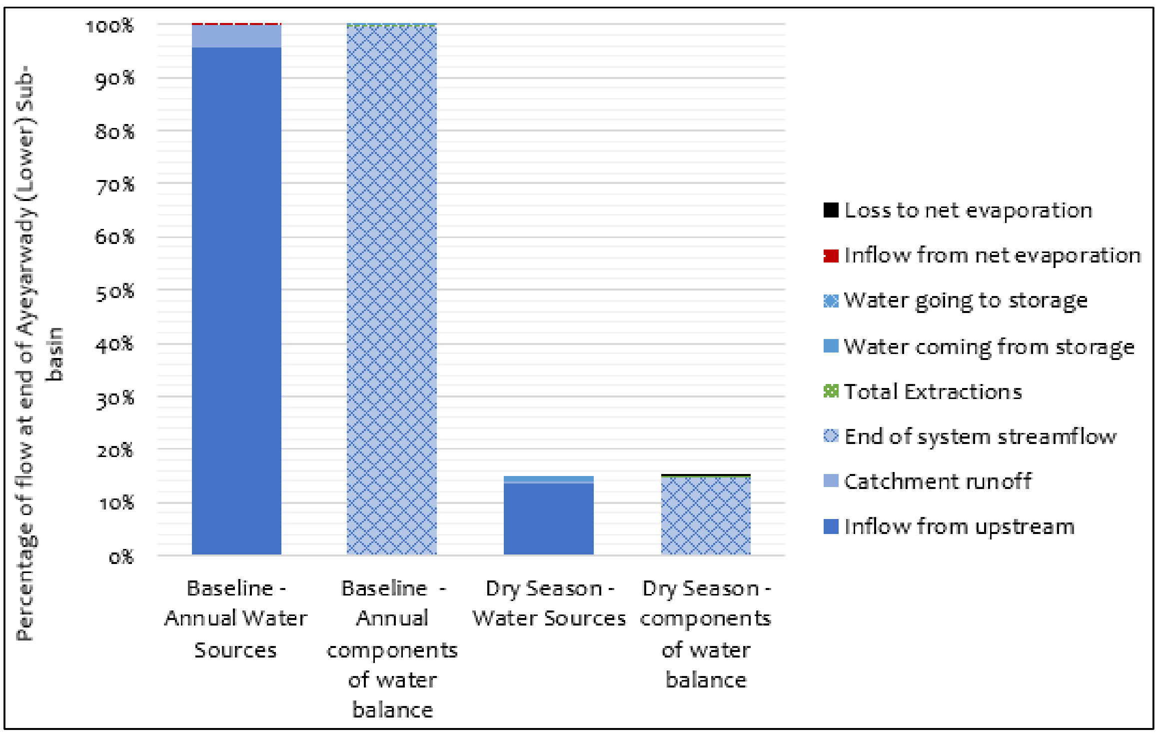
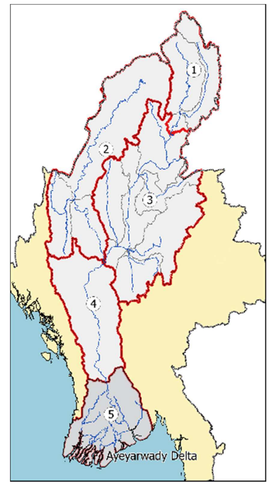


Figure 107 Water balance in the Ayeyarwady (Lower) sub-basin

3.12 Ayeyarwady Delta sub-basin



3.12.1 *Physical and climate description*

Physical and climate characteristics of the Ayeyarwady Delta sub-basin are represented in Figure 109. Table 38 lists the physical characteristics of this sub-basin. The Ayeyarwady Delta sub-basin is the most downstream sub-basin in Ayeyarwady River Basin and is located in HEZ 5 (Ayeyarwady Delta). This sub-basin has been defined to include the area of Yangon, and has a total area of 50 863 km^2.The sub-basin is largely flat and low, with a median elevation of 7 m above mean sea level and a median slope of 1%. Across this flat area the Ayeyarwady River main stem divides into nine distinct distributaries which end in the Andaman Sea. As the connecting 'front' between the rest of the Ayeyarwady River Basin and the sea, this sub-basin is experiences the influence of tides and also salt water intrusion.

Shown in Figure 108, the land cover of the Ayeyarwady Delta sub-basin is dominated by agriculture (63%).

Rainfall across the Ayeyarwady Delta sub-basin is higher than the northern Ayeyarwady (Lower) sub-basin. According to IADS (2017) mean annual rainfall increases from north to south across the sub-basin and can be as high 3,500 mm in the southwestern regions, with 90 % of rainfall occurring during the wet season.

Table 37 Physical characteristics of the Ayeyarwady Delta sub-basin

Sub-basin	HEZ	Area	Main river*		Elevation (m amsl) **				Slope (% rise)**		
		km^2	name	km	min	max	mean	med	min	max	med
Ayeyarwady Delta	5	50,863	various	-	0	1,237	34	7	0	92	1

** River length based on Hydrosheds DEM stream basin threshold of 1350 km^2*
*** Zone elevation and slope based on Hydrosheds DEM*

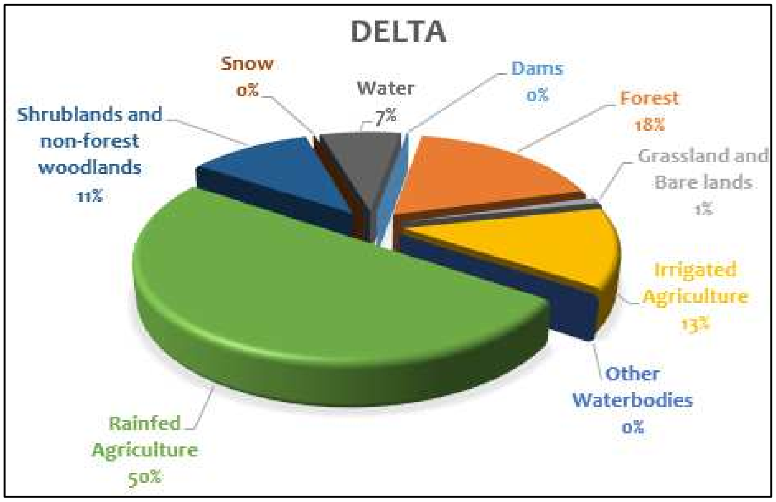


Figure 108 Land cover classes of the Ayeyarwady Delta sub-basin (IWMI, 2014)

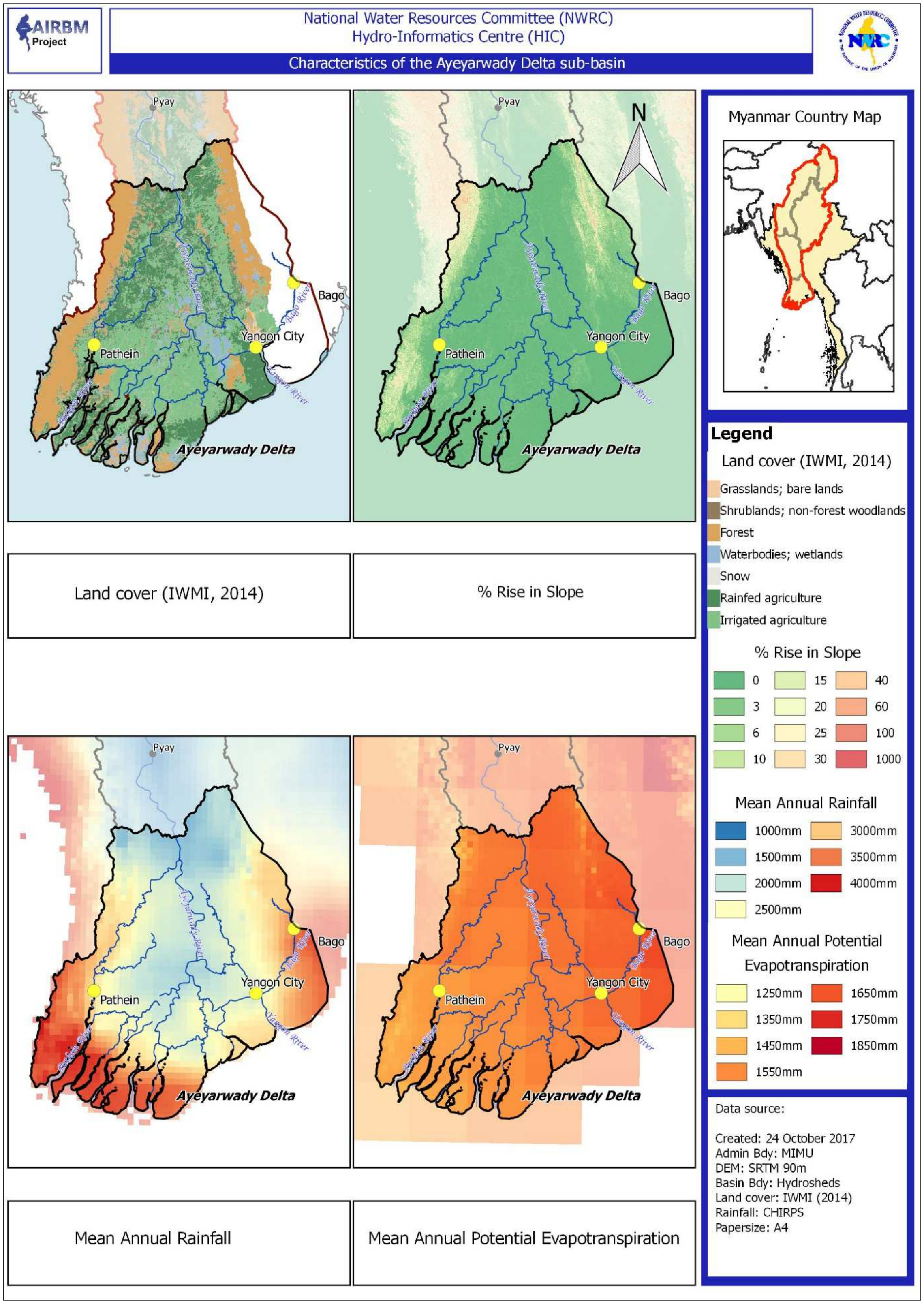


Figure 109 Characteristics of the Ayeyarwady Delta sub-basin

3.12.2 *Water availability*

FLOWS

Flow in the Ayeyarwady Delta sub-basin is divided into 9 distributaries downstream of Hinthada. Approximately 12 % of flow from the main stem Ayeyarwady flows eastwards down the Pathein River and approximately 24 % flows westwards down the Hlaing River. The remainder continues southwards down the Ayeyarwady River main stem, into various smaller streams further downstream.

STORAGES

Total available storage in the Ayeyarwady Delta sub-basin is 1618 MCM, contained in 25 storages built to support irrigated agriculture (Table 39). These storages serve an irrigated area of 785.84 km^2.

Table 38 Reservoir salient features

Name	Purpose	FSC* (MCM)	Height (m)	Surface Area (km^2)	Beneficial Area (km^2)	Installed Capacity (MW)	Year Built	Vol/inflow ratio (%) **
Other (25)	IW	1,618.5 ****	22.8***	-	785.84	-	-	-

**Full Supply Capacity*
*** the ratio of total FSC and runoff upstream of all storages*
****average height*
*****total volume*

WATER USE

Agriculture is the most prevalent land use in the Ayeyarwady Delta sub-basin. About 50 % of the sub-basin is supported by rain-fed agriculture during the wet season. At 13 % this is the sub-basin which has the highest proportion of irrigated agriculture, however the proportion of water which is extracted could not be ascertained.

Yangon is the largest urban area in the Ayeyarwady River Basin and located in the eastern part of the Ayeyarwady Delta sub-basin. Known water requirements for the city are about 250 MCM per year.

3.12.3 *Water balance summary*

The Ayeyarwady Delta sub-basin is not included in the Source modelling of the Ayeyarwady River Basin; therefore no data was collected to make it possible to calculate a water balance for this sub-basin.

4 STATUS AND TRENDS

4.1 Status

4.1.1 *Water availability*

As described in Figure 110 and Figure 111 most of the flow in the basin currently comes from the Upper Chindwin and the N'Mai Hka and Mali Hka river sub-basins of Hydro-Ecological Zones 1 and 2.

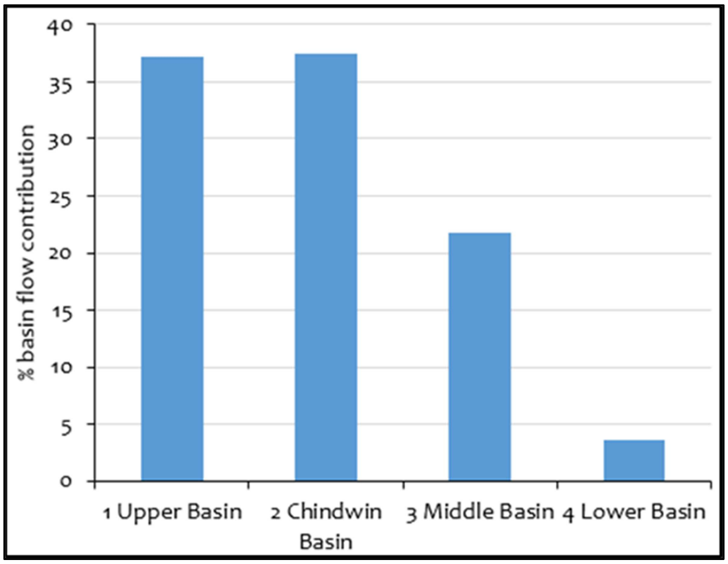


Figure 110 Percent flow contribution per HEZ

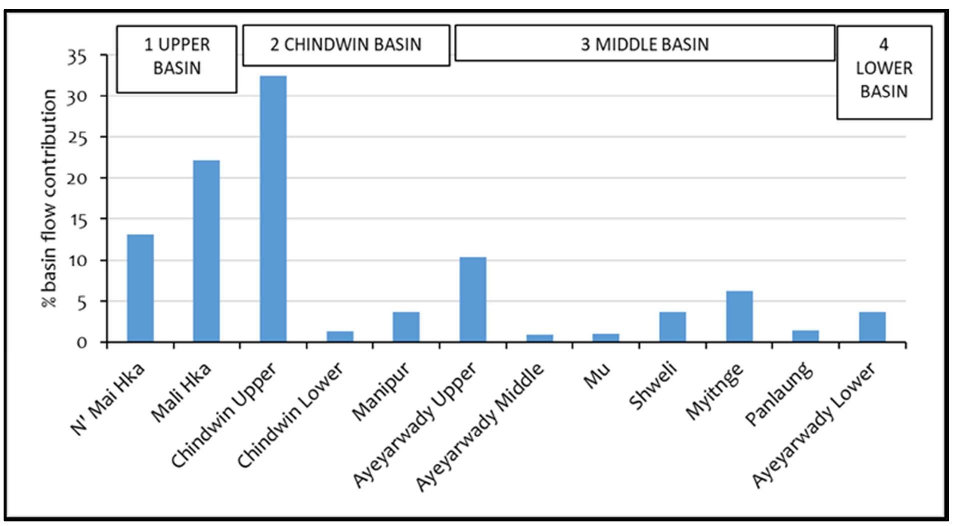


Figure 111 Percent flow volume contribution per sub-basin

The total water available in a sub-basin will be that which comes from sub-basin catchment runoff as a result of local rainfall plus that which enters the sub-basin from upstream. Figure 112 shows this relationship for each sub-basin. Central sub-basins such as the Lower Chindwin and Ayeyarwady Lower and Ayeyarwady Middle have low availability from the surrounding sub-basin but high upstream inflows.

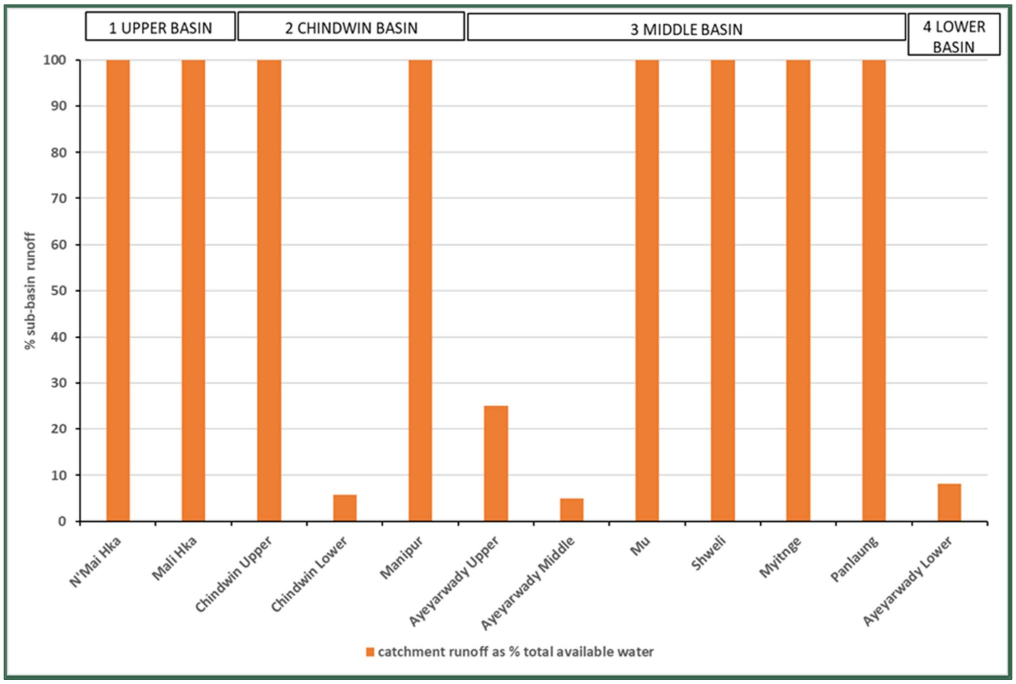


Figure 112 Local sub-catchment runoff as % of total sub-basin available water

4.1.2 Storages

Using available information on known storage volumes, the total storage capacity of major reservoirs in the Ayeyarwady River Basin has increased from approximately 1 000 MCM to approximately 12,000 MCM since 1980, with 27 major reservoirs being built (Figure 113). Including major and minor storages, there was a total in the order of 28,800 MCM of known storage volume in the Ayeyarwady River Basin by 2016.

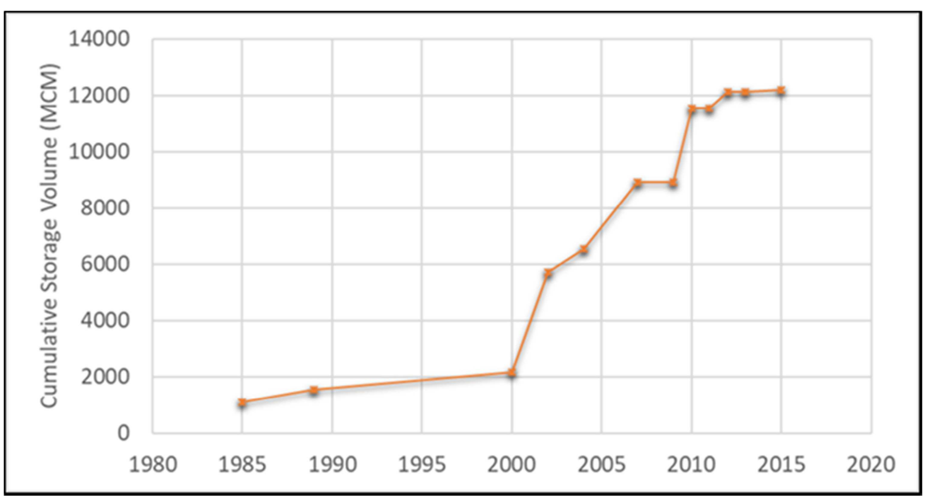


Figure 113 Change in total storage of major reservoirs

Total sub-basin full supply storage capacity as a percentage of mean annual sub-basin available runoff (before extractions and excluding any upstream inflows) is shown in Figure 114. The Mu and Panlaung River sub-basins in the Middle Basin HEZ have the highest ratio of storage capacity to sub-basin runoff.

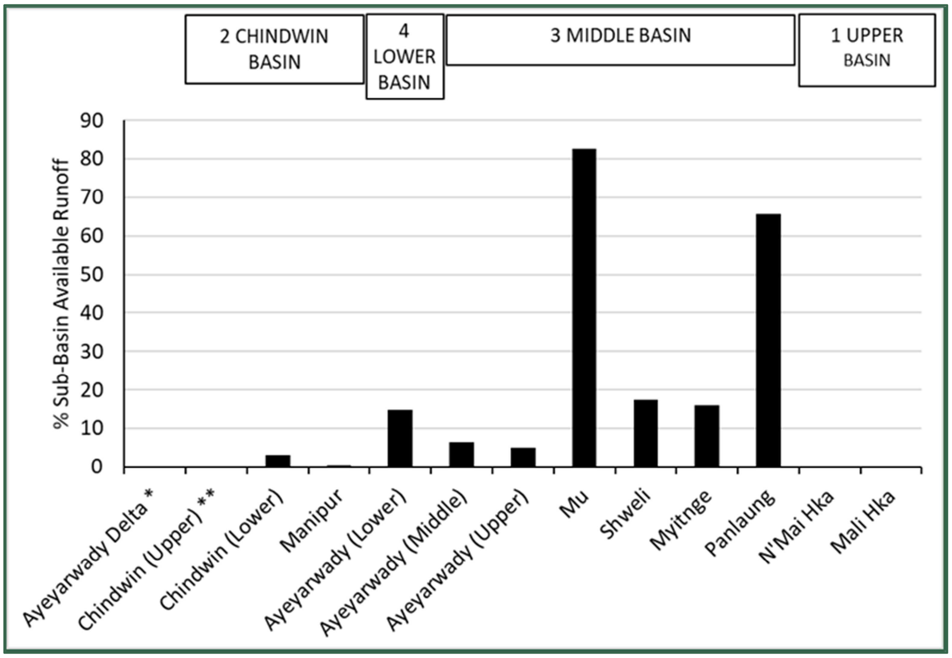


Figure 114 Sub-basin storage capacity as a % of mean annual sub-basin catchment runoff

* Sub-Basin runoff in the Ayeyarwady Delta could not be ascertained
**Actual full supply capacity of storages in the Chindwin Upper sub-basin could not be ascertained, but it is known to be small

4.1.3 Extractions

Since domestic extractions are a very small part of total extractions, they are considered here together with irrigation extractions. These total extractions are viewed in two ways (illustrated in Figure 115):

a) as a proportion of local sub-basin catchment runoff, which assumes the main stream river flowing through the sub-basin is not being used, and
b) as a proportion of the total water available, which assumes the main stream river is also being accessed.

This differentiation is not noticeable in sub-basins such as the Mu or Panlaung, where the main streams are wholly a part of the sub-basin and are already being accessed for water, with no upstream inflows. In these sub-basins the implications of accessing the total amount of water available is evident. However, in the central sub-basins such as the Lower Chindwin, the Ayeyarwady Middle and Ayeyarwady Lower sub-basins, through which the Chindwin and Ayeyarwady rivers flow, distance from the main stream becomes a limiting factor to access to water, since most of the water is in the main stream flowing through the sub-basin.

The upstream high rainfall sub-basins of the N'Mai Hka, Mali Hka and Upper Chindwin remain highly forested (likely due to their steep slopes and high elevations) and proportionally very little water is extracted for either domestic or irrigation usage. However, the sub-basins of the Central Dry Zone are more intensively cropped, requiring more support from irrigation, yet with less water available from their local sub-basins. In both the Mu and Panlaung sub-basins more than 20% of the available water is being extracted. Here large storages such as Thapanseik 2 and Kinda make it possible to support extensive irrigation during the dry season.

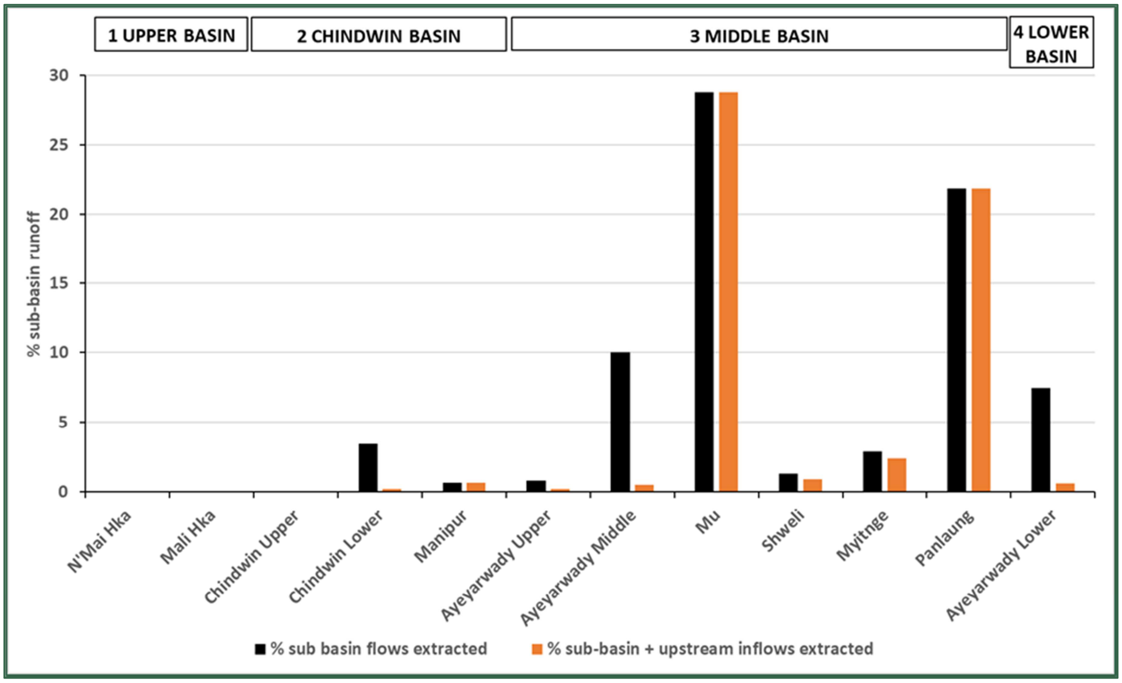


Figure 115 Sub-basin extractions as a proportion of sub-basin catchment runoff extracted and proportion of total sub-basin available water extracted

4.1.4 *Water balance summary*

Figure 116 shows the inflows and losses across the whole Ayeyarwady River Basin north of the Delta for baseline conditions, for the whole year and for the dry season only. Inflows from the sections of the Ayeyarwady River Basin in China are accounted as 'Inflow from upstream'. At a whole of basin scale most of the catchment runoff becomes end of system stream flow. During the dry season water released from storages also contributes to existing flows.

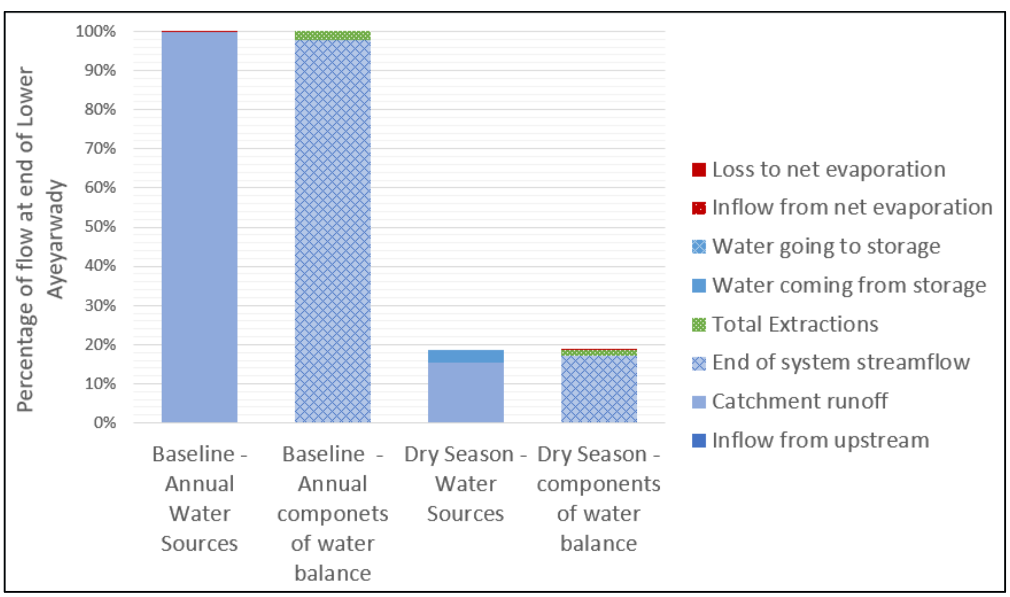


Figure 116 Total water balance of the Ayeyarwady River Basin north of the Delta

By comparison, Figure 117 shows the inflows and losses for the Mu River sub-basin at baseline conditions, for the whole year and for the dry season only. The volume of water released from storage is a significant source of dry season flow. Of the water available during the dry season (i.e. the sum of 'water from storage' and 'catchment runoff'), approximately 50 % goes to extractions and approximately 50 % becomes outflow at the end of the sub-basin. While still very small, the total net loss to evaporation is also still larger in the dry season than during the wet season.

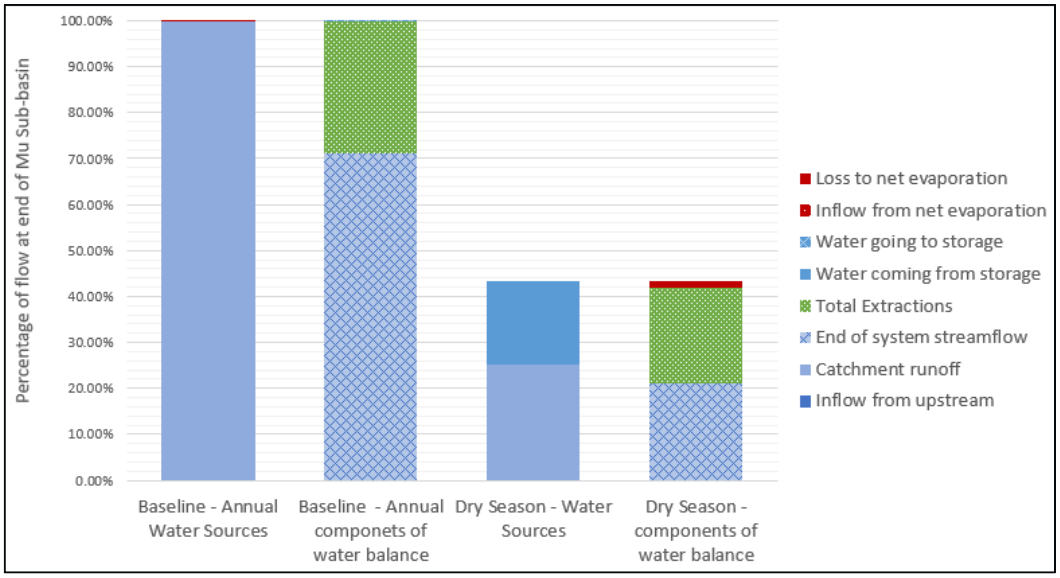


Figure 117 Total water balance of the Mu River sub-basin

4.2 Trends

4.2.1 Climate variability

Because the Ayeyarwady is in a monsoonal area there are annual dry periods. These regular and predictable dry seasons restrict the extent and duration of navigation on water ways. Delays in onset of the wet season have the potential to exacerbate navigation difficulties, especially on the tributaries.

The basin is also subject to inter-annual climatic variability. Water system modelling showed that some storages would have experienced some years of declining storage during the early 1980s, including failing to fill during the wet season. An examination of rainfall from the Source water system model (shown in Figure 118) indicated that parts, though not all, of the Basin experienced drier than average rainfall during this period.

In some sub-catchments (SC) this drier period can be explained by random variability in annual rainfall, e.g. the catchment upstream of Thapanseik 2 reservoir; while other sub-catchments with more extreme differences show statistically proven differences, , e.g. SC #20 which is downstream of Pyay.

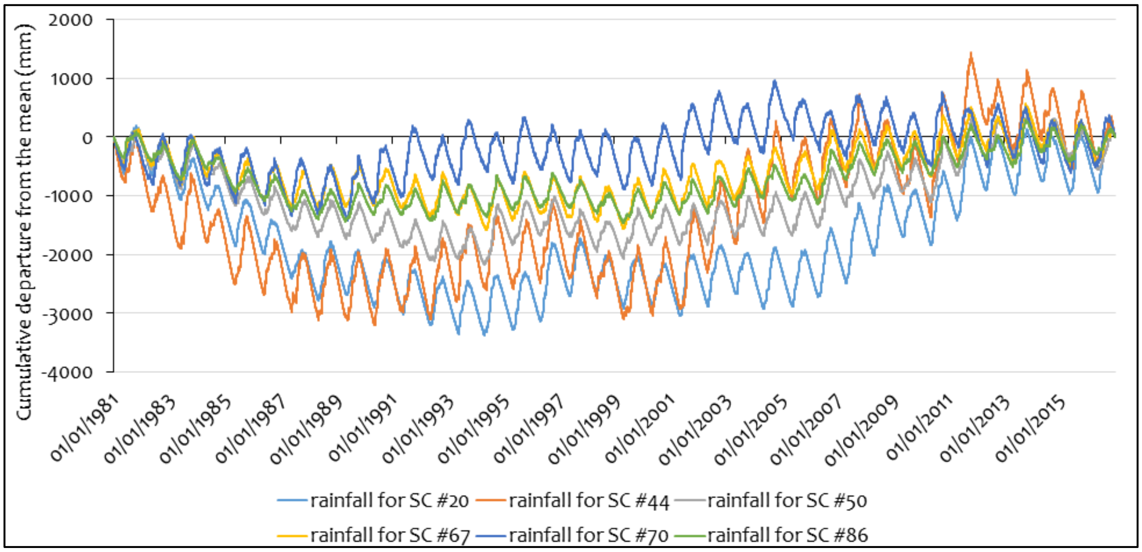


Figure 118 Long-term trends in rainfall at selected sub-catchments

The areas of the Mu River sub-basin above Thapanseik 2 multi-purpose storage had a period of below average rainfall years from 1981 to 1988, and again from 1992 to 1999. Depending on how efficiently the downstream irrigation area is supplied, such runs of dry years have the potential to impact on water supply security. Figure 119 illustrates the cumulative shortfall in rainfall in the basin above Thapanseik 2, and Figure 120 shows the corresponding reduction in runoff from the catchment.

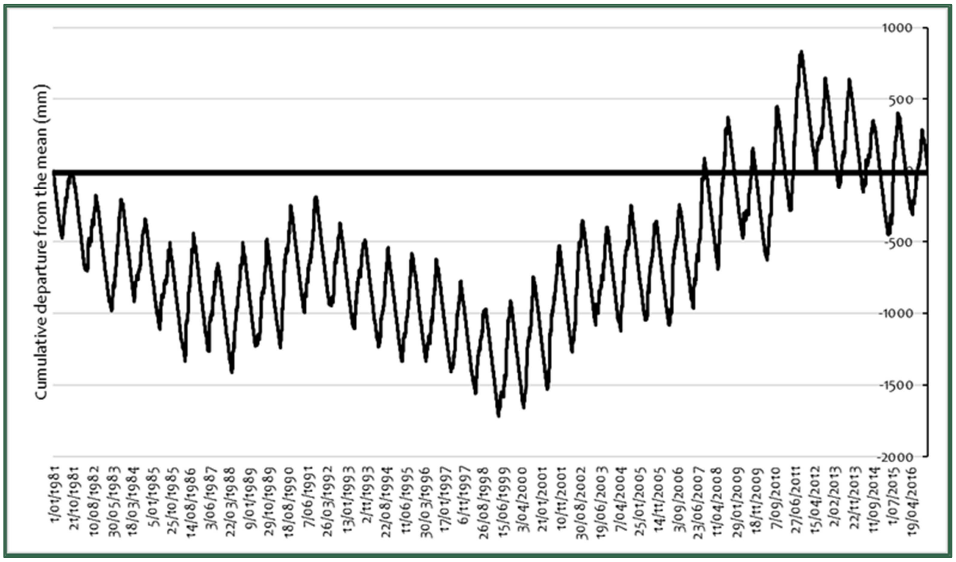


Figure 119 Deviation from the mean of cumulative rainfall upstream of Thapanseik 2

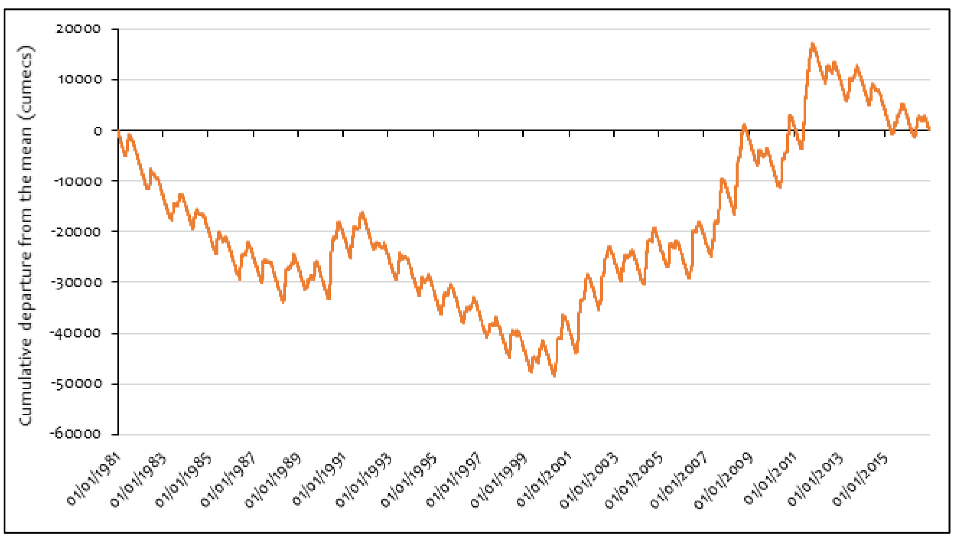


Figure 120 Deviation from the mean of cumulative runoff upstream of Thapanseik 2

4.2.2 Consistency of the monsoon

The start of the high flow period during the wet season is defined as when the flows at a site raise above the mean annual discharge and finishes when the flows fall below the mean annual discharge. Typically flows cross this threshold once at the commencement of the wet season and once at the end of the wet season. There is a range in the start and end dates of the wet season, and also the length of the wet season. Figure 121 illustrates these ranges at Pyay in the Lower Ayeyarwady Basin. Although visual inspection of this range suggests that start dates might be trending to be later in the year, statistical analysis could find no such trend[8].

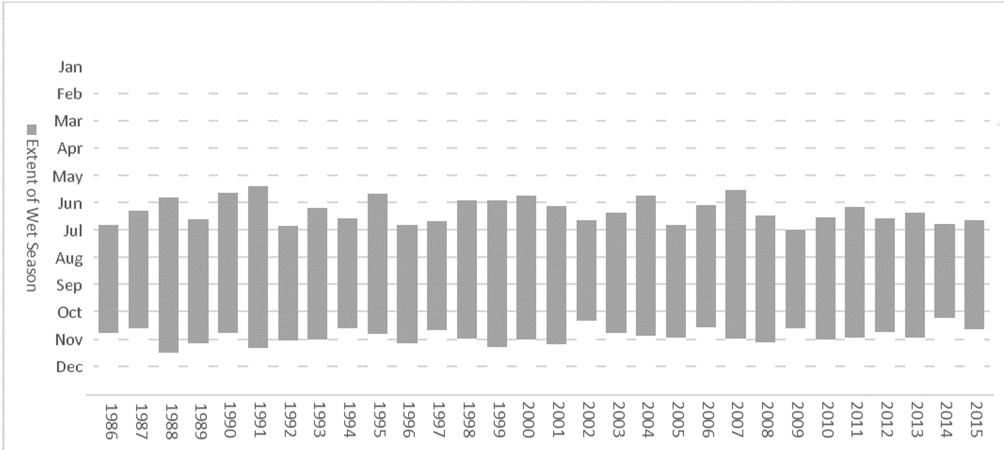


Figure 121 Extent of the wet season at Pyay

4.2.3 Impact of development

For comparative purposes to assess the impacts of development, a baseline model scenario and a 'without development' model scenario was established using the Source water system planning software. The baseline represents the level of development for 2014 - 2016, in particular in terms of storages, irrigation areas and population. The 'without development' model has all storages removed and all extractions turned off. Both models were run with historic climate data for 1981 – 2016. Comparisons were undertaken on 'without development' versus baseline results on an annual basis and for the dry season.

On a whole of basin analysis, considering mean annual volumes at the outlet of the Lower Basin, which includes all of the Ayeyarwady River Basin upstream of the Delta, there is seemingly very little difference between the 'without development' and baseline scenarios. Comparing annual values there is a 2 % increase in flows from the baseline to the 'without development' scenario. Comparing dry season values there is a 1 % increase in flows from the baseline to the 'without development' scenario. The dry season shows less impact because of water released from storages and return flows[9] from irrigation. Figure 122 considers these results more closely. The flow duration curve (A) indicates that the difference between the baseline and 'without development scenarios' is least noticeable in the high flows and most noticeable in the middle flows (start and end of the wet season) and the low flows (dry season). The hydrograph for 2015 in (B) illustrates why this would be the case. As the storages re-fill at the start of each wet season the baseline flows are lower than 'without development' flows. As the wet season recedes, water is released from the storages to support irrigation and irrigation return flows reach the river, causing dry season flows to be higher in the baseline scenario. This change in flow regime can particularly have an ecological impact, affecting wetland ecosystems and riverine habitats as channels change to adapt to the new flows.

[8] A two-tailed t-test of the significance of any trend in start dates indicated that any trend noticed is not significant at the 95 % level.
[9] When examining these comparisons, it is important to consider the impact of dry season return flows from irrigated areas in the baseline scenario. These return flows are dependent on assumptions concerning irrigation efficiencies. A 50 % irrigation efficiency is currently assumed, with all lost water returned to the system.

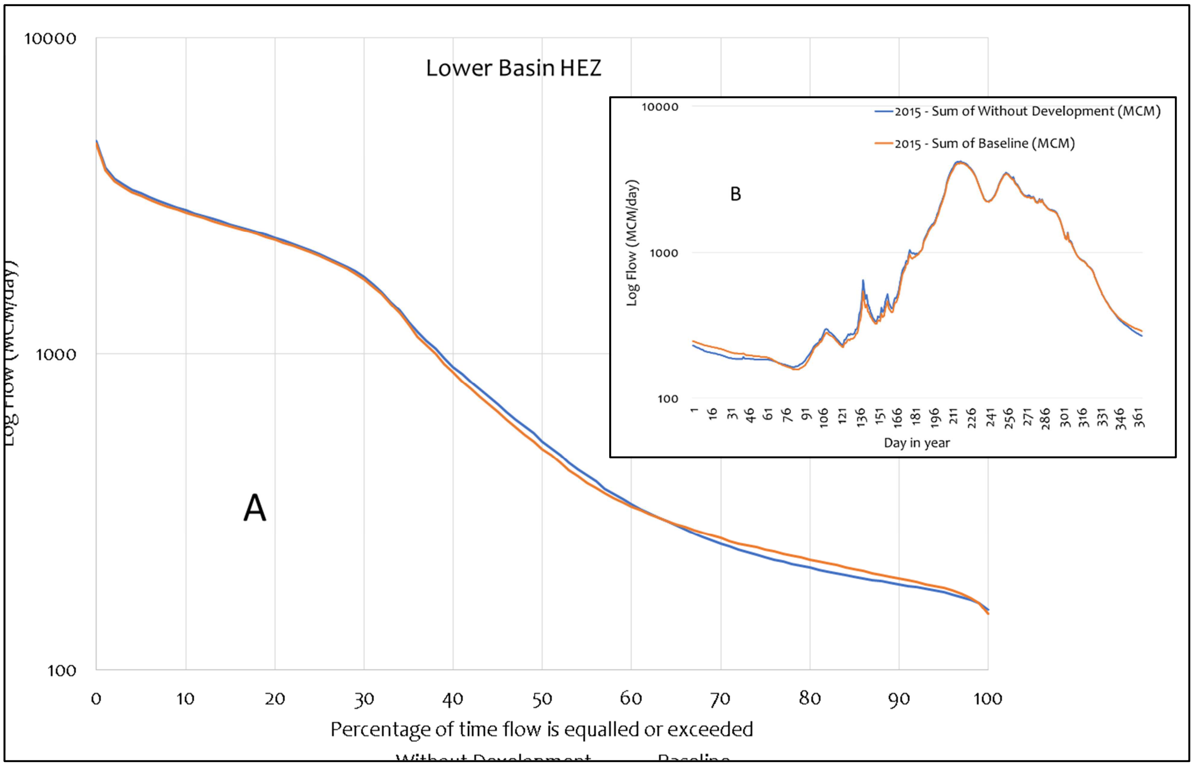


Figure 122 Ayeyarwady River Basin: Flow duration curve (A) and hydrograph (B) - baseline vs 'without development' scenarios

On a sub-basin scale, these impacts of development become more obvious. Figure 123 shows flow duration curves at the outlets of all the sub-basins. Sub-basins where there is currently very little development show very little difference between baseline and 'without development' scenarios. Sub-basins which are currently more developed - such as the Mu, Shweli, Myitnge and Panlaung river sub-basins - will show the biggest difference between baseline and 'without development' scenarios. Comparing annual values in the Mu River sub-basin, as an example, there is a 40 % increase in flows from the baseline to the 'without development' scenario. Comparing only dry season values there is a 20 % increase in flows from the baseline to the 'without development' scenario[9]

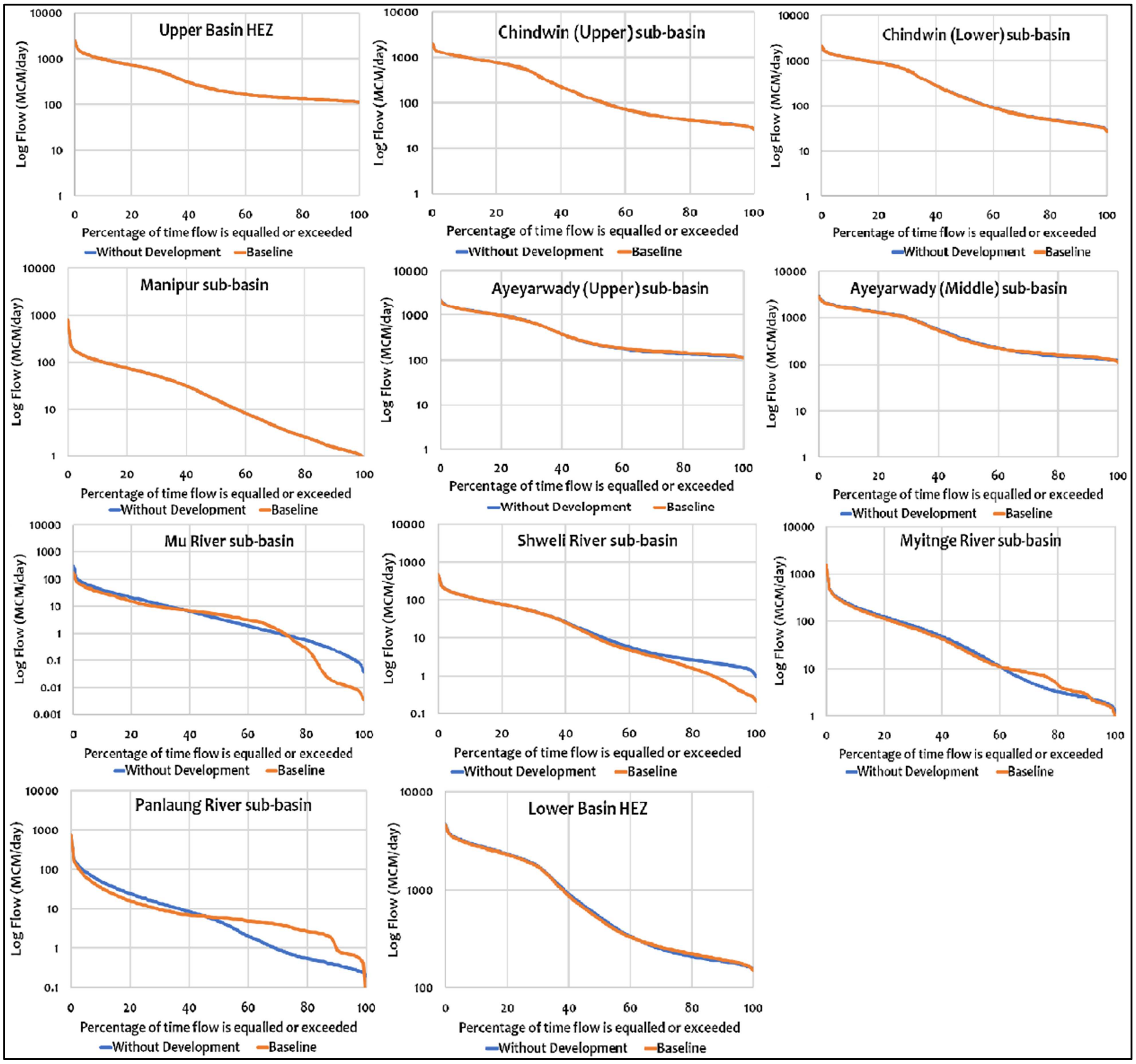


Figure 123 Ayeyarwady River Basin: Flow duration curves - baseline vs 'without development' scenarios for each sub-basin

5 INFORMATION GAPS

5.1 Risks to the assessment

The task of producing a basin wide water system model has highlighted a number of issues around the availability and quality of water resources-related information required to undertake a comprehensive assessment. Figure 124 illustrates the spatial distribution of the available observed climate and flow data required to underpin the modelling.

The uncertainties surrounding these input data increases the uncertainty in modelled outputs. Errors in rainfall resulted in poor representation of the highest flows. Adequate instream measurements are also important to understanding other processes such as groundwater interactions, extractions and local inflows. Uncertainty in water use and storage operations impact on the understanding and simulation of patterns of use at a sub-basin level.

5.1.1 Climate data

5.1.1.1 Precipitation

Data from eighteen recorded rainfall gauges were available for the modelling and analysis. This is too few to understand the rainfall inputs to such a large area especially given the range in topography. Figure 124 illustrates the spatial distribution of the available observed climate data required to underpin the modelling. To attain the required spatial coverage, publicly available, remotely-sensed, precipitation data was used in lieu of observed data, but did not always represent observed conditions adequately.

5.1.1.2 Temperature and Potential evapotranspiration

Data from one recorded evaporation gauge was available (Figure 124). Again, too little to adequately represent variation across the basin and hence remotely-sensed temperature was used to calculate evapotranspiration. Due to the lack of observed data the uncertainty in the remotely-sensed calculated outputs could not be assessed, but it is most likely that actual conditions were not always adequately represented.

Remotely sensed temperature data were used for the snowmelt modelling. The accuracy of these data is not known.

5.1.2 Recorded discharge flow rates

Figure 124 also includes the spatial distribution of the available observed flow data. Data from nine observed discharge sites were available for model calibration and not all sub-basins could be adequately validated. Furthermore, there is a lot of uncertainty about the reliability of the rating curves which went into the calculation of this discharge. Annex I includes details of issues found in the observed discharge data.

5.1.3 Water use

While extensive cropping information is collected in Myanmar, much of this is not yet in an electronically available form at an appropriate scale. Values for full supply capacity and height of many storages could be accessed, but this information is not complete for all storages. The relationship between storage level, volume and surface-area was not available for most storages and information on storage operations was difficult to obtain at the detail required to model any monthly variations in operations.

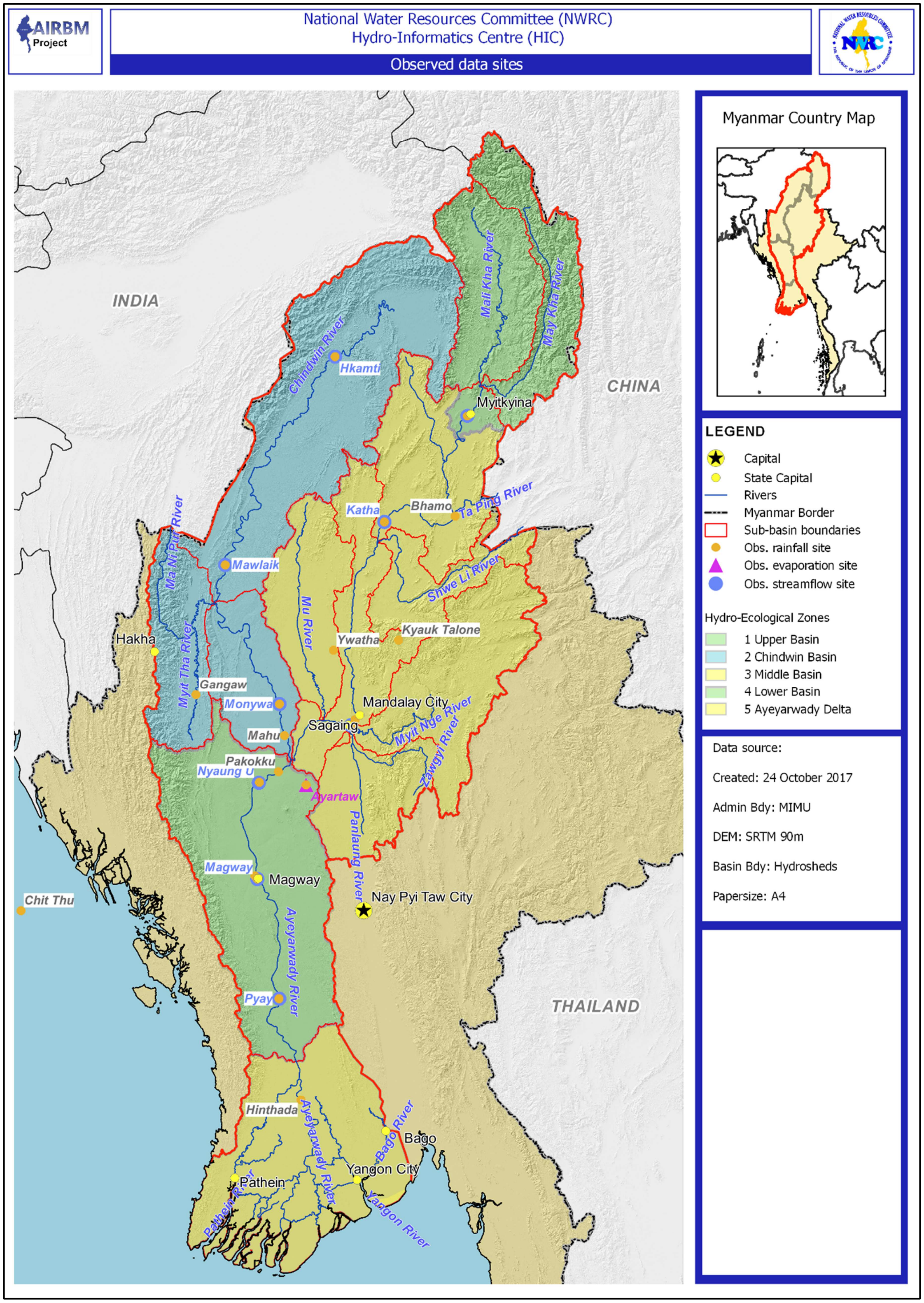


Figure 124 Location of observed rainfall, evaporation and streamflow sites in the Ayeyarwady River Basin

6 CONCLUSIONS

With its source in the Himalayan regions of Myanmar the Ayeyarwady River Basin is the second largest river basin in South East Asia, after the Mekong. It has a drainage basin area of 413,700 km^2. The morphology of the river is controlled by the north-south orientation of the regional geology where the Indian-Australian Plate collides with the Eurasian Plate. The largest tributary of the Ayeyarwady River is the Chindwin River, which joins the right bank of the Ayeyarwady River upstream of Pakokku.

The climate of the Ayeyarwady River Basin is dominated by a monsoonal rainfall regime associated with the south western Indian monsoon and also affected by convectional systems and cyclones from the Bay of Bengal. In addition to the monsoonal wet season, groundwater flows to the streams and snowmelt from the northern regions also contribute to the flows in the Basin. The general climate is also affected by altitude and latitude. Three broad climate zones can be identified:

- The northern parts of the Basin, north of the tropics and in the high-lying Himalayan regions, tend to be cool and wet
- The central low-lying parts of the Basin, in the rain shadow of the Arakan Mountains, tend to be hot and dry
- The southern Delta region of the Basin which tends to be hot and wet

The onset and duration of the wet season varies annually as well as spatially, with no apparent trend in either onset, duration or cessation. This variability in the wet season can however affect water supply, navigation and flooding.

The observed average annual discharge at Pyay above the Delta is estimated at 375,000 MCM/year. Although this is a substantial discharge, it occurs predominately in the six or so months of the wet season, with some smaller tributaries even ceasing to flow in the dry season. Analysis of climate data has revealed that some areas have recorded extended periods of below average rainfall, resulting in potential water supply stress. This is particularly relevant in the Central Dry Zone.

Most of the mean annual flow in the Ayeyarwady River comes from the northern high-lying sections of the river basin. The Mali Hka and N'Mai Hka together contribute 35 % of the mean annual flow at Pyay, with another 32 % coming from the northern parts of the Chindwin River.

The Ayeyarwady River Basin is still a highly undeveloped basin in terms of urban development. Forestry (62 %) and agriculture (27 %) are the dominant uses of land. Most of the agriculture is rain-fed (21 %), with irrigated agriculture comprising 6 %. Although the total area being used for irrigated agriculture is relatively small, the impacts are noticeable, particularly in some sub-basins where large storages have been built to support irrigation.

The surface water resources baseline assessment of the Ayeyarwady Basin is conducted at three spatial scales:

- Basin scale
- Hydro-ecological zone scale
- Sub-basin scale

There are five hydro-ecological zones, and thirteen identified sub-basins.

It has been noted that the impact of water use on the hydrological regime is more evident during the dry season and also more evident as spatial scale decreases, being more noticeable at sub-basin scale than it is at whole basin scale. While water supplies from the main stream of the Ayeyarwady (subject to access) should be reliable year round, tributaries show greater stress in the dry season. In this season, ephemeral streams naturally cease to flow, and heavily regulated sub-systems can also potentially be subjected to stress. Overall, only 1.6 % of total Basin available water is extracted, however during the dry season an amount equivalent to 7 % of total dry season flow is estimated to be extracted. These calculations assume all water, including that in the main stream of the Ayeyarwady and Chindwin rivers, is available for extraction. In the heavily cropped Mu sub-basin, it is estimated that on an annual basis 21 % of available surface water is extracted, with an amount equivalent to 111 % of dry season runoff extracted during the dry season. These dry season extractions are made possible only by releases from the Thapanseik 2 reservoir. More data on extractions, deliveries and return flows are required to better understand these risks. It is currently difficult to precisely determine the impact of extractions on sub-basin outflows in the dry season, due to the impacts of storage draw down, and return flows from irrigation systems.

Furthermore, uncertainties surrounding input data increase the uncertainty in modelled outputs. It is believed that many of these uncertainties will be addressed in time. It is also known that much of the data required was available but could not be accessed due to time constraints. The most important issue to address is the uncertainty in discharge measurements since this will continue to impede adequate modelling of the system. Augmented monitoring and measurement of water flows, stores and climate in the Basin would improve understanding and management of the Ayeyarwady River system, including:

- Stream flow
- Reservoir water storage
- Reservoir releases for consumptive use and hydro-power generation
- Groundwater levels (to improve the understanding of groundwater/surface water interactions)
- Water extractions
- Water deliveries
- Returns of extracted water to the system
- Rainfall, temperature, and other climate data

The model which has been built to underpin this assessment is a first cut at drawing together the information required to adequately understand and simulate the complexities of the Ayeyarwady River Basin. These findings can inform the focus of long term efforts, with the baseline model providing the opportunity to identify gaps in understanding and also forming a framework for continued updating as these gaps are addressed.

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ANNEX I – A SOURCE WATER SYSTEM MODEL

This Annex provides a description of the development, calibration and baseline hydrological modelling work undertaken to underpin the Water Resources Assessment of the Ayeyarwady River Basin. Modelling is used to fill spatial and temporal gaps in available hydrometric data and inform qualitative and quantitative descriptions of hydro-physical processes.

A.1 The Source Water System Model

A Source model of the Ayeyarwady River Basin has been developed to produce a baseline assessment of the hydrology of the basin. This model includes representations of agricultural (crop), domestic, urban and hydropower water use. Major storages supplying these water uses are included in the model. Agricultural areas in the model are based on a 2014 IWMI land cover classification (IWMI, 2014) imported into the model as hydrological Functional Units. The minor contributions from snowmelt are also represented as separate hydrological Functional Units. The model is underpinned by 3 rainfall-runoff models: the GR4J model (Andréassian et al, 2009) and its snowmelt version GR4JSG (Nepal et al, 2015; Nepal et al, 2016)), and an Agricultural Runoff model which represents purely rain fed (monsoonal) agriculture. These rainfall-runoff models are driven by layers of gridded rainfall and evaporation. The model is calibrated to observed discharge at 6 sites. This document describes the input data sets, calibration results, modelling assumptions and limitations.

A.1.1 Representing features and processes in eWater Source

The Ayeyarwady River Basin and its sub-basin features are represented as a hierarchy within the Source model (Figure 1). At the highest level the Ayeyarwady River Basin is divided into hydro-ecological zones (HEZs), each of which is a collection of Sub-Basins. Within each sub-basin key features such as major dams and streamflow gauges are used to identify sub-catchment boundaries. Each sub-catchment is then characterised according to the area of each Functional Unit within the sub-catchment. A Functional Unit is a land use and land type with distinct hydrological response characteristics, for example forest and rain-fed agriculture.

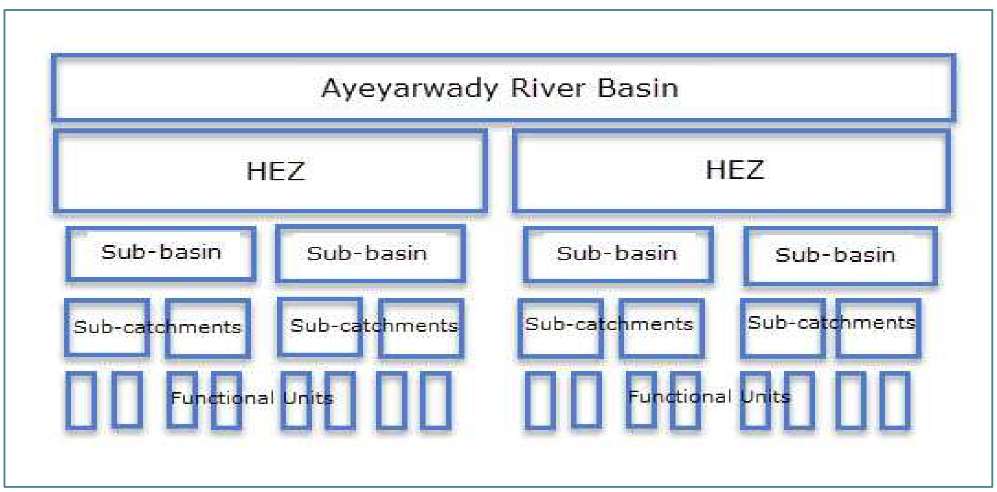


Figure 1 Hierarchical catchment structure within Source

Figure 2 illustrates this hierarchical structure within the Source model in the Mu River sub-basin. The Mu sub-basin comprises 2 sub-catchments (SC # 55 and SC ## 79) which were formed by including the Thapanseik Dam as a major feature to be included in the modelling.

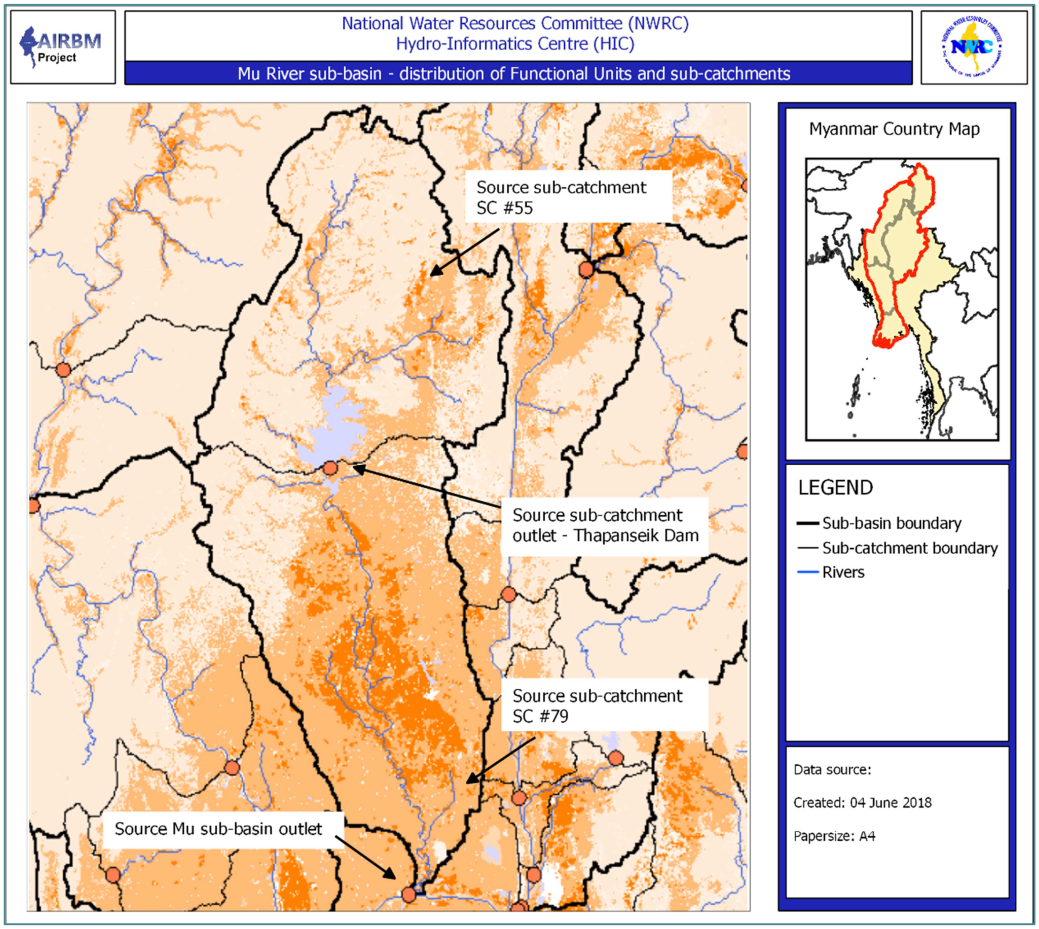


Figure 2 Sub-catchments and Functional Units within the Mu River Sub-basin

Functional Unit areas are not spatially preserved within the Source framework, but are rather stored as areas per model sub-catchment. In this example Thapanseik Dam at 37139 ha makes up 4% of sub-catchment number 55 (Figure 3).

Functional Unit Area Configuration

Subcatch...	Functional Unit	Area (ha)	Area Ratio (%)
SC #55	Forest	566377.375	61
SC #55	Grassland and Bare lands	0	0
SC #55	Shrublands and non-forest woodlands	74279	8
SC #55	Water	0	0
SC #55	Snow	0	0
SC #55	Rainfed Agriculture	222837	24
SC #55	Irrigated Agriculture	27854.625	3
SC #55	Dams	37139.5	4

Figure 3 List of Functional Units and associated areas within sub-catchment SC #55

A.1.2 Workflow

The procedure of building a model in Source follows the steps brought together as a work flow described in Figure 4.

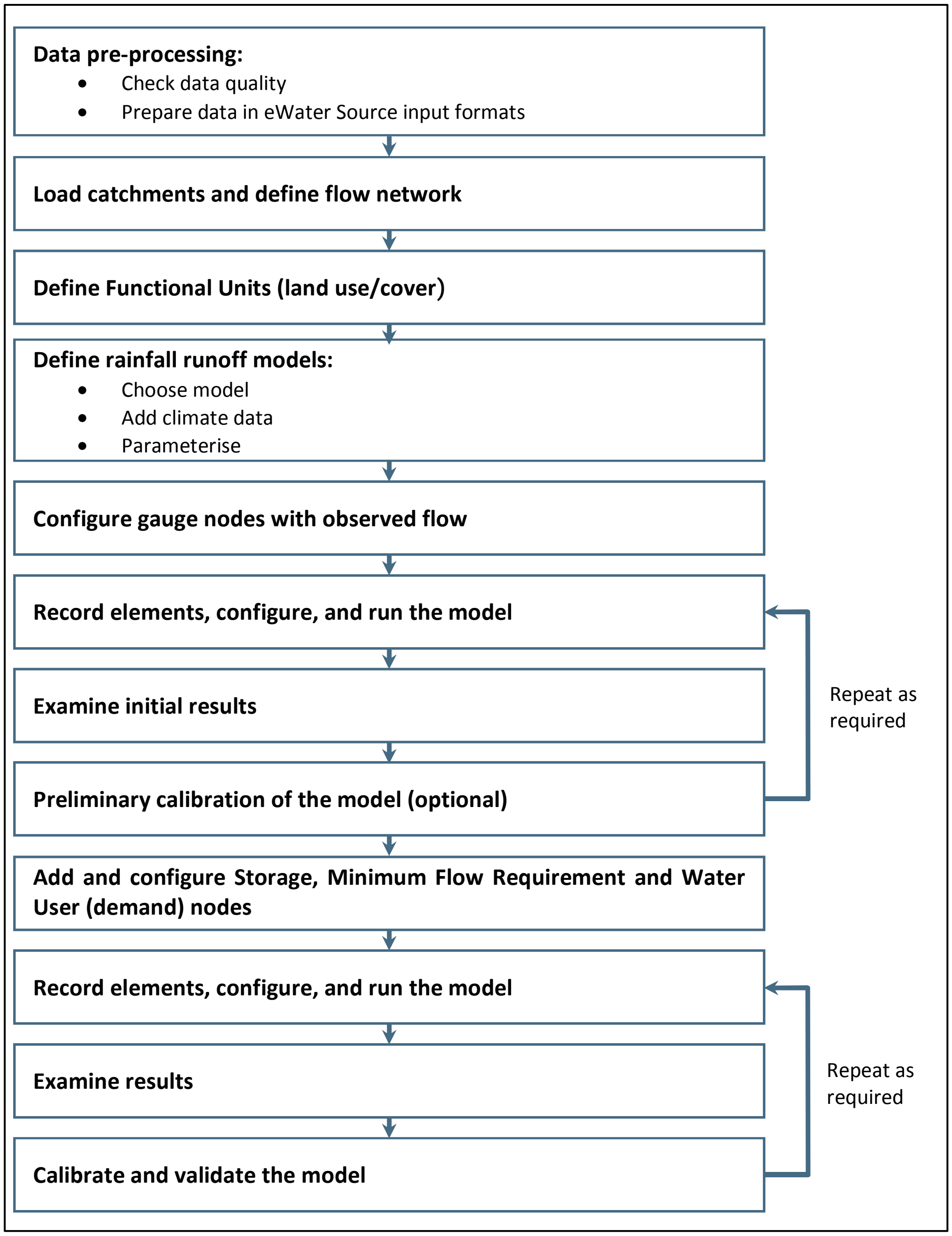


Figure 4 eWater Source model creation workflow

A.2 Data collection and preparation

The initial stage of model development includes the acquisition and manipulation of the data required for the hydrological representation of the catchment. Data collection and preparation is often an ongoing part of the modelling process. An ideal data set is accurate, complete and consistent. However, data are never perfect; there are measurement errors, equipment errors and lost records. Data availability and quality are commonly the limiting factors for both model selection and predictive performance. Typically, data is used to calibrate and validate models and consequently any uncertainty in data will influence the model's predictive capability. Quite often data uncertainty is amplified in models. Consequently, any effort in improving the quality of data will significantly improve the predictive performance of models. Therefore, while data gathering and clean up can be the most time consuming step in a project, the importance of this step cannot be overemphasised (Vaze et al, 2012).

According to the Myanmar IWRM Strategic Study (2014) a lot of the data for Myanmar is often difficult to find or access. They also mention data gaps in terms of number of measuring sites (spatial coverage), number of measurements (temporal coverage) and reliability of measurements (data quality). This has implications for accessing data for model building and verification. Van Der Velden (2015) also comments that model construction and validation is complicated by the fact that data availability is low and the Ayeyarwady is a complex river.

Table 1 lists the types of data identified as important to build a baseline model of the Ayeyarwady River Basin and undertake the surface water resources assessment of the basin. AWP Activity 1 of SOBA Package 1 was tasked to access and examine the data required for building a Source model of the Ayeyarwady River Basin. A vast amount of data was collected under this Activity. However, there remains some information which was difficult to obtain or process, either due to time constraints or availability. These data are discussed in the following sections, highlighting the pre-processing and assumptions that were made for the model build.

Table 1 Data required for the Surface Water Resource baseline modelling and assessment of the ARB

Core Data Sets	Purpose
Digital Elevation Model (DEM)	Source model catchment delineation
Observed Discharge	• Historic hydrological assessment • Model calibration and validation
Observed Rainfall	• Rainfall-runoff Source model input • Crop water use
Observed Evapotranspiration	• Rainfall-runoff Source model input • Crop water use
Land Cover	• Source model Functional Units • Water Use
Storages - current	Modelled Water Use
Crops	Modelled Water Use
Urban water consumption	Modelled Water Use
Supplementary Data Sets	
Storages - planned	Model future scenario building
Water quality (WQ) sites	Future model enhancement to include WQ
Water level	Historic flood level assessment
Bathymetry	Historic flood level assessment
Flooding extent	Historic flood level assessment

A.2.1 Data Quality

Rainfall and evapotranspiration data are used for generating modelled catchment runoff, and the calibration and validation of models is by comparison to observed streamflow and other data. Errors and uncertainties in these input data are the major causes of difficulty in calibrating a rainfall-runoff model (Vaze et al, 2012), making it critical to assess and be confident of, the quality of these data sets. Infilled, extended and transposed data needs to be re-reviewed to ensure it is reasonable, bearing in mind that there could be a trade-off between the completeness of a data set and data quality involved. Data that is inferred from other sources (e.g. remote sensing or other models) and observed data will commonly be of different quality.

A.2.2 Data time step

The modelling time step depends on data availability and also the expected model use. Climate input data required for rainfall-runoff and crop modelling, and observed flow data required for model calibration and validation, are required at this time step. When modelling at a daily time model outputs can be aggregated to provide summaries, and model results will be presented as monthly, seasonal or annual.

A.2.3 Observed time series data inputs

a) ***Discharge***

Observed discharge was made available by the Myanmar Department of Meteorology and Hydrology (DMH) at 9 sites across the ARB.

Figure 5 illustrates the temporal distribution of this data, while Figure 6 illustrates the spatial distribution within the Source model. The location of these discharge sites is used to inform the location of sub-catchment outlets within the Source model.

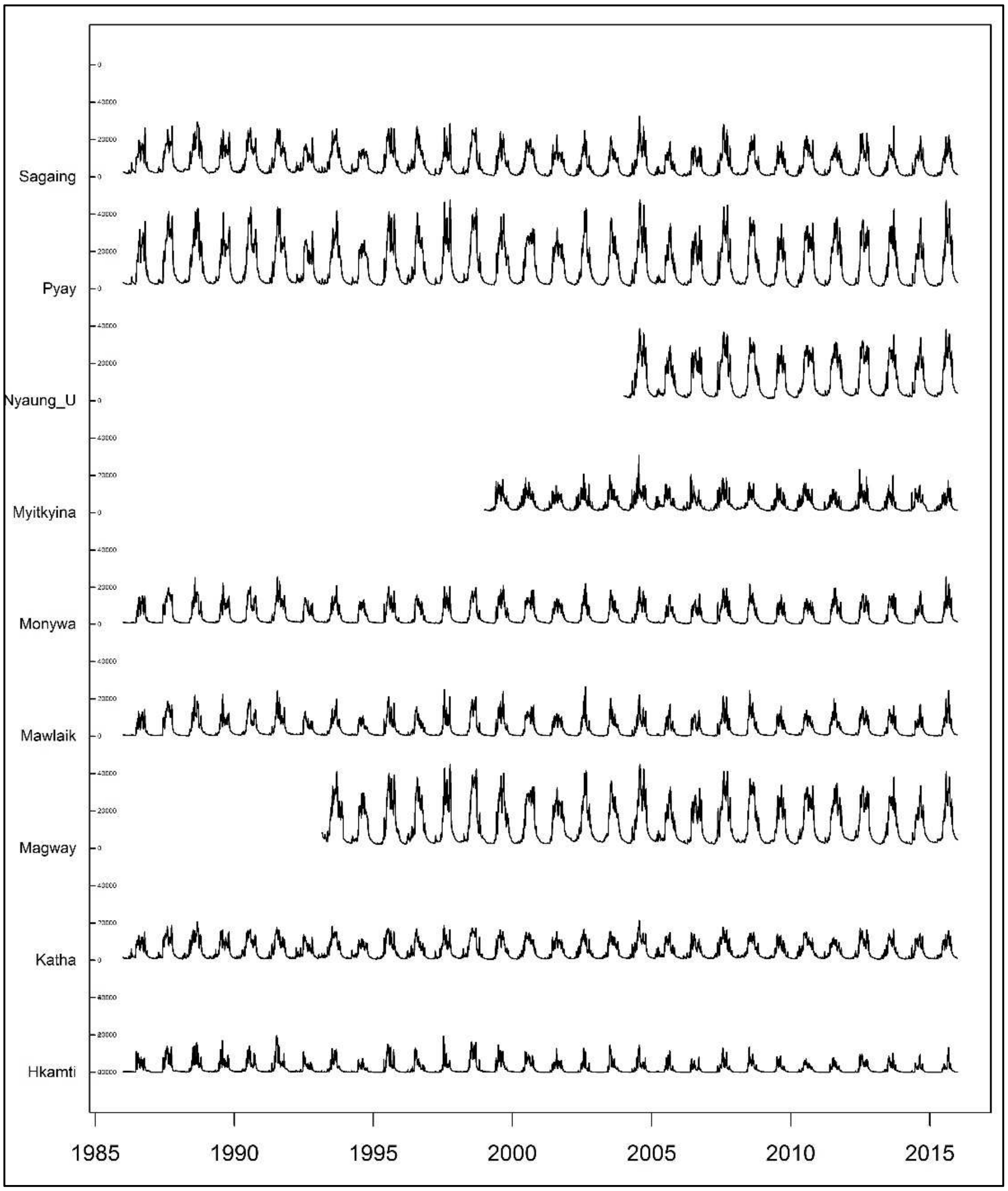


Figure 5 Daily mean discharge (m^3/s) at 9 sites across the ARB

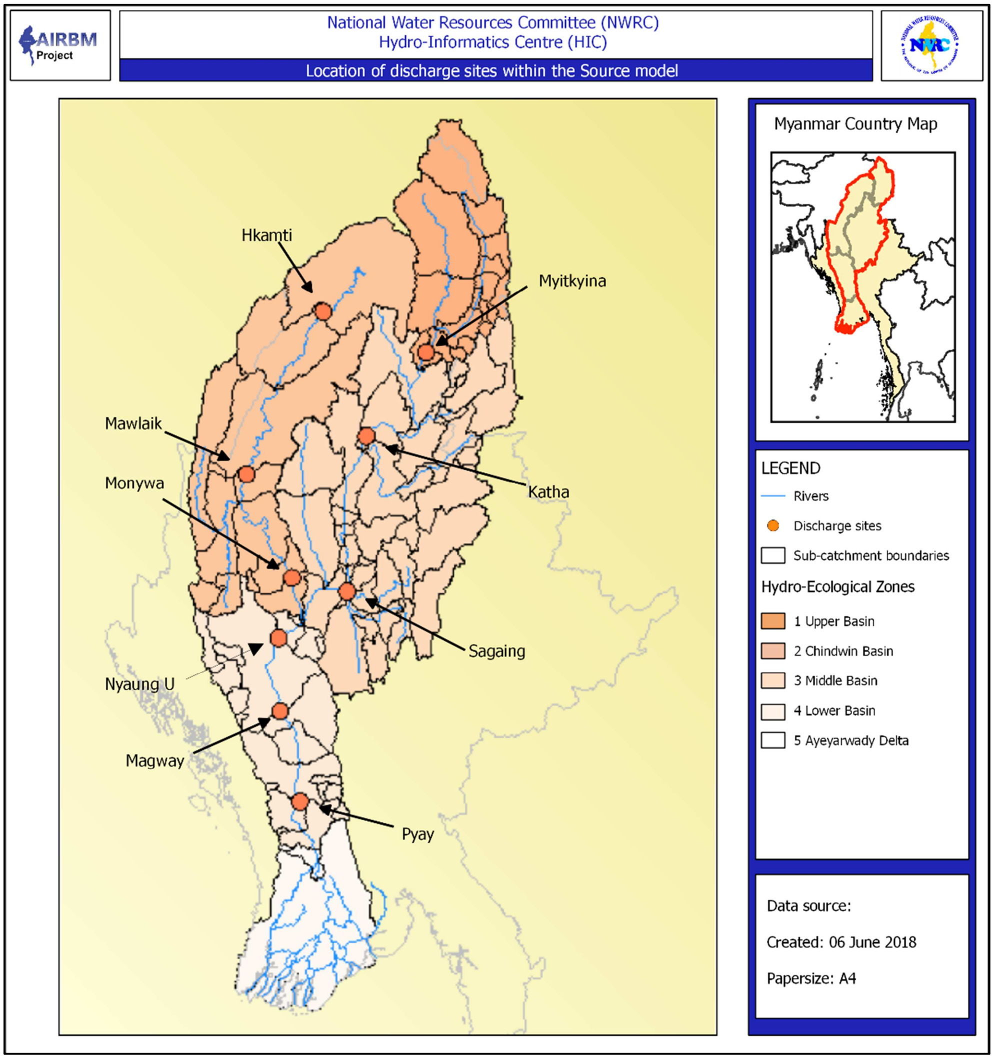


Figure 6 Location of discharge sites at sub-catchment outlets within the Source model

b) ***Climate data – Rainfall, Evapotranspiration and Temperature***

Climate data drives the rainfall-runoff modelling process and the crop modelling process. It is lumped in Source per model sub-catchment.

Observed rainfall was made available by the DMH at 20 sites across the ARB. Figure 7 illustrates the temporal distribution of this data, while Figure 8 illustrates the spatial distribution. Since the data are of varying frequency and large portions of the upland regions of the basin are not covered, global remotely-sensed data sets were considered as an alternative. Five products, listed in Table 2, were explored. The analysis of these products was undertaken by CSIRO (Podger, 2017) and is detailed in 'ANNEX II - Climate data review'. Overall, the CHIRPS data set was found to best represent observed rainfall values as well as having the best temporal coverage (1981-2017), although at Hkamti it was found that the observed rainfall depth could be underestimated by up to 50%.

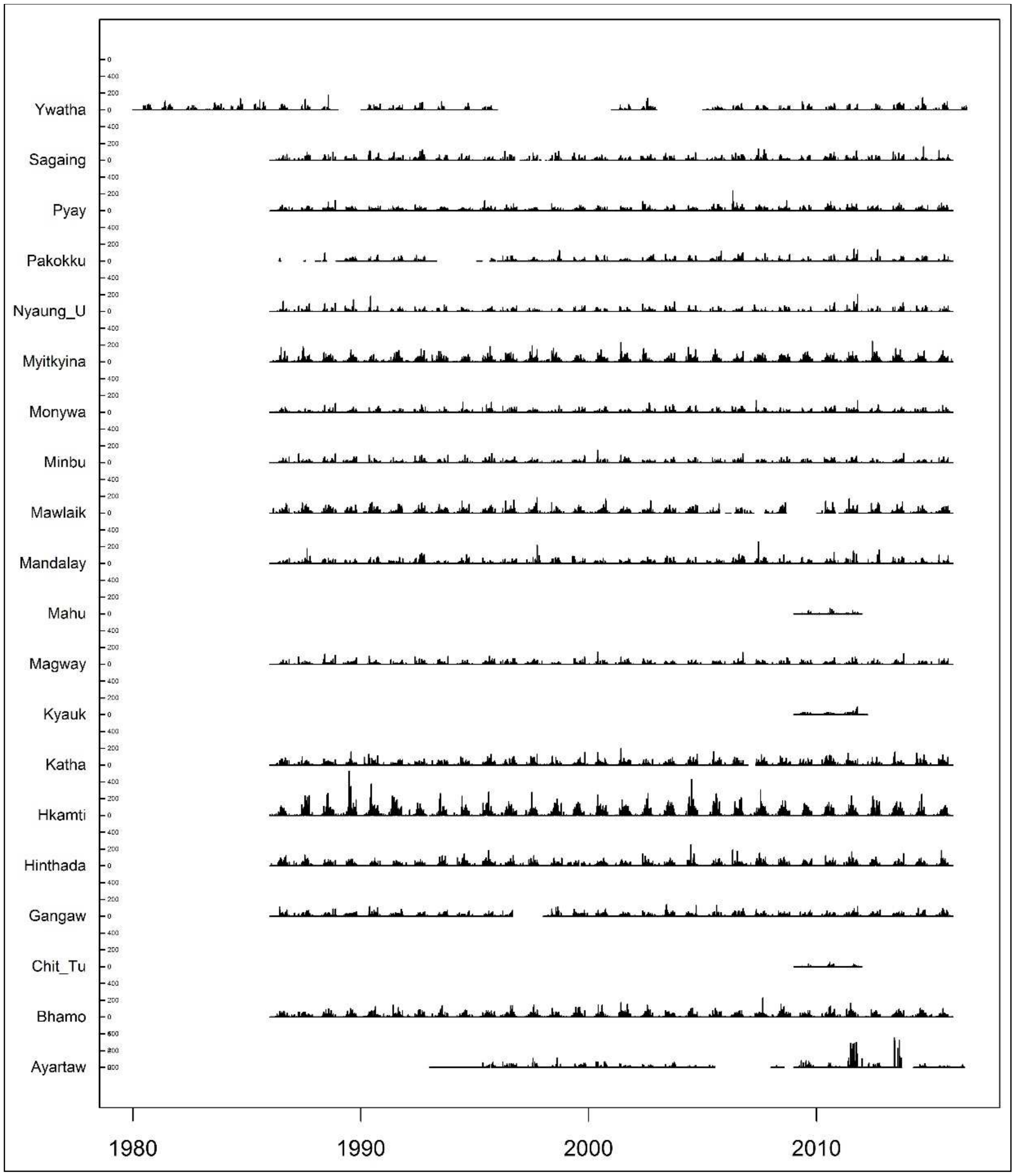


Figure 7 Daily observed rainfall (mm) at 20 sites across the ARB

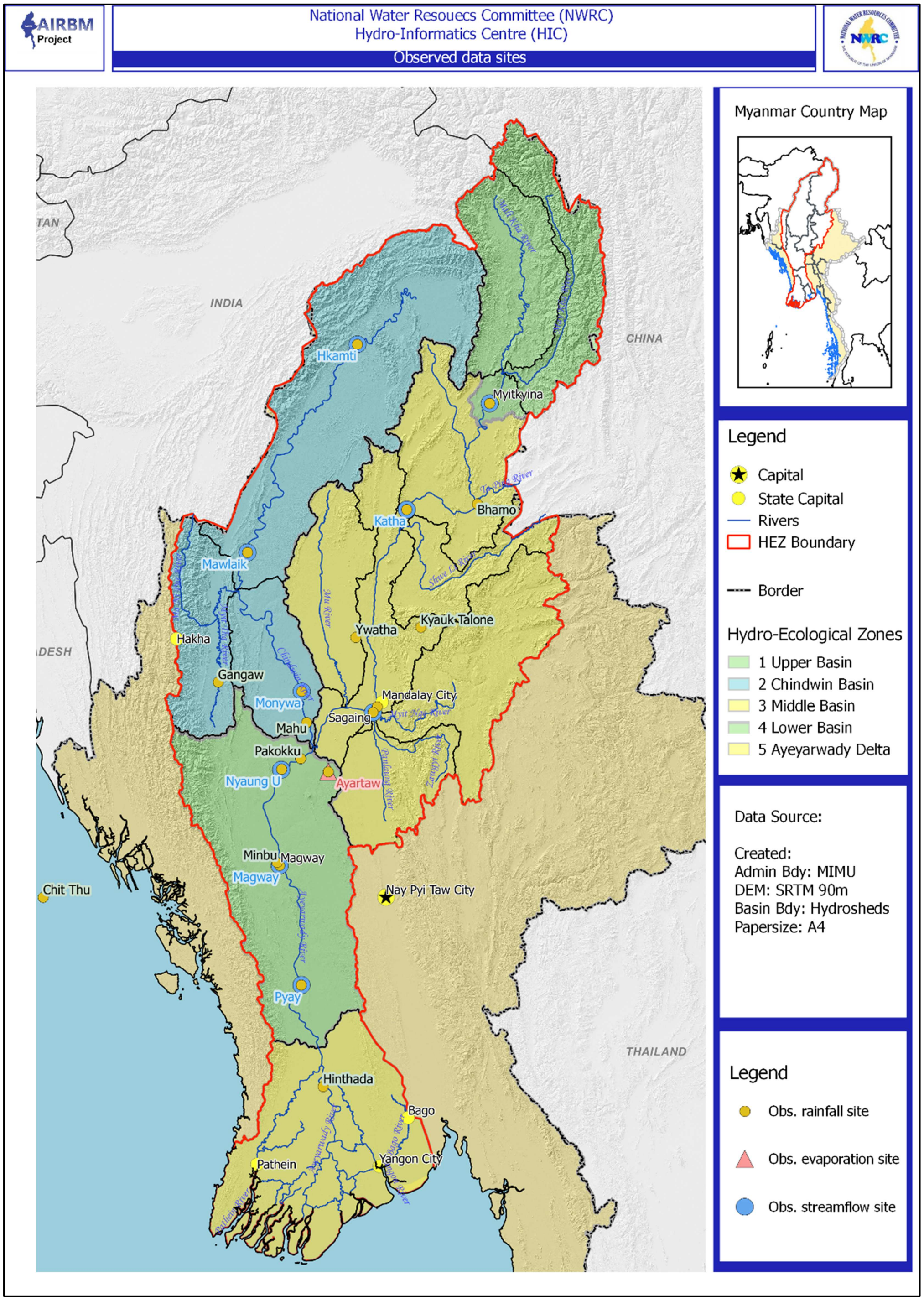


Figure 8 Location of available observed rainfall sites in the ARB

Table 2 Global remotely-sensed rainfall products

Climate data product	Resolution	Period
CHIRPS	0.05 degree	1/1/1981-31/03/2017
APHRODITE	0.25 degree	1/1/1951-31/12/2007
Princeton	0.5 degree	1/1/1948-31/12/2008
PERSIANNE	0.25 degree	1/1/1983-31/082016
WATCH	0.5 degree	1/1/1979-31/12/2012

Evaporation data was available at one site in the ARB – Ayartaw (see Figure 8 above) which is in the central part of the ARB, and minimum and maximum temperature at 15 sites. It was considered that one site will not sufficiently represent evaporation in all climate regions of the Basin, and therefore, the use of globally available remotely-sensed data was examined. The details of this assessment can be found in 'ANNEX II - Climate data review'. To provide a data set of sufficient length to match the available CHIRPS rainfall, temperature and the Hargreaves method were used to estimate evaporation.

c) ***Bathymetry and Water Level***

Water level and bathymetry data was used to inform the analysis of flood levels and inundated areas at various sites across the Basin. Observed water levels were obtained at 25 sites across the ARB from the DMH and the Irrigation and Water Use Management Department (IWUMD). Bathymetry was available in Autocad or .pdf format. Not all sites could be converted to shapefile and had sufficient labelling to be able to extract a river cross section.

d) ***Water quality – sediment and others***

While the generation and transport of sediment and other water quality variables are not included specifically in the Baseline model at this stage, the underlying structure of the model has been set up such that these processes can be included as required. The choice of sub-catchment outlets includes the location of sites at which observed sediment and water quality is available (Figure 9). Future sub-division into sediment sources was taken into consideration in the choice of land cover classes included in the model, and the current Functional Units within the model can be further sub-divided to include slope and soil type to represent sediment generation processes.

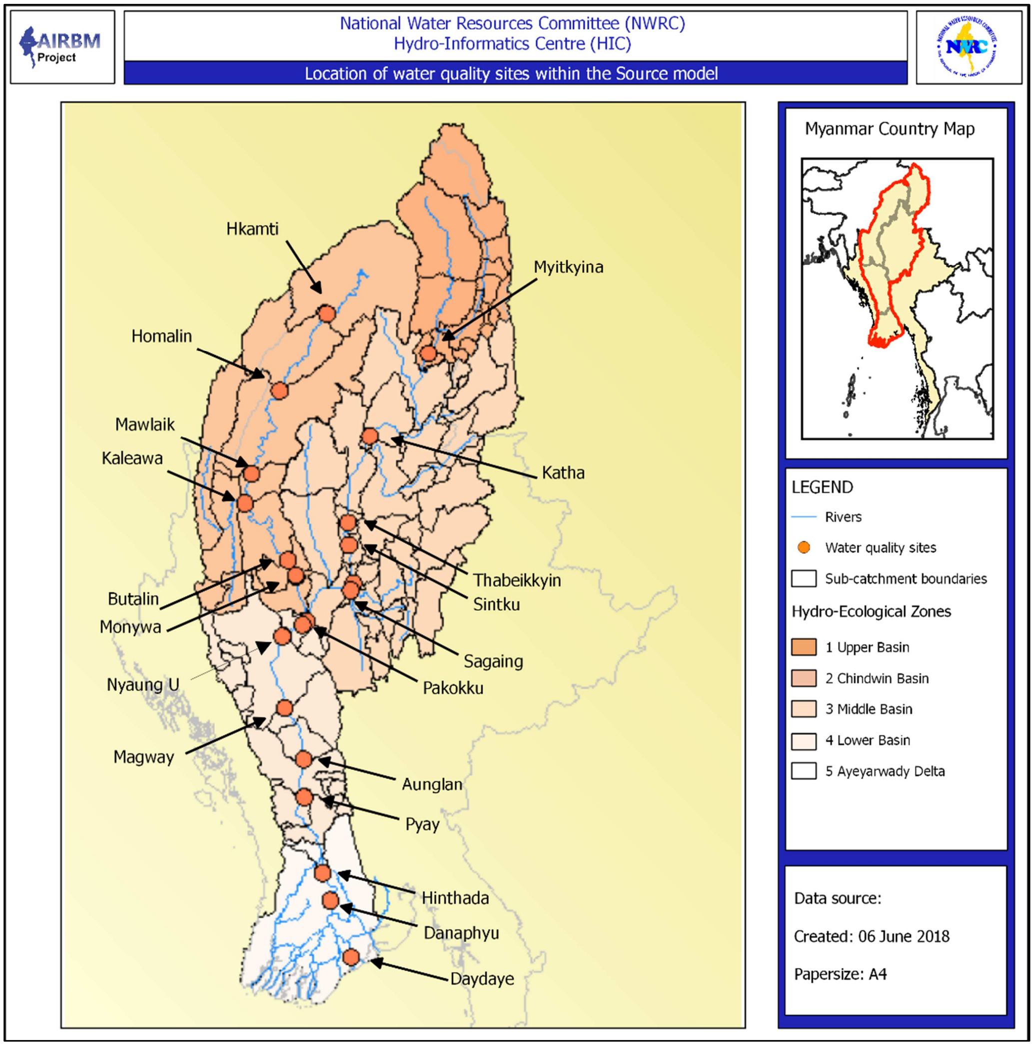


Figure 9 Location of water quality sites within the ARB

A.2.4 Representing Storages in Source

Storages represented in the baseline Source model of the ARB represent Hydropower only, Irrigation works only, or are Multi-Purpose storages used for both hydropower and irrigation supply. Only storages which have been completed prior to 2017 are configured in the baseline model. Table 3 summarises the number of storages in the ARB according to each of these classes. Some of the storages listed are in the Chinese section of the ARB, but must be represented in the model because they could still impact on flows.

Table 3 Storages in the ARB

Storage type	No of storages	No in Myanmar	No in China
Hydropower	57	8	49
Multipurpose	12	7	5
Irrigation works	220	220	None known

Configuring storages in a Source model requires information about:

- Storage level/volume/area relationship
- Level/discharge relationships for outlets
- Hydropower head difference and turbine efficiency
- Operational rules

Most of the storages identified in Table 3 had data regarding volume and crest height, but none had data for all the requirements above. Storages are classified into major and minor storages according to volume, crest height and, where relevant, hydropower production capacity. Major storages within the Myanmar boundary are classified as:

- volume greater than 250 x 10^6 m^3, or
- dam height greater than 40m, or
- installed capacity > 100MW (if hydropower)

Major storages are included as key features in the delineation of model sub-catchment boundaries. Minor storages are grouped per sub-catchment and configured as a single notional storage in the sub-catchment with a capacity equal to the cumulative capacities. Most of these represent a collection of the smaller irrigation storages within the sub-catchment. Similarly, storages located in the China section of the ARB are also grouped and configured as a single notional storage for each of the five tributaries entering Myanmar at the Myanmar/China border. Forty-four storages are configured in the baseline model:

- 5 major hydropower storages in Myanmar
- 5 notional hydropower storages at the Myanmar/China border
- 6 major multi-purpose
- 11 major irrigation works
- 17 minor storages

A.2.5 Choosing catchment areas

Catchment areas and their divisions into sub catchments are chosen to strike a balance between capturing sufficient detail to properly model for project objectives, and not creating an undue computational burden that produces little additional benefit. Catchment area is used in the Source model to convert the rainfall-runoff model output from runoff depth to runoff volume, and is based on points in the model where it is necessary to correctly represent upstream catchment flow for purposes of calibration, validation or analysis.

Sub-catchments in the ARB are determined according to key sites (listed in Table 4). Key sites are not only identified according to their relevance to the baseline model, but also according to any possible relevance to future uses of the model, such as future scenario building and water quality modelling. All major storages (commissioned, planned and currently under construction) are included as points representing catchment outlets, although only existing storages are configured. In several instances the same site may represent more than one feature, e.g. the site at Sagaing includes observed discharge, observed water levels and also observed water quality. Altogether 95 sub-catchments were identified as relevant to the underlying structure of the Source model.

The Source model does not include the Delta Hydro-Ecological Zone.

Table 4 Key sites used to inform sub-catchment outlets

Feature	No included in Source
Observed discharge sites	9
Major storages	26
Observed Water Level sites	25
Observed Water Quality sites	18

A.2.6 Functional units

Source defines areas of expected similar hydrological response as Functional Units. Each Functional Unit can have different rainfall-runoff model types or parameters. Functional Units in the initial Source baseline model are based on land cover, but can be extended to include sediment generation behaviour. The most recent land cover classification for the ARB is for 2014, done by IWMI to support river health studies (IWMI, 2014). This land cover data was chosen to inform the baseline model for two reasons:

- the date matches the most recent climate data available for modelling
- it is the only available land cover data set which distinguishes between rain-fed and irrigated agriculture, accounting for the highly seasonal cropping patterns of the Basin. Rain-fed agriculture is identified as being present only during the monsoon season, while irrigated agriculture is based on areas identified as being present all year round.

Generally, it is recommended that as few Functional Units should be used as possible, to improve model run times and parameter identifiably. Table 5 lists the IWMI land cover classes and the % area of the Basin for each class. An examination of the distribution of the areas of these classes within the ARB indicated four dominant classes. The IWMI land cover classes were combined and re-classified to produce the Functional Units for the Source baseline model. Wetlands, Water bodies and Snow were kept separate since they have a very different hydrological response to other classes, and also Snow will be modelled separately as snow melt.

Table 5 IWMI land cover classification and Source derived Functional Unit (FU) classification

IWMI land cover class	%	Source FU
Forest	**62.5**	Forest
Rainfed-single	**17.1**	Rainfed agriculture
Shrublands, Non - forest wood lands	**7.1**	Shrublands, Non-forest woodlands
Irrigated - Double	**3.9**	Irrigated
Water Managed - Double	2.2	Rainfed agriculture
Waterbody	1.6	Waterbody
Irrigated - Single	1.4	Irrigated
Snow	0.6	Snow
Irrigated - Triple	0.5	Irrigated
Grassland and Bare lands	0.5	Grassland and bare lands
Settlements	0.4	Grassland and bare lands
Wetland	0.4	Waterbody
Plantation	0.3	Forest
Flood Plain - Single	0.2	Rainfed agriculture
Flood Plain - Double	0.09	Rainfed agriculture
Rainfed - Double	0.01	Rainfed agriculture

A.2.7 Crops, crop parameters and agricultural water use

Cropping data is needed to model crop water requirements (demands) in the Basin. Key pieces of information include:

- Rainfall and evapotranspiration time series – *the same as the climate data used in the sub-catchment surrounding the water user*
- Soil data – maximum available soil moisture capacity and seepage rate – *assumed 50% and 10%*
- Crop types – *derived from FAO Agricultural Atlas*
- Crop areas - *derived from FAO Agricultural Atlas*
- Planting dates - *derived from FAO and IWMI cropping patterns*
- Crop factors - *obtained from FAO56 (Allen et al, 1998)*
- Crop root depths - *obtained from FAO56 (Allen et al, 1998)*
- Maximum and minimum ponding levels for rice – *assumed 100mm-150mm*
- Losses - *assumed 50%*

While extensive cropping information is collected in Myanmar, much of this is not yet in an easily available form at the appropriate scale. Therefore, the distribution and proportions of crops planted in the Ayeyarwady River Basin (ARB) were based on 2002 District-level data available in the FAO Agricultural Atlas (FAO, 2002). Thirty-two administrative districts, shown in Figure 10, overlap the modelled extent of the Ayeyarwady Basin (model extent does not include Districts within the Delta region).

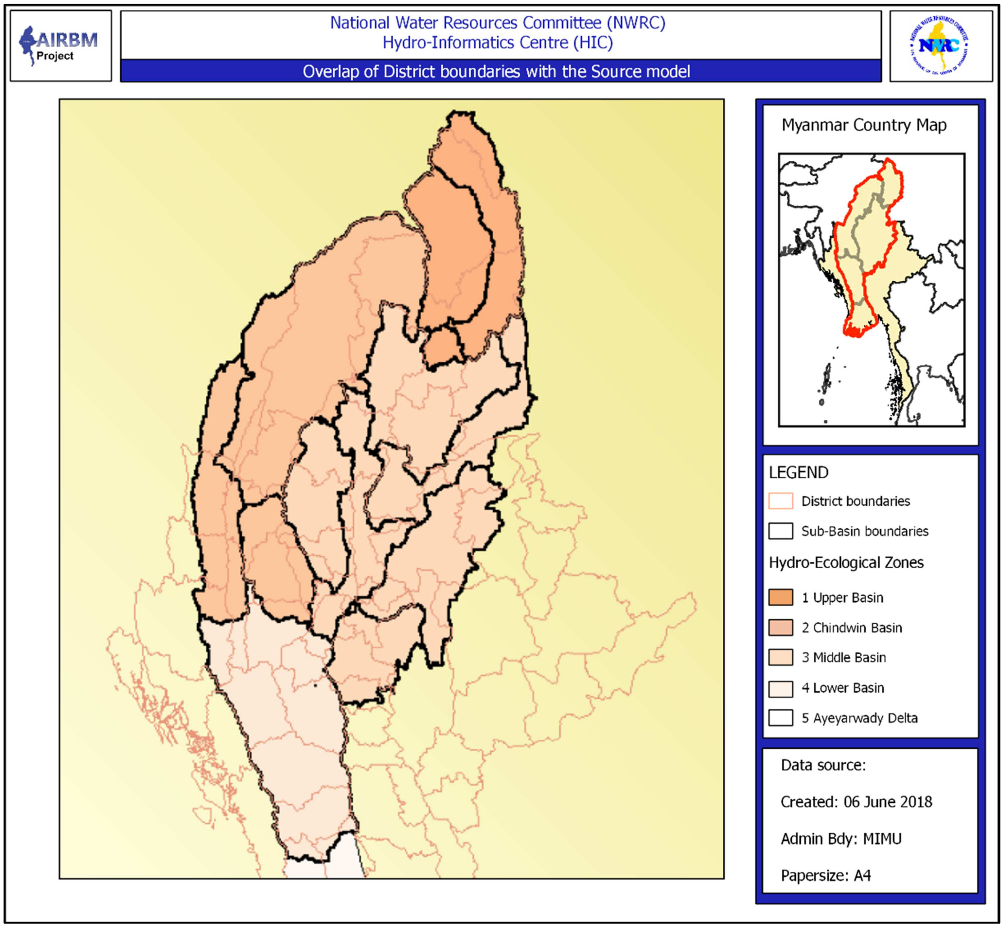


Figure 10 Union of Myanmar Districts overlapping the Source model extent

Twenty-one crop types were included in the FAO Atlas (listed in Table 6). According to the summary in this table:

- no rice was planted during the winter season of 2002
- only rice and sesame were sown during the summer – it can be assumed that crops defined as 'Other' were also being tended during this season

The total sown area will include areas which are sown in multiple seasons and the total sown areas include areas of Districts outside the ARB. The finer scale spatial distribution of crops types within Districts is unknown. The initial assumption is that the same proportion of crops are grown across a whole district.

Table 6 Seasonal distribution of crops types in the 32 districts (including areas which fall outside the ARB)

Crop	Monsoon	Winter	Summer	Other *	% of total sown area
Rice					25
Pulses					25
Sesame					14
Green Gram					5
Groundnut					5
Pidgeon Pea					5
Sunflower					5
Black Gram					4
Cotton					3
Maize					2
Vegetables					2
Sugarcane					1
Soybean					1
Niger Seed					1
Chili					1
Onion					0.6
Mustard					0.4
Potato					0.3
Rubber					0.1
Coffee					0.1
Oil Palm					0.01

*perennial crops and crops planted all year round

Three crop types dominate – rice, pulses and sesame. Furthermore, green and black gram, groundnut, pidgeon pea, soybean, niger seed and sunflower can also be classed together with pulses and sesame seeds. The remaining crop types are small in their proportion of the total sown area. A summary of the crop combinations used for modelling is presented in Table 7. The final combination of crops provided for Rice and Non-Rice in each season, with Non-Rice being represented by the cropping pattern of Sesame as obtained from FAO56 (Allen et al, 1998). A third class, 'Other', takes account of perennial crops and crops planted all year round.

Table 7 Combined crop types for Source Baseline modelling

Combined crop types	Source model crop class	Combined % of total sown area
Rice	Rice	25
Pulses (green and black gram, groundnut, pidgeon pea, and soybean)	Non-rice	46
Sesame (niger seed and sunflower seed)	Non-rice	20
Remaining (cotton, maize, vegetables, sugarcane, chili, onion, mustard, potato, rubber, coffee and oil palm)	Other	10

Seasons are defined as in JICA (2013) (Table 8), but crop plant dates might be adjusted to accommodate growth periods. With a typically 6 month growth cycle, this is particularly the case for rice plant dates. According to the FAO (http://www.fao.org/docrep/005/Y4347E/y4347e18.htm) irrigated (summer/dry) season rice can be planted November/December (Figure 11). IWMI (2014) based the land cover distinction between irrigated and rain-fed rice on the general cropping times shown in Figure 12. Based on these two sources of information, and to avoid seasonal overlap, irrigated (dry season) rice in the model is planted on 1 January and rain-fed (monsoon) rice is planted on 1 July.

Table 8 Identification of seasons within the Source baseline model (JICA, 2013)

Season	Dates
Monsoon	Mid-May to end October
Winter	November to end February
Summer	March to mid-May

	Planting	Harvesting
Normal rainfed lowland and upland	5-6	1--12
Late rainfed lowland	7-8	11-12
Deepwater	4-5	11-12
Mayin (receding) rice	10-11	2-3
Irrigated wet season	5-6	10-11
Irrigated dry season	11-12	4-5

Figure 11 FAO rice seasons for Myanmar

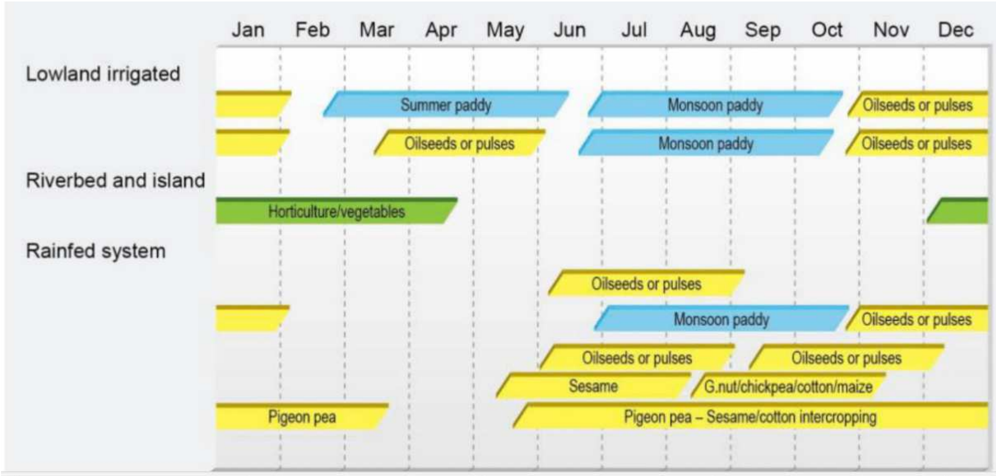


Figure 12 IWMI generalised cropping patterns for the ARB

The rain-fed and irrigated land cover classification (IWMI, 2014) are used in the modelling as the basis for total cropped area per season. However, this layer is more than ten years after the FAO crop information and areas will have changed in that time. Therefore, the FAO crop areas are scaled to represent % per season and per District. These % are then applied to the allocation of crop areas per proportion of each District per modelled sub-catchment. Each District is allocated to a Source model sub-catchment, and the same cropping proportions for the allocated District is then assumed to also apply to the sub-catchment. Major assumptions of this approach are that:

- cropping proportions remain the same each year
- the same proportion of crops is grown across a District (and sub-catchment)

A.2.8 Applying storages and crop water use in the model

Within the Source baseline model a distinction is made between the origins of water for crop use. Two high level unique sources are identified and their areas are based on the IWMI land cover classification:

- Rain-fed
- Irrigated

However, within the irrigated class there is a breakdown according to major and minor storages as water source, and extractions from the stream or groundwater. With no information at an adequate scale, no distinction is made between extractions from the stream or from groundwater. The size of Beneficial Areas are provided together with much of the individual storage information. This information is used to allocate beneficial areas within each sub-catchment. Note, that at all times the beneficial area is modelled with crop models on a Water User node, with the corresponding areas added to the area of the sub-catchments' Irrigated Functional Unit. This Functional Unit does not generate run off to avoid double accounting in the model. Similarly, irrigated crop water use not associated with a beneficial area was modelled with crop models on a Water User node, again with the corresponding areas added to the area of the sub-catchment's Irrigated Functional Unit.

Figure 13 illustrates this breakdown in the Mu River sub-basin. There are two major sub-catchments – upstream and downstream of the major storage, Thapanseik 2 Dam. Upstream of Thapanseik 2 Dam all water extraction is assumed to be unregulated and from a river or from groundwater. However, downstream of Thapanseik 2 Dam, three crop water users are identified:

- the Beneficial Area associated directly with Thapanseik 2 Dam, which receives its inflow from the upstream sub-catchment

- the accumulation of Beneficial Areas associated with minor storages, supplied from a notional storage connected to the local sub-catchment inflow
- a third water user which will have an allocated maximum cropping area equal to any difference between the sum of the all major and minor Beneficial Areas and the Irrigated Functional Unit area – i.e. the area of the Irrigated FU not already allocated to a storage beneficial area.

The same proportion of crop type mix is applied to each water user in a sub-catchment.

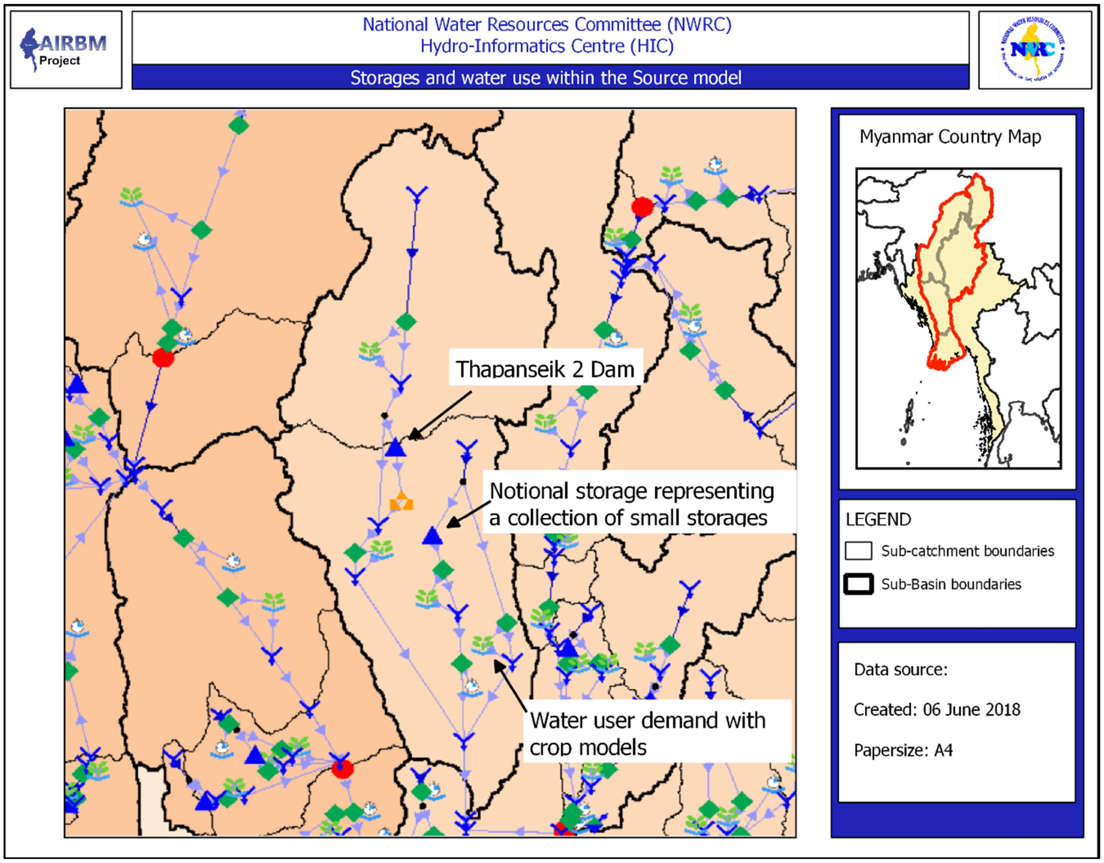


Figure 13 Diagram of storages and crop water users in the Mu River sub-catchments

A.2.9 Urban/domestic water use

Non-crop water use is included in the Source baseline model of the ARB as a function of population per District per sub-catchment. The only exception is Mandalay, where annual surface and ground water use data for the city was available (Table 9). However, these values do not include industrial use within Mandalay, which is largely from privately owned tube-wells, and could not be included in the model.

Table 9 Urban water use in Mandalay (2016)

	m^3 per day
Surface	145 000
Groundwater	59 000

Hasman (2014) divided domestic water use in Myanmar into rural and urban, and then further according to season (wet or dry). He used the following assumptions to estimate domestic water use:

- Rural: 45 litres/capita/day: x 1.25 (dry season), x 0.75 (monsoon season)
- Urban: 95 litres/capita/day: x 1.25 (dry season), x 0.75 (monsoon season

Population figures per Township are available based on the 2014 population census. Townships are classified for Source according to predominantly urban or rural based on the following assumptions:

- > 500 pop/km^2 = Urban
- < 500 pop/km^2 = Rural

Township population numbers are summarised by District to match the scale of the crop water use being used in the model. These numbers are converted to population density per District and scaled according to the proportion of each District within the ARB. The figures are then allocated to each model sub-catchment according to the proportion of District per sub-catchment, and qualitatively classed as predominantly Urban or Rural by referring back to the original Township classes. A major assumption of this approach is that population density is equally distributed across a Township, District or sub-catchment.

Domestic water use is then estimated per sub-catchment as a function of the population and season according to the assumptions of (Hasman, 2014).

A.3 Baseline

While attempting to have a baseline model as recent as possible, the choice of model baseline was ultimately determined by the availability of inputs and observed calibration data sets.

Table 10 lists the dates and temporal scale of the availability of the relevant data layers. Together with the temporal availability it is also important to consider the relevance of the spatial scale of these layers. Information should be available across the entire area of the ARB being modelled. The 2014 land cover layer (IWMI, 2014) was chosen as the most recent reference base for cropping areas. The model is set up to include progression across the basin from 1981 till the end of 2016, with 2014/2015 being considered the baseline for comparison.

Only storages which have been completed before 2017 are configured in the baseline model: 22 major storages and 17 notional storages. However, sub-catchment areas have been identified for all known planned storages and storages under construction up until 2030, allowing for future plan scenarios to be configured as required.

Table 10 Availability of essential model layers

	Temporal	Spatial
Land cover	2014	Whole ARB
Rainfall	1981 – 2017 daily	Whole ARB
Temperature	1981 – 2012 daily (extended to 2017)	Whole ARB
Observed discharge	1986 – 2015 daily	At 9 sites across the ARB
Crops	2000/2001 scaled to 2014 FU areas	Whole ARB at District level
Urban/domestic water use	2014 and 2016	Whole ARB at Township level
Storage volumes	Various dates as commissioned	Whole ARB
Flood damage	2015 for detailed values	Various sites across the ARB

A.4 Crop Modelling

A.4.1 Irrigator Crop Demand Model

The irrigator crop demand model was developed by eWater by combining the best functionality from existing models into a common demand model. A key focus was on keeping the model as simple and parsimonious as possible, while not compromising the key functional requirements. It operates on a daily basis generating demands and extracting water to meet these demands via the water user and supply nodes. The crop water balance for each crop is represented using the method outlined in 'FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration – Guidelines for computing crop water requirements' (Allen et al, 1998).

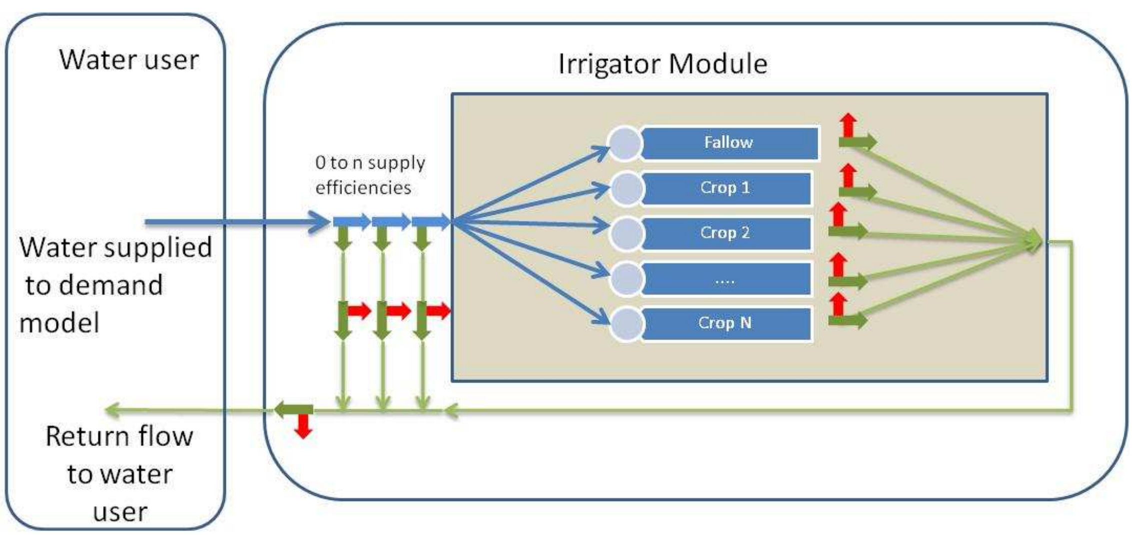


Figure 14 Schematic of the Irrigator Demand Model

The model (illustrated above in Figure 14) can be conceptualised to represent either an irrigation area or an individual irrigator, and also allows crop and water supply based planting decisions, which better aligns with economic modelling. Each district can be configured to have as many cropping areas as desired. Cropping areas are configurable to represent crop specific characteristics and planting decisions can reflect crop water use. Each instance of an Irrigator model is automatically configured to contain a fallow crop. The number and size of cropped areas can be configured to change over time in response to available resource, configurable planting decisions and decision dates.

Irrigator maintains a daily water balance for each cropping area during its growing season to calculate the daily soil water deficit and an irrigation requirement. A water balance of the fallow crop is also maintained and used to initialise the soil moisture store when new crops are established. The fallow cropping area does not order or receive irrigation water. Each crop (including fallow) will generate runoff if the soil profile reaches saturation. A proportion of runoff can be configured to return to the river system. Fluxes represented in the daily water balance include effective rainfall, irrigation, runoff, evapotranspiration, deep percolation that affect changes in soil water storage.

The total requirement for the district is calculated by summing each of the individual cropping area requirements. The district requirement is then adjusted to allow for any district delivery supply escapes and losses associated with delivering water to the district.

When water is supplied, district losses/escapes are firstly removed, and the remaining water is distributed to the crops in proportion to the original demand, crop losses and soil depletion for each crop are updated. Crop losses that can be harvested are summed and added to the harvestable district losses/escapes. The total harvested volume is then returned to the water user, where it can either be stored in the water user storage, returned to the river system or treated as a loss. Return flows from the Water User can be routed to account for delay.

A.5 Rainfall-Runoff modelling

The selection of a model should be based on an understanding of the objectives and the system being modelled (Vaze et al, 2012) and compromises have to be made around the appropriate level of model complexity to adopt. As models gain complexity, or expand the processes represented, the demand for data to calibrate and validate them increases. This data is often not available or is inadequate. Hence, a balance has to be struck between model complexity, availability of data for model calibration and validation, and model predictive performance (Black et al, 2011).

A key consideration is that the model that is chosen should not have more parameters requiring calibration or a greater level of detail than the available data can support, to minimise problems of spurious results and false calibrations (Vaze et al, 2012). This connects with the principle of model parsimony - choose the simplest model that meets the needs of the project and provides an adequate fit to the data. A more 'complicated' rainfall runoff model will have a larger number of parameters, which theoretically increases its flexibility to match the actual recorded flows from a catchment. However, more complex models are more time consuming and expensive to develop and calibrate, more computationally intensive, difficult to analyse, and can 'over-fit' to errors in the data instead of real flows from the catchment.

eWater Source provides an integrated modelling platform that allows for the definition of hydrological processes and water users at various spatial and temporal scales. This provides a flexible modelling environment which can adapt in complexity according to data availability and the detail required in the processes being modelled. Within this it includes a range of rainfall-runoff modelling options for estimating catchment water yield and stream flow data, and a selection of demand models to model crop water use.

Four discrete contributions are identified within the ARB which impact on the choice of rainfall-runoff model. Four rainfall-runoff model options are applied at Functional Unit (FU) scale in the Source model of the ARB (Table 11). Rainfall and PET are inputs to all four models, with temperature also being an input to the snowmelt model. Table 11 provides a summary of the scales at which the models and inputs are applied.

Table 11 Model scale

Process	Spatial scale	Time step
General land cover rainfall-runoff	Functional unit	Daily
Snowmelt	Elevation band FU (400m interval)	Daily
Open water	Functional unit	Daily
Monsoon agriculture	Functional unit	Daily
Rainfall	Source Sub-Catchment	Daily
PET	Source Sub-Catchment	Daily
Temperature	Elevation band (400m interval)	Daily

A.5.1 GR4J for rainfall-runoff modelling and GR4JSG for snowmelt modelling

a) GR4J

Model parsimony is one of the key considerations in choosing a rainfall-runoff model. The GR4J rainfall-runoff model in Source is chosen because it has modest data requirements but also has been widely tested on large sets of catchments in France and in other countries, using demanding testing frameworks (Andréassian et al, 2009). It has been compared with other hydrological models and, despite its simplicity, provided comparatively good results (see eg. Perrin et al, 2001; Perrin et al, 2003; Vaze et al, 2011).

The GR4J rainfall-runoff model outputs daily surface flow, expressed in mm/day. It is an empirical-conceptual, spatially lumped model (Figure 15 Schematic of the GR4J rainfall-runoff model) that contains two stores and has four parameters: x_1, x_2, x_3 and x_4 (Table 12).

Table 12 Rainfall-runoff parameters in GR4J and their default values

Parameter	Description	Units	Default	Range
x_1	Capacity of the production soil store	mm	350	[1, 1500]
x_2	Water exchange coefficient	mm	0	[-10.0, 5.0]
x_3	Capacity of the routing store	mm	40	[1, 500]
x_4	Time parameter for unit hydrographs	days	0.5	[0.5, 4.0]

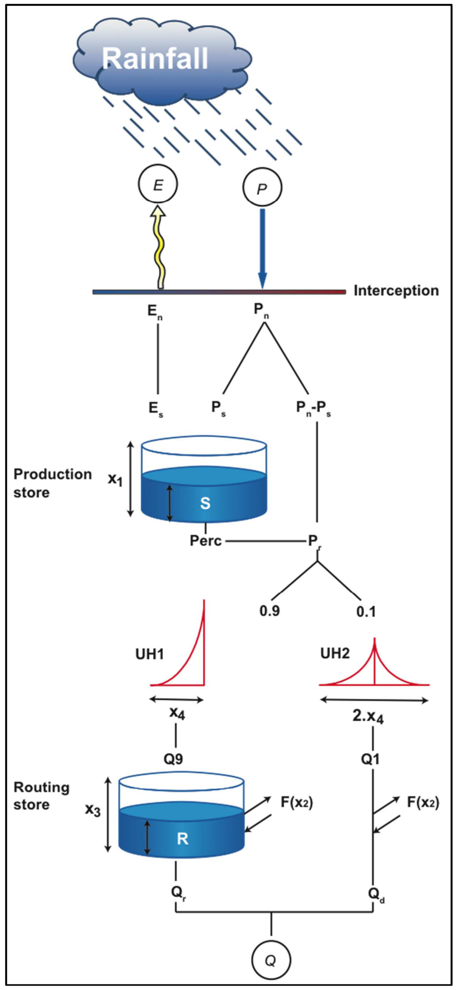


Figure 15 Schematic of the GR4J rainfall-runoff model

b) GR4JSG

GR4JSG is an adaptation of the GR4J model to include parameters describing snow and ice-melt dynamics (Nepal et al, 2016 and Nepal et al, 2015). Snow and glacier processes are represented by the addition of two conceptual stores – one for snow and one for ice (Figure 16). Precipitation is considered as either liquid (rainfall) or solid (snow), depending on temperature. The snow store represents snow accumulation and snow melt, while the ice store represents glacier melt processes. Snow is accumulated in the snow store and is melted in the model before to glacier melting. Temperature drives the accumulation and melt processes.

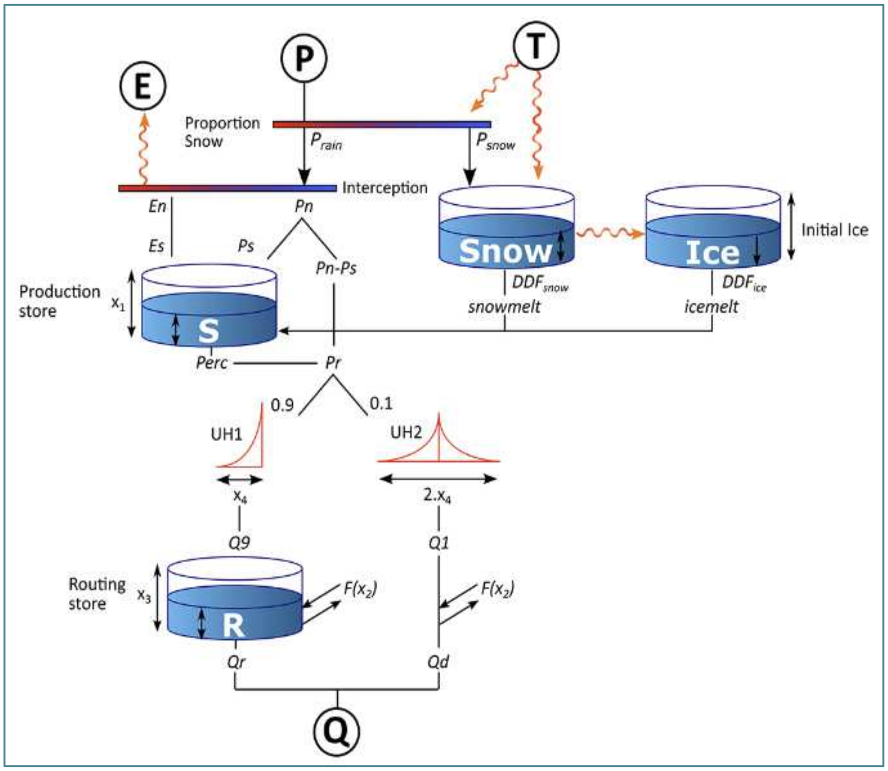


Figure 16 Schematic Representation of the GR4JSG model

A.5.2 Modelling rain-fed agriculture as a Functional Unit

According to the IWMI land cover classification system (IWMI, 2014) the rain-fed Functional Unit represents areas which only show cropping during the monsoon season. For modelling purposes these crops are assumed to be exclusively rain fed and are modelled at the Functional Unit scale by the Agricultural Runoff model. The Agricultural Runoff model is an application of the Irrigator Crop Demand Model which represents crop water balance using the method outlined in 'FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration – Guidelines for computing crop water requirements' (Allen et al, 1998) described in the Crop Model section of this document. This model assumes that crop growth during the monsoon season is considered as driven solely by rainfall, evapotranspiration and soil moisture availability, with no irrigation requirements. Hence it does not need to be connected as a node to extractions from a storage or a river, and can be represented purely as a Functional Unit area within the sub-catchment. Runoff from this Functional Unit is added to total catchment outflow, and can be routed to account for delay and attenuation.

A.5.3 Modelling water bodies as a Functional Unit

Areas defined as water are modelled differently to other Functional Units. There are several ways to model water in eWater Source, all of which are applied in the ARB model:

a) The water body takes up a substantial part of the sub-catchment area and is associated with a storage which is going to be modelled as a Storage node - in this case the water can be modelled using the Nil Rainfall-Runoff model option. Add the rainfall and evaporation associated with this FU to the storage during storage configuration.

b) The water body takes up a substantial part of the sub-catchment area but is not associated with a storage which is going to be modelled as a Storage node (e.g. a very wide river surface) - in this case the water can be modelled using the Open Water Rainfall Runoff Model Source plugin which allows for the addition of rainfall to the surface and loss from the surface through evapotranspiration.

c) The water body is very small relative to the sub-catchment area - in which case it is ignored and modelled as Nil Rainfall Runoff.

A.6 Model calibration

According to Vaze et al (2012) model calibration is the process of optimising or systematically adjusting rainfall-runoff model parameter values to get values which give the best estimate of observed flow. The level of accuracy in this estimate which is considered acceptable will depend on the purpose of the model. The metric used to measure the 'success' of a calibration is then also chosen according to the purpose of the model. It is also important to note that, since calibration involves comparison of model results with recorded data, it is essential for suitable data to be available if a useful and meaningful calibration is to be achieved.

A.6.1 Assessment of Recorded flows for calibration purposes

Under AWP Activity 1, hydrographic surveys and rating table reviews were undertaken at five sites on the Chindwin and Ayeyarwady Rivers: Kalewa on the Chindwin River and Katha, Sagaing, Nyaung U and Zalun on the Ayeyarwady River (Walker et al, 2017). The results of this survey were taken into consideration when choosing sites for calibration of the Source model.

Available discharge sites are shown in Figure 17. According to the rating table review undertaken by AWP Activity 1 the sites at Katha and Nyaung U were found to be the least reliable. These sites were, therefore, not included in the Source model calibration. Nyaung is the first observed discharge site downstream of the Chindwin-Ayeyarwady confluence. An analysis of the observed flows at Nyaung U compared with those upstream at Monywa on the Chindwin River and Sagaing on the Ayeyarwady River revealed several inconsistencies. Figure 18 compares flows at Nyaung U with the flows at Monywa and Sagaing, and Figure 19 highlights the fluctuating trends in minimum annual daily flow rates over time. The sum of flow at Monywa and Sagaing versus flow at Nyaung U is shown in Figure 20. The Myitnge River catchment (which includes the Panlaung River) and the Mu River catchment join the Ayeyarwady River downstream of Sagaing (Figure 17). There are no flow measurements available for these catchments, and therefore their contribution to the total flow at Nyaung U is unknown. While for most years flow at Nyaung U is higher than the sum of flows at Sagaing and Monywa, there are also some years when that is not the case. It is uncertain whether differences in recorded flows can be considered a representation of contributions from the sub-catchments downstream of Sagaing and Monywa. However, it is likely that errors in the rating curves are contributing to the discrepancies. Five lines of evidence support this:

- The river in the central dry zone should gain flow from groundwater (Drury, 2017), therefore flow at the downstream gauge should exceed the sum of the flows at the upstream gauges
- The AWP Activity 1 investigation into the reliability of rating curves in the ARB
- The apparent reduction in minimum dry season flow rates with time, especially at Sagaing (Figure 19), which is more likely due to changes in rating curve (flow rate versus stage relationship) than a real reduction in flow rates
- The reduction in recorded annual flows over time at Sagaing, compared with modelled (Figure 21). The next relatively reliable gauge downstream, Magway, shows no such trend to reducing annual flows

- Different ratings were developed for some gauges at different times (ANNEX III - Observed Water Level vs Discharge)

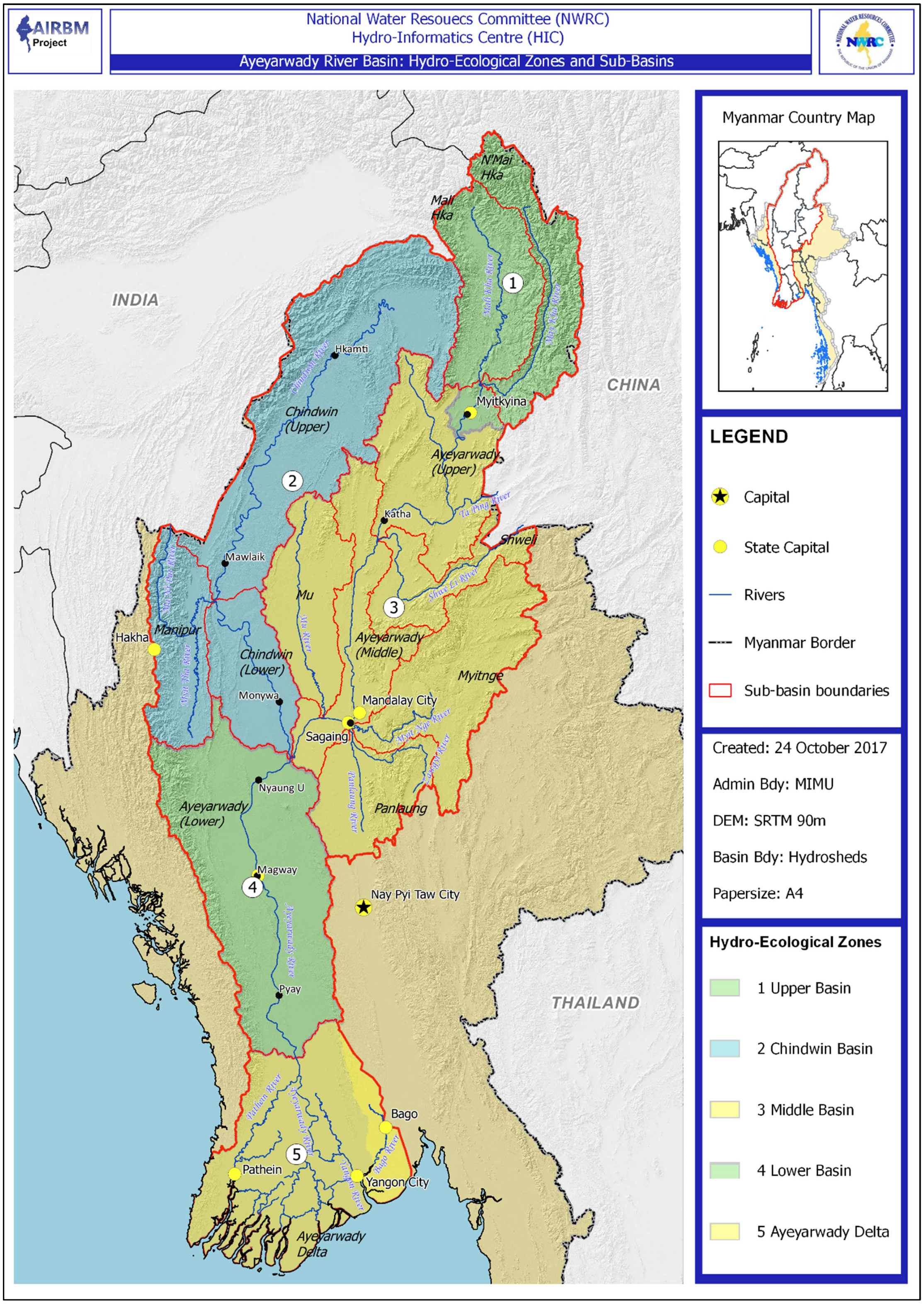


Figure 17 Sub-basins and discharge sites

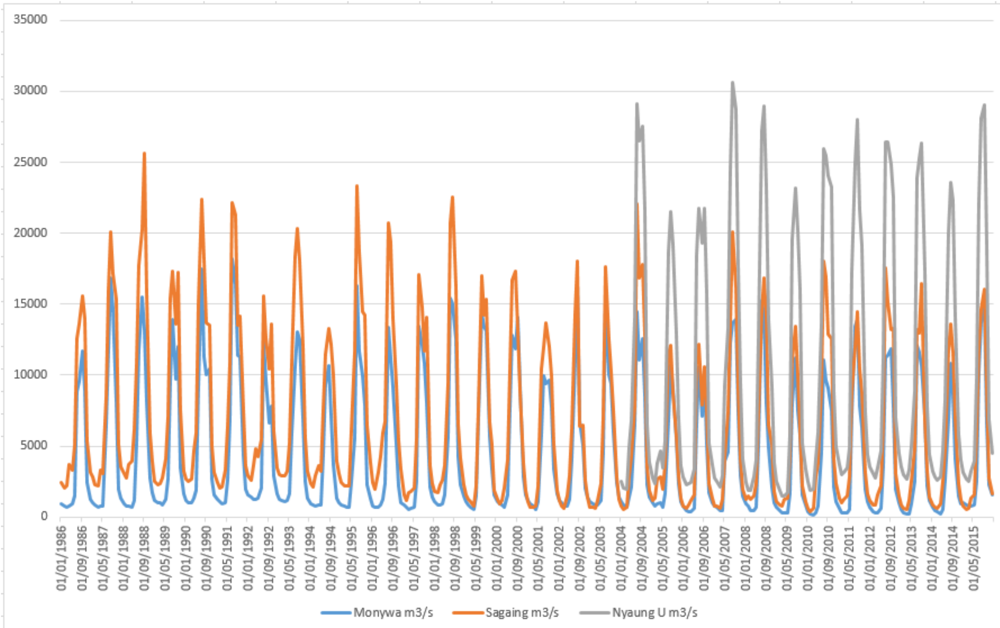


Figure 18 Comparison of mean monthly recorded flows at Nyaung U, Monywa and Sagaing

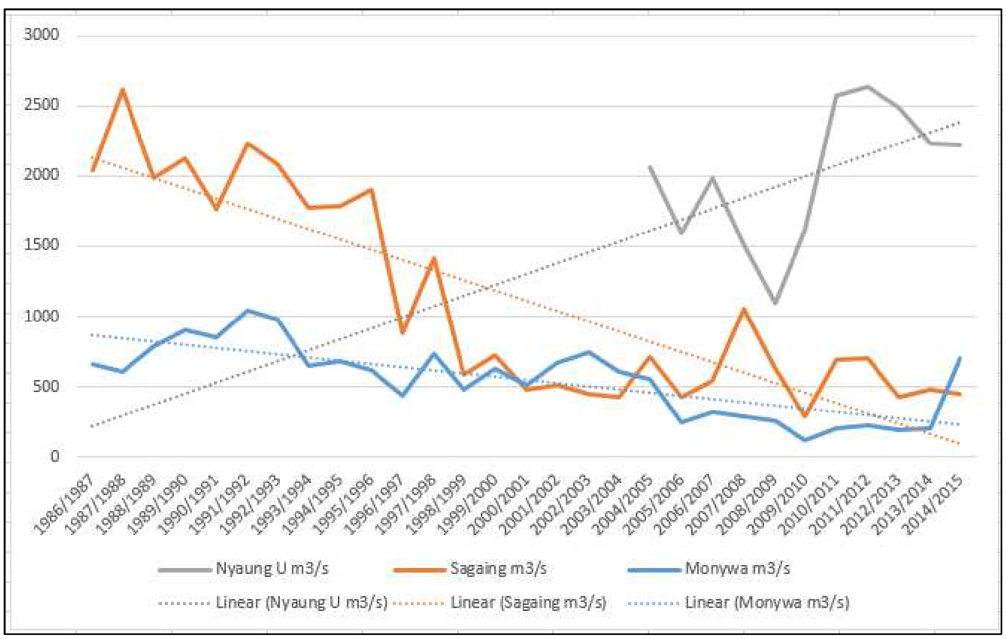


Figure 19 Trends in recorded minimum annual daily flow rates at Nyaung U, Monywa and Sagaing (Year start is 01 August)

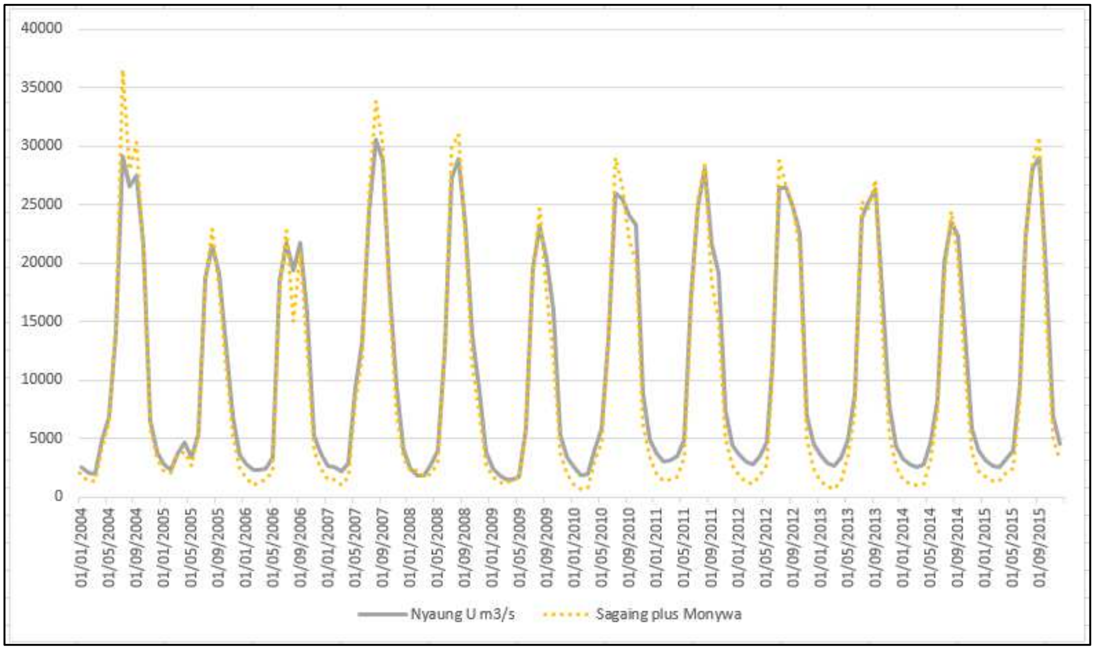


Figure 20 Flow comparisons at Nyaung U

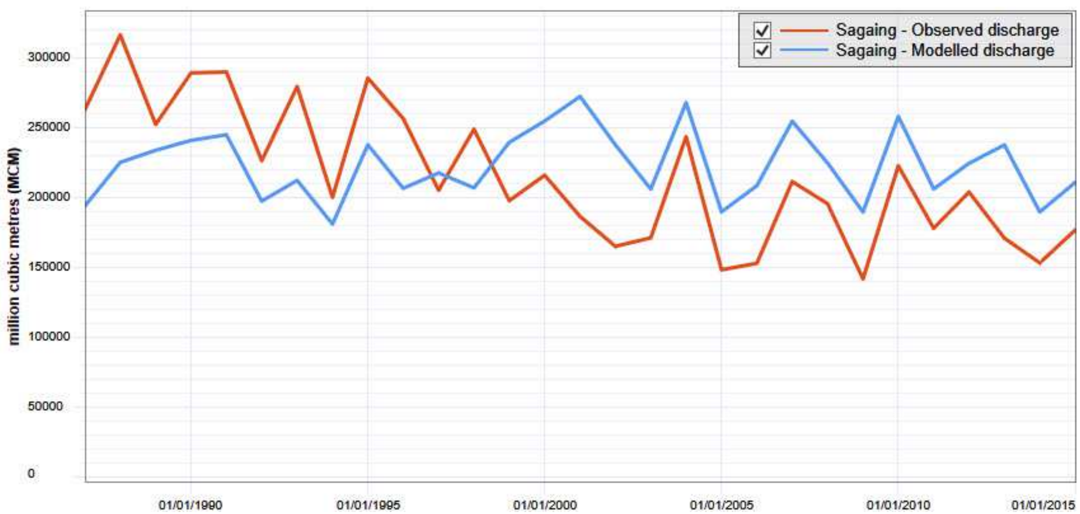


Figure 21 Comparison of modelled and recorded annual flows at Sagaing showing anomalous reduction in recorded flows

An analysis of observed water levels vs recorded discharge at all nine discharge sites in the basin illustrated the changes in rating curves used at each site. Charts illustrating observed water levels vs observed discharge are presented in 'ANNEX III - Observed Water Level vs Discharge'. Many sites indicate more than one curve has been used, but it is unknown when this change in rating curve was applied. In sites where one rating curve appears to have been applied, it is unknown when this curve was derived and probable that the rating curve will changed since this dated.

A.6.2 Observed rainfall assessment for calibration purposes

Five global remotely-sensed rainfall products were compared to observed rainfall data. The results of this comparison are shown on 'ANNEX II - Climate data review'. CHIRPS rainfall was chosen as the best fit to the observed rainfall. The worst performing site, in all instances is at Hkamti, where the CHIRPS rainfall volume is as little as half the measured rainfall for the same time period (Figure 22). This has implications for calibration at the Hkamti stream flow gauge and must be taken into consideration when examining calibration results at this flow gauge.

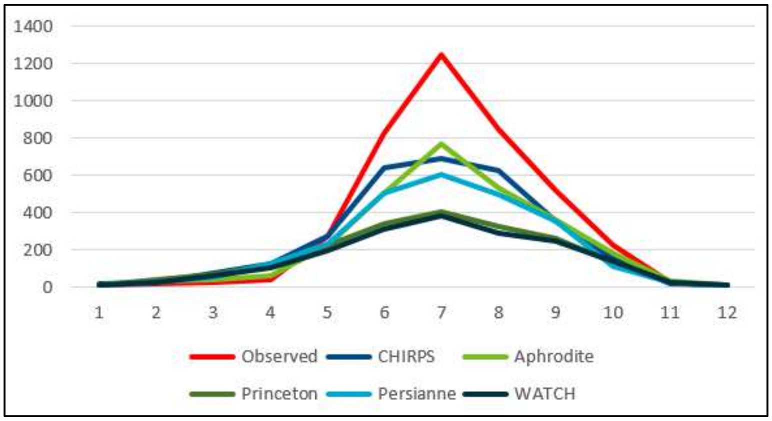


Figure 22 Mean monthly rainfall (mm) at Hkamti

A.6.3

A.6.4 Calibrated flows

Both automatic and manual calibration methods were applied to the calibration of modelled to simulated discharge in the ARB. Six calibration regions were identified (Figure 23):

- Upstream of Myitkyina, including both snowmelt and flows
- The Middle Basin between Myitkyina and Sagaing, including flows from the Shweli Sub-Basin. After the findings of Walker et al (2017) Katha is not included in the calibration
- Sagaing to Magway, which includes flows from the MU, Panlaung and Myitnge Sub-Basins. After the findings of Walker et al (2017) Nyaung U is not included in the calibration
- Lower Ayeyarwady Basin, Magway to Pyay
- Upper Chindwin Basin north of Hkamti
- Chindwin Basin from Hkamti to Monywa

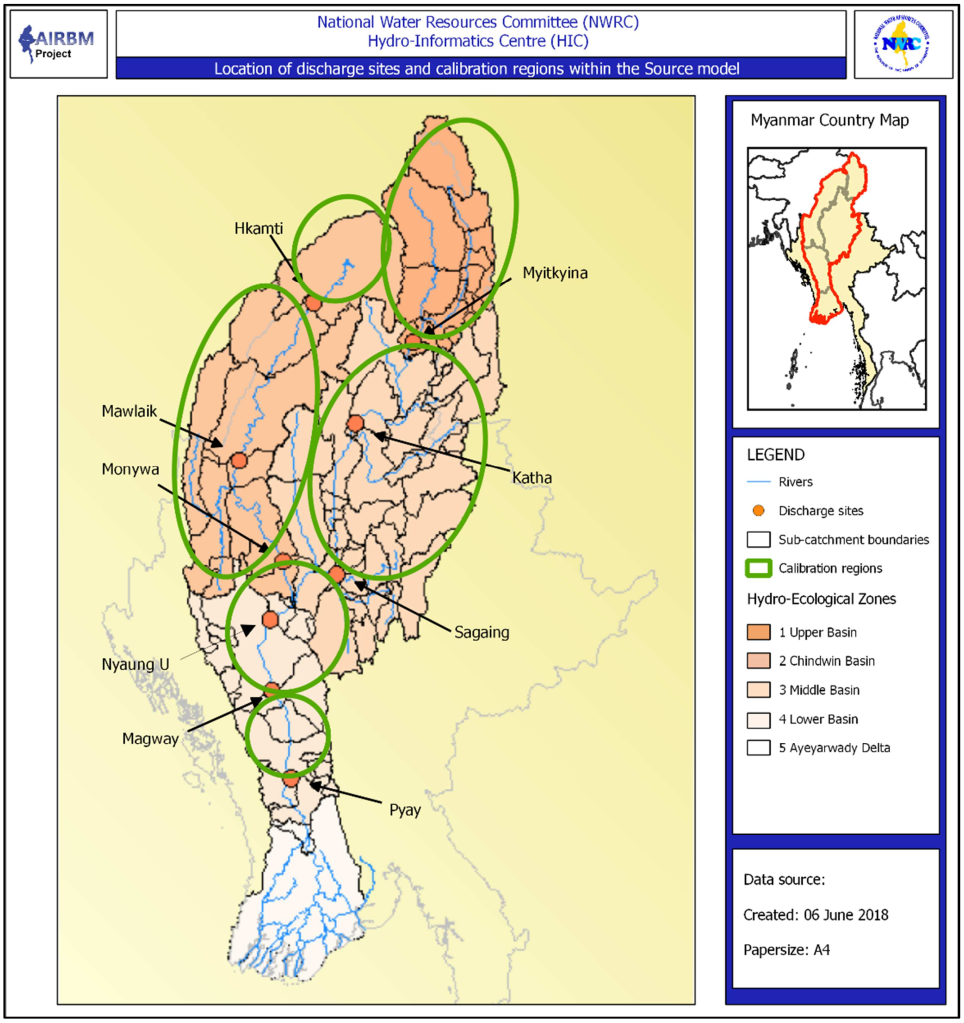


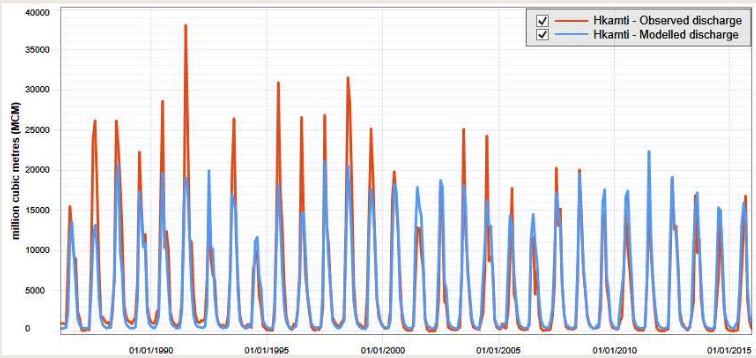
Figure 23 Observed discharge sites and calibration regions

Matching both high flows and low flows is considered important in the calibration of this model. Therefore, objective functions were chosen which will reflect these, and separate calibration runs were done focussing on each.

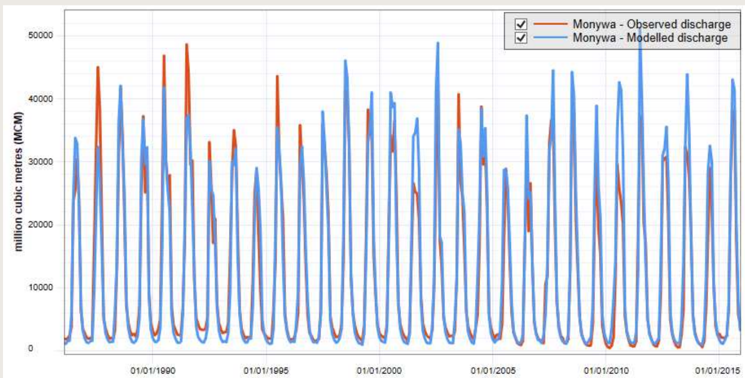
The Nash Sutcliffe Coefficient of Efficiency (NSE) is biased towards matching high flows, and this was used to calibrate for high flows to facilitate flood analyses. It was found that, since the volume of the rainfall during the flood season is not accurately represented by the remotely-sensed data in all parts of the basin, very high flows were frequently underestimated by the modelled data, while in some seasons a low wet season has been overestimated. Until improved rainfall inputs can be found, the model is limited to only broad applications for flood analyses.

A combined Log NSE and Bias Penalty objective function was tested to obtain a general calibration aimed at reproducing low flows. It was found that this objective function did not perform specifically better than the calibration already achieved with NSE only. Table 13 presents observed and modelled discharge and comparison statistics for each of the six calibration regions.

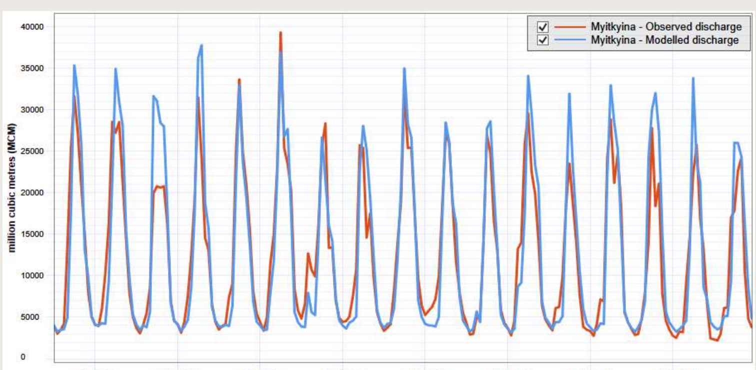
Table 13 Observed and modelled total monthly discharge



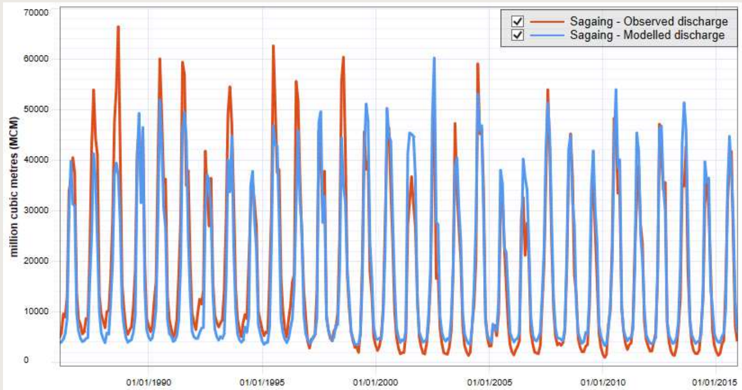
Pearson's Correlation (r)	0.908
Volume Bias (%)	-5.414
Minimise Absolute Bias	0.054
NSE Daily	0.819
NSE Daily & Bias Penalty	0.816
NSE Daily & Flow Duration	0.876
NSE Daily & log Flow Duration	0.522
NSE Log Daily	0.854
NSE Log Daily & Bias Penalty	0.851
NSE Monthly	0.819
NSE Monthly & Bias Penalty	0.816
Square-root Daily, Exceedance, and Bias	870908.613



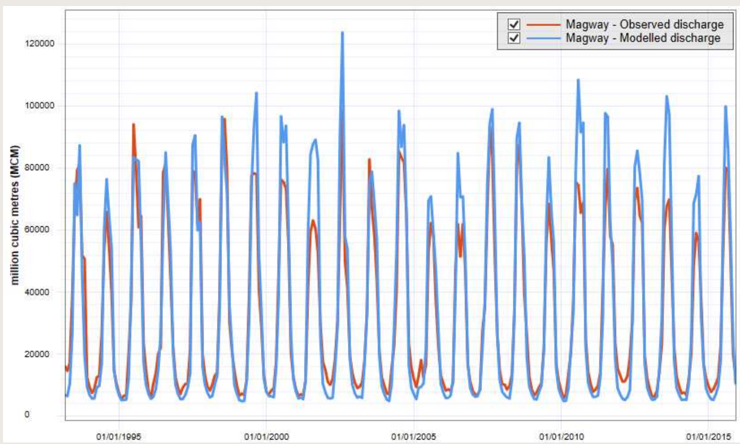
Pearson's Correlation (r)	0.963
Volume Bias (%)	4.862
Minimise Absolute Bias	0.049
NSE Daily	0.912
NSE Daily & Bias Penalty	0.91
NSE Daily & Flow Duration	0.951
NSE Daily & log Flow Duration	0.942
NSE Log Daily	0.938
NSE Log Daily & Bias Penalty	0.936
NSE Monthly	0.912
NSE Monthly & Bias Penalty	0.91
Square-root Daily, Exceedance, and Bias	532789.386



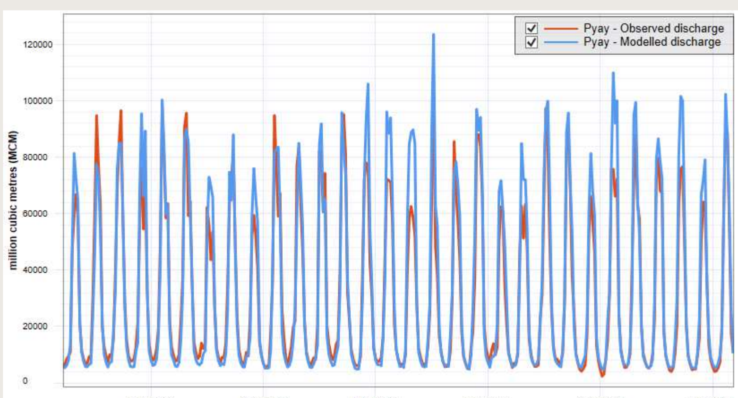
Pearson's Correlation (r)	0.934
Volume Bias (%)	3.429
Minimise Absolute Bias	0.034
NSE Daily	0.813
NSE Daily & Bias Penalty	0.812
NSE Daily & Flow Duration	0.881
NSE Daily & log Flow Duration	0.885
NSE Log Daily	0.859
NSE Log Daily & Bias Penalty	0.858
NSE Monthly	0.813
NSE Monthly & Bias Penalty	0.812
Square-root Daily, Exceedance, and Bias	506589.688



Pearson's Correlation (r)	0.931
Volume Bias (%)	-3.263
Minimise Absolute Bias	0.033
NSE Daily	0.865
NSE Daily & Bias Penalty	0.864
NSE Daily & Flow Duration	0.925
NSE Daily & log Flow Duration	0.895
NSE Log Daily	0.879
NSE Log Daily & Bias Penalty	0.878
NSE Monthly	0.865
NSE Monthly & Bias Penalty	0.864
Square-root Daily, Exceedance, and Bias	1316295.994



Pearson's Correlation (r)	0.97
Volume Bias (%)	5.526
Minimise Absolute Bias	0.055
NSE Daily	0.867
NSE Daily & Bias Penalty	0.863
NSE Daily & Flow Duration	0.901
NSE Daily & log Flow Duration	0.896
NSE Log Daily	0.91
NSE Log Daily & Bias Penalty	0.907
NSE Monthly	0.867
NSE Monthly & Bias Penalty	0.863
Square-root Daily, Exceedance, and Bias	2374352.275



Pearson's Correlation (r)	0.97
Volume Bias (%)	8.212
Minimise Absolute Bias	0.082
NSE Daily	0.9
NSE Daily & Bias Penalty	0.891
NSE Daily & Flow Duration	0.932
NSE Daily & log Flow Duration	0.942
NSE Log Daily	0.953
NSE Log Daily & Bias Penalty	0.944
NSE Monthly	0.9
NSE Monthly & Bias Penalty	0.891
Square-root Daily, Exceedance, and Bias	1620666.134

ANNEX II - CLIMATE DATA REVIEW

The analysis included in this section was undertaken by CSIRO as part of AWP Activity 2 contributions to the SOBA. It has been copied verbatim from the report by Podger (2017).

A.7 Background

Rainfall, temperature and evapotranspiration gridded data sets are required as inputs into catchment and river system models being developed for the Ayeyarwady river Basin in Myanmar. This report compares a range of climate data products against respective observed climate data. It makes recommendations of the most suitable climate data, merges data sets with bias correction and generates an evaporation climate data set of potential evapotranspiration based on temperature data products and Hargreaves method.

A.7.1 Gridded climate data products

5 gridded climate data products were considered as part of this assessment. The product resolution, period of record and climate variables are detailed in Table 1. Details of the various products are provided below.

Table 1 Gridded climate data product details

Climate data product	Resolution	Precipitation	Period	Temperature	Period
CHIRPS	0.05 degree	Yes	1/1/1981-31/03/2017	No	
APHRODITE	0.25 degree	Yes	1/1/1951-31/12/2007	Average	
Princeton	0.5 degree	Yes	1/1/1948-31/12/2008	Tmin & Tmax	1/1/1948-31/12/2008
PERSIANNE	0.25 degree	Yes	1/1/1983-31/082016	No	
WATCH	0.5 degree	Yes	1/1/1979-31/12/2012	Tmin & Tmax	1/1/1979-31/12/2012

A.7.2 CHIRPS

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et. al. 2015) is a 30+ year quasi-global rainfall dataset. Spanning 50°S-50°N (and all longitudes), starting in 1981 to near-present, CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring.

A.7.3 APHRODITE

A daily gridded precipitation and average temperature dataset for the period 1951-2007 was created by collecting and analysing rain-gauge observation data across Asia through the activities of the Asian Precipitation - Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE) of water resources project (Yatagi et. al. 2014). Grid interpolation is based on and Inverse distance Weighting method (Shepherd 1968). A cross validation of the interpolation technique was conducted as part of the Aphrodite method. The method is based on removing 10% randomly selected stations at a time and performing the interpolation for the locations of the removed stations using the remaining 90% stations. This procedure is repeated 10 times to ensure that all stations were withdrawn once. The correlations against the distance between the withdrawn station and the nearest gauge station, and used the distance as a measure of the station density. As a result, the proportion of significant correlations on all correlations decreases more than 30km away.

A.7.4 Princeton

The Princeton dataset developed by the terrestrial hydrology research group of Princeton University (Sheffield et. al. 2006) provides near-surface meteorological data for driving land surface models and other terrestrial modelling systems. It blends reanalysis data with observations and disaggregates in time and space. The dataset is currently available at 0.5 degree, 3-hourly (plus daily and monthly) resolution globally for 1948-2008.

Note: climate reanalysis gives a numerical description of the recent climate, produced by combining models with observations. It contains estimates of atmospheric parameters such as air temperature, pressure and wind at different altitudes, and surface parameters such as rainfall, soil moisture content, and sea-surface temperature.

A.7.5 PERSIANNE

Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANNE) (Hsu et. al. 1997) is a satellite-based precipitation retrieval algorithm. The algorithm uses infrared (IR) satellite data from global geosynchronous satellites as the primary source of precipitation information. Precipitation from IR images is based on statistical relationship between cloud top temperature and precipitation rates. The IR-based precipitation estimates are then calibrated using satellite microwave data available from low Earth orbit satellites such as Tropical Rainfall Measuring Mission Microwave TRMM (Huffman et. al. 2007).

A.7.6 WATCH

The WATCH (WATer and Global CHange) project is a European Union funded project to improve the understanding of the terrestrial water cycle. The WATCH Forcing Data (WFD) is a single data set of climate variables that covers the period 1901 – 2001. It has been produced by combining monthly observations of temperature, "wet days" and cloud cover, plus the GPCCv4 monthly precipitation observations, and the ERA40 reanalysis products (with the addition of corrections for seasonal – and decadal – varying atmospheric aerosols needed to adjust the solar radiation components). WATCH-Forcing-Data-ERA-Interim (WFDEI) was produced post-WATCH using WFD methodology applied to ERA-Interim data. It is a meteorological forcing dataset extending into early 21st C (1979 – 2012). Eight meteorological variables at 3-hourly time steps, and as daily averages.

The seasonal and annual characteristics of Aphrodite, Princeton and WATCH climate products are shown in Figure 1 to Figure 3. The seasonal and annual spatial patterns of these products are similar with rainfall and temperature slightly less in Aphrodite. The wet season is JJA with the largest rainfalls in the south and north-west. There is a drier region in the central basin. The Princeton and WATCH temperatures are very similar. The coldest season is DJF and it is warmer in the south and central basin region. The coldest area is in the mountains in the north of the basin.

Figure 1 Aphrodite mean annual precipitation and temperature

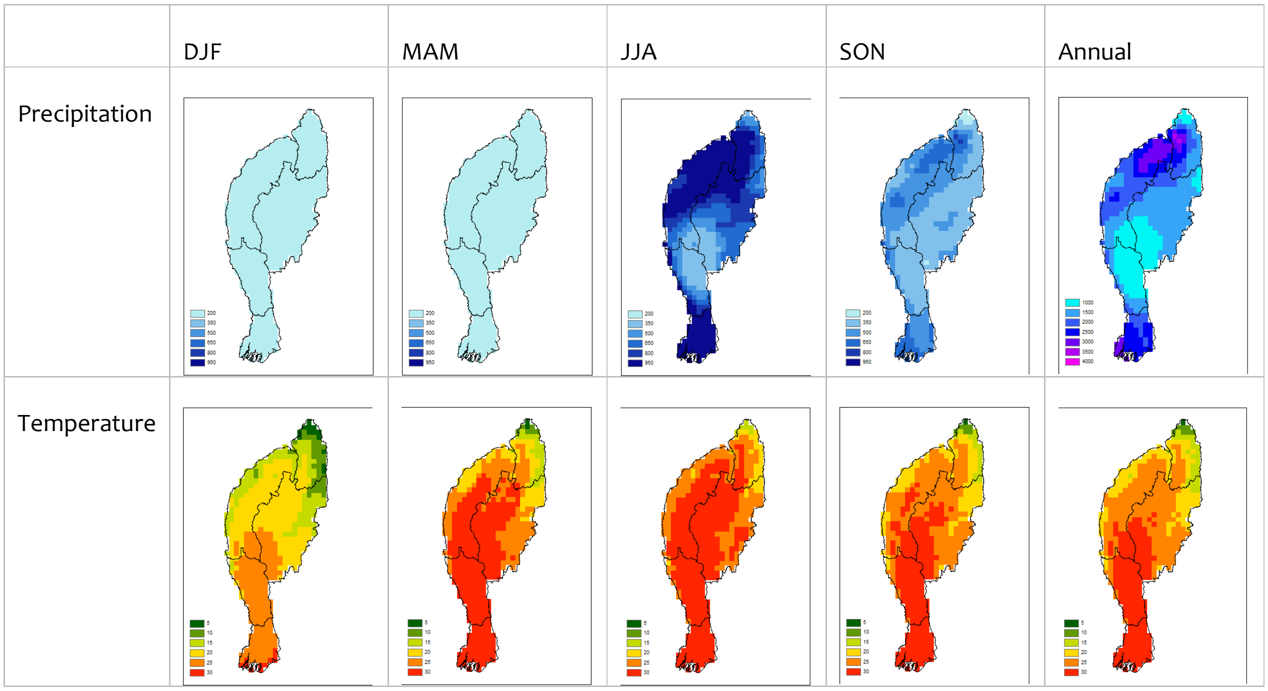
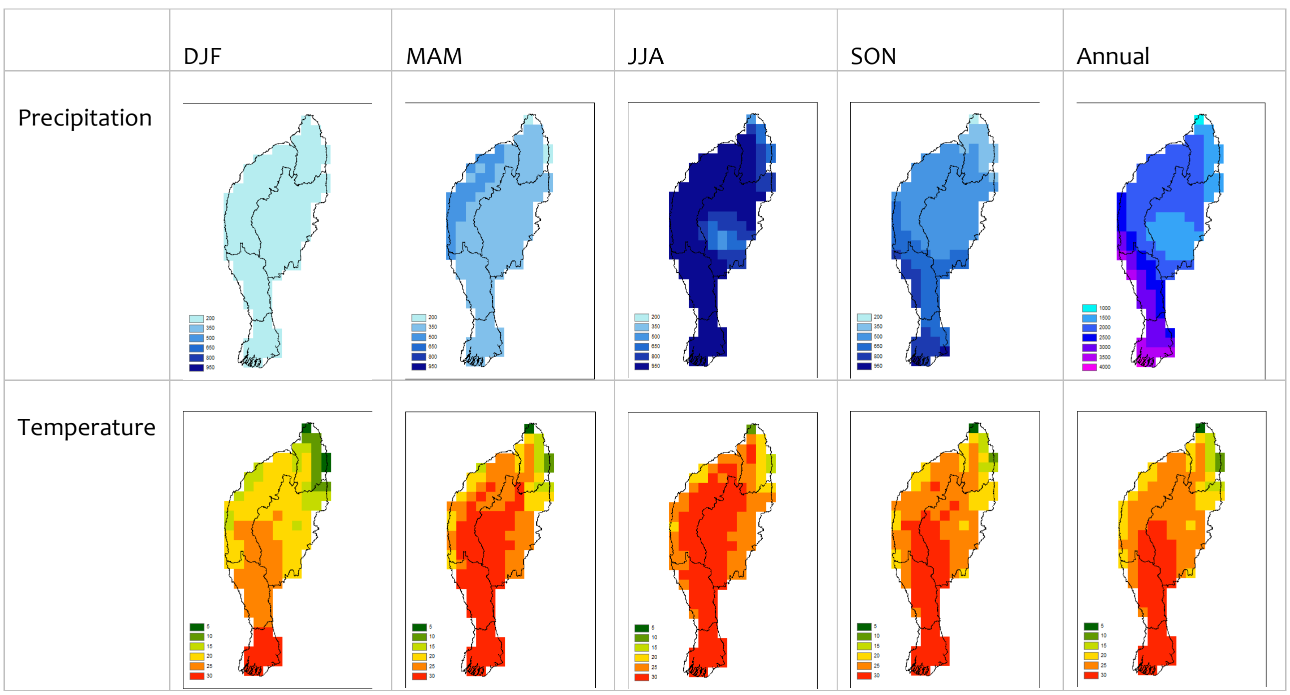


Figure 2 Princeton mean annual precipitation, temperature and PET



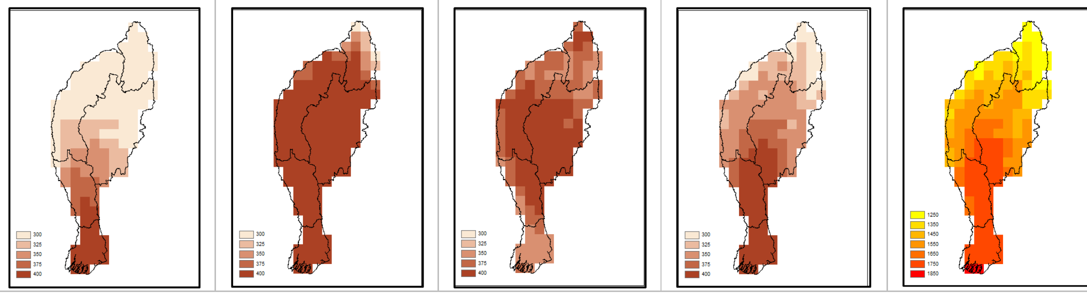
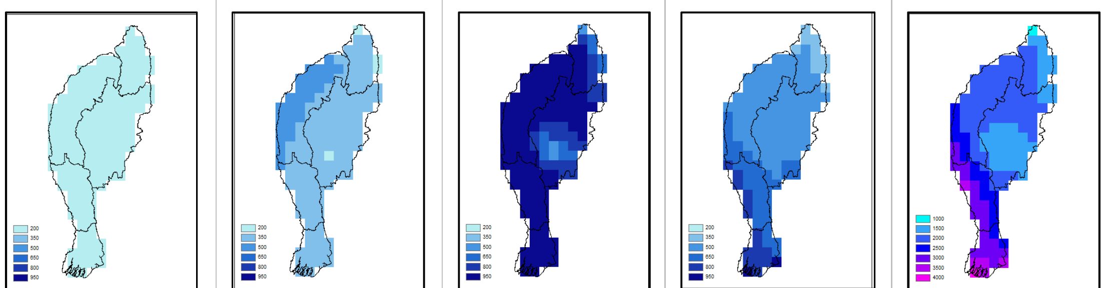
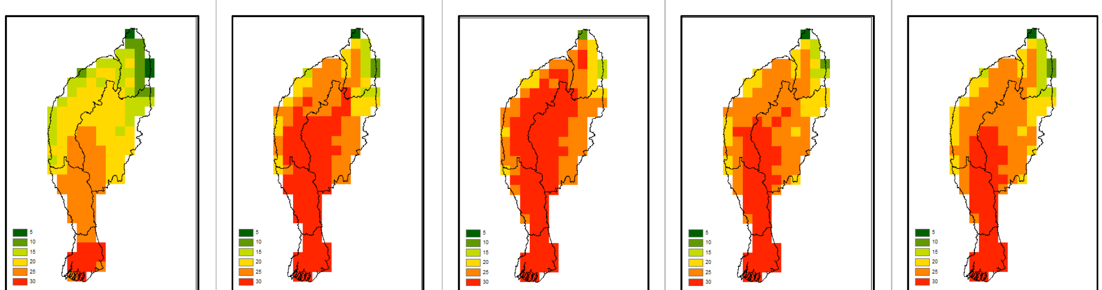
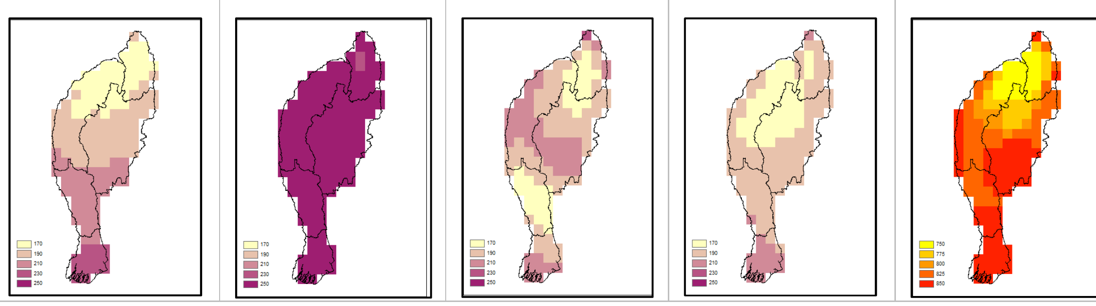
PET					

Figure 3 WATCH mean annual precipitation, temperature and PET

	DJF	MAM	JJA	SON	Annual
Precipitation					
Temperature					
PET					

A.8 Observed data

There is observed rainfall for 19 sites, minimum and maximum temperature for 15 sites and potential evapotranspiration for 1 site. The potential evaporation data was assessed as being unacceptable and was not used for any further analysis.

In terms of the rainfall records most sites have a considerable period of data with occasional breaks. The longest period of record is at Ywatha from 1/1/1980 to 31/07/2016. The Mahu and Kyauk site only have a short record. The Ayartaw site seems to have considerably less rain days compared to other sites and a different rainfall pattern. This may suggest that the data quality is poor at this site.

There are reasonably complete temperature records at all sites spanning from 1/1/1986 to 31/12/2015. The patterns between the different temperature sites are consistent suggesting that all sites are reasonable. Table 2 shows minimum, average and maximum for all sites for minimum and maximum temperatures. The extreme and average values are reasonable for all of the sites.

Table 2 Temperature minimum, average and maximum

Site	Minimum temperature			Maximum temperature		
	Minimum	Average	Maximum	Minimum	Average	Maximum
Bhamo	4.2	19.3	36.4	15.5	30.7	41.5
Gangaw	6.2	20.3	30.2	16.0	32.5	46.4
Hinthada	6.2	21.0	33.5	19.2	33.1	44.0
Hkamti	2.7	18.7	28.0	12.5	29.5	41.3
Katha	2.2	18.3	33.8	16.5	31.4	42.2
Magway	5.0	19.9	29.3	19.5	34.3	46.0
Mandalay	6.0	22.2	32.7	18.5	34.1	46.1
Mawlaik	5.0	20.3	31.0	16.8	31.4	44.3
Minbu	6.0	21.5	33.0	19.3	34.0	45.8
Monywa	7.9	21.5	31.2	17.5	34.2	47.0
Myitkyina	5.5	19.1	29.0	15.2	30.2	40.7
Nyaung U	6.5	22.0	32.8	19.3	34.0	45.2
Pakokku	3.9	21.5	38.9	16.7	33.6	45.1
Pyay	9.8	22.2	29.9	20.0	33.8	44.0
Sagaing	9.8	22.4	33.5	18.5	33.0	44.0

A.9 Assessment of precipitation data sets

Table 3 shows the bias error of CHIRPS, APHRODITE, Princeton, PERSIANNE and WATCH precipitation gridded data sets compared against observed sites. Figure 4 shows a comparison between observed and data product average annual rainfall. Note the Kyauk Talone and Mahu sites have not been included as their records are too short. Generally there are large variances between data products and across sites. With the exception of Aphrodite all other data products over estimate precipitation. CHIRPS is consistently the best or close to best performer with an overall bias of 1%. At the two lowest rainfall sites of Ayartaw and Ywatha most products significantly overestimate rainfall. Noting that Aphrodite performs reasonable well at these sites, which may be due to Aphrodite using these particular sites in its inverse distance weighted method.

Table 3 Bias error of various precipitation gridded data products. The best performing product is highlighted in yellow.

Site	CHIRPS (%)	APHRODITE (%)	Princeton (%)	PERSIANNE (%)	WATCH (%)
Ayartaw	54%	-17%	245%	142%	292%
Bhamo	-2%	-23%	-2%	10%	-9%
Gangaw	33%	-27%	84%	81%	143%
Hinthada	-7%	-14%	16%	5%	25%

Hkamti	-26%	-32%	-52%	-35%	-55%
Katha	-2%	-22%	16%	42%	8%
Magway	0%	-27%	206%	66%	222%
Mandalay	-6%	-35%	33%	59%	50%
Mawlaik	-2%	-17%	9%	34%	11%
Minbu	13%	-18%	247%	87%	265%
Monywa	20%	-17%	117%	131%	196%
Myitkyina	-4%	-24%	-13%	0%	-14%
Nyaung U	31%	-26%	257%	137%	297%
Pakokku	26%	-30%	205%	139%	268%
Pyay	-4%	-17%	107%	44%	139%
Sagaing	0%	-36%	58%	71%	60%
Ywatha	57%	3%	93%	129%	74%
Overall	1%	**-23%**	**47%**	**36%**	**59%**

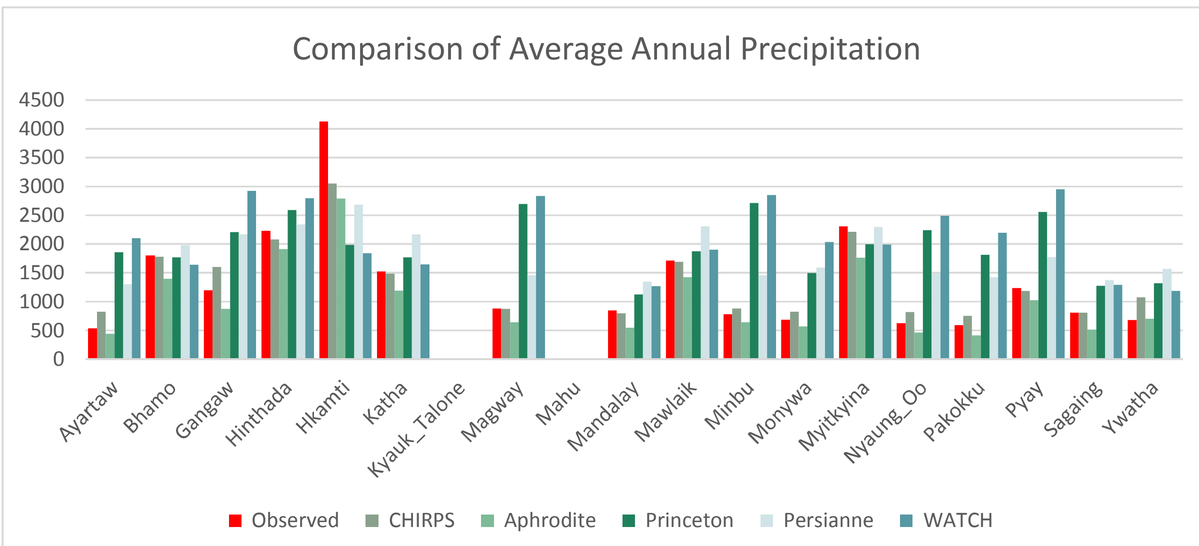


Figure 4 Comparison of average annual rainfall

Figure 5 to Figure 21 show comparisons of mean monthly observed data and precipitation data products. CHIRPS has the most consistent match against observed data with the exception of the Hkamti site where the peak observed monthly precipitation is larger than all data products.

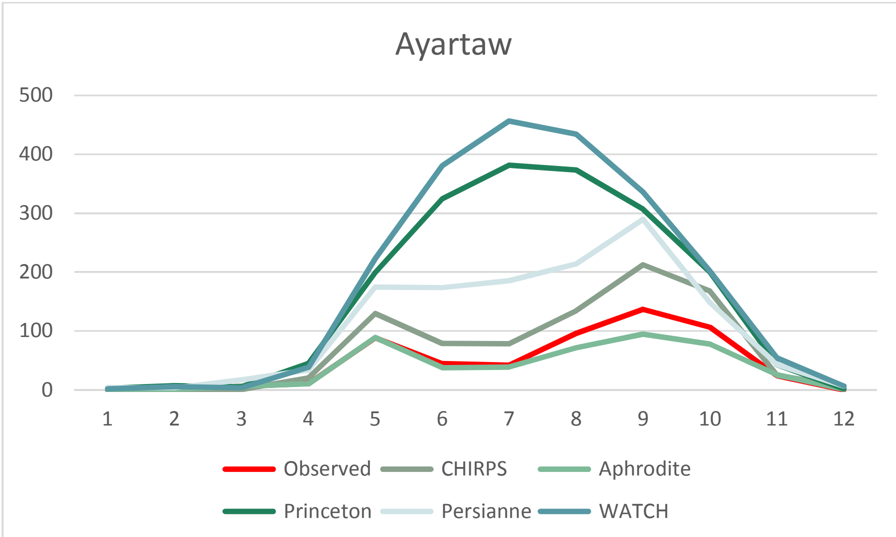


Figure 5 Ayartaw mean monthly precipitation

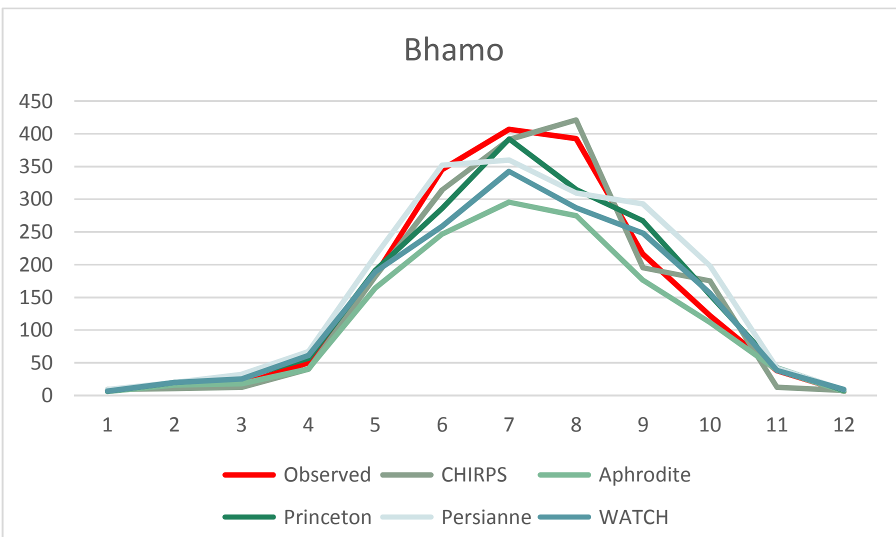


Figure 6 Bhamo mean monthly precipitation

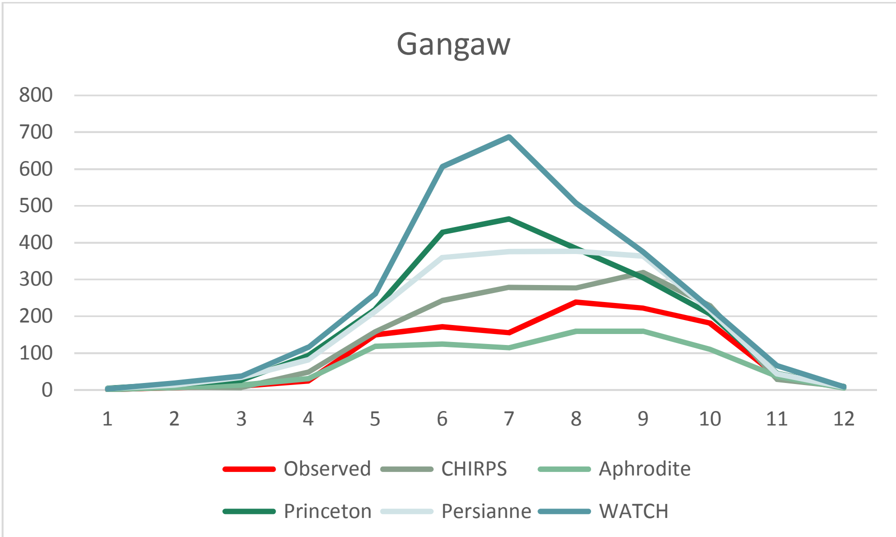


Figure 7 Gangaw mean monthly precipitation

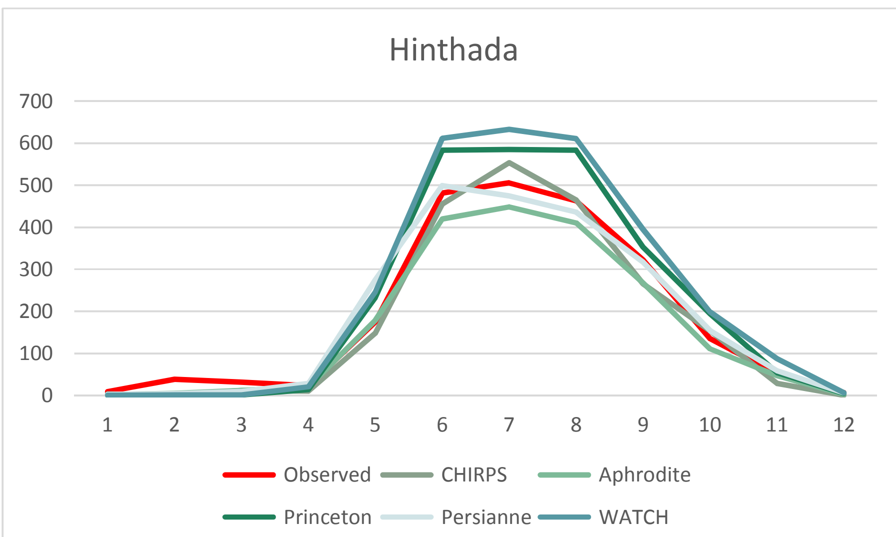


Figure 8 Hinthada mean monthly precipitation

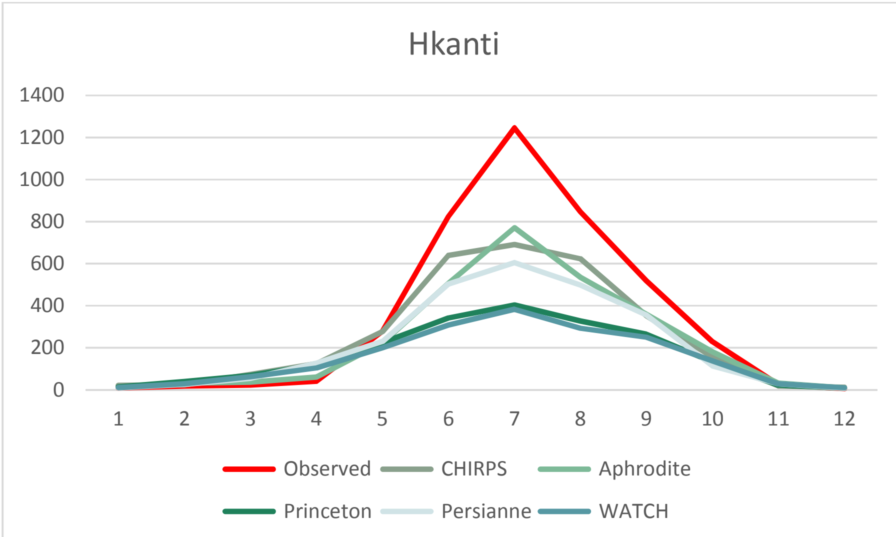


Figure 9 Hkamti mean monthly precipitation

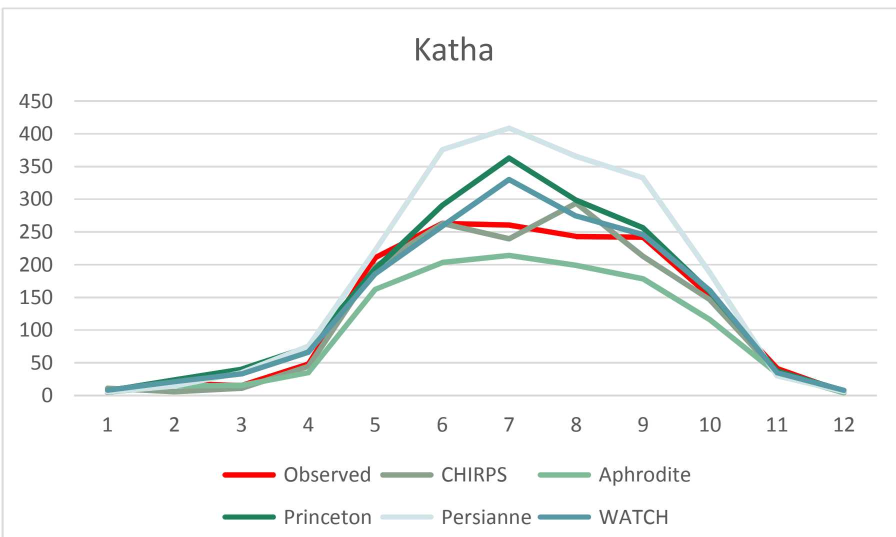


Figure 10 Katha mean monthly precipitation

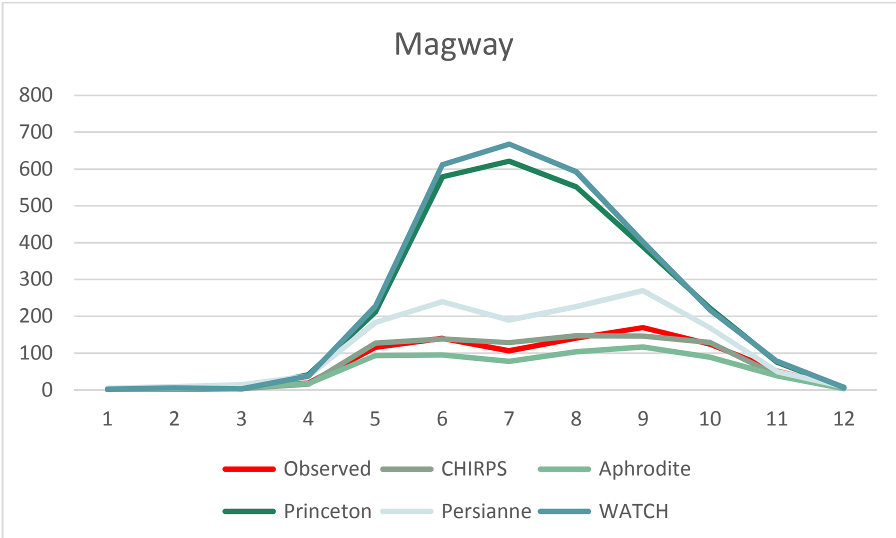


Figure 11 Magway mean monthly precipitation

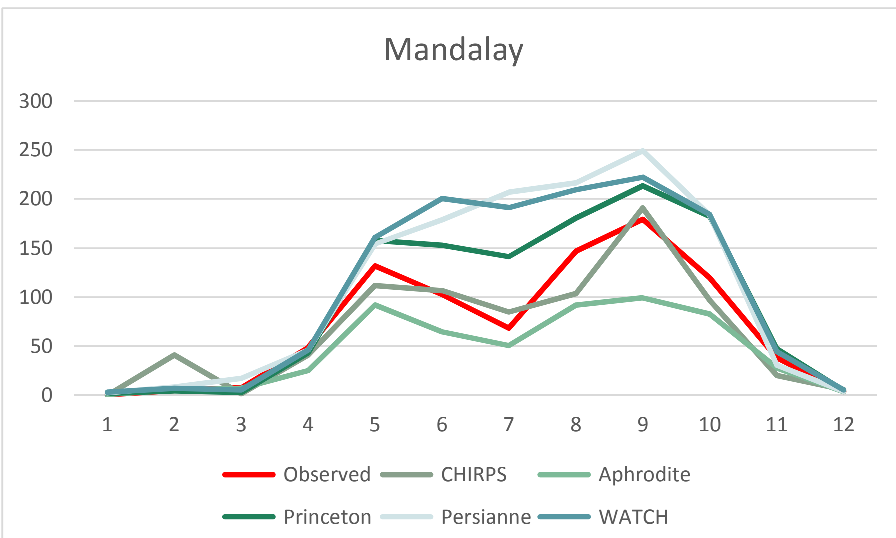


Figure 12 Mandalay mean monthly precipitation

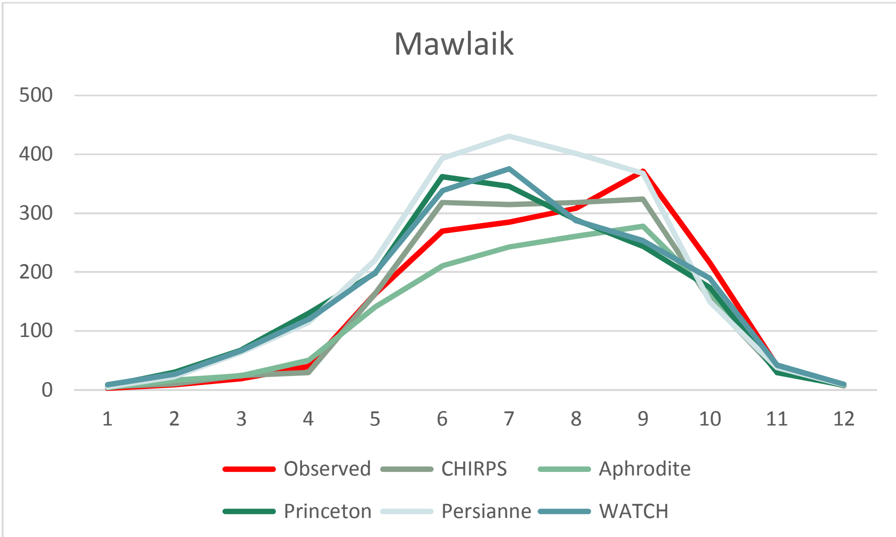


Figure 13 Mawlaik mean monthly precipitation

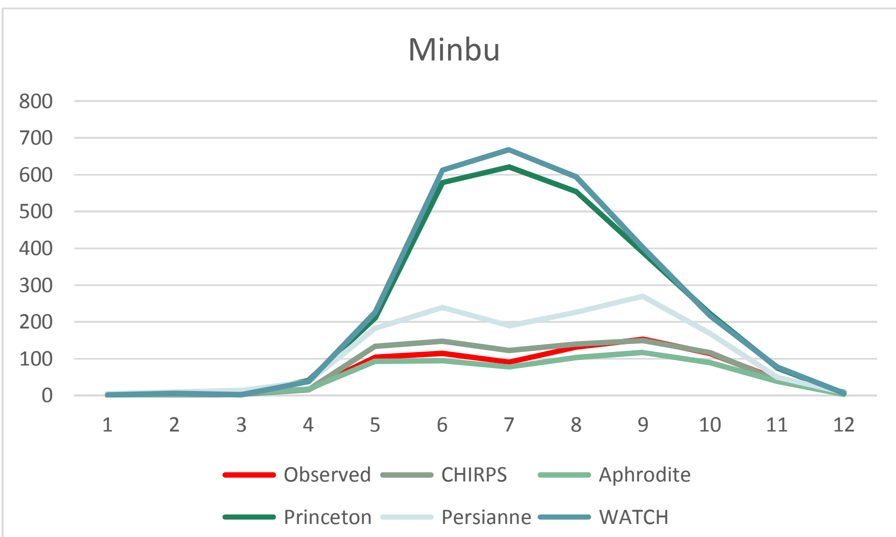


Figure 14 Minbu mean monthly precipitation

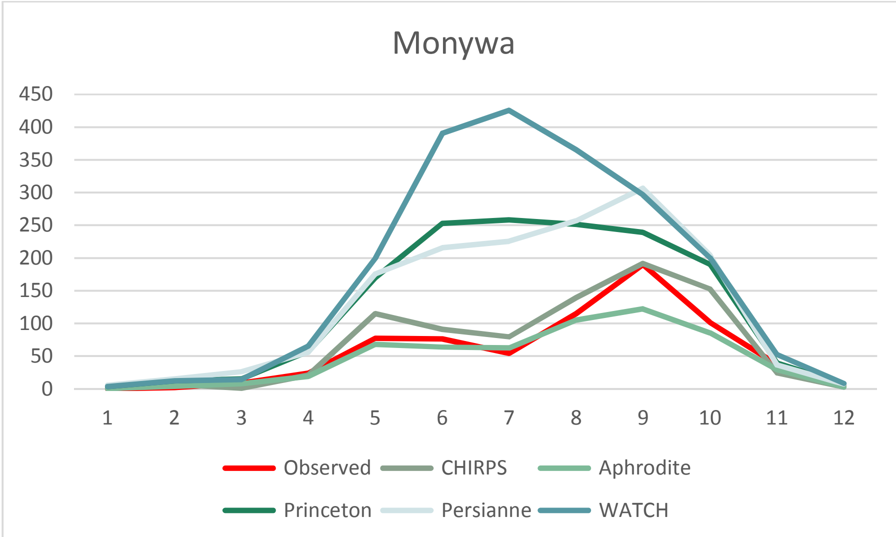


Figure 15 Monywa mean monthly precipitation

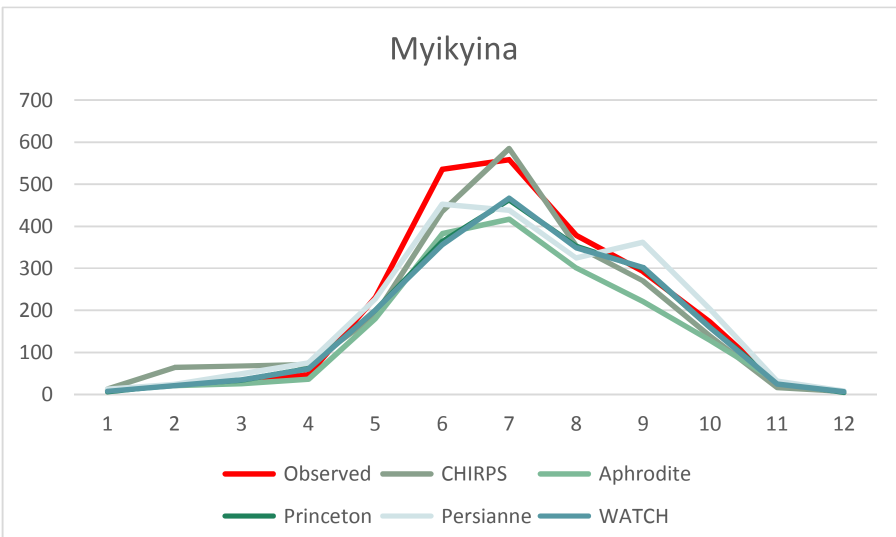


Figure 16 Myitkyina mean monthly precipitation

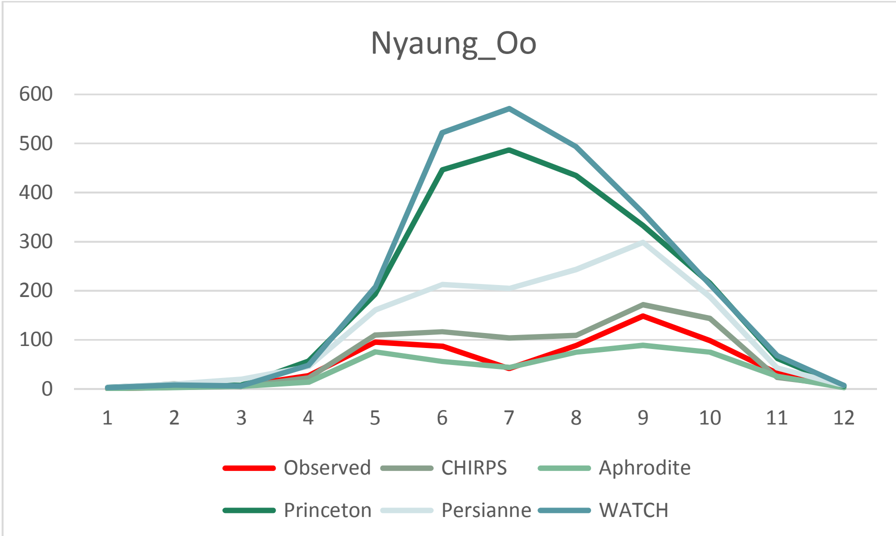


Figure 17 Nyaung U mean monthly precipitation

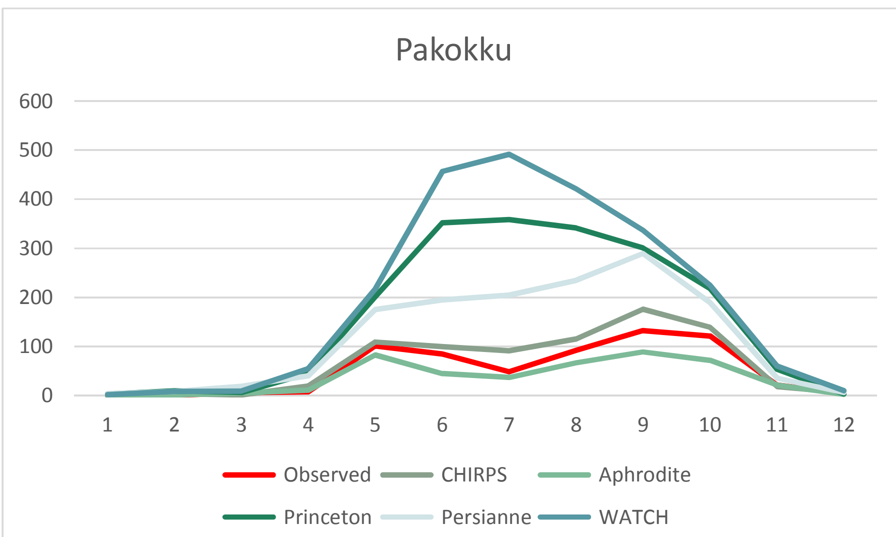


Figure 18 Pakokku mean monthly precipitation

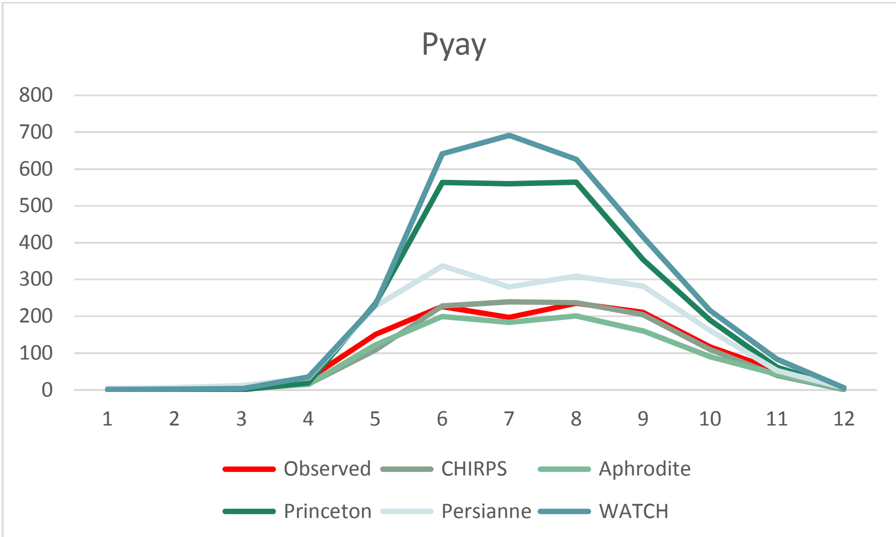


Figure 19 Pyay mean monthly precipitation

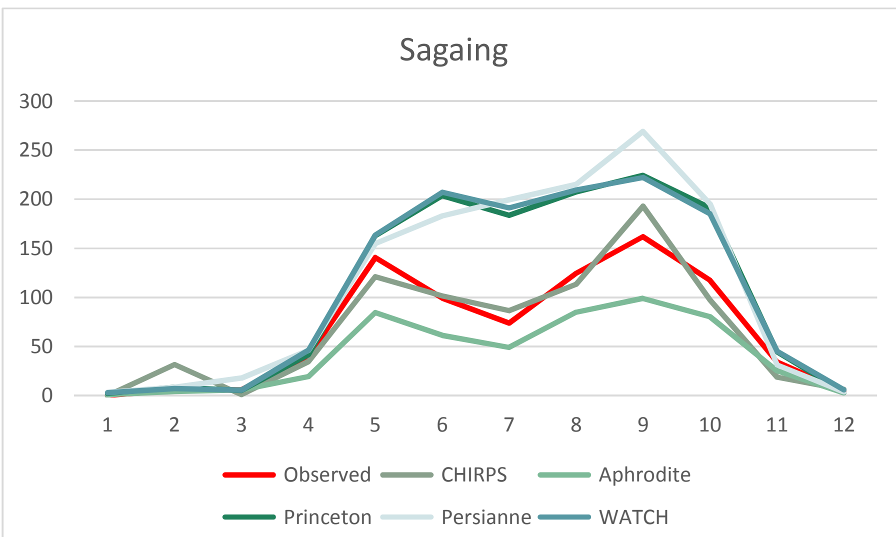


Figure 20 Sagaing mean monthly precipitation

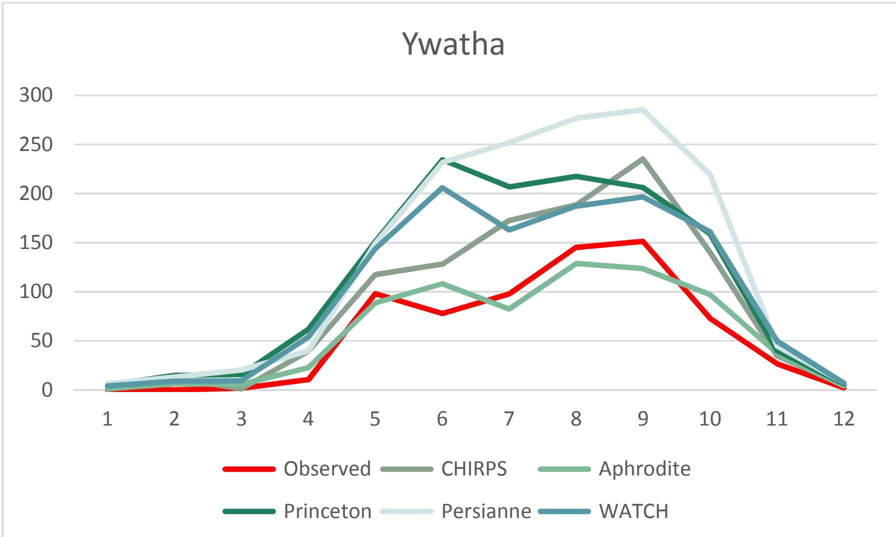


Figure 21 Ywatha mean monthly precipitation

Table 4 shows a comparison between observed monthly rainfall and various data products. CHIRPS, APHRODITE and PERSIANNE are the best performing products with CHIRPS the best or closest to best performer. The notable exception is Minbu where CHIRPS is considerably less than PERSIANNE. Note based on Moriasi et. al. performance ratings for NSE the following is assumed very good (0.75 <NSE <=1.0), good (0.65 <NSE <=0.75), satisfactory (0.5 <NSE <=0.65) and unsatisfactory (NSE<=0.5). On this basis only CHIRPS and PERSIANNE are satisfactory or better at all sites.

Table 4 NSE comparison between observed monthly rainfall and various data products

Site	CHIRPS	APHRODITE	Princeton	PERSIANNE	WATCH
Ayartaw	0.57	0.46	0.30	0.52	0.27
Bhamo	0.82	0.89	0.77	0.79	0.75
Gangaw	0.65	0.56	0.49	0.65	0.42
Hinthada	0.75	0.79	0.75	0.76	0.75
Hkamti	0.79	0.84	0.69	0.86	0.72
Katha	0.67	0.76	0.59	0.74	0.59
Magway	0.65	0.68	0.44	0.69	0.43
Mandalay	0.62	0.53	0.53	0.58	0.47
Mawlaik	0.72	0.79	0.55	0.73	0.59
Minbu	0.63	0.71	0.43	0.72	0.42
Monywa	0.65	0.50	0.38	0.60	0.28
Myitkyina	0.85	0.87	0.80	0.83	0.80
Nyaung U	0.56	0.48	0.28	0.53	0.24
Pakokku	0.62	0.43	0.38	0.61	0.30
Pyay	0.76	0.74	0.69	0.77	0.65
Sagaing	0.61	0.53	0.52	0.60	0.50
Ywatha	0.55	0.49	0.36	0.52	0.38

Table 5 shows a comparison of average annual number of rain days. CHIRPS and Princeton are the best performing products with CHIRPS consistently the closest. The worst performance of all products is at the Ywatha site which has a low number of rain days.

Table 5 Comparison of average annual rain days

Site	Observed	CHIRPS	Aphrodite	Princeton	PERSIANNE	WATCH
Ayartaw	26.6	58.7	70.8	77.2	134.0	180.8
Bhamo	105.3	79.4	145.1	101.2	166.1	198.5
Gangaw	78.6	81.3	126.2	73.7	162.8	185.8
Hinthada	107.7	99.7	157.9	118.0	171.4	190.9
Hkamti	125.1	105.5	180.0	123.6	185.6	217.8
Katha	84.2	84.2	133.2	91.6	168.3	202.2
Magway	66.8	61.1	91.4	89.1	140.1	187.9
Mandalay	54.0	67.3	82.8	88.3	141.6	179.7
Mawlaik	94.8	88.2	148.1	66.0	171.3	201.8
Minbu	60.1	60.8	91.6	89.7	140.1	188.6
Monywa	46.8	61.9	82.5	65.0	144.5	186.3
Myitkyina	115.6	87.3	143.5	100.1	173.2	193.3
Nyaung U	43.8	60.4	88.7	85.7	134.0	183.4
Pakokku	39.5	57.7	70.2	80.0	134.9	184.2
Pyay	91.2	83.3	137.7	116.0	163.2	188.1
Sagaing	51.6	67.7	83.4	78.0	139.6	181.2
Ywatha	31.5	72.1	102.8	65.6	146.6	180.5

Based on performance ratings recommended by Moriasi et.al. the best performing product (CHIRPS) is very good for 9 sites, good for 1 site, satisfactory for 3 sites and unsatisfactory for four sites (Ayartaw, Gangaw, Nyaung U and Ywatha).

A.10 Assessment and Generation of Temperature Data

A.10.1 Assessment of Princeton and WATCH temperature data sets

A monthly comparison between Princeton and WATCH minimum and maximum temperatures against 15 observed data sites is shown below in Figure 22 to Figure 36.

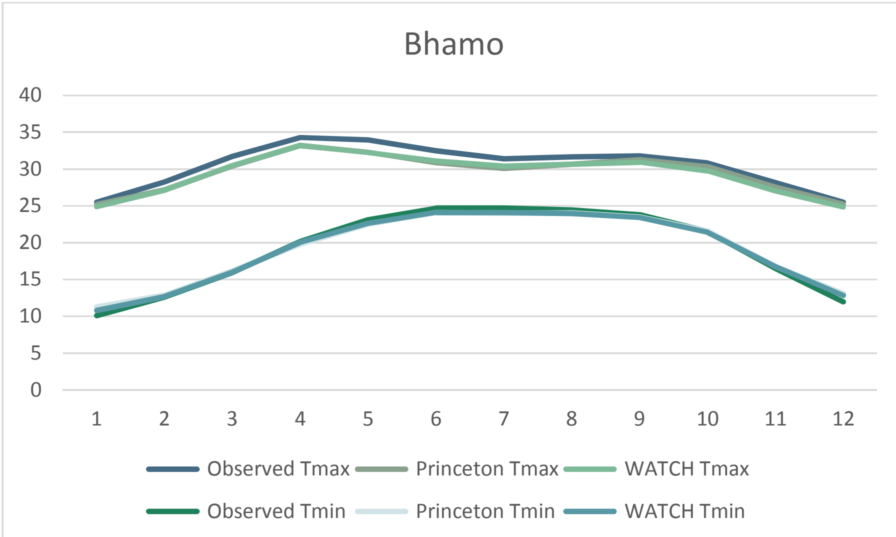


Figure 22 Bhamo minimum and maximum temperature comparison

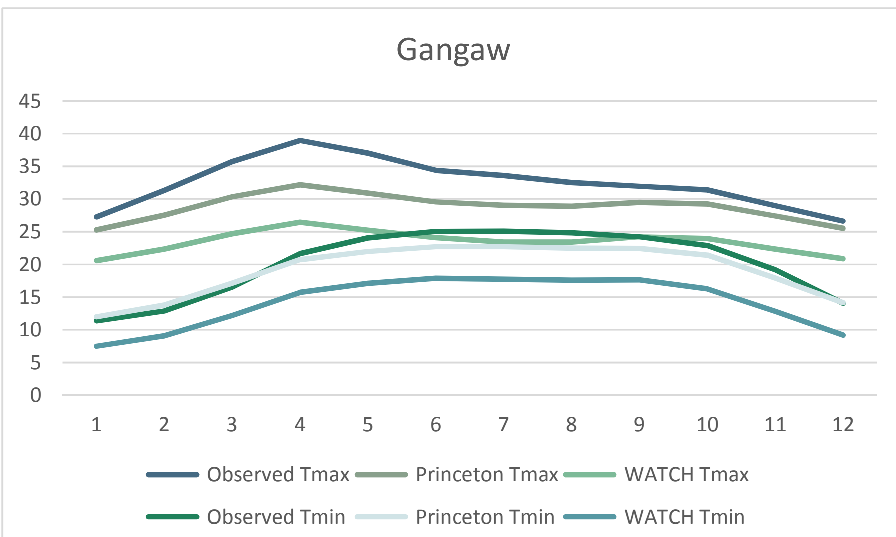


Figure 23 Gangaw minimum and maximum temperature comparison

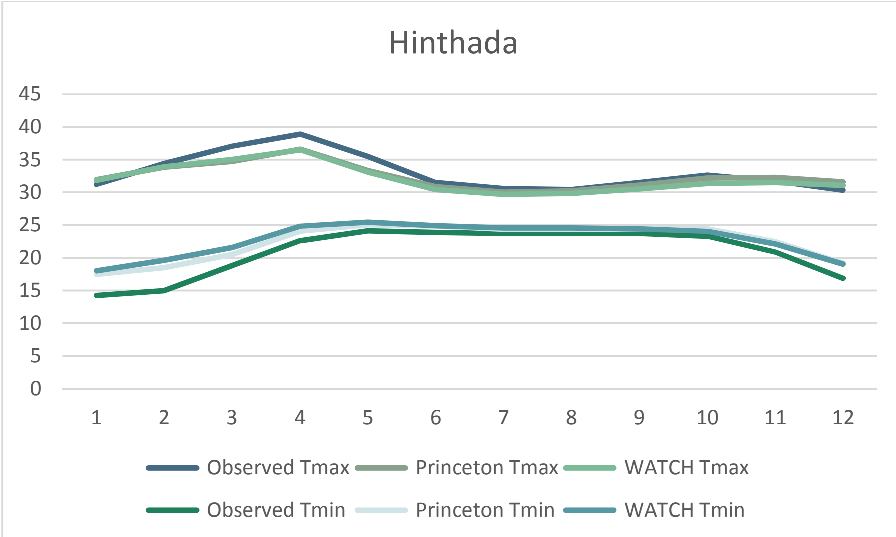


Figure 24 Hinthada minimum and maximum temperature comparison

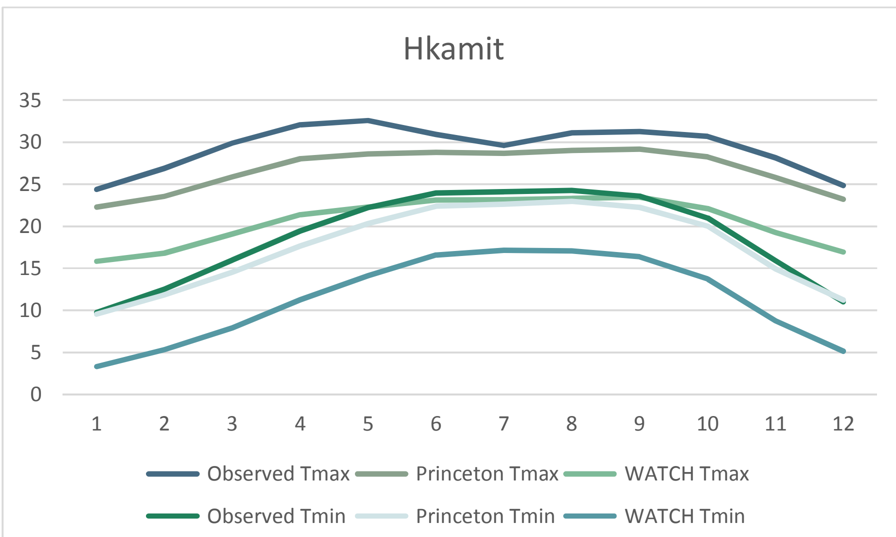


Figure 25 Hkamti minimum and maximum temperature comparison

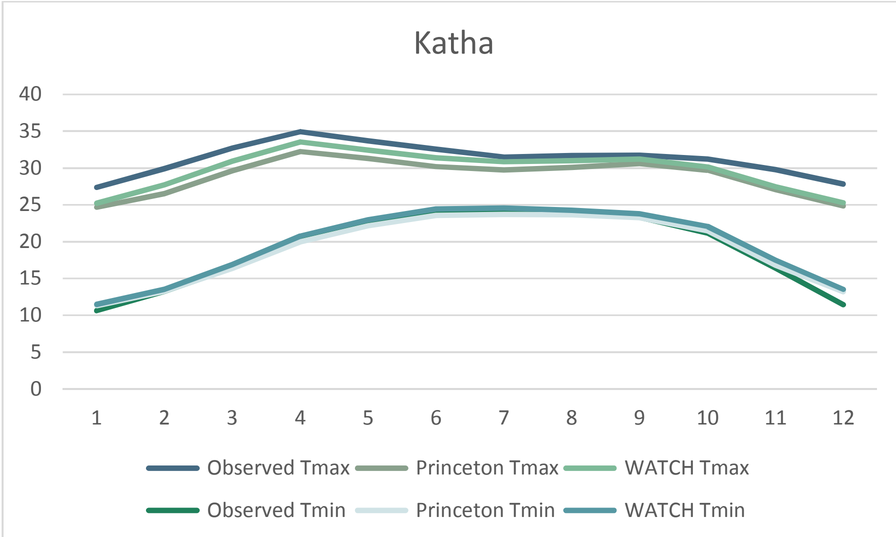


Figure 26 Katha minimum and maximum temperature comparison

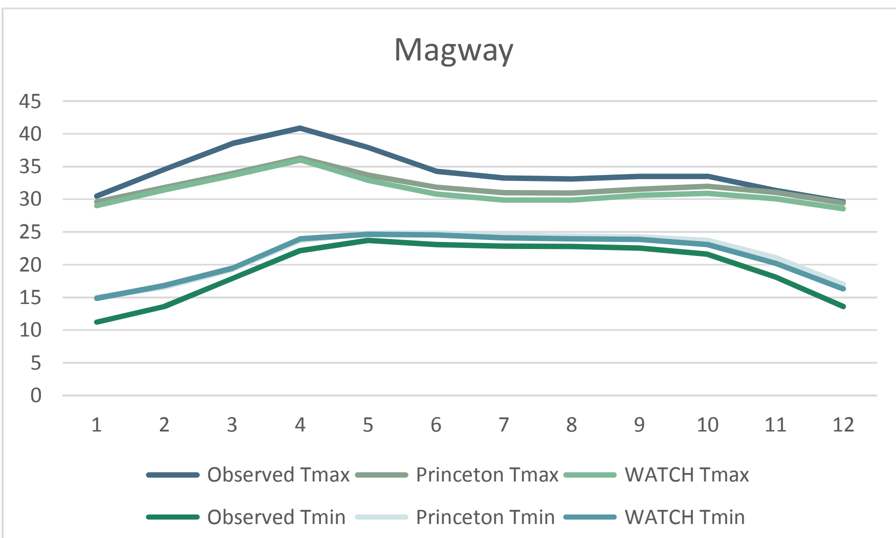


Figure 27 Magway minimum and maximum temperature comparison

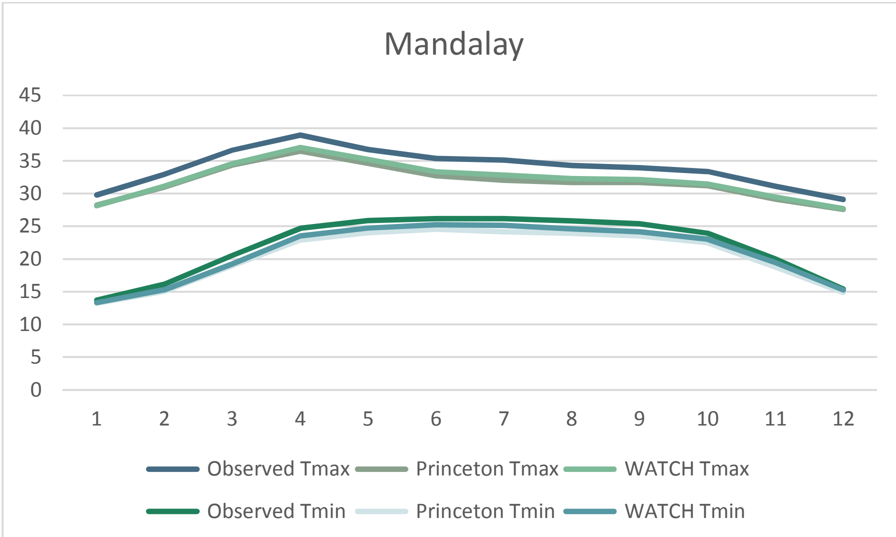


Figure 28 Mandalay minimum and maximum temperature comparison

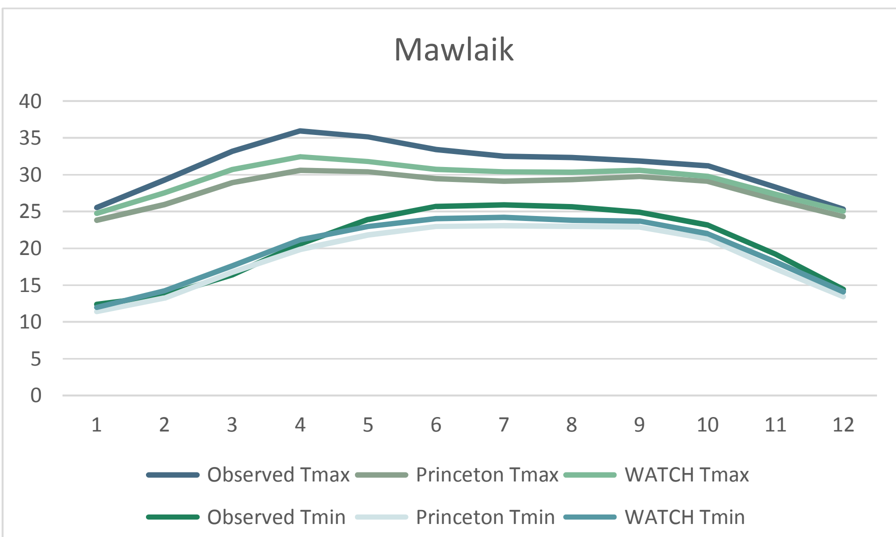


Figure 29 Mawlaik minimum and maximum temperature comparison

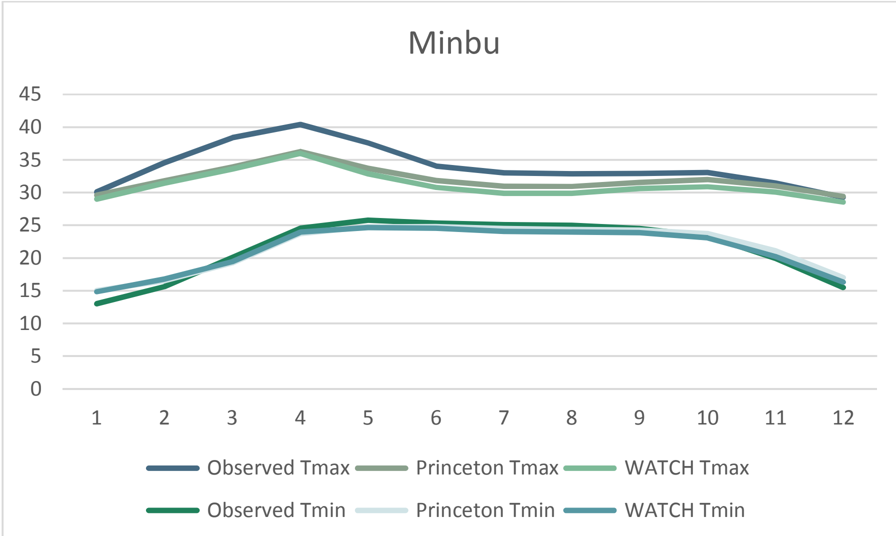


Figure 30 Minbu minimum and maximum temperature comparison

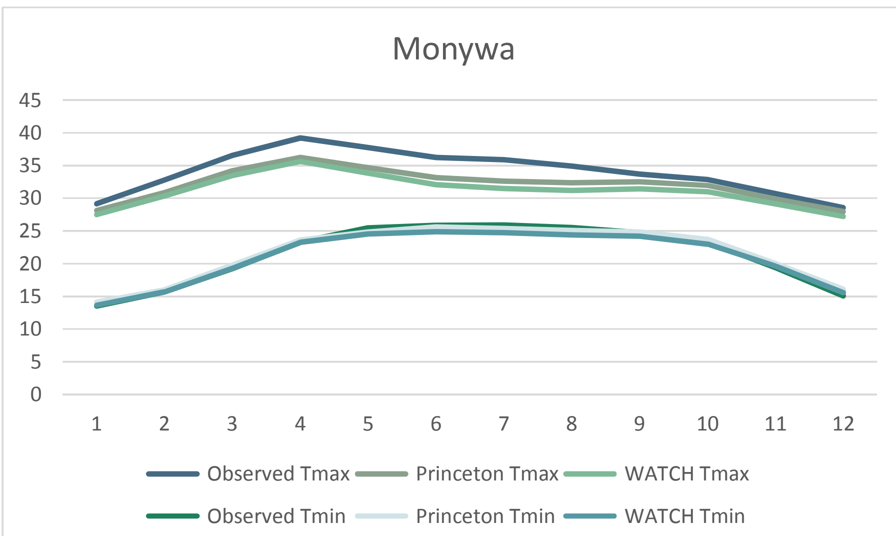


Figure 31 Monywa minimum and maximum temperature comparison

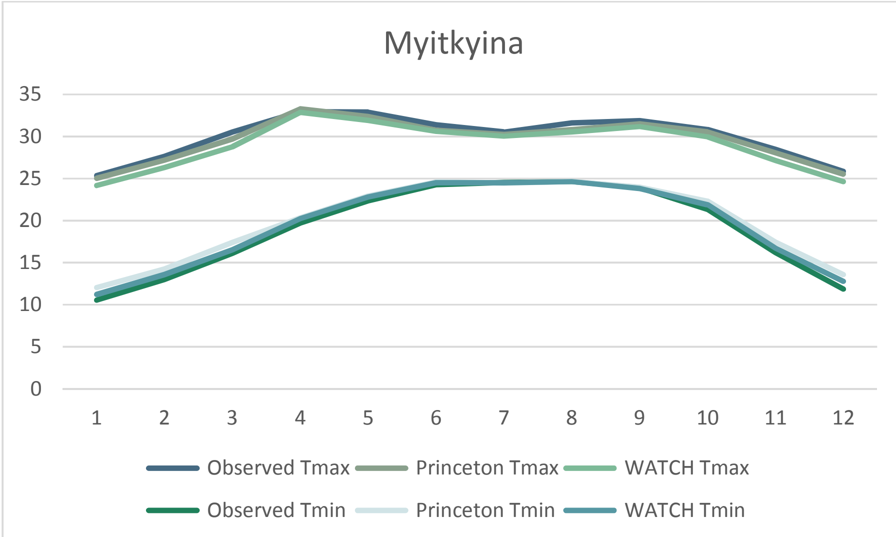


Figure 32 Myitkyina minimum and maximum temperature comparison

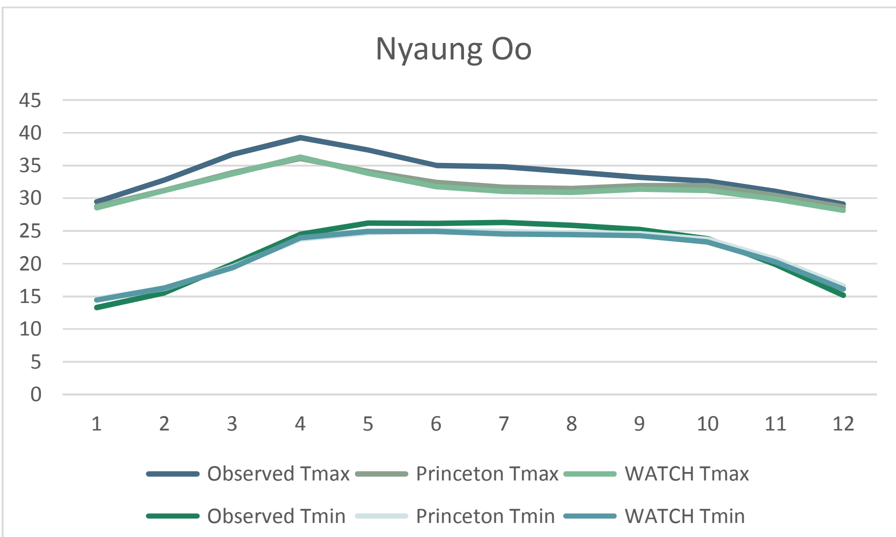


Figure 33 Nyaung U minimum and maximum temperature comparison

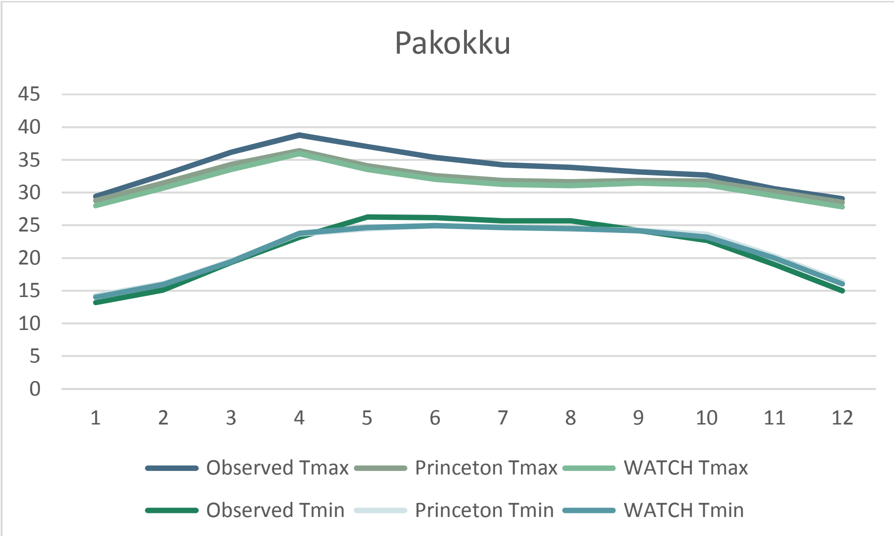


Figure 34 Pakokku minimum and maximum temperature comparison

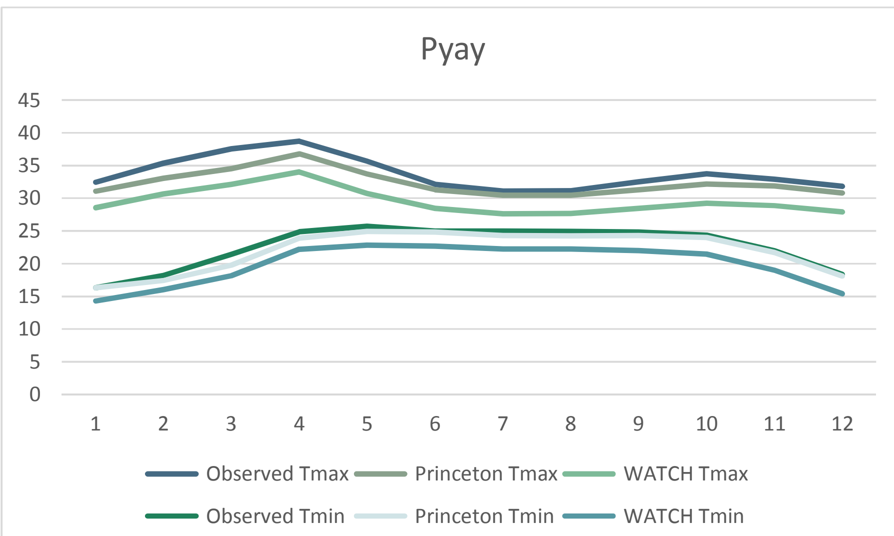


Figure 35 Pyay minimum and maximum temperature comparison

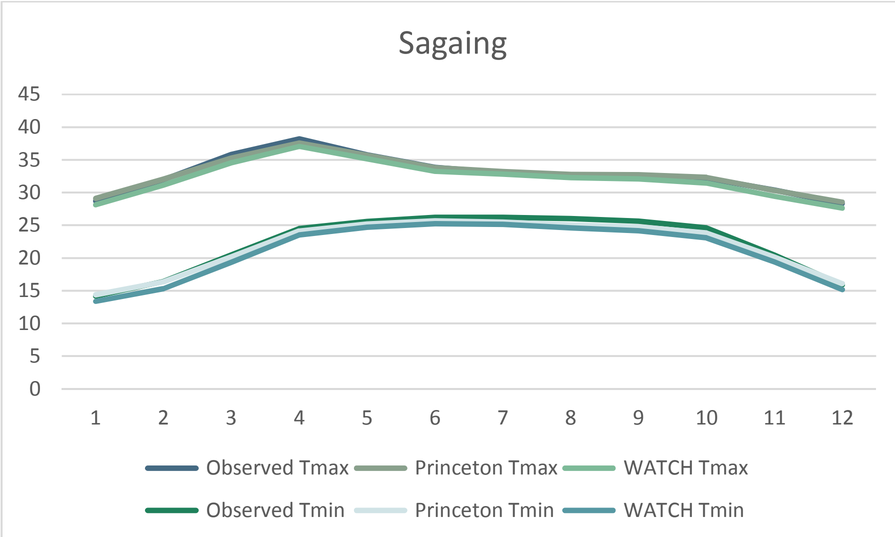


Figure 36 Sagaing minimum and maximum temperature comparison

There is generally a very close match between all observed data sites and the two data products. The two worst performing sites are Gangaw and Hkamti. At Gangaw and Hkamti observed temperatures are higher than the data products with the best match against Princeton data. The coefficient of efficiency match for minimum and maximum monthly temperature is shown in Table 6. Note all sites are very good with the worst performing site Pakokku at 0.76.

Table 6 Coefficient of efficiency for monthly temperature

Site	Minimum temperature		Maximum temperature	
Bhamo	Princeton	WATCH	Princeton	WATCH
Bhamo	0.97	0.98	0.92	0.93
Gangaw	0.96	0.96	0.79	0.76
Hinthada	0.90	0.87	0.81	0.83
Hkamti	0.97	0.97	0.84	0.77
Katha	0.86	0.87	0.87	0.87
Magway	0.91	0.92	0.83	0.85
Mandalay	0.97	0.98	0.92	0.92
Mawlaik	0.96	0.96	0.86	0.92
Minbu	0.93	0.94	0.82	0.84
Monywa	0.95	0.95	0.90	0.88
Myitkyina	0.98	0.98	0.95	0.93
Nyaung U	0.91	0.92	0.86	0.87
Pakokku	0.76	0.77	0.79	0.79
Pyay	0.92	0.92	0.82	0.85
Sagaing	0.96	0.97	0.83	0.81

A.10.2 Generation of temperature data set

The CHIRPS rainfall data set is at 0.05 degree resolution. To be consistent with this the temperature data set was also generated at a matching resolution. This was done for the period 1981 to 2012. For the period prior to 1997 Princeton data was used and for the more recent period (1998-2012) WATCH data was used.

As the Princeton data product matched reasonably close to observed data no bias correction was applied. However, a monthly bias correction was estimated between Princeton and WATCH for the overlapping period between 1997 and 2008. These bias corrections were applied to the WATCH data on each grid cell on a monthly basis.

The 90m resolution elevation data derived from shuttle radar (Farr et. al. 2007) was used to work out an average elevation for each Princeton and WATCH cell as well as for each CHIRPS cell. The elevation difference between temperature cells was corrected to precipitation data resolutions by a lapse rate that was derived by CSIRO in previous studies in Himalayan region (Table 7). This correction was applied to corresponding 0.05 degree resolutions cells that sat within Princeton and WATCH cells on each day for minimum and maximum temperatures to produce the gridded minimum and maximum temperature gridded data surfaces at the same resolutions as CHIRPS.

Table 7 Monthly lapse rates in degrees/km

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-6.7	-6.9	-7.2	-7.1	-6.1	-6	-5.8	-6	-6.1	-6.2	-6.3	-6.5

A.11 Assessment and generation of potential evapotranspiration data sets

A.11.1 Assessment of potential evaporation data products

There are a range of different methods for calculating potential evapotranspiration such as Penman-Monteith (Penman, 1948 and Monteith, 1965), Priestley-Taylor (Priestley and Taylor, 1972), Morton (Morton, 1983) and Hargreaves (Hargreaves, 1982) methods.

CSIRO had previously applied the Morton method to WATCH data to produce surfaces for south Asia. In addition to this the FAO has produced a global data set of daily PET at 0.166 degree resolution from 1998 to 2012. As the Hargreaves method only requires minimum and maximum temperature and this was available for Princeton and WATCH climate products the bias corrected temperature surface was used to produce PET gridded data products.

The Hargreaves method was implemented as follows:

$$Dr = 1.0 + 0.033cos\left(\frac{2\pi * jd}{ndy}\right)$$

$$Decl = 0.409sin\left(\frac{2\pi jd}{ndy} - 1.39\right)$$

$$Ws = \frac{\pi}{2} - atan\left(\frac{-tan(lat_i) * tan(Decl)}{\sqrt{max\left(0.00001, 1 - \left(tan(lat_i) * tan(Decl)\right)^2\right)}}\right)$$

$$Ra = 37.586 * Dr * \left(Ws * sin(lat_i) * sin(Decl) + cos(lat_i) * cos(Decl) * sin(Ws)\right)$$

$$PET = 0.0009384\,(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}\,R_a$$

Where:

jd is the Julian day of the year

ndy is the number of days in the year

lat_i is the latitude of the centroid of cell i

T_{max} is the maximum temperature of the cell

T_{min} is the minimum temperature of the cell

Note 37.586 is assumed as the radiation constant and 0.009384 as the evaporation constant. If there was more/any observed data available these could have been calibrated. As this was not available the default values recommended by Hargreaves were adopted.

The results were compared at all 15 temperature sites on an average monthly basis. The average of these comparisons is shown in Figure 37. The results show similar results when compare to the FAO mean monthly evapotranspiration estimates (http://www.fao.org/geonetwork/srv/en/main.home)

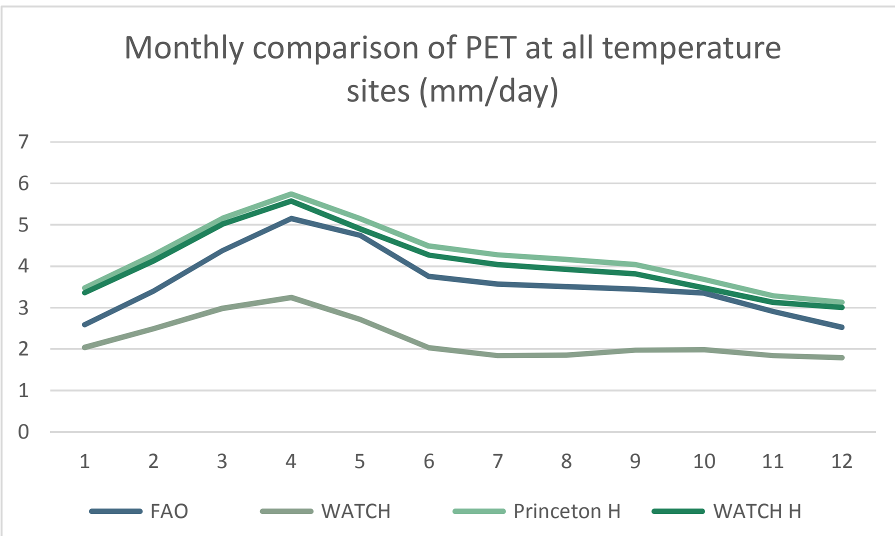


Figure 37 Comparison of derived monthly PET averaged across 15 temperature sites

A.11.2 Generation of PET

The Princeton and WATCH data products were used to generate minimum and maximum temperatures at CHIRPS resolution i.e. 0.05 degree. The Hargreaves PET generated from these two data products show a reasonable match to the FAO Penman-Monteith data product. (http://www.fao.org/geonetwork/srv/en/main.home). On this basis the temperature data products detailed in the previous chapter were applied to the Hargreaves method to generate a PET data product at the same resolution.

A.12 Recommendations

A.12.1 Precipitation

The best performing product is CHIRPS, it is at a resolution of 0.05 degrees and runs up to recent times. The product has an overall bias of 1% compared at 19 climate stations and on this basis, it does not seem to warrant any bias correction. It is worth noting that CHIRPS was unsatisfactory for four sites (Ayartaw, Gangaw, Nyaung U and Ywatha).

A.12.2 Temperature

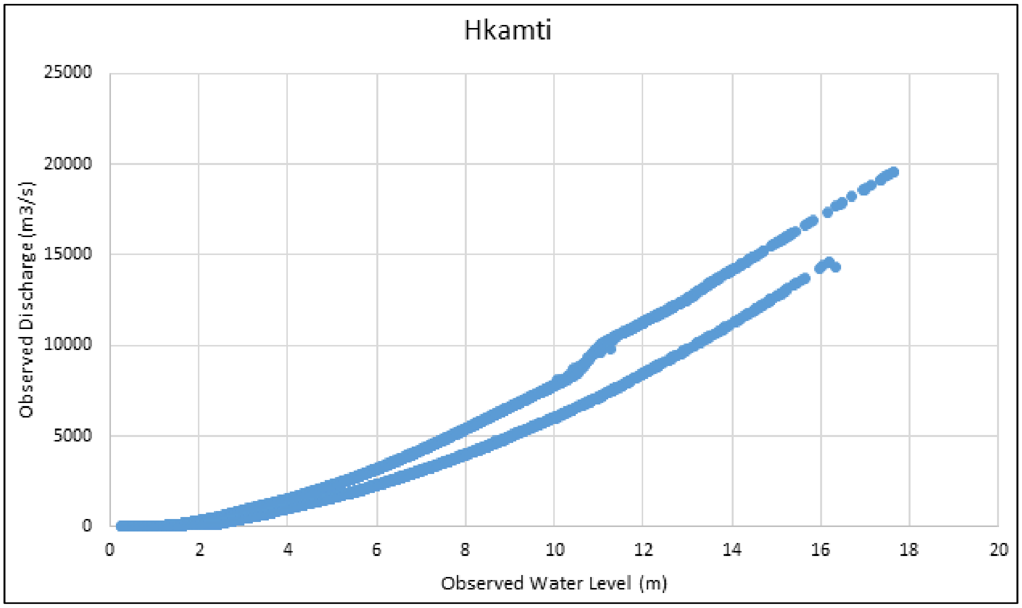
There are only two data products (Princeton and WATCH) that have minimum and maximum temperature and they both perform reasonably well for most sites. It was decided to create a temperature record by combining both of these records together which required monthly bias correction for the WATCH product. A 0.05 degree minimum and maximum gridded temperature data set was created from these by correcting for elevation differences.

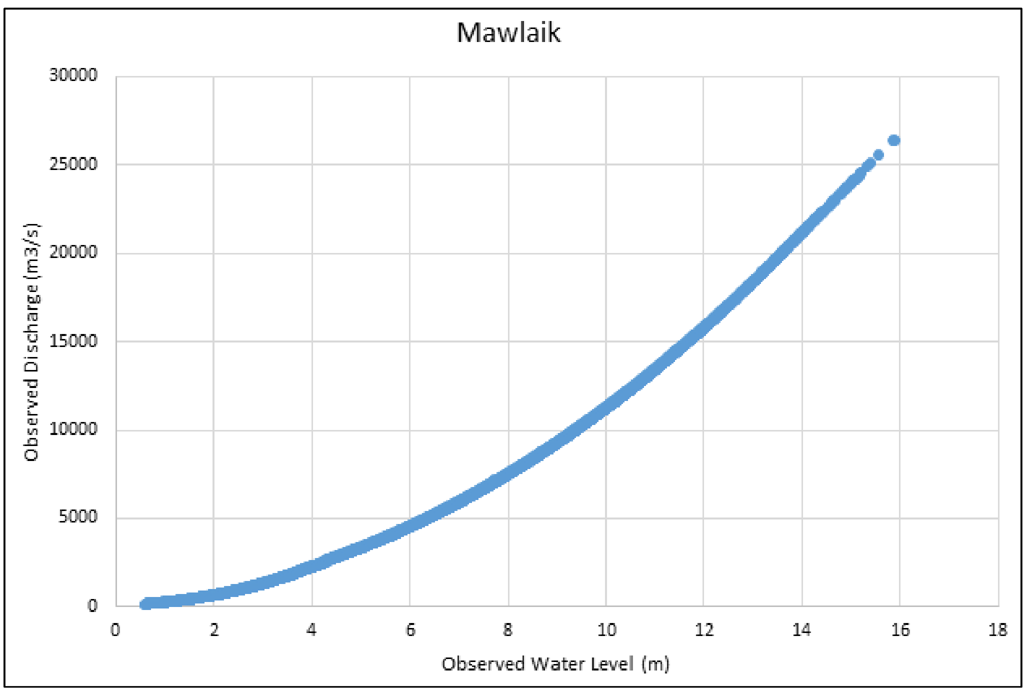
A.12.3 Potential evapotranspiration

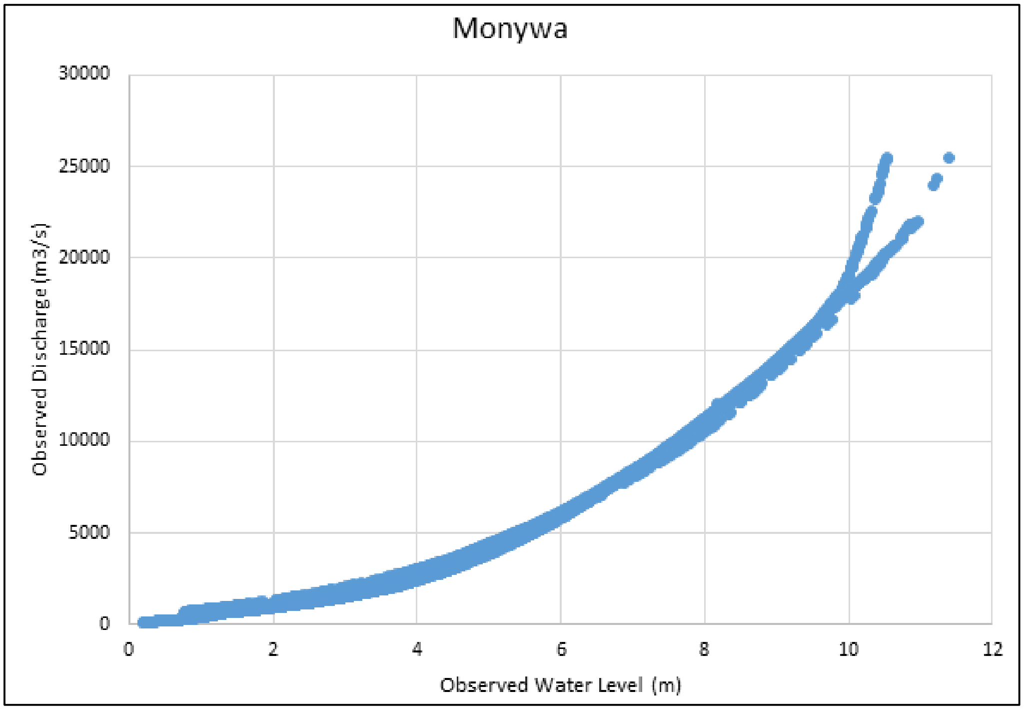
There was no suitable observed evaporation data, so data products were assessed against each other. The FAO, Princeton Hargreaves and WATCH Hargreaves were similar. However, the combined Princeton and WATCH were for a longer period and the gridded temperature data products were at a finer resolution. On this basis PET was generated using Hargreaves method based on the gridded temperature product.

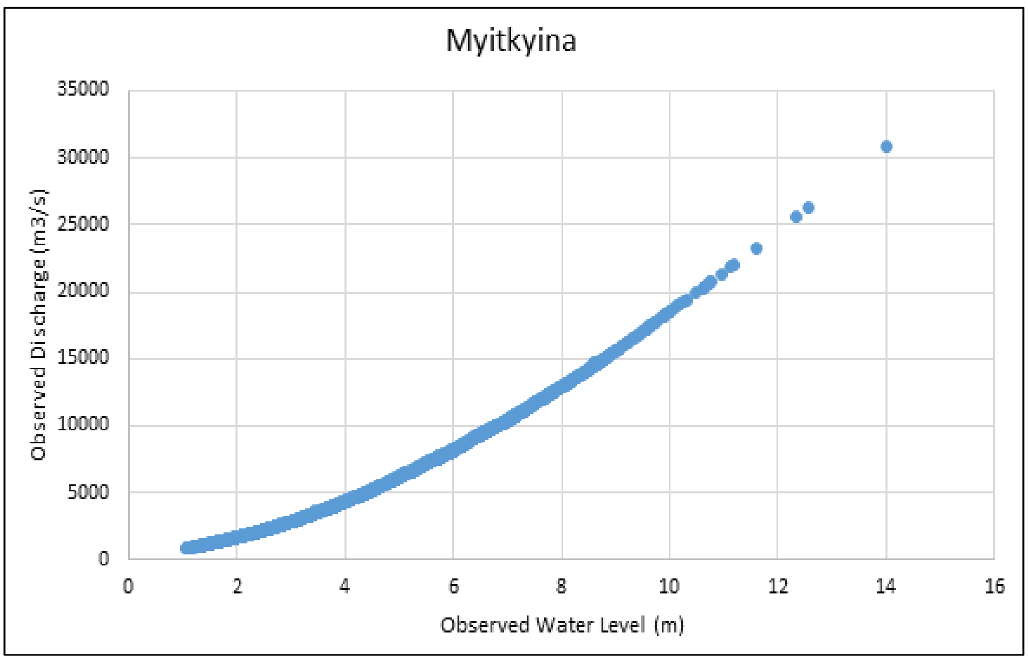
It is worth noting that the FAO product was based on Penman-Monteith method and is at 0.1666 degree resolution averaged from 1961 to 1990.

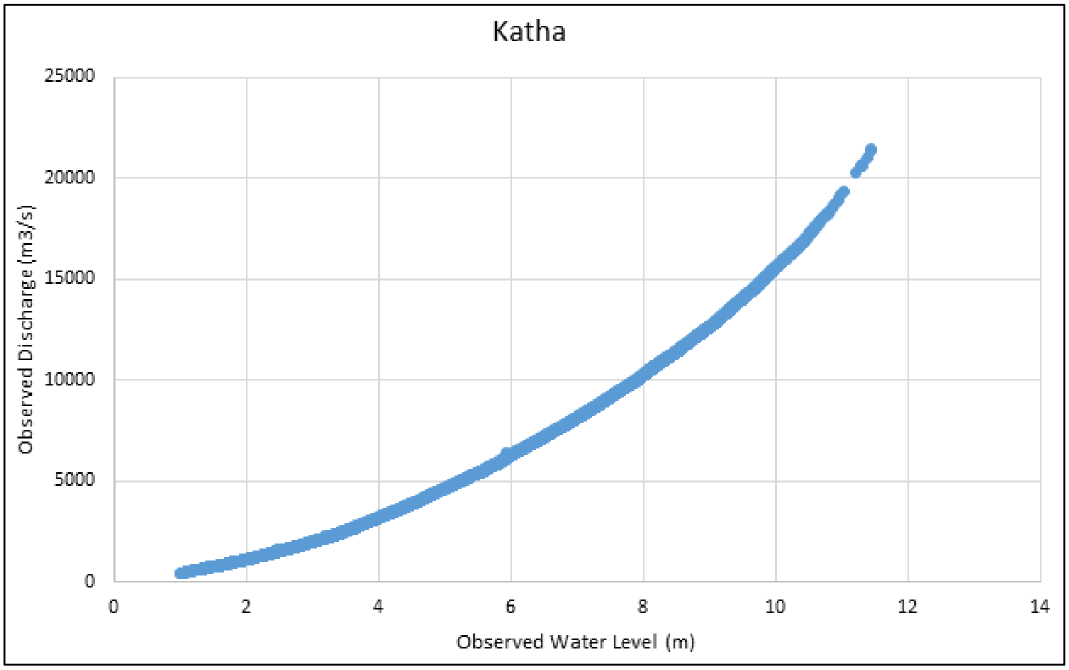
ANNEX III - OBSERVED WATER LEVEL VS DISCHARGE

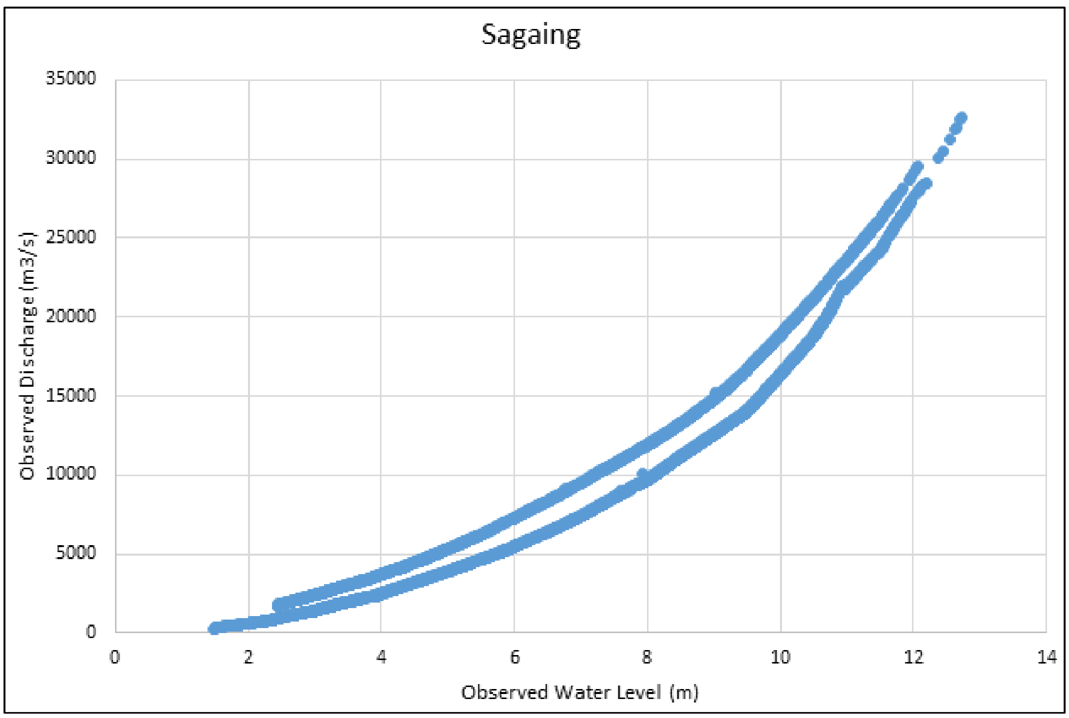


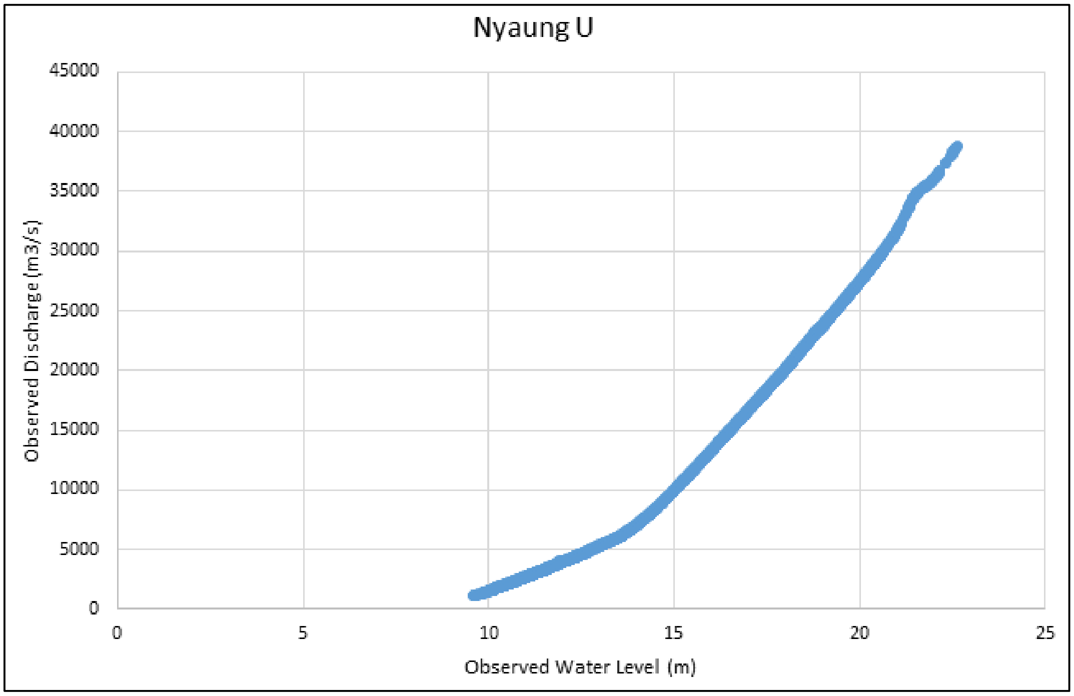


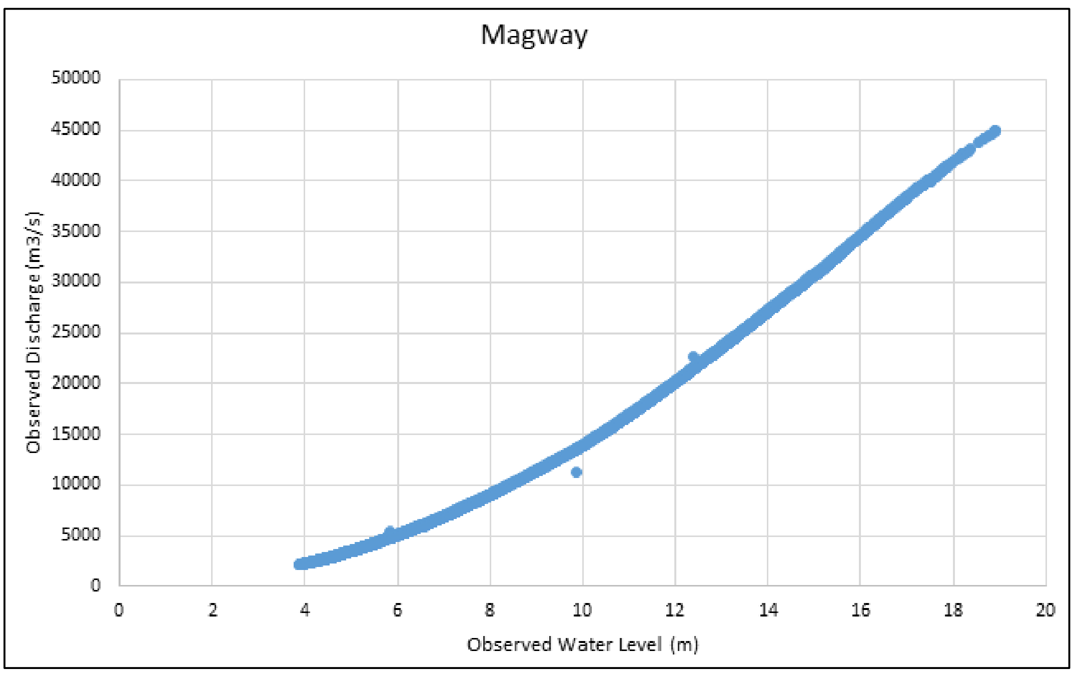

Monywa
30000
25000
20000
15000
10000
5000
0
Observed Discharge (m3/s)
0
2
4
6
8
10
12
Observed Water Level (m)

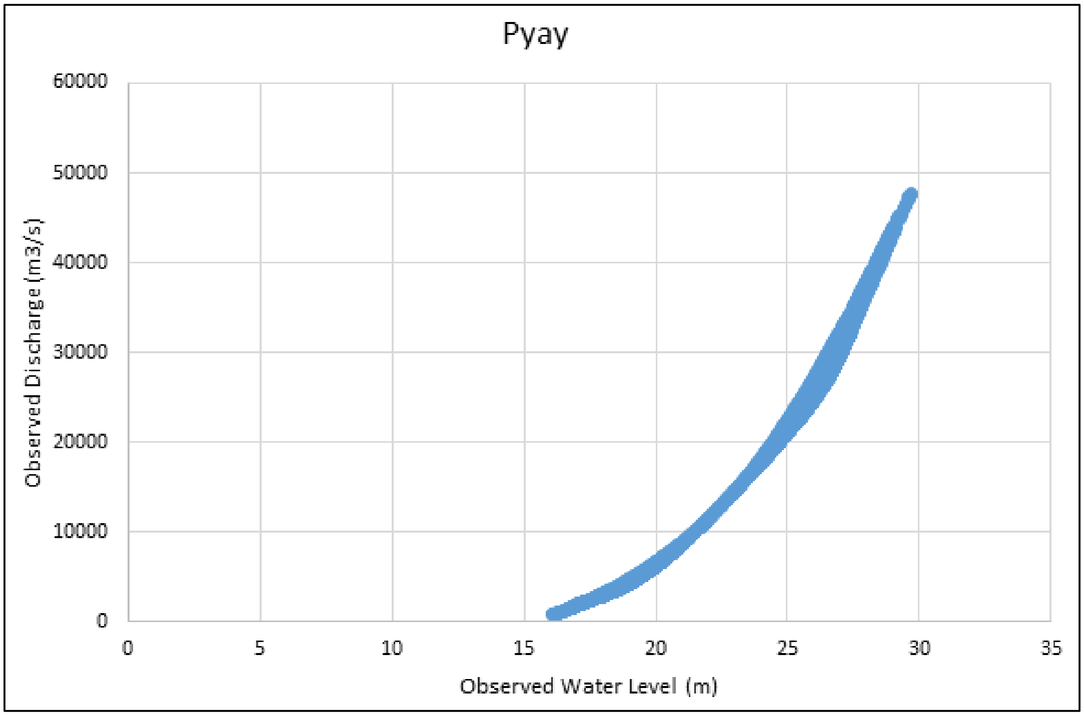

Myitkyina
35000
30000
25000
20000
15000
10000
5000
0
Observed Discharge (m3/s)
0
2
4
6
8
10
12
14
16
Observed Water Level (m)


Katha
Observed Discharge (m3/s)
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
Observed Water Level (m)


Sagaing
Observed Discharge (m3/s)
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
Observed Water Level (m)


Nyaung U
Observed Discharge (m3/s)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
5
10
15
20
25
Observed Water Level (m)


Magway
Observed Discharge (m3/s)
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
16
18
20
Observed Water Level (m)


Pyay
60000
50000
40000
30000
20000
10000
0
Observed Discharge (m3/s)
0
5
10
15
20
25
30
35
Observed Water Level (m)