2. FLOW

The River's Journey

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FLOW

The river's journey

THE YARLUNG TSANGPO-Siang-Brahmaputra-Jamuna river system is truly one of the most intriguing, vigorous and imposing fluvial systems in the world. The River originates in Tibet, China from a glacier over 5,300 meters above sea level and flows as the Yarlung-Tsangpo then as Siang and Brahmaputra in India and the Jamuna in Bangladesh. The basin is spread across 712,035 square kilometers[1] in four countries. On its 3,350 kilometers journey, the River flows through China, India and Bangladesh and is joined by numerous tributaries creating a huge network of water courses throughout its basin. Although the main channel does not flow through Bhutan a large number of tributaries originate from the Bhutanese Himalayas, thus Bhutan is also a part of the basin. In Bangladesh, the River joins the Ganges (Padma) and together they converge with Meghna, from where on the river is called the Lower Meghna, which eventually drains into the Bay of Bengal (shown in the Basin Map).

Each year, especially in the monsoon, the River carries not only a huge amount of water but also sediment towards the sea. The River is one of the most heavily sediment-laden large rivers of the world. As the ultimate carrier of freshwater and sediment in the region, the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna drives the hydrometeorological interactions, dynamics, and processes of the entire region.

The Yarlung Tsangpo-Siang-Brahmaputra-Jamuna Basin

THE PHYSICAL SETTING OF THE BASIN

Depending on topography and morphology, the basin of the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna is a mosaic of five different zones, the cold dry plateau of Tibet, the rain-drenched Himalayan slopes, the landlocked Brahmaputra Valley, the distinctive Lower Assam mountainous region and the vast deltaic floodplains.

THE TIBETAN PLATEAU covers around 50.5 percent of the basin, with elevations of 3,500 meters and above in the northern most part of the basin[2].

THE HIMALAYA BELT covers around 23 percent of the basin with elevations ranging between 100 meters to 3,500 meters above mean sea level and is sandwiched between the Tibetan Plateau and Brahmaputra Valley[3].

THE LOWER ASSAM MOUNTAINOUS REGION covers only 6.4 percent of the basin and includes the Shillong Plateau and Mikir Hills with elevation between 600 meters and 1,800 meters above sea level[4].

The River basin and adjoining mountain ranges are tectonically active, and a large part of the basin is geologically young

THE BRAHMAPUTRA VALLEY is long and narrow with elevations below 155 meters above sea level and takes up 9.7 percent of the basin.

THE DELTAIC FLOODPLAINS of Jamuna, situated in Bangladesh and West Bengal, India cover the remaining part of the basin. This region is extremely flat, and elevations vary from less than 10 meters above sea level to just under 90 meters above sea level[5].

The River basin and adjoining mountain ranges are tectonically active, and a large part of the basin is geologically young. Yet, the rivers in this region are antecedent[6], older than the mountains they flow through. Major morphological evolutions started to take place in Early Eocene[7], when the Indian plate collided with the Asian mainland and the rise of the Himalaya was initiated between 40 and 50 million years ago[8] (some scientists suggest this to be 55 million years ago[9]). The Yarlung Tsangpo currently flows through the suture zone that separates the Indian plate from the Asian Plate situated in the Tibetan Plateau. With vast expanses of pristine flatness at high elevations, this is the world's highest and widest plateau, and the geological history is closely linked to that of the Himalayas. East of this Plateau is the geologic wonder, the narrow deep Yarlung Tsangpo Grand Canyon entrenched between the Namcha Barwa and Gyala Peri mountains[10].

The Siang-Brahmaputra valley is bounded by the Himalayan ranges of northeastern India and Bhutan in the north; and the Shillong Plateau in the south. Huge amounts of sediment carried down from the Himalayas and deposited at the foothills, have created and shaped the valley. In the last leg of the journey, the River enters the Bengal Basin, one of the largest reservoirs of fluvial sediments in the world and represents the lower floodplain and delta plain deposits of the Brahmaputra, Ganges and Meghna rivers.

Sediments from the eroding Himalayas create huge alluvial fans in the plains[11]. The Bengal Basin slopes into the spectacular Bengal Deep Sea Fan, the largest submarine fan in the world and the ultimate destination of the waters and sediments carried by the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna River system.

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Expedition to the Tsangpo bend

Harish Kapadia

WE WERE standing at a bend in the river. Flowing fast from the Tibetan plateau, it made a large "S" turn and came rushing towards us. It is a river known by many names: in Tibet, it is the Yarlung Tsangpo, followed by Siang, and Brahmaputra as it enters India. We could see the mouth of the Nugong Asi nala flowing from the snow-capped Dapang peak (5,570 meters) in Tibet merging with the Siang. We had reached a point that explorers had been trying to reach for decades. It was a historical moment—the last piece of an almost century-old puzzle. That the Yarlung-Tsangpo and Brahmaputra were one river!

It took almost a century of exploration to solve this question. One school of thought believed that the river traversed further east till it merged with the Salween river and turned south into Burma. Another school believed that it took a turn to the south much sooner and flowed towards India, either into the Siang valley or the Subansiri valley. Several exploratory trips were made, and many different results were obtained.

The Survey of India deputed the first of its pundit explorers, Nain Singh Rawat, to trace the route of the Tsangpo. These native explorers were trained to survey the area


Liu Rui/China Plus

The Great Bend

while travelling in disguise. By this time, Tibet was closed to outsiders, but in two epic journeys in 1865 and 1873, Singh followed the course of the river to Lhasa and beyond. Reaching Chetang, east of Lhasa, he was forced to turn south after his subterfuge was revealed.

In 1874, the Assam survey was placed under Lieutenant Henry Harman. He measured the flow of various rivers and found that the flow of the Siang was greater than that of the others, proving that the river was most likely the Tsangpo. He dispatched another pundit explorer, Nem Singh, to Tibet in 1878-79, accompanied by Kinthup, a tailor from Darjeeling. They followed the Tsangpo from Chetang onwards, between the gorge of Namcha Barwa and Gyala Peri, and turned south to reach Gyala Sindong before returning. They made a major contribution, taking the exploration further upstream by 460 kilometers.

Harman, then posted in Darjeeling, again deputed Kinthup to travel to Tibet in 1880. Kinthup was instructed to cut 500 logs, make a marking on them and throw them into the Tsangpo river. If the logs emerged in the plains of Assam it would conclusively prove that the river turned south to enter Assam. As Kinthup was illiterate, a Chinese lama accompanied him. From Darjeeling, they went to Lhasa and followed the course of the Tsangpo to Chetang and Gyala Sindong. Around 24 kilometers later, they reached Pemakochung village, where the Tsangpo fell 150 feet in a waterfall which came to be known as the "rainbow falls".

Lieutenant Henry Harman measured the flow of various rivers and found that the flow of the Siang was greater than that of the others, proving that the river was most likely the Tsangpo

Unfortunately, Kinthup was sold into slavery at a monastery, from where he escaped two years later, but was captured again at Marpung, 56 kilometers downstream of the river. He was, however, allowed to go on a pilgrimage. He crossed the Tsangpo to the opposite bank, cut and marked 500 logs with special markings and threw them into the river.

Kinthup sent a letter to Harman about this, unaware that the Englishman had already left India, the letter remained unopened, and there was no one to check on those logs even if they reached Assam. He followed the Tsangpo downstream as far as Onlet, a small village near the Indian border. He could see the haze of the Assam plains; he was about 64 kilometers in a straight line from the border. He concluded that the Tsangpo did indeed flow into the Brahmaputra.

Kinthup returned to Darjeeling in 1884 and resumed tailoring. Two years later, he was debriefed by the Survey of India, but no one believed him. It was only in 1913, following a report by Bailey, that Kinthup's description was acknowledged as remarkably accurate. Aerial photography and satellite imagery have now confirmed beyond doubt that the Tsangpo enters India, is called the Siang, and forms a major tributary of the Brahmaputra.

View of Siang as it leaves the mountains and hits the plains for the first time

After the journey of Kinthup, no further physical explorations were undertaken, but the journey of the river was known through technology. In the year 2003 a party of Indian explorers including myself, trekked from the south, coming from the plains of Assam to reach the entry point of the river into India and named it, the "S" bend, completing the physical exploration of the Tsangpo. Standing there and completing a historic exploration was the elixir of my trekking life.

The Tsangpo bend expedition from 16 November to 5 December 2004 was organised with two main objectives: firstly, to see and photograph the bend where Tsangpo enters India and secondly to see if Namcha Barwa, the massif, around which the river takes a right angle southwards to reach Guyor La could be visualised from the Upper Siang valley. The expedition comprised of Motup Chewang (adventure tour professional, Ladakh), Wing Commander V K Sashindran (Assistant Professor, Armed Forces Medical College, Pune), with Lt. Rippon Bora (17 Kumaon, Indian Army) and myself.

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THE ORIGIN OF THE YARLUNG TSANGPO RIVER

Xiawei Liao

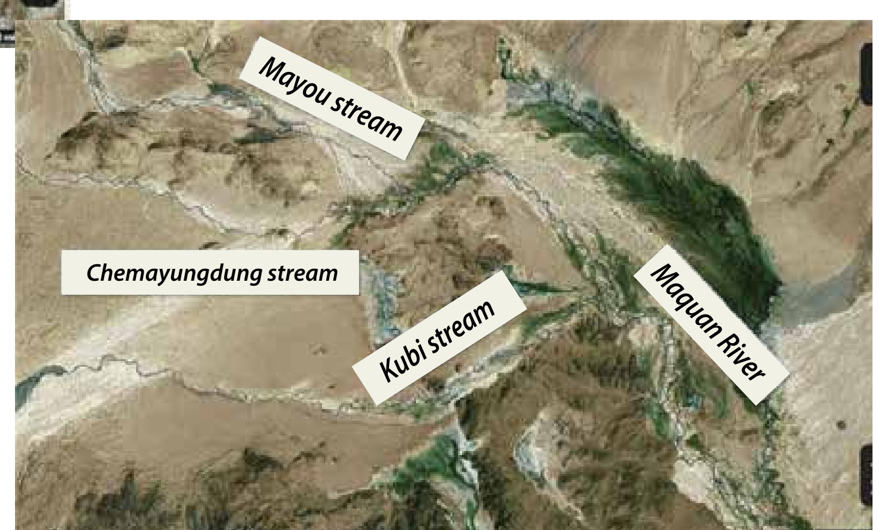
From 2007 to 2010, Chinese Academy of Sciences and the National Geomatics Center of China under the National Administration of Surveying, Mapping and Geo-information formed joint expedition teams to conduct field investigations in the headwater areas of the Yarlung-Tsangpo River in Tibet Autonomous Region of China. The field investigations showed that the Yarlung-Tsangpo River originates from the Angsi Glacier (82°03′20″E, 30°22′06″N), located on the northern side of the Himalayas and southeast of Mount Kailash and Lake Manasarovar in the Burang County in Tibet. The altitude of the origin is 5319.7 meters[45].

Based on the identification of the origin the river length is 3,848 kilometers and the drainage area is 712,035 square kilometers.

(Left) The headwater region of the Yarlung-Tsangpo River

Before the expedition, the origin of the Yarlung-Tsangpo River was thought to be the Chemayungdung Glacier (Figure 2), according to what was proposed by the Indian geographer Swami Pranavananda in the 1930s based on traditional Tibetan information.

(Below) The upstream of the Yarlung-Tsangpo River



The Chemayungdung Stream converges with the Mayou Stream from the north and Kubi stream from the south (Figure 3) and becomes Maquan River (meaning the horse river in Tibetan), the upper stream of the Yarlung Tsangpo.

Against the global context of climate change, glacier retreating has raised growing concerns. Liu and Xiao (2011) analyzed topographic data of the Chemayungdung Glacier from 1974 to 2010 and concluded that the glacier area has decreased by 5.02% and the glacier terminal has retreated 768 meters at a rate of 21 meters per year. The terminal lake area has increased by 63.7 percent, from 0.7 square kilometers to 1.14 square kilometers. The volume of the lake has increased by about 9.8 million cubic meters.

This may be surprising and counterintuitive. The headwater region of the Yarlung-Tsangpo River actually suffers from serious desertification issues due to the high altitude, dry climate and wind disasters (Figure 4). Desertification has also resulted in serious grassland retreat and conflicts between grassland conservation and animal grazing[46].

(Below) Desertification in the headwater region of the Yarlung-Tsangpo River

Tributaries of the River

IN THE course of its 3,350 kilometers journey, the River receives as many as 22 major tributaries in Tibet, 33 in India[12] (another estimate indicates 50 tributaries in India, 30 of these coming from the north and 20 from the south[13]), and 5 in Bangladesh. Like the main channel, many of the tributaries take on different names at their origin and as they cross the borders or meet with another tributary. In this narrative, the local names of the tributaries as they join the main channel have been used (shown in the Basin Map and Figure 1).

The tributaries of the Yarlung Tsangpo are mostly snow fed, as they originate in snow covered high mountains. As mentioned earlier, in this region the major tributaries are Doxung Zangbo, Nianchu, Lhasa, Nyang, Parlung Zangbo and Yigong Zangbo.

Although the Yarlung Tsangpo flows west to east, the tributaries flow in the opposite direction that is in a westerly direction before joining the main channel, assuming a barbed drainage pattern[14]. The longest tributary is the Lhasa, which joins the River from the north near the city of Lhasa. Another tributary, the Parlung Tsangpo rises in mountain glaciers situated at the eastern margin of the Tibetan Plateau and flows from east to west to join the Yarlung Tsangpo, before it plunges into the Yarlung Tsangpo Grand Canyon. The Siang is joined by Dibang and Lohit about 30 kilometers downstream of Pasighat in north-east India. Both these tributaries originate from the extreme eastern flank of the Himalayas. The Brahmaputra gradually gains in size and becomes more silt laden, as it collects water from scores of tributaries flowing from the Himalayas in the north and from the Patkai hills, North Cachar hills and Shillong plateau to its south. The tributaries of the Brahmaputra valley are of two categories. The north bank tributaries originate in high precipation intensity catchments, have very steep channel gradient, carry a lot of sediment and cause choking of river beds resulting in channel shifting or change in drainage pattern; the tributaries from the south have comparatively lower gradient with deep meandering channels, a lower sediment yield, and are more stable than their northern counterparts. The major tributaries that join the northern bank from east to west are Subansiri, Jia Bareli, Dhansiri and Manas; the tributaries that meet the river on its southern bank are Buridihing, Dhansiri (south), Kopili, Krishnai and Jinjiram[15]. The flow contributions of these tributaries are shown in Table 1. The table shows that Subansiri contributes the highest flow to the main channel.

Table 1: Tributary flow contributions to the Brahmaputra
(Source: based on 1995 data, Mahanta et al, 2014)

Tributary	Average flow in million cubic meter (MCM)/yr
Subansiri	52,705
Lohit	46,964
Dibang	37,818
Jia Bharali	28,844
Burhi Dihing	11,906
Kapili Kalang	9,023
Other tributaries above Pandu	121,938
Brahmaputra at Pandu	494,300

The Dhansiri, Manas, Dudhkumar and Dharla originate in the mountains of Bhutan and contribute substantially to the discharge of the Brahmaputra-Jamuna

The Jamuna, on its southbound course towards the Ganges, is joined by the Dudhkumar, Dharla, Teesta, Ghagot and Karatoya-Atrai rivers on its right bank and the Jinjiram on its left bank. Twenty kilometers south of its entrance, the Old Brahmaputra flows out from the left bank of the Jamuna. Another left bank distributary is the Dhalesawri. The Dhansiri, Manas, Dudhkumar and Dharla originate in the mountains of Bhutan and contribute substantially to the discharge of the Brahmaputra-Jamuna. Many of these tributaries are large rivers in their own right, draining out large catchments while receiving higher-order discharges along their banks. However, only the transboundary tributaries of the River, Lohit, Subansiri, Manas, Dudhkumar, Dharla and Teesta will be detailed in this section.

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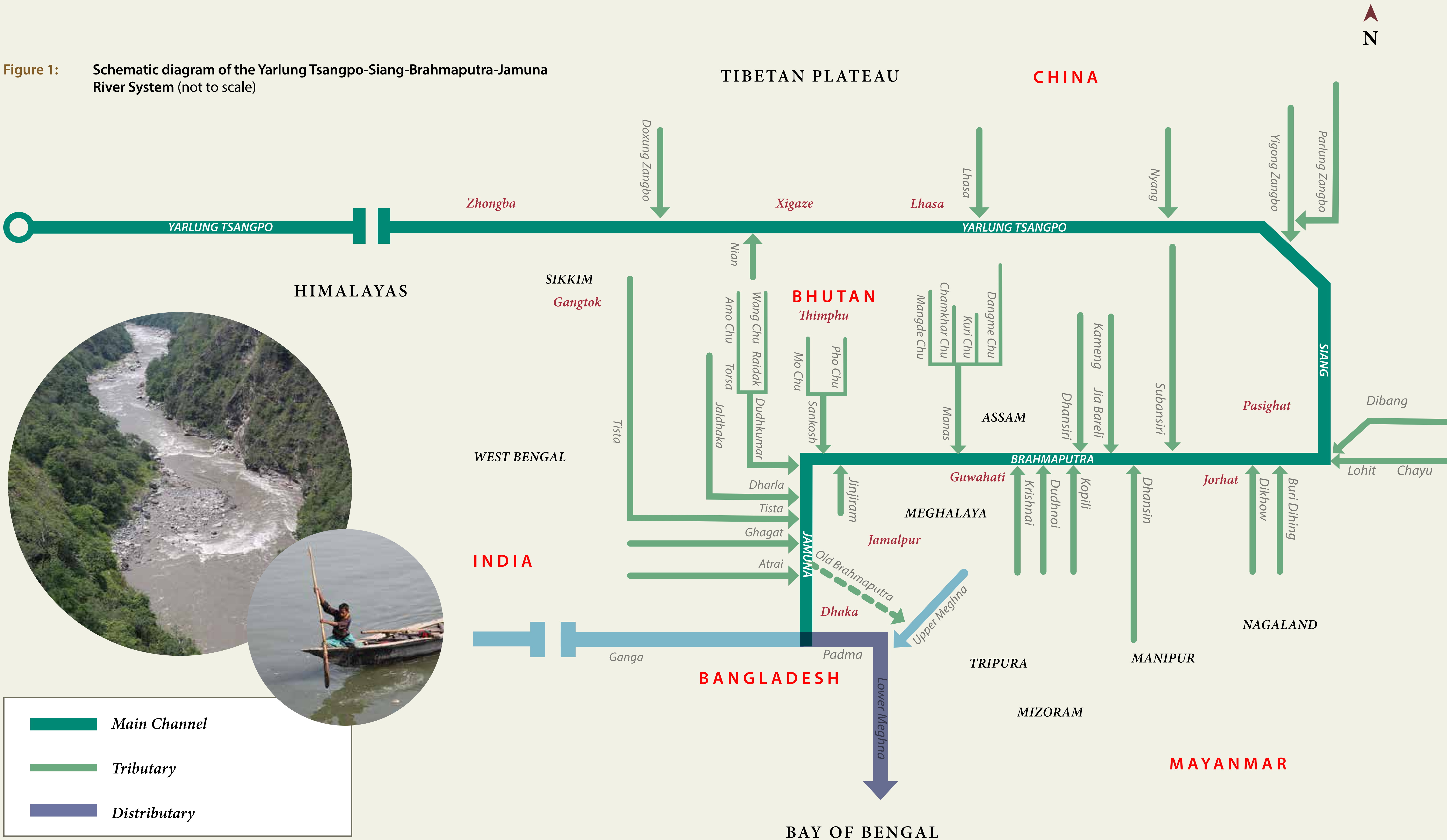
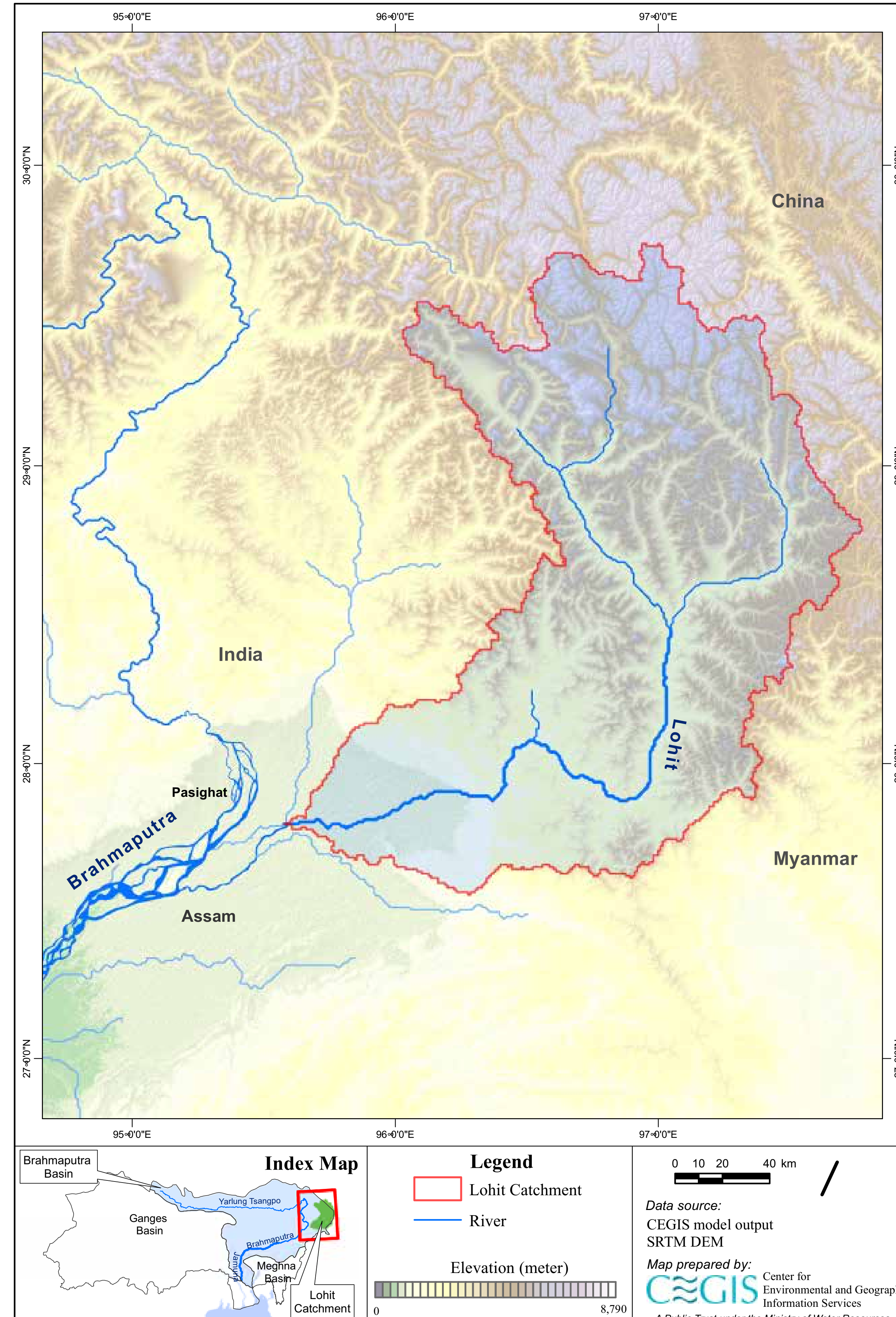
In the course of its journey, the River receives more than 75 major tributaries. Like the main channel, many of the tributaries take on different names at their origin and as they cross the borders.

Figure 1: **Schematic diagram of the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna River System** (not to scale)





June 2020

Tributary: Lohit River (Zayul River)

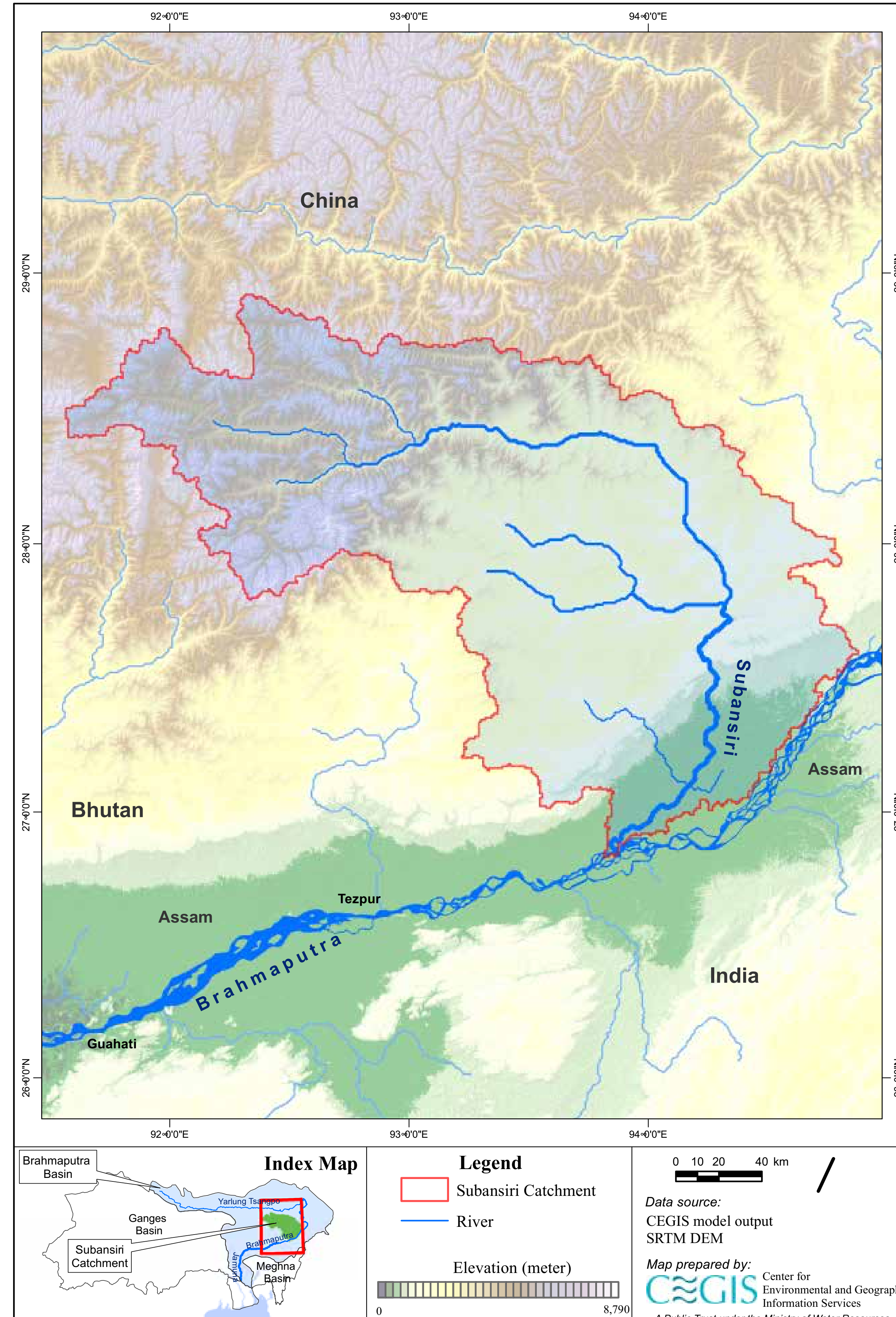
Bushra Nishat

LITERALLY MEANING river of blood, the turbulent Lohit is the eastern most tributary of the Brahmaputra. In ancient times, the Lohit was considered as the main channel of the Brahmaputra. According to folklore, the Brahmaputra originated from the Brahmakunda or Parshuram Kunda, a holy site currently nestled on the lower reaches of Lohit, at the foothills of the Mishimi Hills. The river originates from the Kangri Garpo mountain range of Eastern Tibet as the Zayul and then enters India through the northeastern tip of the country, flows through the Mishmi Hills and descends to join the Siang and Dibang at the head of the Brahmaputra valley. On its travels, the Lohit is joined by numerous tributaries; all these streams are perennially snowfed rivers[17]. A very small part (less than 1 percent) of the Lohit catchment falls in Myanmar.

Tributary: Subansiri River

Bushra Nishat

THE SUBANSIRI is the largest, longest and most important tributary of the Brahmaputra, and contributes around 12 percent of the annual flow of the Brahmaputra. The Subansiri is 442 kilometers long, with a drainage basin covering 32,640 square kilometers in China and India. The Subansiri River originates in the Himalayas, in China at an elevation of 5,591 meters above sea level. It flows east and southeast into India, then south to the Assam Valley, where it joins the Brahmaputra on its northern bank. Many tributaries such as Kamala, Kurung and Ranga join the Subansiri as it descends into the Brahmaputra valley[18]. Subansiri meaning the flow of gold in Assamese was a potential site for the valuable mineral. Religious Epics record that, the Kings of Brahmaputra valley offered Yudhistira, son of the Hindu God of justice and death, a gift of gold shipped on elephant back. Legends claim, this gold was carried by the water and washed since ancient times by the local tribes called Sonowals[19].



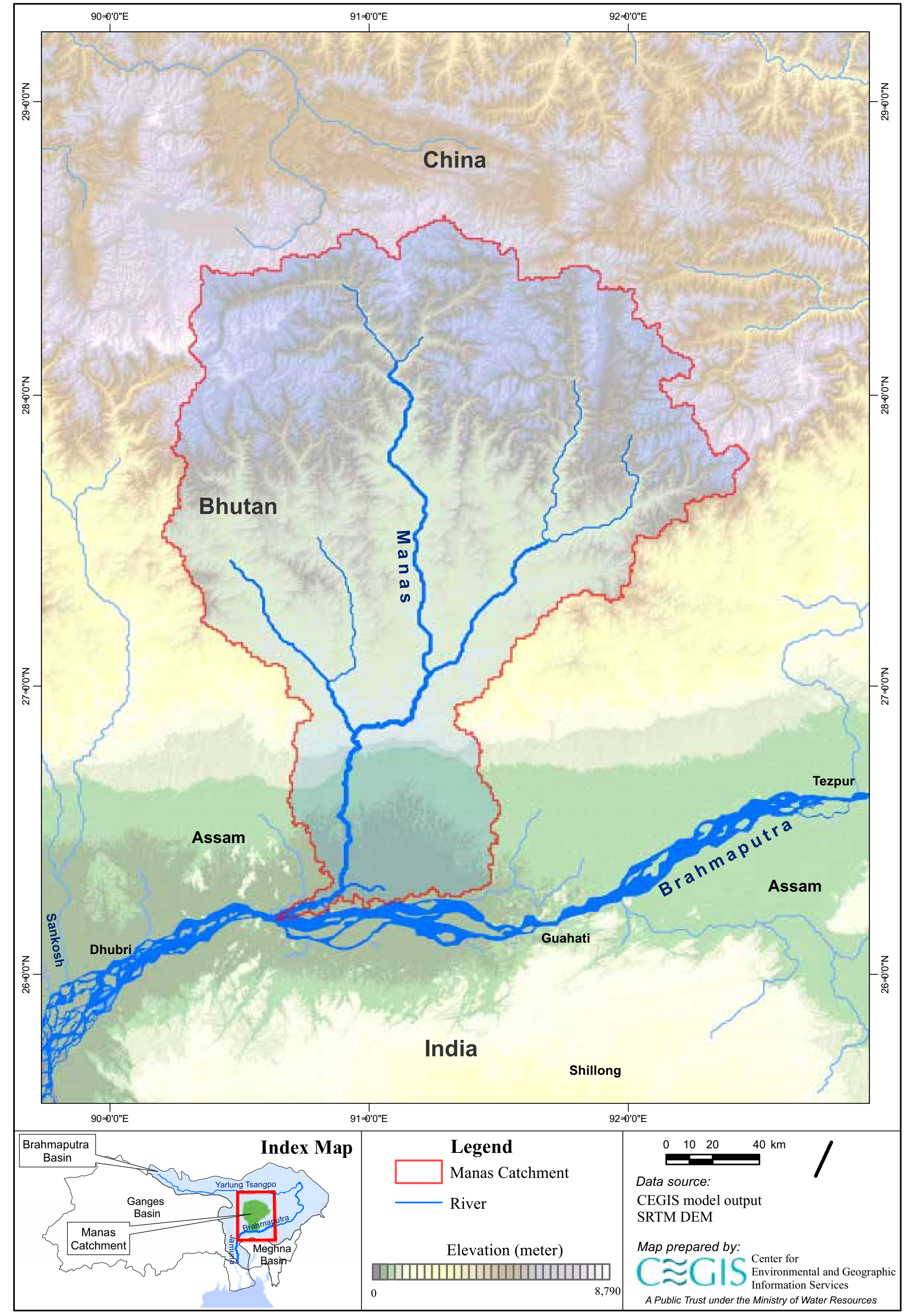
June 2020

Tributary: Manas River

Md Monowar-ul-Haq

THE MANAS is the largest river system of Bhutan, which drains almost all the catchments of the central and eastern regions of the country. It comprises of four major sub-basins, namely Mangde Chhu and Chamkhar Chhu; Kuri Chhu, which originates from Tibet; and Dangmechhu, formed by joining two main tributaries Kholongchhu that originates from the northeastern part of the country and Gongri that originates from Tibet and flows into India before entering Bhutan. Mangde Chhu and Chamkhar Chhu both originate close to Gangkhar Puensum which has a height of 7,570 meters above sea level, is the highest peak of Bhutan and one of the highest unclimbed mountains in the world. The Manas basin covers 8,457 square kilometeres, which represents 22 percent of the total area of Bhutan[20]. The catchment is mostly covered by steep mountainous terrain, rising within a space of 140 kilometers from an elevation of about 100 meters near the Indian border to the great Himalayan peaks at over 7,500 meters along the main Himalayan range bordering Bhutan and Tibet. The huge elevation range and varied climatic conditions are reflected in the great ecological diversity and rich fauna and flora in the river catchment[21].

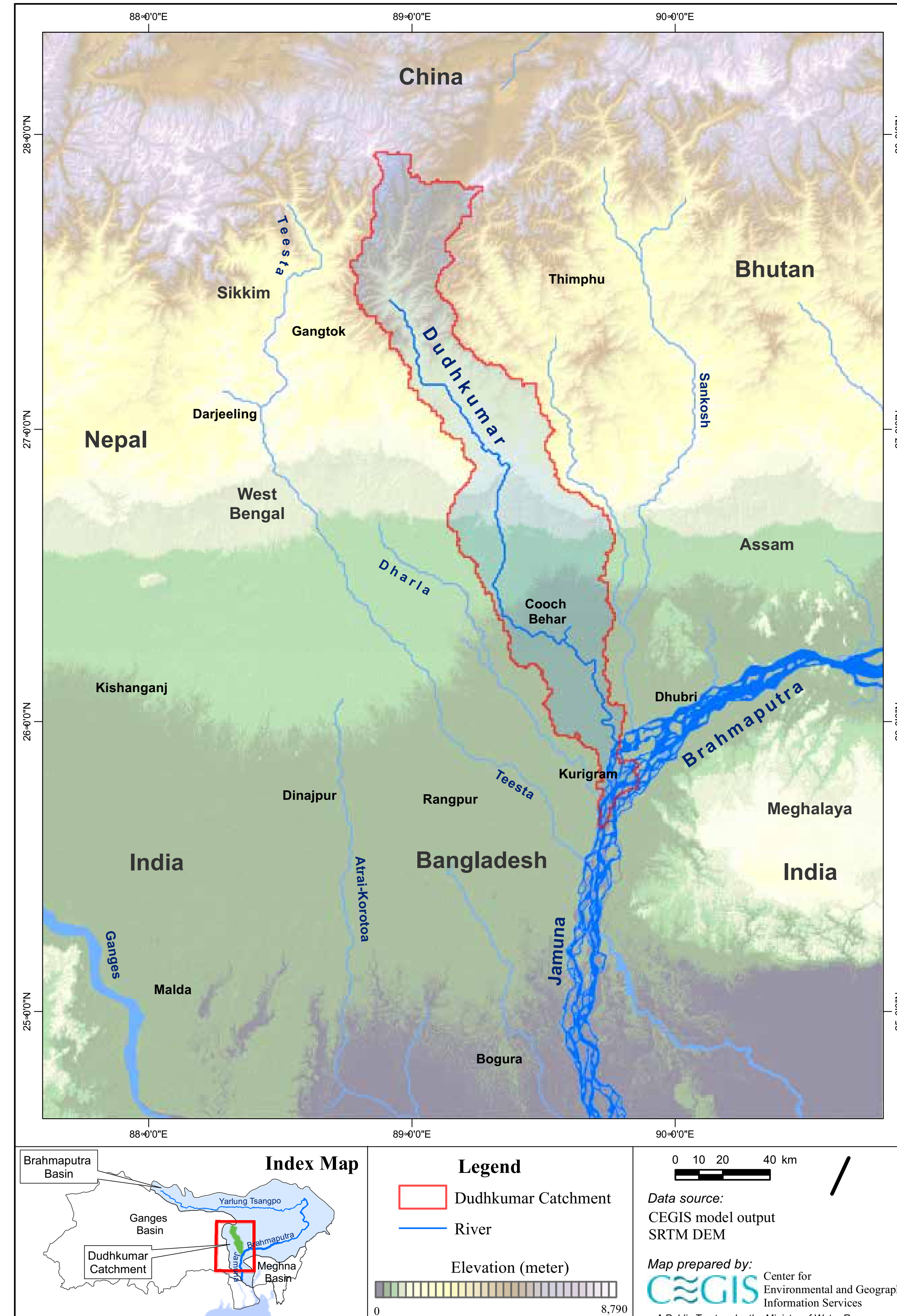
The climate is extremely varied, ranging from hot and humid subtropical conditions in the south to cold and dry alpine conditions in the north. From May to October, the southwest monsoon brings heavy rainfall, more than 6,000 millimeters to the southern part and there is a pronounced dry season in winter[22]. The difference between maximum and minimum river flow in monsoon and the dry months is said to be as much as 20 times. The Manas merges with the Brahmaputra in Duars[23] of India, has a recorded maximum discharge of 7,641 cubic meters and contributes 5.48 percent of the total flows of the Brahmaputra[24].



Tributary: Dudhkumar River/ Torsa-Raidak River system

Md Monowar-ul-Haq

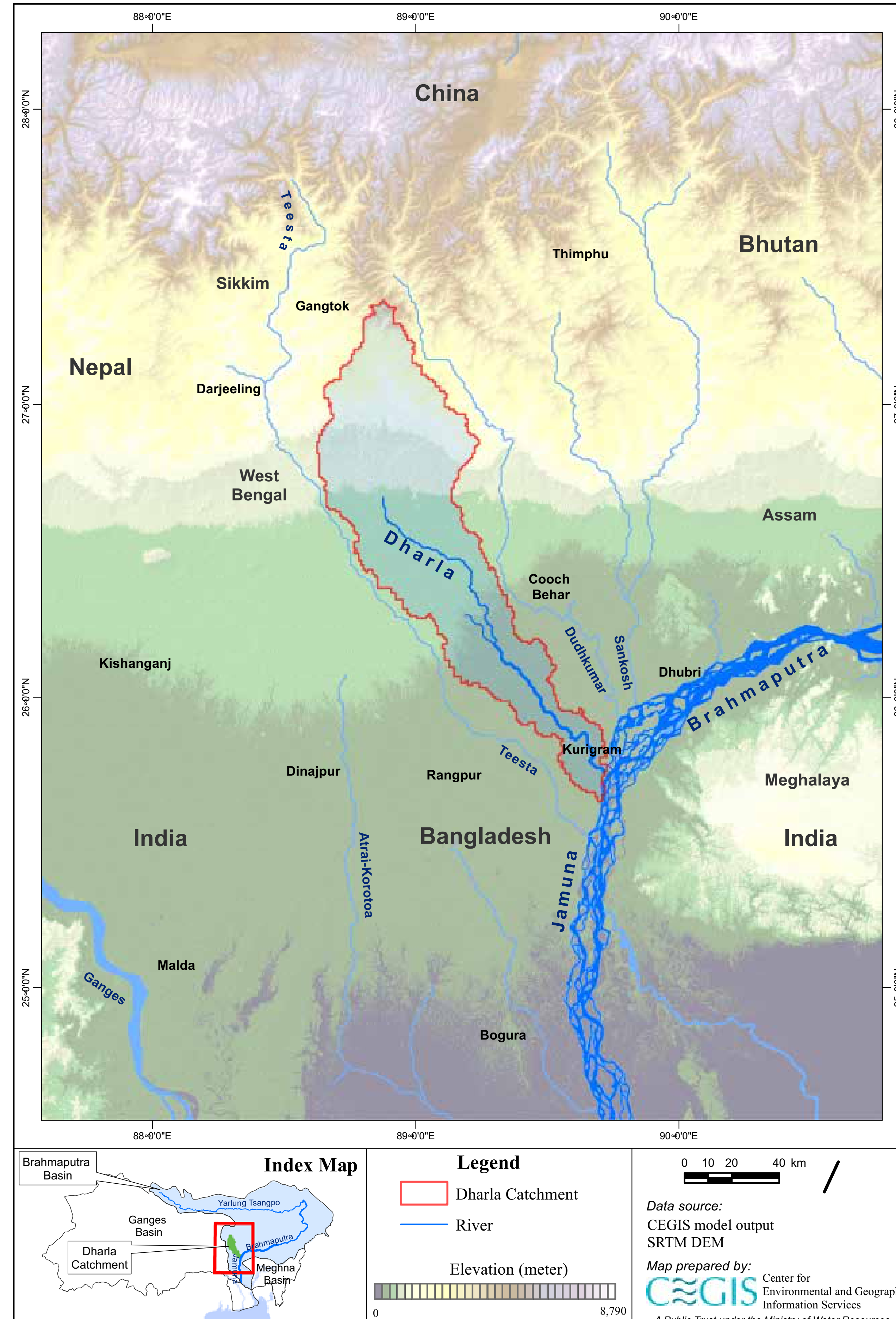
THE TWIN streams of Torsa and Raidak draw their source-waters from high glacial valleys that fringe western Bhutan and the Tibetan plateau and merge in West Bengal, India as the Dudhkumar, which flows through northeastern Bangladesh as a major tributary to join the Jamuna. In Bhutan the Torsa and Raidak are known as the Amuchhu and Wang Chhu respectively. Just before the Torsa-Raidak confluence, one Raidak distributary combines with Sankosh, another Indian tributary to flow into the Brahmaputra near the Assam-Bengal border. The Raidak thus contributes to the Brahmaputra through two river systems, one branch of which is gaining prominence as the other shrinks. However, till the downstream flows of the Torsa and Raidak unite, they are widely seen as separate rivers in their upper, middle and lower segments. Therefore, a real sense of their regional importance is better gained if they are viewed initially as distinct systems[25].



Tributary: Dharla River/Jaldhaka River

Bushra Nishat

FROM ITS source and most part of its upstream, this tributary emerges as Jaldhaka from the eastern part of Sikkim, the southwestern highlands of Bhutan and the Darjeeling hills of West Bengal in India. Flowing east of Teesta, it gathers waters from several mountain streams as it descends on the low lying Duars of northern Bengal. As it flows downstream, the Jaldhaka, also known as Mansai in some areas of Jalpaiguri, assumes a new name Dharla as it crosses the international border and joins the Jamuna north of the Teesta-Jamuna confluence. The Dharla is completely rainfed. With a large and well-developed higher-order catchment, it receives major tributary rivers along both its banks. These include the Jaldhaka that separates India from Bhutan, as well as the various segments, Mansai, Jaldhaka, Singimari, that feed into the Jaldhaka downstream. This variety of names also identifies the Jaldhaka as another transboundary river that has swung widely over its floodplains in the past[26].



June 2020

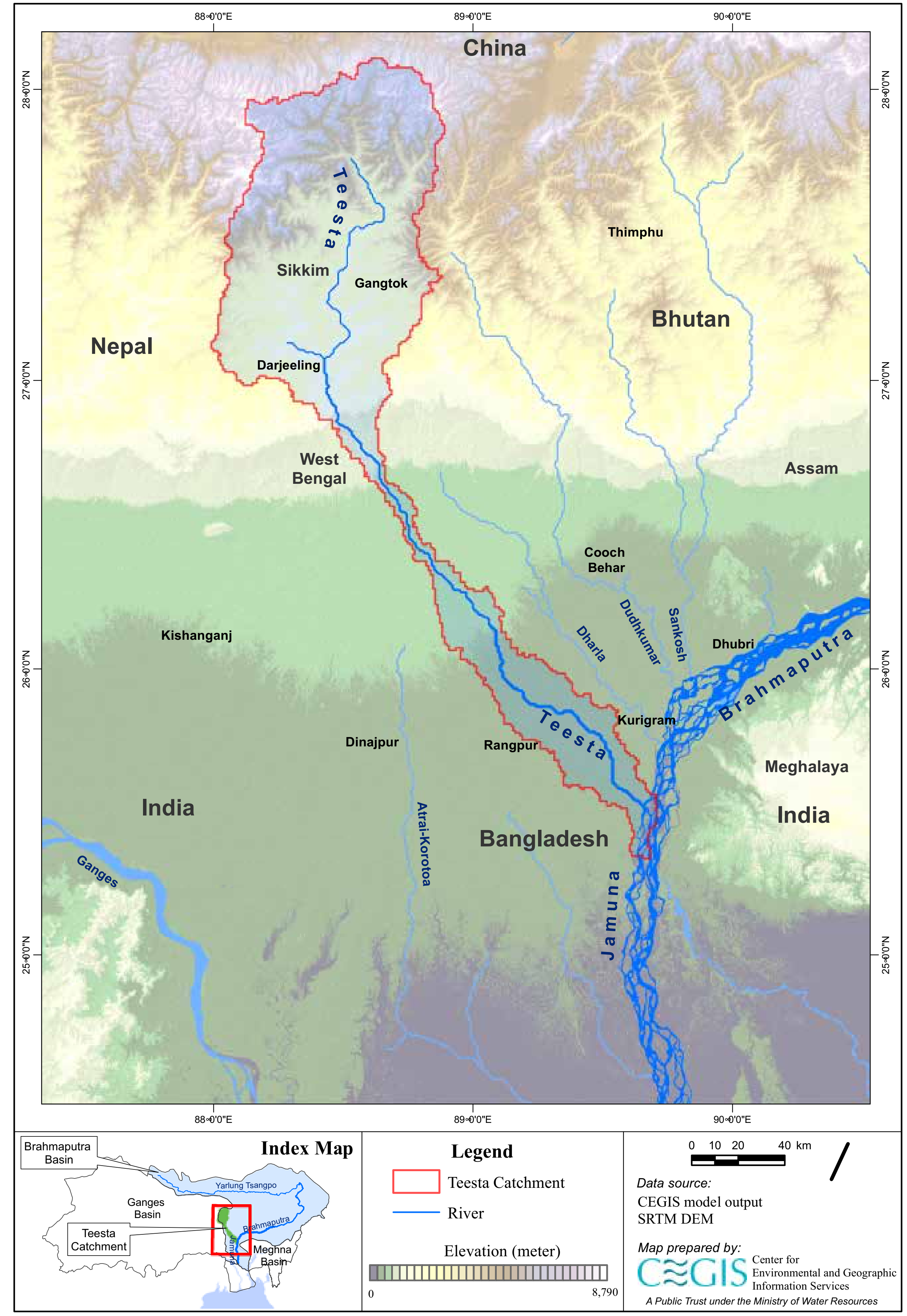
Tributary: Teesta River

Malik Fida Abdullah Khan

THE TEESTA originates high in the Himalaya at an elevation of 5,330 meters above sea level from the Cholamo Lake and crosses Sikkim and West Bengal states of India before joining the Jamuna in Bangladesh. This river is the main tributary of the Jamuna and a river of high importance in Sikkim, northern part of West Bengal and northwest Bangladesh. In the northern state of Sikkim of India, the emerald green waters of the Teesta dominate the landscape of the mountains and valleys. As the river winds its way through the Himalayan temperate and tropical valleys it is fed by smaller rivers which arise from Thangu, Yumthang and Donkia-La ranges. The main tributaries being the snow and rainfed – Lachen and Lachung, Rangeet and the Rongni-chu rivers[27].

Historians believe the name Teesta comes from the Bengali word Trisrota (having three torrents) as once this river split up into three distributaries, the Punarbhaba, the Karatoya and the Atrai. This tendency to shift course is displayed by most mountain-sourced rivers of this region, the Teesta is the largest among these to have periodically undergone such shifts. Each swing of the river has irretrievably transformed the economic life and activities of the eco-region through which the Teesta flows[28].

The rain and snow fed river is perennial but flow in the dry season goes down drastically. The average annual rainfall varies from 1,200 millimeters to 2,500 millimeters in the Teesta basin[29].



CLIMATE OF THE BASIN

Fanyu Zhao and Di Long

THE LOCATION, complex topography and tremendous height of the Himalayas impedes the passage of cold continental air from the north into the Brahmaputra valley and Jamuna floodplains in winter and also forces the rain-bearing summer monsoon from the Bay of Bengal to limit moisture content before crossing the range northward. The result is heavy rain in lowlands and snow at higher elevations on the southern part of the basin but arid conditions in the Tibetan Plateau[30]. The Himalayas thus divides the entire basin into two distinct climatic zones:

(1) **the mountain climate**, characterized as cold and dry, dominates the northern part of the basin; and (2) **the tropical monsoon climate**, characterized as warm and humid, dominates the southern part.
However, based on climate and topography there are three distinctive physiographic zones, the Tibetan Plateau, the Himalayan Belt and the lowlying flood plains[31].

The Himalayas thus divides the entire basin into two distinct climatic zones: the mountain climate and the tropical monsoon climate

Temperatures in the three physiographic zones

Average temperature and precipitation in the basin vary in the three physiographic zones. Typically, December and January are the coldest months, and May to August are the warmest months of each year. The mean annual precipitation in the basin is about 1,350 millimeters[32], of which 60 to 70 percent occurs during the summer monsoon months (June to September)[33], 20 to 25 percent in the pre-monsoon months from March through May.

The Tibetan Plateau is coldest with average temperatures ranging from −10 °C in winter to 7 °C in summer. Winter temperatures in the Himalayan Belt fluctuate around 2 °C, whereas summer temperatures are approximately 15 °C on average. The low-lying flood plains are the warmest among the three zones, with mean winter temperatures around 17 °C and mean summer temperatures about 27 °C. For all zones the seasonal temperature variation is largest in winter but smallest in summer[34].

Precipitation in the three physiographic zones

The dry Tibetan Plateau has a mean annual precipitation of 734 millimeters, however, around the Yarlung Tsangpo Grand Canyon, channels of moisture and precipitation extend northwards, which translates into significant rainfall, around 2,000 millimeters or less per year north of the Himalayan front in the syntax region[35]. Snowpack of the Tibetan Plateau also plays a crucial role in the variation in inter-annual precipitation. Upper-tropospheric air temperatures above the Plateau are amongst the warmest on the planet as a result of the heating of the elevated land with altitudes of over 3,500 meters above sea level. The tropospheric temperature gradient between the Tibetan Plateau and the Indian Ocean is essential for the occurrence of the Indian monsoon. The snow depth on the Tibetan Plateau affects the land surface thermodynamics and

reduces this thermal gradient[36].

The Himalayan Belt is situated in the periphery of the extra-tropical circulation and tropical monsoon circulation in the north and south respectively. Southwesterly monsoon currents channel moist air toward the eastern Himalayas, where the moisture rising over the steep terrain cools and condenses to fall as rain or snow. Annual average precipitation varies between 1,000 millimeters and 1,600 millimeters in the north to higher than 4,000 millimeters in the south at the lower reaches of the mountain ranges[37].

The Brahmaputra floodplains are the wettest part of the basin with an average precipitation of 3,500 to 4,000 millimeters. Within Bangladesh, the annual rainfall within the Jamuna floodplains varies between 1,500 millimeters and 3,000 millimeters[38].

Glaciers of the Basin

Due to the high altitude and low temperature, glaciers are widely distributed in the basin, with an area of about 9,513 square kilometers[39]. These glaciers are mainly distributed in the high altitude areas of the Himalayan mountain ranges. In the eastern Nyainqentanglha range, the glaciers are extremely developed, mainly affected by the Indian monsoon, with a low elevation (minimum 2,400 meters), and glacier tongues generally extend into forests. The impact of climate change on glaciers is becoming apparent with the majority of glaciers shrinking. Rising temperatures is one of the major causes of snow-melting in the Yarlung Tsangpo catchment. The increased rates of snow and glacial melt are likely to increase summer flows for a few decades and accelerate glacial lake expansion[40].

Climate change in the Basin

Over the past decades and across the basin, temperatures are changing over time and showing mixed trends across seasons and in different areas of the basin. Overall, mean winter minimum temperatures show increasing trends, and nighttime temperature shows a highly significant warming trend for winter as well as summer. There has been a significant rise of 0.5 °C in mean minimum winter temperature across the basin. As for precipitation, no specific trend of change in the amount of rainfall has been observed between the baseline period of 1951–1980 and 1981–2007. Extreme rainfall appears to be decreasing in the north but increasing over eastern portions of the basin. Rainfall intensity has increased slightly over eastern portions of the basin[41]. Therefore, there could be more disastrous problems like flood frequency and lake outburst.

Glacial reserves combined with the extremely dynamic monsoon regime interacting in a unique physiographic setting and active seismo-tectonic geological base have moulded the river into one of the world's most massive fluvial systems

HYDROLOGY

Glacial reserves combined with the extremely dynamic monsoon regime interacting in a unique physiographic setting and active seismo-tectonic geological base have moulded the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna into one of the world's most massive fluvial systems. The inter annual discharge and repetitive patterns of rise and fall of flow correspond to the seasonal variation of monsoon precipitation and freeze-thaw cycle of the glaciers and snowpack in the basin. The seasonal variation in flow is thus highly skewed with around 70 to 80 percent of the flow occurring during monsoon and very small flow during dry season[42]. Floods inundate the landscape during the summer monsoon every year as rainfall and snowmelt from the mountains cause the rivers to spill over their banks. These inundations frequently develop into devastating floods, especially in India and Bangladesh. The average annual runoff of the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna River at Majuli and Pandu in India is 278 and 509 billion cubic meters[43] respectively, and at Bahadurabad in Bangladesh the flow becomes 660 billion cubic meters[44].

This section describes the network of the main channel, tributaries and drainage outlets, the hydrology and floods of the River.

Hydrology of the River System

Md Monowar-ul-Haq, Malik Fida Abdullah Khan, Tanvir Ahmed

The water yield of the river basin is one of the highest in the world; the drainage area is the fourteenth largest in the world, yet, in terms of flow the River carries the fifth largest discharge

THE WATER yield of the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna basin is one of the highest in the world; the drainage area is the fourteenth largest in the world, yet, in terms of flow the River carries the fifth largest discharge[47]. It should be noted that the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna catchment is largely ungauged; moreover, topography, accessibility and to a large extent, economic considerations restrict the routine data collection which can consequently limit the accuracy of the data owing to the fact that the river through its course, traverses some of the steepest jagged ravines and dense temperate and tropical forest landscapes[48].

Figure 5 illustrates the catchment-wise flow contributions for the River system. The estimations of flow are based on basin level hydrological modelling using the ArcSWAT model tool based on the Soil & Water Assessment Tool (SWAT) with precipitation data for the period 1981 to 2012[49]. River, tributaries and sub-basin delineation has been principally based on georeferenced Digital Elevation Models. The delineated Brahmaputra Basin was sub-divided into 223 watersheds for flow calculations. For weather data (precipitation, temperature, relative humidity etc.), a combination of both local (Bangladesh portion of GBM) and global (transboundary portion of GBM) sourced data have been used. The model has been calibrated and validated against monthly discharge data at Bahadurabad inside Bangladesh and simulated for a period between 1981 and 2012 and annual average flow was estimated for each catchment to assess the percentage of catchment contribution.

Figure 5: Sub-catchment flow contributions for Yarlung Tsangpo-Brahmaputra-Jamuna Basin

Source: Analysis by Center for Environmental and Geographic Information Services (CEGIS) based on Shuttle Radar Topographic Mission (SRTM) 90 meter Digital Elevation Data of 2016 (resampled to 900 meter from 90 meter) and the Bangladesh National 300 meter resolution (resampled to 200 meter) Digital Elevation Model[50]

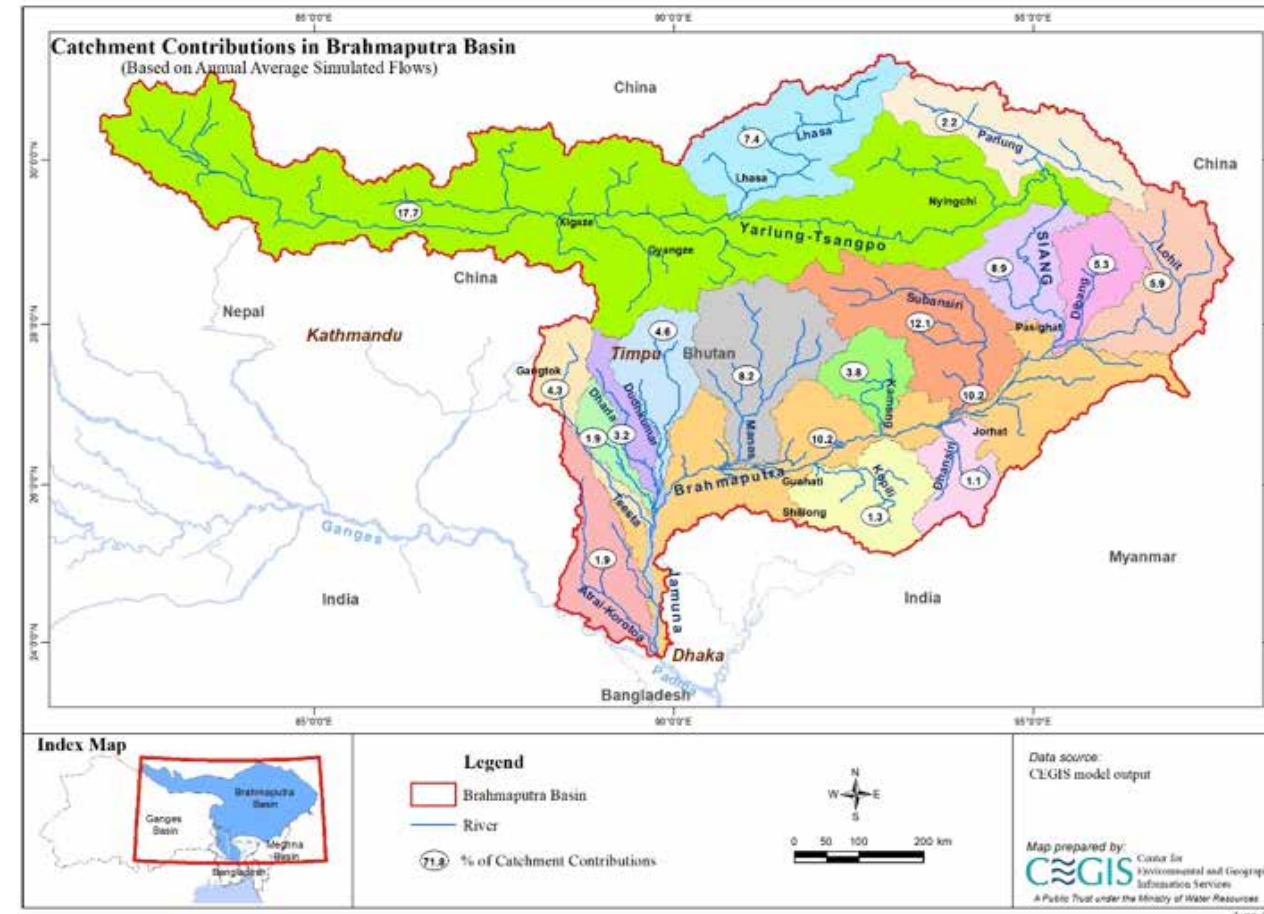
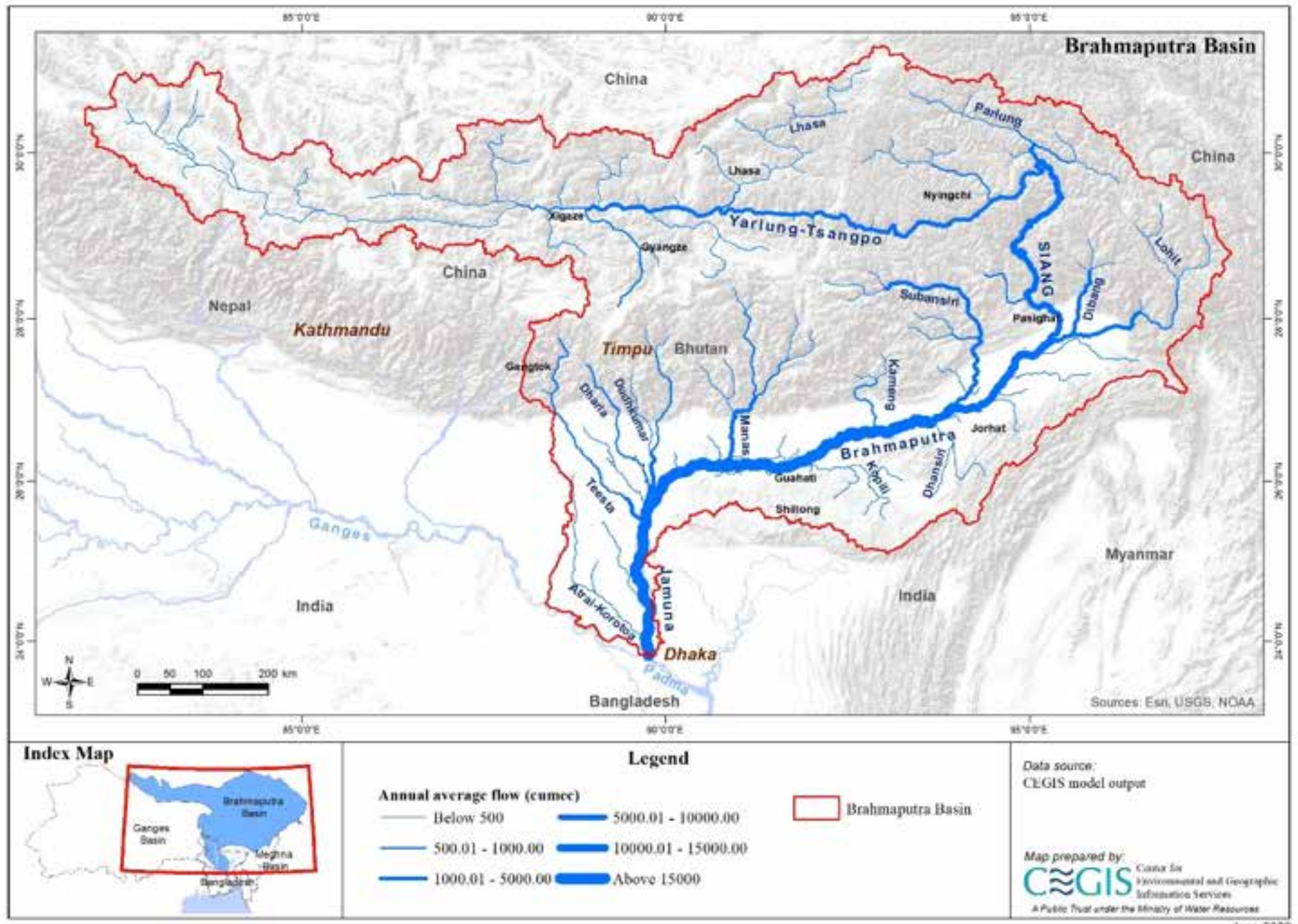


Figure 5 shows the Yarlung Tsangpo is the largest of the catchments which covers nearly half of the entire basin of the River system, but with less than one-fifth (17.7 percent) of the annual flow indicating relatively less precipitation from within the upper catchment bounds[51]. The Figure shows that the Yarlung Tsangpo has been further subdivided into three sub-basins for easier calibration. The Brahmaputra sub-catchments which are mainly within India and Bhutan contribute substantially to the flow as these regions see some of the highest rainfall in the world. The six sub-catchments totaling to roughly one-third (34 percent) of the entire basin contribute almost half (47.7 percent) of the total basin flow. The combined flows of Siang, Dibang and Lohit contribute 20.2 percent of the total Brahmaputra flow[52]. By the time the River enters Bangladesh, it already carries almost the entirety of its total flow (93.7 percent). Only 9 percent of the basin is situated in Bangladesh, and this portion experiences relatively low rainfall, so contribution to Jamuna flow from Bangladesh is also compartitively low.

Figure 6 illustrates flow river reach-wise distribution as displayed as proportionate width. It depicts the gradual increase in river discharge as it gains flow via tributary sub-catchments.

Figure 6: Reach-wise flow distribution proportion to flow width for Yarlung Tsangpo-Siang-Brahmaputra-Jamuna System



Hydrology of Yarlung Tsangpo River Basin

Fuqiang Tian, Ran Xu, Yi Nan

THE YARLUNG Tsangpo is one of the largest rivers originating from the Tibetan Plateau in Southwest China. The mean annual discharge is approximately 20,000 cumec[53]. The climate of the basin is monsoon-driven with an obvious wet season from June to September, which accounts for 60–70 percent of the total annual rainfall. Yarlung Tsangpo basin covers Lhasa, Shannan, Shigatse, Nyingchi and Nagqu, and southern Tibet regions. There are four main hydrological stations located along the main stream, i.e., from upstream to downstream, Lazi, Nugesha, Yangcun and Nuxia hydrological stations. Yarlung Tsangpo River has several tributaries. Information of the six main tributaries is listed in Table 2.

Table 2: Length of channel and area of basin of the six major tributaries of Yarlung Tsangpo

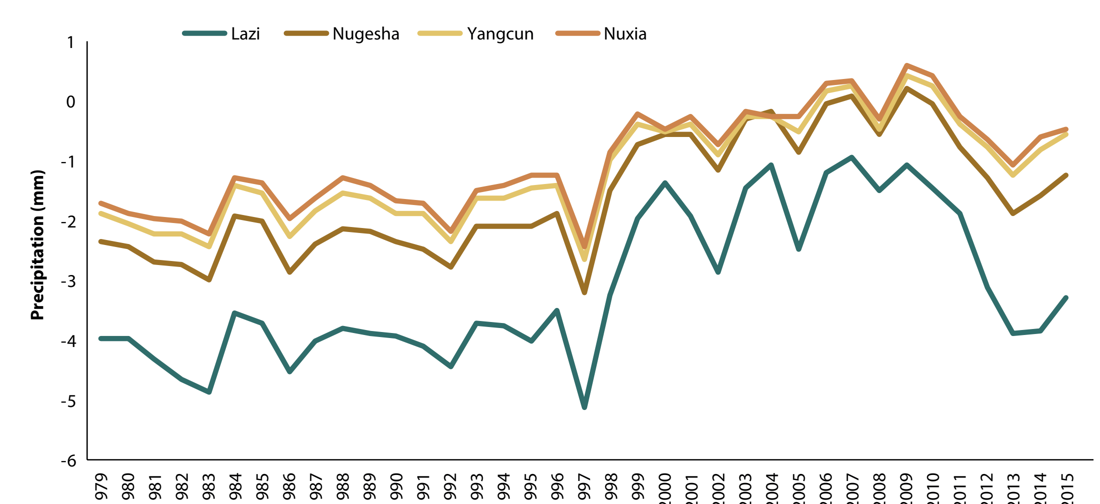
Name	Length (km)	Area (km²)
Doxung Zangbo	303	19697
Nianchu	217	11130
Lhasa	551	32471
Nyang	286	17535
Parlung Zangbo	266	28631
Yigong Zangbo	295	13533

In terms of climate, due to the barrier effect of the high Himalayas and the high altitude of the Tibetan Plateau, the upper and middle sections of the basin, classified as semi-arid climate and cold temperate zone, are extremely cold with little precipitation. The downstream section is humid, rainy and warm and can be classified as mountainous subtropical and tropical climates.

Precipitation in the Yarlung Tsangpo River Basin

The mean annual precipitation of the Yarlung Tsangpo River Basin is 470 millimeters (data from China Meteorological Forcing Data, CMFD). The precipitation shows an increasing trend from the upstream Lazi station to the downstream Nuxia station (Figure 7). The precipitation at Lazi, Nugesha, Yangcun, and Nuxia stations are 410 millimeters, 404 millimeters, 428 millimeters and 470 millimeters, respectively.

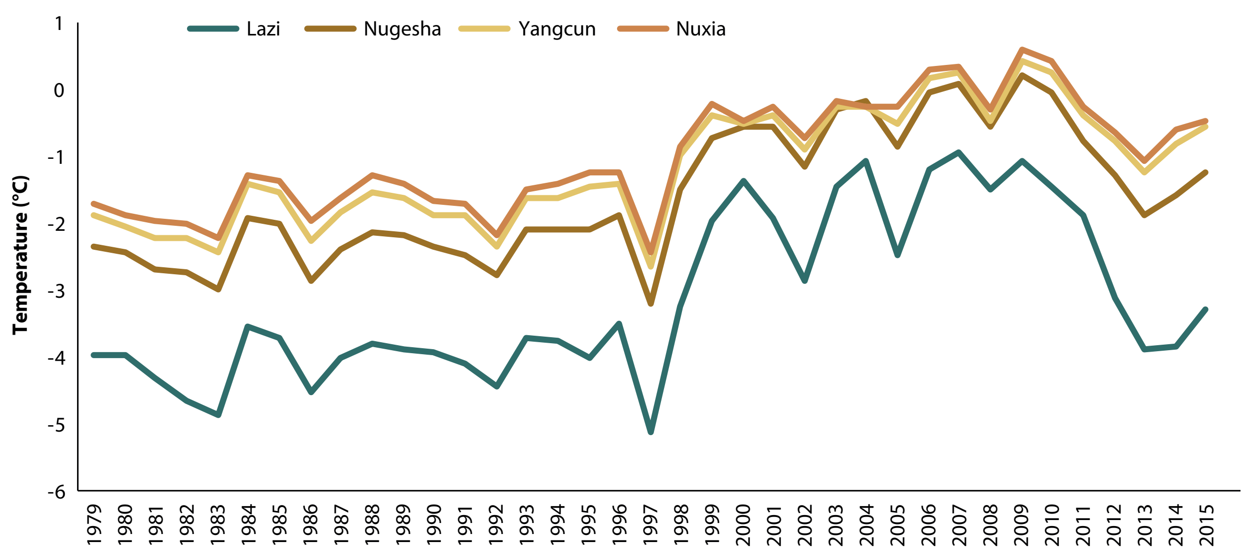
Figure 7. Mean annual precipitation in Yarlung Tsangpo River Basin



Temperature of the Yarlung Tsangpo River Basin

The mean annual temperature of the Yarlung Tsangpo River Basin is -1.01°C (data from CMFD). As shown in Figure 8, the temperature gradually increases as the altitude decreases from upstream to downstream. Mean annual temperature at Lazi, Nugesha, Yangcun, and Nuxiazhan are -3.15°C, -1.59°C, -1.18°C, and -1.01°C, respectively. In terms of temporal pattern, the graph shows a slow increasing trend, which is consistent with global warming.

Figure 8. **Mean annual temperature in Yarlung Tsangpo River Basin**



Hydrology of the Yarlung Tsangpo River Basin

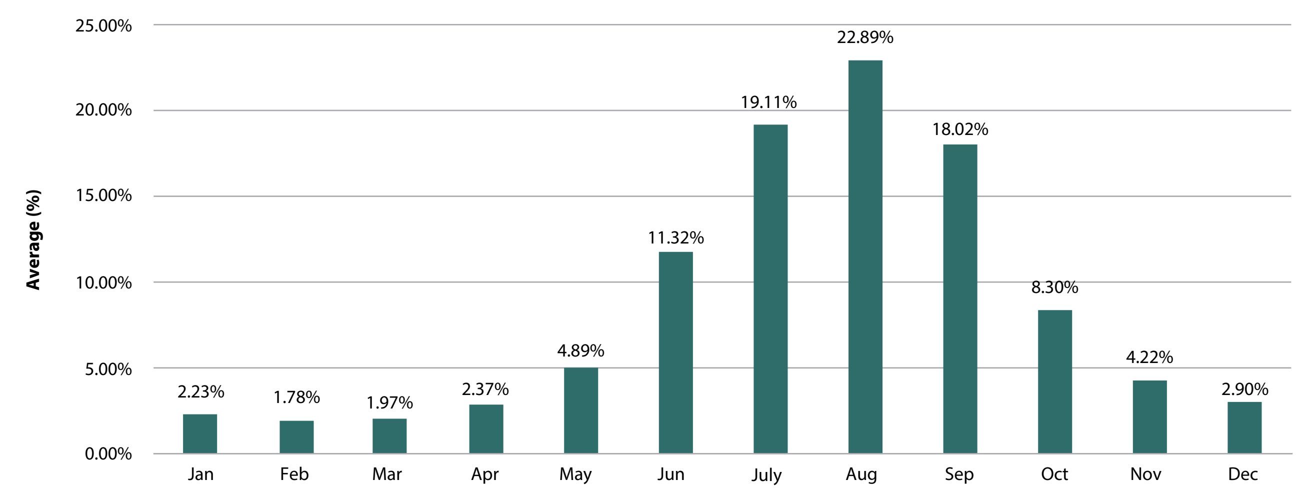
The mean annual runoff depth or water level of the Yarlung Tsangpo River Basin at Nuxia is about 300 millimeters. In terms of spatial pattern, similar to precipitation, the runoff depth increases from upstream to downstream, and the average runoff depth at Lazi, Nugesha, Yangcun, and Nuxia stations are 106 millimeters, 152 millimeters, 184 millimeters, and 292 millimeters, respectively (see Table 3). Due to the effect of monsoon, there is an obvious wet season from June to September, which accounts for more than 70 percent of the runoff (Figure 9).

The runoff of Yarlung Tsangpo River is a mixture of various components. In dry season from October to April of the next year, baseflow dominates the hydrograph. With the increasing temperature, from April to June, snowmelt contributes to the runoff. During the wet season from June to September, the runoff is a mixture of precipitation, snowmelt, glacier melt and baseflow, resulting in a comparatively large discharge[54].

Table 3: **Spatial variation of hydrometeorological elements in Yarlung Tsangpo River Basin**

Name	Mean Annual Precipitation (mm)	Mean Annual Temperature (°C)	Potential Evapotranspiration (mm)	Mean Annual Actual Evapotranspiration (mm)	Runoff Depth (mm)
Nuxia	470	-1.01	2043	195	292
Yangcun	428	-1.18	2104	223	184
Nugesha	404	-1.59	2129	253	152
Lazi	410	-3.15	2012	225	106

Figure 9: **Average seasonal cycles of streamflow at Nuxia station from 1980 to 2012**



Hydrometeorology of Siang-Brahmaputra River Basin

Bushra Nishat

THE SIANG and Brahmaputra along with their network of tributaries dominates the landscape and controls the geomorphic regime of the entire region, especially the Brahmaputra Valley. This is the middle reach and the strongest segment in terms of discharge for the entire River system. Almost 80 percent of this flow occurs in the monsoon season between June and September which corresponds to high monsoon rainfall, especially in the upper reaches of the tributaries. The tributaries have been detailed in a separate section, so in this section the hydro-meteorological conditions of the main channel of the Siang and Brahmaputra is being described.

Climate in the Siang-Brahmaputra River Basin

The climate of this part of the basin is humid sub-tropical characterized by high rainfall and humidity. The physiographic configuration, enormous water bodies and upper air circulation has shaped the climate of this region. The valley is bounded by high mountainous formations and table land in the north, northeast and south; and is wide open in the southwest. The valley thus predominantly receives southwest tropical monsoons during April through October through two inlets, through the southwest and also through hill gaps in the eastern boundary[55]. The monsoon rain accounts for 70 to 80 percent of the annual rainfall with an average between 2,500 and 3,200 millimeters. However, spatial distribution of monsoon rainfall is influenced by orography and varies from 1,200 millimeters in the eastern part to over 6,000 millimeters in the southern slopes of the Himalayas[56]. The higher mountain areas in the north experience snowfall in the winter.

The smaller tributaries are mostly fed by rain and spring water, but the major tributaries orginate from high precipitation areas and in combination with snow and glacier melt contribute large flows to the main channel

The region experiences four distinct seasons, the relatively dry, cool winter from December through February; the dry, hot pre-monsoon season from March through May; the southwest monsoon from June through September when the predominating southwest maritime winds bring rains; and the retreating monsoon of October and November[57]. Post winter, a wide thermal gap is created between the valley and surrounding mountains, this thermal fluctuation and the moisture from the Brahmaputra and its tributaries creates dense fogs, especially in the morning hours[58]. The pre-monsoon season is characterized by a gradual rise in temperature, disappearance of fog, occasional thunderstorms, cool mornings and hot afternoon winds. The hottest month for most of the basin is May when temperatures can rise as high as 40°C, and winter becomes extremely cold as freezing winds from the north depress temperatures in the valley.

Hydrology of the Siang-Brahmaputra River Basin

The Siang-Brahmaputra and their major tributaries show a seasonal variation in discharge pattern, which corresponds to a tropical monsoon climate. The smaller tributaries are mostly fed by rain and spring water, but the major tributaries orginate from high precipitation areas and in combination with snow and glacier melt contribute large flows to the main channel. Since peaking characteristics of flood flows are different in different tributaries, due to catchment physiography and time lag in rainfall, there is a time lag in tributary floods draining into the river. As a result, the flood hydrograph for the Brahmaputra often shows multiple peaks as can be seen from Figure 10.

Figure 10. Hydrograph of Brahmaputra
(Source: Mahanta et al 2014[59])

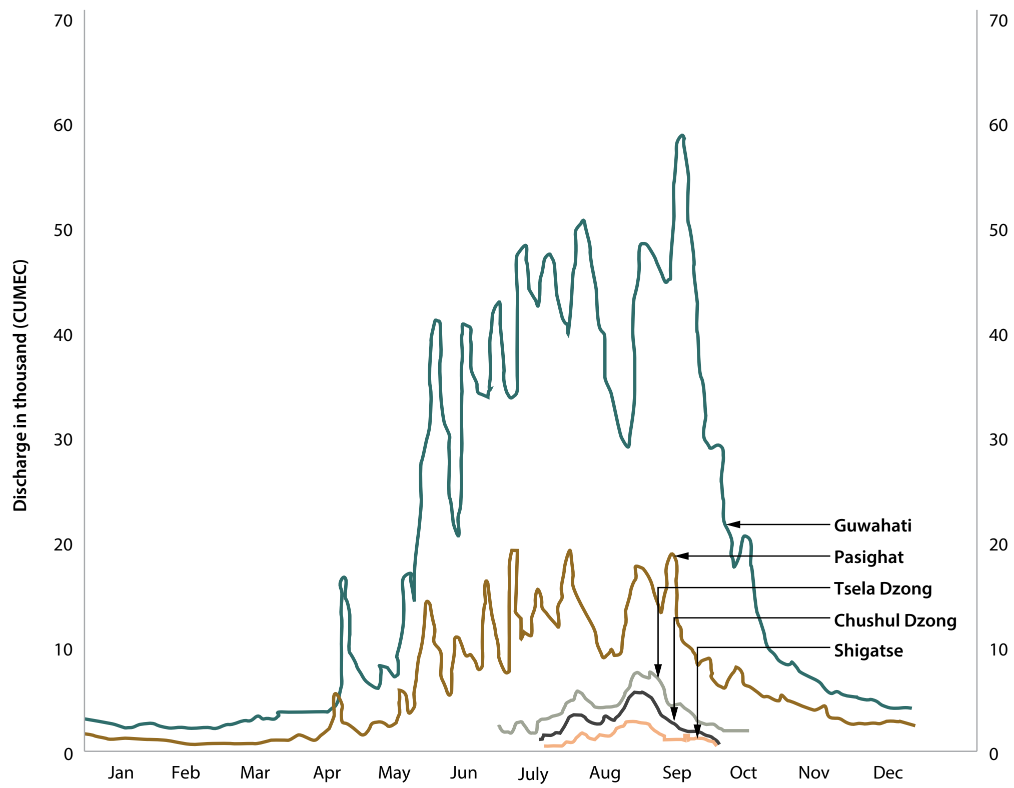
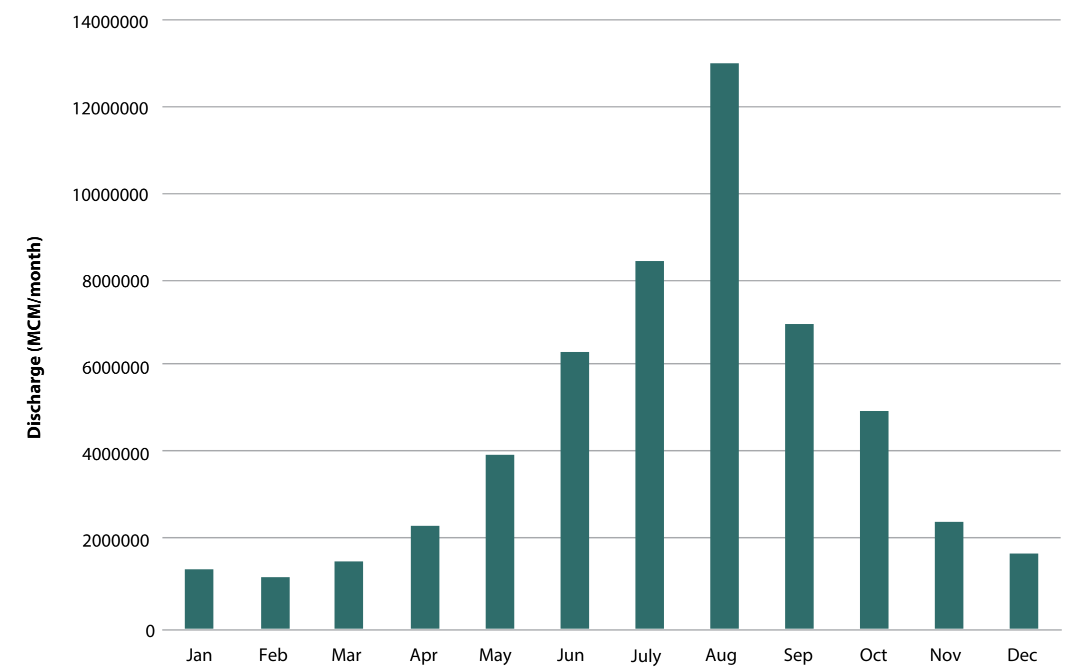


Table 4 shows the different flows of the Siang-Brahmaputra at different locations of the basin at Pasighat, Majuli, Pandu and Pancharatna. It shows that the flow of the main channel increases substantially and almost doubles by the time the River reaches Bangladesh. As seen from Figures 10 and 11, this increase is more prominent in the monsoon[60].

Table 4: Mean annual flows at various locations on the Brahmaputra
(Source: Mahanta et al 2014[61])

Location	Mean Flow (MCM/yr)
Bechamara, Majuli	278,447
Bhurbandha, Bhurgaon	365,550
Pancharatna, Goalpara	509,435
Pandu, Guwahati	526,092

Figure 11. Average seasonal cycles of streamflow at Pandu
(Based on Mahanta et al 2014[62])



The Brahmaputra channel is governed by the peak and dry period discharge during which the channel bed undergoes tremendous adjustment, which in turn affects the flow regime of the river. While the Siang-Brahmaputra is considered a water abundant basin and the main channel and tributaries are perennial in nature, flows reduce considerably between October and May (shown in Figure 11). Since all tributaries pass through alluvial plains, underground seepage is quite high, especially during flood events, providing a substantial base flow for the rivers during dry season[63].

With a catchment area of 47,000 square kilometers, the four river basins of Bhutan cover around 9% of Brahmaputra basin

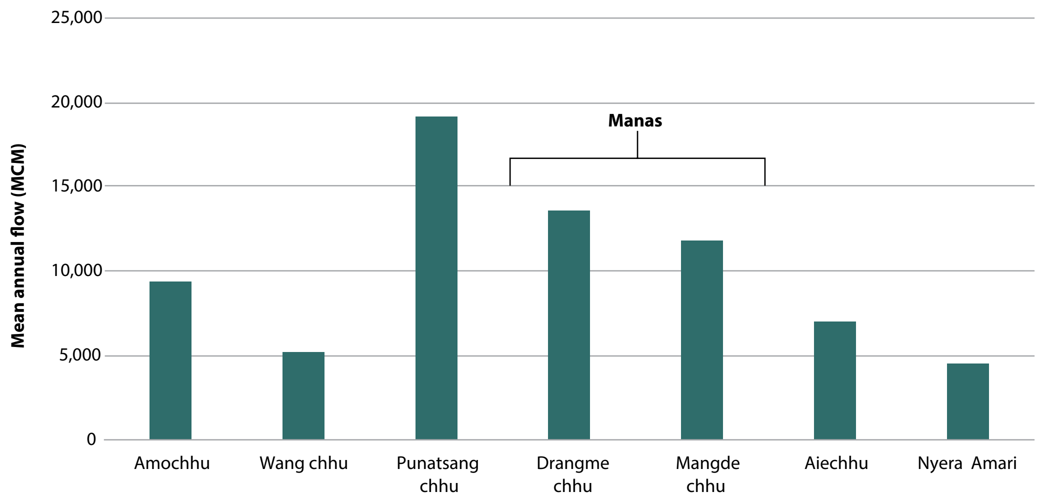
❄

Hydrometeorology of tributaries flowing through Bhutan

Ahmmed Zulfiqar Rahaman

BHUTAN HAS four[64] major river basins viz Amohchu, Wangchhu, Punatsangchhu, and Manas with a catchment area of around 47,000 square kilometers, which covers around 9 percent of Brahmaputra basin[65]. The Manas is the largest river basin with the highest flow, which drains almost all the catchments of central and eastern Bhutan. The basin is around 15,837[66] square kilometers inside Bhutan and covers around 41 percent of the country's territory.

Figure 12: Mean annual flow of rivers of Bhutan
(Source: National Environment Commission (NEC), 2016)[67]



These rivers are mostly fed by rainfall and supplemented by glaciers (2 percent to 12 percent)[68] and snowmelt, which attributes an estimated 70,576 million cubic meters flow from Bhutan into the Brahmaputra-Jamuna river and corresponds to around 12 percent of the flow of Jamuna at Bahadurabad Water and Discharge Guaging Station[69].

The rivers of Bhutan generally have steep gradients in the scale of 1:1140[70] on an average, and narrow steep-sided valleys, which occasionally open up to give small areas of flat land for human settlement and cultivation[71]. They carry large volumes of flow and sediment during the monsoon season and significant snowmelt at the end of the dry season. Average annual suspended load of the Manas River is 2,1660 tonnes and the annual sediment yield is 1,581 tonnes per square kilometer per year[72].

Hydrology of Jamuna River Basin

Md Monowar-ul-Haq and Malik Fida Abdullah Khan

THE BRAHMAPUTRA enters Bangladesh east of Bhabanipur (Assam, India) and northeast of Kurigram district and the river is now called the Jamuna. The Jamuna has an annual average discharge of around 667 billion cubic meters as measured at Bahadurabad Water and Discharge Guaging Station. Over 75 percent of the discharge of the Jamuna river is generated from rainfall and snowmelt from upstream countries, as a result, the flow pattern is not strongly related to local precipitation.

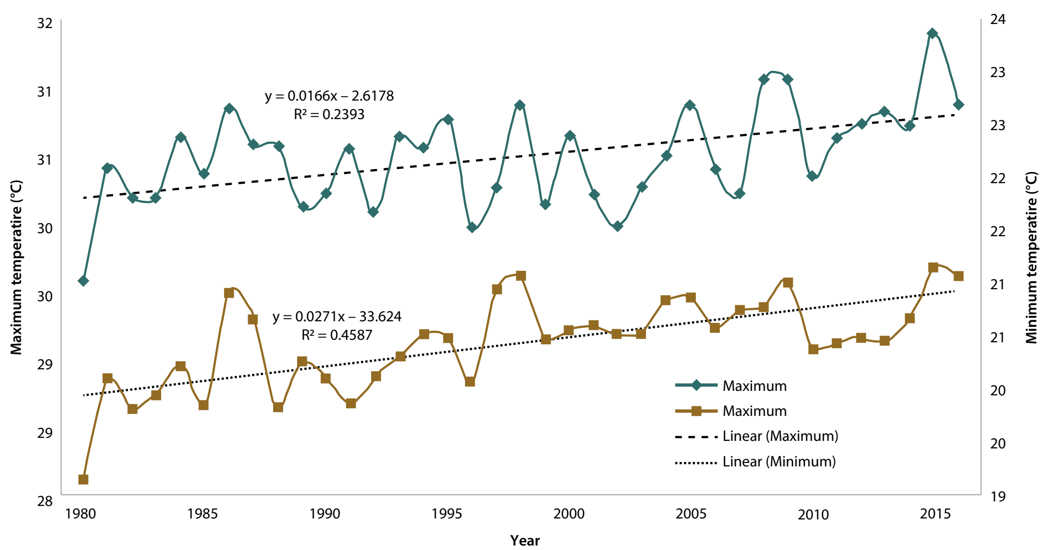
Climate

The Jamuna basin lies in the northwest part of Bangladesh where the climate is sub-tropical in nature with three seasons namely summer/pre-monsoon from March to May, monsoon between June to September, and winter season from October to February. Lower rainfall makes this area atmospherically drier than the rest of the country. The rainy season is hot and humid with about 70 percent to 80 percent of the annual rainfall. The winter is predominately cool and dry.

Maximum temperature occurs in the month of April and minimum temperature in January. Monthly maximum temperature varies from 25°C to 35°C.The average temperature during monsoon is about 34°C[73]. Figure 13 presents a temperature trend analysis for the Jamuna Basin within Bangladesh. Plots are generated for both maximum and minimum temperature values using data for the years 1981-2017. Trends indicate an increase for both maximum and minimum temperatures.

Figure 13: Temperature trend analysis for Jamuna Basin

(Data source: National Water Resources Database, Bangladesh. Analysis by Centre for Environmental and Geographic Information Services (CEGIS))



Average annual rainfall in this region is around 1,900 millimeters which is below the average of Bangladesh, which is around 2,300 mm[74]. Trend analysis of precipitation in the Jamuna basin is shown in Figure 13. Rainfall data for the plot was prepared using the average data for the years 1948-2017 and is compared with the discharge for Jamuna river at Bahadurabad.

Between 1953 and 2016 the Brahmaputra valley experienced major floods on thirty-nine occasions, affecting over a million people

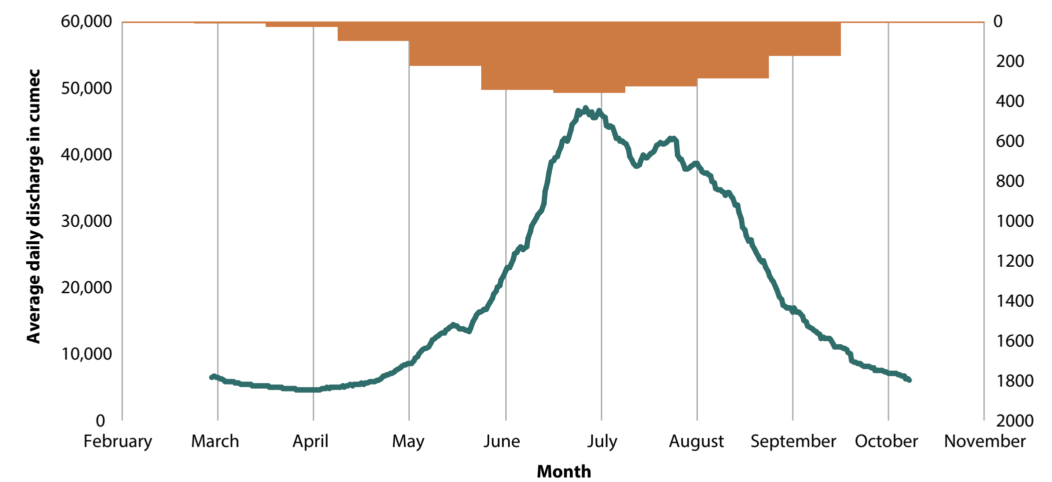
Hydrology

The Jamuna usually peaks in July when the average maximum discharge is about 60,000 cumec and flow reduces in the dry season with average lowest in February at 4,700 cumec[75]. Around 70 percent of total average annual flow is discharged during monsoon.

Figure 14 presents the flood hydrograph for Jamuna at Bahadurabad with data between 1999 to 2019 with monthly average values. The flow hydrograph represents the typical bi-modal nature as observed for Brahmaputra with back-to-back peaks occurring in between July-August and August-September. Onset of these peaks are from the beginning of the monsoon season.

Figure 14: Flood Hydrograph for Jamuna River at Bahadurabad

(Data source: National Water Resources Database, Bangladesh. Analysis by Centre for Environmental and Geographic Information Services (CEGIS))



As mentioned earlier, around 55 percent of the discharge at Lower Meghna is contributed by the Jamuna. Dry season contribution of Jamuna to the Bay of Bengal is even more significant as this river alone discharges around 70 percent of the average Ganges-Brahmaputra-Meghna flow for the month of December, January and February to the Bay of Bengal. During monsoon, the freshwater boundary lies close to the coast, but as the rains die down after monsoon and the flows decline, the saline front advances, penetrating further and further landward over the dry months. The flows of the Jamuna strongly affect the salinity of the Meghna estuary and neighbouring coastal areas by pushing back the coastal salinity line.

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Historical and Future Climate and Hydrology

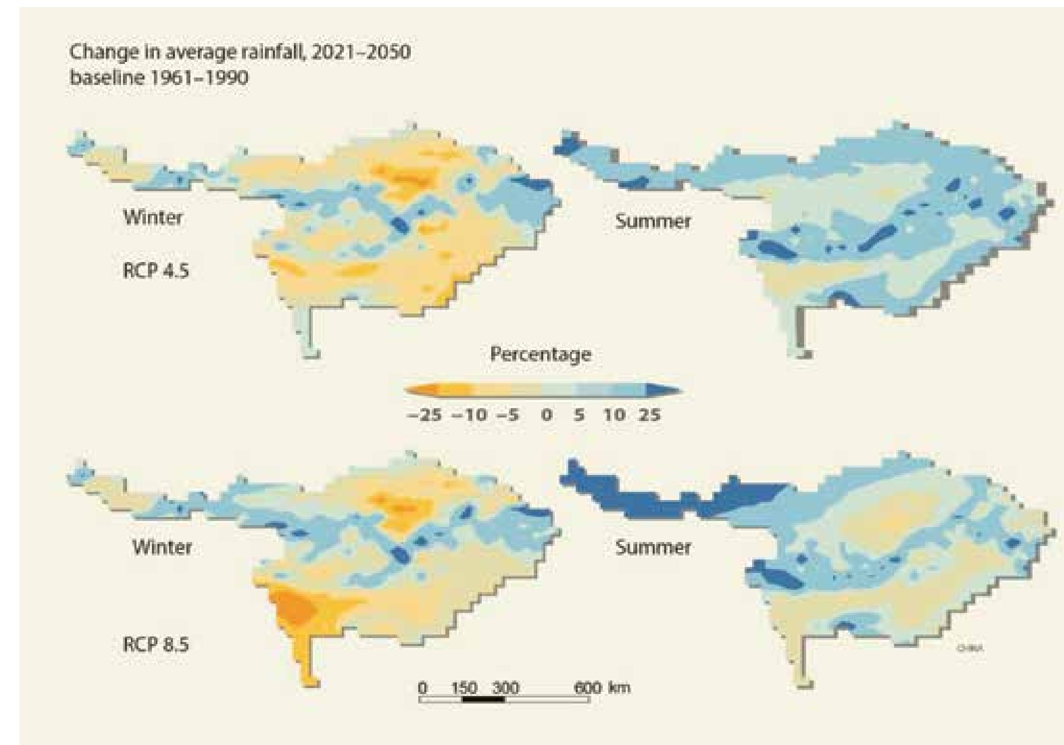
Arun B Shrestha and Nisha Wagle

Precipitation: Historical and Projected

The average annual precipitation in the Yarlung Tsangpo-Siang-Brahmaputra-Jamuna basin is just over 1,100 mm, 70 percent of which is received in the monsoon (June-October). The lower basin receives almost three times more rainfall than the upper basin[76]. Majority of the studies do not report significant trends in the rainfall in the basin. For example, Shrestha et al. found no significant trends in the past rainfall records (1951-1980 and 1981-2007) but found slight increase in average and extreme rainfall in the eastern basin[77]. Immerzeel also reported no clear trend from 100 year (1900-2002) monthly precipitation data and suggested that annual precipitation was determined by the monsoon[78]. Flügel et al., reported slight increase in annual and seasonal precipitation from 1961-2005, but with no statistical significance[79]. In contrast, Apurv et al. report increasing trend in summer monsoon during 1990-2000[80].

Unlike in the past, precipitation is projected to increase in the future, including the extremes but with strong spatial and seasonal differences. Shrestha et al.[81] suggest an increase of about 10 percent (from both RCP 4.5[82] and RCP 8.5[83]) in the monsoon season in the mid-century (2050) when compared with 1961-1990, while winter precipitation in the southwest and central northern part are projected to decrease (Figure 15). Likewise, Pervez & Henebey[84] reported seasonal variation in future precipitation with increase in monsoon, post-monsoon and decrease in pre-monsoon, and also suggested monsoon shift from July to August in comparison with 1988-2010. Wijngaard et al.,[85] projected increase in annual (upto 56 percent) and extremes (P99 upto 104 percent) towards the end of 21st century as compared to 1981-2010. Lutz et al.,[86] also projected increase in both annual and extreme precipitation when compared with 1981-2010 with small decrease in monsoon precipitation in the eastern part for 1.5°C global temperature scenario. Lutz et al.,[87] projected increases in precipitation in 2050 when compared with 1998-2007, in a range between 12 percent and 18 percent under two emission scenarios (RCP 4.5 and RCP 8.5).

Figure 15: Change in future precipitation (2021-2050), when compared with the base period (1961-1990) *(Source: Shrestha et al., 2015)*[88]



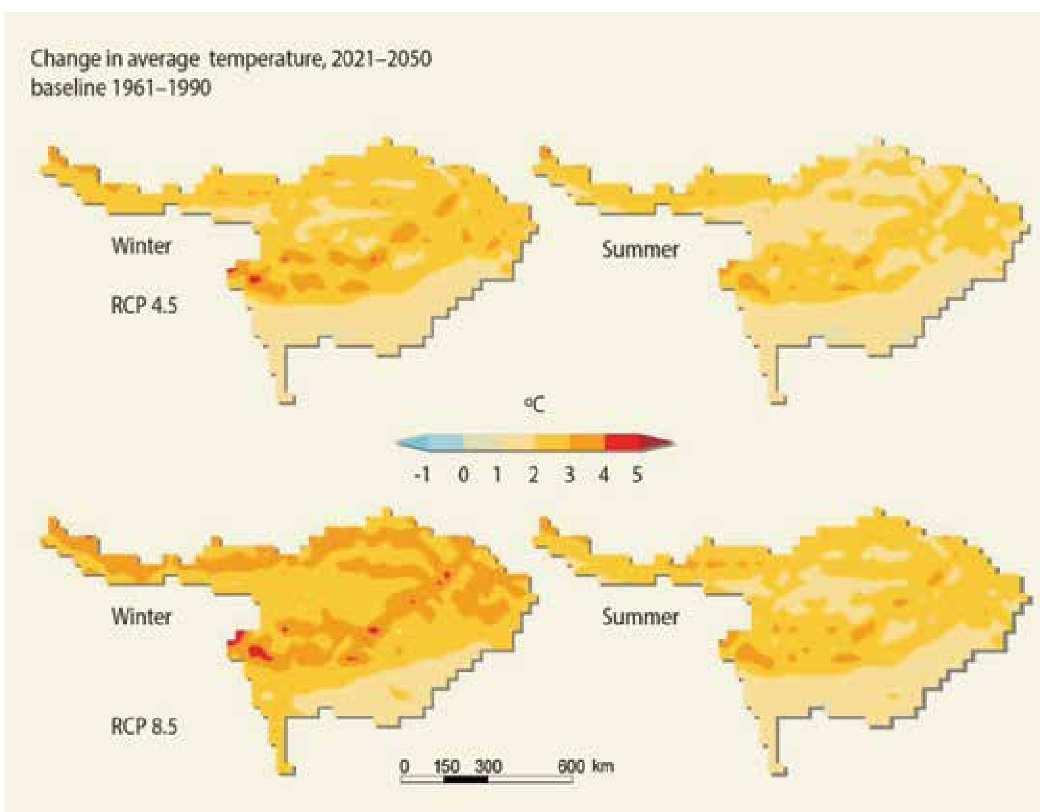
The basin has experienced a general warming trend in the past, but with seasonal and spatial differences with higher warming observed in winter season

Temperature: Historical and Projected

The basin has experienced a general warming trend in the past, but with seasonal and spatial differences with higher warming observed in winter season. Overall, winter minimum (+0.5°C), pre and post monsoon (+0.3°C and +0.4°C), and night-time temperature (both winter and summer) are seen to increase between 1951-1980 and 1981-2007, while the change in summer temperature is not significant. Moreover, extremes (highest maximum) are increasing over the northern parts (Tibetan Plateau), but decreasing east and southwards, and extreme minimum temperatures are decreasing in the center of the basin[89]. Immerzeel[90], reported warming at an average rate of 0.6°C per decade between 1900 and 2002, with 10 percent of the warmest years occurring between 1995 and 2002. Increase in both average annual (+0.28°C per decade) and seasonal temperature (highest in winter: 0.37°C per decade) during the period 1961-2005 with 95 percent significant level was reported by Flügel et al.[91].

The warming is projected to continue and intensify in the future with some indications of elevation dependent warming and more prominent warming in the Tibetan Plateau. Annual temperature is projected to increase in the range of 1-3°C by mid-century (2050) under RCP4.5 and RCP 8.5, with the northern part of the basin projected to warm more prominently. Higher increases are projected for winter temperatures over a major portion of the basin with some areas projected to warm more than by 3°C for RCP8.5 as compared to 1961-1990 (Figure 16; Shrestha et al.,[92]). Immerzeel[93] also projected increase in average temperature from 2000-2100 by up to 3.5°C under B2 scenario (SRES[94] scenarios)[95] as compared to 1961-1990, with highest increase in the Tibetan Plateau. Similar result was obtained by Dobler et al.[96], where increase in annual temperature by 5°C (A1B scenario) and 4°C (B1 scenario) until 2100 as compared to 1971-2000 was projected, and also reported more warming in higher altitude and highest increase in maximum temperature. Wijngaard et al.,[97] also projected increase in average annual temperature towards the end of 21st century in the range of 0.7°C to 5°C for both RCP4.5 and RCP8.5, when compared with 1981-2010. Likewise, recently Lutz et al.,[98] also projected increase in average temperature, higher in the Tibetan Plateau under 1.5°C and 2°C global average warming scenario, when compared with 1981-2010.

Figure 16: Change in future average temperature (2021-2050), when compared with the base period (1961-1990)[99]
(Source: Shrestha et al., 2015)



Hydrology

The basin is rainfall dominated with glacier and snow contribution of about 25 percent[100]. Under changing climatic condition, the snow and glacier melt water will reduce, while the rainfall-runoff will increase[101]. The climate change will have significant impact on the hydrological cycle[102], and likely lead to more severe and extreme flooding events[103]. Shrestha et al.,[104] projected an increase in runoff in the range of 0-13 percent up to 2050, with no significant seasonal shift. Lutz et al., [105]also projected year-round increase in flow for 2041-2050 under RCP 4.5 and RCP 8.5.

Gaini et al., [106]analyzed both extreme low and high flows and indicated that extreme low flow conditions are less likely to occur, while projected strong increase in peak flow, which is in line with steep increase in monsoon precipitation. Likewise, Immerzeel, [107]also projected increase in average monthly discharge in the range of 20-30 percent under A2 and B2 scenario as compared to 1956-1993, with seasonal variation. The winter discharge showed slight positive change, autumn and spring showed intermediate increase, and monsoon discharge showed the highest increase from 2005 to 2100. Lutz et al.,[108] also projected consistent increase in runoff at least up to 2050, primarily due to increased precipitation and melt runoff, and will likely increase the extremes as compared to 1998-2007. The recent study conducted by Lutz et al.,[109] is consistent with the findings reporting increase in precipitation, and extreme events. Ghosh & Dutta[110], projected increase in peak discharge for all the major tributaries and monsoon and pre-monsoon flood-waves under A2 scenario, which is more pronounced in the downstream area. Wijngaard et al.,[111], also projected increase in mean discharge in both near future (2035-2064) and far future (2075-2100), up to 49 percent at the end of century, along with increase in high flow condition, as compared with 1981-2100.

Under changing climatic condition, the snow and glacier melt water will reduce, while the rainfall-runoff will increase. The climate change will have significant impact on the hydrological cycle

On the other hand, Immerzeel et al., [112]projected decrease in mean water supply in the upstream by 19.6 percent for 2046-2065 as compared with 2000-2007, which is partly compensated by increase in mean rainfall. Prasch et al. [113]predicted reduction in water availability from 2011 to 2080, due to decrease in glacier melt after 2040.

The hydrology of Brahmaputra basin is a complex interplay between temperature and precipitation. Increased temperature, particularly in the high elevation and Tibetan Plateau and resulting melting of cryosphere is likely to cause decrease in the water availability in the upstream part. In the downstream, the meltwater reduction is compensated by precipitation. Therefore, overall, studies show increase in future discharge, due to increased precipitation together with increased occurrences of the extreme flows[114]. There is still uncertainty in future projections of climatic parameters and its impact on the hydrology[115], but a no regret strategy for basin planners would be to prepare for reduced water availability in the upstream and increased floods in the downstream.

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UNDERSTANDING FLOODS

The Brahmaputra and Jamuna sections of the River system are prone to heavy annual flooding during the monsoon season. The Brahmaputra flows through the state of Assam in the northeastern part of India which is a high rainfall area. Currently, 5,000 kilometers of embankments stand along the Brahmaputra river and its tributaries to manage floods but often fail to withstand the increased pressure during heavy rainfall leading to breaches and flooding in the adjoining lowlands. In Bangladesh, the hydrology and inundation cycles of almost 40 percent of the flood plains are influenced by the Jamuna.

Floods in the Brahmaputra river[116]

S.S. Nandargi

FLOODS IN the Brahmaputra Valley of Assam are caused by a combination of several natural and anthropogenic factors such as unique geographic features of the region, highly potent monsoon rainfall region, easily erodible geological formations in the upper catchments, recurrent and high seismic activities, numerous landslides in the hilly areas of the Valley, accelerated rates of basin erosion, massive deforestation, intense land use practices, increasing population growth especially in the flood plain areas and temporary measures of flood controls.

The two heaviest rainfall stations of India, viz. Cherrapunji and Mawsynram, are located just to the south of the Brahmaputra basin

In India, the southwest monsoon occuring between mid-May and mid-October is responsible for causing 65 percent of the annual rainfall over the Brahmaputra basin, generating 70 percent flow of the Brahmaputra river. The other cause of heavy rainfall is the 'Break monsoon' which occurs when the monsoon trough moves towards the foothills of the Himalayas. In addition, cyclonic circulations like low pressure areas, depressions and storms when they move in a northerly or northeasterly direction, cause very heavy rainfall over Assam region. The two heaviest rainfall stations of India, viz. Cherrapunji and Mawsynram, are located just to the south of the Brahmaputra basin. One-day extreme point rainfall over the basin varies from about 40 centimeters to 90 centimeters. Most of the runoff of this river is contributed by heavy rainfall of 510 centimeters to 640 centimeters in the Abor and Mishmi hills in Siang basin and 250 to 510 centimeters in the Brahmaputra plains.

According to the Rashtriya Badh Ayog (RBA), or National Flood Commission, the total flood-prone area in Assam is about 32 lakh hectares which comprises nearly 9.4 percent of the country's total area. Therefore, the Brahmaputra Valley in Assam represents an acutely flood-prone region of the country causing devastating floods almost every year with tremendous loss and damage to public property, infrastructure and environment. The annual loss due to flooding in Brahmaputra basin is also observed to be increasing since 1953.

Eklavya Prasad

Flood analysis shows that thirteen sites on eleven tributaries and three sites on the main Brahmaputra river experienced flood deviation more than 2.0 meters above their respective danger levels in a period of 33 years. The highest flood deviation recorded by different measurement sites above their respective danger levels (D. Ls) at these rivers (Table 6) showed that northern tributaries, Jaibareilly and Manas recorded highest flood deviation of more than 10.0 meters in the last 25 years.

Table 6: Most severe floods in the Brahmaputra basin in northeast India when flood levels were 5 m and more above their respective Danger Levels D.Ls. (updated up to 2019)

River	Gauge/ Discharge Site	State	Deviation of Highest flood from DL (m)	Date & year of occurrence
Kushiyara	Karimganj	Assam and neighbouring states	5.37	24.09.2010
Barak	Lakhipur		6.05	12.09.1979
Manas	N.H. Crossing		11.03	13.07.1984
Kopili	Kampur		8.30	13.08.2002
Jaibareilly	N.T.Rd. Crossing		12.22	22.09.2010

However, detailed flood frequency analysis at individual gauge/discharge sites of the main Brahmaputra river, its northern and southern tributaries of recent past indicate that there is decrease in frequency of floods in the main river and its northern tributaries as compared to its southern tributaries but there is increase in the intensity of floods in the Assam valley and surrounding region. This is mostly because of man-made interventions or obstructions made to the free flow of water such as bridges, or for agriculture purposes, to meet the increasing population demands.

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Brahmaputra, floods and people

Eklavya Prasad

Between 1953 and 2016 the Brahmaputra valley experienced major floods on thirty-nine occasions when more than one million people were affected

THE BRAHMAPUTRA Valley, home to 85 percent of Assam's population, is one of the most hazard-prone regions of the country, with more than 40 percent of its land (3.2 million hectares) susceptible to flood damage. This is 9.4 percent of the country's total flood-prone area. About seven per cent of land in the state's 17 riverine districts has been lost because of river erosion over the past years.[117] Between 1953 and 2016 the Brahmaputra valley experienced major floods on thirty-nine occasions when more than one million people were affected.

A total of 51.564 million hectares land area was affected by cumulative flood damage induced by the Brahmaputra and its tributaries between 1953 and 2016, of which the maximum was 3.820 million hectares during the 1988 floods. As per the figures, the value of damaged crops from 1953 till 2016 is approximately Rs 24.07 billion (approximately 40 million USD) whereas 25.351 million hectares of agricultural land was damaged. The cost of total damages (crops, houses, and public utilities) during this period is estimated at Rs 78.97 billion (approximately 1 billion USD).

Assam's proneness to high, extreme precipitation, frequent earthquakes, landslide hazards, and sediments from the upper catchments increases the possibility and intensity of floods in the region. Apart from the geo-climatic setting, human activities like deforestation, accelerated change in land use, filling up of low lying areas for the construction of buildings, urban development and temporary flood control measures are some changes which contribute to the overall vulnerability of the Brahmaputra valley to floods. Sudden and excessive release of water from dams also lead to flooding, a mega-disaster because of the huge loss of life and property associated with it. The reliability and effectiveness of the embankments from the Brahmaputra flooding are generally insufficient because of structural deterioration and ongoing riverbank erosion.[118]

Eklavya Prasad

The eighteen districts along the main Brahmaputra stem encounter different kinds of floods with multi-layered complexities involving social, cultural, and economic dimensions which lead to differential impacts. Therefore, typologizing floods in the Brahmaputra valley on the basis of spatial location and character of flood hazard, will help define the area specific vulnerabilities which will further help in preparedness and minimization of losses through addressing area specific prerequisites, rather than adopting a generalist approach.

In Brahmaputra valley there are multiple flood typologies, but the one that is widespread and impacts the poorest are: riverine flood with riverbank erosion on the river side, between the embankments of the same river; riverine flood with riverbank erosion adjacent to the river without the embankments; riverine flood with riverbank erosion adjacent to the embankments on the riverside; flash floods with riverbank erosion on the riverside between the embankments of the same river and flash floods with riverbank erosion adjacent to the river without embankments.

Riverbank erosion is a natural phenomenon that results in the removal of material from the banks of a river. Most of the rivers in the Ganga-Brahmaputra basin are essentially braided alluvial channels that cause erosion through a combination of three different processes. The pre-weakening process involves repeated cycles of wetting and drying of the bank, which prepares it for erosion. While the phenomenon is natural, the impact it has is disastrous on the life and livelihoods of the riparian community who are settled on or close to the unstable banks of these channels. The resettlement is often an involuntary decision as the land gets eroded. Given the impoverished state of the riparian population, the resettlement happens close to the river, since land prices increase as one moves farther away from the river.[119]

Floods are diverse, multi-layered and must be attended to as per its location, reason, severity and diversity

Development induced displacements tend to displace people once, the families affected by bank erosion are subjected to multiple displacement. It is estimated that annually nearly 8,000 hectares of land is lost to erosion. The intensity of the problem can be gauged from the fact that the total land lost due to bank erosion caused by the Brahmaputra River in Assam alone has ranged between 72.5 square kilometers per year and 80 square kilometers per year between 1997 and 2007-2008.[120] Hazards like riverbank erosion that continuously affect the poorest and the most impoverished sections of the community residing in the Brahmaputra flood plains, has to be considered as a typology of floods, to demystify floods as homogenous entity. Floods are diverse, multi-layered and must be attended to as per its location, reason, severity and diversity. Therefore, there is a need to re-examine the flood management plans and strategies in the changing times.

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Floods of the Jamuna Basin

Malik Fida Abdullah Khan

EACH YEAR in Bangladesh about 26,000 square kilometers, that is around 18 percent of the country is flooded[121]. During severe floods, the affected area may exceed to 55 percent of the total area of the country. In the event of catastrophic floods, it has been anticipated that about two-thirds of the country can get affected[122].

The hydrology and inundation cycles of almost 40 percent of the flood plains in Bangladesh are influenced by the Jamuna. Major extreme flood events contributed by Jamuna inundates between 18,000 square kilometers 23,000 square kilometers area in the surrounding flood plains on an average, which is equivalent to 12 percent to 16 percent of the total country area. However, impacts of those floods are even higher when combined with peak discharge of Ganges and Meghna. Table 7 summarizes extent of flooding during major flood years for the Jamuna and corresponding impacts on the entire country when combined with Ganges and Meghna flows.

Table 7: Notable flood disasters in Jamuna floodplains and their impacts

(Source: Analysis by Centre for Environmental and Geographic Information Services (CEGIS) based on satellite images, Hossain, 2006[124] and Reliefweb, 2017[125]

Year	Flooded area (sq km) in Jamuna floodplains[123]	Countrywide impacts due to floods (from Jamuna, Ganges and Meghna)
1954	23,132 (16% of the country area)	Affected 55% of the country.
1988	23,200 (16% of the country area)	Inundated 61% of country, estimated damage US$ 1.2 billion, more than 45 million homeless, between 2000-6500 deaths.
1998	21,232 (14% of the country area)	1100 deaths inundated nearly 100000 km^2, rendered 30 million people homeless, damaged 500000 homes, heavy loss to infrastructure, estimated damage US$ 2.8 billion.
2000	10,601 (7% of the country area)	Estimation unavailable
2002	16,395 (11% of the country area)	Estimation unavailable
2003	13,027 (9% of the country area)	Estimation unavailable
2004	17,477 (12% of the country area)	Inundation 38%, damage US$ 6.6 billion, deaths 700, affected people nearly 3.8 million.
2007	14,068 (10% of the country area)	8 million people displaced; 2000 people died from drowning and water borne diseases. Estimated damage US$1billion, Dhaka was badly affected.
2017	Estimation unavailable	July floods affected about 1.6 million people, damaged over 100000 houses and 40000 hectares of cropped lands were inundated. August floods affected 31 districts, and about 16000 ha were fully lost and 560000 ha of standing crops were partially damaged.

The floods of 2007 and 2017 mostly affected the northern districts due to high water level and discharge in the Brahmaputra. In 2007, many countries in South Asia experienced floods, thus all the rivers, especially the Brahmaputra and Ganges peaked at the same time. In 2017, the northern districts faced severe floods in July and August (there were also flash floods in the northeast part of the country in March-April). These floods impacted standing crops. Prices of rice, the country's main staple, reached record high levels in September, mostly reflecting flood-induced crop losses in 2017.

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Plethora of Pains: Living with floods and erosion

Imtiaz Ahmed

EVERY YEAR during the monsoon season, floods arrive in the Jamuna river basin. Riverbank erosion is also an annual phenomenon. Flooding and erosion have become a part of the lives of the people living on the banks and the *chars*[126] or riverine islands of the Jamuna. In Bangladesh, flooding begins from the middle of July and continues till September.

The Bengali language distinguishes between the normal floods of the rainy season, which are locally known as *barsha*, and the more harmful floods of abnormal depth and timing, which are termed *bonna*. The *barsha*, which occurs more frequently than *bonna*, is often deemed a necessity for survival, especially to farmers[127].

Flooding and erosion have become a part of the lives of the people living on the banks and the chars *or riverine islands of the Jamuna*

Huge tracts of paddy and other crops, ponds and fish enclosures go under water, livestock is also damaged, crippling already poor rural communities. Stranded in waterlogged areas, people lose their livelihoods, with little access to food and drinking water. In the wake of floods, outbreak of water-borne diseases such as diarrhoea, skin diseases, dysentery and cholera cause immense suffering and even loss of lives. Roads, railways and key infrastructures are damaged, communication system is disrupted, homesteads, schools, hospitals are also submerged in flood waters. In the period between 10 July and 24 July 2019 alone, torrential rains damaged more than 580,000 houses forcing an estimated 307,000 people from their homes across Bangladesh. Public health officials confirmed 14,781 flood induced medical cases in northern Bangladesh[128].

Although in Bangladesh, more than 10,000 kilometers of embankments have been constructed throughout the country[129], embankments are often overtopped or breached. The people living in the region, having suffered from the *bonna* or 'big floods' in their own lifetime more than once, have learned to 'live with floods'. This is manifested not only in the coping mechanisms, for instance, in containing diarrhoea and other water-borne diseases, but also in agricultural practices and the construction of secured infrastructures in flood prone areas. The people residing in the vicinity of these rivers have learned to grow flood-tolerant crops, live in portable houses, store food, household items and crops on a platform in the main living room and plant flood tolerant vegetation such as bamboo and banana. Flood resistant houses constructed on a two-foot-high concrete plinth with walls made from jute panels helps to reduce loss from damage to property[130].

People in this region are resilient, and over the years have adapted with coping mechanisms

Erosion caused from the flooding and receding of the waters of the Jamuna results in huge loss of land and property every year. Embankments collapse from erosion, causing flood inundation in previously flood protected lands. Huge number of people become homeless for uncertain periods due to erosion[131]. People in this region are resilient, and over the years have adapted with coping mechanisms. People in *char* areas (riverine islands), where erosion occurs the most, live in portable houses; the house and assets can be easily relocated to safer places. Many people have to eventually leave their lands and migrate to nearby districts and urban areas[132].

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Community based flood early warning system

Neera Shrestha Pradhan and Partha J Das

"That one hour of early flood warning makes all the difference to ensure that my investments are safe, and livelihood ensured"- Osman Ali, Barsola 2 village, Assam, India

DEVASTATING FLOODS inundate large areas of the Brahmaputra River Basin every year crossing national and inter-state borders resulting in loss of lives and livelihoods, and displacing millions of people in India. Though early warning systems have been developed in many parts of the world to provide flood information, there are gaps – identified by the Hyogo Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) Special Report on Extreme Events and Disasters (SREX 2012) – in getting this information to communities that are most vulnerable. In the absence of reliable and timely early warning of flooding, damage and loss to private and public property, economy, lives and livelihoods have increased, making people more vulnerable worldwide.

A community-based flood early warning system (CBFEWS) was envisioned and executed by ICIMOD jointly with the District Disaster Management Authority (DDMA) in Dhemaji and Lakhimpur, and Aaranyak- an NGO partner in Assam, India, to provide near real time flood information to prepare the vulnerable communities for the upcoming flood risk during 2010-2016. CBFEWS is an integrated system of tools and plans in which upstream communities, upon detecting flood risk, disseminate the information to vulnerable downstream communities through mobile phones for preparedness and response using local resources and capacities.

The first version of CBFEWS was tested and used during 2010-2012 on the Jiadhal river of Dhemaji District in Assam. In 2013, five units of an advanced version of the CBFEWS were installed in the Jiadhal (Dhimaji district) and Singora (Lakhimpur district) rivers in Assam with active involvement and ownership of local people and DDMA reaching out to 45 vulnerable communities downstream to provide flood early warning. With an investment of approximately USD 1,000 per instrument, the information disseminated by CBFEWS was able to save assets worth USD 3,300 in the flood of 5 September 2013 in the Dihiri village of Dhemaji. Dhemaji DDMA officer explained, "After receiving a warning, we deployed the National Disaster Response Force to the affected downstream areas of the Jiadhal River, which helped the district administration prevent a disaster situation". The communities, who had to stay awake all through the night to monitor rivers and floods earlier, expressed their happiness as they were able to have "sound sleep at night" after the installation of CBFEWS.

Providing the life-saving information to the villagers, a woman caretaker of the system stated, "I feel empowered and important because even the Gaon-Burha (Village Head Man) of the village comes to me to ask about the flood situation".

The project's impact was acknowledged by the UNFCCC by awarding it the Momentum for Change 2014 Lighthouse Activity Award as a shining example of innovative use of Information and Communication Technology for Disaster Risk Reduction and Climate Change Adaptation. Encouraged by the impact on the ground, the DDMA of Lakhimpur District replicated the CBFEWS in Ranganadi river in 2016. The Government of Assam, Flood and River Erosion Management Agency of Assam discussed the upscaling of CBFEWS in Assam and mentioned, "We have been informed that the only Early Warning System (EWS) established in Assam has proved to be successful in generating and disseminating flood signals that not only helped people to save their assets but also supported District Disaster Management Authorities to deploy flood rescue teams to the vulnerable sites".

The river displays a variety of channel patterns on its journey towards the sea, at times meandering, but mostly in braided form

Inspired by the success achieved in Assam, CBFEWS instrument was improved from wireless to telemetry based EWS and scaled up in different tributaries in Nepal, India, Pakistan and Afghanistan in the Hindu Kush Himalayan region. From 2020 onwards, CBFEWS is also out scaled in 33 tributaries in Malawi, South Africa jointly with the relevant government line agencies and local partner organization.

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MORPHOLOGICAL CHARACTERISTICS OF THE RIVER

The Yarlung Tsangpo-Siang-Brahmaputra-Jamuna displays a variety of channel patterns on its journey towards the sea, at times meandering, but mostly in braided form. The Yarlung Tsangpo consists of alternating sections of wide valleys with braided channels and narrow gorges with single deeply incised channels amid shallow layers of boulders that cover bedrocks. In the Brahmaputra valley and flood plains of Jamuna the River is highly braided, marked by the presence of numerous alluvial channels with lateral bars and islands between meeting and dividing again[133]. This section briefly describes the historical development, planform[134] characteristics and morpho-dynamics of the main channel.

Geological history

Bushra Nishat

THE YARLUNG-Siang-Brahmaputra-Jamuna and its tributaries are morphologically dynamic, and the fluvial patterns have continuously been reshaped by continental tectonics, surface processes and climate feedbacks.

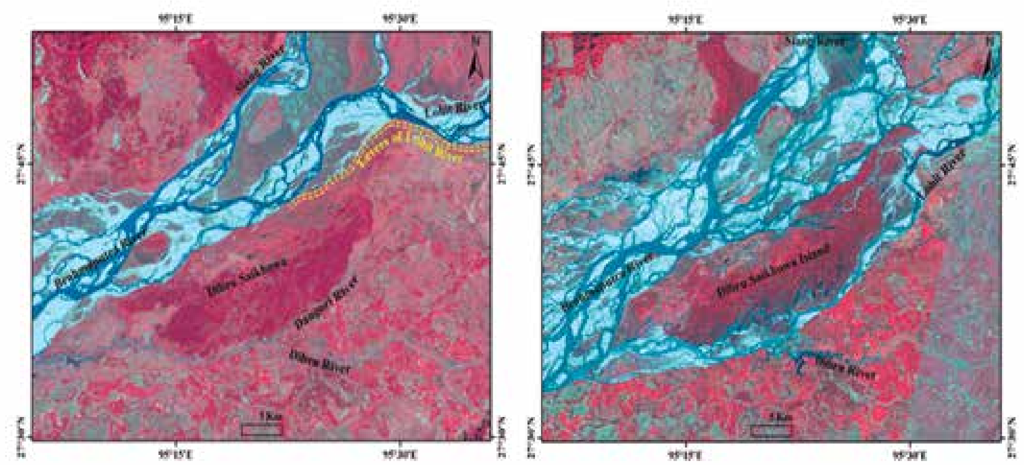
To the south across the flood plains major channel avulsion[135] has taken place within the last 250 years. Historical maps and tell-tale palaeo-channel markers show that the Teesta, the largest tributary of the Jamuna shifted course several times in the past. British geographer Major James Rennel's[136] maps of 1764 and 1777 show Teesta flowing into three branches while travelling through North Bengal and ultimately discharging into the Ganges at several places. Devastating floods and neo-tectonic activities led to a change of direction and the Teesta swung eastward flowing towards the Jamuna around 1787[137]. This sudden eastward shifting combined with the tectonic tilting of the Madhupur Tract triggered avulsion of the Brahmaputra channel. Historical mapping of the last 250 years indicates that the main active channel of the river used to flow through the east of the Madhupur tract and join the Meghna River directly at Bhairab Bazaar in Bangladesh. In the late eighteenth century, the Brahmaputra began to diverge towards a small spill channel known as the Konai-Jenai, shifting gradually southwards to join the Ganges and by 1810, emerged as the Jamuna, leaving the eastward channel which is now known as Old Brahmaputra[138].

Historical maps and tell-tale palaeo-channel markers show that the Teesta, the largest tributary of the Jamuna shifted course several times in the past

The middle reach of the river has also experienced channel migration in more recent times. The Assam earthquake of 1950 and more contemporary processes of erosion and aggradation through bar formation caused bankline migration of the Subansiri, a major tributary of the Brahmaputra. Additionally, abnormal high flood level in 1988, and difference in gradient due to topographic elevations led to avulsion of the Lohit River, a south bank tributary of the Siang. A small channel of the Lohit captured the Dangori river of the Dibru Saikhowa region, and gradually by 1995, the main flows of the Lohit began flowing through the captured channel. This transference in combination with the southward adjustment of the Brahmaputra caused significant shifting of the Lohit-Siang confluence point. But the most noticeable response to this avulsion has been its effect on the Dibru Saikhowa National Park. As can be seen from Figure 17, previously the park area was a part of the left (south) bank of the Brahmaputra river, but in response to the migration of the river, the area has become a *char* or river island in the main channel of the Siang[139].

Figure 17: Landsat image over Dibru Saikhowa. A 15 November 1973; B, 28 November 2000

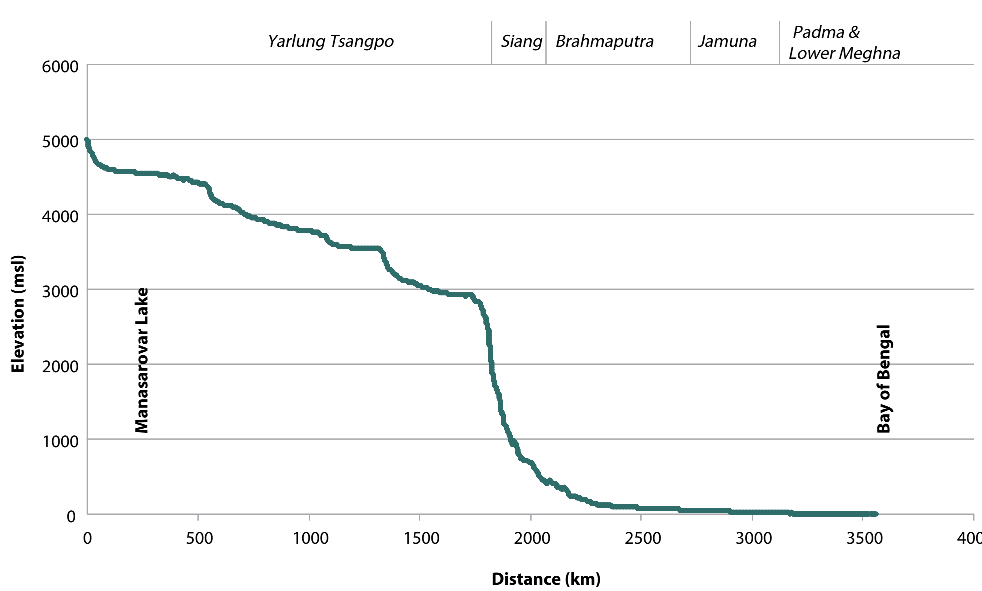
(Source: Borgohain et al 2016)[140]



Longitudinal profile of riverbed

In the upper reaches in Tibet, the river channel displays mild gradient in the wide valleys and large gradient in narrower sections. The gradient of the basin and River channel is as steep as 4.3 meters per kilometer to 16.8 meters per kilometer in the gorge section and the slope decreases suddenly in the Brahamputra valley after the Siang-Lohit confluence. Near Guwahati in Assam, the Brahmaputra is as flat as 0.1 meters per kilometer as can be seen in Figure 18[141]. The low gradient results in high width to depth ratios causing high deposition of sediment and development of a braided channel.

Figure 18: Longitudinal profile of the Yarlung-Tsangpo-Siang-Brahmaputra-Jamuna River *(Based on SRTM 90m DEM)*



GEOMORPHOLOGICAL CHARACTERISTICS

Yarlung Tsangpo

Sun Jian and Lin Binliang

THE GEOMORPHOLOGICAL characteristics of the Yarlung Tsangpo river is significantly affected by the uplift of the Tibetan Plateau and the movement of geological structures, with a hydrographic network developed on a rock-based gravel bed. Its slope goes steeper, and its undercut goes deeper at the edge of the Tibetan Plateau. In recent decades, the runoff and sediment transport of the river are strongly affected by climate change and the potentially ever-increasing human activities. Local geological structure and lithology, as well as the temperature difference and water erosion, lead to the variety of spatial scales and plane view of the fluvial network.

Geology background

The staggered width of the Yarlung Tsangpo river looks like the shape of a lotus. The canyon sections of the lotus roots are mainly dominated by granite and significant uplift by a lateral fracture in a nearly north-south direction. The glacier-mantled mountains, with an elevation higher than 5,500 meters, is steep along the canyon, and the river mainly has straight or slightly bending patterns. The riverbed here is deeply cut down into the bedrock with little sediment on the riverbed, because of the high riverbed slope and flow velocity. The branches drained into the mainstream also takes the form of deep-cut canyons. Wide valley sections are mainly developed in the large fault zone, where sandstone and mudstone widely distribute. The mountains along both sides of the wide valley have elevations less than 5,500 meters and have gentle slopes. The river's longitudinal slope and flow velocity are small in these reaches, with thick sediment deposition and widely distributed braided rivers. In addition, the shape of the branch estuary in the wide valley sections is mostly trumpet-shaped. In the middle reaches, canyon valleys are restricted by narrow gorges, while the width of the valleys is between 2 and 8 kilometers. Multiple bars in the channel constitute unique complex braided channels of the Yarlung Tsangpo river.

In recent decades, the runoff and sediment transport of the river are strongly affected by climate change and the potentially ever-increasing human activities

The uneven elevation of the Tibetan Plateau in the east-west direction and the sediment deposition over thousands of years have formed lotus-shaped river valleys of the Yarlung Tsangpo River. The river alternately distributes with large-width and shallow-depth lakes. The river reach is characterized by slow flow velocity contributed by a relatively static water environment.

Impacts of climate change and human activities on river geomorphology

Because of the high elevation, the hydro-sediment dynamics, river pattern, the sediment erosion/ deposition of the Yarlung Tsangpo river are basically in a natural state. However, climate change has accelerated the glaciers melting and changed the plateau monsoon over the past few decades. Given the long-term impact of climate change on hydrological elements, it will gradually change the water and sediment flux, the sediment transport capacity, the riverbed morphology and promote river pattern transformation.

The ever-increasing human activities in the river basin will also have potential impacts on the river evolution. For example, over-grazing will lead to grassland degradation and even desertification, which may decrease the flow discharge and increase the sediment flux. The road networks constructions and the mineral resources exploitations produce numerous soil and slag accumulation and expose the bare surface of mountains, which will also increase the sediment flux. Besides, reservoir constructions are the most direct and strongest human activity that influences the evolution of natural rivers. It works in intercepting coarse sediment in the upstream, decreasing the riverbed slope. As a result, sediment in the downstream river reach is reduced and the riverbed is likely scoured by the clean water with lower sediment concentration. These human activities are likely to partially change the flow and sediment transport process of the river channel and bring a series of issues on sediment engineering as well as water-sediment conservation.

The high-elevation terrain and neotectonic movement of the Tibet Plateau play a fundamental role in the geomorphic diversity of the Yarlung Tsangpo river. The plateau uplift is the long-term and large-scale geological background of the Yarlung Tsangpo river's evolvement, especially for the bedrock undercut, headward erosion, and landslide or debris in the riverbank slopes. It is notable that, as a sensitive area for climate change in the Tibetan Plateau, Yarlung Tsangpo river is gradually suffering the water and sediment changes as well as the complex river evolution against the background of global warming. Meanwhile, the human activities such as the hydropower development, road constructions, mineral exploitations and grazing expansion have been increasingly enhanced on the plateau. The changes will break the balance between sediment erosion and deposition in local river reaches, sharply change the alluvial river patterns and accelerate the deep cut of the riverbed, result in the changes in the evolutionary process of the Yarlung Tsangpo River.

Siang-Brahmaputra

Malik Fida Abdullah Khan

SIANG RIVER meanders along its southbound path until it reaches the confluence with Dihang and Lohit Rivers. After the confluence, the main channel of the Brahmaputra becomes braided. The number of major channels in the braided Brahmaputra varies across the segment, with the planform being dominated by a range of vegetated and non-vegetated bars that divide the channel into a hierarchy of channel sizes[142].

Planform characteristics

Planform characteristics of the Brahmaputra River has significant spatial and temporal variability from upstream to downstream reaches, which is caused by tectonic zonation of the river, channel slope and sediment load. Further, the tributaries joining the northern and southern banks of the Brahmaputra vary in terms of river dynamics and sediment load resulting in differences in tectonic regimes. From the recent studies, the average widening over the last 90 years has been estimated at 44 percent; from the average width of 9.74 kilometers in 1915, the channel has widened to the average width of 14.03 kilometers in 2005 and in certain reaches the average widening is as high as 250 percent while the shifting of bankline is not uniform towards both banks[143].

The River is one of the widest rivers in the world. In the plains of Assam, the average width is almost 10 kilometers and some places the width is as high as 18.6 kilometers

The great Assam earthquake of 1950 with an epicenter within the Brahmaputra basin has triggered multiple transformations in planform in the main channel and tributaries of the Siang-Brahmaputra and downstream reaches. This earthquake induced large-scale landslides in the Himalayas, and the loose debris and barren slopes together resulted in 45 billion m^3 of sediment into the river system choking and raising the bed of the Brahmaputra, which was as high as 3 meters in Dibrugarh. As the river became shallower, it became wider to accommodate its regular flow subsequent to 1950[144].

Even in average conditions, the River is one of the widest rivers in the world. The narrowest part of the Yarlung Tsangpo is when it passes through the big bend within the Great Canyon entrenched between the Namcha Barwa and Gyala Peri mountains, which stand only 21 kilometers apart[145]. In the plains of Assam, the average width is almost 10 kilometers and some places the width is as high as 18.6 kilometers, although rock outcrops at several places confine the river width. At Saraighat, a place near Guwahati, Assam the bank-to-bank width narrows down to 1 kilometer[146].

In certain reaches the braiding intensity, which measures the channel multiplicity has also increased. The Brahmaputra River consists of large, deep and active primary channels in combination with smaller and shallower secondary channels. The width and depth of the primary channels as well as the bed profiles vary significantly from place to place with time. During low flow period, the primary channel of the Brahmaputra occasionally splits up into multiple smaller primary and secondary channels and they are part of the main channel having average width of approximately 1 kilometer[147].

Erosion-Accretion

Erosion and accretion have been identified as a major challenge in the northeast region of India[148]. The combined effects of large and highly variable discharge, high silt content, heavy rainfall, and unstable geology have resulted in a very unsteady river channel of Siang-Brahmaputra causing heavy lateral erosion[149]. The river shows a tendency to migrate south as the south bank faces active bank erosion. Erosion is more prominent during recession stages of floods when the water level drops very quickly. The Brahmaputra in the reach from Dibrugarh to Dhubri (near Bangladesh border), between 1990 and 2008, around 1,464 square kilometers land was lost due to riverbank erosion, compared to accretion of 214 square kilometers. Erosion was higher in the south bank (920 square kilometers) compared to north bank (544 square kilometers) while it is vice-versa for accretion. This high amount of erosion along both banks of the river resulted in the deterioration of living standard of people by affecting the people living near the bank as well as loss of infrastructures. The highest erosion occurred in the segment upstream of Dibrugarh until the confluence of Siang-Lohit Rivers[150].

Between 1990 and 2008, around 1,464 square kilometers land was lost due to riverbank erosion, compared to accretion of 214 square kilometers

Sediment Transport

The Brahmaputra flows with a huge load of sediment acquired from the rain-soaked Himalayan tributaries. Estimates of the sediment load of the Brahmaputra River are highly variable, ranging from 270 to 720 million tonnes per year[151]. Similar to discharge, sediment load varies throughout the year, and is highest during monsoon season.

The source of this sediment is the Himalayan region, the distribution of erosion contributing to the sediment flux in the mountain range is heterogeneous. Recent studies show, the eastern syntaxis including the Namche Barwa mountains is a major source of sediments and supplies about 50 percent of the bulk sediment inflow to the Brahmaputra system[152].

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Jamuna

Sudipta Kumar Hore

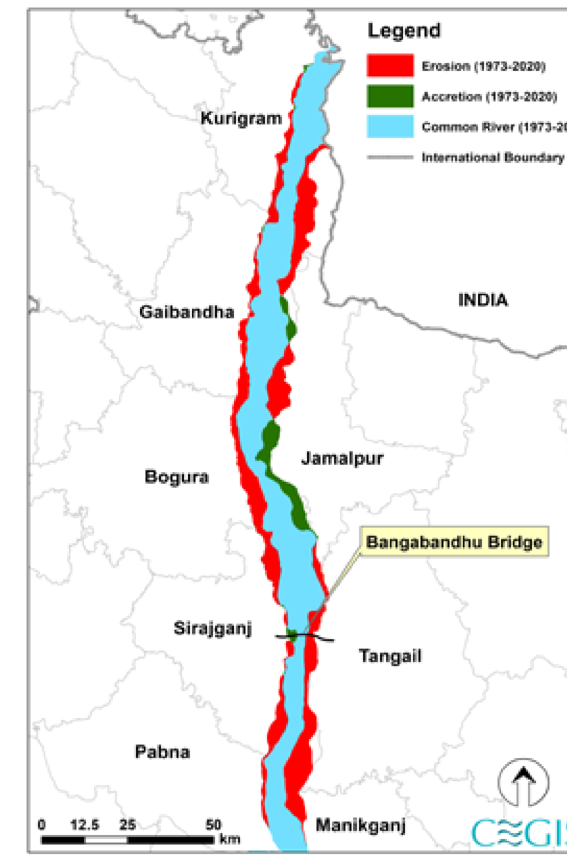
JAMUNA IS a large sand bed braided river. As discussed earlier, the main channel and tributaries of the River have changed courses rerouting drainage patterns frequently in historic and prehistoric times. Geomorphologically this segment of the river is in dynamic equilibrium and migration of channels, shifting of banklines and widening of watercourse are a frequent phenomenon. However, within the last decade the morphological instability of the Jamuna has slowed down.

Planform Characteristics

The Jamuna has multiple channels separated by small bars and *chars*, typically showing two to three channels per cross-section. Migration of channels and shifting of banklines are very frequent. The high variability of discharge, averaging 60,000 cumec during flood and 4,250 cumec during dry period leads to erosion and accretion in the channel respectively.

In Bangladesh the average width of the first order channel increases to almost 12 kilometers and in some places, width can be up to 16 kilometers, especially during monsoon period. Similar to the Brahmaputra, the Assam Earthquake of 1950 has had a massive impact in the planform changes of the Jamuna. Mainly coarse sediment (sand portion) from the earthquake induced landslides played a significant role to alter the morphology in the last 70 years which propagated gradually as sand wave to the Bay of Bengal. This additional input of sediment made the river more dynamic, and energy was dissipated by the process of the erosion and river widening[153]. In most places there is a tendency of the Jamuna to migrate westward. Migration from the center line of the Jamuna took place at about 45 meters per year between 1973 and 2010 as a result of channel shifting and widening[154].

Figure 19: Erosion-Accretion of the Brahmaputra-Jamuna River in the last 46 years *(Analysis based on satellite images)*



Erosion-Accretion

The instability of the Jamuna river coupled with erodible alluvial banks causes heavy bank erosion. Erosion is not similar to a meandering river where erosion takes place in the outer bend at one bank and deposition in the inner bend at the other bank. Erosion occurs in both banks in the Jamuna. It is very difficult to predict the erosion as vulnerable channels shift within one season. Historical analysis shows that erosion has been dominating in the past six decades compared to accretion in the Jamuna. In the Jamuna in the past 46 years (from 1973) total erosion was 928 square kilometers and net accretion was 148 square kilometers (shown in Figure 19). This erosion often takes place in populated areas and erosion is responsible for land loss causing damage to agricultural land and physical infrastructure such as homesteads, embankments and roads. On the other hand, newly accreted area needs time to mature and become productive or create opportunities for inhabitation and economic activities.

The *chars* of the Brahmaputra-Jamuna

Created from sedimentation or avulsion of river channel, river islands or shoals, locally known as *chars* in India and Bangladesh are an important feature of braided rivers. *Char* dynamics are interrelated with the bank erosion processes, widening and narrowing of rivers. While there are river islands of various sizes and shapes in the braided portion of the Yarlung Tsangpo channel, these remain mostly uninhabited and unexploited. In India and Bangladesh, development of *chars* provides opportunities for settlement of people and crop cultivation and for decades, many *chars*, especially mature *chars* have established rural areas including schools, hospitals and other infrastructure. Typically, a new *char* land continuously emerges and submerges and requires at least 10 years of continuous survival before it becomes fit for human habitation. In 2000, approximately 76 percent of the *chars* in the Jamuna were less than nine years old while only 7.2 percent *chars* were mature having existed for 21 years or higher[155]. But there are also very old *chars* such as Majuli, the world's largest riverine island which was formed around 1750.

Analysis of satellite images show that the *char* area in the Brahmaputra channel was 1,460 square kilometers in 2018[156] and in the Jamuna the area was 760 square kilometers in 2016. Widening of the river caused increasing trend of the *char* area. However, the widening process has slowed down recently. This does not mean the formation of *chars* will stop. Rather loss of *char* in one area may compensate in another area within the riverbank.

The Ganga-Brahmaputra-Meghna delta is the largest in the world.

Sediment Transport

Although estimates vary, on average the Brahmaputra-Jamuna carries an amount of about 607 million tons of sediment every year which is the third highest sediment transport river in the world after Amazon and Huang Ho Rivers[157]. However, the combined suspended sediment load of the Ganges-Brahmaputra-Meghna (GBM) region is around 1,050 million tons per year, the second largest sediment load in the world. Almost 60 percent of this sediment load originates in the Brahmaputra basin. The sediment carried by the Jamuna originates in the Himalayas with nominal contribution by the tributaries in Bangladesh and the Jamuna[158].

Around 55 percent of this load is deposited in the rivers, floodplains and deltas, accretion is most rapid in the river braid belt and adjacent floodplain[159]. Annual precipitation and associated runoff rework accumulated sediments in adjacent floodplain surfaces and transport remobilized deposits to local catchments distant from the river. The remaining sediment is circulated in the bay and acts as a source of alluvial delta development across the Bay of Bengal. This process is important for land building in the coastal region of Bangladesh and East India.

Sediment transported through Brahmaputra-Jamuna and deposited to the Bay of Bengal over thousands of years had a significant role in the development of the Bengal Delta[160]. More recently, a large amount of accretion due to the Assam earthquake resulted in the delta progradation in the 1950s and 1960s and accelerated the delta shifting process[161]. Even though there is influx of high sediment, the shoreline remains mostly unchanged, as most of the sediment brought to the rivers bypasses the estuary and is deposited into deeper waters by way of the Swatch of No Ground, a shelf canyon that deeply incises the Bay of Bengal near the Meghna Estuary[162].

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