2.2.3 Fluvial Landforms in the Humid Tropics

What fluvial landforms can be found in the humid tropics?

- Fluvial landforms: meanders, braided channels and deltas
- Features of meanders: sinuous channel, river cliff, point bar
- Features of braided channels: mid-channel bars
- Features of deltas: delta plain, delta front, prodelta

Fluvial landforms are landforms produced by the erosion and deposition of streams or rivers, in another words, fluvial processes. Examples of fluvial landforms include bars, levees, braided channels, meanders and deltas. As you have learnt, fluvial processes are affected by both river energy, discharge and sediment characteristics.

1. River Energy

Once water reaches the channel, it moves downstream towards the mouth of the river. This moving water possesses energy, which varies along its course. This energy is required for the three main fluvial processes—erosion, transportation and deposition. An increase in river energy usually results in an increase in erosion and transport, whereas a decrease results in deposition.

A still body of water at any point above sea level has a certain amount of stored energy as a result of its position. This supply of potential energy, when converted to kinetic energy when the river flows downstream, enables it to erode the river channels and transport the eroded material. The amount of kinetic energy is determined by:

1. The **volume** of the flowing water.
2. Its mean **velocity**.

The energy possessed by the river is therefore determined by its **discharge** (defined as a measure of the water flow at a particular point). An increase in any one of these two factors will thus mean an increase in the amount of kinetic energy.

1.1 Measuring River Discharge

River discharge varies greatly over time and space. It is calculated as follows:

$$Q = A\,V$$

Q = discharge (usually expressed in m^3/s)

A = cross-sectional area of the river (in m^2)

V = mean river velocity

The volume of water is important since an increase in the amount of water will mean a higher discharge and a more efficient river. This explains why floods can unleash so much energy and cause massive destruction to the environment.

1.2 Measuring river velocity

Velocity is one very important determinant of river discharge and energy. Factors affecting the velocity of rivers are spelled out by the **Manning's equation**.

$$V = \frac{1.49\, R^{\frac{2}{3}} S^{\frac{1}{2}}}{n}$$

V = velocity S = channel slope

R = hydraulic radius n = coefficient of roughness

(1.49 is English units conversion factor, set to 1 for metric. However, you do not need to remember this formula for A Levels)

1.2.1 Channel Slope

Since stream flow is caused by the force of gravity, a change in the **channel's gradient** will affect the amount of energy the stream possesses. The gradient of a channel is calculated as such:

$$S = \frac{height\ above\ sea\ level}{channel\ length}$$

If channel gradient is steep, the change from potential to kinetic energy is rapid and the velocity of the river is high. Conversely, on gentle gradients the velocity is low.

1.2.2 Coefficient of Roughness

Channel roughness is another factor affecting velocity. Some of Manning's coefficient of bed roughness is given in table 1 below. Notice that the higher the value the rougher the bed and the lower the velocity.

Table 1: Manning's coefficient of bed roughness.

Surface	Manning's n
Very smooth e.g. glass	0.010
Concrete	0.013
Unlined earth drainage channels	0.017
Winding natural channels	0.025
Mountain streams with rocky beds	0.040 - 0.050
Alluvial channels with small ripples	0.014 – 0.024
Alluvial channels with large dunes	0.020 – 0.035

In a downstream direction the river channel tends to become smoother because it is more likely that the banks and beds of the river will be made up of clay/silt/sand instead of boulders and pebbles. As the n value reduces the V value increases. Irregular beds in the upper course contain large protruding grains or boulder which increases turbulence, reducing velocity upstream.

1.2.3 The Hydraulic Radius

A close relationship exists between the velocity of water in a river and the characteristics of the channel in which the water is flowing. These characteristics (which include depth, width and channel roughness) are collectively referred to as the hydraulic geometry of the channel. The width-to-depth ratio, for instance, is often used as a means of comparing different channel shapes and its influence on river velocity is illustrated below.

The **hydraulic radius** is the ratio between the area of the cross-section of a river channel and the length of its **wetted perimeter** (the total length of the bed and bank sides in contact with the water in the channel), i.e.:

$$\text{Hydraulic radius} = \frac{cross\ sectional\ area}{wetted\ perimeter}$$

Figure 1 shows how the hydraulic radius is calculated for two channels with the same cross-sectional area (i.e. with the same size) but different shapes.

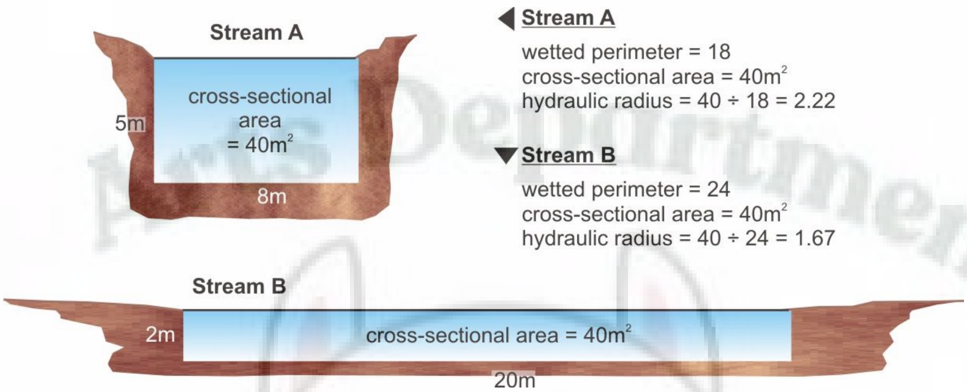


Figure 1: Calculation of the hydraulic radius

Stream A with a more balanced **width depth ratio** has a larger hydraulic radius because of the smaller wetted perimeter. This means that a smaller amount of water is in contact with the bed and banks of the channel which in turn creates less friction and energy loss. The river velocity is subsequently higher than that of stream B.

In essence, the shape of a channel is determined by the materials forming the channel sides and the river forces working on them. Normally, channels in silt and clay tend to be deeper and narrower than those in sand and gravel, because the finer materials are cohesive and promote bank stability.

Besides channel shape, channel size also affects the hydraulic radius. This can be easily illustrated by calculating the R value of two different sized rivers with the same shape.

2. Channel Morphology

To study the features and formation of fluvial landforms, it is important to under the concept of channel morphology. **Channel morphology** is the study of the shape, size, and characteristics of a river or stream channel. It primarily includes the analysis of the channel's width, depth, gradient, cross-sectional area and the channel patterns they form. For this topic, we will need to understand channel morphology in terms of a river's long profile (gradient), cross-sectional profile and plan form (patterns). Channel patterns such as meanders and braided channels are derived from looking at the plan forms of the rivers. As sediment transported by any river must eventually be deposited at or near the river mouth, the important landform produced will be a delta.

2.1 Long / Longitudinal Profile

You have learnt this earlier on. The **long profile** refers to the gradient of a river from its source to mouth. For rivers in the humid tropics, it's typical to see a concave profile where the slope becomes gentler downstream.

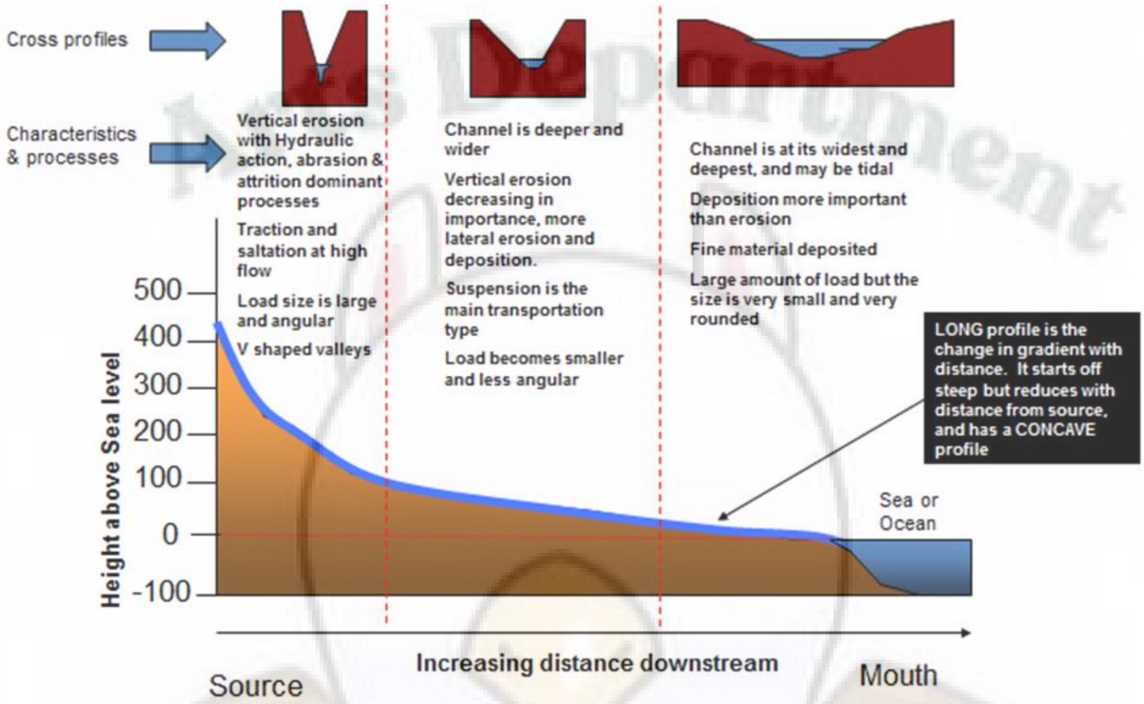


Figure 1a: Long Profile and Cross Sections of a River

2.2 Cross / Cross-sectional Profile

The cross-section or the **cross profile** of a river channel allows for the analysis of width and depth. Generally, cross sectional area increases downstream due to the increased volume of water added by the tributaries of the river (fig. 1a). It is also heavily influenced by the sediment load. Channels with a high percentage of silt and clay in their banks tend to be narrower and deeper (low **width-depth ratio**) than sand and gravel-bed rivers. Vegetation also controls the cross section of a channel, since its roots hold the bank sediment together, preventing undercutting and subsequent lateral erosion. Vegetated channels tend to be narrower than non-vegetated channels.

3. Channel Pattern

Channel patterns can come in three forms – straight, meandering and braided (fig. 2). These develop as a response to discharge and sediment load variables and will be discussed in greater detail below.

Figure 2: Plan forms of types of river

Straight rivers are not common and most rivers are rarely straight for lengths of more than ten times their average width. However, there are two reasons for some rivers following a straight course:

1. When they are flowing down steep slopes.
2. When they are strongly influenced by joints or faults in the underlying rocks.

3.1 Meanders

Of the three different types of channels, meandering channels are the most common.

3.1.1 Main Features of Meanders

Sinuous Channel

Meandering channels are single channels and their course is **sinuous**. The classification of straight and meandering channels is based on the calculation of the rivers' **sinuosity ratio**:

1. This is the ratio between distance along the centre line of the valley and the distance along the channel—i.e. it shows the extent to which the river deviates from a straight course (figure 3).
2. Alternatively, the degree of sinuosity can also be determined by calculating the ratio of the actual channel length to the straight-line distance between two points.

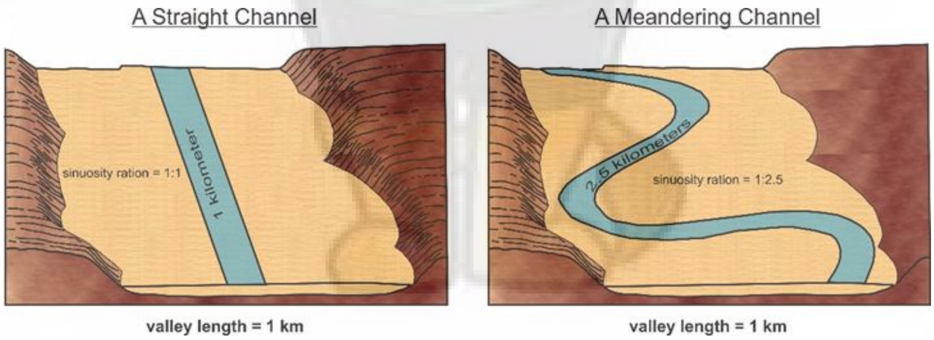


Figure 3: Calculation of sinuosity ratio.

A river is said to be meandering only when the sinuosity ratio exceeds 1:1.5. Figure 3 for example, shows a straight channel with a ratio of 1:1 and a meandering channel with a ratio of 1:2.5.

Point bar and River cliff

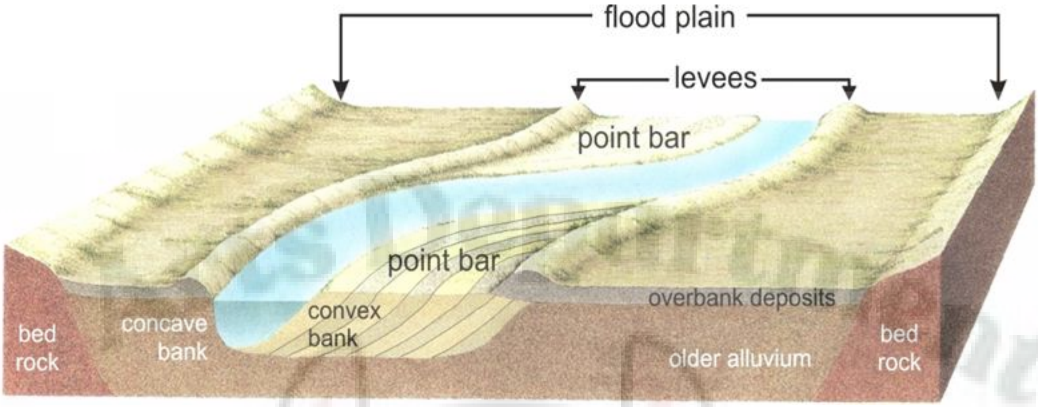


Figure 4: Point Bar and River Cliff at Concave Bank

Point bars are crescent-shaped accumulation of alluvium deposits of sand or gravel located on the inner banks (convex bank) of meanders (Fig. 4). They are depositional features whose development is linked to the spiral flow of water in meanders known as **helicoidal flow.** The sediment on the point bars can be sorted according to their **caliber** due to **channel migration**. Larger particles are found on the lower surface of the point bar and finer sediments are found towards the upper surface. Point bars is found where the slope is gentler on the **convex bank** (slip-off slope).

And on the steeper concave bank, **river cliff** can be found. River cliffs are of different sizes and steepness, depending on the size of the rivers, amount of the discharge and the geology of the river banks.

While fluvial deposition forms the point bars, fluvial erosion forms the river cliff. The river erosion processes (hydraulic action and abrasion) are very much responsible for the formation of such a cliff. Very often mass movements like falls and slides take place at the river cliffs and they, together with the river erosion, are responsible for the recession of river cliffs.

3.2 Braided Channels

Braided channels are channels characterized by sub-division of water flow—i.e. where there is the separation of the main channel into a number of smaller, interlocking channels. These series of channels, or **anabranches**, are separated by islands known as **mid-channel bars** (figure 5).

3.2.1 Main Features of Braided Channels

High Width-depth Ratio

The banks of braided channels are often composed *of* **incoherent sand and gravel** that experience strong bank erosion during high discharge. This tends to widen the channel as a whole to result in an inefficient channel due to its **high width-depth ratio** (which may exceed 300:1 in certain cases).

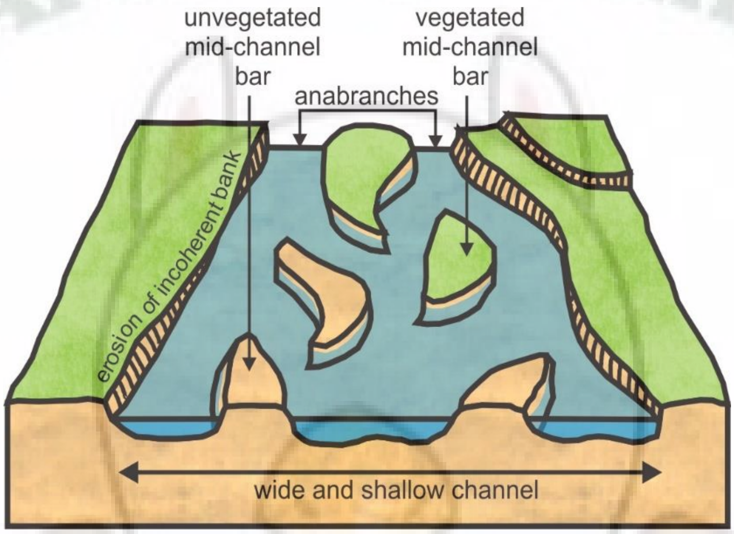


Figure 5: A braided channel

This is illustrated in figure 6 which shows that in general, wide and shallow channels develop where the materials which make up the bank are loose and non-cohesive. Sand and gravel, for example, are unstable at steep angles and collapse if the stream cuts deeply into them. Where the banks are composed of more **cohesive materials, such as silt and clay**, the channel is often deeper and narrower. The ratio of width to depth of stream channels is therefore inversely related to the silt and clay content of the bank material.

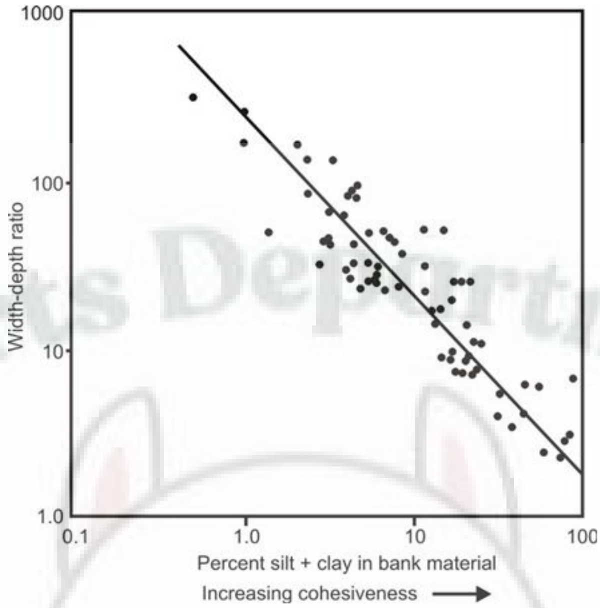


Figure 6: The relationship between channel shape and the clay + silt content of the bank materials.

Mid-channel Bars

Since a large amount of **coarse bedload** characterizes braided channels, these will be deposited during low discharge to form the **mid-channel bars**. These are low elongated unvegetated bars of sand and gravel and vegetated islands which normally stand above water level. Mid-channel bars are the result from the deposition of load within the channel by the rivers as energy decreases. Some of these mid-channel bars are more stable and more permanent than the others and can withstand erosion better. Finally, the water flows in between as **anabranches**.

3.3 Deltas

Deltas are fluvial landforms formed at the mouths of rivers where sediment carried by the river is deposited as it enters a body of water, such as an ocean, and when it supplies sediment more rapidly than can be dispersed by wave or tidal action. The deposition of sediment at the mouth of the river is due to the decrease in velocity of water known as the **backwater effect**. The sediment that accumulates results in an irregular **protuberance** of a shoreline. The process of building out into the sea is called **progradation** (usually occurs when tide and wave energies are low).

3.3.1 Main Features of Deltas

Delta Plain

The **delta plain** (topset beds) is the area of a delta that is composed of flat, low-lying land created by the deposition of sediment carried by the river forming the **subaerial** part of the delta. It is typically situated at the farthest inland part of the delta, furthest away from the main body of water. The **upper delta plain** is furthest away from the coast and is above the level of the highest tide. The **lower delta plain** can be submerged by high tides at regular intervals. The delta plain has an accumulation of a range of sediments. Along the distributaries when flooding occur, natural levees of coarser sediment and deposition of finer sediment on the marshy delta surface can be observed on the **distributary bay**. (fig.7)

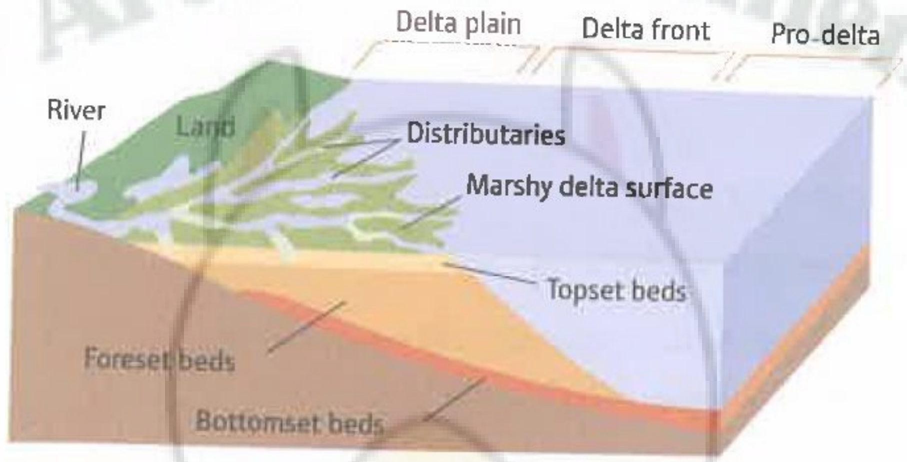


Figure 7: Delta Plain (topset beds), Delta Front (foreset beds) and Prodelta (bottomset beds)

Delta Front

The **delta front** (foreset beds) is the region of the delta that lies at the seaward edge of the delta plain. It is the **subaqueous area** in which the sediment laden river water meets the saline seawater. Deposition increased when water is salty. The salt particles group together in a process known as **flocculation**, became heavier and are deposited. Erosion and deposition are highly active in this zone due to the constant interplay of river flow and ocean currents. Delta fronts might display various sedimentary features due to progradation. These features include distributary mouth bars formed by the accumulation of sediment carried by waves and tides. Erosional features such as cliffs or irregularities could be also present.

Prodelta

The **prodelta** (bottomset beds) is the **subaqueous** low edge of the delta in front of and below the delta front. It lies seaward as a layer of clay and slit on the floor of the basin. This is because the fine-grained sediments settle out of suspension, deposit and accumulate in this lower energy environment.

<u>When deltas prograde, delta plain, delta front and prodelta move forward, overriding each other.</u>

4. Meanders, Braided Channels and Deltas in the Humid Tropics

Most parts of a tropical river are located within the tropical climate belt but its origin or a large proportion of its drainage basin can lie in a more arid or temperate climate. Thus, some tropical rivers can be fed by melting snow or glaciers (e.g., the Mekong, Indus, Ganges, Brahmaputra and Paraná).

Tropical rivers include many important river systems (Fig. 8), such as:

- the Nile, Niger, Congo and Zambezi in Africa;
- the Magdalena, Orinoco and Amazon in South America;
- the Indus, Ganges, Brahmaputra, Salween, Irrawaddy, Chao Phraya, Mekong, Pearl and Red River in Asia; and
- the rivers draining many islands in Indonesia, the Philippines, Borneo, Papua New Guinea and other areas.

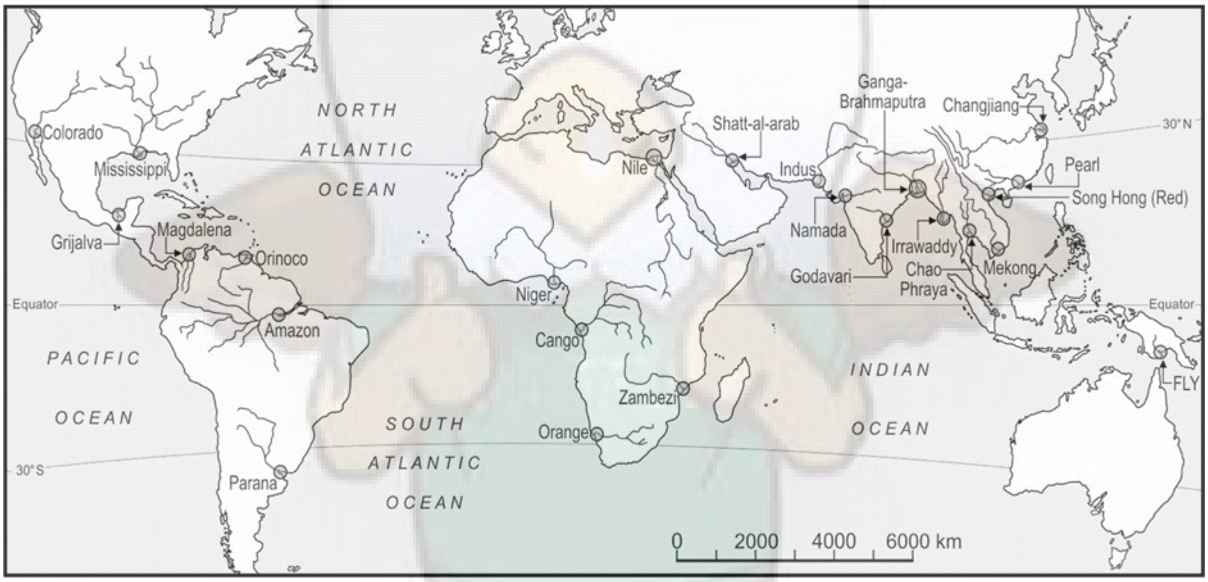


Figure 8: Major Rivers and Deltas in the Tropics

4.1 Climate and Flooding in the Humid Tropics

Tropical rivers are particularly affected by tropical cyclones and monsoons, which can result in extremely heavy rain and river flooding that has devastating effects on the environment. Land surface change such as deforestation and urbanisation can also exacerbate flooding. For example, deforestation in the upper basin of the Ganges and Brahmaputra caused soil erosion that reduced infiltration rates and hence resulted in increased sedimentation, increasing flood risk.

4.2 Sediment Yield in the Humid Tropics

Though dense vegetation cover protects tropical river basins from water erosion, **sediment yields** can be enormously high in the rivers because of high precipitation and intensity, especially after vegetation is removed through deforestation. Another important factor influencing sediment yield is **terrain**. Originating from mountains belts across the world, tropical rivers drain through a variety of geomorphologic settings, transporting large amounts of sediment towards lower-lying land areas and creating large, fertile deltas. These mountains have high relief and steep slopes that are subjected to soil erosion and sediment production under high precipitation. Hence, the rivers from the Himalayas and the island arcs of the East Indies have high sediment yields. The rivers draining from these two regions are estimated to account for more than 70 per cent of the sediment loads entering the oceans in the entire world.

Originating from the Himalayas, the Brahmaputra and Ganges are the largest sediment-producing basins and annually transport more than 1,500 million tonnes of sediment. Apart from the rugged terrain, intense monsoonal rains (often over 3,000 mm/year) at the southern slope of the Himalayas also contribute to high sediment production.

In the next section, we are going to focus on the role of geomorphic processes in the formation of fluvial landforms. While erosion, transportation and deposition are important geomorphic processes, let’s not forget that weathering, both chemical and physical are required to break down the rocks in situ before sediment can be entrained and eroded by running water.

2.2.3 Fluvial Landforms in the Humid Tropics

What factors influence the formation of fluvial landforms in the humid tropics?

- Role of geomorphic processes in the formation of fluvial landforms including the role of sediment removal and dispersal by waves and tides in the formation of deltas
- Factors influencing the formation of fluvial landforms

1. Meandering rivers

A river is said to be meandering only when the sinuosity ratio exceeds 1:1.5. Figure 3 (p. 6) for example, shows a straight channel with a ratio of 1:1 and a meandering channel with a ratio of 1:2.5.

1.1 Reasons for Meander Development

The reason for the development of meanders is still something of a mystery and a number of explanations have been proposed over the years. The most credible reason involves the concept of the need of the stream to lose energy as its sediment size decreases while its discharge increases—i.e. meanders develop in response to an excess of free energy in the stream.

Downstream, the discharge tends to increase (due to the contribution of the tributaries) while the sediment becomes finer (thus requiring less energy to be transported), resulting in the stream possessing more energy but relatively less work to do. There is therefore more free energy within the system and meanders help to expend this free energy.

1.1.1 Role of Geomorphic Processes in Meander Formation

Meanders tend to be found in catchments where river discharge is constant throughout the year. They appear to begin with the development of pools and riffles in straight channels:

- In low flow conditions straight channels are seen to have regularly spaced bars of sediment on the river bed where coarser material such as pebbles and cobbles has built up. These are the riffles and where they are found the river is shallower and more symmetrical.
- Between the riffles occur the pools floored by finer sediment such as gravel and sand. This is the deeper part of the channel where the cross-section of the river is more asymmetrical.

- This alternate arrangement of pools and riffles is known as the pool-and-riffle sequence (fig. 9). Because of this swing of the flow induced by the riffles, the zone of maximum velocity tends to be directed/deflected to one side of the channel or the other. This corkscrew like flow is known as **helicoidal flow** that is the main agent for meander development.

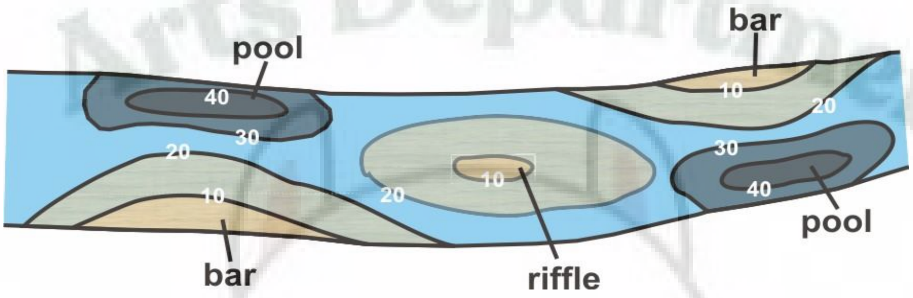


Figure 9: Pool-and-riffle sequence showing depth of bed below water surface (contours labelled in cm)

- Where deflection of a river occurs, **bank erosion** taking the form of **hydraulic action** will be concentrated on the concave side of the channel.
- Concentrated erosion here will lead to the formation of river cliffs (fig. 10a).
- However, after the water is being dragged across the river bed to the convex banks, there will be a loss of energy due to frictional drag.

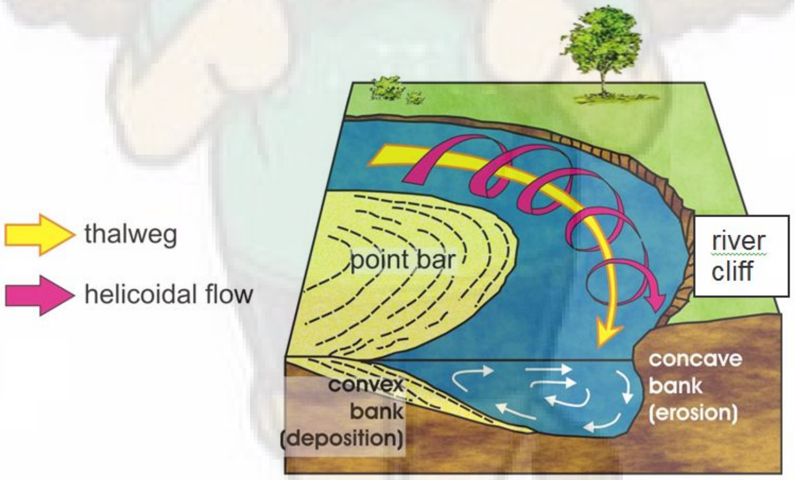


Figure 10a: The formation of meander

- This, coupled with the expenditure of energy when erosion was conducted at the concave banks and the reduced depth of the water at the convex bank, will lead to the **deposition** of the coarser sediment load to form point bars at the convex banks. This is because coarser sediment has a higher settling velocity and will be deposited first.

- Over time, the deposition at the convex bank and the erosion at the concave bank lead to an increase in the **meander amplitude** and sinuosity which over time will lead to the formation of a well-developed or pronounced meander (fig. 10b).
- The narrow area of land between two concave banks is known as a neck. As **lateral erosion** continues, the river may erode through the neck forming a cutoff and an ox bow lake. This marks an abrupt change in the sinuosity ratio as the stream now becomes straighter.
- As the concave bank gets eroded and deposition at the convex bank continues (fig. 10b), the meander migrates laterally across the floodplain over time. The presence of ox bow lakes and meander scars serve as indicators of the previous positions of the river channel on the floodplain.

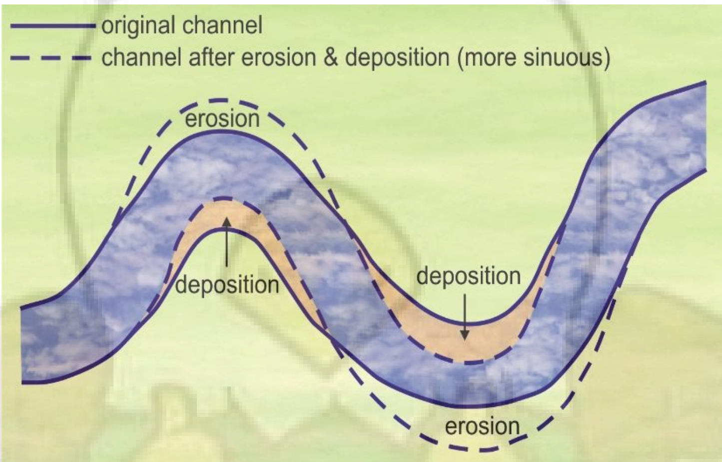


Figure 10b: Development of a more sinuous meander after erosion and deposition

- An example of meandering river is the Amazon River, the second-longest river in the world, meanders through the tropical rainforests of South America. Its extensive network of meanders creates fluvial landforms such as point bars, river cliffs as well as floodplains.
- Mekong River is another example of a meandering river flowing through several Southeast Asian countries in the humid tropics, including Cambodia and Vietnam. The meanders are found at its lower course. The river's meanders are vital for transportation of large volumes of sediment which are deposited at the floodplains and at the Mekong Delta.

2. Braided Channels

Braided channels are channels characterized by sub-division of water flow—i.e. where there is the separation of the main channel into a number of smaller, interlocking channels. These series of channels, or anabranches, are separated by islands known as mid-channel bars (fig. 5, p. 5). These are low elongated islands which normally stand above water level and can be vegetated or unvegetated.

Although braided streams are highly active during periods of high discharge, they are not necessarily unstable. Individual channels may be abandoned, buried by vast quantities of sediment carried by the streams, or eroded, but the overall character of the stream is retained and the pattern persists.

2.1 Conditions for Formation of Braided Channels

There are 3 main conditions required for the formation of braided channels:

- The banks of braided channels are often composed of coarse sand and gravel that are unstable at steep angles and collapse if the stream cuts deeply into them. They experience **strong bank erosion during high discharge**. This tends to widen the channel as a whole to result in an inefficient channel due to its high width-depth ratio (which may exceed 300:1 in certain cases).
- A large amount of coarse bedload also characterizes braided channels. For example, coarse sediment on the bank in the Aw climates will be washed into the channel during the wet season. This forms the coarse bedload needed for the formation of mid-channel bars. These result from the **deposition of load within the channel by the rivers as energy decreases**. Some of these mid-channel bars are more stable and more permanent than the others and can withstand erosion better.
- The river/flow regime of braided channels is unstable or markedly seasonal. Such **fluctuating discharge** is a pre-requisite for braiding since it allows for the required erosion and deposition to take place. Braiding is therefore common in Aw climates with distinct seasons or BSh and BWh regions prone to irregular, sudden downpours.

2.1.1 Role of Geomorphic Processes Formation of Braided Channels

The processes of erosion and deposition when the discharge of a river fluctuates are responsible for the formation of braided rivers:

- During periods of high discharge, **river discharge exceeds the critical erosion velocity of coarse particles**. Large amounts of sediment are **entrained** as bedload and move downstream.
- This also results in the river banks being undermined since coarse particles are unstable at steep angles, so that they collapse into the channel giving a wider channel.

- During periods of lower discharge when energy decreases, the **overloaded river will start depositing** some of its load to form mid-channel bars.
- Starting from the coarse bedload with a higher settling velocity, deposition will occur within the channel to form the nuclei of bars (figure 11). As the flow is disrupted and velocity decreases downstream, finer sediment accumulates and the bars of sand and gravel grow.
- Channel flow is deflected around the bar, concentrating **lateral erosion** on the river banks. At the same time, the river channel is deepened.
- Together, this enlarges the channel on both sides of the bar, allowing the water level to be lower for the same discharge. The bar emerges as an island flanked by two distinct channel branches.
- Some of the sand and gravel bars will be washed away during subsequent floods due to lateral erosion but others will grow and become colonized by vegetation. These will become more stable as the plants assist the trapping of more sediment and the roots help to bind the sediment together. These vegetated bars will eventually become islands that are rarely inundated.
- The Brahmaputra River in Bangladesh and India exhibits braided channel patterns in its lower course, especially in the Assam Valley. This is unique as the river's braided pattern is found at the lower course where river discharge is high. A combination of factors such as sediment transport, monsoon rains and the dynamic tectonic setting of the region leads to its formation.
- Braiding can also be found at the Amazon Basin. The Tocantins River in Brazil, flowing through the Amazon rainforest, may display braided features in certain sections, influenced by seasonal variations in water flow and sediment transport.

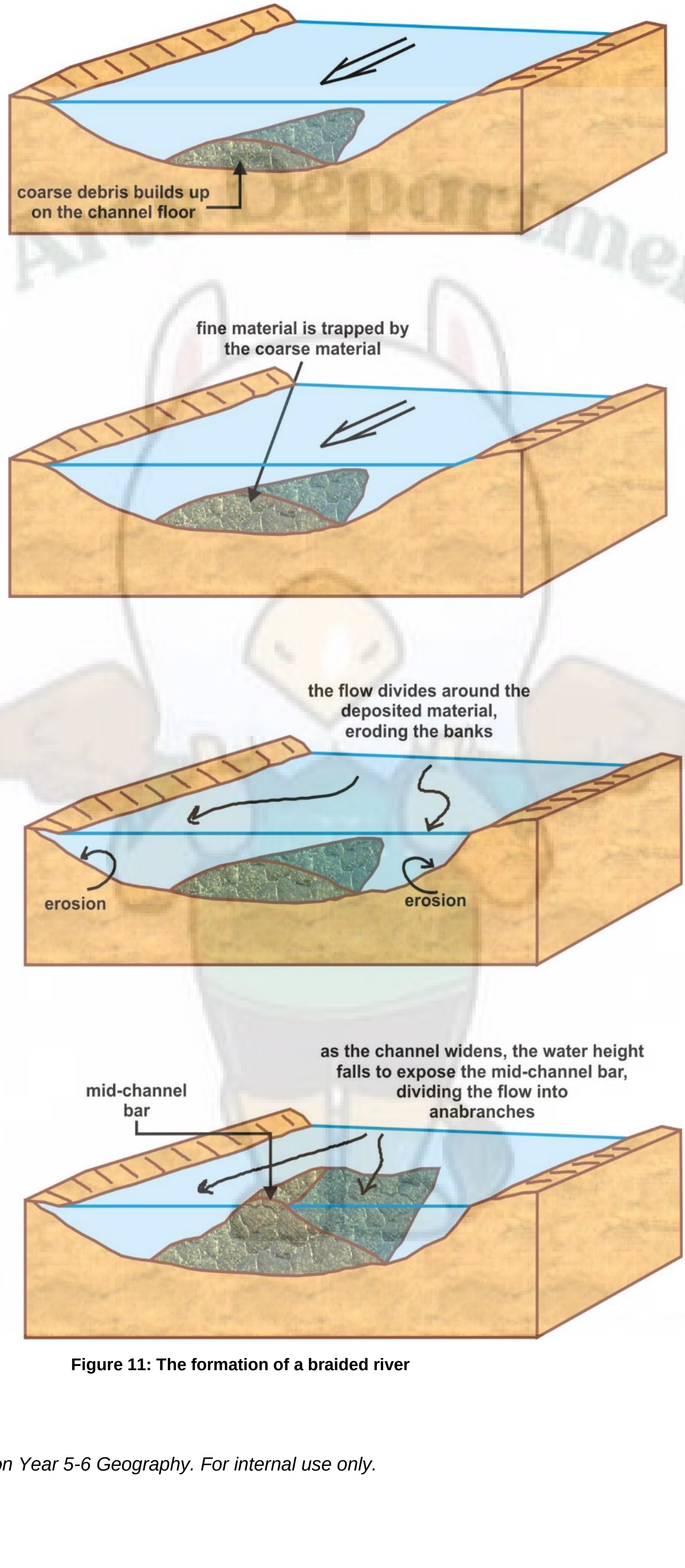


Figure 11: The formation of a braided river

5. Delta

Deltas are formed where sediment carried by the river is deposited faster than dispersed by wave or tidal action. The process of building out into the sea is **progradation** and usually occurs when tide and wave energies are low.

3.1 Conditions for Delta Formation

There are some main conditions required for the formation of deltas:

- Rivers having very large volumes of suspended sediment.
- A broad continental shelf margin at the river mouth that provides a platform for the deposition and accumulation of sediment. (fig.12)

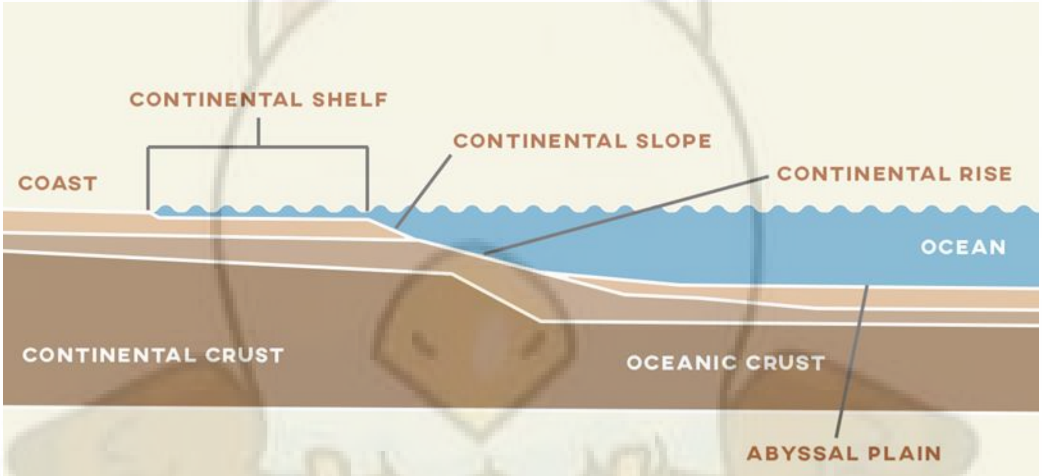


Figure 12: Continental Shelf

3.1.1 Role of Geomorphic Processes Formation of Deltas

- The **upper delta plain** is furthest away from the coast and is above the level of the highest tide. The **lower delta plain** can be submerged by high tides at regular intervals as well as river floods. Sediments accumulated at the **distributary bays** forming marshes or mangroves. **Accretion** of fine sediments gradually fills up the distributary bays and elevates these bays above the high tide level.

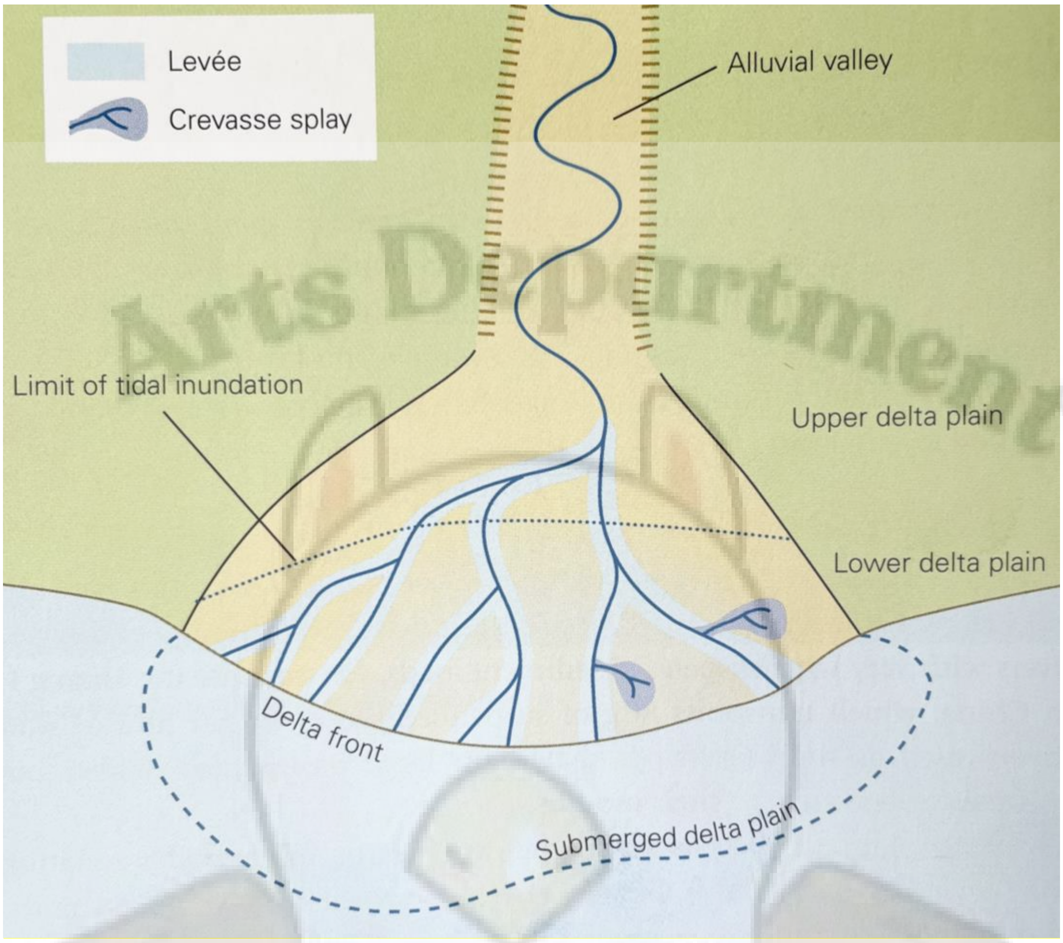


Figure 13a: Division of Upper and Lower Delta Plain

- Distributary channels criss-cross the delta plain (fig. 13a), they split and merge. These channels are bounded by levees that are formed by deposition along the channels. At high flow, levees may be breached. Water spilling out of the distributary channels to the adjacent areas experiences a sudden decrease in velocity, causing **deposition**. Crevasse splays (small alluvial fans) may form (fig.13b).

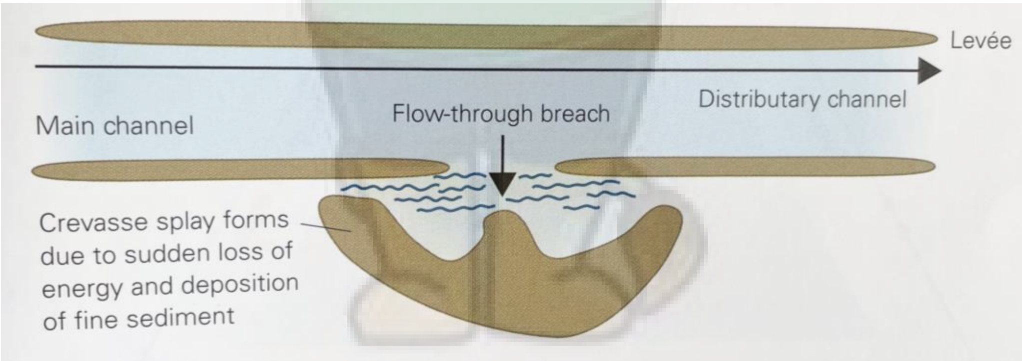


Figure 13b: Leeves and Crevasse Splays in a Distributary

- Extension of the lower delta plain seawards occurs at the mouths of the distributary channels where levees are poorly developed, and flow of water no longer confined. So, the flow expands, loses energy and builds up **distributary mouth bars**.

- As the distributary mouth bars grows, it splits the flow, causing the channels to bifurcate (split into two). Channels may also converge or suddenly switch direction (avulsion) and merge.
- The formation of distributary mouth bars and levees take place together. Levees often contain distributaries on the lower delta plain. Continued flooding by tides and rivers leads to gradual **infilling** and allows the growth of delta seawards. The process may be repeated frequently giving the entire depositional zone a vein-like appearance (fig. 13a) and prograding the delta front.
- At the delta front, deposition also occurs when the fresh river water meets the saline seawater. Deposition increased when water is salty as the salt particles group together in a process known as **flocculation**, became heavier and are deposited. Vegetation may also increase deposition by slowing down the water, a process known as bioconstruction.
- When deltas prograde, delta plain, delta front and prodelta move forward, overriding each other. There's regular succession of deposits. The finest sediment are deposited furthest from land on the bottomset beds, medium sediment on fore-set beds and coarser sediment are deposited on the topset beds. (See fig 7, p.7)

Depending on tides, waves and currents, three types of delta (fig. 14) can be formed **(1) river dominated (2) tide dominated (3) wave dominated**:

(1) **River dominated delta** is formed when river flows into waters with **weak tidal currents**, **small tidal range** and **weak wave action**. It drains a huge basin, carries a large sediment load and advance into the shallow sea. An example will be the Mississippi delta flowing into the Gulf of Mexico which expanded aerially forming a classic bird's foot shape.

(2) **Tide dominated delta** is formed when river flows into waters with **strong tidal currents** and **high tidal range**. Tide-dominated deltas are inundated at high tide and drained through the distributary channels at low tide. The sediment moved back and forth over the length of the distributary channels where flocculation takes place. With **moderate wave action** and **weak longshore currents**, sediments are **dispersed** in an elongated manner in the direction of tidal movement and deposited perpendicularly to the coastline. An example will be the Ganges-Brahmaputra delta where mangroves tend to grow on marshy distributaries anchoring the fine-grained sediments as it flows into the Bay of Bengal.

(3) **Wave dominated delta** is formed when river flows into waters with **strong longshore currents**. As strong longshore currents **remove** sediment from the delta face, limiting the size of the delta. Also, when **waves are strong**, sediment may be **pushed back** to give the delta edge a straighter appearance. The delta does not protrude into the sea. This often leads to well-developed beaches and smooth coastlines are formed. The Amazon discharges a large volume of sediment into the South Atlantic and are carried northwest parallel to the coast.

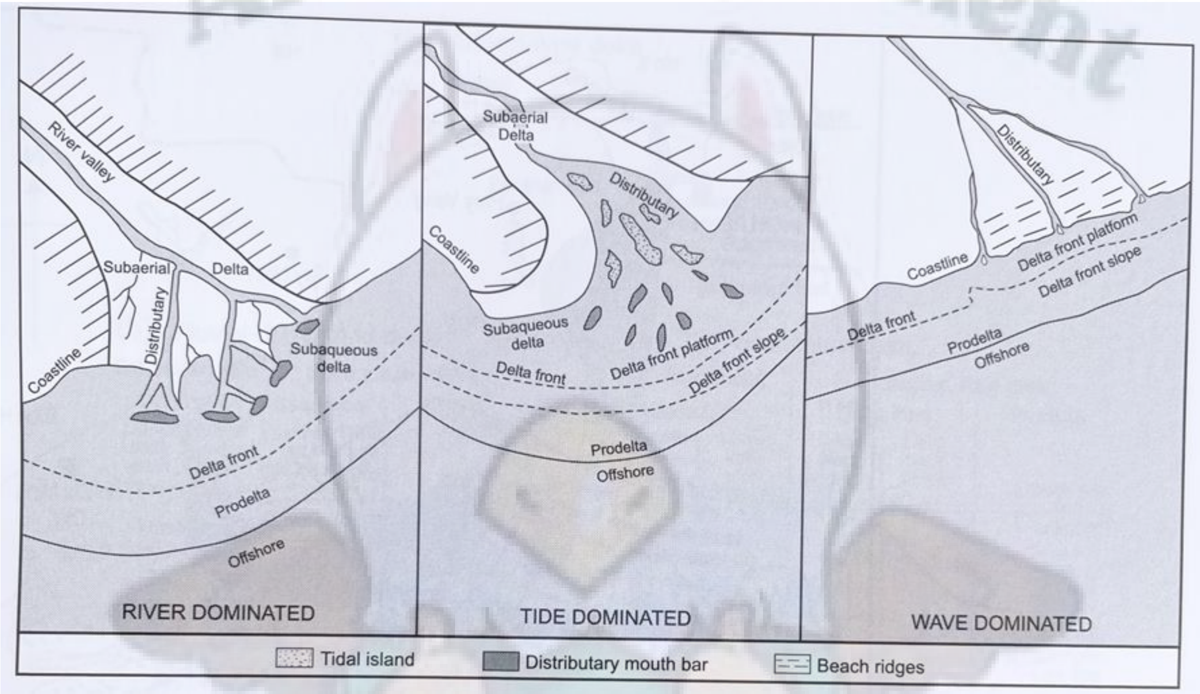


Figure 14: Types of Deltas

- River-dominated deltas are known to be constructive due to the deposition of sediment on the basin while tide and wave-deltas can be destructive or constructive depending on the degree of dispersion and removal.
- The classification of types of delta is rather broad. The lower Mekong delta, for example, has wide beaches while the upper Mekong exhibits multiple distributary channels with levees separated by marshy swamps. While the upper Mekong was built in sheltered bay hence tide dominated, the lower Mekong was exposed to waves and become wave dominated.

A Glossary of Terms
Tide *- the alternate rising and falling of the sea*
Tidal range *- the difference in height between high tide and low tide*
Tidal current *- horizontal movement of water often accompanies the rising and falling of the sea*
Longshore current *- When a wave reaches a beach or coastline, it releases a burst of energy that generates a current, which runs parallel to the shoreline.*
Wave *- up and down movement of water (drive my wind, in any direction)*

4. Factors Influencing the Formation of Fluvial Landforms

4.1 Discharge Regime

We've learnt that the river's discharge regime expresses the variation in the discharge over a year or many years. These variations can be plotted on a graph to form an annual hydrograph.

The discharge regime is clearly climate dependent. Seasonal variations in discharge are characteristic of many of the world's rivers and are most pronounced in climates with distinct seasonality (Fig 15) The development of meanders, braided channels and deltas are influenced by their discharge regimes.

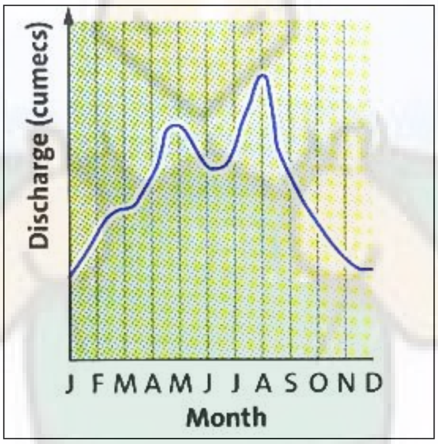


Figure 15: Discharge regime that displays seasonality

Monsoon rains in the Am climates can cause the channels to change its discharge by over a hundred metres a day. The rivers can have channel migration in short periods due to changes in the velocity of the river. The most significant migration take place during falling flood stages (lower velocity) when excess load is deposited, as bars form within the meandering channel.

Erosion, transport and deposition in ephemeral rivers are constrained to short periods during storms when discharge and velocity is higher. Therefore, the appearance of an ephemeral river may change drastically after a storm, but fluvial processes will stop completely, sometimes for years, until the next storm arrives. Hence, braided channels can be found in the seasonally humid and arid tropics.

High river discharge can transport large amounts of sediment, depositing it near the river mouth. This sedimentation contributes to the growth and expansion of the delta.

4.2 Sediment Regime

Calibre of Sediment

Ephemeral rivers in the arid tropics are very wide compared to perennial rivers running through catchments of the same size. The incoherent bed and banks tend to be composed of coarser sediment with a low silt-clay content, therefore leading to a higher width depth ratio. You will also learn in in the topic of Weathering that physical weathering result in coarser sediments. Thus, most ephemeral rivers in the arid tropics have low sinuosity ratios and river beds are flat and shallow with few features. Presence of coarse sediments may lead to the formation of a braided river, although the time needed for formation will be very long due to the lower precipitation received.

Many braided streams in the seasonally humid climates have very low flow depths compared with the channel width (width/depth ratios may exceed 300), consequently only the very largest braided rivers like the Brahmaputra, which is 3-10 km wide, have flow depths. Some mid-channel bars in sand-bed braided channels are so large that at low discharge. Some in the Brahmaputra are 8-15 m high. However, since water is retained within the sediment on the channel bed, trees are commonly found growing on the channel banks or bed. Similarly, vegetation can grow on the delta plains.

Amount of sediment

Although the absence of precipitation most of the time means that fluvial processes rarely occur, ephemeral rivers in the arid tropics are much more effective at erosion and transport than perennial rivers in times of occasional desert storms. This is because of the lack of vegetation on the slopes of the catchment as well as the non-cohesive nature of the channel bed. Bedload and suspended load measurements are much higher than for perennial rivers. In catchments where vegetation cover has been further reduced by human activity, sediment transport is higher than undisturbed rivers in the same climate.

Waves and tidal currents can also contribute to sediment supply by dispersing and transporting sediments along the coastline and offshore areas.

4.3 Response Time

A change in river discharge does not lead to a proportionate or instantaneous response in fluvial landforms. Furthermore, the response time for different characteristics also varies. For example, if there is a flood, the width of the channel may increase immediately due to lateral erosion as a result of hydraulic action. On the other hand, the migration of a meander takes many years and requires repeated flood episodes before it is complete. Finally, it takes time for delta to respond to the upstream changes

4.4 Human Activities

Human activities, such as channelization and damming to prevent flooding will affect discharge while deforestation will affect the sediment regime.

2.2.3 Fluvial Landforms in the Humid Tropics

What is the importance of deltas in the humid tropics?

- Ecosystem services provided by deltas
- Impact of human activities on ecosystem services provided by deltas

Recap:

Ecosystem services are defined as the goods and services provided by ecosystems to humans. **Ecosystem services are "the benefits people obtain from ecosystems"** and people must have access to these ecosystems for their services to be realized. There are four categories of ecosystem services—supporting, provisioning, regulating, and cultural.

- A **provisioning** service is any type of benefit to people that can be extracted from nature such as food, drinking water, timber and fuels.
- A **regulating** service is the benefit provided by ecosystem processes that moderate natural phenomena such as purification of water and carbon sequestration.
- A **cultural service** is a non-material benefit that contributes to the development and cultural advancement of people.
- **Supporting** services encompass functions and processes that provide the foundation for the provisioning, regulatory and cultural services. Deltas and karst landscapes are rich in biodiversity and provide a foundation for the three ecosystem services mentioned above.

Figure 15: Ecosystems Services of the Karsts Landscapes

1. Ecosystems within Deltas

Deltas are distinct in terms of the concentration of freshwater, nutrients and especially sediment inputs to a small area of the coastal zone, creating conditions ideal for fertile ecosystems, dense population and high economic activity. This set of notes will focus on ecosystems services provided by deltas as well as the related processes and impact of human activities on them (fig. 16).

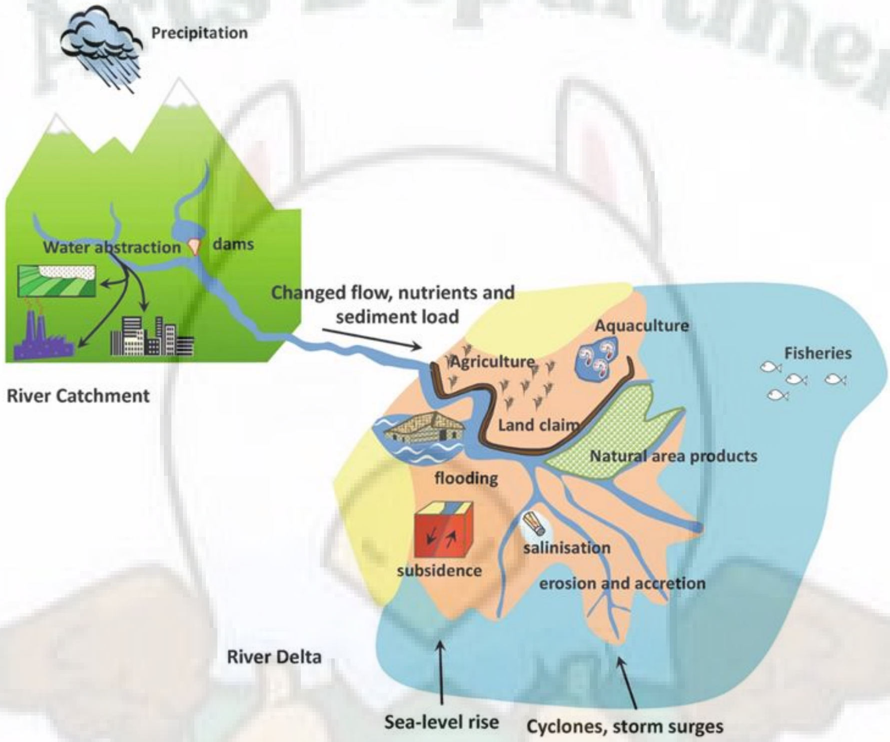


Figure 16: Ecosystem Services, Related Processes and Human Intervention of Deltas

1.1 Cultivated and Grazed Land Ecosystems

Deltas in humid tropics are often suitable for various crops due to fertile alluvial soils. Rice is a common crop in delta regions, given the availability of water for paddy fields. Deltas often support aquaculture (fish farming) due to the proximity to water bodies. Some farmers may adopt integrated farming systems where both crops and livestock complement each other. For example, livestock manure can be used to fertilize crops.

1.2 Vegetated Natural Areas Ecosystems

These are usually the wetlands such as mangrove swamps and marshes. Mangrove ecosystems in deltas are known for their high biodiversity. They serve as nurseries for many marine species, providing a crucial habitat for various fish and invertebrates. Just like karsts, mangrove swamps function as regulating service and contribute to carbon sequestration.

1.3 Non-vegetated Natural Areas Ecosystems

Despite the lack of vegetation, these areas can still support diverse forms of life. Other than animals and micro-organisms, the sediment itself is an important component, influencing the physical and chemical characteristics of the environment. It serves as a substrate for various organisms and supports diverse microhabitats.

1.4 Open Waters

Deltas often exhibit brackish water conditions, resulting from the mixing of freshwater from rivers and saltwater from the ocean or sea. This creates a gradient of salinity that influences the types of species that can thrive in different parts of the delta.

2. Ecosystem Services Provided by Deltas

The processes supporting ecosystem services in deltas have developed over thousands of years. The link between the delta and its river catchment means processes occurring in one place within the deltaic system can lead to benefits or losses elsewhere.

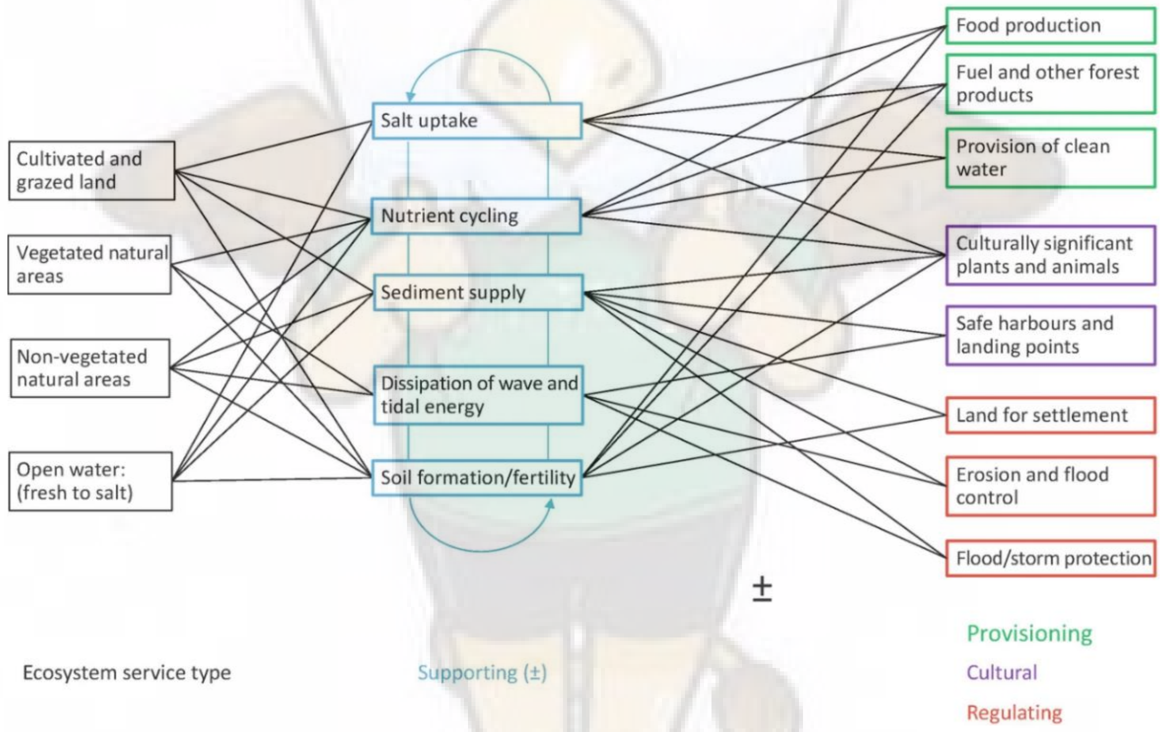


Figure 17: Ecosystems Services Provided by Deltas

2.1 Provisioning Services

2.1.1 Provision of Water

The fresh water supply from rivers aided agricultural activities and ensuring a consistent water supply for sustained productivity in both cultivated fields and grazing lands. Clean water is essential for sustaining agriculture, which is an important economic activity in the

Ganges-Brahmaputra Delta. Reliable and uncontaminated water sources are indispensable for irrigation, ensuring the productivity of crops and the livelihoods of farmers. Swamps and marshes in deltas contribute to water provision by absorbing excess water during heavy rainfall and releasing it during dry periods.

2.1.2 Provision of Food

Rice, a staple food for many delta communities, is well-suited to the wet conditions found in delta environments. The availability of water for paddy fields supports rice cultivation, contributing significantly to food security. Mangroves serve as nursery areas for shrimp fry, offering protection and abundant food sources. Additionally, the intricate root systems of mangroves provide a natural habitat for various aquatic organisms, forming the base of the food chain that supports shrimp production. Ganges-Brahmaputra Delta provides a unique environment where freshwater from the river meets the saltwater from the Bay of Bengal. This creates brackish water conditions that are conducive to shrimp farming.

2.1.3 Provision of Fuel and Other Forest Products

Mangrove forests provide an abundant source of fuelwood for the communities living in proximity. The dense vegetation of mangroves is often utilized for cooking and heating purposes, meeting the energy needs of households in these areas. Deltas also yield a variety of non-timber forest products (NTFPs) beyond fuel. These products, including fruits, nuts, honey, and medicinal plants found in the forested areas of the delta, contribute to the subsistence and livelihoods of delta communities. The Sundarbans mangrove swamp at the Ganges- Brahmaputra delta is extensive and has intricate waterways. The dense and resilient wood of mangrove trees is well-suited for cooking and heating purposes, meeting the daily energy requirements of households in the region. The accessibility of these mangrove forests provides a readily available and locally sourced fuel option for the communities living in and around the Sundarbans.

2.2 Regulating Services

2.2.1 Land for Settlement

Deltas often feature extensive floodplains and flat topography, providing suitable areas for human settlement. The spatial distribution of land in deltas allows for the establishment of communities in proximity to water resources and facilitates various economic activities such as agriculture, trade, and transportation.

2.2.2 Erosion and Flood Control

The expansive wetlands within deltas can reduce the energy of flowing water and redistributing sediments transported by the river, reducing the erosive impact from the energy of high discharge upstream. Mangrove swamps also play a dual role in erosion control and flood control. Their intricate root systems act as natural barriers, stabilizing shorelines and protecting against erosion. Simultaneously, mangroves serve as a buffer against storm surges and tidal waves, absorbing and dispersing the energy of tropical cyclones before they reach inland areas. The low-lying nature of deltas allows for the controlled dissipation of energy from floodwaters. In short, deltas serve as natural sponges that aid in the infiltration of excess waters.

2.2.3 Storm Protection

Tropical cyclones or intense rains are common at the Bay of Bengal. Human settlements in the Ganges-Brahmaputra Delta benefit significantly from this regulating service of its delta. The mangrove-fringed coastlines is the first line of defense from the devastating effects of storm surges, high winds, and flooding associated with tropical cyclones. The settlements are located behind the mangroves on the delta plain, exemplifies an age-old understanding of the delta's ability to provide storm resilience.

2.3 Cultural Services

2.3.1 Culturally Significant Plants and Animals

The Sundarbans is the largest mangrove forest in the world is dominated by the Sundari tree. The Sundari holds immense cultural significance, and its name translates to "beautiful" in Bengali. The wood from the Sundari tree is traditionally used for construction, and the tree is considered sacred by many communities in the Ganges-Brahmaputra Delta. Also, The cultivation and consumption of betel leaves are deeply ingrained in the cultural practices of the Ganges-Brahmaputra Delta. Betel leaves are an essential component of social and religious ceremonies, symbolizing hospitality and cultural traditions. The Sundarbans is also home to the iconic Royal Bengal Tiger, a symbol of strength and power in local folklore. Also, the Hilsa fish is not only a staple in the diet of delta communities but is also associated with the Bengali New Year celebrated in literature, songs, and art.

2.3.2 Safe Harbours and Landing Points

Delta’s locations at the confluence of rivers and seas have made them strategic locations for trade and commerce. They provide ease of access to both inland waterways and the open sea facilitates transportation and trade routes. Deltas often accumulate sediments, resulting in shallower waters near the coastline. While this may present challenges for larger vessels, it can also provide safer conditions for smaller boats and ships, offering easier navigation and reducing the risk of grounding. Throughout history, many major civilizations have flourished along the deltas of great rivers, utilizing the natural advantages for maritime activities. The deltas of the Nile, Ganges, Yangtze, and Mississippi, among others, have been hubs for trade, transportation, and cultural exchange.

2.4 Supporting Services

2.4.1 Sediment Supply and Nutrient Recycling

The sediment deposited at the deltas are a primary source of nutrients, supporting plant growth. The wetlands then function as nutrient filters, capturing sediments and modulating nutrient concentrations. These zones serve as nutrient processing centers, impacting the chemical composition of the water and creating suitable conditions for biodiversity. For example, the intricate root structures of mangroves trap organic matter and sediments, fostering microbial decomposition. This decomposition releases essential nutrients, sustaining the nutrient balance in the ecosystem and providing habitat for a diverse array of species. Finally, decomposition of microorganisms releases nitrogen, phosphorus, and other nutrients into forms accessible to plants and microorganisms.

2.4.3 Soil Formation

The mineral composition of soils is influenced by the upstream rivers. As deltas are located at the lower course of the river, the sediment are eroded by abrasion and attrition into silt and clay. At the deltas, the deposition of organic matter, including plant debris, contributes to the development of organic-rich layers in the soil. This organic matter originates from upstream vegetation, wetland plants, and mangrove forests. Decomposition of organic material by microbial activity adds nutrients to the soil.

2.4.4 Salt Uptake

Vegetation in deltaic areas, including mangroves and salt-tolerant plants, actively takes up salt from the soil and water. This process helps regulate salinity levels, preventing excessive salt concentrations that could harm both soil fertility and freshwater resources. Salt-tolerant vegetation, such as mangroves and certain grass species, contribute to maintaining soil fertility in deltas. These plants have specialized mechanisms to exclude or excrete salts, preventing the accumulation of harmful levels in the soil. By doing so, they support the growth of other plant species that may be less tolerant to salinity hence supporting biodiversity.

2.4.5 Dissipation of Wave and Tidal Energy

The removal and dispersal of sediments at wave and tide-dominant deltas contribute significantly to the dissipation of these energies and aid in the thriving of biodiversity. The Ganges-Brahmaputra Delta is a tide-dominated delta and unique hydrodynamic setting creates diverse habitats that support a rich array of biodiversity in the various ecosystems mentioned above.

3. Negative Impacts of Human Activities on Ecosystem Services provided by Deltas

3.1 Dams and Water Extraction

Dams interrupt the natural flow of rivers and prevent the transportation of sediment downstream preventing them from reaching the deltas. Sediment load is critical in the formation of deltas. The reduction of sediment load to deltas can lead to erosion and channel bed incision, making these areas more vulnerable to sea-level rise.

Over the years, the construction of dams upstream, particularly on the Ganges and Brahmaputra rivers such as Tehri on the Ganges have led to decreasing sediment load in the delta and increased vulnerability to erosion and **land subsidence**. This is made worse by the low-lying topography and intricate network of tidal channels. Reduced freshwater flow from upstream, coupled with rising sea levels, allows saltwater to penetrate further inland. Higher salinity levels can negatively impact shrimp production. Farmers may find it challenging to grow a diverse range of crops. Dependence on a narrow range of crops and livestock increases vulnerability to environmental changes and market fluctuations.

Excessive water extraction can also reduce the freshwater flow reaching the delta, allowing saltwater from the sea to intrude further inland. **Salinisation** can have detrimental effects on both the ecosystems and agriculture. Groundwater extraction can also lead to land subsidence. When groundwater is over-extracted, the pore spaces in the soil collapse, causing the land to sink.

Dhaka, the capital of Bangladesh and located in the Ganges Delta, has experienced significant groundwater extraction for both domestic and industrial purposes. As groundwater is pumped out, the land compacts, leading to subsidence. There are instances of small islands in the Ganges-Brahmaputra Delta sinking vertically due to lack of sediment and groundwater extraction. As communities rely on groundwater for drinking water and agriculture, excessive extraction can contribute to subsidence, making these low-lying areas more susceptible to inundation.

3.2 Deforestation, Agriculture and Urban Development

Deforestation, often associated with agricultural expansion and urban development can (1) increase soil erosion upstream (2) reduces the protective cover of forests and mangroves. This *may lead to* ***accretion*** and delta progradation. <u>However, it's more usual for damming and water extraction to cause delta shrinkage. In fact, most of the major deltas in the world, Amazon, Mekong, Ganges-Brahmaputra ae found to have their vertical sinking rates exceeding the rates of sediment deposition.</u>

3.3 Climate Change and Sea Level Rise

The flat nature of deltas made them especially vulnerable to sea level rise, tropical cycles, and fluvial, tidal and storm surge flooding. Ganges- Brahmaputra delta is tide-dominated with a large tidal range between 3m to 6m. The tides coupled with monsoons intensify floods situation . With sea level rise and increase in frequency of tropical cyclones, the negative impact of floods will likely to be be more extensive and affect the economies at the delta. Fig. 18 shows the fluctuation of temperatures, rainfall, sea level and tropical cyclones on damage of crops at the Ganges- Brahmaputra River.

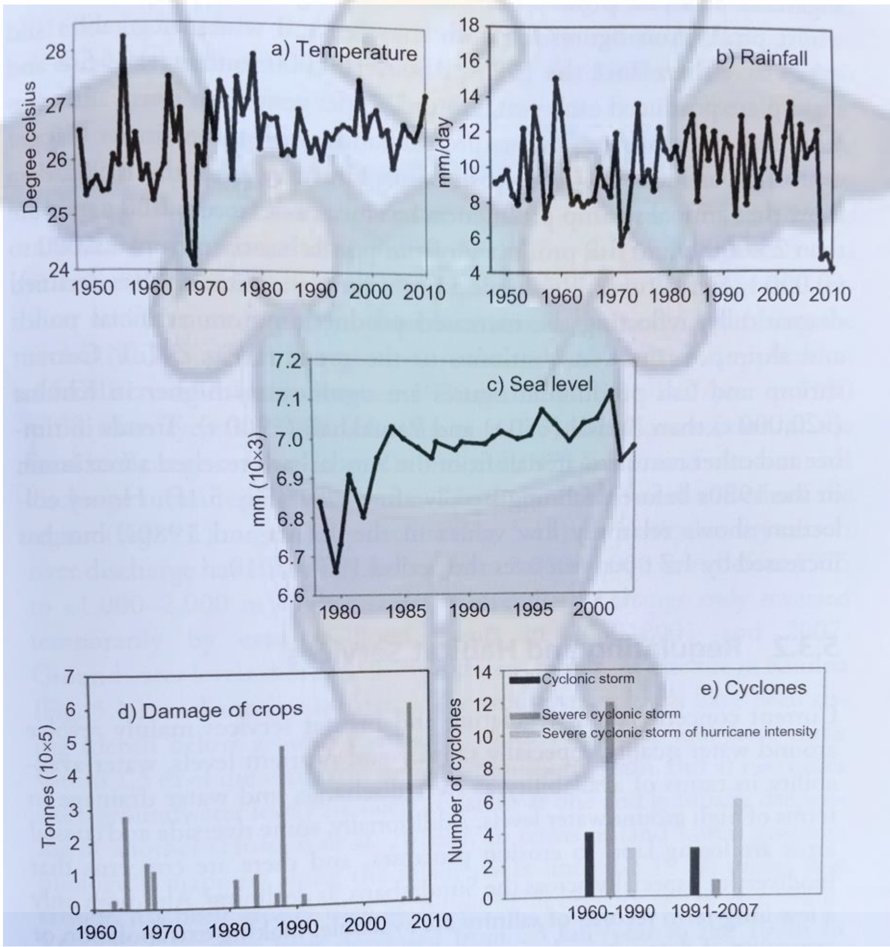


Figure 18 Climate and Crop Damage at Ganges-Brahmaputra Delta

3.4 Land Claims

The dynamic nature of deltas makes it challenging to define and enforce static property boundaries. Land that may be occupied today could be significantly altered or submerged over time, creating uncertainties about tenure and property rights.

4. Protecting the Delta Ecosystems

4.1 Mangrove Conservation

For Ganges, Brahmaputra delta, both India and Bangladesh have enacted policies and legislation to protect mangroves. These may include regulations against illegal logging, fishing, and other activities that harm mangrove ecosystems. Sundarbans is a UNESCO World Heritage Site. Both countries have implemented conservation programs within the Sundarbans Reserve Forest, focusing on sustainable management. Given the transboundary nature, international collaboration is needed and usually will collaborate NGOs such as Mangroves for the Future (MFF), often on mangrove conservation projects. MFF is a regional initiative that promotes the conservation and sustainable management of mangroves in the Indian Ocean region.

4.2 Riparian Buffer Zone

Riparian buffer zones act as natural filters, trapping sediments, nutrients, and pollutants from surface runoff before they enter the water. This helps to improve water quality by reducing the amount of sedimentation and pollutants that reach the rivers. In delta environments, where sediment dynamics are essential for land-building, maintaining this balance is crucial.

4.3 Education and Awareness

Research programs are important to understand the ecology, biodiversity, and dynamics of ecosystems of the deltas. Publications such as Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis are important for the government to understand the ground and make polices. Also, education and awareness programs target schools, local communities, and the general public to communicate the importance of deltas. These programs aim to instill a sense of responsibility and need for conservation.

2.2.2 Karsts Landscapes in the Humid Tropics

What is the importance of karst landforms in the humid tropics?

- Ecosystem services provided by karst landforms
- Impact of human activities on ecosystem services provided by karst landforms

Let's take a look at the various ecosystems within the karst landscapes before moving on the ecosystem services in greater detail.

1. Ecosystems within the Karst Landscapes

1.1 Karst Forest Ecosystems

Karst forests are largely prevalent in the tropics. The unique microclimate of karsts creates shallow soils and porous limestone via chemical weathering, physical weathering and lack of weathered end product. In addition, the extensive drainage and shallow karst soils leads to limited nutrient availability and retention. Nonetheless, it serves as a rich habitat for a large variety of flora and fauna that adapt to these nutrient-poor soils and intermittent water availability.

1.2 Cave and Subterranean Ecosystems

Caves within karst landscapes uniquely adapt to environments with low or no light, limited nutrient availability and high diurnal temperature fluctuations. Some subterranean species like troglobites and troglophiles have also evolved to survive in complete darkness.

1.3 Water and Riparian Ecosystems

Karst hydrological processes contribute to the clear waters, high oxygen levels, and temperature stability of rivers and springs. The carbonation-solution of limestone forms underground caves, where natural filtration occurs as the soluble rock removes sediments and impurities from the water. The highly permeable karst landforms and movement of water facilitate oxygen exchange, while the underground caves also act as thermal regulators through providing insulation. This stability and pristine environment create favourable conditions for many aquatic organisms like cave shrimp and bacterial mat communities.

1.4 Karst Steppe and Grassland Ecosystems

These ecosystems are located in karst regions with open terrain and sparse vegetation. Arid or semi-arid conditions in BWh and BSh climates have caused plants to develop drought tolerance through deep root systems which can reach underlying karst aquifers, xerophytic adaptations to minimise water loss, and higher photosynthesis rates to optimise water uptake.

2. Ecosystem Services Provided by the Karst Landforms

2.1 Provisioning Services

2.1.1 Provision of Water

The hydrogeological systems of karst landforms are characterised by highly permeable limestone, underground cavities and interconnected aquifers, which contribute to water storage and distribution for human consumption, agriculture and ecological systems. (fig. 19)

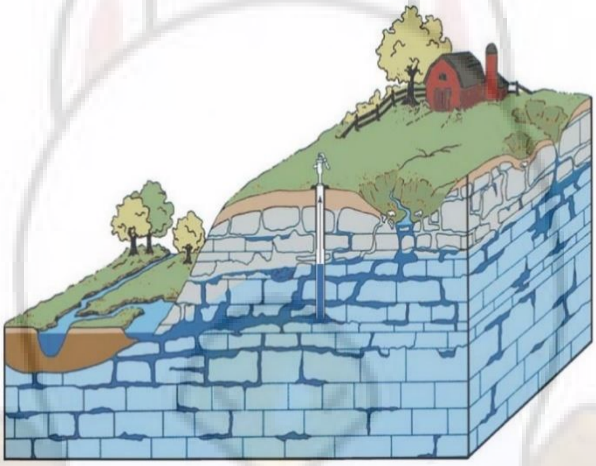


Figure 19: Karst Water Ecosystem

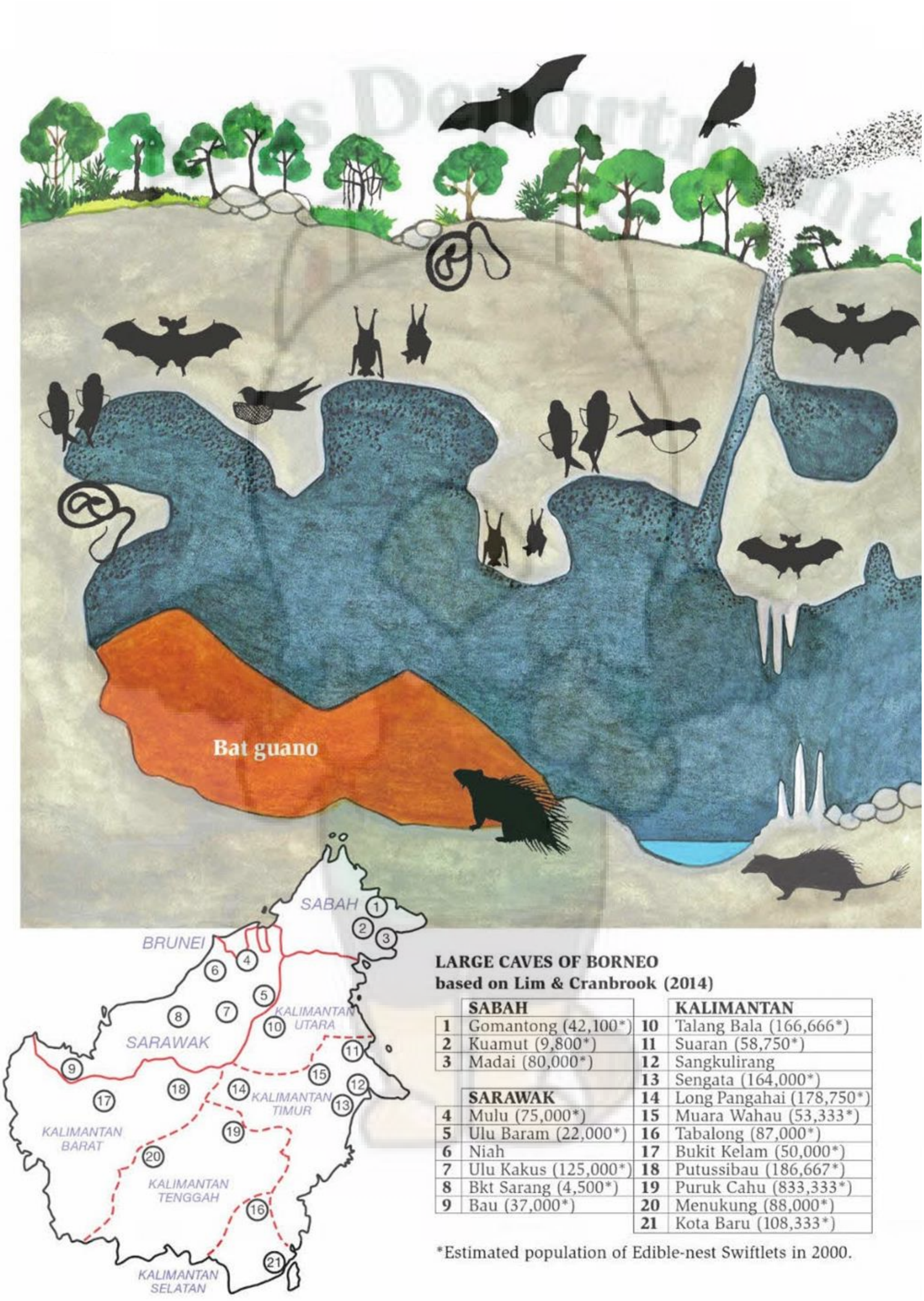
2.1.2 Provision of food, medicine and raw materials

Generally, resources such as food, fiber, and timber are harvested from the karst forest and aquatic ecosystems.

More specifically, many products are extracted from the cave and subterranean ecosystems, like bat guano and edible swiftlet nests. Large populations of bats and swiftlets live in these caves, producing enormous amounts of guano that accumulate on the cave floors. Guano is harvested for fertiliser in large caves on a commercial scale throughout Malaysian, Borneo and the Tropical East Asia region. The Sarawak Museum in Malaysian Borneo operates a cooperative that sells guano harvested from the Niah karsts to fertilise local black pepper fields.

An Asian culinary delicacy, edible birds nest soup, is made from nests built by swiftlets on karst cave walls. In fact, the 15 caves in the Gomantong karst formation in Sabah have an annual yield of five metric tons of nests, which bring in US$2.5 million a year.

Also, limestone is extracted from the karst formations for the production of cement and marble, and other industrial uses.



LARGE CAVES OF BORNEO
based on Lim & Cranbrook (2014)

	SABAH		KALIMANTAN
1	Gomantong (42,100*)	10	Talang Bala (166,666*)
2	Kuamut (9,800*)	11	Suaran (58,750*)
3	Madai (80,000*)	12	Sangkulirang
		13	Sengata (164,000*)
	SARAWAK	14	Long Pangahai (178,750*)
4	Mulu (75,000*)	15	Muara Wahau (53,333*)
5	Ulu Baram (22,000*)	16	Tabalong (87,000*)
6	Niah	17	Bukit Kelam (50,000*)
7	Ulu Kakus (125,000*)	18	Putussibau (186,667*)
8	Bkt Sarang (4,500*)	19	Puruk Cahu (833,333*)
9	Bau (37,000*)	20	Menukung (88,000*)
		21	Kota Baru (108,333*)

*Estimated population of Edible-nest Swiftlets in 2000.

Figure 20: Cave and Subterranean Ecosystem of Borneo

2.2 Regulating Services

2.2.1 Climate Regulation

In karst landforms, the dissolution of limestone forms calcium carbonate, which traps and stores carbon in the long run. Karst forests and vegetation help to reduce the concentration of carbon dioxide in the atmosphere, which helps to mitigate climate change. Jamaica's Cockpit Country has substantial **carbon sequestration** potential due to two main features: (1) the deep sinkholes and (2) densely vegetated limestone hills. Its extensive network of sinkholes, underground rivers and caves allows for rainwater to infiltrate and percolate through limestone, quickening the dissolution process. The wide variety of plants such as Silvertop Fern and Jamaican Dogwood help to absorb carbon dioxide from the atmosphere and convert it into organic carbon compounds, while storing it in their biomass and organic matter in the soil.

2.2.2 Nutrient cycling

The intricate network of underground channels and interconnected caves allows for the transport of nutrients, organic matter, and sediments. As precipitation percolates through soil and limestone, it carries dissolved nutrients such as nitrogen, potassium and phosphorus, which originate from atmospheric deposition and organic matter decomposition. The carbonation-solution of limestone also contributes to nutrient availability through the release of calcium. Sinkholes and underground rivers in karst regions can act as nutrient reservoirs, because of their high water-retention capacity of limestone formations which facilitates the gradual release of nutrients. This prevents nutrient runoff, increasing the productivity and efficiency of nutrient cycling. Microorganisms like bacteria and fungi also contribute via the decomposition of organic matter and symbiotic interactions with plant roots to enhance nutrient uptake.

2.2.3 Hydrological Regulation and Water Filtration

Karst landforms also contribute to water accessibility and quality primarily due to the high secondary permeability of limestone. As precipitation easily percolates through fractures, joints and conduits within rocks, it undergoes natural filtration and purification in an efficient manner to remove impurities and contaminants like suspended silt and organic matter. This improves the quality of groundwater, which is heavily relied upon to supply potable freshwater for local communities. In addition, the carbonation-solution of limestone creates more conduits within rocks, enhancing the efficiency of filtration.

2.2.4 Pollination

In the karst landscapes of Southeast Asia, the cave nectar bat is one of the primary pollinators of many durian and mangrove apple species in Malaysia. Durian flowers that accessible to bats were found to have significantly higher fruit yields compared with flowers that were completely closed to animal visitors or those that could only be visited by insects. This suggests that bats were the primary durian pollinators. A study found out that the cave nectar bat visited more flowers and had longer visits than other pollinators and the study also calculated that bat pollination services were valued at approximately US$117 per hectare per fruiting season.

2.3 Cultural Services

Karst landscapes provide a multitude of cultural services ranging from ecotourism, education, recreation and religion. Many countries have profited from tourism due to the aesthetic beauty of karst landscapes such as the flooded karst towers of Ha Long Bay in Vietnam. We have also learnt about the Gunung Mulu National Park in Borneo, which was named a UNESCO World Heritage site in 2000 and contains the famous Sarawak Chamber and Deer Cave, which are famous for their colony of bats (fig. 20).

Figure 21: Gunung Mulu National Park, Borneo

Caves have been used as places of worship (e.g., by the Buddhists and Hindus) for several centuries. Cultural and religion-based tourism, especially during important festivals held at temples located in karst landscapes, has greatly benefited the economies of Thailand and Malaysia. The state of Sarawak receives more than US$80,000 annually from ecotourism due to conservation efforts in these areas.

One of the more unknown and ancient uses of caves in these karst landscapes of Southeast Asia is for burial sites. 1,000-year-old coffins were found in caves around Sabah made out of very dense, rot- and insect-resistant ironwood or belian trees. On the east coast of Sabah, archaeologists identified 13 cave burial sites with coffins, with the highest density found in the Kinabatangan River valley.

2.4 Supporting Services

Supporting services are the conditions and processes that form the basis for all ecosystems and their services and on which society depends more directly. All ecosystem services are maintained by complex physical, chemical and biological cycles fueled by insolation from the Sun. Karst landscapes support a **high biodiversity** of flora and fauna, both common and endemic.

The slopes and valleys of karsts have greater soil depths which can sustain larger trees, while the steep rocky faces and summits have much thinner soil and are usually colonised by herbaceous plants. Common plant species and limestone obligates (species only associated with limestone karsts formations) found in steeper areas and cave openings include aroids, begonias, pandans, and slipper orchids. For example, in the opening to the Supu Cave in Sabah, the unique Christmas orchid can be found flowering in December. The uniquely adapted venomous cave centipede is a predator and can be found in caves like the Supu Cave. Also, the Halong Bay of Vietnam, the tower karsts can reach 300 to 1600 metres in height, forming solid limestone and soils that support a highly zonal vegetation of tropical evergreen, semi-deciduous forest, broad- leaved and mixed forests. The unique climate, geology and soils also result in an extraordinary abundance and diversity of orchid species.

Karst landforms are hotspots of endemism (Endemic species are found in a single defined geographic location, such as an island, state, nation, country or other defined zone) due to their isolation and are usually populated by highly specialised species with limited dispersal ability (ability to grow at a distance from the mother plant). In Laos, two of the largest limestone karst areas are found in two National Protected Areas (Phou Hin Poun National Biodiversity Conservation Area (NBCA) and Hin Namno NBCA) in the Khammouan Province in a limestone belt 290 km long that stretches from the northwest to the southeast across the entire country. The Khammouan Limestone belt also supports a high diversity of animals and plants, including several globally threatened species, endemic species and karst specialist species. The elusive, almost extinct and critically endangered red-shanked douc langur is thought to live in the Phou Hin Poun NBCA, a landscape comprising more than 50% of limestone karst formations.

3. Negative Impacts of Human Activities on Ecosystem Services provided by Karst landforms

3.1 Quarrying and Mining

Limestone quarrying in Southeast Asia is increasing at 5.7 percent a year, the highest rate in the world resulting in the region's construction boom. The development of roads into mining sites further fragments the landscape, while blasting and heavy metal leakage impact karst formations and degrade their ecosystem services. The destruction of adjacent ecosystems, often by loggers or for agricultural practices, threatens the biodiversity of karsts and their ecosystem services — especially among animals that move to surrounding areas to feed, and can even cause some species to go extinct.

The low light, limited nutrient supply, high humidity and relatively stable temperatures of karst caves create unique habitats for cave-dwelling organisms which in turn have very narrow distributions and small population. Karst caves in China and throughout Southeast Asia are threatened by extractive limestone mining and quarrying for the concrete industry, fracking, commercial guano harvesting, and the poaching of swiftlet nests for edible birds-nest-soup. Quarrying can cause water shortages in surrounding communities and water contamination. The extraction of shale gas in the karst region in southwestern China has caused the core forest area to decrease by approximately 4.0% from 2012 to 2017.

3.2 Agriculture and Deforestation

The conversion of karst landforms for large-scale monoculture plantations can lead to habitat loss, soil erosion, and the disruption of karst hydrological processes. It also increases vulnerability to natural hazards, such as landslides and sinkhole formation. As vegetation cover decreases, the thin layer of soil covering the underlying limestone is slowly eroded via both aeolian and fluvial erosion. This destabilises the soil and decreases the shear strength of the slopes on karst landforms. The frequency and intensity of sinkhole formation also increases, as the construction of irrigation channels can disrupt the natural hydrological flow throughout karst landforms. This is evident in Puerto Rico, where the cultivation of sugarcane and citrus fruits in northern municipalities such as Arecibo and Hatillo have led to increased soil erosion. A study by the University of Puerto Rico in 2008 concluded that soil loss within the Arecibo Watershed occurred at an average of 1.903 tonnes a year. Sedimentation from agricultural practices like excessive plowing can be carried by surface runoff to sinkholes and underground conduits, where deposition can reduce their capacity to transport water, impeding flow patterns of the karst hydrological system. This adversely affects both the quantity and quality of water, due to the decrease in channel storage capacity as well as the pollutants that the eroded soil particles carry. Such pollutants include fertilisers and pesticides which can contaminate groundwater and lead to nutrient enrichment, which poses significant risks to human and ecological health.

3.3 Tourism and Infrastructure Development

Uncontrolled tourism activities can lead to habitat degradation in karst landforms due to the fragmentation and destruction of natural habitats like forests, rivers, caves and wildlife corridors. This disrupts entire forest and riparian ecosystems by reducing the shelter and food available to them. Noise pollution can also alter nesting behaviours of animals while increasing their stress levels, which in some circumstances lead to reduced reproduction and even local extinction. In Halong Bay, a UNESCO World Heritage site in northern Vietnam, the total number of visitors in 2022 reached 11.6 million. According to an urban report by NUS in 2020, pollution from boat traffic and improper waste disposal has degraded the water quality of Halong Bay, especially through heavy metal contamination which has impacted both human health and fragile marine ecosystems. Presently, water sample measurements in Halong Bay show signs of pollution by oil and coliform bacteria, which are attributed to dumping of domestic and industrial waste. In addition, pollutants like cyanide and phenol can be stored in fat, tissue and even marine sediment, thereby highlighting the impact of water pollution on delicate karst and marine ecosystems. When the aesthetic value of a tourism destination decreases, tourists may also be less willing to visit them, which decreases the local economic advantages gained through tourist dollars. Furthermore, infrastructure development catering to tourism such as road expansion and urban development increases the percentage of impervious surfaces. This increases surface runoff while decreasing infiltration and percolation, which can lead to soil erosion and sedimentation too.

Figure 22: Boats in Halong Bay

3.4 Land Subsidence

Excessive extraction of groundwater from karst aquifers causes the water table in underground drainage systems to significantly decline. This creates voids in the drainage systems over time, where the weight of overlying soil and rock layers can collapse and compact the limestone, resulting in land subsidence. Unfortunately, this could directly result in sinkholes and the sinking of ground surfaces, which can pose risks to the stability of properties and human safety. When the structural integrity of infrastructure is compromised, the costs of upkeep will increase while reducing the value of such properties. Underground utilities such as water pipes, sewage lines and electrical cables could also lead to service interruptions or hazardous leaks. In addition, the compaction of limestone can further reduce the storage capacity of karst aquifers, which reduces accessibility to freshwater for human consumption, thereby limiting the ecological service of provision of water.

An example of land subsidence in karst landscapes can be observed in the Yucatan Peninsula of Mexico. In 2015, 1.5 billion cubic metres of groundwater was used for agricultural irrigation, while 300 million cubic metres was used for urban water supply. This excessive pumping of groundwater has accelerated the rate of land subsidence in recent decades, with Merida City in particular facing land subsidence rates as high as 20 centimeters per year. Its physical environment has also suffered loss of wetlands and degradation of coral reefs in the Mesoamerican Barrier Reef System. Furthermore, according to a study by Hungarian researchers from the University of Szeged in 2011, karst water levels can be expected to decrease heavily by 2050 as a result of global climate change, especially in areas of low and mid latitudes.

4 Protecting the Karsts Ecosystems

4.1 Biodiversity Conservation

By designating and managing protected areas around karst landforms, important biodiversity hotspots can be safeguarded. In Sarawak, Malaysia, the Gunung Mulu National Park prohibits logging and strictly regulates tourist numbers, which are enforced by rangers who patrol the park regularly. Community involvement is also present here, with the Sarawak government partnering with World Heritage Site and residents with revegetation programs and to promote conservation knowledge. Local communities in Sabah have built swiftlet houses funded by NGOs to try to develop a sustainable way of obtaining swiftlet nests, instead of poaching them from nearby caves (Figure 22). Nature reserves, national parks, national biodiversity conservation areas, ASEAN heritage parks and heritage site protected areas in karst landscapes in Borneo, Laos and Vietnam have started to ensure a minimum level of protection of ecosystem services in the region. Unfortunately, areas like the Preah

Monivong Bokor National Park near Kompot, Cambodia continue to be threatened by development and extractive mining despite their protection status.

4.2 Sustainable Water Management

By mapping and identifying karst aquifers, buffer zones can be established and pollution sources can be better controlled. In terms of water conservation, efficient irrigation methods and water recycling can be used to enhance the ecological service of the provision of water. This would reduce overall water consumption for agricultural and domestic purposes respectively, while minimising the strain on karst aquifers and groundwater sources.

4.3 Land Use Planning and Regulation

By implementing urban planning strategies which prioritise sustainable development in all three dimensions, ecological services offered by karst landforms can be maximised. For instance, prohibiting construction of residential and commercial buildings in sensitive areas prone to sinkholes or landslides would promote soil stability and more cohesion within nearby ecosystems. The mapping of caves and sinkholes and also help to identify areas where properties and people are at higher risk. More importantly, state authorities could step in to promote sustainable tourism and enforce environmental regulations, while cooperating with transnational corporations to control harmful practices like quarrying, mining and improper waste disposal. In Yunnan, China, the number of tourists allowed to enter Shilin Stone Forest is capped at 10,000 and 5,000 during the peak and non-peak seasons respectively. This aims to reduce overcrowding and environmental damage to surrounding biodiversity, by limiting footfall and trash generated. Guided tours are also mandatory for all visitors, to ensure that visitors stay on designated paths, prevent soil erosion, and to protect sensitive flora and fauna.

4.4 Education and Awareness

Promoting awareness and understanding of the ecological services of karst landforms amongst policymakers and the public alike can foster a greater sense of responsibility and financial support for conservation efforts. Conducting scientific research and monitoring programs to better understand the ecological processes and dynamics of karst landforms can also inform management decisions and support evidence-based conservation strategies. A poll conducted by the Jamaica Environment Trust (JET) in 2018 found that 85% of Jamaicans supported the establishment of a protected area in Cockpit Country, after their public awareness campaign named "Protect Cockpit Country" in 2017. The current Cockpit Country Protected Area now covers 78,024 hectares, while the JET has also worked with school, community groups and local tour operators to raise awareness about the environmental value and unique features of the surrounding karst landscape. This aims to safeguard its rich ecological biodiversity and cultural heritage for present and future generations.

5. SDGs and Karsts Ecosystems

The 15th Sustainable Development Goal (SDG) aims to "protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss". This would include protecting the instrumental value of ecosystem services in karst landforms and maintaining the balance between the physical environment and human systems. The SDGs proposed for aquatic (Clean Water and Sanitation - SDG 6) and terrestrial ecosystem biodiversity and health (Life on Land - SDG 15) have targets for restoring and maintaining ecosystems to provide services associated with karst landforms. Through SDG 6, ensuring access to water and sanitation for all, karst formations must be protected in order for rivers, stream and groundwater aquifers are clean. SDG 15 aims to protect and restore terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and stop biodiversity loss.

A balance must be reached between exploiting natural resources for socio-economic development and protecting ecosystem services that are critical to the wellbeing and livelihoods of communities adjacent to karst landforms. However, this balance is often difficult to achieve and there is no one single method that can be applied to every resource in every location.

Figure 23: Sustainable Development Goals