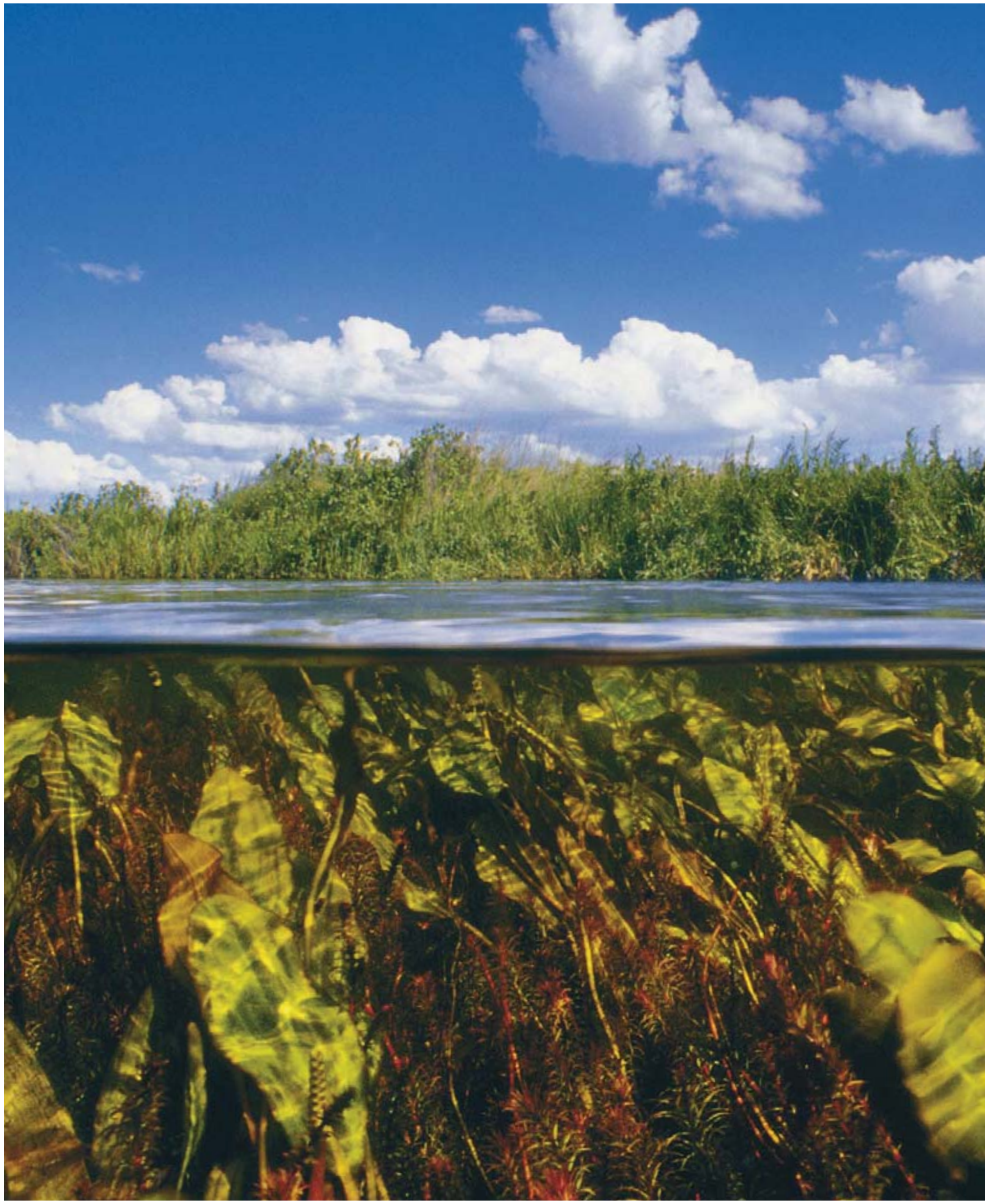


4 The functioning Delta

Some people compare the Delta to an organism. Water enters the Delta through its mouth and oesophagus, the Panhandle. Further down, arterial channels distribute water across the alluvial fan.

Island plants work as kidneys to remove salts. Sediments accumulate as plaque in the channels, later creating blockages equivalent to clots in the arteries. When water is forced to bypass the blockages, new channels are formed which feed water to places that have not recently been flooded. And like body fat reserves, nutrient resources have accumulated in these places over very long periods.[1]

This chapter explores three of these metaphorical systems in some detail. The first is the blood system, to develop an understanding of how water is distributed across the Delta, and how the spread of water varies in time and space. Second, are the processes that remove salts and keep the waters of the Delta fresh. Third, are the fat or nutrient reserves, to see where they come from, how they are stored and how they are mobilised to produce the wealth of life that characterises the Delta.

The flow of water

Flows into the Delta through the Panhandle are usually smallest between September and November when they are about five times lower than the highest volumes of water coming in between March and April **(Figure 13)**. In many years there is also a small, early surge in December or January which is then followed several weeks later by the main seasonal peak. The first pulse comes very largely from the Cubango sub-catchment (*see page 28*) because its flows are rapid and it often receives early rains before a short dry spell in mid-summer, while the later inflows come from both the Cubango and Cuito sub-catchments. Those from the sluggish Cuito contribute progressively more water as the year wears on, especially during winter and autumn. But overall, the two sub-catchments provide roughly equal proportions of all water flowing into the Delta **(see Figure 11**, *page 29***)**.[2]

Seasonal changes in water levels, reaching up to two metres, are greatest in the Panhandle because the spread of water is confined by dense reeds and the elevated margins either side of the Panhandle. From there, fluctuations progressively decline downstream as the water spreads out across the alluvial fans. However, levels along the Kunyere and Thamalakane faults also change substantially during the year because of the damming effects of the faults (*see page 20*).

Having entered Botswana, water takes one to two months to meander through the main 190 kilometre-long channel of the Panhandle from Mohembo to Seronga. And from the head of the alluvial fan at Seronga, the water then takes another two to three months before reaching the lowest, most distal reaches of the Delta along the Thamalakane, lower Kunyere and Khwai Rivers. Flows in the Thamalakane River at Maun are thus highest in July, August and September **(Figure 14)**. The distance along the shortest path of flow from the top of the alluvial fan to the Thamalakane is 210 kilometres.

Water flow is most obvious along the many channels throughout the Delta. These are widest in the Panhandle and in the apex of the alluvial fan, whereas the channels narrow progressively downstream into the fan. They also become increasingly liable to closure and being diverted in new directions, as we shall see below. Flows in the channels are relatively rapid: usually at speeds of 120 to 300 centimetres per second in the Panhandle, 40 to 80 centimetres in the major channels of the alluvial fan, but only 10 to 20 centimetres per second in the small, distal channels.

While water is most conspicuous in the channels, there is also considerable leakage from the channels into the surrounding back swamps and

The gauging station at Mohembo where Botswana measures the volume of water entering the Delta.

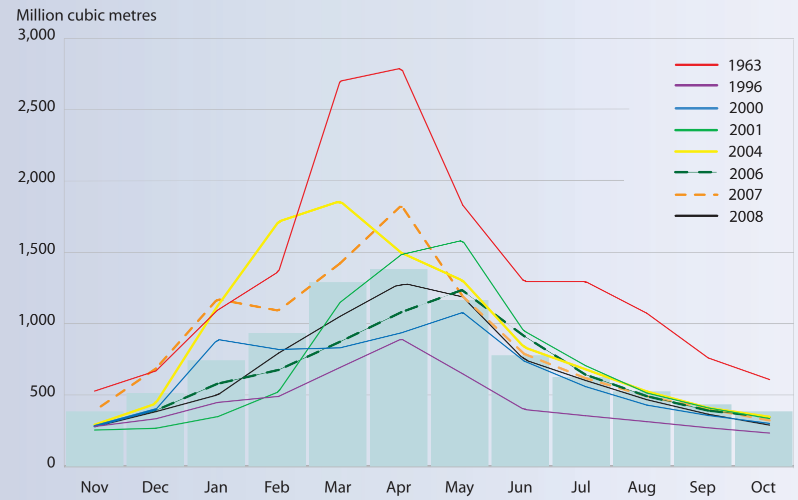


Figure 13 | *Average monthly flows of water measured at the head of the Delta at Mohembo* (blue columns), *and examples of flows each month for a number of years. Note how peak flows are early in some years and later in others, and how flows in the dry season are much more consistent than those during periods of high flow. The highest recorded inflow was in 1963 while the lowest was in 1996.*[3]

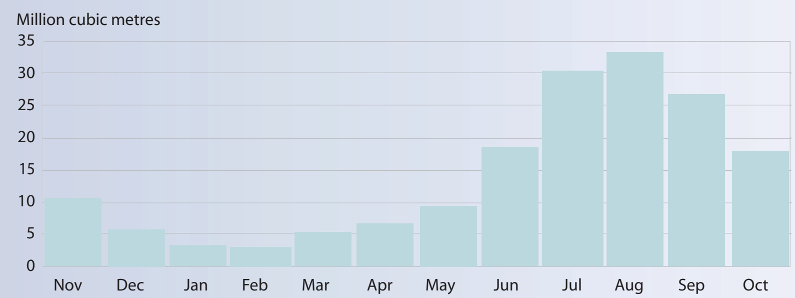


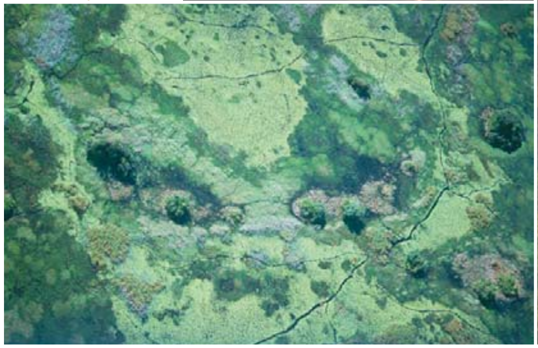
Figure 14 | *Average monthly flows at Maun, showing how levels in the Thamalakane are highest several months after the peak intakes at Mohembo. These are averages, and in many dry years no water reaches the Thamalakane. Note that the y-axis scale covers a tiny range compared to the scale for Mohembo above.*

floodplains. Some of this is through long tunnels maintained by hippos under the papyrus that lead between the channels and isolated lagoons or lakes. But most leakage is through the permeable margins of the channels from where water slowly percolates out through the extensive beds of papyrus, reeds and sedges. Here the flows are extremely sluggish – at less than 1 centimetre per second – as a result of the hindering effects of plants and shallow gradients, which become ever gentler away from the main channels.

Much of the water that filters into back-swamps remains there until it eventually evaporates, is transpired into the atmosphere by plants or seeps away into the ground. The rates of infiltration can be high, amounting to between 10 and 40 centimetres of water per day as a result of the predominance of permeable Kalahari Sand.[4] As we will see, this percolation is a critical first step towards maintaining the Delta as a fresh-water system.

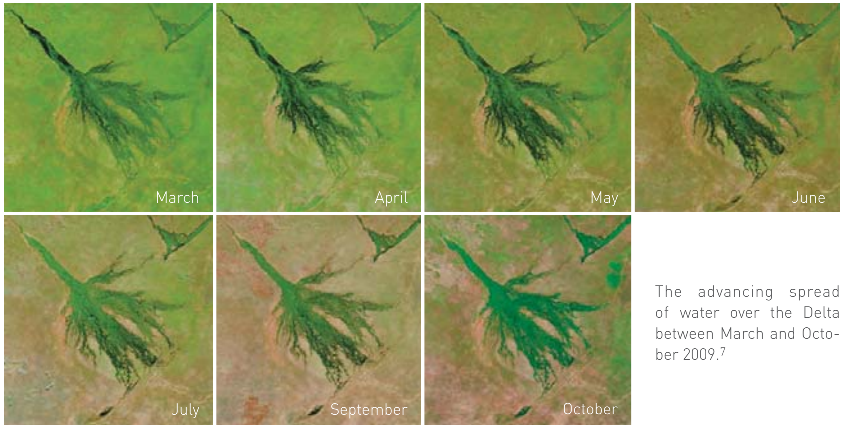
Annual variation in water flow and the extent of flooding

Flows into the Delta have been monitored since 1934. From these records, average intakes amount to 9.3 million cubic metres per year, which is equivalent to 9.3 cubic kilometres of water. The lowest intake of 6 cubic kilometres was in 1996 while the highest of 16.4 cubic kilometers was recorded in 1963 (Figure 13 and 15).[5] This variation is entirely due to year-to-year changes in rainfall in the Angolan catchment.



Hippo tunnels under the papyrus beds aid the distribution of water across the Delta, as do the many surface paths worn by hippos, elephants and other large mammals.

Many lakes or *madiba* (singular *lediba* in Setswana) lie along belts of ancient meandering channels that were subsequently blocked or diverted. The lakes are thus remnants of deep channels, and remain as open water because they are too deep for the growth of reeds, papyrus and other emergent vegetation.[6]



The advancing spread of water over the Delta between March and October 2009.[7]

Two features stand out in Figure 15. One is the high degree of year-to-year change, much of which appears erratic and unpredictable. Years of high flow may be followed with equal likelihood by further good intakes or by very poor flows. The second obvious pattern is the cycles. While these are made clear by the running average line, it is not that easy to determine their length or periodicity by eye. However, statistical analyses of these figures from Mohembo – as well as from rainfall at Maun and in western Zambia, water flows along the Zambezi River, and signatures of climate in stalagmites, pollen and tree rings – indicate that rainfall and river flows follow two cycles: one lasting from 16–18 years and another 60–80 years.[8] It seems that a new period of higher rainfall and greater inflow started during the mid-1990s, but whether this will continue over the next two or three decades remains to be seen.

Volumes of inflow largely determine the extent of flooding or inundation, so the spread of water is limited in years with low inflows, while the biggest and lasting flooding occurs when flows are highest. Examples from the interpretation of satellite images in Figure 16 show how the extent of flooding varies. Data obtained from those kinds of analyses and extrapolations from water inflows indicate that at the height of flooding an average of about 9,000 square kilometres is inundated. However, in 1996, which was the driest year on record, a maximum of about 5,300 square kilometres was under water, while about 15,500 square kilometres was flooded in 1963.[9] These are the extents of flooding at its maximum each year. Areas of inundation range between about 5,000 and 6,000 square kilometres during low water months before the annual pulse of inflow.'

In addition to inflow, the expanse of flooding in any one year is influenced by two other factors. One is the extent of inundation in the previous year, since flood waters spread further on top of existing sheets of water or if the soil is already relatively saturated. Rainfall over the Delta also affects flooding, both by adding to surface inflow from the catchment and by wetting the soil so that less new floodwater infiltrates the sands. Separating out these three influences on the extent of inundation shows that rainfall accounts for 21% of the variation in flooding each year, the extent of previous inundation explains another 1%, while inflows account for the major share of variation: 49%.[10]

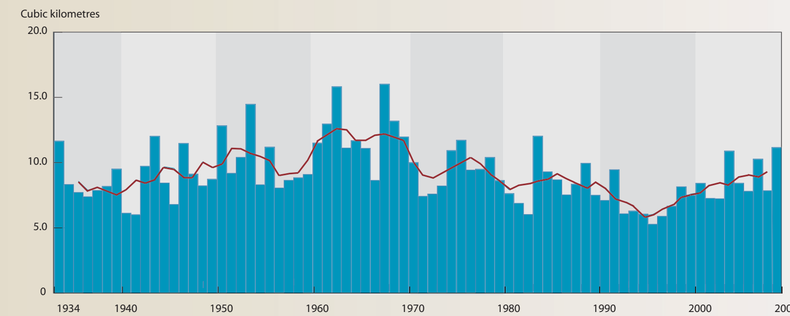


Figure 15 | *The total volume of water entering the Delta each year at Mohembo. The line is a 5-year moving average to help highlight trends and cycles. Note: the flow given for each year is actually the total flow between November of the previous year and October of the given year; in other words from the beginning to the end of each season of inflow.*

Figure 16 | *The maximum extent of flooding each year from 2003 to 2008. Most of the annual variation in the extent of flooding is in the southern and western areas. The eastern areas are flooded more permanently and regularly, by contrast.*[11]

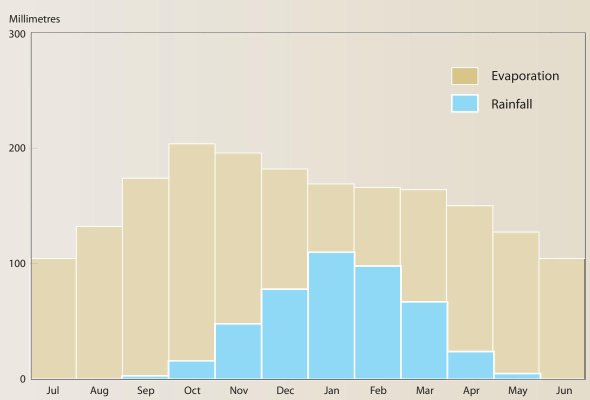
Rainfall in the northern parts of the Delta averages about 550 millimetres per year, whereas Maun and Sehitwa in the south receive about 450 millimetres. Most of this falls during afternoon thunderstorms between November and March (Figure 17). Since this is several months before the annual floodwaters spread across the area, animals and plants in the Delta enjoy an unusually long season of at least some wetness. By contrast, rain-fed wetlands elsewhere in southern Africa only have water for a few months. Biological production in those wetlands is thus limited to much shorter periods than in the Delta.

Rain is of particular importance as the main source of water for the growth of dryland vegetation scattered in and around Delta. Thus, the growth of grass and many other plants depends on precipitation. Numerous pans and pools in these areas are only ever filled by rain, and they often hold the only available fresh water for many miles around. The length of time the pools hold water depends largely on the amount and frequency of rainfall. Those that fill after sporadic heavy falls during spring usually dry up quickly if further rain does not fall, since evaporation rates are also highest in early summer (Figure 17).

Of all the water entering the Delta, an average of only 2% ever leaves as surface flow. Much of this is down the Boteti River, but significant losses can occur along the Kunyere River into Lake Ngami and Khwai River into the southern areas of the Mababe Depression. These outflows only happen during good years when flood waters reach that far south. Similarly, only about 0.2% of water ever sinks into the deeper groundwater. Of the remaining 98%, about 74% evaporates directly from surface waters, with the highest rates of evaporation being in spring and early summer (Figure 17). The other 24% is also lost to the atmosphere, but only after first percolating into shallow ground waters and then later being transpired by island plants, as discussed below.[12] It is the predominance of permeable Kalahari Sand that allows so much water to percolate and be available for the growth and transpiration of island vegetation.

Most of the water flow down the Panhandle is along a single, main channel. Upon reaching the alluvial fan, the channel splits into four main distributaries, from east to west, the Selinda, Nqoga, Jao and Thaoge channels. These channels then split into further distributaries downstream (Figure 18). However, flows are not divided equally between the four main channels, and

Figure 17 | *Average monthly rainfall and evaporation at Maun. While rainfall varies greatly, evaporation rates are rather similar from year to year. The overall aridity of the environment around the Delta is more an effect of high evaporation than low rainfall. Thus, total evaporation at Maun – at 1,884 millimeters per year, on average – is almost four times the average rainfall of 448 millimetres.*



Most of the Delta's rainfall buckets down during dramatic afternoon thunderstorms.

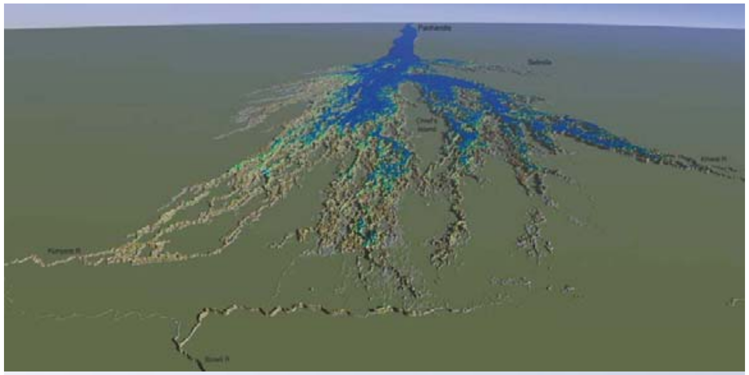


Figure 18 | *A model of flooding frequency based on an analysis of satellite images taken between 1989 and 2007.[13] Places that were inundated most often are higher and bluer than those that seldom received water.*

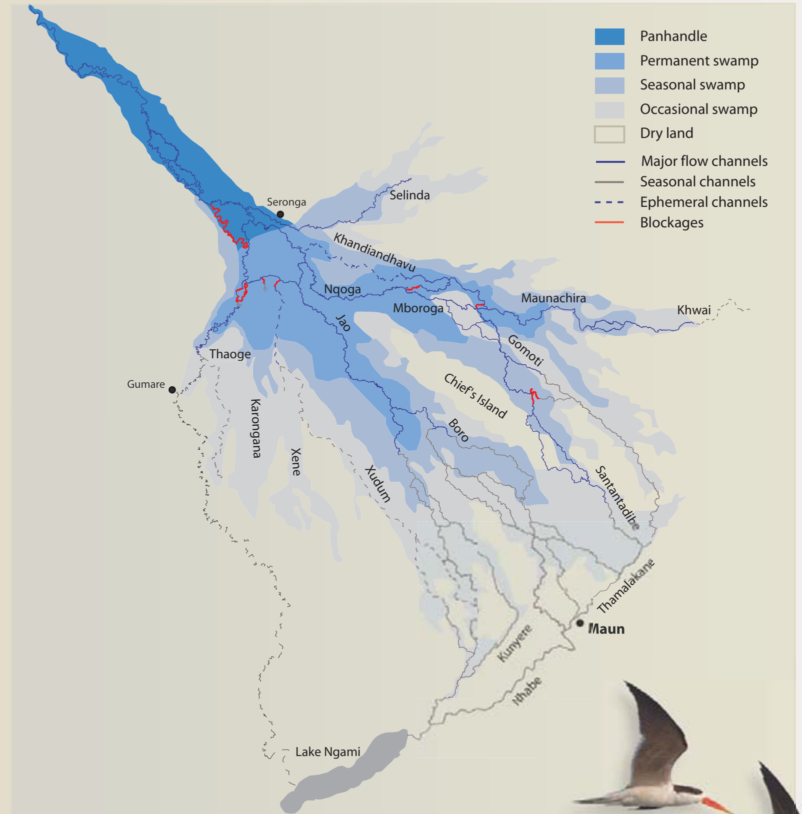
therefore do not radiate out equally across the alluvial fan. In recent decades, most water has flowed to the south-east into the Nqoga, Mboroga, Manuchira and Khwai areas north of Chief's Island, and also into the central Jao and upper Boro. By contrast, flows north-eastward to the Selinda channel and south into the Thaoge and Karongana areas have usually been weak, and have only occurred in years with exceptional floods.

There are two reasons for the unequal distribution of water from the head of the fan. One is the result of blockages, especially along the Thaoge (Figure 19, and see the account below of how these obstacles redistribute water). Another factor is the current location of the main Panhandle channel close to the eastern ridge that separates the permanent swamps from the higher adjoining woodlands. As a result, water percolating eastwards out of the main channel soon dams up because it can't spread beyond the ridge. However, there are no immediate barriers on the other side where large volumes of water can filter out of the main channel to make their way slowly west and then south. What this means is that flows to the west and south first have to permeate through extensive reed beds before reaching the southern extremities of the Delta. By contrast, flows to the south-east and east are more channeled and regular, and therefore sustain large areas of permanent swamp north and south of Chief's Island.

The changing distribution of water

The broad zones shown in Figure 19 reflect flooding conditions seen in recent decades. While these conditions change seasonally, the changes are usually rather predictable as flows from Angola rise and fall. But events and processes occurring within the Delta also alter the distribution of water, but they do so in ways and directions that are largely unpredictable! These unexpected changes result in wetting and drying that are markedly different from those experienced normally. Expanses of swamp may suddenly dry up when water diverts elsewhere, for example, and new floodplains may develop in places that have been arid for decades.

Most distributional changes are due to blockages of channels which forces water to take new directions. Sites where major blockages are known are shown in Figure 19, but those on the



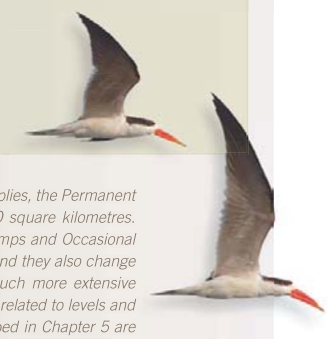


Figure 19 | *The main channels and flood zones of the Delta. As the name implies, the Permanent Swamps hardly vary in size from year to year and usually cover about 3,000 square kilometres. Annual changes in the extent of flooding are thus largely in the Seasonal Swamps and Occasional Floodplains. Boundaries between these two zones are usually hard to define, and they also change during wet and dry phases. For instance, the Seasonal Swamps become much more extensive during repeated years of high inflow.[14] Vegetation growth and types are closely related to levels and frequencies of inundation, and so the categories of plant communities described in Chapter 5 are closely linked to these zones.*

Thaoge provide the most impressive example of what happens once a channel stops flowing. Up until 130 years ago, much of the water entering the alluvial fan flowed down the Thaoge and its distributaries, thus regularly flooding what are now the dry grasslands of the western half of the Delta. Flows down the Thaoge also reached and filled Lake Ngami. Indeed, Charles Andersson boated up the Thaoge from Lake Ngami for 13 days in August 1854, travelling an average speed of eight kilometres per day.[15]

Then in about 1883 and 1884, the Thaoge became progressively blocked by accumulations of floating vegetation – or sudd – and encroaching vegetation, especially papyrus. And despite numerous attempts to open and canalise the channel it still remains largely dormant.

Probably as a result of flows along the Thaoge being halted, flooding to the east then increased, raising water levels in the Maunachira, Mboroga and Santantadibe. However, the northern reaches of the Mboroga became blocked in the 1970s, which then led to reduced flows into the Santantadibe and Gomoti, but also greater inputs to the Khandiandhavu, Maunachira and Khwai distributary areas.

At least some of Lake Ngami's former glory has now been restored through a new feeder. In about 1996, flows into the Xudum and Xene began and have continued to increase until the large inflow from Angola in 2004 eventually pushed water down the Kunyere River and into the Lake (Figure 20).[16] Just what caused increased flows into the Xudum and Xene is

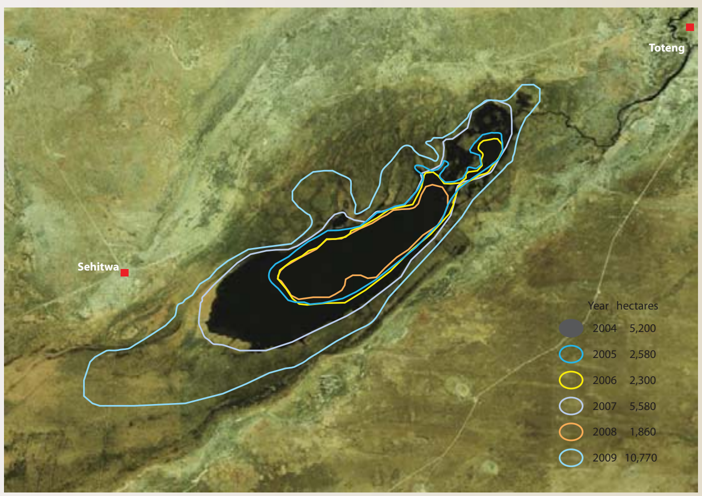


Figure 20 | *The black expanse is water in an image of Lake Ngami taken in September 2004, which was the first year that the lake had had water since 1989. Levels of the lake were lower in 2005, 2006 and 2008, rather higher in 2007 and then much higher in 2009, as shown by the lines marking the expanse of water in each year.*[17]

unknown, but many people speculated that it was due to a small tectonic event. This is quite likely in such a flat landscape, where a shift of a few centimeters up or down could cause flows to speed up or slow down considerably. Nevertheless, firm evidence has yet to be found for tectonic movements causing recent distributional changes anywhere in the Delta.

The best explanation for changes in flow directions starts with, and rests on the fact that almost all the solid, sandy sediments carried in from Angola remain in, and close to the beds of channels. Here, the solid, mostly quartz grains are gently rolled along as far as the speed of water permits. However, speeds slow as increasing proportions of water leak out of the channels, and this causes more and more sediment to be deposited and the channel beds to rise in a process called aggradation (see Figure 21). Dense margins of papyrus stabilize the position of the rising channels, thus preventing them from shifting to lower adjacent ground. And as the water slows even further, papyrus growth impinges on the channels and floating sudd and debris increasingly get stuck in the channels.

As blockages become more and more impermeable, water in the channel is dammed and starts to rise. At some point, it breaks through the walls of the channel upstream of the obstructions, and makes its way along newfound courses into the surrounding, lower-lying floodplains. This is known as channel avulsion. It is widely held that these new courses often follow the paths worn through the swamp vegetation by hippos. However, fire almost certainly plays a major role in charting new directions of flow by burning away elevated levees of dry papyrus. Large channels may thus be diverted into new waterways which go off in quite different directions.[18]

Other factors thought to cause flows to change direction include the subsidence of the ground, perhaps as a result of tectonic shifts, and simple damming due to the build-up of floating sudd and encroachment of aquatic plants without the aggrading effects of sediments.

Changes in the distribution of water often cause annoyance, especially when water no longer reaches places that have enjoyed consistent flooding and flows. Those affected, for example villages that lose fishing grounds or lodges that no longer have access to channels, observe the losses as permanent and sometimes blame other people who use the Delta.

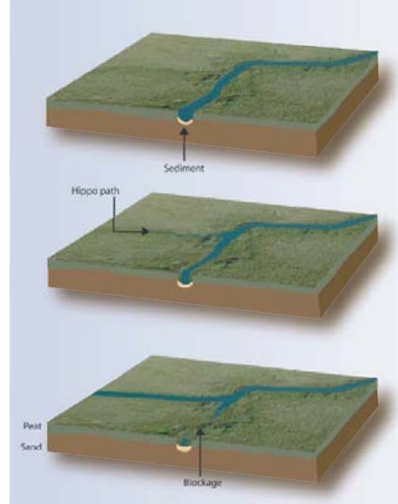
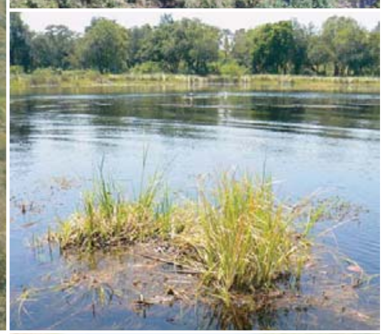
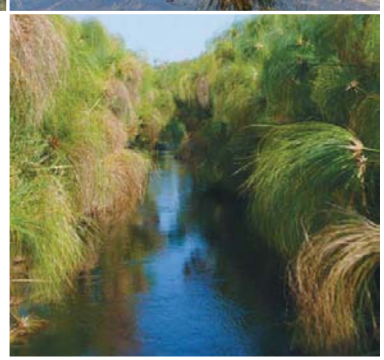


Figure 21 | *Snapshots during the development of a blockage along a channel and the subsequent diversion of its flow along a newly formed channel. Note the rising levels of sediment and the narrowing of the main channel, and the development of the blockage as the speed of flow decreases.*

However, such changes are normal and temporary in the longer term.[19] The changes are also inevitable in this flat, aggrading landscape and they contribute to the greater productivity of the Delta. Indeed, significant features of the Delta are consequences of the distributional changes:

- Habitat diversity is increased
- Habitats change rapidly
- As a result of drying, nutrients trapped in aquatic plants are released for use by other organisms
- When inundated, nutrients lying dormant in sediments are mobilised into new cycles of production (*see page 62*)
- Once flooded, mounds built by termites become islands on which transpiration by trees helps to concentrate salts and thus maintain the fresh waters of the Delta





The blockage of water flow and its redistribution to other areas of the Delta is crucial to the functioning of the Delta. Sudd (*2nd from bottom right*), encroaching papyrus (*bottom right*) and floating debris (*2nd from top right*) all help clog channels, which later become overgrown by papyrus and other aquatic plants (*top right and bottom left*). The channels are also raised as a result of sediment deposition so that they later stand above the surrounding floodplains (*top left*).

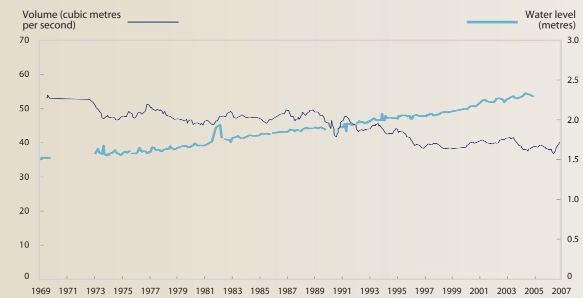


Figure 22 | *The gradual build-up of the Nqoga channel at Gaenga between 1969 and 2007. Rates of sand accumulation can be substantial, perhaps as much as five centimetres per year, or half a metre in 10 years. Water levels then rise* (right axis) *causing the volumes of water discharge to decrease* (left axis).[20]

The quality of water

Anyone visiting the Delta or using its water must be astonished at its clarity and purity, qualities that stem from the nature of water coming off the catchment (*see page 32*). Here, few particles or nutrients are available to be washed into the Okavango River and, in any case, dense barriers of aquatic plants trap much of any material that does get into the river. To put the purity in context, the conductivity of water entering Botswana is 15–20 times lower (i.e. better) than would be classified as *Ideal* water for drinking, and about 40 times better than water of *Acceptable* quality, as established by standards of the Botswana government.

Conductivity is a measure of the quantities of salts and other solids dissolved in water. Of course, there are other dimensions to water quality, such as its colour, odour, turbidity and acidity but, again, all the monitoring work done so far indicates that the inflowing water is exceptionally clear of dissolved and suspended materials. Average pHs of between 5.9 and 7.6, or near neutral, are measured throughout the Delta. Slight acidity or alkalinity is sometimes detected locally and is usually the result of the decomposition of organic matter or of concentrations of algal growth, respectively.

These comments refer to concentrations of chemicals and particles, and not to the quantities of material swept into the Delta. These are indeed substantial when the tiny concentrations in the huge volumes of water are added up. In fact, an estimated 170,000 tonnes of bed load (mainly minute grains of quartz sand), 30,000 tonnes of suspended material (largely clay and organic matter) and some 381,000 tonnes of salts are carried down the Okavango River each year.[21] What happens to all these tonnes?

Because water speeds are so slow in its meandering channels, about 90% of the sandy bed load settles in the Panhandle, while most of the remaining 10% is deposited close to the head of the alluvial fan. Much of the lighter matter in suspension also remains in the permanent swamps of the Panhandle and at the top of the alluvial fan. That entrapment and the fact that so few clayey particles come down the Okavango River is crucial in retaining the permeability of Delta's substrate.[22] Lots of surface water can therefore sink into the groundwater which then allows for the concentration of salts beneath islands, as described below. For example, rates of infiltration in one seasonal floodplain ranged between 45 and 54 millimetres of water per day, which was 9 to 10 times higher than the amounts of water lost by evaporation.[23]

Most dissolved salts eventually permeate through the sandy substrate and into the groundwater. This happens after they have been distributed by surface waters, and their concentrations increase progressively as a

Water almost everywhere in the Delta is so clear and clean of salts, nutrients and floating particles that it surpasses the quality of bottled water.

result of surface evaporation. Concentrations in samples steadily increase by an average factor of 10 between the head of the Panhandle and the distal reaches of the alluvial fan in the south-east. But in terms of conductivity, even the highest concentrations found at the bottom of the Delta are similar to those found in most bottled water.

Quantities of nutrients in the inflowing water are likewise very low. Most nitrogen, phosphorous, sodium and potassium, for example, is quickly absorbed by papyrus and phragmites reeds growing in the Panhandle and along the main channels at the base of the alluvial fan. Very small amounts of these elements therefore make their way to the seasonal and occasional floodplains. Here, most biological production is fed by nutrients that accumulated in their sediments over long periods (*see page 62*).

While the waters of the Okavango are usually clean and clear, local conditions of impurity sometimes develop. For example, high concentrations of salts may develop as a result of evaporation in pools that are isolated from the main Delta flows. Water percolating through the papyrus beds in the Panhandle is sometimes so depleted of oxygen as a result of aerobic respiration by bacteria, that substantial numbers of fish die (*see page 102*). And with the growing number of people living in and around the Delta, the chances of local pollution escalate, particularly in places where people are concentrated, such as at Maun and along the Panhandle (*see page 115*).

Maintaining water quality: permeable substrates, islands and sinking salt

Makgadikgadi and Etosha are open expanses of salty sediments. Why did yet another pan not form here, perhaps called the Okavango Pan? Three separate processes – all of which have to do with the removal of salts – explain the anomaly of the freshwater Delta in this arid region. The combination of these processes in one place is probably unique in the world.[24]

The first process involves the very high rates of water infiltration made possible by the limited intake of clay from the catchment and the permeability of the Delta substrate. The large volumes of water that disappear into the ground therefore carry and remove salts from the surface water.

The second process stems from the abundance of islands within the Delta on which trees and other woody plants grow. In all, there are about 150,000 islands covering a combined area of some 4,500 square kilometres. Most are tiny, consisting of just a few square metres, but others extend over hundreds of hectares; an estimated 43,000 islands are larger than 50 by 50 metres.[25] These numbers and areas provide places to grow for very many trees which draw water out of the ground and then transpire it through their leaves. As the water is pumped up through the roots, water levels beneath the islands drop, causing a substantial gradient (of 1:100 to 1:200) between groundwater levels below the surrounding floodplains and those under the islands (Figure 23). The water – accompanied by its salts – thus flows laterally and continually from

Xigera lagoon is the most prominent and last major site of sand deposition as water flows down through the alluvial fan. The sand settles and forms a mini delta because the speed of flow immediately drops when the water enters the lagoon.

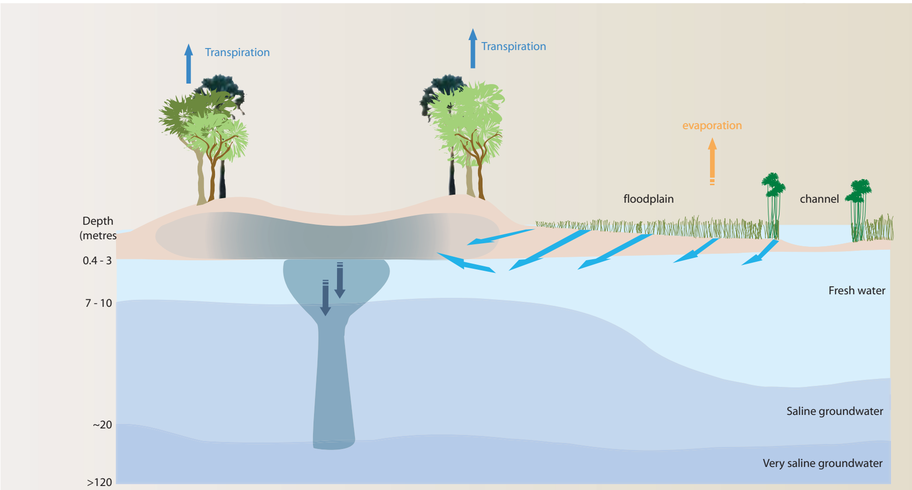


Figure 23 | *A horizontal cross-section through an island and its surrounding floodplain. Note the higher margins of the islands formed from deposits of calcium and magnesium carbonate and the accumulation of organic debris beneath the trees and shrubs. Few plants can tolerate the very salty soils in the island centres. It may take 200 years for an island to grow from a small copse of trees and shrubs into one looking like an atoll with a barren centre.*[26]

beneath the floodplains to below the islands. In essence, this second process moves salts from the floodplains and concentrates them below island vegetation.

The rates of concentration are considerable. For example, chlorine in water below the islands is 500–1,000 times more concentrated than floodplain surface water. According to their chemical properties, different salts and elements react differently once they are concentrated. Magnesium and calcium are precipitated into solid calcrete carbonates, while precipitates of silica and potassium form clayey soils that are between 3 and 10 metres deep below the islands. Dissolved organic carbon and sodium bicarbonate remains in solution in the island groundwater, but as their concentrations increase, sodium bicarbonate crusts may form on the surface and the island centres become too saline for most plants. As a result, most trees only grow on their margins, leaving the central areas of islands to grasses and a few palm trees that tolerate the salty soils.

Most islands are thought to originate as termite mounds on which copses of trees grow when the mounds are later flooded. The islands then expand and continue growing as more and more clayey deposits and calcretes are added to their volume. Organic matter, such as leaves, that accumulates beneath the trees further contributes to their growth. While some islands remain small and rounded, reflecting their origins as termite mounds, others have grown and merged with other islands into large, irregularly shaped areas.

The majority of the approximately 150,000 wooded islands are in the occasional floodplains where they make up about 50% of the area. By contrast, about 25% of the seasonal swamp area and only 5% of the permanent swamps are covered by islands. Most islands grew from termite mounds (*bottom left*), but others formed on ridges where old channels were raised by aggradation above the swamps. The relics of the channels are now visible as lines of islands (*second from top left*).

The third and final process in removing salts from the Delta also occurs below the islands. Once particularly high concentrations are reached, the saline groundwater becomes denser, and therefore heavier, than the water which lies further down. 'Density fingering' then occurs as the hyper-saline water sinks down to much deeper levels.[27] This is the final fate of dissolved salts that originated hundreds of kilometres away in Angola.

Of the estimated 381,000 tonnes of dissolved material entering the Delta each year, 56% eventually turns into precipitates that expand the islands while another 38% will later sink away as very saline water. The small remaining fraction of 6% is carried off down the Boteti River during its sporadic flows.

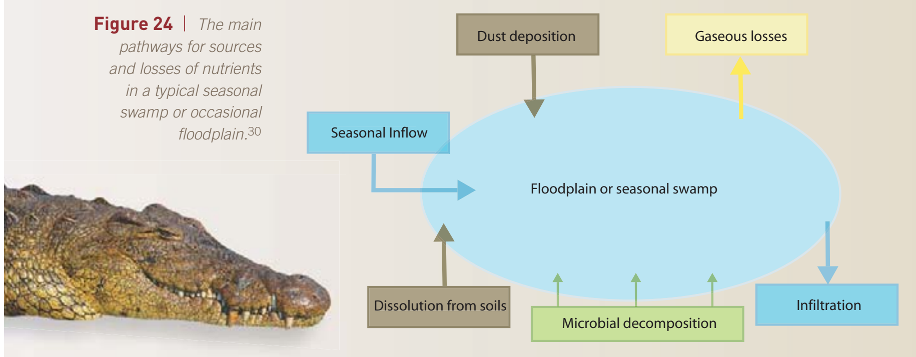
Nutrients

There are many aspects of the Delta that are odd. This is an oasis in a semi-desert of sand, and it is a body of water that remains fresh even though 98% of the water evaporates. Another peculiarity is that living organisms are abundant despite the fact that few nutrients enter the Delta. A measure of this wealth is provided by the number of large mammals. Based on the carrying capacity of soil and rainfall conditions at different places elsewhere in Africa, northern Botswana should be able to sustain about 1,200 kilogrammes of large mammals per square kilometre. In reality, however, the biomass of large mammals in the Delta is almost 10 times higher.[28]

Clearly, there is more to support so many animals than meets the eye. But without special equipment, eyeing the abundant nutrients that feed so many animals and plants is difficult. In addition, research on nutrients has been rather limited; while we have a pretty clear idea of the water budget, the food budget of the Delta has not been well documented.

Three nutrients are essential to all plants and animals: carbon for building bodies, nitrogen for proteins and phosphorous for the molecule ATP (adenosine tri-phosphate; also called the 'universal energy currency of life') which stores energy produced during respiration. Although other nutrients are required for metabolism and growth, it is these three elements that are needed in the most significant quantities. They are thus more routinely monitored than other nutrients, and these measures provide indications of the overall nutrient status of the Delta.[29] Since carbon is usually less constraining on production than nitrogen and phosphorous, it is these two nutrients, and particularly phosphorous, that often limit the growth and reproduction of plants and animals everywhere.

Figure 24 | *The main pathways for sources and losses of nutrients in a typical seasonal swamp or occasional floodplain.*[30]



Nutrients are cycled and recycled between sediments beneath the floodplains, living swamp vegetation, peat and surrounding woodlands.

Sources and losses of nutrients

Although nutrients are limiting, how so much nitrogen, phosphorous and carbon came to be in the Delta has yet to be fully explained. However, there appear to be five main sources (Figure 24). The first is the Okavango River. While nutrient concentrations in its waters are tiny, they add up to significant amounts when the volumes of water that have come to settle on the sediments over hundreds and thousands of years are considered. The concentrations of nitrogen and phosphorous measured at Mohembo are typically in the order of 1–2 and 0.0–0.1 milligrams per litre, respectively. There are no significant seasonal changes in the concentrations.

Aerosols are a second source. The Delta happens to be located in a zone where anti-cyclonic conditions often prevail, and air laden with dust then subsides. This happens particularly during the dry winter months that coincide with flooding. As a result, an estimated 250,000 tonnes of dust (or 570 grams per hectare) are deposited each year on the Delta.[31] Significant quantities of nutrients come with the dust, and these may contribute up to 40% of all nitrogen and 60% of phosphorous added to the Delta.[32] The aerosol nutrients settle both on water surfaces, where they may dissolve and immediately become available to biological processes, and on dry land, where they dissolve later when flooding occurs. It is almost impossible to separate out those that settle on dry land from a third supply, which is that comprised of nutrients that dissolve out of soil particles. However, this third source is probably of minor significance because inert grains of quartz comprise much of the sandy soil.

Fourthly, nutrients are made available by microbes, such as diazotrophic bacteria living on the roots of floodplain

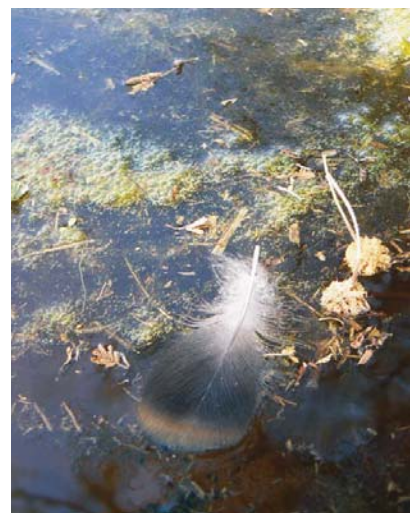
Nutrients are added to the Delta's water in the form of faeces produced from food obtained in the surrounding dry woodlands.

Peat fires are not often seen but they play a crucial role in releasing nutrients that are bound up in the organic debris of which peat is largely comprised.

vegetation. They convert gaseous atmospheric nitrogen into ammonia and other forms which can be used by living organisms. Blue-green algae likewise fix nitrogen in water, and bacteria associated with the roots of the common rice grass *Oryza breviligulata* probably also fix nitrogen. Mycorrhizae of fungi found in and among roots convert ions of phosphorous into forms that can be used by plants.[33]

Finally, nutrients are imported in the faecal matter of animals that visit the Delta. This happens most often and typically by animals that drink regularly after long bouts of foraging in the surrounding woodlands and dryland pastures. Obvious examples are elephants, cattle and impala, of which there are very large numbers (*see page 106*) that dump considerable volumes of faeces and nutrients into the Delta on a daily basis. But conversely, smaller amounts of nutrients are lost when animals that have fed on aquatic food leave and defeacate elsewhere.

One of the reasons that phosphorus is so limiting is that much of it is held in insoluble compounds bound to such elements as iron, aluminum, calcium and manganese, and also to clay. Other insoluble phosphorus lies trapped in the decayed remains of microbes, animals and plants.



The relative importance of each of the nutrient sources varies across the Delta, both in time and space. For example, inflowing nutrients contribute most to production along channel margins, especially in the Panhandle. In the back-swamps, more nutrients are supplied by aerosol sources and by the limited breaking down (and thus recycling) of organic molecules bound into peat. On seasonally flooded plains, soil nutrients are the prime source once the floodwaters arrive, but deposits from dust become increasingly important as the season wears on. Production in occasional swamps probably depends largely upon nutrients lying dormant in the sediments, having accumulated there over long periods from various origins: aerosols, mineralized plant matter and faeces, for instance.

The overall abundance of nutrients means that the Delta is a sink, with more nutrients having accumulated here than have left. The losses may, nonetheless, be significant, particularly through fire which can accelerate the rate at which nitrogen is lost to the atmosphere as a gas, and through the leaching of phosphorus into deep sediments. Considerable quantities of organic carbon and phosphorous also disappear in the flow of water from floodplains to beneath islands where the nutrients remain trapped in the very saline groundwater and clays.

Dung beetles help to release nutrients originally locked into plant matter for new cycles of animal and plant production.

Nutrient cycles and uses

Most nutrient losses are, however, temporary in the sense that nutrients become locked into reservoirs where they are unavailable to new rounds of biological production. There are two principal reservoirs in the Delta: living plants, and dead peat and detritus. Nutrients locked into plants are recycled when floodwaters dry up and the plants die. This happens seasonally in areas that are inundated each year, but also in permanent swamps where large nutrient stocks are held in the expanses of papyrus, phragmites reeds and other aquatic plants. These only die off when channels change course to switch the flow of water to other places. Once the swamps dry, their degradation is often hastened by fires that burn the desiccated plants (*see page 84*). On a smaller scale, nutrients embedded in plants also are released by grazers, especially the very abundant lechwe and buffalo (*see page 106*). Dung beetles and other insects that consume manure are the first to use these nutrients, which then get cycled into other organisms that eat, parasitise or decompose the insects.

Peat in the permanent swamps holds even greater volumes of nutrients than the green vegetation above, since peat consists of dense masses of decomposed roots, rhizomes, charcoal and other organic and inorganic detritus.[34] However, nitrogen and phosphorus in peat is largely present in the form of organic compounds which cannot be readily used for growth and reproduction. Further recycling is thus needed before they are available as ammonium, nitrates and phosphates. While some of this is achieved by aerobic actinomycetes bacteria and fungi that also break down cellulose into carbon, most of the nutrient pool is only released once peat is dried or burnt.

Thus, great quantities of potential food remain inert in various forms in the Delta. The most impressive and final release of nutrients into blooms of production occurs when water reaches the seasonal and occasional floodplains.[35] The soils of the floodplains contain huge numbers of spores of anaerobic bacteria that spring to life when the waters arrive. By decomposing detritus, the living activated bacteria produce and release carbon and soluble nitrogen and phosphorous into the floodwaters. Diatoms and other phytoplankton blossom, aquatic plants grow rapidly, and eggs that have lain dormant in the sediments hatch and develop into dense swarms of zooplankton (*see page 100*). Fish migrate into the temporary waters, spawning to produce large numbers of fish fry which feast on the zooplankton. In turn, these and the fingerlings feed countless frogs, birds and predatory fish. As the flood continues and later abates, the frogs and birds breed quickly to produce new generations, surviving young fish swim back to populate the main channels and waters of the permanent swamps, while nutrients parcelled in the bodies of insects, herbivores and other animals are redistributed elsewhere to add life to the Delta.

To conclude

It is mainly in the seasonal swamps and occasional floodplains – where the aquatic and terrestrial worlds meet – that the Delta comes to life, and its wealth is produced. The annual pulse of water mobilises nutrients which, in turn, are largely provided by the terrestrial environment. The pulsing happens regularly in the seasonal swamps and episodically in the occasional floodplains in a great number of places over a wide area. An ever-changing patchwork of different levels of nutrients, at different stages of biological succession is thus created. And all of this is aided by the extended period of water availability due to rain and flood waters being received at different times.

Wetting is thus important, but so is drying. Without desiccation, most nutrients would not be released from living plants and peat. Changes to the distribution of water make much of the drying possible and, likewise, the switching of channels allows water to inundate new ground. Most biological production occurs in places that have lain dry for some years after periods of repeated flooding in the past. The most productive sites have long histories of flooding because each flood added more nutrients that were washed in, trapped from aerosols or dropped by animals attracted to the water. When the water dries and aquatic plants die back, the nutrients lie embedded in soils and detritus, waiting – as it were – again to be mobilised into production when catalyzing water next arrives.

The wetting, drying and consumption of the Delta's larders. After the arrival of flood waters, mats of algae and emergent aquatic plants cover Lake Ngami (*left top and middle*) and water among trees near the Gomoti River (*right top*); masses of birds feeding on fish trapped in a shrinking pool, isolated as the seasonal swamps dry up (*right bottom*); and the receding waters that lead to the death of plants and recycling of nutrients (*left bottom*).

Concentrations of greenery close to channels are due to those plants having better access to nutrients in the channels than those growing in the more sterile backwaters.

Central to the abundance of life in the Delta is this shifting kaleidoscope of water and land, with water enabling plants and animals to use larders of nutrients to grow and reproduce. Each year, floodwaters bring life but then recede so that nutrients are returned to the soil, ready for further bouts of production in the years ahead.

Because the distribution of water changes so frequently, many plants and animals have evolved opportunistic strategies. Those that are able to shift to new supplies of water do so, making the move as quickly as possible. Those that can't move, lie in wait for years, perhaps decades. And they lie waiting in a variety of forms: as eggs, seeds, spores, pupae or as aestivating, slumbering adults.

One of the best places to see and learn about episodic production is at Lake Ngami. As an outlier on the most distal margins of the Delta, the lake has often been dry. But there have also been long periods of inundation which led to the accumulation of huge nutrient reserves in its sediments. These are now augmented by the manure of cattle herds that graze around the lake, and wildlife doubtless did the same before the area was populated by stock farmers. Cattle now also graze the aquatic grasses in and around the lake, thus returning nutrients to the soil that would otherwise be trapped in vegetation. The lake waters are thus highly productive as a result of these processes that accumulate and recycle nutrients. When flooded, Lake Ngami attracts more birds than any other wetland in Botswana. For example, 5,200 white pelicans, 20,000 red-billed teal and 3,000 little egrets were counted there in 2004,[36] and the Lake supported a vibrant fisheries industry during the 1970s. The Mababe Depression is certain to be equally productive when its waters again return.

Several processes must be conserved if the Delta is to remain as productive as it now. The first is the necessity of seasonal pulses of water flow to maintain the wetting and drying that mobilize and release stocks of nutrients. Secondly, the distribution of water has to keep changing, which means that the agents that cause the redistribution of flow (papyrus growth, fine sediment accumulation and hippos) have to keep working. Third, processes that make this this an oasis of freshwater need to be sustained, for example by ensuring that inflows of suspended clays do not increase and escalating elephant populations (*see page 87*) do not decimate the riparian trees that transpire large volumes of water from islands.

These kinds of cautions come from an understanding of processes that mould the organism we call the Okavango Delta. Other cautions will be offered later in the pages ahead, and understandings of different processes will emerge as a result of further research in the years ahead. People charged with caring for the health of the Delta must be good physicians, basing their diagnoses and treatments on the best knowledge.

KEY POINTS

1. Annual pulses of water entering the Delta reach peak levels in March and April when inflows are about five times greater than the lowest discharges in October and November. The March/April pulses then take several months to flow down the Panhandle and spread across the alluvial fan.
2. Flooding thus occurs in the dry winter months after the summer rains, and life in the Delta enjoys much longer periods of water supply than other freshwater wetlands in southern Africa.
3. Inflows and the extent of flooding change substantially from year to year – and also between longer wet and dry cycles – as a result of varying rainfall in the Angolan catchment of the Okavango River.
4. The biggest floods cover about three times more of the alluvial fan than the smallest floods. The expanse of flooding is not only influenced by inflow, but also by rainfall and the levels of inundation during the previous year.
5. The confinement and deposition of sand in the channels leads to their beds rising, the water flow slowing, vegetation encroaching along their margins, and to their eventual blockage. As a result, areas of swamp dry up as the dammed water cuts new channels, often to areas that have not flooded in recent years.
6. Of the little clay carried down the Okavango River, much is trapped in the permanent swamps. This allows the Delta's substrate of Kalahari Sand to remain permeable. The water's percolation through the sands and its transpiration by island vegetation results in the concentration of salts beneath islands. Eventually the accumulated salts sink to substantial depths below the Delta. It is these processes that keep the Delta's water fresh.
7. The Delta is a rich sink of nutrients that accumulated here over long periods from river water sources, aerosol deposits, fixation by microbes and faecal deposits of large mammals.
8. Most nutrients are however trapped in peat and living swamp vegetation. They are only *released by drying* when water is redistributed (through channel blockages and switching) and the dry organic debris is decomposed or burnt.
9. However, the nutrients are only *mobilised by wetting* into new cycles of biological production when floodwaters reach the seasonal swamps and occasional floodplains.
10. Much of the wealth of life in the Delta is therefore generated by wetting and drying caused by the repeated pulsing and redistribution of floodwaters.
11. It is vital that conservation measures maintain the processes that enable some areas to be flooded and others to be dried.