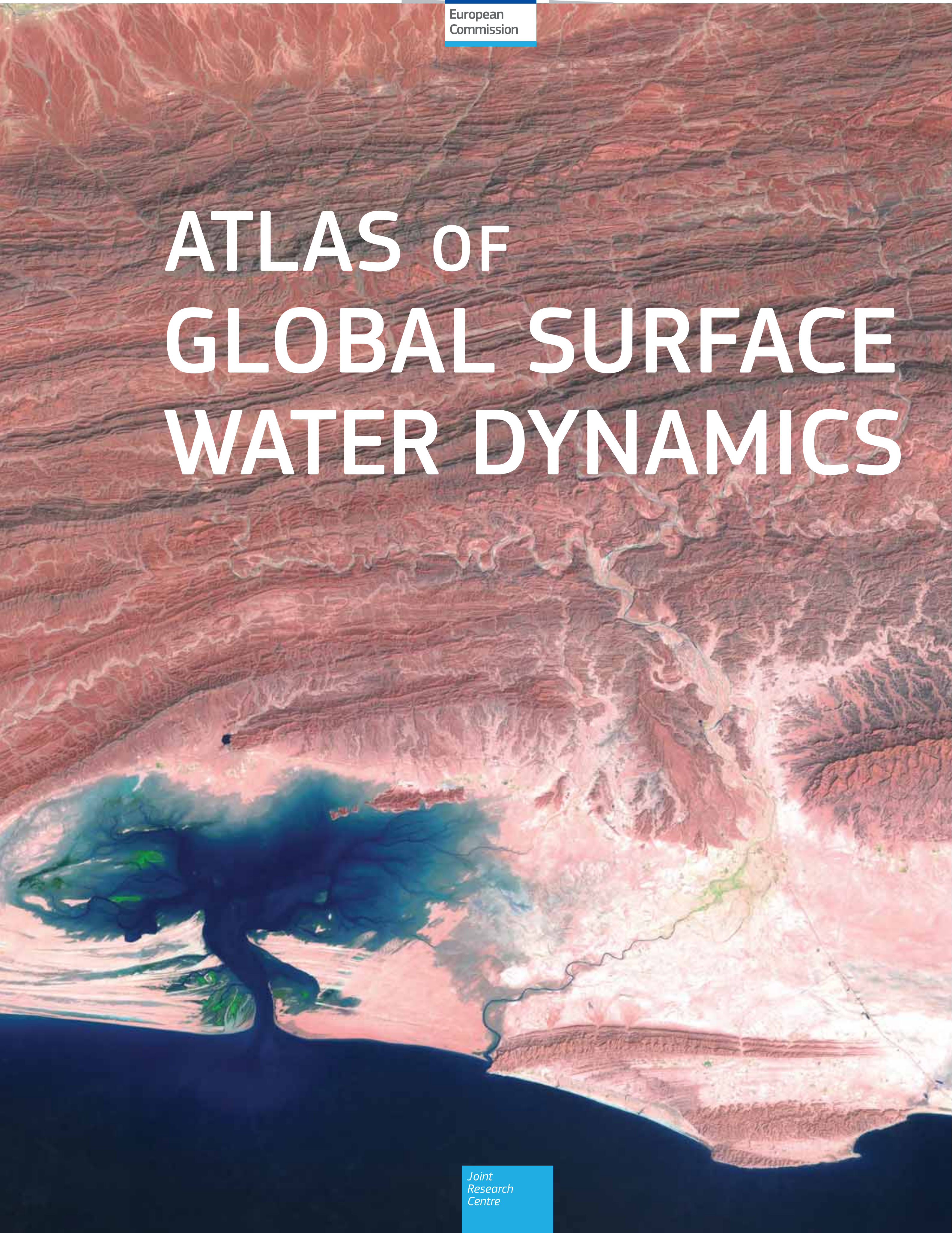
European Commission

ATLAS OF GLOBAL SURFACE WATER DYNAMICS



Joint Research Centre

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Preamble

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This URL links to the full online version of the Atlas, where the most updated content and data may be freely accessed.

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Atlas of Global Surface Water Dynamics

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http://en.wikipedia.org/wiki/Digital_Chart_of_the_World

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The maps depicting surface water dynamics in this Atlas are all derived from the Global Surface Water Explorer

https://global-surface-water.appspot.com/)
(source JRC/Google Earth Engine team).

Due to the resolution of the underlying data which is often still too large to represent small islands, the maps in this Atlas might not or not always represent a number of small Pacific islands. These are included in the interactive online version when provided in the datasets.

The world maps in 'Part 3 - Global overview' are represented according to the Robinson projection. All the projections of Global Surface Water Explorer data are Universal Transverse Mercator (UTM), apart from Greenland which is Albers Equal Area Conic.

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Cover image:
The Buzi Makola Wildlife Sanctuary in Sindh, Pakistan. This cloud-free mosaic was created from Sentinel-2 imagery acquired in 2018 and 2019. The region is a managed Nature Reserve, which received designated status in 1974.
Source Jean-François Pekel using Sentinel-2 imagery, courtesy EU Copernicus Programme.

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Loch Arkaig at dusk. Lochaber, Scotland, UK.
Source: © Peter Dibdin Photography | www.peterdibdin.com

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Preamble

Niger River, Mopti, Mali.
Part of the Niger River's internal delta, near Mopti, Mali; satellite image from the EU Copernicus Programme's Sentinel-2A satellite, acquired 29 November 2019. Open water appears dark blue and black in the image, vegetation green, bare earth in the brown tones, and towns and roads are grey. The image is 100 km North-South (top to bottom).
Source: Alan Belward using Sentinel-2 imagery, courtesy EU Copernicus Programme.

Foreword

It is impossible to overstate the importance of water in our daily lives – for proof, try going without it for any length of time. Surface waterbodies (lakes, ponds, rivers, creeks, estuaries… it doesn't matter what name they go under) are particularly important because they come into direct contact with us and our biophysical environment. But our knowledge concerning where and when waterbodies might be found was, until recently, surprisingly sparse. The paucity of information was due to the fact that trying to map a moving target is actually very difficult – and waterbodies undeniably move, in both geographical space and time. By 2013, the U.S. Geological Survey and NASA were making petabyte-scale archives of satellite imagery freely available, archives that covered the entire planet's surface and stretched back decades. Others, such as the European Commission/European Space Agency Copernicus Programme, were also putting full free and open data access policies into place, and Google's Earth Engine had become a mature, powerful cloud-based platform for processing very large geospatial datasets.

Back in 2013, a small team working at the European Commission's Joint Research Centre were looking at ways satellite imagery could be used to capture surface waterbody dynamics, and create new maps that accurately incorporated time dimensions. Concurrently, the Google Earth Engine team were focussing their massive computational capabilities on major issues facing humanity, such as deforestation, food security, climate change - and water management. The two teams came together in a partnership based not on financial transactions but on a mutual exchange of complementary capabilities, and devoted thousands of person hours and thousands of CPU years into turning petabytes of Landsat satellite imagery into unique, validated surface water maps, first published in 2016, and made available to everyone through a dedicated web portal, the **Global Surface Water Explorer** (https://global-surface-water.appspot.com/). Since then, satellites have continued to image the Earth, surface water has continued to change and the JRC/Google Earth Engine partnership has continued to work on improving our knowledge of surface water dynamics and making sure this knowledge benefits as many people as possible.

This Atlas is part of the outreach; it is not a guide to the Global Surface Water Explorer, it is not a Google Earth Engine tutorial (though if it inspires you to visit either of these resources then it has achieved one of its objectives), but it is a stand-alone window on how people and nature affect, and are affected by, the 4.46 million km^2 of the Earth's landmass that have been under water at some time over the past 35 years.

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https://global-surface-water.appspot.com/

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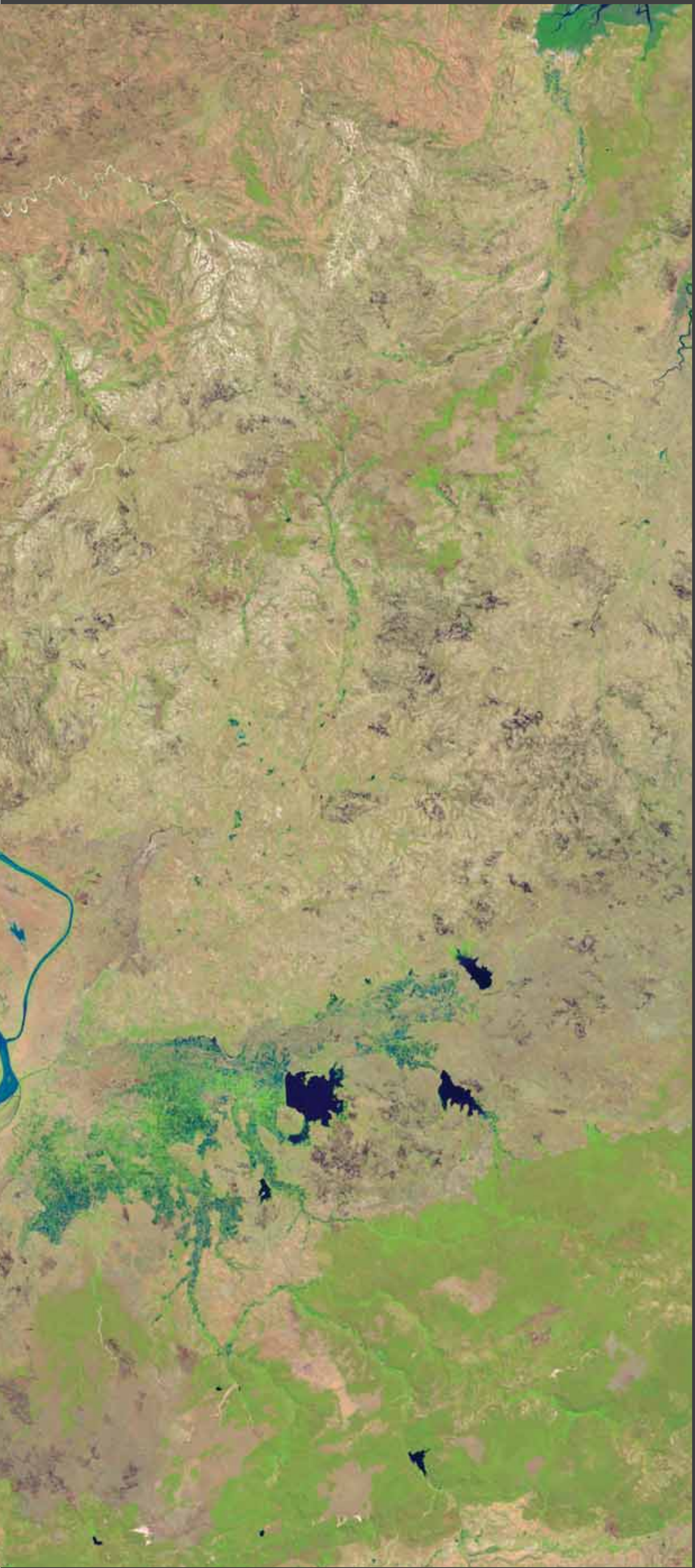


Part 1 - Why is surface water important?

The world's most precious resource

Why water? No water, no life. Water is the engine behind the distribution and movement of the Earth's plant and animal life. The presence or absence of water affects energy, gas and water vapour exchange with the atmosphere, and thus climate. Without water, hydroelectricity and thermoelectricity generation isn't possible, nor can we grow crops and raise animals. It underpins industrial processes and manufacturing, forms part of our transport network, influences the spread of disease, toxins, and pollutants, can cause loss of life and damage. Surface water has immense cultural and spiritual value, and profoundly affects human security and well-being.

Betsiboka River Delta, Madagascar, satellite image from the EU Copernicus Programme's Sentinel-2A satellite, acquired 29 November 2019. Open water appears dark blue and black in the image, the lighter blue tones indicate higher sediment loads, vegetation appears green and bare earth appears in the brown tones. The image is 83 km North-South (top to bottom).
Source: Alan Belward using Sentinel-2 imagery, courtesy EU Copernicus Programme.

Why is surface water important?

Distribution of the Earth's water

Water exists as a gas (water vapour), a solid (hail, ice crystals, ice and snow) and liquid (rain, rivers, lakes, wetlands, oceans, groundwater and in the biosphere - around 60% of an adult human's body weight is water). The water in all three states forms the Earth's hydrosphere.

Water in the hydrosphere is in constant motion, passing from liquid to solid or gaseous states and back again through the hydrological cycle. Our hydrosphere contains about 1386 million cubic kilometres of water[1] (it would take almost 1000 Empire State Buildings to fill one cubic km). A hydrosphere this massive is one reason the Earth is referred to as the 'Blue Planet'.

Most of the hydrosphere (97.5%) is saline water, nearly all of which is found in the seas and oceans that cover over 70% of the planet's surface. (Less than 0.1% of the world's saline water sits in lakes on the Earth's surface, and less than 1% is found in groundwater.) Only 2.5% of the hydrosphere is fresh water, of which a tiny fraction (0.3%) is found on the Earth's surface, stored in lakes, wetlands and rivers. But this tiny fraction is immensely important; the location and persistence of surface water affects our planet's climate[2,3], its biological diversity[4] and human well-being[5,6], and climate and human activity in turn affect the location and persistence of surface water[7].

Between lakes, wetlands and rivers, lakes hold the most water; 87% of the total from all three are in the world's lakes, compared with 11% in wetlands and just 2% in rivers[8].

It would take almost 1000 Empire State Buildings to fill one cubic km.

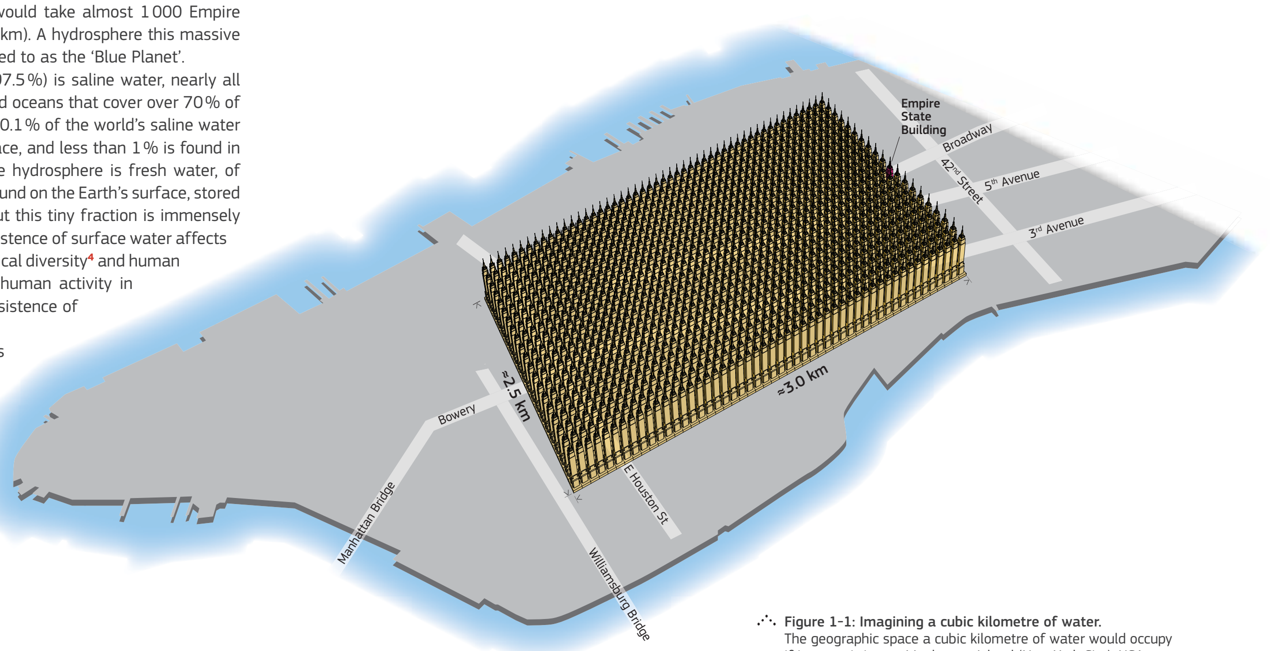
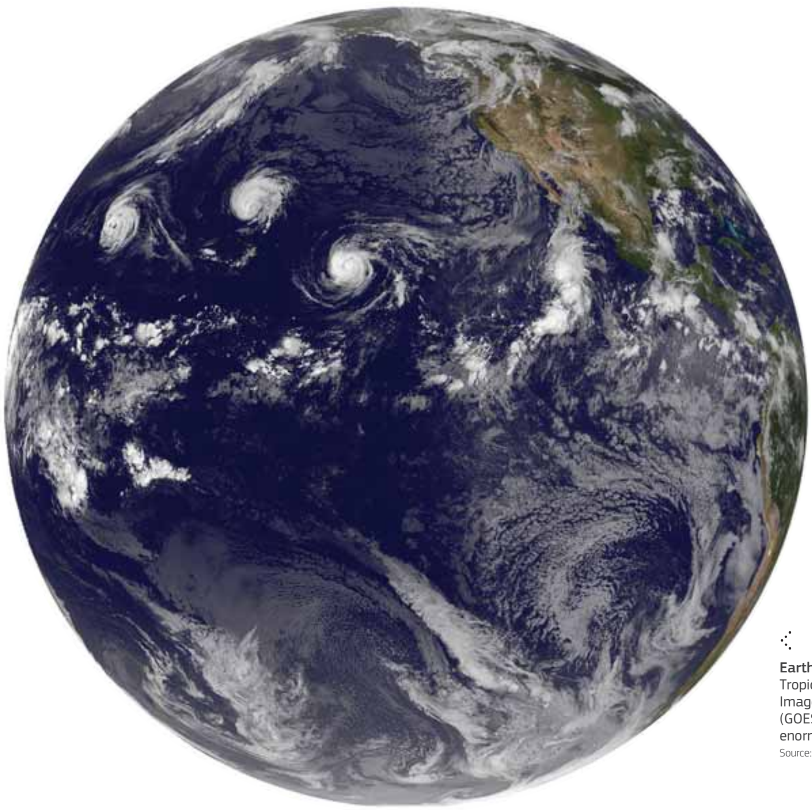


Figure 1-1: Imagining a cubic kilometre of water. The geographic space a cubic kilometre of water would occupy if it were sitting on Manhattan Island (New York City), USA.
Source: Lovell Johns Ltd.

The Earth's hydrosphere contains 1386000000 km^3 of water.



Surface waterbodies fill from precipitation falling directly on them, from water seeping in from underground and from water flowing into them over the surrounding land (this is called overland flow or runoff, and the land sloping into a waterbody is called the catchment area). Groundwater occurs when water seeps below the land surface and moves in the spaces between soil and rock particles. When the rock/soil is permeable enough, all the air spaces can fill with water. This saturated zone is called an aquifer. Water will continue to flow to lower-lying spaces and may eventually be discharged onto the land surface via a spring, seep into a river or lake, and even be abstracted by pumps and wells. Surface water and groundwater can be fresh or saline. Figure 1-2 shows that over 23 times as much fresh water is held in the ground than sits on the surface, and over 13 times as much saline water is held in the ground than in saltwater lakes.

Earth – the planet's surface is mostly water.
Tropical cyclones forming over the Pacific Ocean on 2 September 2015. Image from the US Geostationary Operational Environmental Satellite 15 (GOES 15) (courtesy NASA/NOAA GOES project science team). The Earth's enormous hydrosphere gives rise to its 'Blue Planet' nickname.
Source: Jesse Allen using GOES 15 imagery, courtesy NASA/NOAA GOES Project Science team.

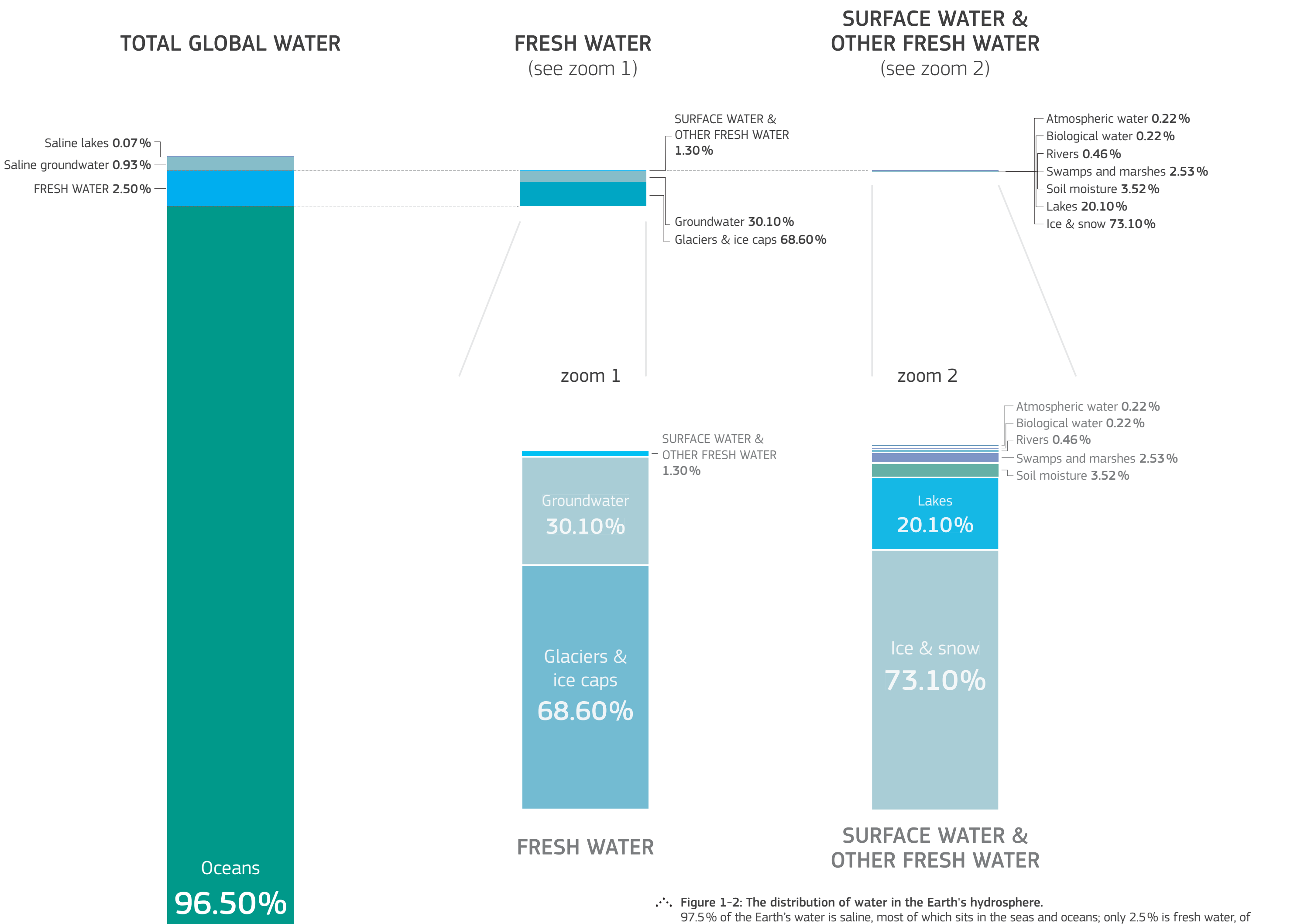


Figure 1-2: The distribution of water in the Earth's hydrosphere.
97.5 % of the Earth's water is saline, most of which sits in the seas and oceans; only 2.5 % is fresh water, of which just 0.3 % sits in lakes, rivers and wetlands. Salt- and fresh water mix naturally as rivers flow into seas and saline lakes, forming the brackish waters of estuaries. Saline lakes occur on every continent (including Antarctica) and are most common in semi-arid regions (where evaporation rates are high), including the high elevation lakes on the Himalayan Plateau. Saline and fresh water waterbodies share many attributes (after all, they are both principally the same chemical compound [H_2O] and provide many of the same functions, such as transport), but they generally support different biological communities – though there are exceptions, such as the well-known migrations of salmon, spawned in fresh water and spending much of their adult lives in sea water.
Source: Based on Igor Shiklomanov's Chapter 2 in Water in crisis: a guide to the world's fresh water resources, edited by Peter H. Gleick (Oxford University Press) 1993. Redrawn by Lovell Johns Ltd.

Less than 1 in 1 000 litres of the Earth's water sits in surface waterbodies, but it affects our planet's climate, its biodiversity, our daily lives – and we affect it.

Lakes and seas are fed directly by rivers, as well as through precipitation, runoff and underground seepage. Smaller rivers can flow into larger rivers; the smaller river is called a tributary. Rivers can divide and not rejoin, in which case the smaller splitting river is called a distributary. Distributaries are less common than tributaries and usually occur in river deltas. Lakes can be open or closed. In an open system, water flows out of the lake through a river. Where there is no outlet, the lake is described as closed, or endorheic. In these cases, lake levels depend on the balance between the amount of water entering and loss from evaporation and seepage. Lakes, rivers and wetlands may fill and flow all year round or may only exist on the surface for a few months of the year, and perhaps not every year.

Definitions.
This Atlas follows the definitions for lakes, rivers and wetlands as set out here.

lake: *n*
body of water, enclosed by land, sitting in a depression on the land surface. Other common names include pond, pool, mere, reservoir, tank, tarn, loch or lagoon.

river: *n*
body of water flowing in a channel into the sea or to/from a lake or another river. Other names for rivers include streams, brooks, becks, burns and creeks.

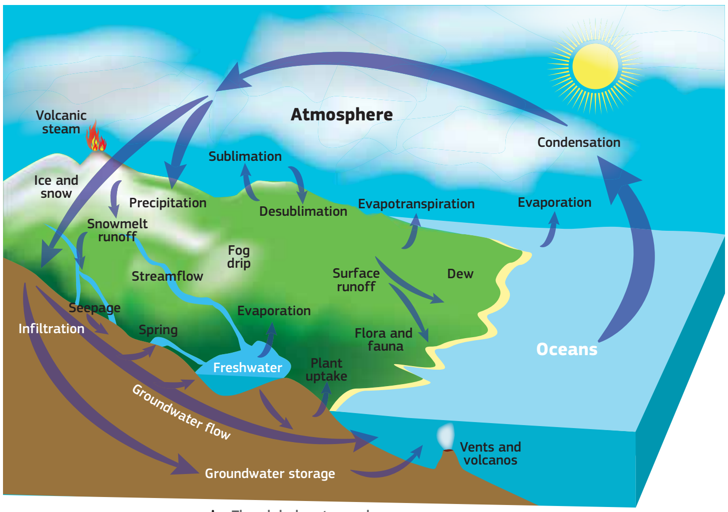
wetlands: *n*
where land is saturated with water. They may contain standing water all year, every year, or may be dry for months, even years at a time. They may even have saturated soils and no standing water. Wetlands include swamps, mangroves, marshes, estuaries, bogs, mudflats, fens and peatlands – fish ponds, rice paddies and shallow reservoirs too are sometimes classified as wetlands.

Why is surface water important?

Surface water and climate

Climates are determined by the weather conditions prevailing over a long period of time. The World Meteorological Organization uses 30-year averages of weather variables such as temperature and precipitation to establish what are referred to as 'climate normals'[9]. These provide a basis for characterising a region's climate and a reference point from which change can be measured. Weather systems are largely driven by the movement of water, energy and gas between the Earth's atmosphere, land and oceans[10], and this in large part depends on land and ocean properties. This variation is typically captured in climate and numerical weather prediction models through descriptions of 'land surface processes'[11]. These are factors such as energy fluxes, gas, water and aerosol exchange, roughness and momentum. Inland waterbodies and coastal areas are purposely represented in such models because the surface processes of open water are different to those of vegetated areas, snow and ice or bare ground[12,13,14]. The models need to know exactly where unchanging open surface water will be found, or where (and when) water occurs seasonally or inter-annually[15]. Surface water occurrence can also be an indicator of changes in the climate system[16]. For example, disappearing arctic lakes have been linked to permafrost melting, which results in faster drainage of the lake into the underlying ground[17]. Climatic fluctuations are also thought to have contributed to the disappearance of lakes by accelerating the drying out of lakes in arid areas[18]. In other parts of the world, it is lake expansion, rather than disappearance, that has been connected with climate change; most lakes on the Tibetan plateau are growing in size due to accelerated glacier melting[19]. Because of its importance in the climate system, the UN-sponsored Global Climate Observing System has identified lake area as one of its Essential Climate Variables[20].

Tidal Basin, Washington, D.C., USA.
Clouds forming over the Tidal Basin, a partially man-made reservoir between the Potomac River and the Washington Channel in Washington, D.C.
Source: Alan Belward.



The global water cycle
The mass of water on the Earth remains fairly constant over time, but its partitioning into the major reservoirs of ice, fresh water, saline water and atmospheric water varies depending on a wide range of climatic variables. The water moves from one reservoir to another, such as from a river to the ocean, or from the ocean to the atmosphere, by the physical processes of evaporation, condensation, precipitation, infiltration, surface runoff and subsurface flow.
Source: WAD3-JRC, 2018.

Cloud streets over Lake Superior, North America.
Long rows of white clouds called 'cloud streets' occur when frigid, dry air blows across a warmer lake, where it picks up water vapour. This water vapour freezes into ice crystals, and clouds form in the shape of the wind as it blows over the water. The same process can also cause snow or rain when the cold, moist air blows ashore on the lee side of the lake. Signs of lake effect snow can be seen here along the southern shore of Lake Superior.
Source: MODIS Rapid Response team using MODIS Terra imagery, courtesy NASA.

The location and persistence of surface water affects, and is affected by, the Earth's climate.

Surface water and biodiversity

Nothing lives without water, though life has evolved in such a way that its dependence on water is incredibly variable. Anhydrobiotic organisms[21] can survive in an almost completely desiccated state for extended periods[22], aquatic species live entirely in water[23] and amphibious species can move between terrestrial and aquatic environments[24]. Natural lakes and free-flowing rivers provide some of the world's most species-rich ecosystems[25], but all too often rivers are not free flowing, and lakes are not natural. Rivers and lakes can (and do) appear, disappear, expand, contract and change course naturally, but flow regimes can be constrained by dykes, levees and embankments, rivers are often cut by dams and weirs, floodplains are sealed over with concrete or asphalt and entire rivers can be encased in pipes and tunnels. Moreover, lakes might be artificially drained, or indeed artificially created. Whether the transition from an aquatic to terrestrial environment (or vice versa) is natural or anthropogenic, it has a profound impact on biodiversity[26]. Except for amphibious organisms, life in and on the land or in, on and around waterbodies isn't interchangeable. The movement, viable range, population and diversity of species change whenever lakes disappear, rivers move, coastlines expand or retreat, or when new lakes and rivers form and land drowns[27,28].

If the flow of water at a given location changes, the physical characteristics of that aquatic habitat (and thus what lives there) is also altered[29]. The lateral and longitudinal connectivity within and between waterbodies can be disrupted, again affecting species viability (lateral movement is where a waterbody can swell and shrink within and beyond its natural banks; longitudinal movement describes connectivity between headwaters and deltas for rivers or inlets and outlets for lakes). Even vertical connectivity can be broken between a waterbody and the atmosphere or the land below it. Seasonal variations in flow regimes can be changed too if artificial reservoirs hold back water. Thus, mapping surface water habitats is among the Essential Biodiversity Variables proposed as a means of informing science, policy and the public about the state of our planet's biodiversity[30,31].

Natural lakes and free-flowing rivers provide some of the world's most species-rich ecosystems[25].

Once water, now land.
Relicts of the Aral Sea's once-thriving fishing industry. In 1961, the industry harvested around 34 500 tonnes of fish (around 7 % of the Soviet Union's entire fish stock); by 1984 the industry harvested nothing[32].
Source: Arian Zwegers, Flickr.com

Organisms that live in or on the land can't usually live in or on water, and vice versa.

Once land, now water.
The transition from an aquatic to terrestrial environment (or vice versa), whether natural or anthropogenic, has a profound impact on the biodiversity of a location.
Source: May on Unsplash.

Changes in the location and persistence of surface water cause profound changes to biodiversity.

Why is surface water important?

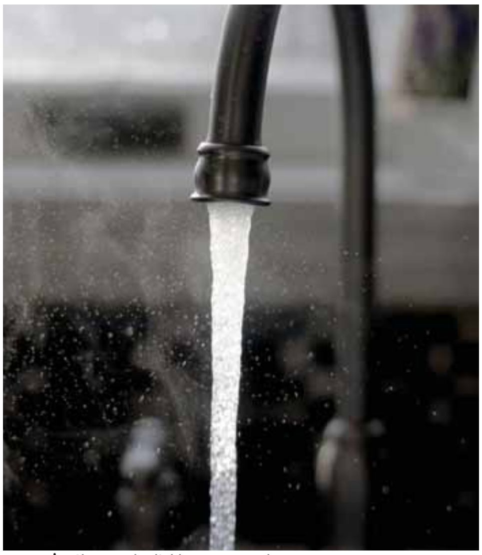
Surface water for domestic use

A 'rule of three' has been used to set boundaries for human survival, which states we can live for three minutes without air, three days without water and three weeks without food. The 'rule' is of course a generalisation and will vary enormously depending on the individual and circumstances – how much water is needed every three days certainly isn't specified. The 'rule' basically deals with biological functioning, yet humans also consume water for hygiene, to grow food, for commerce and industry, to produce energy, for transport and for social development. When all uses are taken into account the amount needed per person, per day is hugely variable, and exact numbers are hard to come by. Anything from as little as 20 to over 4600 litres per person per day has been reported[33] (and the FAO even go as high as 5000 litres/day[34]). But whatever the number, the rule is in essence correct - humans need regular access to water to live. In fact, access to water was explicitly recognised as a fundamental human right by the United Nations General Assembly on 28 July 2010[35]. A second truth is that water use worldwide has increased by around 1% every year since the 1980s[36] because of population growth and socio-economic development. Surface water occupies a key place in terms of human use because it is pretty much instantly accessible. There is no need to dig a well where surface water is concerned, and if the source is close enough to its user, no need for pumps or pipework either. Thus, small communities can be served by direct abstraction from lakes and rivers. Even large communities depend on surface water.

Around 78% of the world's large cities (urban areas with more than 750000 people) get their water from surface sources, though rather than direct abstraction, many of these cities collectively move billions of litres of water thousands of kilometres every day[38]. Reliance on surface water does come with risks – in part health-related (discussed below), in part matching supply and demand, when prolonged periods of dry weather rapidly increase demands and reduce supplies. Dry periods accelerate evaporative loss from reservoir and river surfaces, reduce recharge from precipitation and deplete the reserves held in surrounding hydraulically connected groundwater. Urban population growth and increasing demand from surrounding regions for agriculture, industry, energy production and other uses are putting increasing pressure on surface water resources, and a number of cities around the world have seen supplies fail alarmingly in recent years[39].

Surface waterbodies supply most of the world's large cities with essential daily water.

The demand for accessible surface water supplies increases every day.



Clean and reliable water supply.
Access to water is a fundamental human right, but by 2025, half the world's population will be living in water-stressed areas[37].
Source: Imani on Unsplash.

Theewaterskloof Dam, Cape Town, South Africa.
Theewaterskloof Dam was near operational capacity in April 2014 before a three-year drought began. By 3 March 2018, water levels were dangerously low and supplies to the city of Cape Town were seriously threatened. Day Zero (12 April 2018) was the day the city was forecast to run out of water. Strict reductions in water allocations for agriculture and conservation efforts by the people of Cape Town averted disaster, and by 13 October 2018 the Dam, whilst not full, was once more operational. The threat to the city of a repeat performance remains very real, especially if demand continues to increase, whilst climate change reduces supply. All images 16 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

Surface water and health

For the majority of the Earth's 7.5 billion humans, life-sustaining water comes from surface water (around 2.5 billion people rely exclusively on ground water[40]). As a supply and storage system, surface waterbodies present health risks[41] precisely because they are on the surface; they are open to the elements, interact directly with the surrounding environment, and living organisms can get on and into the water, not just exist beside it. They can be homes to toxic cyanobacterial blooms; they can contain pathogens (enteric and other) from human contamination as well as wildlife excreta and zoonotic disease; polluted water, can easily enter the supply either directly or through cross contamination from wastewater and storm drains. River and lake catchment areas can collect pesticides and nutrient runoff from agriculture, or excreta, feed, and disease-control chemicals from aquaculture, as well as the extractive chemicals and pollutants from mining; even fuel, engine emissions, de-icing chemicals and waste from passengers can be picked up from ship/road/rail/air traffic. Nature also directly plays a part, with the underlying waterbody geochemistry adding substances such as iron or fluorides, and atmospheric deposition adding anything from wind-blown soil particles to volcanic ash, whilst the surface water can provide a home and transport network for disease vectors – malaria vector populations, for example, are usually increased by paddy rice cultivation or in lakes, pools and slow-flowing rivers[42]. Catchment-specific management plans can be drawn up to help mitigate the threats. Such plans include risk assessments in which the surrounding environment and catchment dynamics are described, along with characteristics of the surface waterbodies such as stream flow dimensions and floodplain dynamics, as well as seasonal flow patterns and connectivity. Many of our planet's citizens do benefit from clean water supplies and purification facilities, but three out of ten people in the world still have no access to safe drinking water[43].

For the majority of the Earth's 7.5 billion humans, life-sustaining water comes from surface water.

Polluted inner-city water in Bình Thanh, Ho Chi Minh City, Vietnam.
Source: Photo by Anh Vy on Unsplash.

Most of the people, most of the time, get their water from lakes and rivers, yet this water can threaten their health.

Algal bloom on Lake Erie, North America, October 2011.
Record torrential spring rains led to the worst algae bloom that Lake Erie had experienced in decades. Rains washed fertilisers into the lake, promoting the growth of microcystin-producing cyanobacteria blooms. Image is 98 km North-South (top to bottom).
Source: Jesse Allen and Robert Simmon using Landsat imagery, courtesy USGS/NASA https://commons.wikimedia.org/w/index.php?curid=16981673.

Three out of ten people in the world still have no access to safe drinking water[42].

Surface water as drinking water.
Surface water may be immediately accessible, but unless it passes through some intermediate infrastructure or process, it is not treated. When the water source is pristine, this may not present problems. But surface water is all too often not pristine, and brings with it considerable health risks to anyone drinking it.
Source: MD Duran on Unsplash.

Why is surface water important?

Surface water and food

Water resource managers need to take into account two processes, firstly, water withdrawal (which describes the amount of water taken from a given source) and secondly, water consumption (which is the quantity of the withdrawn water that is completely used because it is biologically consumed, evaporated or transpired, or permanently incorporated into something else). By either measure, agriculture is the biggest user of fresh water in the world. Numbers vary, but in most countries agriculture uses somewhere from 70 to over 85 % of available fresh water[44,45]. These numbers are set to grow. Agriculture provides around 99 % of our calories[46] with the rest coming directly from aquatic environments. Our growing population means that by 2050 we are going to have to produce 70 % more food than today[47]. This in turn will call for even more water, and for an ability to deal with climate extremes[48]. Pastoralists, for example, rely on surface water in many parts of the world for their animals' survival. Nomadic pastoralists track both grazing land and water resources when herding their livestock. The recurrence of seasonal waterbodies is particularly important to such agricultural production systems. Knowing that a particular location will provide water at a particular time of year is incredibly valuable knowledge[49].

Crop sprinklers near Rio Vista, California, USA.
Irrigating a 50-hectare wheat field can use as much water in a day as 40 000 people taking a shower.
Source: Sr. Photographer, Paul Hames / California Department of Water Resources [Public domain].

Numbers vary, but in most countries agriculture uses somewhere from 70 to over 85 % of freshwater[43,44].

Agriculture and aquaculture don't just consume water, they also shape the occurrence of water on our planet's surface. Rice paddies, flooded as part of the crop's growth cycle, and fishponds[50] produce temporary wetlands that recur year after year. The infrastructure needed for crop irrigation has led to intricate networks of canals and reservoirs across our planet. Some, like the cross-slope earthen dams used to harvest rainwater for irrigation in Southern India, or the rice terraces in China's Yunnan Province, create unique waterscapes. Agriculture and aquaculture also affect the quality of surface water. Humans have always farmed aquatic organisms (including oysters, shrimp as well as fish for food and to supplement fish stocks for sport fishing). Aquaculture can take place in coastal impoundments as well as inland ponds. The concentration of organisms in a confined area plus the intensive use of feed and disease-control chemicals can lead to harmful effects on the local aquatic environment, such as excess nutrient levels, eutrophication and organic pollution. This may be confined to the immediate environs of the aquaculture site, or can transfer to the wider surface water system[51]. Agriculture is not just the biggest user of freshwater, it is also a major disruptor of surface water systems. This disruption affects water quality through nutrients, pesticides and other forms of contamination through runoff, and also physical factors, such as drainage patterns, river channel dimensions and connectivity and the occurrence of surface storage in ponds and lakes[52].

Irrigation of farmland in Punjab, India.
Without water there would be no agiculture, anywhere.
Source: Ammarkh at English Wikipedia [Public domain].

Agriculture and aquaculture feed us, but they are the biggest consumers of water today, and both will need to consume even more in the future.

Surface water and energy

Capturing the movement of a flowing river to grind grain in watermills was among the earliest ways humans obtained energy from surface water[53,54]. **Hydroelectricity** generation is a direct descendant from this. Rather than the milling, rolling or hammering movements typical of watermills, the movement of water in a hydroelectric plant turns a turbine, which then turns an electrical generator. Micro-hydroelectric power generators can draw water directly from a river, and provide power to a single house or small community.

Larger-scale power generation uses the release of stored water, usually by damming a river. Global hydropower capacity in 2017 was 1 114 GW[55] (just over 16 % of global electricity production), and whilst hydroelectric dam construction has abated in some parts of the world (USA and Europe for example[56]) it is expanding in China, Brazil, India, Turkey, Vietnam and parts of Africa. Ethiopia's Grand Renaissance Dam is among the latest developments. Nearing completion, this will be Africa's largest hydroelectric power plant, generating 6 000 MW of much needed electricity. The 155 m-high, 1.78 km-long dam across the Blue Nile (a few kilometres upstream from the Sudan border), and a 50 m-high, 5.2 km-long saddle dam in a currently dry valley to the south of the river, will create an artificial lake holding over 70 billion cubic metres of water covering over 1 800 km²[57]. This is 1 800 km of land that is about to become water (see also page 21). Around the world, many thousands of hydroelectric power plant dams have created artificial lakes. The five largest artificial reservoirs by area (not volume), all of which have hydroelectric power stations at their dammed outlets, have covered an area of land roughly the size of Belgium.

Hydroelectric power, Hoover Dam, Nevada, USA.
Hoover Dam impounds Lake Mead, the largest reservoir in the United States by volume (when it is full). The dam's generators provide power for public and private utilities in Nevada, Arizona and California.
Source: https://en.wikipedia.org/w/index.php?curid=55898806 [CC0].

Over 90 % of current global electricity production would cease without surface water.

In terms of water withdrawal however, hydroelectricity pales next to **thermal electricity**. Thermal power stations, which collectively provide well over three quarters of the world's electricity, use steam generated by heating water to turn the turbines that drive the generators. They also use copious quantities of water to cool the infrastructure. This is why so many are sited next to lakes, rivers or the coast. Heated water cannot be returned directly to seas, lakes and rivers without harming the biosphere, so thermal power stations are sometimes accompanied by artificial lakes used for cooling before returning. In addition to hydro- and thermal power plants, newer technology makes direct use of cold water for cooling buildings in hot weather, heat pumps to recover heat directly from water, and tidal barrages for alternative electricity generation. Although solar, wind, geothermal and biomass power are growing, collectively they account for just over 6 % of all electricity produced in the world[58], so for today at least, without surface water we would have next to no electricity.

Surgut Power Station, Russia.
Heated water cannot be returned directly to seas, lakes and rivers without harming the biosphere, so thermal power stations are sometimes accompanied by artificial lakes used for cooling before returning.
Source: dedmaxopka@gmail.com

Power cooling towers, Westfalen, Germany.
Forced draft wet cooling towers (height: 34 m) and a natural draft wet cooling tower (height: 122 m). Thermal electric power generation requires huge quantities of water to condense steam from the turbine exhaust.
Source: Tim Reckmann [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].

Lamma Power Station, Hong Kong, China.
Thermal power stations use steam generated by heating water to turn the turbines that drive the generators. They also use copious quantities of water to cool the infrastructure, which is why so many are sited next to lakes, rivers or the coast.
Source: Photo by Ben Tatlow on Unsplash.

Why is surface water important?

Surface water for commerce and industry

The water industry across the globe aims to deliver clean water, and treat wastewater. The positive cost-benefits of this industry to humans in terms of time gained, increased productivity and better health are universal – they apply to all world regions and all societies[59]. Unfortunately, not all in the world benefit from an efficient water industry, and this shortcoming is among the drivers behind the United Nations Agenda 2030's Sustainable Development Goal (SDG) 6 to 'ensure availability and sustainable management of water and sanitation for all'[60]. The central position of water for the achievement of all other SDGs is increasingly confirmed[61], especially for poverty reduction and ending hunger, and this central position is also keenly felt by commerce and industry.

Commercial (or service) activities, such as schools, hospitals, banks, shops and restaurants, use water on scales roughly equivalent to domestic use (it is by and large the people involved in the service delivery that use the water).

Industrial activities operate on a much bigger scale. Worldwide, industry consumes 19% of water supplies, though in industrially developed regions this can be even higher. For example, water withdrawal for industrial use in Europe represents 54% of the total, compared to 4% for Africa[62]. Unlike agriculture though, industry usually returns its water to the environment, albeit often polluted. Water is directly incorporated into products such as paper, but more widely it is used to cool machinery, to wash and clean, to dilute and transport. In fact, it is almost impossible to imagine any commercial or industrial activity that does not require access to water. This access goes both ways; just as commerce and industry take water out of the supply chain, they also put it back - sometimes with devastating consequences. Mineral and chemical pollutants and biological contaminants (for example from washing carcasses in meat processing facilities) find their way into the wastewater from industrial complexes, and this wastewater can find its way into surface water bodies through overland flow or direct discharge[63].

Commerce and manufacturing without water are unimaginable.

Papermaking.
Papermaking has been part of human civilisation since around 105 CE[64]. Depending on the production process, producing one A4 sheet of printing/writing paper uses between 2 and 13 litres of water[65].

Worldwide, industry consumes 19% of water supplies, and in industrially developed regions the figure can be much higher.

Surface water pollution in harbours.
The commerce and industry sector sometimes puts water back into the system in a worse condition than when it was extracted. In Boston Harbour, measures are taken to constrain surface pollution by employing booms.
Source: Alan Belward.

Stills used for whiskey production in Ireland.
Fresh water is used at various stages of alcohol production, including yeast fermentation, distillation, dilution, bottling and effluent treatment[66].
Source: Alan Belward.

Surface water and transport

Natural harbours and rivers provide socio-economic advantages to any region[67]. Development is strongly favoured in regions of the world that enjoy good links between coasts and ocean-navigable waterways, and hampered in regions that don't[68]. For example, most of Africa's people live at least 100 km away from navigable rivers and harbours, which has not helped the continent to build either inter- or intra-continental trade[69]. Water is such a fundamental part of our transport network that artificial harbour construction has occurred throughout human history. Furthermore, on which navigable rivers are lacking, and if physical geography and economics allow, humans build artificial rivers, which we call canals. Lechaion harbour in Corinth (Greece), built around 600 - 500 BCE[70], is one of the oldest artificial harbours, and China's Grand Canal, where construction began in 486 BCE, is not just the world's oldest canal it is also, at over 1 700 km, still the world's longest. Building waterways have been among the costliest projects humans have ever undertaken, both financially and in terms of loss of human life[71]. But, they have changed society fundamentally – world trade without the Panama and Suez canals would be very different (the Panama Canal is so important for international trade and shipping that many ships are built to the maximum size allowed through the canal's locks[72]), and a world without canal cities such as Venice, Bangkok, St Petersburg, Amsterdam or Cape Coral would undoubtedly be culturally poorer.

Suez Canal, Egypt.
Northbound convoy waits in the Great Bitter Lake as southbound convoy passes, October 2014.
Source: Gregor Rom [CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)].

Waterways have been used to transport people and goods throughout human history.

Paris, France.
Transporting scrap metal through the centre of Paris, France.
Source: Alan Belward.

Bangkok, Thailand.
Many of Bangkok's canals (khlongs) were drained or filled because of the risk of cholera they posed, or to make way for roads. Little or no trade passes along those that remain, although they are still visited by tourists to see the traditional way of life in a modern city.
Source: Evan Krause on Unsplash.

Why is surface water important?

Surface water and society

Typing the word 'water' into the UNESCO World Heritage Sites List[73] identifies 289 cultural, 149 natural and 24 mixed sites distributed across all continents (except Antarctica). The list includes culturally valuable landscapes (such as China's West Lake Hangzou), cities famed for their water (such as Venice, Amsterdam, Stockholm, Bangkok, Tigre and St Petersburg), the exceptional wetland biodiversity of the Sundarbans, and sites documenting pivotal moments in human history (such as Valongo Wharf in Rio di Janeiro). Surface waters have been places of pilgrimage across geography and time[74], sacred rivers and lakes[75] are crucial for many societies today, and artificial water features enrich architecture and national identity[76]. Whilst the value placed on heritage, culture and religious significance may be subjective (though no less real), surface water has explicit quantifiable value in terms of recreation and leisure activities – tourists bring money into an area[77] and views of water command a clear price premium for residential property - people pay more for a home with a view of water than one without[78].

The Sundarbans, Bangladesh, appears deep green, surrounded to the north by a landscape of agricultural lands, which appear lighter green, towns, which appear tan, and streams, which are blue. Ponds for shrimp aquaculture, especially in Bangladesh, sit right at the edge of the protected area, a potential problem for the water quality and biodiversity of the area.
Source: Jesse Allen using Landsat 7 imagery, courtesy USGS/NASA.

The Blue Lagoon, Iceland, is a man-made lagoon fed by the water output of the nearby geothermal power plant. Superheated water is vented from the ground near a lava flow and used to run turbines that generate electricity. After going through the turbines, the steam and hot water passes through a heat exchanger to provide heat for a municipal water heating system. The water is then fed into the lagoon for recreational and medicinal uses by bathers.
Source: Jeff Sheldon on Unsplash.

The aesthetic, cultural, historical, architectural and recreational value of surface water is immense, irreplicable and irreplaceable.

Ganga Dussehra Festival, the most ancient river festival in existence, is a Hindu festival celebrating the avatarana (descent) of the Holy Ganga (Ganges) from the celestial regions to the Earth. Taking a dip in the river on the holy 10th day of the festival is believed to purify the devotee to a state of purification and also heal any physical ailments they may have.
Source: Barry Silver from Tokyo [CC BY (https://creativecommons.org/licenses/by/2.0)]

Studley Royal Water Garden, UK.
The water garden at Studley Royal Park (a designated World Heritage Site in North Yorkshire, England) was created by John Aislabie in 1718. It comprises man-made ornamental lakes, canals and cascades to create a series of beautiful vistas for the visitor.
Source: Iain Gilmour - www.silverexpressions.co.uk [CC BY (https://creativecommons.org/licenses/by/2.0)]

Surface water and security

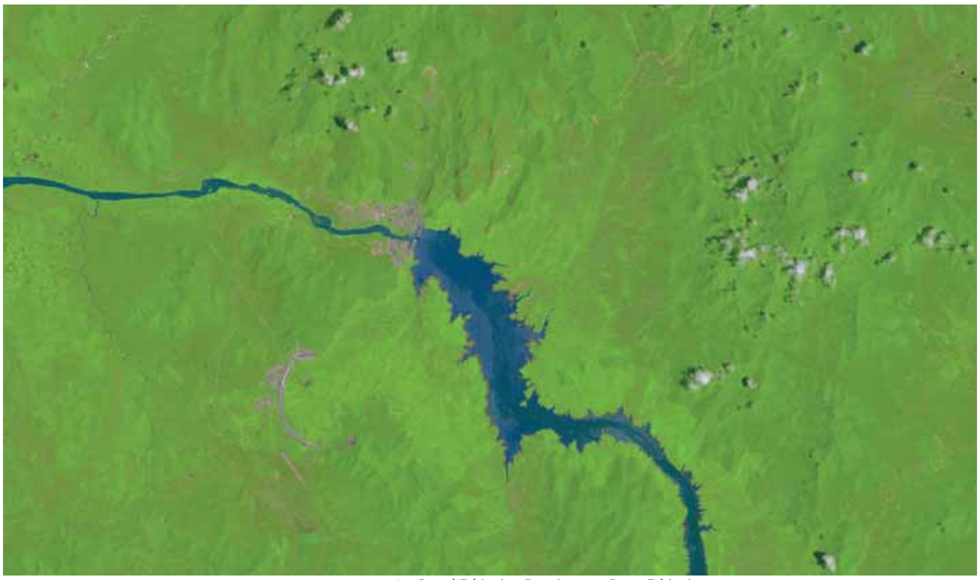
Flooding has killed people across every continent, and many disastrous floods will occur every year[79]. Floods are usually caused by severe winds, high tides and tsunamis, failures in drainage systems, flash flooding when the land becomes saturated and all falling water flows overland, causing rapid expansion of lakes, rivers and wetlands or rising seas. River floods in Asia are among the deadliest natural floods as measured by the number of people killed and affected[80]. Extreme weather events are generally the driver, though the failure of surface water infrastructures, such as levees or dams, present enormous risks to human security[81] and have catastrophic impacts when they fail[82]. Knowing the location of coastlines and surface waterbodies and how they change over time is important information for flood control and disaster management[83]. Threats to human security also come from the competition for secure access to water. Ethical positions, values and people's behaviour can cause divergent views on water management within a region or country[84], and because water is so important, legal disputes over water rights and water withdrawal can occur at local[85], regional[86] and national levels.

Disputes over water rights and water withdrawals can escalate and result in violent conflict. These situations can occur between different communities in close proximity, such as herders and farmers, sometimes with fatal consequences[87]. Disputes even extend beyond communities to entire nations. However, whilst political tensions arising from water resources undoubtedly exist between nation states, no one has yet gone to war over water – skirmishes yes, war no[88].

Lakes, rivers, wetlands and seas all cross international boundaries. **Transboundary** water management is currently assured through agreement. There are 263 transboundary lake and river basins in the world, which collectively cover nearly half of the planet's land surface. Yet, in the past 50 years only 37 violent disputes over water have occurred, compared to 150 treaties established to encourage (if not fully guarantee) peaceful management[89].

Just as too much, or competition for access to, water threatens human security, so does too little. On a local scale, and at specific times, people undoubtedly have too little. A recent estimate is that at least four billion people experience severe shortages for at least one month per year[90]. Water is a renewable resource, but that doesn't mean we will always have enough to meet every need[91]. Meeting all human needs outlined above, whilst sustaining the vital functions that surface water provides for climate and biodiversity, in the face of growing populations, expanding agriculture, aquaculture and economies, let alone a changing climate, requires new and integrated approaches to water management.

Too much, too little, and competition for water all directly threaten our security.



Grand Ethiopian Renaissance Dam, Ethiopia.
The Nile River temporarily formed part of a new lake behind the Grand Renaissance Dam in Ethiopia, when the dam was temporarily closed for testing in 2017. The saddle dam visible in the left of the image gives some idea of the lake's eventual size when it reaches full capacity. The water never reached this dam in 2017. At the time of writing, the dam is not closed and the Nile continues to flow uninterrupted into neighbouring Sudan and Egypt. True colour satellite image from the EU Copernicus Programme's Sentinel-2A satellite, acquired 12 September 2017. Image is 37 km North-South (top to bottom).
Source: Alan Belward using Sentinel-2 imagery, courtesy EU Copernicus Programme.

Conflicts can occur between different communities, such as herders and farmers[87].

Competition for surface water.
Different land uses, such as crop production or pastoralism, sometimes compete for finite land and surface water resources.
Source: Both images Andreas Brink, JRC.

Why is surface water important?

Surface water and the UN Sustainable Development Goals

Goal 6 - Clean Water and Sanitation - is a fundamental goal; if the targets it sets are missed, other SDGs will be difficult, if not impossible, to reach.

In 2015, the UN General Assembly set out an ambitious agenda, aiming at nothing less than a sustainable future for the whole world[92]. This wide-reaching plan is based around 17 Sustainable Development Goals (SDGs) that address different social, economic and environmental aspects. Each goal has a number of targets (169 in total) for the year 2030. The goals and targets are not legally binding, but they universally apply to all countries. Individuals can take actions that support them too[93]. SDG6 focuses on ensuring the availability and sustainable management of water and sanitation for all. The connections between SDG6 targets and surface water are unmistakable, as shown by target 6.6: "By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes". But, because surface water affects so many dimensions of human existence, links can be made between water and *all* 17 of the SDGs.

Links between SDG targets may not always be direct. Sometimes the relationship may be interdependent. For example, ensuring all people have equal access to basic services and natural resources (target 1.4) can't be achieved without access to water and sanitation (targets 6.1, 6.2 and 6.3). However, there is also potential for conflict between targets. For example, doubling agricultural production (target 2.3) will inevitably increase demand for water, which may not be compatible with ensuring sustainable freshwater withdrawals (target 6.4). Other combinations may be mutually beneficial. For example, reducing the impact of alien species in water ecosystems (target 15.8) will contribute to protecting and restoring water-related ecosystems (target 6.6). Understanding linkages will help stakeholders maximise synergies, avoid gaps and counter conflicts when trying to reach the SDGs[94].

There are many ways of examining interlinkages. The table presented here provides one perspective on links with surface water. The 17 goals are listed, along with descriptions of 47 of the targets, against each of which comment is made concerning the potential links with surface water occurrence. This is not exhaustive, and is open to interpretation (which is encouraged), but nonetheless highlights how many of the SDG targets depend on and/or support a reliable, high-quality surface water supply.

The United Nations Environment Programme (UNEP) is the Custodian Agency for three of the water indicators within Goal 6. In this role, UNEP is responsible for supporting UN member states with collecting and compiling SDG indicator data and reporting national progress towards the SDG6 targets. It is also responsible for developing international standards and methods for monitoring, and strengthening countries' capacity for such monitoring. The UN has developed a global indicator framework, which currently lists 244 indicators against which progress towards the targets can be measured[95]. This list includes "Indicator 6.6.1 Change in the extent of water-related ecosystems over time". UNEP provides free and open access to national, sub-national, basin and sub-basin aggregated data on water extent through a dedicated web service[96], which uses the water detection methods and maps developed by the European Commission's Joint Research Centre and Google Earth Engine presented in this Atlas.

Goals and targets (from the 2030 Agenda for Sustainable Development)	Comments
Goal 1. End poverty in all its forms everywhere	
1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	Access to water is a fundamental human right. Knowing where and when this natural resource occurs is a first step in securing fair and equal rights of access
1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	Too much or too little surface water at any given place and time can have catastrophic consequences for anyone, but the poorest are usually disproportionately hit, have fewer resources to deal with the shock and least resilience
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	
2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment	Are available surface water resources compatible with a doubling of agricultural productivity and will such doubling affect the sustainability and quality of these water resources?
2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	Productive and sustainable agriculture is not possible without water. Are surface water resources changing as climate changes? Are these changes compatible with prevailing agricultural practices? Can local agriculture change in ways that enhance the sustainability of the surface water resource and mitigate against extremes (such as drought and flooding)?
Goal 3. Ensure healthy lives and promote well-being for all at all ages	
3.3 By 2030, end the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases and other communicable diseases	Surface water persistence can be linked to attenuation, transport, connectivity and disruptions in terms of pollutants and disease. This knowledge can in turn help combat such health threats
3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Knowing when and where surface water occurs can help build catchment-specific management plans that address water-borne threats to health
3.d Strengthen the capacity of all countries, in particular developing countries, for early warning, risk reduction and management of national and global health risks	Knowledge concerning surface water occurrence, and its transfer to those who need this knowledge, are important steps in capacity building
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	
4.1 By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes	How much time do children devote to collecting domestic water? Does this leave them time for education? Are sanitary arrangements for both boys and girls compatible with educational equality?
Goal 5. Achieve gender equality and empower all women and girls	
5.a Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws	Where (and when) are surface water resources located, and how does this relate to tenure and access?
5.b Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women	Can surface water occurrence information be distributed directly to individuals?
Goal 6. Ensure availability and sustainable management of water and sanitation for all	
6.1 By 2030, achieve universal and equitable access to safe and affordable drinking water for all	Where (and when) are surface water resources located, and how does this relate to population distribution, dwellings and farmland?
6.2 By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations	Do sanitation arrangements risk contaminating surface water supplies? Are surface water supplies adequately linked to sanitation?
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	Do lakes and rivers connect to potential sources of pollution? Once surface water is 'used', is it returned to the surface water system in a clean state?
6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	How much water is being used in a specific area? What are abstraction rates like when linked to source? Are surface water resources adequate to meet demands? Are demands causing surface resources to contract, for example?
6.5 By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate	Where do surface water resources sit with respect to transboundary catchments? How do they connect? Do changes in one area (e.g. dam building or canal construction) influence resource occurrence elsewhere?
6.6 By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes	What are the changes in the extent of water-related ecosystems over time? The **Global Surface Water Explorer** provides input for reporting on indicator 6.6.1: Change in the extent of water-related ecosystems over time
6.a By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies	Does water harvesting in one area affect occurrence elsewhere?
6.b Support and strengthen the participation of local communities in improving water and sanitation management	Provide local communities with baseline information on water resource occurrence
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all	
7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	Can the surface water consumption requirements of existing and/or expanded thermoelectric generation be adequately met? Is there untapped hydroelectric capacity? How does existing and/or an expanded thermoelectric/hydroelectric energy generation infrastructure affect the dynamics of connecting elements of the surface water system?

A sustainable future for the world isn't possible if surface water is ignored.

7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	What is the share of hydroelectric generation in the current mix?
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	
8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead	Do trends in surface water occurrence over time equate with sustainable use?
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation	
9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all	Are there observable impacts of major infrastructure developments, such as canal, harbour and dam construction, on the immediate and surrounding surface water network? Does this affect navigability and connectivity? How does major infrastructure development, such as artificial islands, affect surrounding aquatic ecosystems?
Goal 10. Reduce inequality within and among countries	
10.7 Facilitate orderly, safe, regular and responsible migration and mobility of people, including through the implementation of planned and well-managed migration policies	Do changes in surface water resource (either an increase or decrease) drive the displacement and/or migration of people?
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	Are surface water resources equitably linked to housing and population concentrations? Do rich population centres get priority access first?
11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons	What is the role of the surface water network (natural and anthropogenic) in the transport mix? Is this sustainable throughout the year?
11.3 By 2030, enhance inclusive and sustainable urbanisation and capacity for participatory, integrated and sustainable human settlement planning and management in all countries	Do surface water resources meet current and future demands in a sustainable manner?
11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage	Are iconic aquatic landscapes and water features adequately protected?
11.5 By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations	Can risk assessments be produced? Are changes in surface water occurrence linked to past disasters, and can lessons be learned?
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	How do population concentrations relate to surface water sources and possible contamination and disease sources/vectors?
11.7 By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities	Do surface water features play a role in a city's cultural life? Are they accessible and are they sustained?
11.a Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning	Do surface water resources flowing in and through peri-urban and rural settlements benefit or suffer from proximity to urban areas?
11.b By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels	Are the surface water resources associated with urban settlements (e.g. reservoirs) adequate and resilient? Are there 'early-warning' signs that there might be problems (e.g. reservoirs drying up and shrinking already)?
Goal 12. Ensure sustainable consumption and production patterns	
12.2 By 2030, achieve the sustainable management and efficient use of natural resources	Are there sustainable management plans in place for surface water resources, and if so, are these based on factual measurement of trends, status and condition of the resources?
12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimise their adverse impacts on human health and the environment	Are surface water resources at risk from chemical and pollutant release? How do threatened water-bodies connect with the rest of the hydrographic network?
12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	Are people in a given region aware of the changes the surface water resources in their region are undergoing?
12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	Are surface water resources used for tourism in good condition?
Goal 13. Take urgent action to combat climate change and its impacts	
13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	Is there risk associated with failing, expanding or migrating surface water resource in a given country and/or region?
13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	Are people in a given region aware of the changes the surface water resources in their region are undergoing? Can better knowledge of surface water dynamics be used to improve climate change modelling?
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	
14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	How do the dynamics of river systems at particular risk of pollution (from diverse sources, including housing, manufacturing, industry, energy production and agriculture) relate to specific coastal ecosystems?
14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans	Are coastlines stable, and if not, how are they changing?
14.5 By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information	How do protected areas relate to changing and stable coastlines?
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	
15.1 By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements	Where are inland freshwater ecosystems located, and how have the surface areas of these changed over time?
15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	Are areas of drought or flooding linked to changes in surface water persistence?
15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	Are the boundaries of inland freshwater ecosystems changing (expanding or contracting) in a way that will have adverse effects on biodiversity?
15.8 By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species	How does the incidence of invasive species relate to the hydrographic network? Are there obvious migratory routes that may be blocked?
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	
16.8 Broaden and strengthen the participation of developing countries in the institutions of global governance	Can partnership with developing countries produce meaningful and relevant statistics on surface water resources at the national and regional level?
Goal 17. Strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development	
17.6 Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge-sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism	Are there opportunities for technology transfer concerning surface water mapping from Earth-observing satellites?

Part 2 - Mapping surface water

Why produce surface water maps?

Where's the world's surface water now?

Where was it?

Where has water area increased, and where has it decreased? How long does the water remain on the surface?

How consistently does it stay there from year to year and month to month?

What causes changes and what are the consequences?

Maps can help us model 'real world' processes, make measurements, visualise information, provide statistics, and thus support better decision-making concerning what we do with, and what we do to, the world's waterbodies.

Don Edwards San Francisco Bay National Wildlife Refuge, to the south of the Bay (shown here in a satellite image from the EU Copernicus Programme's Sentinel-2A satellite, acquired 27 October 2019) contains a number of salt evaporation ponds which can change colour, depending on salinity level and microorganism population. The image is 64 km top to bottom.
Source: Alan Belward using Sentinel-2 imagery, courtesy EU Copernicus Programme.

Mapping surface water

Why produce surface water maps?

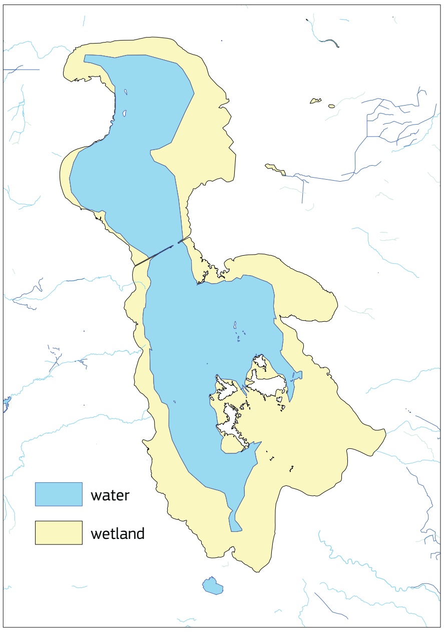
Mapping allows us to visualise information concerning when and where surface water occurs. We organise the information and present this as a series of images documenting unchanging and changing patterns. These maps are created to a consistent scale and projection, which means that the relative size and position of objects in the maps is an accurate representation of their size and position in the real world; if a lake shown on a water map looks twice as big as its neighbour on the map, you can be sure that in reality it is twice as big – and that it actually is a neighbour. Each map is a representation of reality, but at reduced size. Because maps reduce size, they inevitably reduce information too. The maps in this Atlas show surface water – everything else is intentionally removed.

Because the maps use known geographic projections and scales, they can be used to make measurements of length, width, area, position and distance. They provide information on spatial connections, put all objects depicted into context and give reference points from which to record change. The maps can also be combined with other maps (everything from roads, Nation States' borders, administrative units, population – basically anything that has been mapped) to provide additional information. Especially when held in digital form, maps can be used in computer models that aim to emulate and reproduce 'real world' processes, such as forecasting weather[1] and climate changes[2] or water consumption and demand.

The maps provide statistical information, such as surface water area in any given geographic region at any given time. But they give more than just numbers. The maps provide us with a new perspective of where and when water appears on our planet's surface and on how these changing waterbodies relate to each other. The information in the maps highlights important issues (such as the effects climate fluctuations are having on water distribution) as to how human actions are affecting its persistence and location, along with what this might mean for biodiversity, food production, industry, health, transport, energy, even social development and security. They should provoke critical thought and debate, their aesthetic qualities should help raise awareness of the importance of surface water, and the maps should help to tell stories by showing not just what has happened, but where and when.

Maps are created to a consistent scale and projection as an accurate representation of the real world.

Lake size comparison.
Maps produced to a constant scale and projection allow direct, meaningful comparisons to be made concerning shape and size (among other cartographic parameters). These extracts from the Global Surface Water Explorer illustrate the huge variety of shapes and sizes the Earth's lakes have. All lakes are shown at the same scale and geographic projection.
Source: JRC/Google Earth Engine team, graphic by Lovell Johns Ltd.



The most accurate water map ever created?
As the Global Surface Water Explorer (GSWE) Water Occurrence (1984 - 2018) maps include time (discussed on page 40 "A new approach: Capturing time in maps"), they could be considered the most accurate ever created to date. In this example, Lake Urmia, Iran, is shown from OpenStreetMap (top) and the GSWE (bottom). The GSWE map provides a continuous record of the persistence with which each part of the lake was under water, whilst the conventional OpenStreetMap presents only two water classes (water or wetland): the boundaries are entirely fixed and there is no indication as to what actually differentiates water from wetland. The 'wetland' in this case in fact used to be water!
Sources: Contains OpenStreetMap.org data © OpenStreetMap contributors, CC-BY-SA (top); JRC/Google Earth Engine team (bottom).

The right maps can help to tell the story of what is happening to our planet's surface water area, and also where, when and why change occurs.

The challenges of mapping surface water

Surface water is an ever-changing system

People were mapping surface waterbodies three thousand years ago. The oldest surviving world map, the Imago Mundi (the Babylonian map of the world), dated to circa 600 to 700 BCE (a copy of an original composition from 900 BCE), includes an ocean, an unnamed river (probably the Euphrates), a swamp and also a canal[3]. By depicting these waterbodies on the Imago Mundi, the people of the time emphasise the importance these waterbodies hold for them. The ocean, river, swamp and canal were critical reference points, defining their view of the world in which they lived. Three thousand years later, the information the map contains concerning the dimensions, location and connectivity of these waterbodies is for all practical purposes useless. This is partly because of the limited cartographic expertise and technologies available in 900 BCE, but also because most maps are wrong some of the time where waterbodies are concerned, and some maps are wrong all of the time. Maps are usually wrong because the locations they assign to the margins of any waterbody (shorelines and channel banks) are fixed at the exact time the map was drawn. But waterbody margins don't remain fixed, even waterbodies themselves appear and disappear over time.

Babylonian Map of the World (or Imago Mundi).
This partially broken clay tablet contains both cuneiform (one of the earliest systems of writing) inscriptions and a map of the Mesopotamian world. Surface water features are highlighted as: 1. River (Euphrates?) dissecting Babylon (shaded); 2. Canal; 3. Swamp; and 4. Ocean.
Source: Osama Shukir Muhammed Amin FRCP(Glasg) [CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)].

Natural change

The changes in surface water location and persistence can take place on timescales from millennia to months, even hours in the case of flooding. Africa's Lake Tanganyika began to form some 9 to 12 million years ago[4], though even this is young compared to the 25-million-year-old Lake Baikal in Russia[5]. Most lakes on Earth are less than 18 000 years old[6]. Many rivers are considerably older, with their formation linked to ancient geological events that created mountain ranges, which are at their source[7].

On human timescales, many locations on Earth can be considered as being permanently under water. Most lakes, wetlands or rivers have been more or less in the same place for as long as anyone can remember, and are extremely likely to be there for future generations too. Some locations are regularly under water for several months each year; everyone knows which months will be wet and which dry, and the seasonal waterbodies appear and disappear like clockwork. Other waterbodies are far less predictable. They appear irregularly, certainly not every year, and yet other locations are never inundated.

But even the margins of otherwise permanent, predictable waterbodies vary from time to time, as changing temperature, rainfall and snowmelt patterns from season to season and year to year affect the amount of water entering or leaving the waterbody. Prevailing weather conditions cause wetlands and lakes to diminish or grow in size, and rivers to swell or contract. Erosion and accretion patterns cause shorelines to move, rivers to meander, oxbow lakes and lagoons to form, rivers to change course entirely and deltas to either reduce or expand[8]. Entirely new shorelines also occasionally come into being when volcanic activity creates new landmasses[9] and previously permanent water disappears, such as Surtsey, Iceland or more recently Hunga Ha'apai Island, Tonga (see below).

The boundaries of the world's most established waterbodies, such as Lake Baikal and the Amazon River, change from season to season, if not year to year.

Most maps are wrong some of the time where waterbodies are concerned, and some maps are wrong all of the time.

Lake Baikal, Russia.
Lake Baikal, formed as an ancient rift valley, is the largest freshwater lake by volume in the world. It contains more water than the North American Great Lakes combined, with 22 - 23 % of the world's fresh surface water.
Source: Philipp Trubchenko on Unsplash.

Hunga Ha'apai Island, Tonga.
Hunga Ha'apai formed when a submarine volcano erupted in December 2014. The ash and rock interacted with the seawater and solidified. The new island even has its own permanent surface waterbody due to a lake forming in the volcano's crater.
Source: Jean-François Pekel and Alan Belward using 2019 Sentinel-2 imagery, courtesy EU Copernicus Programme.

Mapping surface water

Anthropogenic change

People play a vital part in surface water changes as water is withdrawn for various uses, and hydro-engineering projects take shape. Throughout our entire history, humans have 'managed' surface water: to protect against too much and too little, to improve navigability and provide safe harbours, to trap and farm food, provide power, to protect - even reclaim - land and for cultural and social reasons. Trajan's harbour, built outside Rome 100-112 CE, is no longer coastal, but the hexagonal structure is still intact and, whilst it no longer serves its original function, it is still a cultural asset and important contributor to local biodiversity almost 2000 years later.

Throughout history, humans have 'managed' surface water.

As our water engineering capabilities have increased, so too has the scale of the projects, and the effects these have on surface water location and persistence.

Humans build entirely artificial rivers, digging out and lining the channel in the case of canals, and extending this to tunnels, pipes and special bridges in the case of aqueducts. Humans also extensively modify natural river flow by constructing dykes, levees and embankments that restrict lateral movement, dams and weirs that break longitudinal and temporal connections (by cutting the river and holding back seasonal river flow) and, occasionally, fully encase rivers in pipes (these completely block groundwater recharge and seepage, and stop any direct connection between the river and precipitation). Extraction from aquifers and impermeable surfaces on floodplains and catchment areas also disrupt free flow.

Trajan's harbour, Lazio, Italy.
Trajan's hexagonal harbour (modern day "Lago Traiano") can clearly be seen in this Sentinel-2B image from 13 September 2019. The harbour now sits next to Rome's Fiumicino airport around 2 km from the coastline. Image is 12 km North-South (top to bottom).
Source: Alan Belward using Sentinel-2 imagery, courtesy EU Copernicus Programme.

Panama Canal, Panama.
Agua Clara Locks, Gatun (viewed from the Atlantic side) before entering Gatun Lake, a large artificial lake (created between 1907 and 1913 by the building of the Gatun Dam across the Chagres River) that forms a major part of the Panama Canal.
Source: US DOT [Public domain].

River Rea, Birmingham, UK.
The river is channelled and culverted as it passes through parks and built-up areas in central Birmingham, UK.
Sources: Brian Robert Marshall / The bridge on the River Rea, Cannon Hill Park, Birmingham / CC BY-SA 2.0 (top);
By flamenc [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)] (bottom).

Broken levee on the Feather River, California, USA.
Aerial view of a broken levee under repair by U.S. Army Corps of Engineers on the Feather River near Nicolaus, California, USA.
Source: Michael Nevins, U.S. Army Corps of Engineers [Public domain].

Humans modify natural waterways and build entirely artificial lakes (reservoirs) and rivers (canals).

Pont du Gard aqueduct, Gard, France.
The Pont du Gard is an ancient Roman aqueduct bridge built in the first century AD to carry water over 50 km to the Roman colony of Nemausus. It crosses the Gardon River near the town of Vers-Pont-du-Gard in southern France. The Pont du Gard is the highest of all Roman aqueduct bridges, and one of the best preserved.
Source: Xuan Nguyen on Unsplash.

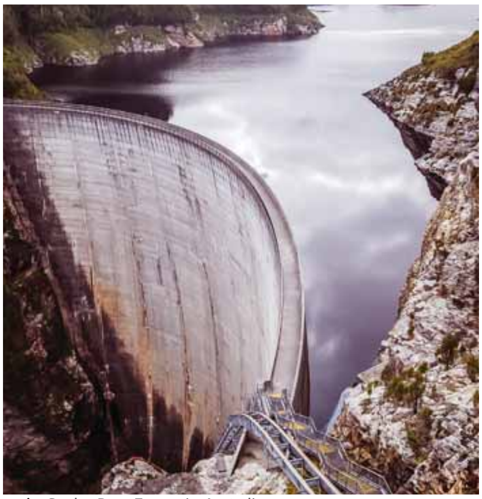
Dam building

The biggest change humans cause to surface water (in terms of actual surface area affected) is brought about by dam building. A dam is any barrier across a river that holds back water. They range in sophistication from simple rock and earth embankments to some of the world's most expensive engineering and construction projects. Damming can create spectacularly large lakes. The five largest (by surface area) alone cover over 32 500 km² of land, which is slightly larger than the US state of Maryland, or Belgium in Europe.

There are many benefits to dam building. They guarantee local water supply for multiple uses, they regulate flow and protect against flooding, they can help regulate debris movement, stop the spread of pollution (e.g. mine tailings), reduce soil erosion, they can improve waterborne transport systems by regulating and stabilising river/lake flows and levels, and dams even have recreational value for boating, picnics, sports-fishing and the like.

Dam building has drawbacks too. Transforming land into a lake (or canal) has an immediate impact on ecosystems both in the backwaters and downstream, and the services they provide[10]. Dams drown land in their backwaters and can cause fragmentation and desiccation of downstream fluvial systems, they restrict the movement of fish (in spite of cannons, ladders and elevators, all of which are used to help fish get over dams), other animal and plant life, sediments and people (more than one million people had to move because of one project alone[11]). Dams impact human and animal health by affecting pollution attenuation (dispersion, dilution and concentration in sediments), and altering the spread and concentration of pathogens and disease vectors, waste water, and harmful products from aquaculture and agriculture. They also have a profound effect on global biogeochemical cycles, emitting huge amounts of carbon dioxide (CO_2)[12].

Dams built by humans cause some of the biggest changes to our planet's surface.

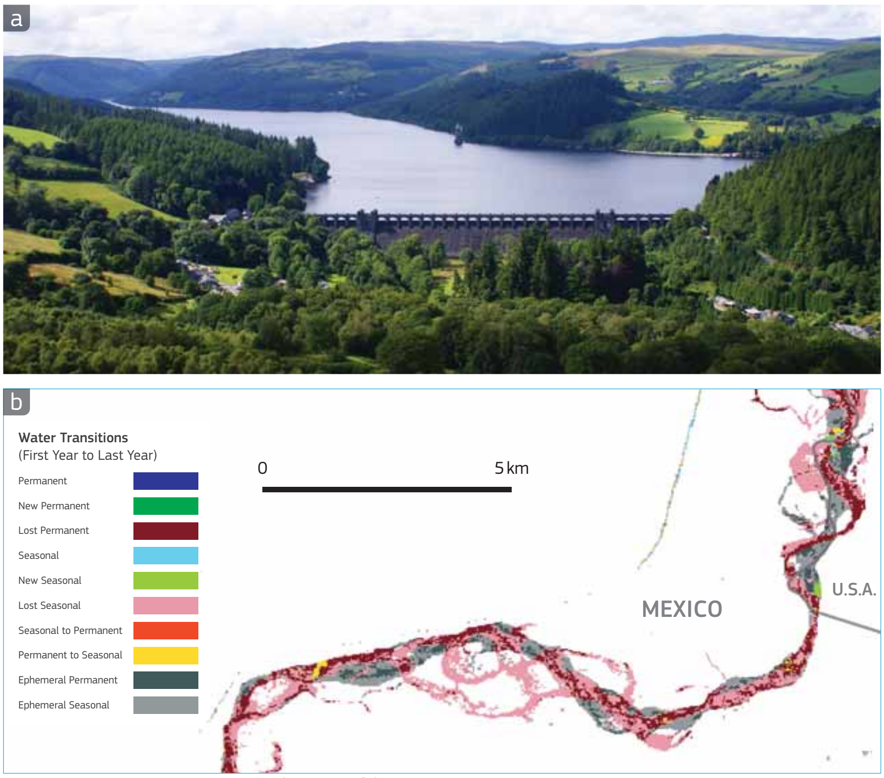


Gordon Dam, Tasmania, Australia.
Constructed in 1974, the Gordon Dam is a major gated double curvature concrete arch dam that generates hydroelectric power via the conventional Gordon Power Station located below the dam wall.
Source: Lode Lagrainge on Unsplash.

Tehri Dam, Bhagirathi River near Tehri Uttarakhand, India.
The Tehri Dam on the Bhagirathi River is a 260 m-high rock- and earthfill embankment dam. The reservoir of the dam drowned the District headquarters of Tehri, which have now been shifted to New Tehri. Furthermore, as the Bhagirathi River is considered part of the sacred Ganges, it has created resentment in some communities, who claim that the sanctity of the Ganges has been compromised for the generation of electricity.
Source: Jeewannegi [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].

Leisure benefits from dam building.
Sailing on Foulridge Reservoir, Lancashire, UK.
Source: Tim Green from Bradford - CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=52270799.

Dam building has an immediate impact on ecosystems, both in the backwaters and downstream.



The impact of dams.
a. Dams drown land in their backwaters, as seen at Lake Vyrnwy Reservoir, Powys, Wales, UK; and
b. can cause fragmentation and desiccation of downstream fluvial systems, shown here in the Global Surface Water Explorer (GSWE) as 'Lost Permanent' and 'Lost Seasonal' water in the lower reaches of the Colorado River (the dark red and pink colours in the map).
Sources: a. By Sean the Spook at English Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=12421048 and b. JRC/Google Earth Engine team; contains OpenStreetMap.org data © OpenStreetMap contributors, CC-BY-SA.

Fish cannon…
Pressurised flexible tubes (sometimes called fish cannons) provide river connectivity for migratory fish. The example shown is a volitional entry, fully autonomous fish passage system that selectively passes desired species over dams so that they can easily continue on their migratory journey, a vital part of their life cycle.
Source: The Whooshh Passage Portal™ installed on the Chief Joseph Dam, Columbia River, USA, courtesy Whooshh Innovations (www.whooshh.com).

ladder…
Large pool-and-weir fish ladder at Bonneville Dam on the Columbia River, USA.
Source: Don Graham [CC BY-SA (https://creativecommons.org/licenses/by-sa/2.0)].

and elevator.
Fish elevator at the hydroelectric power plant Grenzach-Wyhlen is located on the river Rhein, on the border between Germany and Switzerland. Once enough fish accumulate in the collection area, they are nudged into a hopper that carries them into a flume that empties into the river above the barrier.
Source: St.Hinni [CC BY-SA (http://creativecommons.org/licenses/by-sa/3.0/)].

Gravel pit lake, Geinsheim am Rhein, Hesse, Germany.
Aerial photograph of a gravel plant and lake occupying the pit following open-pit mining for the extraction of gravel deposited by the adjacent River Rhine.
Source: Fritz Geller-Grimm [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].

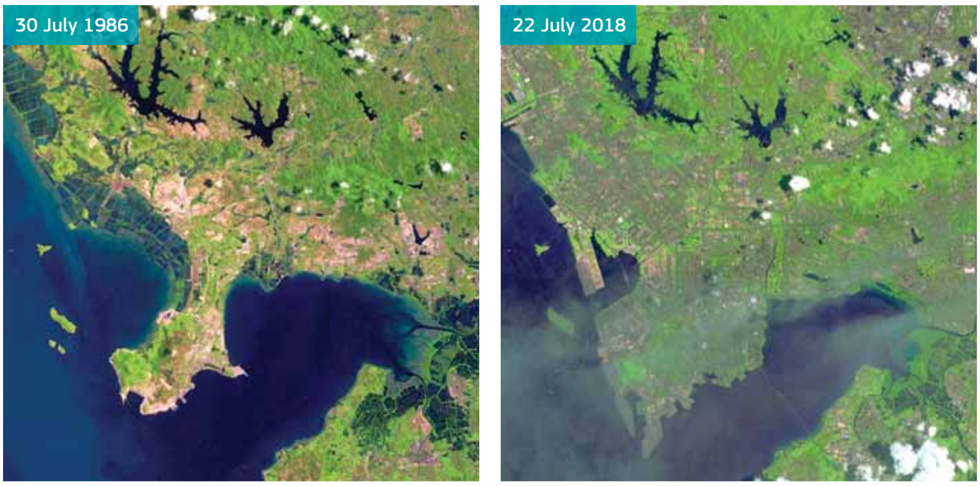
The Lincoln Memorial Reflecting Pool, Washington, D.C., USA.
People walking over the ice covering the Lincoln Memorial Reflecting Pool, a waterbody built purely for cultural/leisure reasons.
Source: Something Original at English Wikipedia [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].

Artificial lakes also form in the aftermath of industrial activity, and pit lakes form through flooding of abandoned open-cut mines (coal, sand, gravel, clay) and quarries. The remaining pit fills with ground, surface and rain water. These lakes also affect local ecosystems, even climate systems, and culture. Some ex-industrial or mining sites are used for recreation and some artificial waterbodies are constructed purely for recreational or cultural reasons.

Artificial archipelagos, Dubai, United Arab Emirates, 2010.
This false-colour image shows two artificial archipelagos along the Dubai coast: Palm Jumeirah and The World. Bare ground appears brown, vegetation appears red, water appears dark blue, and buildings and paved surfaces appear light blue or grey.
Source: Jesse Allen using ASTER imagery, courtesy JAXA/NASA and the US/JAPAN ASTER Science Team.

Markermeer, the Netherlands, 2018.
In 1932, Dutch engineers turned a saltwater bay of the North Sea into a freshwater lake. In subsequent years large tracts of land (the polders) were drained and turned into farmland. This land reclamation process still continues, and a new artificial archipelago, the Marker Wadden, is currently under creation. Work started in April 2016. The still expanding islands can be seen close to the centre of this image, and are shown in a zoomed inset. Landsat scene acquired 26 July 2018, main image is 105 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

Land reclamation and drainage schemes replace surface water with new land.



Land reclamation, Shenzhen, China.
Two comparative images showing the level of reclamation to accommodate Shenzhen's ever-increasing population. Extensive land reclamation along the Qianhai Bay and Shenzhen Bay area has rendered the coastline almost unrecognisable over a period of little more than three decades. Images are 25 km North-South (top to bottom).
Source: Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

Humans also remove surface water, sometimes temporarily by draining lakes and wetlands[13], sometimes with more permanent intentions through land reclamation and the creation of artificial islands[14].

Our planet's surface water cover is intensely dynamic. Ideally, we should be able to map these changes as they happen, or soon after, and travel back in time to build up a picture of what has already changed. Furthermore, this mapping should be equally accurate in all places and at all times. However, checking the entire planet's surface for the appearance - or disappearance - of water every day is quite a challenge.

Mapping surface water

Global mapping made possible with satellites

Photogrammetry (the science of obtaining measurements from photographs[15]) and aerial photography revolutionised map making. Aerial photography provides many advantages over ground-based surveying, by providing access to difficult to reach geographic regions[16], providing a synoptic view, consistency and uniformity of observation, through the ability to freeze motion, by the creation of a permanent record and because distortions (caused by factors such as terrain displacement, camera tilt and aircraft movement) can be removed to make accurate cartographic products.

In spite of the advantages, aerial photography has never provided regular global coverage. The costs in terms of time requried to collect and process photographs covering very large areas, let alone the logistical challenges of negotiating sovereignty of air space, and dealing with poor flying weather conditions, make this a non-starter. Earth-observing satellites on the other hand don't suffer from these drawbacks. Permission isn't needed to overfly sovereign territory if you are in space, and if the satellite is in a near-polar orbit it can acquire imagery of anywhere on the planet's surface again and again.

In near-polar orbit, satellites pass above the Earth slightly inclined from the two geographic poles[17]. A satellite in such an orbit follows an almost circular path, and as the satellite orbits the Earth, the Earth is turning on its own axis beneath the satellite, which means that the satellite will fly over a different strip of land with each successive orbit. Eventually the satellite will fly over land that it has already flown over. This provides the time dimension to mapping from satellite images. At an altitude of 1 000 km it takes around 100 minutes for a satellite to complete one orbit, so it will complete 14 orbits every 24 hours. The time it takes for the satellite to fly over the same strip of land again is called the revisit period. This can vary from a day to around two weeks or so, depending on the orbit and the characteristics of the sensor carried by the satellite. Some sensors just look at a narrow strip of ground underneath the satellite (but in great detail), others see less detail, but a far greater area. The width of the strip of ground is described as 'swath-width'. This is typically somewhere between 100 and 1 000 km. A sensor with a narrow swath width will need to fly more orbits to image the entire planet's surface than a wide-swath-width instrument.

By the 1960s, photographs of Earth were being obtained from satellite[18]. The exposed film was parachuted back to Earth in capsules, which were caught in mid-air on special winches by aircraft. This technology was primarily for military use[19], though the photographs entered the public domain when the Clinton Administration declassified US reconnaissance imagery from the 1960s and '70s[20]. The photographs provide a unique historical view of selected parts of our planet at specific dates, but only for selected parts and only for specific dates. There were too few satellites flying, and the cameras they carried didn't contain enough film to photograph all of the Earth's surface repeatedly.

Satellites no longer carry film cameras. Earth-observing satellites carry electronic imagers capable of recording multispectral information at multiple wavelengths. Some collect imagery analogous to panchromatic film, others collect information in multiple, but separate, wavebands, including measurements of visible, near and middle infrared light. Some carry thermal sensors, and others imaging radars that can see through clouds and at night[21]. The images are transmitted to data-receiving stations on Earth. Some satellites use on-board recorders to capture images when the satellite cannot see a station's data-receiving dish (data are transmitted the next time the satellite does see the dish), and some transmit the images to a separate communications satellite that can see the station[22]. Through a combination of line of sight, on-board recording and data relay satellites, repeated global image acquisition is truly possible.

The Kremlin, Moscow, 28 May 1970.
Military 'spy' images were the only high resolution images taken during the 1960s and early 70s.
Source: CIA/National Reconnaissance Office using KH-4B imagery, courtesy http://www.digitalvaults.org/tags/m/moscow.html

Catching a satellite.
An Air Force JC-130B catching a satellite with grappling gear and winch at Edwards AFB, California, 1969.
Source: United States Air Force [Public domain].

Permission isn't needed to overfly sovereign territory if you are in space.

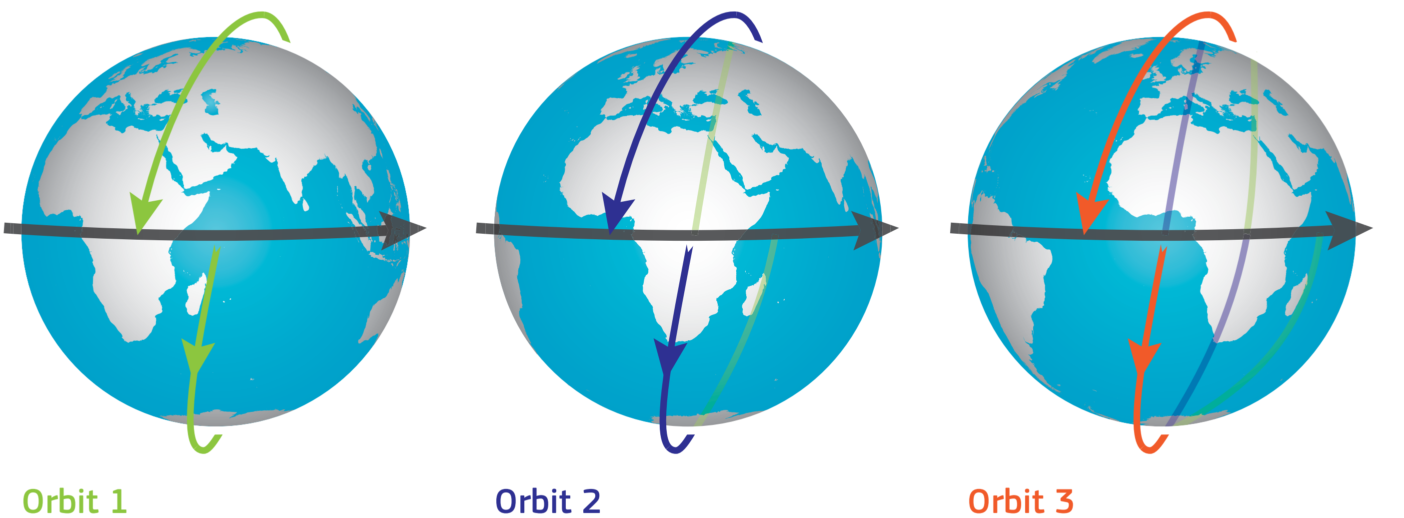


Figure 2-1 | Satellite orbits.
A satellite in near-polar orbit follows an almost circular path. Orbit 1 shows the track followed by the satellite during the first 99 minutes of flight time. By the time the next 99-minute orbit begins (Orbit 2) the Earth has turned on its own axis and the satellite is now flying over a new strip of land; the ground track followed by the satellite during the first orbit is shown in fainter green, successive orbits in blue and orange.
Source: Robert Simmon, NASA, redrawn by Lovell Johns Ltd.

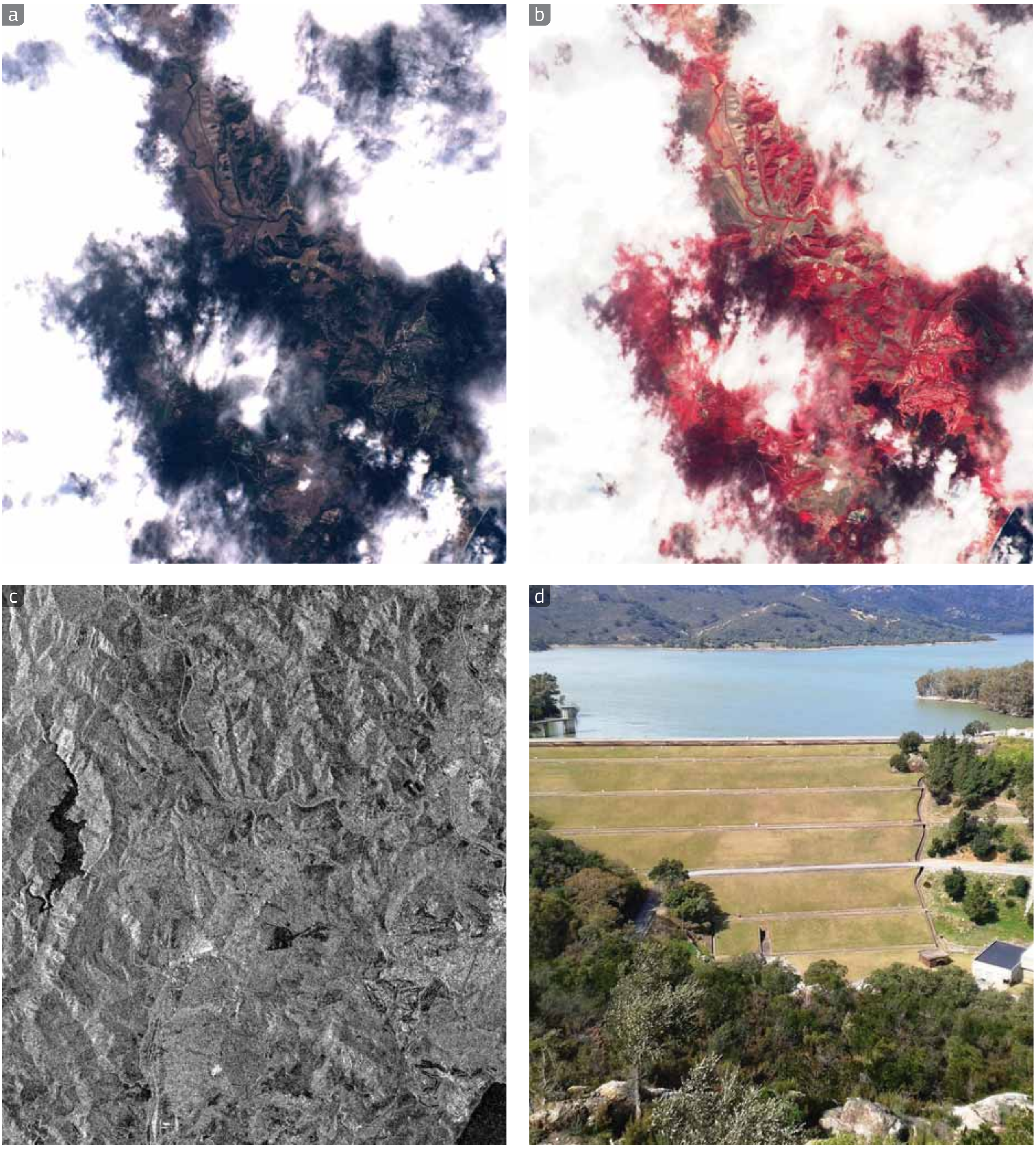
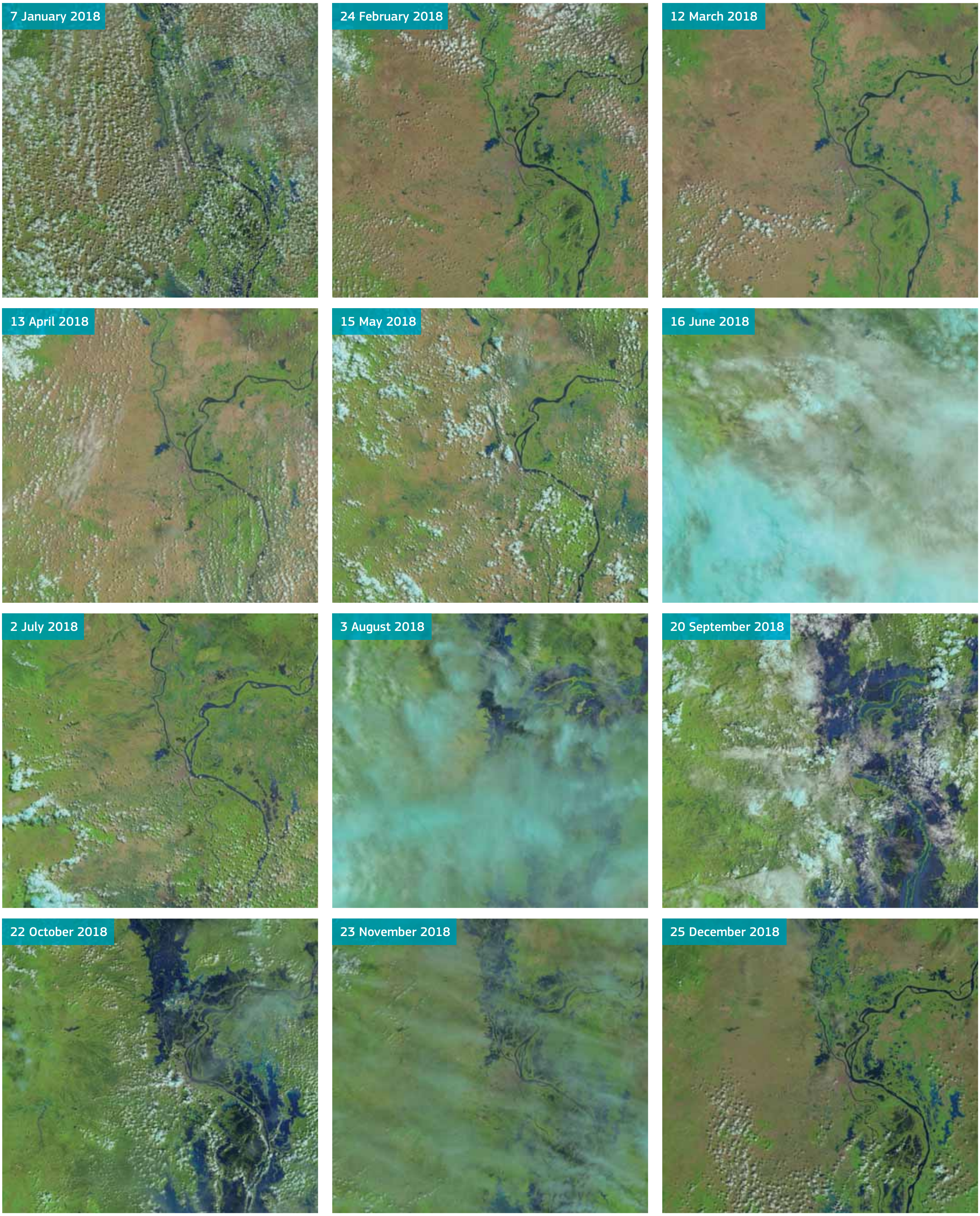


Figure 2-2 | Some satellite sensors see things you can't.
The sensors on many satellites measure electromagnetic radiation [light] at wavelengths beyond the range of the human eye.
Figure 2-2a shows a true colour image collected by the Copernicus Sentinel-2 satellite of the Guadiaro River flowing into the Mediterranean Sea and the Guadarranque Reservoir (Cadiz Province, Spain). The line of the river can just be seen in the centre of the picture. The reservoir and river estuary are completely obscured by clouds. True colour images like this are roughly the same as a photograph you would take with your smartphone.
Figure 2-2b is from the same satellite on the same day (13 November 2019) but this is a false colour image, where the sensor has captured near infrared reflectance (which your eyes, or smartphone, cannot see).
Figure 2-2c is an image of exactly the same area, acquired on the same cloudy day, but by a different satellite, Sentinel-1. Sentinel-1 is a radar imaging satellite and its sensors are sensitive to electromagnetic radiation at such long wavelengths that they can pass completely uninterrupted through the clouds. The reservoir and estuary can clearly be seen from space at these wavelengths in spite of the cloudy day.
Figure 2-2d is a (true colour) photograph of the Guadarranque Reservoir's Dam.
Sources:
a-c. Alan Belward using Sentinel-1 and 2 imagery, courtesy EU Copernicus Programme.
d. 15Gitte (1 March 2015) This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Spain.

Satellites repeatedly fly over the same ground, month after month, year after year.

Next page: The regular revisit period of the Landsat satellites allows us to capture patterns.
This sequence of Landsat 8 images, collected throughout 2018, show Phnom Penh, Cambodia, sited at the confluence of the Tonlé Sap River (flowing top to bottom in the images) with the Mekong River (flowing from the top right corner in the images). This river system flows at reduced levels from January through to July, before expanding dramatically in August, September and October, then retreating again in November and December. The regular revisit period of the Landsat satellites allows us to capture this annual pattern and to see how it changes from year to year. The image sequence also reveals one of the biggest challenges to mapping from satellite time-series where optical imagery is used… clouds. Using an expert system, we are able to avoid the clouds and only analyse the cloud-free pixels in each image. Each scene is 135 km North-South (top to bottom).
(Top left to bottom right: 7 January, 24 February, 12 March, 13 April, 15 May, 16 June, 2 July, 3 August, 20 September, 22 October, 23 November, 25 December 2018.
Source: All images Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.


7 January 2018
24 February 2018
12 March 2018
13 April 2018
15 May 2018
16 June 2018
2 July 2018
3 August 2018
20 September 2018
22 October 2018
23 November 2018
25 December 2018

The colour of water

Multispectral scanners on polar-orbiting satellites are in effect measuring colour. In general, vegetation, soil, bare rock, buildings and water all reflect, transmit and absorb light differently. The fractions of reflectance absorption or transmission of visible light in turn determines the colour of the object as we perceive it. Actively growing vegetation looks green to us[23], soils can appear anything from almost black, to red, yellow and almost white[24], buildings often look grey. But what colour is water?

Pure water is largely transparent to visible light - most just passes straight through it. Pure water does reflect slightly more blue light than any other visible light, which is why deep bodies of clean water appear to be a deeper, more intense blue than shallow waters; there is a greater column of water reflecting blue light back to the eye, whilst absorbing more of the other wavelengths[25]. Because water is so transparent, the apparent colour of a waterbody depends very much on what's under it and what's in it. Chlorophyll concentration (e.g. from phytoplankton in the water), total suspended solids (such as soil particles) and coloured dissolved organic matter load, the depth of the water and waterbody bottom material for shallow waters all affect the way it will look in a satellite image.

Unfortunately, other surfaces can share some of the spectral properties of water under certain illumination or viewing conditions. Shadows cast by buildings, trees, mountains and clouds can all look very like a waterbody when seen from space, so too can glacier moraines, the lava outflow from volcanoes, dark, wet soils, coal and spoil heaps linked to mining and industrial sites, and the burn scars from fires. Even parking lots, roofing and solar panel arrays in photovoltaic farms can sometimes look like waterbodies. Waterbody mapping using multispectral satellite imagery has to resolve this spectral overlap.

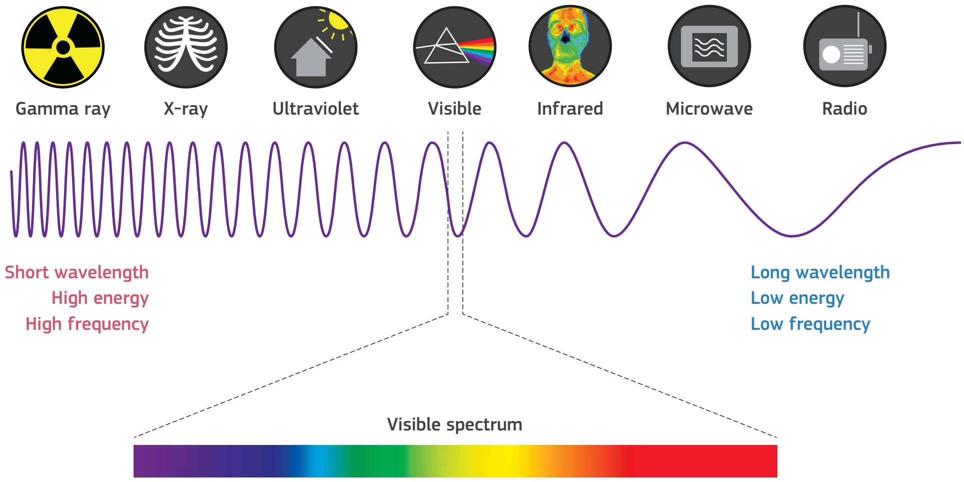


Figure 2-3. | The electromagnetic spectrum.
The radiation behind radio waves, visible light and nuclear blasts is all electromagnetic radiation, just with different amounts of energy and different wavelengths. The human eye is sensitive to a very small part of the electromagnetic spectrum: visible light. Our eyes perceive electromagnetic radiation with different wavelengths/energy levels as different colours.
Source: http://www.abc.net.au/science/articles/2010/02/18/2817543.htm
Redrawn by Lovell Johns Ltd.

Water isn't one colour.
Earth-observation satellites measure light (in terms of our eyes, this means colour). Mapping different objects in a satellite image relies, at least in part, on measuring differences in their colour. Mapping water all across the globe on the basis of colour is a huge challenge, because water isn't one colour; its colour depends on what's in it, and what's under it. On the global scale a multitude of combinations of 'in' and 'under' occur.
Sources: All photos Alan Belward except Lake Urmia (bottom left), Tasnim News, Creative Commons Attribution 4.0 International.

From space, certain objects can appear to be water when they aren't.
From space a lot of things, such as shadows, solar panels, and buildings, can mimic the colours of water. This colour confusion (or technically speaking, overlapping multispectral reflectance characteristics) needs to be resolved. This is achieved using an expert system that employs both subtle multispectral discriminators, and time.
Sources: All photos Alan Belward except Glacier, (top centre) Andrew Grandison Creative Commons Attribution-Share Alike 3.0 Unported; (middle left) Montaña Blanca lava, QuartiCreative Commons Attribution-Share Alike 3.0 Unported; (middle right) Photovoltaic panels, U.S. Navy's Bill Mesta Public Domain.

Making the Global Surface Water Explorer's maps

An appropriate data source – the Landsats

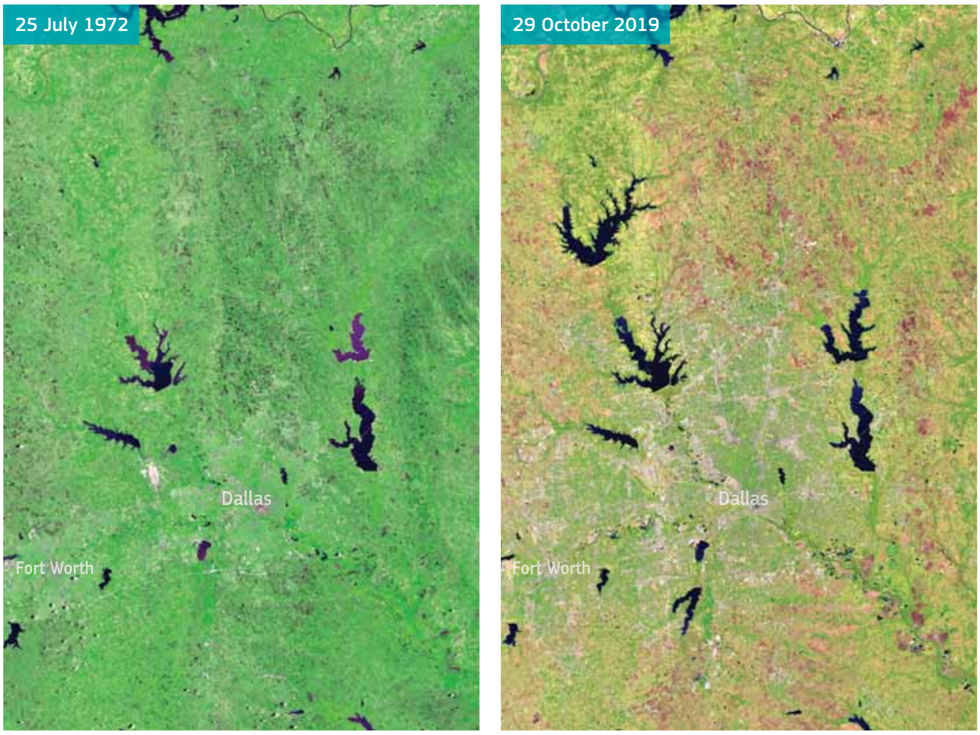
To tell the stories and answer questions concerning the persistence and location of the Earth's surface water, maps need to cover the planet's entire landmass, they need to go back in time, and they need to describe the changes over time in sufficient detail, spatially and temporally. Multispectral images collected by polar-orbiting satellites can support this, and data from these have been used to map various attributes of land cover for many years[26,27,28,29].

A map's value is significantly enhanced if it provides consistent detail (both geographically and over time) along with consistent, documented accuracy across the entire map, and at all periods if the map includes a time dimension. Achieving consistency is most likely if the map maker uses the same methods and same data for all locations and dates. The Landsat program provides the longest unbroken record of satellite images of our planet[30]. The maps in this Atlas were produced using these data.

The first generation Landsats (1 to 3), launched in the 1970s, collected imagery with a spatial resolution of around 60 metres. By 1984 the Landsats carried multispectral sensors collecting imagery with a spatial resolution of 30 m. The sensor carried by Landsats 4 and 5 was called the Thematic Mapper (TM), on Landsat 7 it was a slightly improved Enhanced Thematic Mapper-plus (ETM+), and Landsat 8 carries the Operational Land Imager (OLI). All three sensors provide the same level of spatial information (30 m pixel), all collect data at visible, near and middle infrared wavebands, and all satellites in the Landsat series, from Landsat 3 onwards (launched in 1978), also acquire thermal imagery.

The United States Geological Survey (USGS) teams operating the Landsat program and their science partners put a huge amount of effort into ensuring that the images they archive and distribute are geographically and radiometrically stable. Distortions due to terrain and tilting of the sensor/satellite are removed through a process called orthorectification. The digital counts recorded by the satellite are converted into a physical measurement - reflectance - in a step that also takes instrument calibration into account. Calibration is needed because sensor performance changes over time. This process is carefully measured and calibration coefficients are applied to ensure that the same amount of reflected radiation received by the sensor will always translate into the same value in a digital image, even when images are acquired many years apart. Orthorectified, top-of-atmosphere reflectance and brightness temperature images, called Level One Terrain (L1T)[31], are processed, archived and freely distributed by the Landsat program[32,33]. The Landsat program has collected many millions of individual images in the course of its operation, and hundreds more are added to the archive each day[34]. The maps shown in this Atlas were created using the archive of L1T images from Landsats 5, 7 and 8 acquired between 1984 and 2018. Of course, surface waterbodies changed before 1984 as well as since 2018. The maps in this Atlas are a snapshot of the water dynamics during the 1984–2018 period; the Global Surface Water Explorer continues to monitor new surface water dynamics as satellite images are acquired and archived.

The Landsat program's satellites have collected images of the Earth since 1972.



Dallas-Fort Worth, Texas, USA.
The first image collected by the Landsat program was of the Dallas-Fort Worth area, Texas. Part of this historically significant image, acquired on 25 July 1972, is reproduced here. Even with a spatial resolution of about 60 m the Red River can be seen flowing across the top and flowing into, and out of, Lake Texoma (only part of the lake is seen). It is one of the largest reservoirs in the USA, formed by the Denison Dam, completed in 1944. Smaller reservoirs surround the Dallas-Fort Worth metropolitan area in the lower half of the image. The Landsat program has continued uninterrupted since this date. The right-hand image acquired by Landsat 8 on 29 October 2019 shows the metropolitan area where the number of artificial lakes have both noticeably increased. Images are 110 km East-West (left to right).
Source: Alan Belward using Landsat 1 and 8 imagery, courtesy USGS/NASA.

Artist's impression of Landsat 8 satellite in orbit.
Source: NASA/Goddard Space Flight Center Conceptual Image Lab.

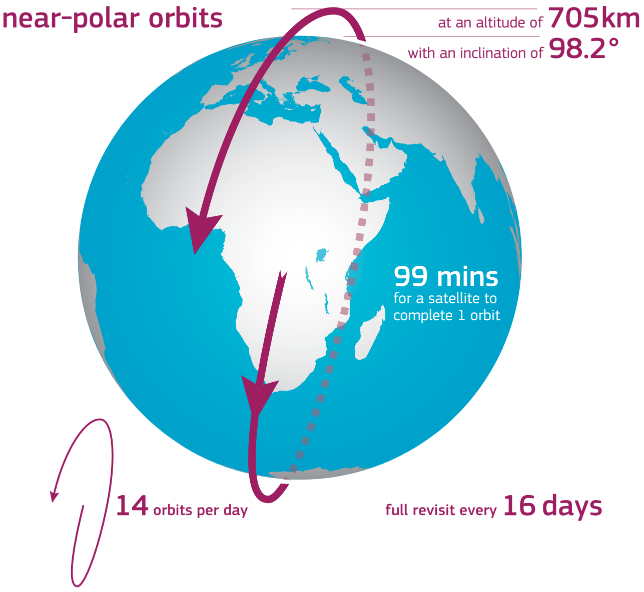
Millions of images, billions of pixels

The Landsat 4, 5, 7 and 8 satellites occupy near-polar orbits at an altitude of 705 km. It takes 99 minutes for each satellite to complete one orbit, and thus each satellite completes over 14 orbits per day, with full revisit every 16 days (except at the extreme poles)[35]. There has often been more than one Landsat flying at any time, and two Landsat satellites operate concurrently, with the orbits positioned to deliver an 8-day revisit period. The Landsat satellite images are gathered in a continuous strip, with the width of the strip determined by the height of the orbit and the field of view of the sensor; in the case of the Landsats these give a 'swath width' of 185 km. However, the swaths overlap by 7 % at the equator and, as the orbits get closer together at high latitudes, overlap increases to 68 % at 70 degrees latitude[36]. The adjacent orbit to the west of a previous one is collected a week later, thus pixels in the side-lap areas from both swaths provide unique views of the surface. The continuous image swath is divided into individual image frames, and for convenience these are provided in 185-km blocks. Thus, each Landsat image is 185 by 185 km in size. The division of image frames along an orbit track is made so that there is a small amount of overlap (to avoid unwanted gaps) but, unlike the side-lap images, these overlapping areas along a single orbit track display identical data, not unique views.

Every unique view represents an opportunity to check for surface water. Landsat 5, launched 1 March 1984, collected TM imagery until November 2011. Landsat 7, launched 15 April 1999, acquired imagery normally until 31 May 2003 when part of the sensor, the scan line corrector (SLC), stopped working (images collected after the failure have a slatted appearance, because parts of the data are missing). SLC failure causes around 22 % of each scene to be lost[37], but any pixel actually collected is a valid observation and provides a unique view[38]. Two Landsats operated from April 1999 onwards, and the program began a dedicated global acquisition strategy then too[39]. Landsat 8 began operational imaging in April 2013. From April 2013, the program made available virtually every image of the Earth's landmass collected by the satellite, and in 2010 the USGS began to recover historic archive holdings from receiving stations around the world.

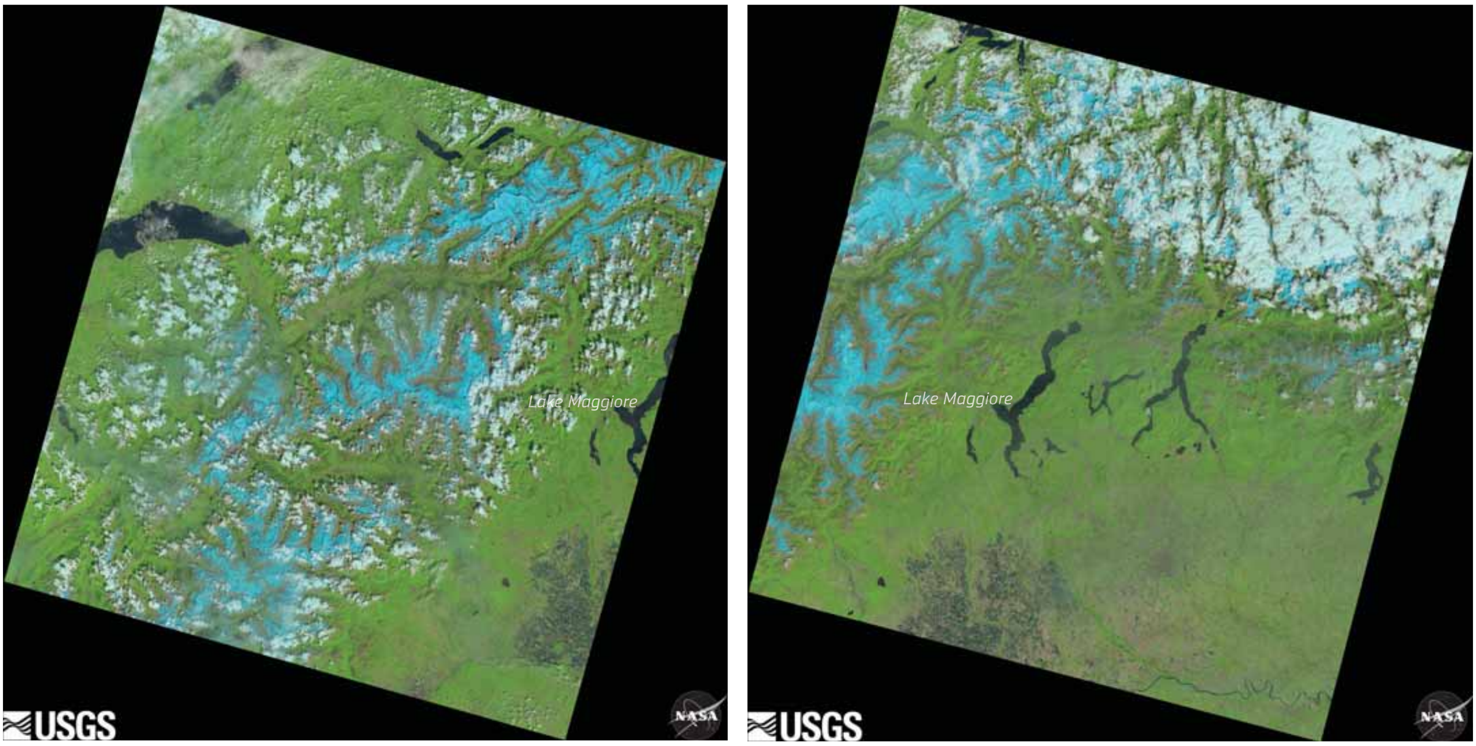
Each image has multiple bands. The Global Surface Water Explorer (GSWE) uses three visible, one near infrared, two short-wave infrared and a thermal band[1]. There is thus an enormous stack of data covering every 30 × 30 m square of the Earth; seven individual measurements per image, one image possibly every 16 days, sometimes every 8 days, and sometimes every week, for the entire operational life of the satellites. By 2018, the GSWE was based on 3 865 618 L1T images (1 823 terabytes of data), covering 99.95 % of Earth's landmass. All of these data were copied to the Google Earth Engine, which provided the processing and analysis environment for the GSWE[40].

1 The thermal bands have a slightly lower spatial resolution than 30 m, but for data management purposes they are usually mapped to the same 30 × 30 m grid.



Nearly 4 000 000 Landsat scenes were analysed to produce the maps in this Atlas.

Lake Maggiore, Italy, Landsat scenes.
Two official Landsat 8 'quicklook' natural colour composites as downloaded from the USGS Earth Explorer data distribution service (https://earthexplorer.usgs.gov/). Each image covers 185 by 185 km. Both images show Lake Maggiore and neighbouring lakes in Italy, Switzerland and France on the southern edge of the Alpine mountain chain. The lakes are the darkest colours. The very pale blue colours are snow on the mountains, the brighter white colours are clouds. Vegetation appears green. The image on the left is from path (orbit) 195, row (scene centre) 28 acquired on 31 May 2017. Most, but not quite all of Lake Maggiore appears on the right-hand edge of the scene. The image on the right (to the west) is from path (orbit) 194, row (scene centre) 28 and was acquired one week earlier on 24 May 2017. All of Lake Maggiore can be seen in this scene. Each of these paths was overflown by the satellite every 16 days before these images were acquired, and every 16 days since. The Earth's surface outside the side-lap is only seen once during the 16-day orbit cycle, whilst it is seen twice in the overlapping region.
Source: USGS Earth Explorer with labels, Lovell Johns Ltd. using Landsat 8 imagery, courtesy USGS/NASA.



Mapping surface water

The data processing challenge

Separating water pixels from everything else around the globe is in itself demanding, doing this for petabytes of satellite imagery is truly demanding. As described earlier, water doesn't come in one colour - its spectral properties at the wavelengths measured by the TM, ETM+ and OLI sensors vary enormously according to what's in and under it. Variations in observation conditions (sun-target-sensor geometry, and optical thickness) also add to the variability. On the global scale, across multiple years, all possible conditions will be encountered somewhere at some time.

To address this challenge, a dedicated expert system was developed to assign each pixel to one of three target classes, either water, land or non-valid observations (snow, ice, or cloud). However, not all pixels could be unambiguously assigned to these three classes on the basis of spectral characteristics alone. This is where the expert system uses 'evidential reasoning' to guide class assignment. The evidence being a mixture of geographic location and changes in reflectance over time at that specific location. Geographic location is important because spectral confusion between water and other surfaces can only occur in locations where those other surfaces are found, and time is important because this spectral overlap may occur at specific times of the year and not at others. Spectral confusion between water and glaciers can only occur in parts of the world that have glaciers – these were identified using the Randolph Glacier Inventory 5.0[41]. Similarly, confusion with volcanic lava can only occur where there is lava! So, a global scale lava mask was established from both spectral characterisation and visual interpretation of Landsat images. And finally, shadows from buildings, terrain and clouds had to be identified and separated from water. In the case of buildings, the Global Human Settlement Layer (GHSL)[42,43] targeted areas where shadows cast by buildings would occur, terrain shadowing problems were targeted using one of four Digital Elevation Model (DEMs)[44,45,46,47] (four were used to provide the best available DEM resolution at any given location) and cloud shadows were targeted by first detecting clouds in each image. In every case, spectral behaviour over time was the final deciding factor. Shadows move over time, while water surfaces move far less frequently (even seasonal water can be expected in some months, and not at all in others). Visual inspection of the water maps identified any scattered residual false detections, which were manually removed. Less than 0.002 % (72 km²) of the maximum water extent was cleaned in this way. These errors were linked to industrial sites, photovoltaic farms and urban infrastructure that were not represented in the GHSL data. Some errors may still remain in the maps, but their impact is accounted for in the map accuracy assessment, or validation step.

The expert system was run in Google's Earth Engine, a computational infrastructure optimised for parallel processing of geospatial data. Running the expert system on a single computer CPU would have taken 1 212 years, but using 10 000 computers in Earth Engine the processing was completed in around 45 days, although building, testing and validating the expert system took almost two years[48].

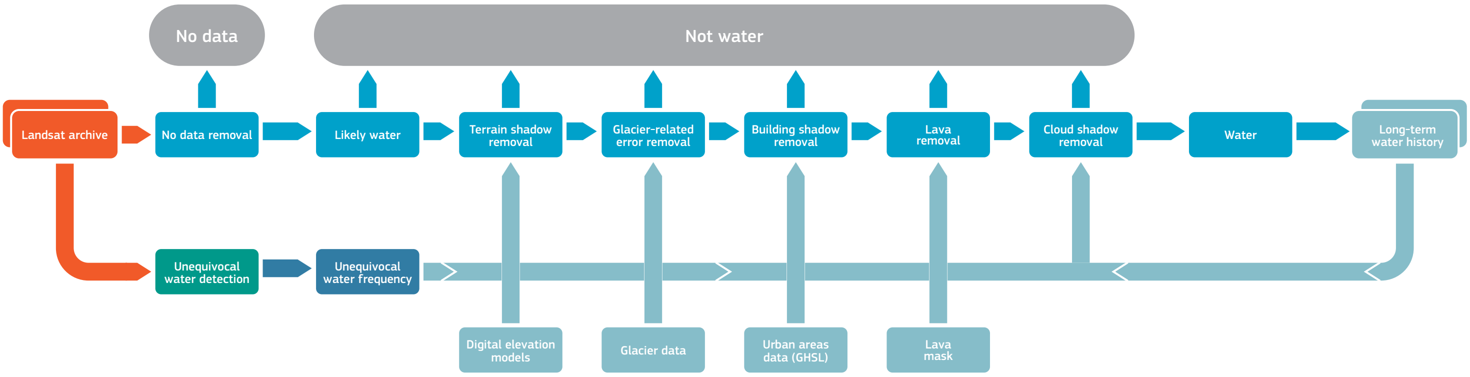
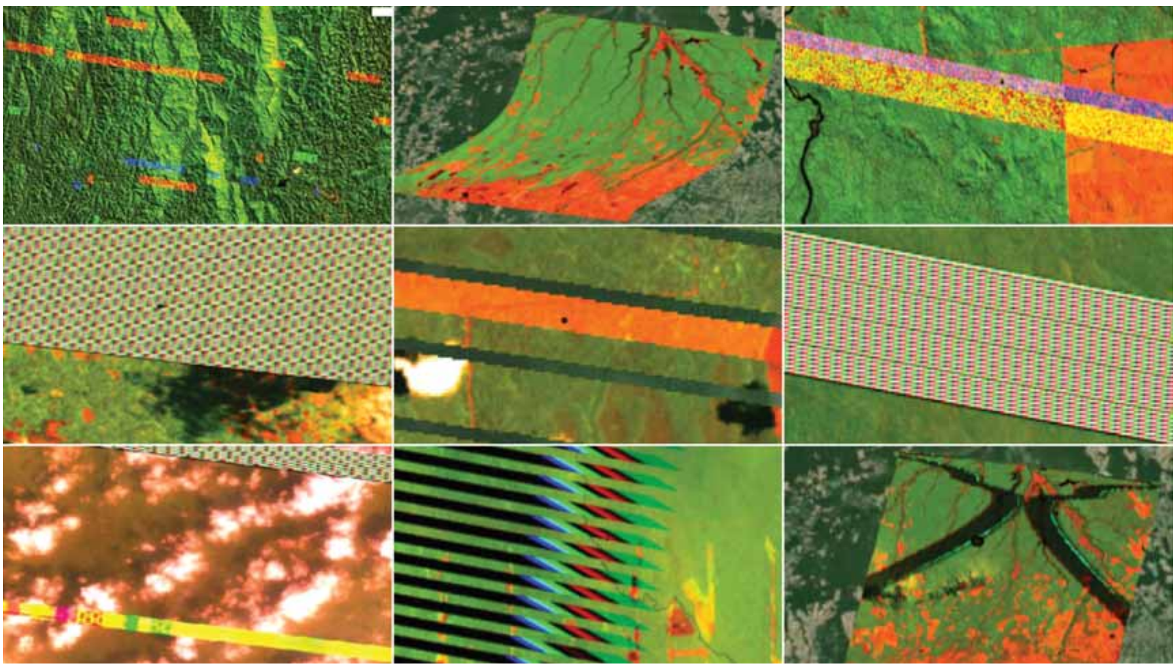


Figure 2-4.
Diagram of the expert system classifier used to detect water.
Source: Pekel et al., 2016.



Data anomalies.
Although most Landsat scenes are error free, occasional glitches do occur. The expert system has to deal with data anomalies, such as those illustrated above, as well as detect clouds and separate water from all other possibilities.
Source: Jean-François Pekel using Landsat imagery, courtesy USGS/NASA.

How accurate are the maps?

The accuracy of a map can be measured in terms of its geographic qualities (are all objects presented correctly and consistently in terms of relative size and position?) and thematic content (is the surface water depicted in the map actually surface water, or have areas of water been missed (errors of omission?) and have areas that are not really water been mapped as water (errors of commission?))

The geographic accuracy of the maps in this Atlas are directly linked to the orthorectification and remapping processes applied to the Landsat imagery used to identify water. The geometric accuracy of the Landsat L1T products is such that all objects should be placed to within 25 metres of their true position[49,50].

The thematic accuracy was determined by comparing the classified water maps with over 40 000 control points, where water was confirmed to actually occur at a specific time. These control points were distributed across the globe, spanned more than three decades, and sampled imagery from all three sensors (TM, ETM+ and OLI). Errors of omission overall were less than 5 %, and errors of commission less than 1 %. Omission for seasonal water classes was higher than that for permanent, but overall less than 1 % of the points in the validation database where water was actually present remained entirely unmapped over time (see Figures 2-5 and 2-6). In other words, if the water maps say water occurred at a given location at a given time, over 95 % of the time the map will be right!

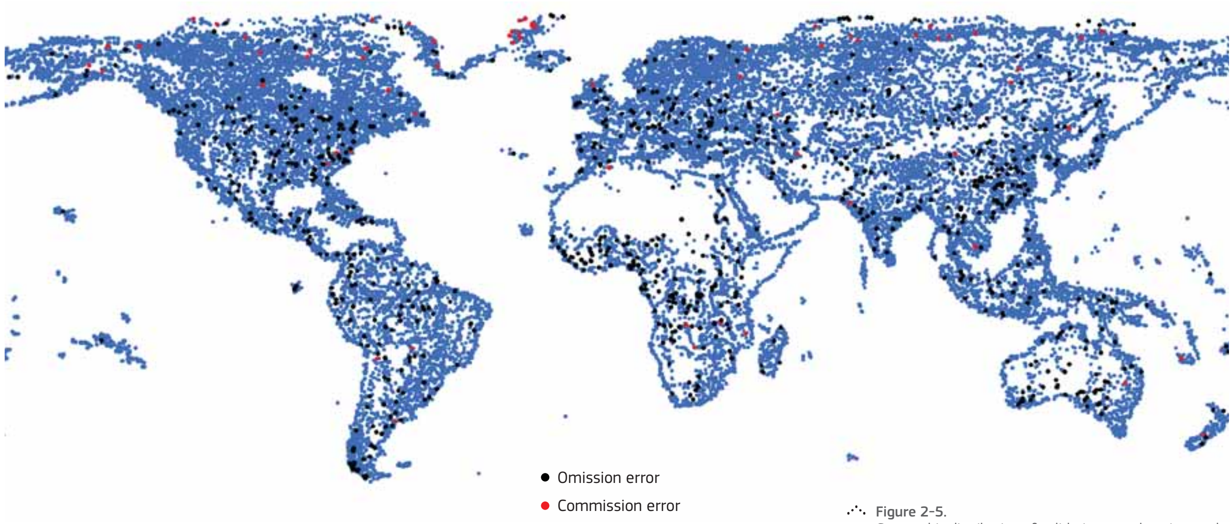


Figure 2-5.
Geographic distribution of validation sample points and errors.
Source: Pekel et al., 2016.

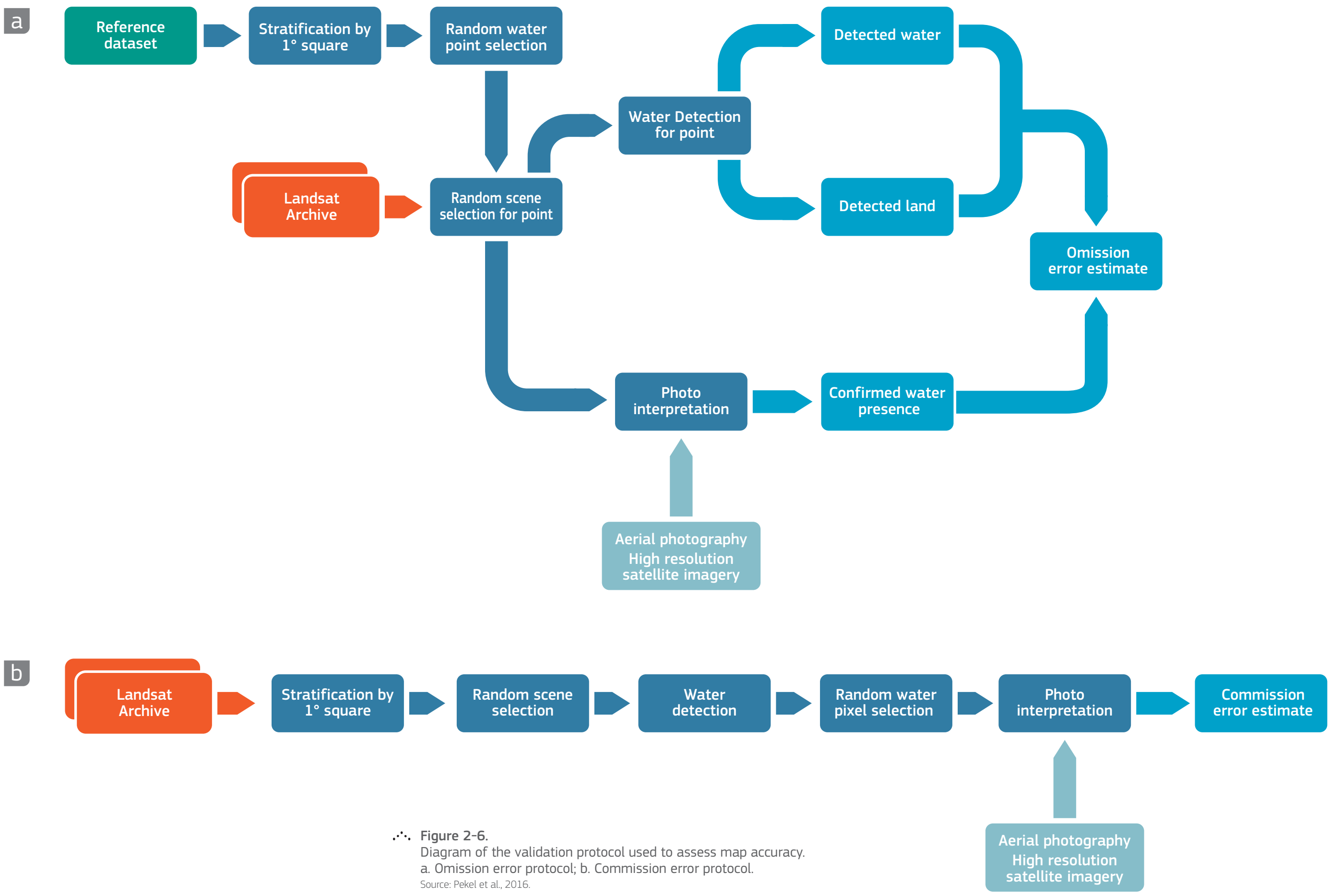


Figure 2-6.
Diagram of the validation protocol used to assess map accuracy.
a. Omission error protocol; b. Commission error protocol.
Source: Pekel et al., 2016.

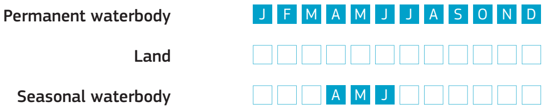
A new approach: Capturing time in maps

The water-mapping process creates a three-dimensional space/time matrix, in which every 30 × 30m square of the Earth's landmass can be identified as either land or water, month by month, stretching back across the entire satellite image archive. The dataset used for the maps shown in this Atlas had 418 layers (one per month from March 1984 to December 2018 inclusive), though not all 30 × 30m cells in all layers are full. A cell will only contain a value if there was a valid observation at that location during the month / year in question. If there was a valid observation, then the cell will either be registered as a 'water detection' or as land. As new satellite images are continuously added to the archive, new layers are continuously added to the matrix, and the Global Surface Water Explorer continues to capture surface water dynamics in the months and years beyond 2018.

Some 30 by 30m locations in the matrix will be classified as water every time the satellite observes them – these are the permanent water locations, with a 100% recurrence pattern; typically, the world's stable river channels, the main body of a lake away from the shoreline, the permanent ponds in wetlands and the open seas. Others are water for some months of the year, but the pattern repeats annually – these are seasonal waterbodies with a 100% recurrence pattern. There are also locations where water is more intermittent, it may be there for a month or two, or even a few years, but isn't permanent – these are seasonal or permanent water bodies with a low recurrence rate. There are also places on Earth that used to be water but are now land, locations that were once land but are now water, locations that have transitioned from one state to another, and finally, we have locations that are always land and never water.

Scenario 1 cannot change. For a waterbody to be truly permanent, water must be present on the surface throughout the year and for every year of observation. Over time though, permanent waterbodies can appear (Scenario 2) or disappear (Scenario 3). Seasonal waterbodies (Scenario 4) never have water present throughout the year; there will always be some 'wet' and some 'dry' months. The exact pattern of 'wet' and 'dry' months might be the same year after year, but inter-annual variation is more likely. Scenario 4 shows inter-annual variability for a fully recurrent seasonal waterbody. The seasonal waterbody has a 100% recurrence because 'wet' months occur every year. But the recurrence pattern by month is only 100% for May, other months have a lower recurrence rate. As with permanent waterbodies, seasonal waterbodies too can appear (Scenario 5) and disappear (Scenario 6) over time. And of course, seasonal can become permanent (Scenario 7), permanent become seasonal (Scenario 8). A waterbody, whether permanent or seasonal, may not be present every year; wet years may be interspersed with dry (Scenarios 9 and 10). All scenarios are illustrative. Any combination of start dates, end dates and transitions is possible.

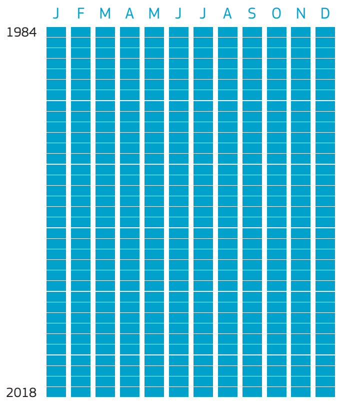
a. In any single year of observation, 1 of 3 conditions are possible:



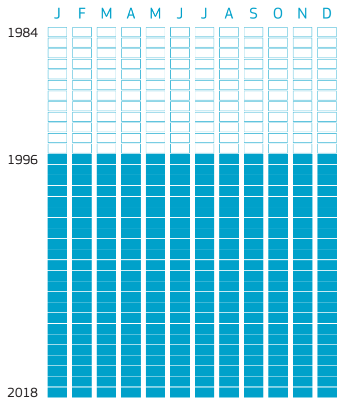
In this example, seasonal water is present in April, May and June. Seasonal water can occur in any month/set of months, but will never be present throughout the year. April, May and June are given for the purpose of illustration. It is far more likely that the months/set of months will vary somewhat from year to year; the same waterbody could contain water in April, May and June in one year, in May, June and July the following year, and only April and May the year after that. The Global Surface Water Explorer captures this inter-annual variability.

b. Examples of water occurrence and recurrence for the main water classes mapped by the Global Surface Water Explorer:

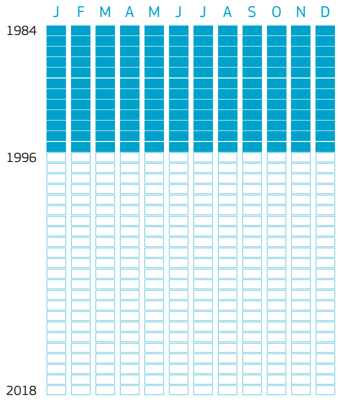
Scenario 1:
Permanent waterbody
remaining in place continuously (100% recurrence)



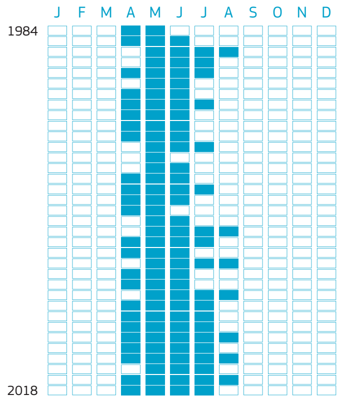
Scenario 2:
New Permanent waterbody
In this example, the waterbody formed in 1996 and remained in place ever since



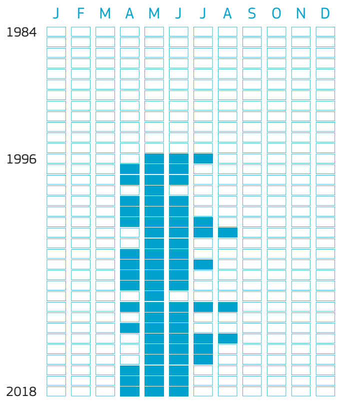
Scenario 3:
Lost Permanent waterbody
In this example, the waterbody disappeared in 1995 and never reappeared



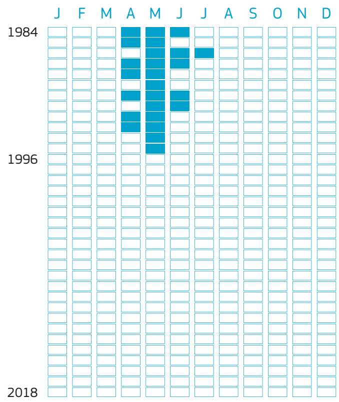
Scenario 4:
Seasonal waterbody
In this example, the waterbody is present every year. It is present in May each year (100% recurrence for this month), but the full period when the seasonal waterbody is present varies from year to year.



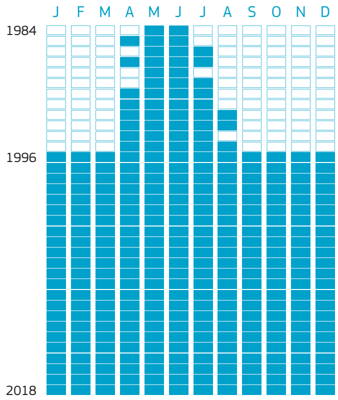
Scenario 5:
New Seasonal waterbody
In this example, the waterbody formed in 1996 and remained in place ever since



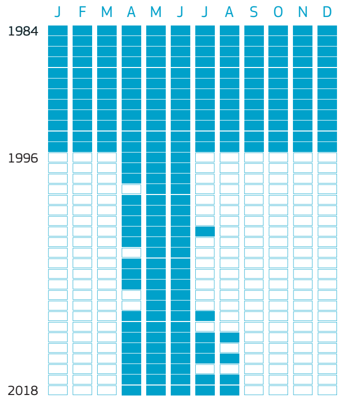
Scenario 6:
Lost Seasonal waterbody
In this example, the waterbody disappeared in 1995 and never reappeared



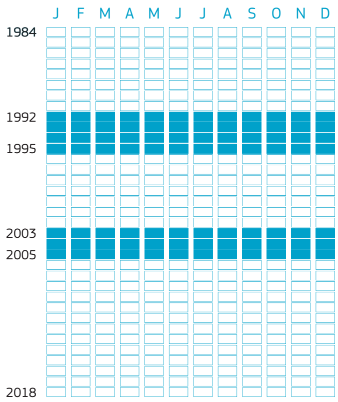
Scenario 7:
Seasonal to Permanent waterbody
In this example, the seasonal waterbody became permanent in 1996 and remained in place ever since



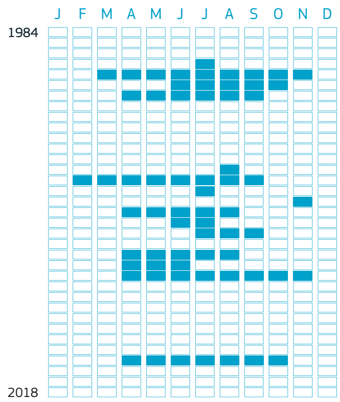
Scenario 8:
Permanent to Seasonal waterbody
In this example, the permanent waterbody became seasonal in 1996 and remained in place ever since



Scenario 9:
Ephemeral Permanent waterbody
In this example, the pernament waterbody formed between 1992 and 1995, and again between 2003 and 2005



Scenario 10:
Ephemeral Seasonal waterbody
In this example, the seasonal waterbody formed in 15 different years, but the months where water was present varied from year to year



c. **A number of transitions between water and land are possible. These can occur between any two dates:**

Scenario	Water Transition	Water Transition type	Real world example
1	Permanent	$W^P > W^P$	Middle of Lake Superior, North America
2	New Permanent	$L > W^P$	Damming of the Nile River (and creation of Merowe Lake, Sudan, Africa)
3	Lost Permanent	$W^P > L$	Disappearing lake (Aral Sea, Asia)
4	Seasonal	$W^S > W^S$	Flooded rice field (Po Valley, Italy, Europe)
5	New Seasonal	$L > W^S$	Margins of an expanding reservoir
6	Lost Seasonal	$W^S > L$	Disappearing wetlnds (Paraná floodplains, South America)
7	Seasonal to Permanent	$W^S > W^P$	Permanent flooding of a formerly seasonal wetland (damming)
8	Permanent to Seasonal	$W^P > W^S$	Retreating lake (i.e. Razzaza Lake, Iraq, Asia)
9	Ephemeral Permanent	$W^P > L > W^P$ (in any combination)	Toshka Lake, Egypt, Africa
10	Ephemeral Seasonal	$W^S > L > W^S$ (in any combination)	Lake Eyre, Australia

L = land, W^S= seasonal water, W^P = permanent water

The same waterbody, geographically speaking, can contain cells of various classes, especially at the margins of a waterbody. For example, the central part of most lakes will fall into Scenario 1, 'Permanent' water, yet the lake margins may well fluctuate from month to month, or even year to year, thus they could fall into any of the other scenarios.

Visualising time

In the Global Surface Water Explorer (GSWE), the surface water dynamics are captured in six unique water maps, each of which catches and depicts a different aspect of how surface water changes with time:

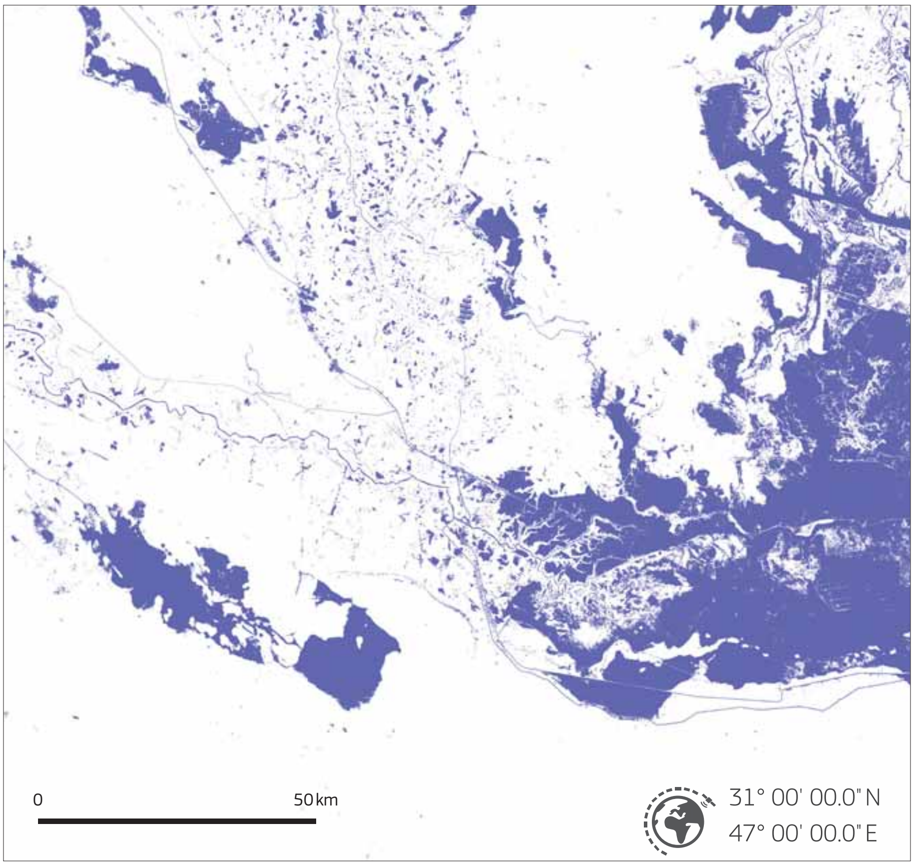
1. Maximum Water Extent (1984 – 2018)
2. Water Occurrence (1984 – 2018)
3. Water Occurrence Change Intensity (1984 – 1999 to 2000 – 2018)
4. Water Seasonality (2018)
5. Annual Water Recurrence (1984 – 2018)
6. Water Transitions (First Year to Last Year)

Full details on how each map is made can be found in a 2016 paper by Pekel et al.[51]

Mapping surface water

Q: Where has water appeared on the Earth's surface?

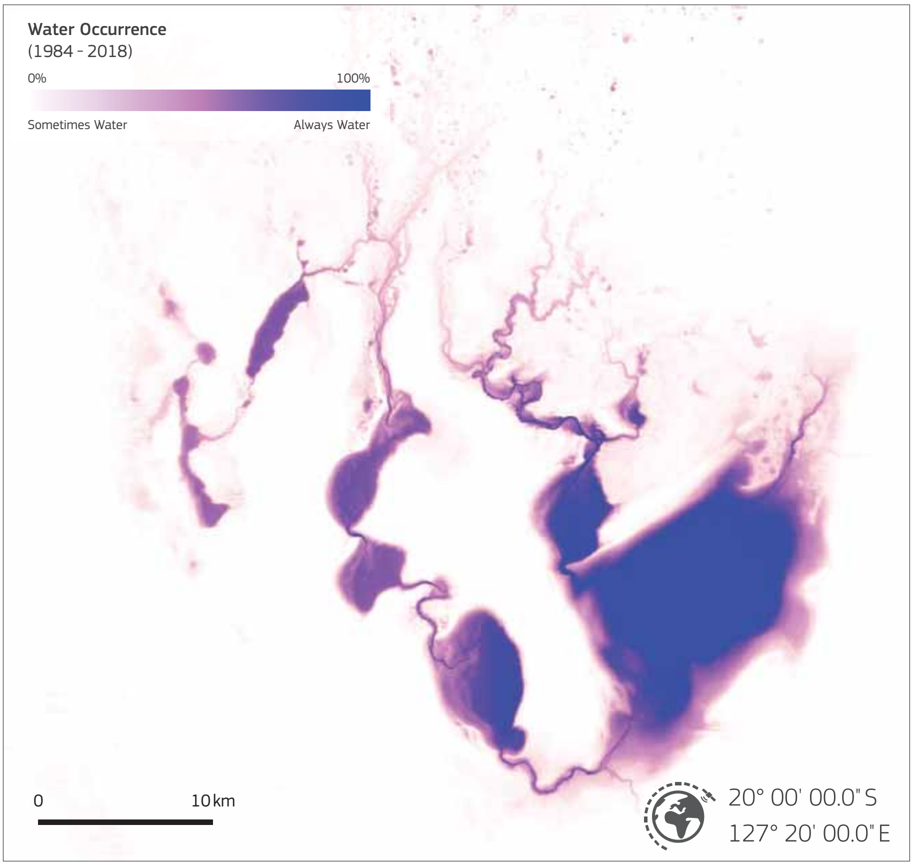
The Global Surface Water Explorer (GSWE)'s **Maximum Water Extent (1984 – 2018) maps** depict all locations ever identified as water in the satellite image archive. The Maximum Water Extent map makes no attempt to separate permanent features, seasonal water, increases or decreases. This is simply a way of visualising where the Earth has had standing water on its surface for at least one month – and where it has never been inundated for any appreciable length of time.



Mesopotamian marshes, around the confluence of the Tigris and Euphrates rivers, northwest of Basra in Iraq.
The marshes (a UNESCO World Heritage Site since 2016) have undergone dramatic changes over the past few decades, as draining to reclaim land for agriculture, and even to evict people for politically motivated reasons, followed by partial recovery (due to political change) and prolonged pressure (due to upstream dam building) have taken their toll on the extent of this important ecosystem. The Maximum Water Extent can be used to map the maximum area of the ecosystem's open water since 1984.

Q: How persistent is water on the Earth's surface?

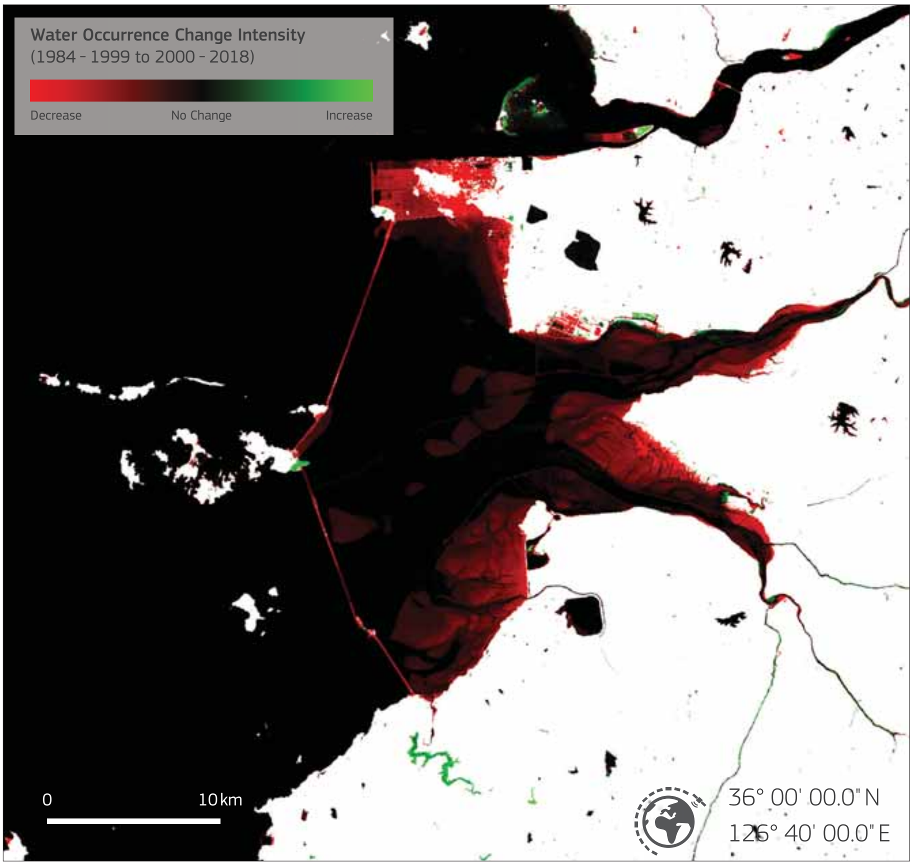
The GSWE's **Water Occurrence maps** provide information concerning the overall persistence of water on the Earth's surface. The examples in this Atlas span the period 1984 to 2018, though the exact period documented by the Global Surface Water Explorer depends on the length of the archive at that point. And the archive is constantly expanding. Water Occurrence captures both intra- and inter-annual variability. The occurrence is a measurement of the water presence (expressed as a percentage of the available observations over time actually identified as water). This ranges from 0% (never water), shown as white tones in the maps, through to 100% (truly permanent water) shown as purple. Tonal variation from purple to white captures variations in persistence over time, with the palest shades being areas where water occurs less frequently.



Lake Gregory (Paraku), Australia.
The Lake Gregory system (known as Paraku to the region's indigenous people) is one of Australia's few natural, (nearly) permanent, lakes. The lake is fed by a creek system with its origins in Australia's humid zone, so usually receives enough water to keep it full. Even so, as shown by the occurrence map here, the shorelines shift considerably, with the persistence of water being far from permanent in the margins. As an endorheic lake (a closed system with no outflowing river) the levels fluctuate depending on inflow and loss from evaporation. In particularly hot, dry years, the water can become saline, though the lake is usually classified as freshwater. In 1990 the lake pretty much dried out completely, with water only present for a month or so. In fact, most of Australia's lakes, including the largest waterbody, Lake Eyre, are ephemeral, only filling in the wettest years.

Q: Where has surface water occurrence increased, decreased or remained constant?

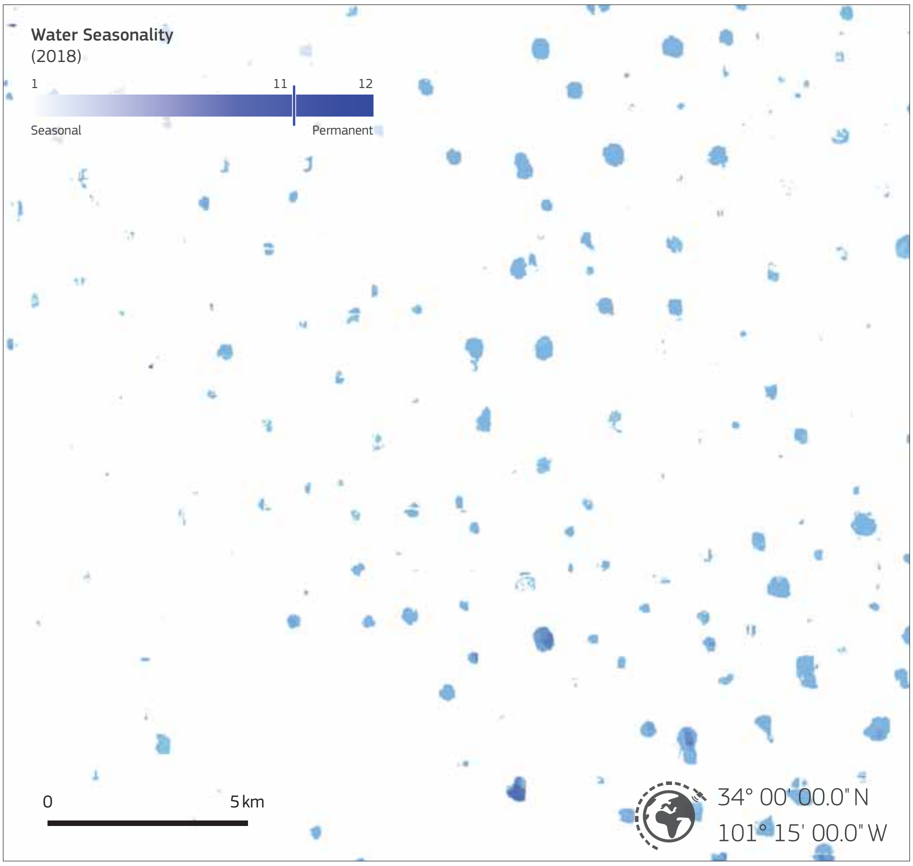
The GSWE's **Water Occurrence Change Intensity maps** show where surface water occurrence increased, decreased or remained the same between 1984 and 2018. The direction of change and its intensity are documented. The occurrence change accommodates variations in data acquisition over time in order to provide a consistent measurement. Increasing and decreasing surface water occurrence may not automatically translate into gains or losses. Just think of the consequences in terms of biodiversity. Increases in water occurrence are shown in green and decreases are shown in red. Black areas are those areas where there was no significant change in the water occurrence during the 1984–2018 period. The intensity of the colour represents the degree of change (as a percentage). For example, bright red areas show greater decrease in water occurrence than light red areas. Areas that appear grey in the maps are locations where there are insufficient observations to compute meaningful change statistics.



Saemangeum Seawall, South Korea.
The Saemangeum Seawall is (at the time of writing) the world's longest man-made dyke (33 kilometres long). It separates the Yellow Sea from the former estuary at the mouths of the Dongjin and Mangyeong rivers. The dyke is creating new farmland and a freshwater reservoir - although coastal reservoirs such as this don't in themselves drown land, saltwater is swapped for fresh, so has profound impacts on biodiversity. The construction of the wall, surrounding infrastructure and new farmland are all seen in the decrease in surface water occurrence.

Q: How much seasonal water and permanent water is there in any particular year?

The GSWE's **Water Seasonality maps** describe the intra-annual distribution of water. For any given year, these maps discriminate between 'permanent' and 'seasonal' water surfaces. A permanent water surface is under water throughout the year, whilst a seasonal water surface is under water for less than 12 months of the year. Some locations don't have observations for all months of the year (e.g. because of the polar night in winter) and in these cases water is considered as seasonal if the number of months where water is present is less than the number of months for which valid observations were acquired. A second consideration is lakes that freeze for part of the year. Even when the surface is solid, liquid water is still present under the ice layer, both for lakes and seas. The classification system used to create the water maps treats ice as a non-valid observation, so the observation period only corresponds to the unfrozen months. If water is present throughout the observation period (i.e. unfrozen period), the lake is considered as a permanent water surface. If the area of the lake contracts or expands during the unfrozen period, then the pixels along the borders of the lake are no longer water (or land, depending on the direction of area change) and those pixels will be considered as a seasonal water surface. The degree of seasonality is shown as variations in blue tones; again, white indicates areas that have never been under water during that particular year, the darkest blue represents permanent water (present for all observed months) whilst tones get lighter as fewer observed months show water and the water season effectively gets shorter.

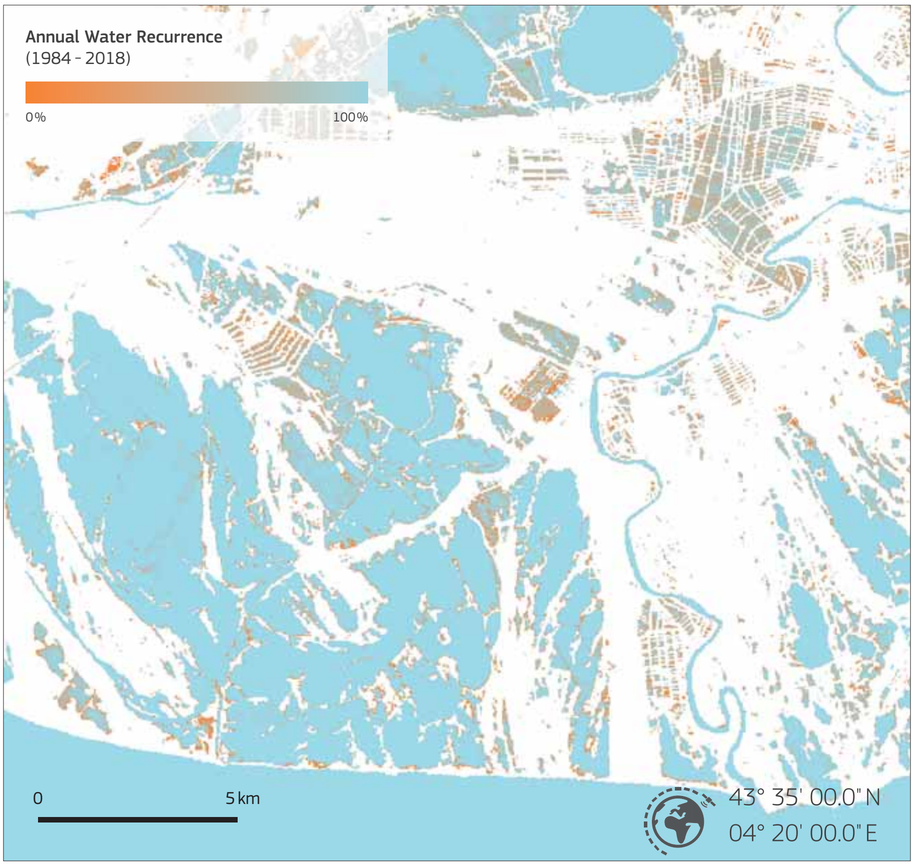


Vernal pools, Texas.
Vernal pools are found all across Northern Texas. The majority of these are absent from traditional maps. These temporary waterbodies form in depressions most years following rains. Fish are usually absent, and this missing predator element encourages much other biodiversity in these important (temporary) ecosystems.

Mapping surface water

Q: How much does the surface water pattern change from year to year?

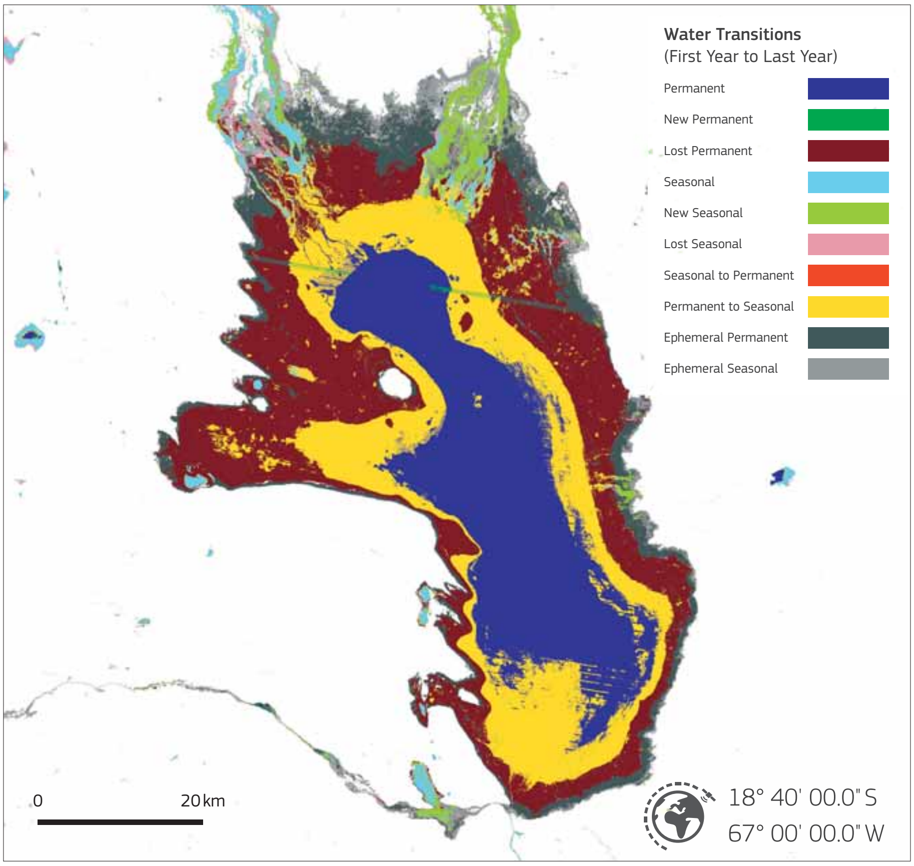
The GSWE's **Water Recurrence maps** measure inter-annual variability in water's presence. They describe how frequently water returns from one year to another (expressed as a percentage). Unlike occurrence, recurrence is not systematically computed over the full span of the satellite image archive, because water may not have been present from the beginning to the end. A 'water period' is first established. This identifies the dates when water was first and last observed at any location. A 'water season' is then identified (this is not equivalent to a 'wet season'). The water season is identified as those months of the year that sometimes (or always) have water. A 'water-year' is a year with at least one water observation, whilst an 'observation-year' is a year with at least one valid observation within the water season. Water recurrence is then calculated as the ratio of the number of 'water years' to 'observation years'. Years that only contain observations outside the water season are not counted; we have no way of knowing if water might have occurred in the water season because we have no observations. The recurrence is expressed as a percentage. As the percentage of recurrence increases from 1 to 100, the colour changes from bright orange, fading into light blue. A recurrence of 100% means that the surface water occurrence (whether a permanent waterbody or seasonal) is unvarying over time.



Rice fields, pools, lagoons and rivers of the Camargue, France.
Rice has been grown in the Camargue wetlands around the lower reaches of the Rhône river since the end of the 13th Century. Most fields are in regular use, so although the fields are only open water for two to three months of the year, they have similar levels of water recurrence to the permanent waters of the Rhône and the surrounding wetland pools.

Q: Where has the location and persistence of surface water completely changed?

The GSWE's **Water Transition maps** document changes in water state between any two years of observation. The map identifies unchanging permanent water surfaces; new permanent water surfaces (the transition from land to permanent water); lost permanent water surfaces (the transition from permanent water to land); unchanging seasonal water surfaces; new seasonal water surfaces (transition from land to seasonal water); lost seasonal water surfaces (transition from a seasonal waterbody to land); transition of permanent water to seasonal water; and the transition of seasonal water into permanent water. The maps don't describe what happened in the intervening years. Unchanging water surfaces in this map means that the surface water class at that particular point was the same in the first and last year it was observed, and not that it was stable throughout. Stability must be checked by using the recurrence map, the occurrence change intensity map or the long-term water history captured in the individual layers. Occasionally water isn't present at the beginning or the end of the observation record but does appear at some intermediate point in time. These 'ephemeral' events can be tracked as ephemeral permanent water (land replaced by permanent water that subsequently disappears) or ephemeral seasonal water (land replaced by seasonal water that subsequently disappears).



Lake Poopó, Bolivia.
Lake Poopó, Bolivia, sits at an altitude of around 3700m, and is the country's second-largest lake, after Lake Titicaca, which Bolivia shares with Peru. Lake Poopó is almost endorheic (there is a small outlet at its southern tip) and is very shallow (mean depth is less than 3m), which means its surface area fluctuates greatly within and between years, occasionally drying out almost completely. Indeed, the lake disappeared completely from 2015 to the end of 2017, but by 2018 it had recovered. However, the transition map shows how small the current permanent surface water area is compared with the surrounding lost permanent water and water that is now only present for a few months of the year.

The Global Surface Water Explorer overview | https://global-surface-water.appspot.com/

Go deeper into the data

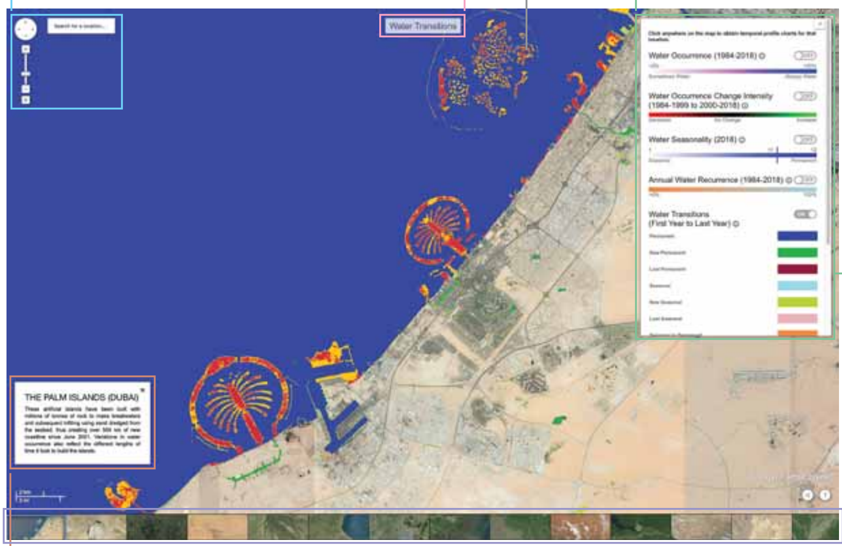
Clicking anywhere on the map provides exact latitude/longitude coordinates, and access to histograms describing the monthly water occurrence plus the year-by-year water history. Clicking on the histogram bar for any specific year displays a third histogram depicting the entire month-by-month water history for that specific year. The user can then return to the full water history to display additional years' information if desired.

Datasets

As discussed in 'A new approach: Capturing time in maps' (page 40), there are 6 datasets that each catch and depict a different aspect of how surface water changes over time.

Standard map navigation tools

Dataset selected



Summary explanation of the selected regional highlight

Regional highlights (see Part 4)

Clicking on the selection of regional highlights at the foot of the window centres the map on the particular highlight and opens the summary explanation.

Select the map backdrop

Earth Time-Lapse allows the user to view the surface-water changes over time. The time-lapse can be paused on any year to see the particular snapshot.

World Map provides the user with location context as well as an indicaion of terrain.

Satellite adds a detailed backdrop of land use to contextualise the water data.

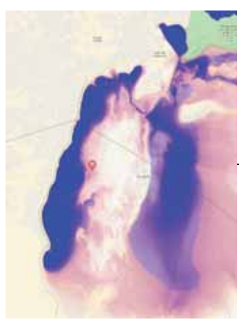
White presents an unimpeded view of the, often stunning, data.

More than maps

The space/time matrix records the appearance and disappearance of water on the Earth's surface month by month, year by year at each location. This full history can be displayed for any individual pixel as a temporal profile (see Figure 2-7). These profiles highlight specific months/years in which conditions change. At any geographic location, three histograms can be generated from the profiles. A monthly recurrence histogram (2-7a) shows the intra-annual distribution of the water, and characterises water seasonality. It also provides information on the water recurrence for each month. A water history chart shows the class (land, seasonal water and permanent water) for each year in which valid observations were acquired (2-7b). The month-by-month presence of water and observations within any single year can also be extracted (2-7c).

Finally, water area statistics can be calculated for any geographic region. The national, continental and global statistics reported in this Atlas are obtained from the occurrence, recurrence and transition maps plus the long-term water history by combining the maps with the Global Administrative Unit Layers dataset (GAUL)[52]. Area measurements (km²) are reported for:

- maximum surface water occurrence over 35 years (1984-2018);
- permanent water in the first year of observation;
- permanent water in the last year of observation;
- permanent water with 100% recurrence;
- transition from land to permanent water;
- transition from seasonal to permanent water;
- transition from permanent water to land;
- transition of permanent water to seasonal;
- seasonal water in the first year of observation;
- seasonal water in the last year of observation; and
- seasonal water with 100% recurrence.



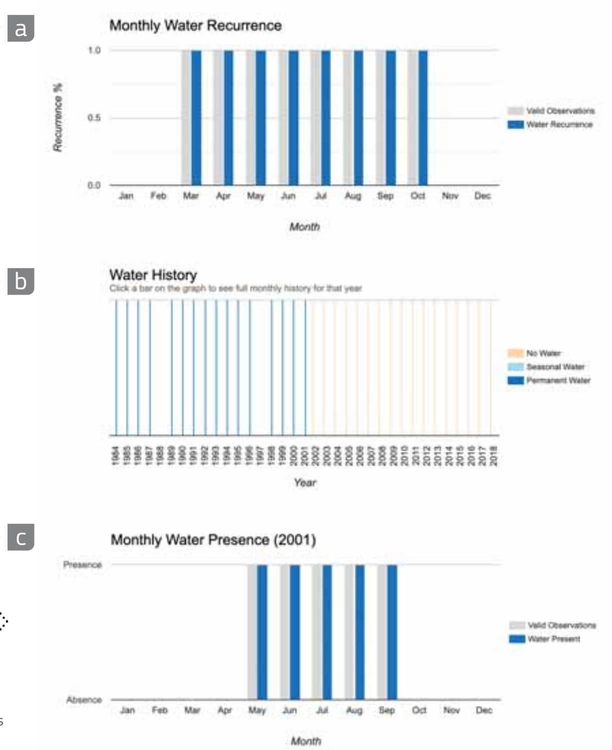
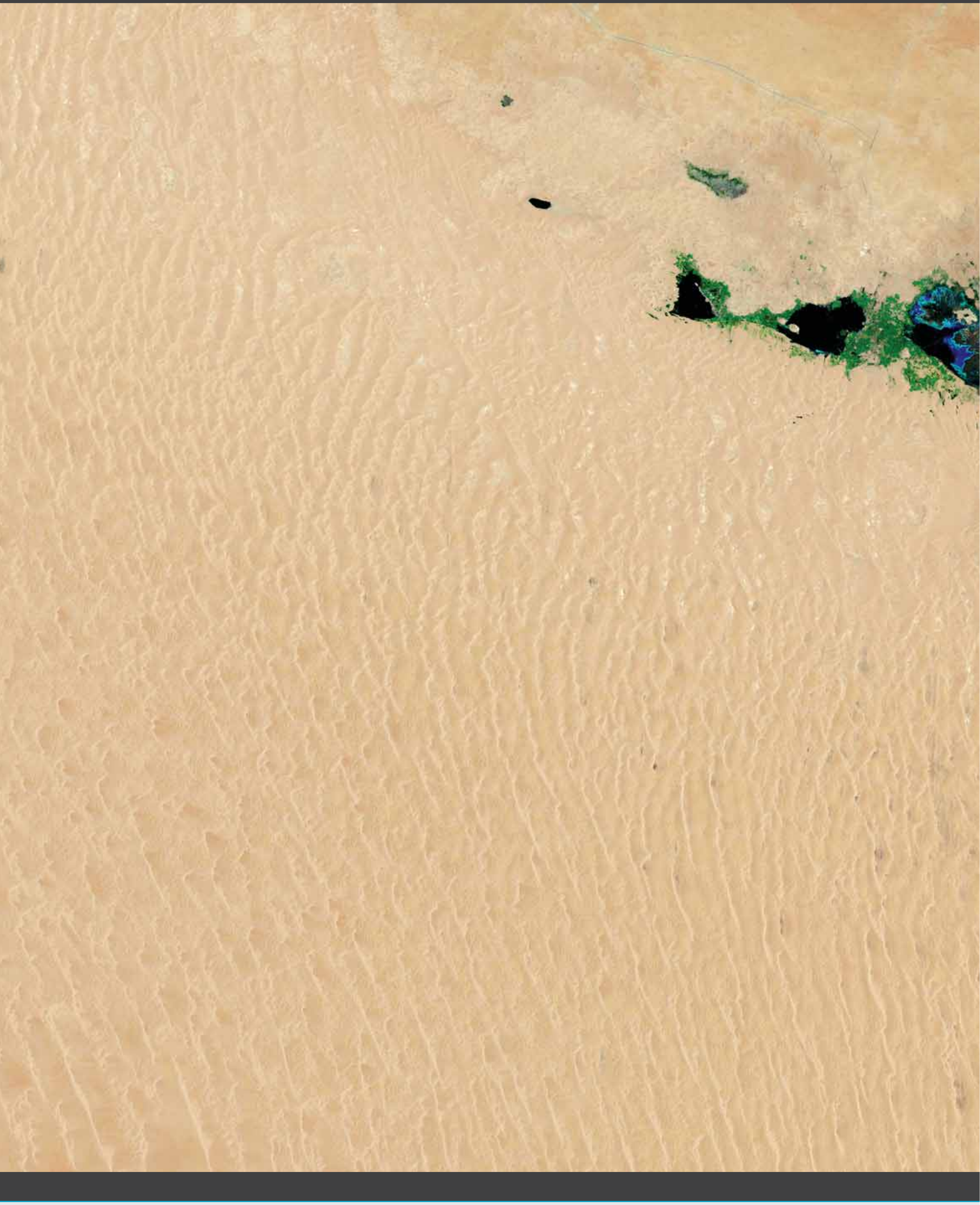


Figure 2-7.
Temporal profiles for an area of the Aral Sea;
a. Monthly Water Recurrence
b. Full Water History (1984-2018)
c. Monthly Water Presence (i.e. 1 year's record)
The 35-year stack of monthly water classifications at the pixel level form the basis of the water history. The water history is used to create 6 maps, each of which depicts a different facet of surface water distribution over time (see above).



Part 3 - Global overview

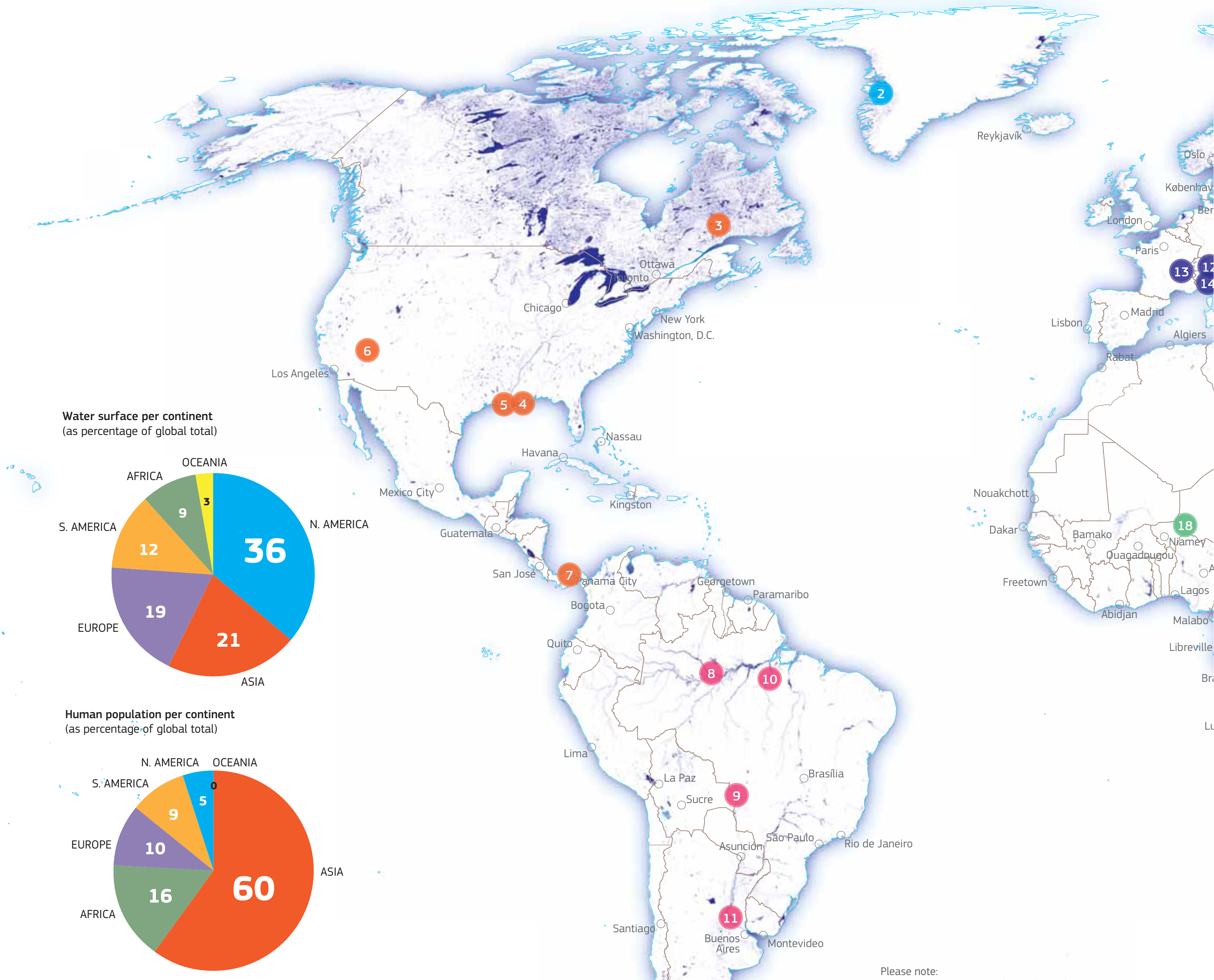
Water, water everywhere?

For the “Blue Planet”, surprisingly little of the Earth’s landmass is permanently under water. Less than 2 % of the landmass (2.4 million km^2) is covered by lakes and rivers that haven’t moved, geographically speaking, over the past 35 years. But, during the same 35 years, around 90 000 km^2 of what were once permanent lakes and rivers have completely disappeared, 184 000 km^2 of what used to be land is now permanently under water, and on a seasonal basis more than 800 000 km^2 can be covered by water for months at a time in any given year. Both the constant and changing patterns of the world’s surface water have one thing in common: neither is evenly distributed across our blue planet’s landmass.

The Siwa Oasis, Egypt is about 80 km long and around 23 km across at the widest point. The oasis one of Egypt's most isolated settlements. Landsat 8 image acquired 12 May 2019. Open water appears in black and blue tones, and vegetation in green. The image is around 150 km East-West (left to right).

Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

Global distribution of surface water varies dramatically in space and time



The disparities between population and the presence of surface water. Shares of global water surface area and human population.
Sources: water surfaces[1]; human population[2].

Please note:
1. Data stops at 78° N and 59° S latitudes.
2. Permanent water of the oceans is represented by a blue vignette (as opposed to a solid blue fill) to enhance clarity.

This map shows the global distribution of permanent and seasonal wetlands for the year 2018. The permanent waterbodies are shown in the darkest blue tones, and depict where water was present on the surface throughout 2018. The seasonal waterbodies are shown in lighter blue tones. Seasonal water only sits on the surface for a few months of the year. The lightest blue tones show the shortest inundation periods.

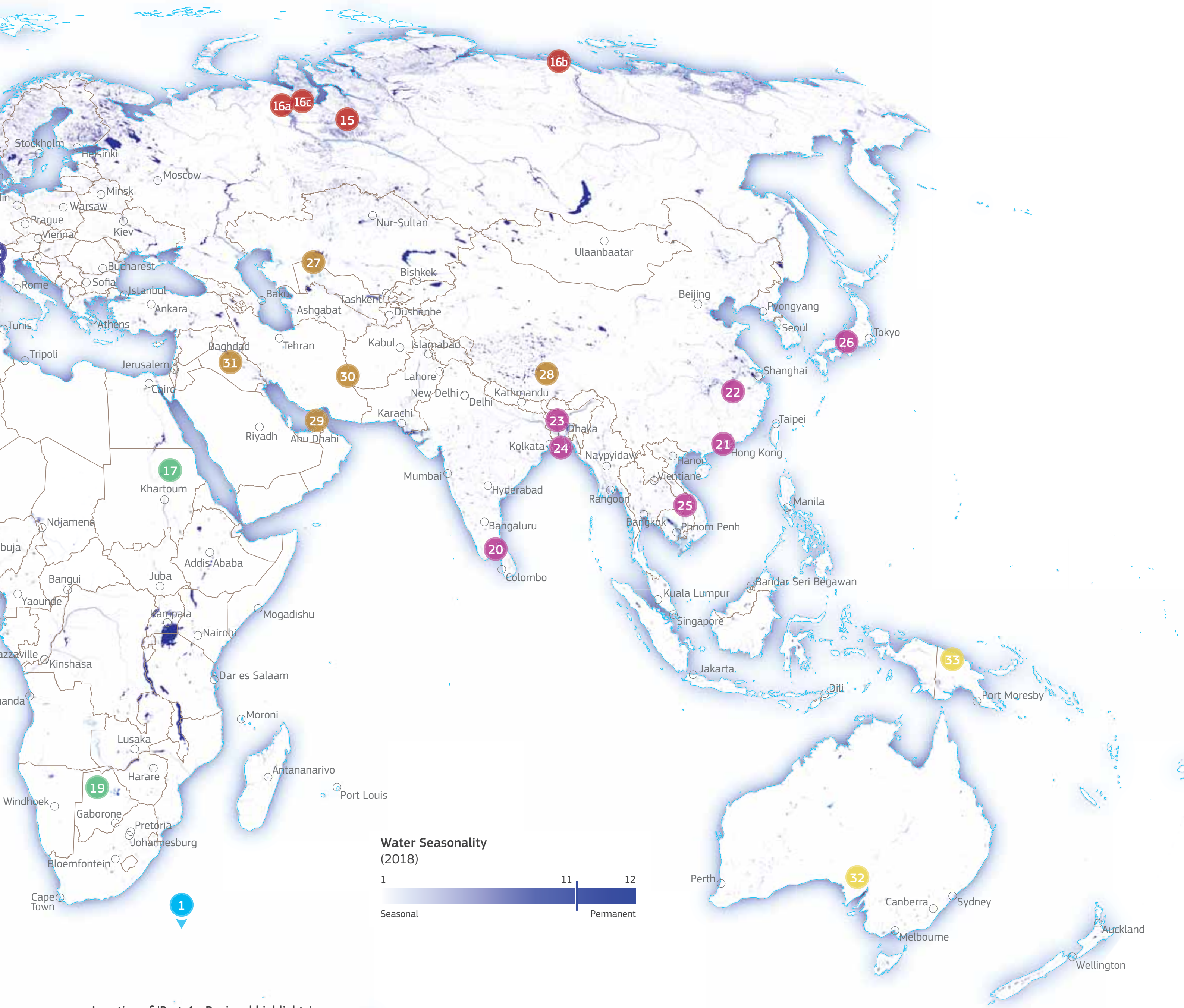
The patterns shown in the map may not repeat exactly every year, though most of the world's lakes and rivers are in fact found in the same place year after year; the ancient lakes such as Baikal in Siberia, Tanganyika in Africa's Great Rift Valley and Lake Titicaca in the Andes have existed for millions of years. North America's Great Lakes and the Alpine lakes in Europe are much younger, but have still been around for many thousands of years. These lakes, and the world's iconic rivers, such as the Amazon, Nile, Mississippi, Yangtze, Ganges, Volga, Danube, Euphrates and Murray, make up part of the circa 2.8 million km^2 of permanent water shown in the map here. The area of seasonal water can account for around 40 % of the total surface water area in a given year. In 2015, for example, seasonal water covered a little over 800 000 km^2 of the landmass[3].

Taken together, permanent and seasonal water covers less than 3 % of our planet's landmass. Forests cover ten times this area, as do the combination of grass and shrublands[4]. By some estimates, roads and buildings already cover about the same amount of land as is covered by lakes, rivers and wetlands[5].

The map also shows that surface water is very unevenly distributed around the planet. Unsurprisingly, the great deserts of the world, such as the Sahara, Gobi and Victoria, are largely devoid of surface water features. The tropics are characterised by major rivers, whilst the high northern latitudes contain many, many thousands of individual ponds, as well as huge expanses of water such as the northern reaches of the Great Lakes of North America.

At the continental scale, another level of asymmetry emerges. North America is immensely water-rich; it has around 36 % of the global surface water area (seasonal and permanent combined), but has just 5 % of the human population. In contrast Asia, with 60 % of the human population, has just over 20% of the surface water and is the world's water-poorest continent in terms of surface water area per person. Africa too has a small share of the surface water (9 %) compared with its share of the world's people (16 %). Africa also has the fastest growing human population in the world, and will account for more than half of the global population increase between now and 2050[6].

The map doesn't show Antarctica, although surface water in the form of meltwater lakes[7] does occur during the Antarctic summer. Unfortunately, there is insufficient imagery throughout the early period of the 1984–2018 timeframe to apply the metrics and methods used in the mapping covered by this Atlas. This situation is changing, and regular observation of this most southern continent by Landsat[8] and the European Copernicus Programme's Sentinels[9] has become a reality.



Location of 'Part 4 – Regional highlights':

The Polar Regions

1 - Lakes, ponds and streams (Antarctica)
2 - Meltwater lakes (Greenland)

North and Central America

3 - Manicouagan Impact Crater (Canada)
4 - Mississippi River Delta (USA)
5 - The Atchafalaya River (USA)
6 - Lake Mead (USA)
7 - Panama Canal (Panama)

South America

8 - Amazon River (Brazil)
9 - The Pantanal (Brazil)
10 - The Xingu River (Brazil)
11 - The Paraná River (Argentina)

Europe

12 - Alpine lakes (Italy and Switzerland)
13 - The Dombes (France)
14 - Rice fields (Italy)

Russia

15 - Thermokarst lakes (Russia)
16 - The Great Siberian rivers (Russia)

Africa

17 - Merowe Dam (Sudan)
18 - The Sahel, and Lake Chad (West and Central Africa)
19 - The Okavango Delta (Botswana)

South and East Asia

20 - Ramanathapuram (India)
21 - The Pearl River Delta (China)
22 - Poyang Lake (China)
23 - Brahmaputra River (Bangladesh)
24 - The Sundarbans (Bangladesh and India)
25 - Paksong Dam (Laos)
26 - Lake Biwa and Ise Bay (Japan)

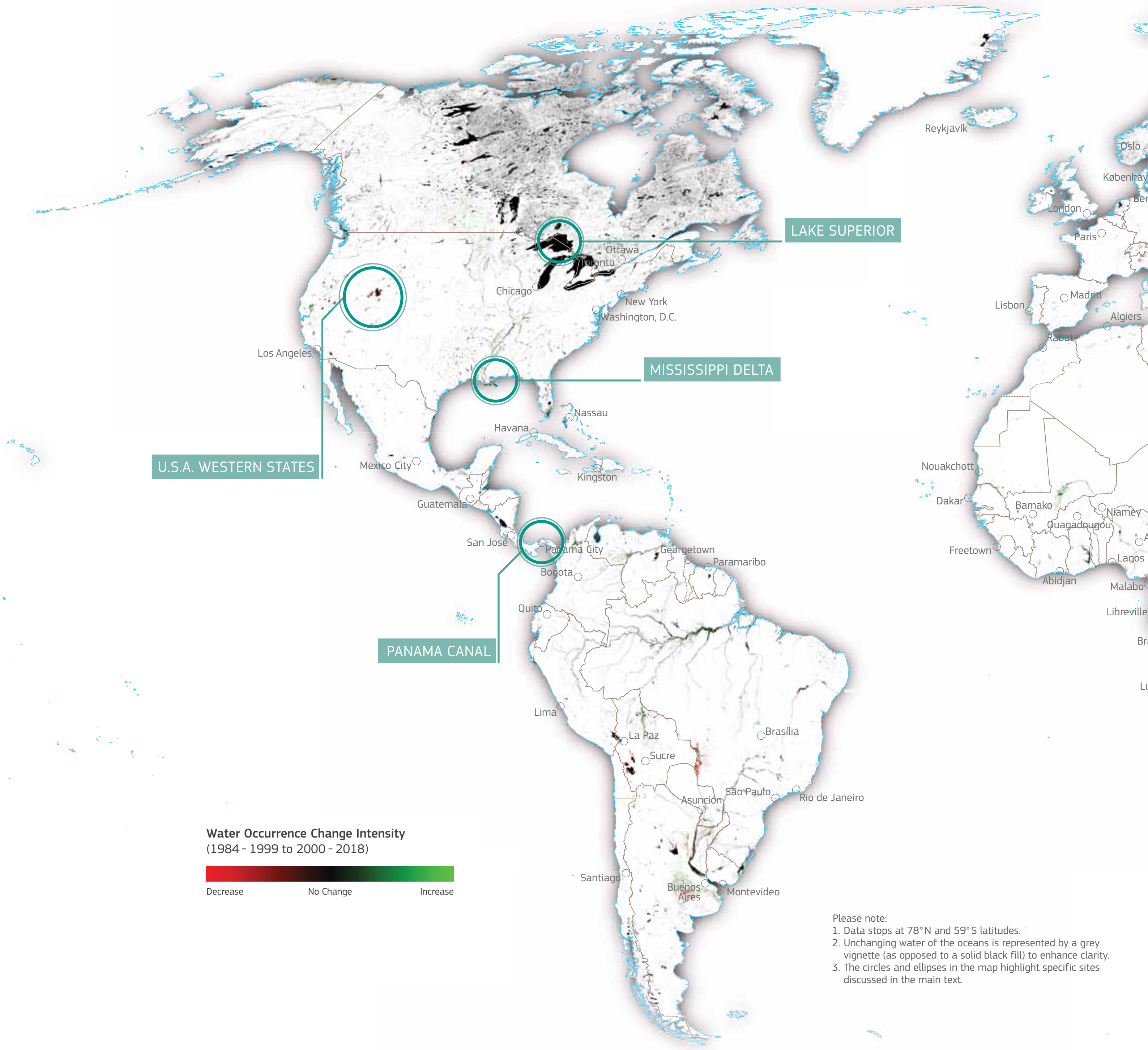
Central Asia and the Middle East

27 - Aral Sea (Kazakhstan and Uzbekistan)
28 - High-elevation lakes (Tibetan Plateau)
29 - The Palm Islands (United Arab Emirates)
30 - Lake Hāmūn (Afghanistan/Iran)
31 - Razzaza Lake (Iraq)

Oceania

32 - Lake Gairdner (Australia)
33 - The Sepik River (Papua New Guinea)

Nature and humans cause changes in surface water persistence across the planet



Please note:
1. Data stops at 78° N and 59° S latitudes.
2. Unchanging water of the oceans is represented by a grey vignette (as opposed to a solid black fill) to enhance clarity.
3. The circles and ellipses in the map highlight specific sites discussed in the main text.

Patterns of Change

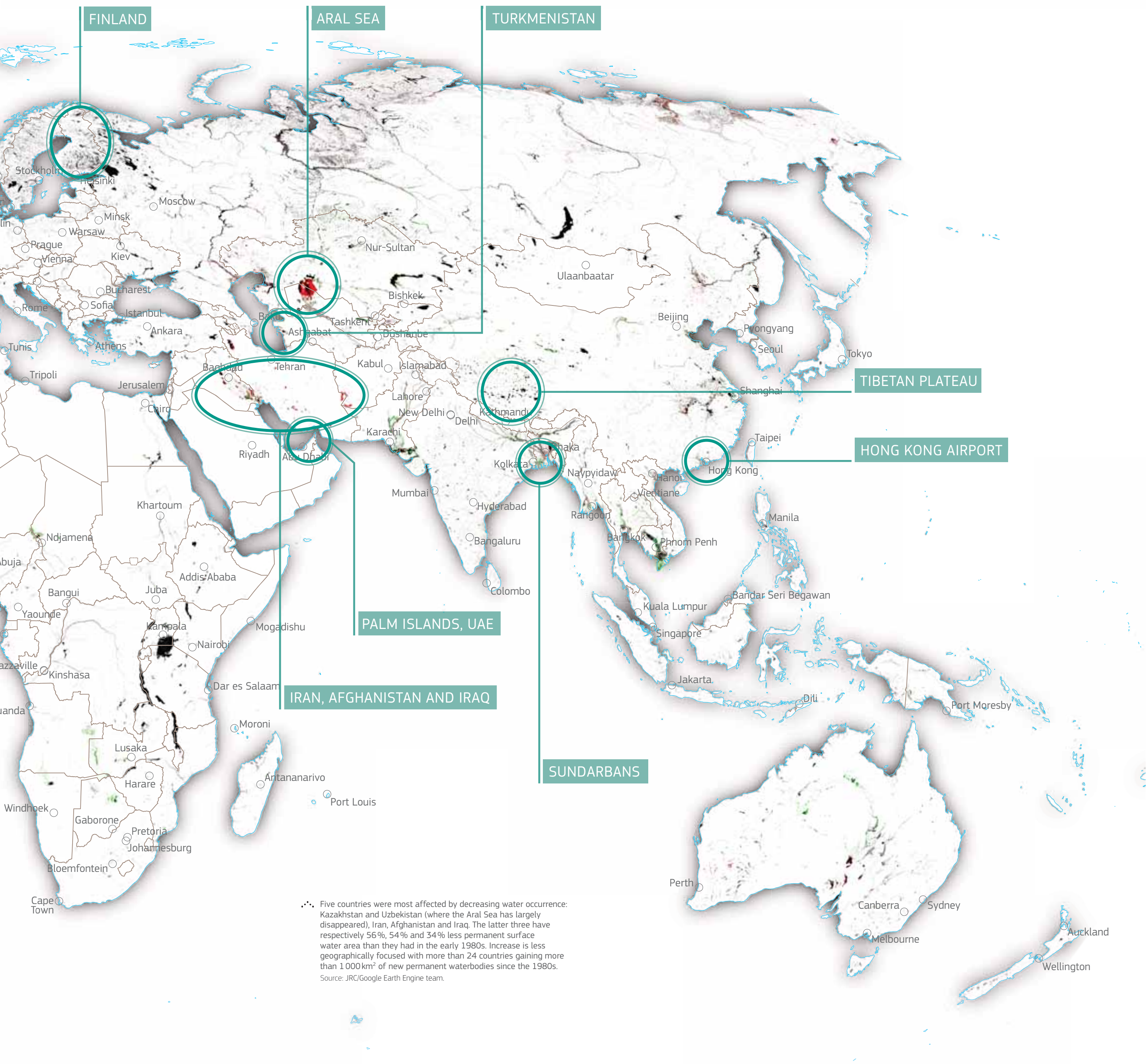
This map depicts changes in water occurrence over the period 1984 to 2018. The red tones show where water used to occur, the green shows where new waterbodies are found and the black tones show where things have not changed. Lakes and rivers naturally swell and contract, they even come and go entirely. Yet 87 % of the Earth's lakes, rivers and wetlands really are permanent, with around 2.4 million km² of surface water area remaining in the same geographic location throughout the 35 years of mapping. But this still leaves much that has changed. Since the 1980s, almost 90 000 km² of what was once permanent surface water have disappeared. And, new permanent surface waterbodies covering 184 000 km² have formed elsewhere in the same timeframe. All continents show a net increase in permanent water, except Oceania, which has a fractional (1 %) net loss. Levels of decrease are more geographically concentrated than levels of increase.

Increases in surface water occurrence

Major hydro-engineering projects such as the construction of the Panama Canal (first phase finished in 1913), and the Hoover Dam (completed in 1936) have caused localised increases in surface water area in the past. Humans are still altering surface water occurrence today, and 24 countries have each gained at least 1 000 km² of new permanent waterbodies since the 1980s[1]. Much comes from reservoir construction, with most of these countries featuring prominently in the International Commission on Large Dams register of dam builders[10]. Reservoirs usually take one of three forms: valley, embankment or coastal. Valley reservoirs are created by building a dam across a river, embankment reservoirs are created by supplying water to a depression via canals or pumps, and coastal reservoirs are created in the sea (artificial walls are constructed near river deltas and salt water is swapped for fresh, thus coastal reservoirs don't actually drown land[11]).

Increasing surface water area is not always linked to dam construction. Turkmenistan is one exception; in 1992, this country gained over 14 000 km² of surface water by breaching the dam previously built between the Garabogazköl Aylagy lagoon and the Caspian Sea[12]. In recent years the permanent surface water area has also increased across the Tibetan Plateau, yet as with Garabogazköl Aylagy this has nothing to do with dam building. Nearly all the lakes in the region are expanding, and there are even entirely new lakes forming. In total, the Plateau has seen an extra 8 300 km² of water appear on the surface since the 1980s (a 20 % increase in lake surface area). This expansion has been linked to increased run-off from accelerated snowmelt and glacier melt caused by higher temperatures and annual precipitation[13].

1 Russia, Canada, China, Turkmenistan, Brazil, United States, India, Kazakhstan, Argentina, Turkey, Peru, Uzbekistan, Myanmar, Indonesia, Australia, Pakistan, Mexico, Vietnam, Egypt, Bangladesh, Colombia, Venezuela, Thailand, Mozambique.

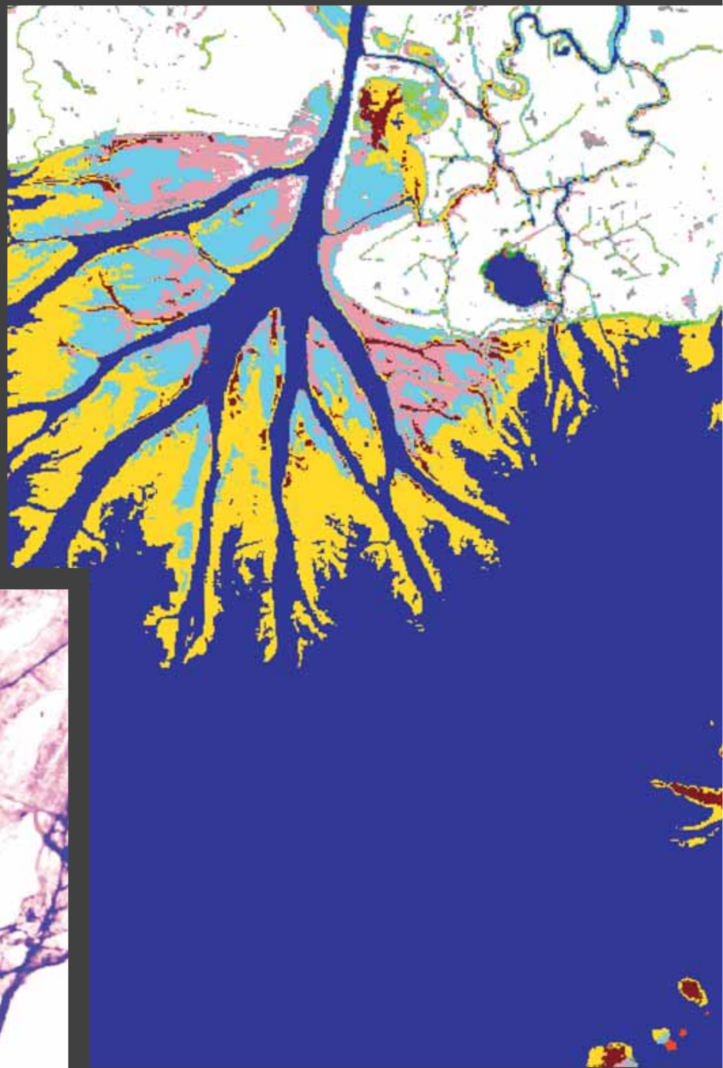
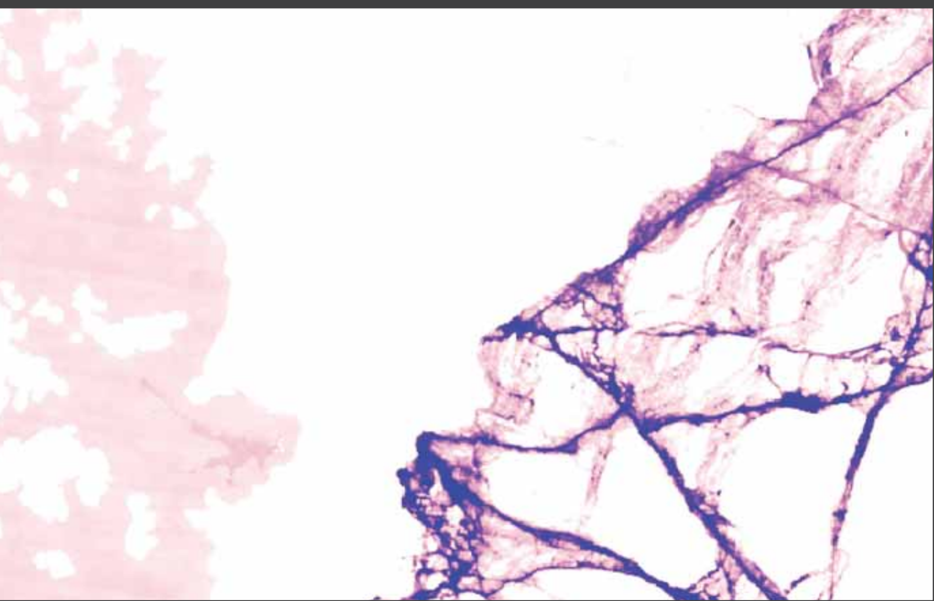


Five countries were most affected by decreasing water occurrence: Kazakhstan and Uzbekistan (where the Aral Sea has largely disappeared), Iran, Afghanistan and Iraq. The latter three have respectively 56%, 54% and 34% less permanent surface water area than they had in the early 1980s. Increase is less geographically focused with more than 24 countries gaining more than 1 000 km² of new permanent waterbodies since the 1980s.
Source: JRC/Google Earth Engine team.

Adapting to climate change involves many challenges, including grazing land reduction due to inundation, grassland degradation linked to an increase in salinity following the expansion of brackish waters, and threats to transport infrastructure[14]. Increases in surface water area in coastal regions also occur. These have been linked to sea level rises and changes in sediment discharge. This can result in significant loss of landmass, for example the Sundarbans (India and Bangladesh) have lost around 170 km² of land since the 1980s[15] and land in the Mississippi Delta is already contracting, with significant drowning of land seen as inevitable in the coming years[16].

Decreases in surface water occurrence

90 000 km² is a lot of water to lose. To put this number into perspective, just reflect on the fact that Lake Superior (the largest freshwater lake in the world, by surface area) only covers 82 103 km², and Finland, "the land of a thousand lakes" (which actually has well over a *hundred and sixty thousand lakes*[17]) has a freshwater area of less than 35 000 km². Over 70 % of this water loss is concentrated in five countries: Kazakhstan and Uzbekistan have lost much of the Aral Sea, with rates of loss being greatest between 1994 and 2009. Latterly the disappearance of the Aral Sea has slowed, and even partially reversed. Diversion of, and withdrawal from, the Amu and Syr rivers that once fed the lake are the main causes of loss, but changes in water management give hope for stabilisation and partial restoration[18]. Iran, Afghanistan and Iraq have also experienced major losses, having respectively 56 %, 54 % and 34 % less permanent surface water today than in the 1980s. Decreases on this scale raise serious questions concerning long-term access to water for the region's people, and highlight the need for informed and careful transboundary water management[19]. The causes of such decreased water occurrence are complex, and include multiple factors such as unregulated withdrawal, dams that change river flow rates and direction, and droughts[20]. Decreases in Australia[21] and the USA[22] linked to long-term droughts can also be seen. Surface water in coastal areas can also disappear, partly because of natural movement of sand bars and other forms of sediment deposition, but also as a result of major land reclamation projects[23] such as the construction of Hong Kong's Chek Lap Kok airport (completed 1998), or the Palm Islands complex off the coast of Dubai, United Arab Emirates (where work started in 2001).


Part 4 - Regional highlights

Infinite variety

Every continent has stories that lie behind the beauty and diversity of the world's waterscapes. Sometimes these stories tell of human ingenuity on scales from the modest to monumental, some tell of human actions where the consequences are apparent on an epic scale, and sometimes it's nature that has the first and last words.

Clockwise from top-left:

Lake Gairdner is one of the largest inland salt lakes in South Australia.
Source: Murray Foubister [CC BY-SA (https://creativecommons.org/licenses/by-sa/2.0)].

The Atchafalaya distributary flows away from the Mississippi and discharges a high sediment load into the bay area. In contrast to much of the Mississippi Delta, which is drowning, this region's land area has increased over the past 30 years.
Source: JRC/Google Earth Engine team.

Panorama of Yamdrok Lake in the Tibetian Plateau.
Source: hao chen on Unsplash.

Brazil's Xingu River, just upstream of Belo Monte, is transformed into a series of geometric shapes and sharp-angled bends as the river is constrained by the fracture and fault lines in the underlying rock.
Source: JRC/Google Earth Engine team.

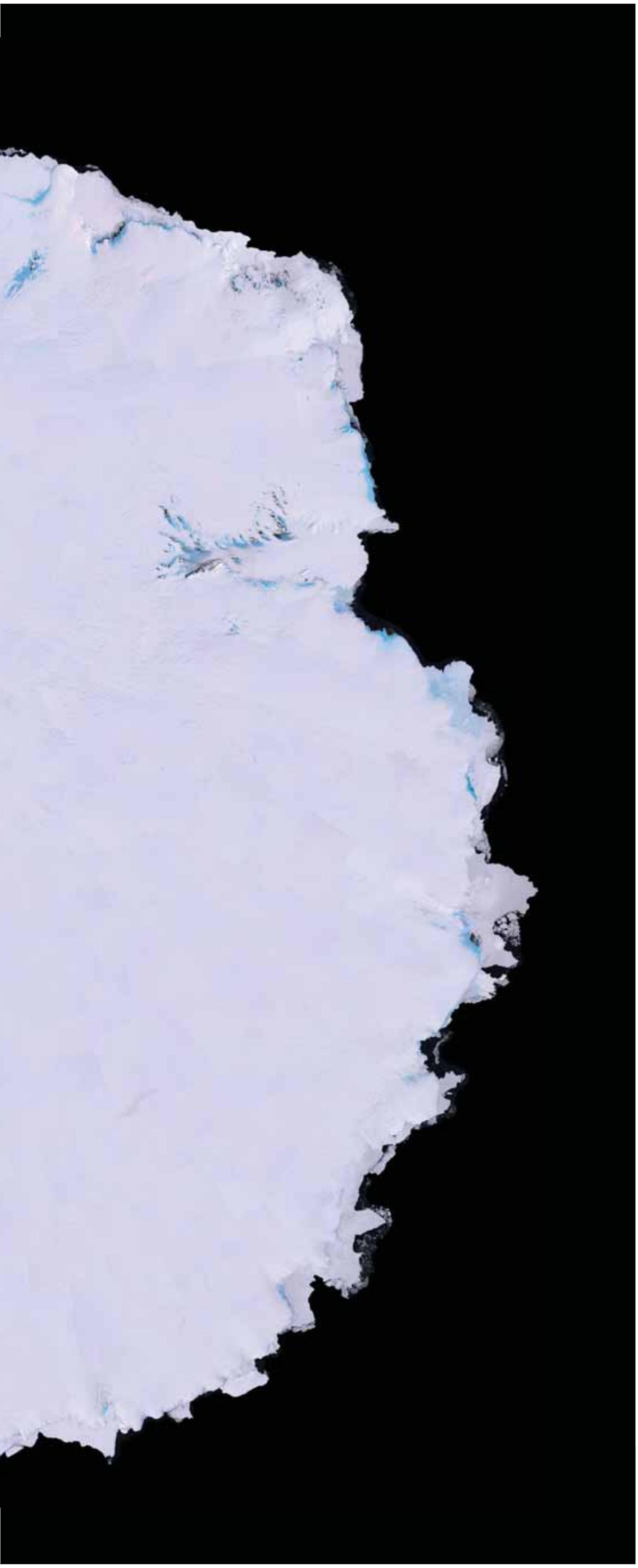
1 | Lakes, ponds and streams (The Antarctic)

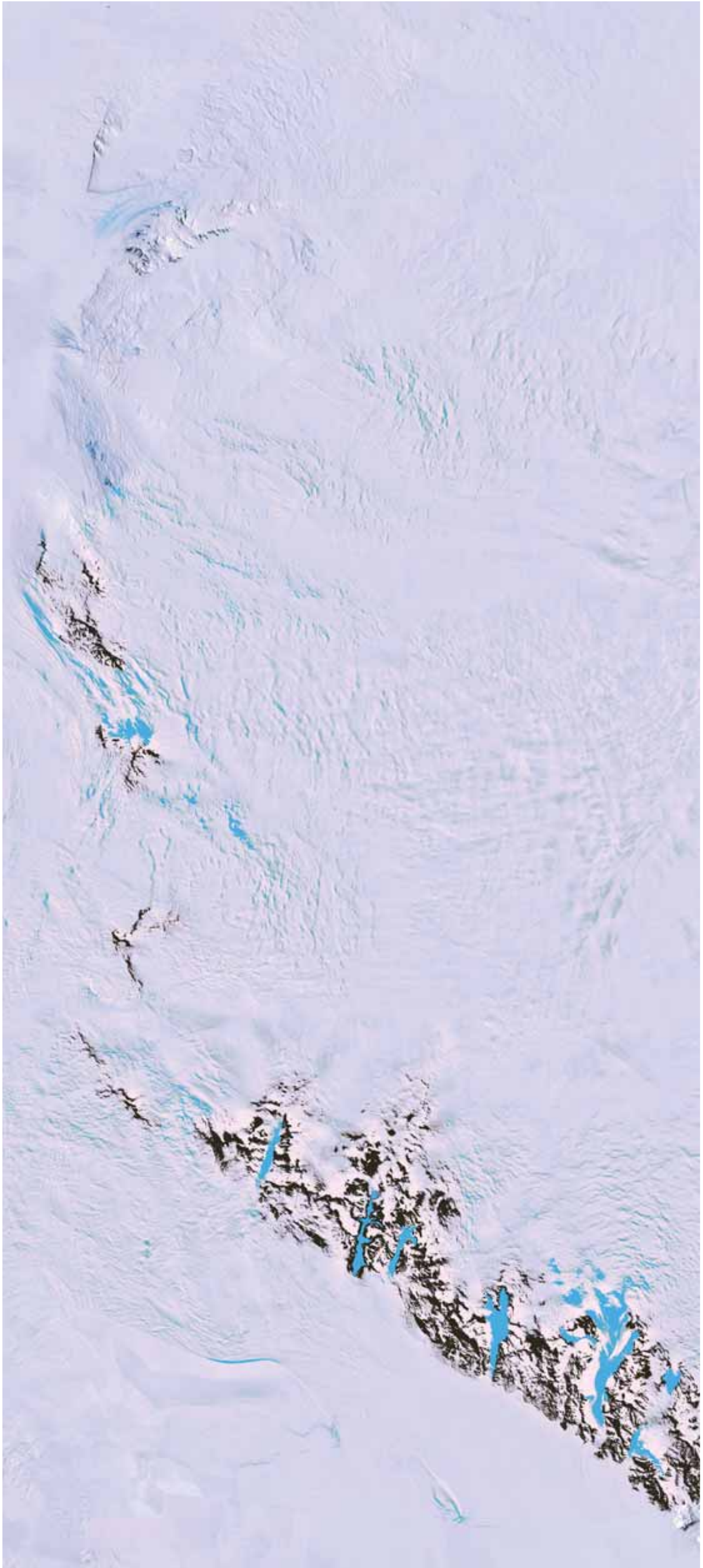
Lakes, ponds and streams

The Antarctic

Mapping surface water dynamics in Antarctica has to overcome at least three challenges. First, satellite image archives are historically sparse (though improving), second, there is no sunlight for many months of the year (no sunlight, no optical imagery), third, for most of the year all water is frozen (Antarctica is the coldest continent on the Earth). For these reasons, Antarctica has not yet been integrated into the Global Surface Water Explorer. However, during the Antarctic summer, thousands of meltwater lakes, along with channels and braided streams, appear. Some lakes and ponds can cover many tens of square kilometres. These affect surface / atmosphere energy exchange (the lakes are darker and absorb more solar energy), and hydro-fracturing induced by the lakes has been linked to ice shelf disintegration. Dedicated mapping projects, such as the Landsat Image Mosaic of Antarctica (shown here) and Copernicus Sentinel-2 imagery, are being used to map the meltwater lakes[1]. Future editions of the Global Surface Water Explorer may extend to these high latitudes.

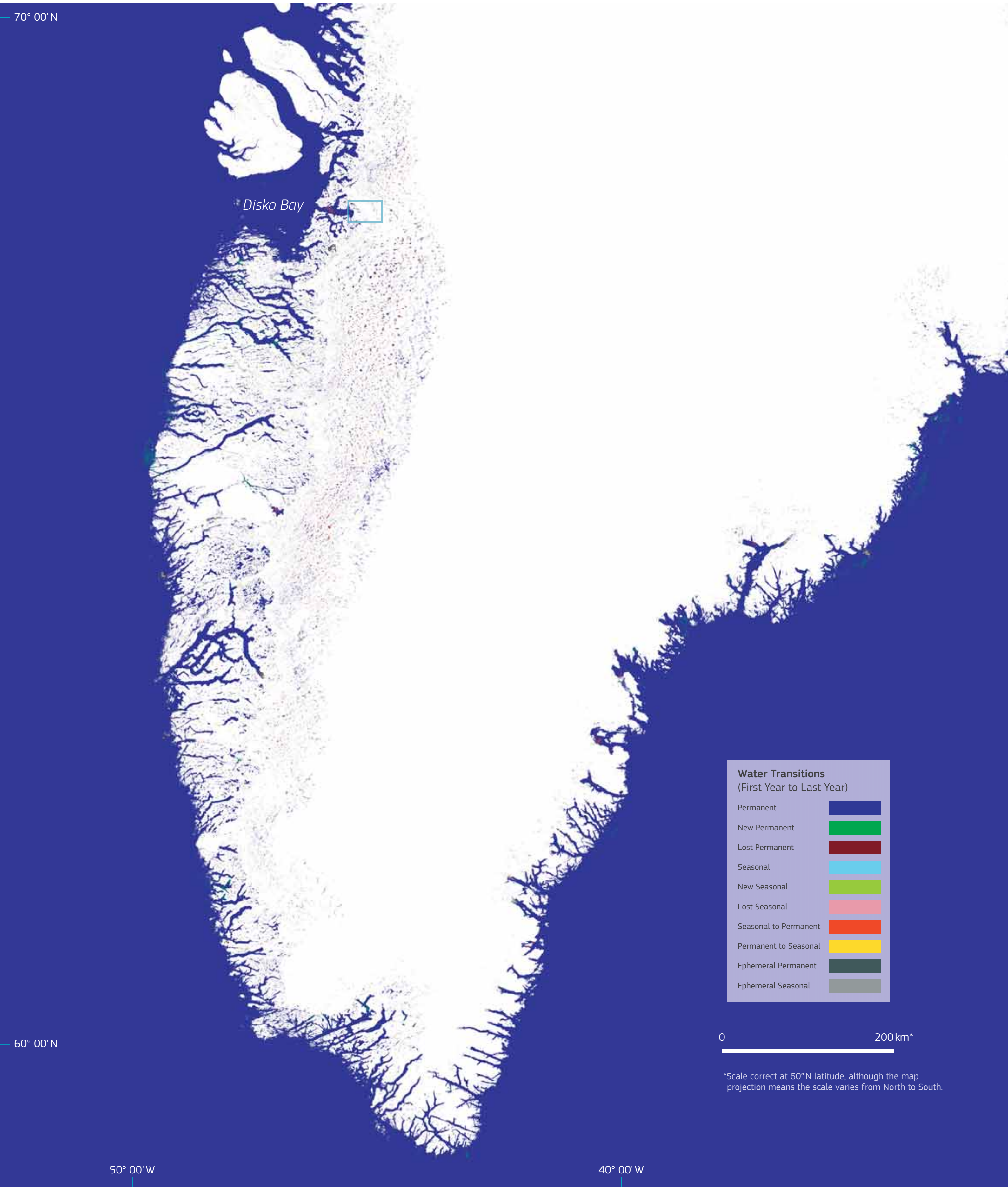
90° 00' 00.0" S
00° 00' 00.0" W





Blue ice.
Landsat Image Mosaic of Antarctica (LIMA)'s true-colour imaging highlights one of Antarctica's most fascinating features, blue ice. Larger-than-average ice crystals make the absorption of red light (and reflection of blue light) more pronounced. As the blue ice is darker, it absorbs more solar energy, which causes melting. The blue ice is one source of meltwater streams.
Source: National Science Foundation and the British Antarctic Survey using Landsat imagery, courtesy USGS/NASA.

2 | Meltwater lakes (Greenland)



Meltwater lakes

Greenland

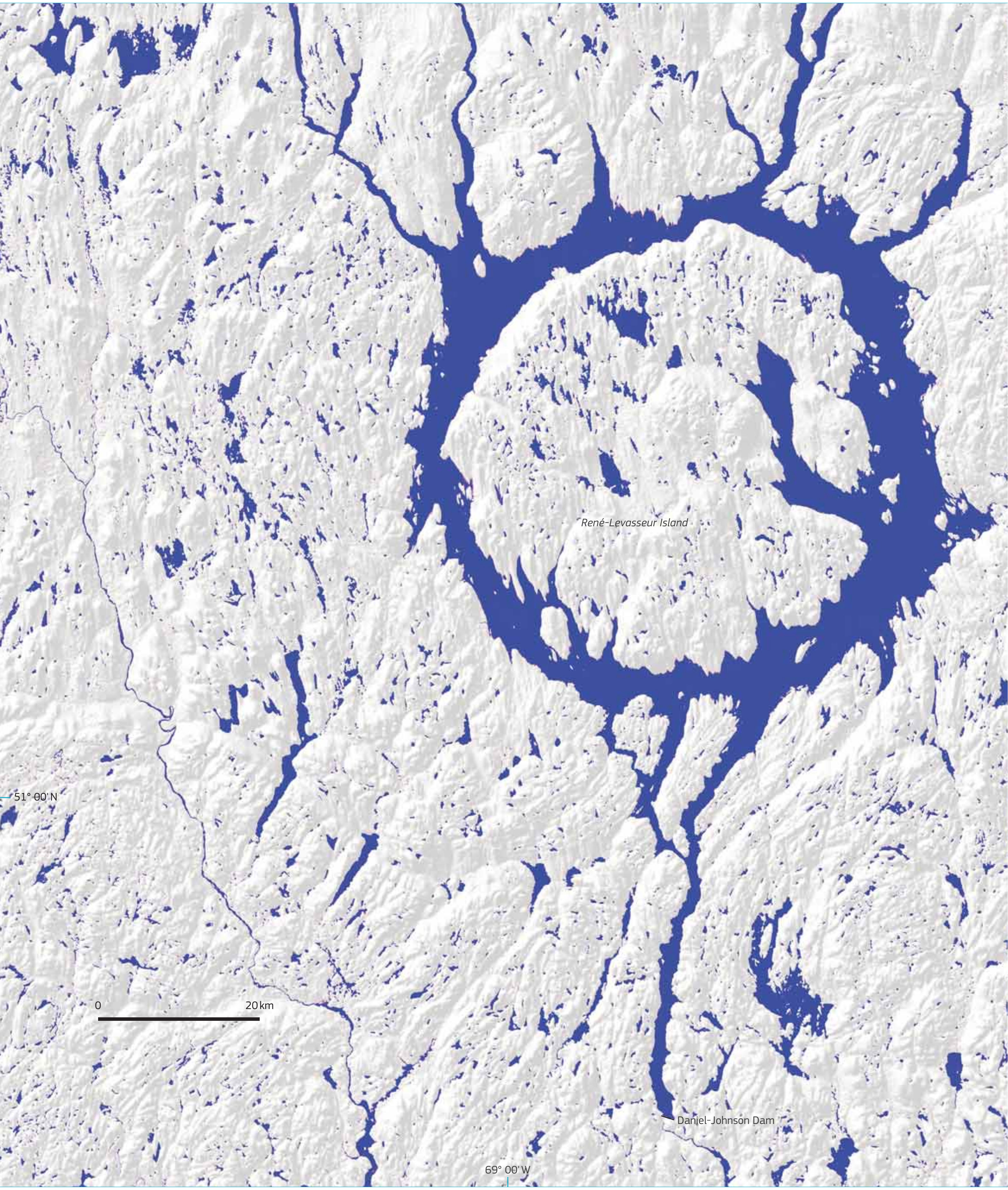
During the Arctic summer (June, July and August) meltwater lakes form at low elevations all around the Greenland Ice Sheet. Eastern Greenland is much steeper than the West, and this topographic difference is evident in the distribution of the meltwater lakes. There is a far greater concentration on the west of the Ice Sheet than to the east. Meltwater lakes are important as they bring water into contact with previously frozen ice beds. The lubrication and warming this provides can cause the ice beds to slide downslope. Expansion of meltwater lake area could thus accelerate rates of ice mass loss[1], which in turn will accelerate sea level rises. Over recent decades lakes have begun to form at higher elevations, effectively moving inland. Rising temperatures will likely see the formation new supraglacial lakes, bringing water and heat into contact with ever greater parts of the Ice Sheet[2].

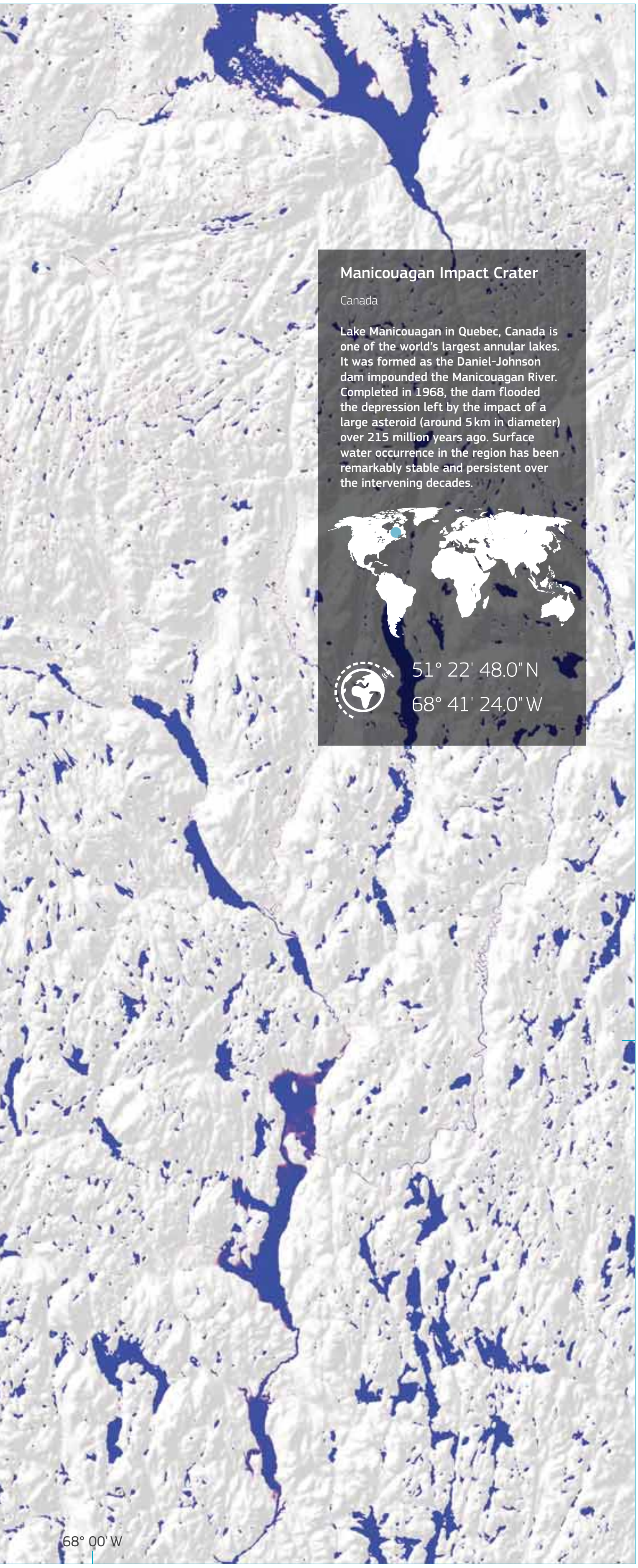
69° 12' 42.7" N
49° 10' 18.4" W

Steep terrain is not conducive to meltwater lake formation. In contrast to the west coast, Greenland's eastern shoreline, with its steep terrain, is largely free of meltwater lakes.
Source: Alan Belward.

Meltwater lakes.
The pair of Landsat scenes (from 29 August 1985 and 27 August 2019) provide detail of the Greenland Ice Sheet flowing into Disko Bay. The bottom-left corner of each image shows how the rocky coastline and broken ice-flow in the bay have both expanded into the Ice Sheet. The number, size and distribution of the meltwater lakes (the very dark patches) have significantly grown. Both images obtained from Landsat (5 and 8). Images are 35 km North-South (top to bottom). Location indicated on main map.
Source: Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

3 | Manicouagan Impact Crater (Canada)





Manicouagan Impact Crater

Canada

Lake Manicouagan in Quebec, Canada is one of the world's largest annular lakes. It was formed as the Daniel-Johnson dam impounded the Manicouagan River. Completed in 1968, the dam flooded the depression left by the impact of a large asteroid (around 5 km in diameter) over 215 million years ago. Surface water occurrence in the region has been remarkably stable and persistent over the intervening decades.

51° 22' 48.0" N
68° 41' 24.0" W

Daniel-Johnson Dam, Manicouagan River, Quebec, Canada.
The Daniel-Johnson Dam impounds the Manicouagan River and is the primary dam forming the Manicouagan Reservoir. It supports a major hydroelectric power station called Manic-5.
Source: guyvail [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].

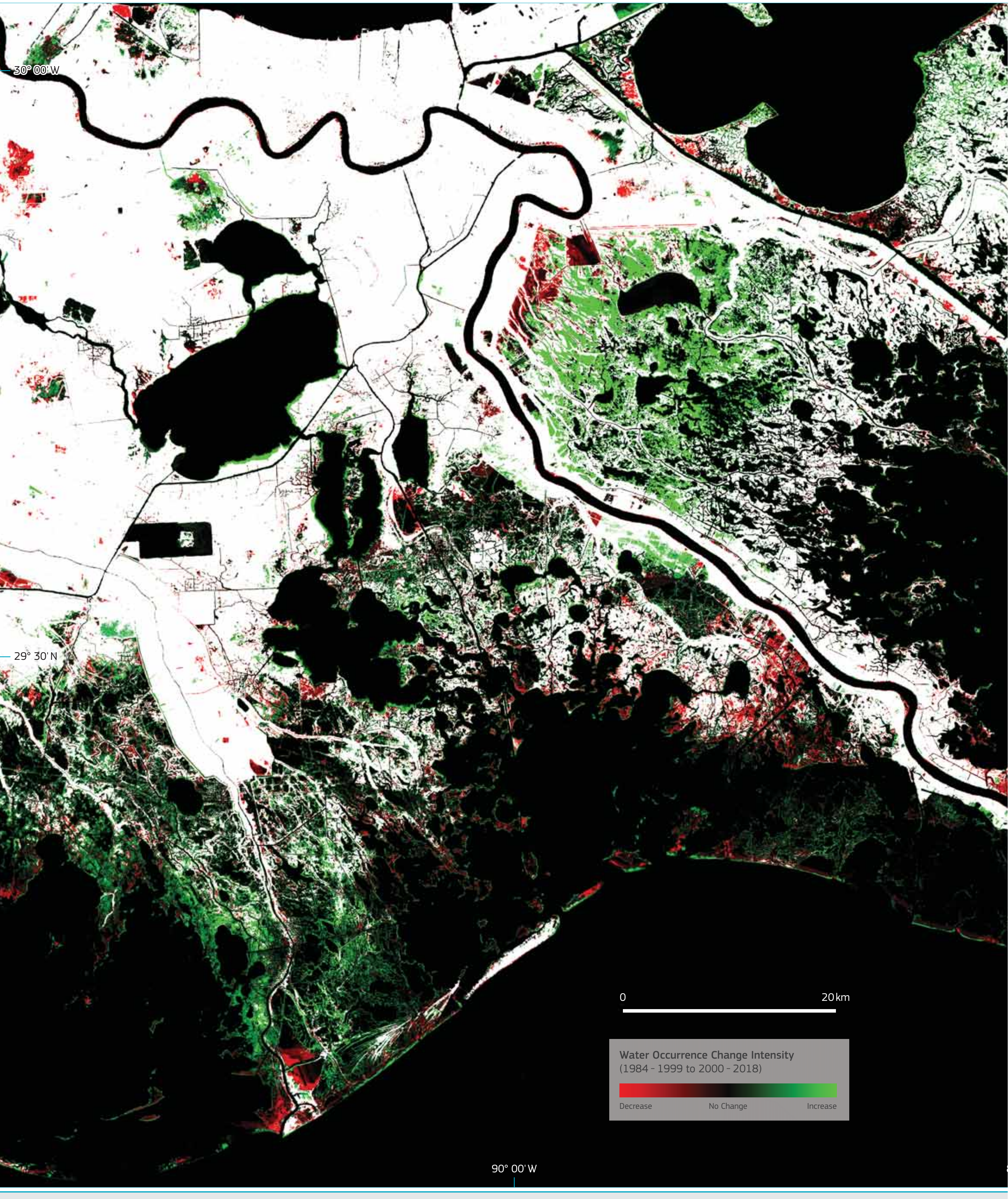
Oblique view of Lake Manicouagan.
This photograph of the Manicouagan Impact Crater was taken by a member of the International Space Station's crew, Expedition 12, from the West of the Lake, looking East, on 3 February 2012.
Source: International Space Station (ISS), Expedition 12 [Public domain].

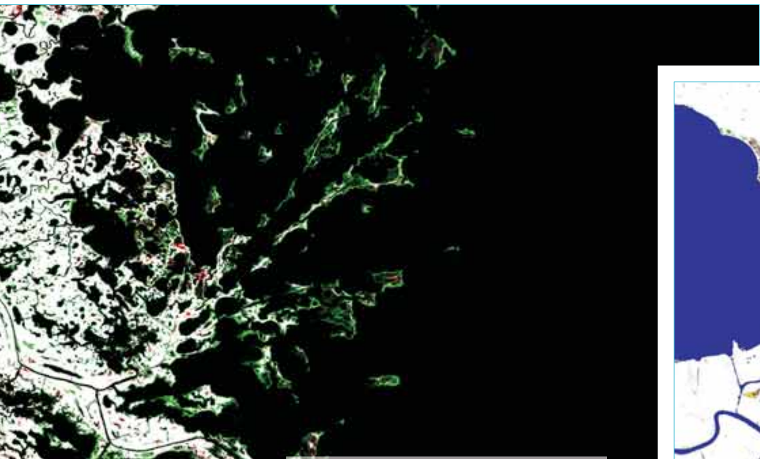
Winter view of Lake Manicouagan.
This oblique photograph of the lake was taken during International Space Station Expedition 38. It shows the lake in a frozen state (typically September to May/June).
Source: International Space Station (ISS), Expedition 38 [Public domain].

Water Occurrence
(1984 - 2018)

0% — 100%
Sometimes Water — Always Water

4 | Mississippi River Delta (USA)



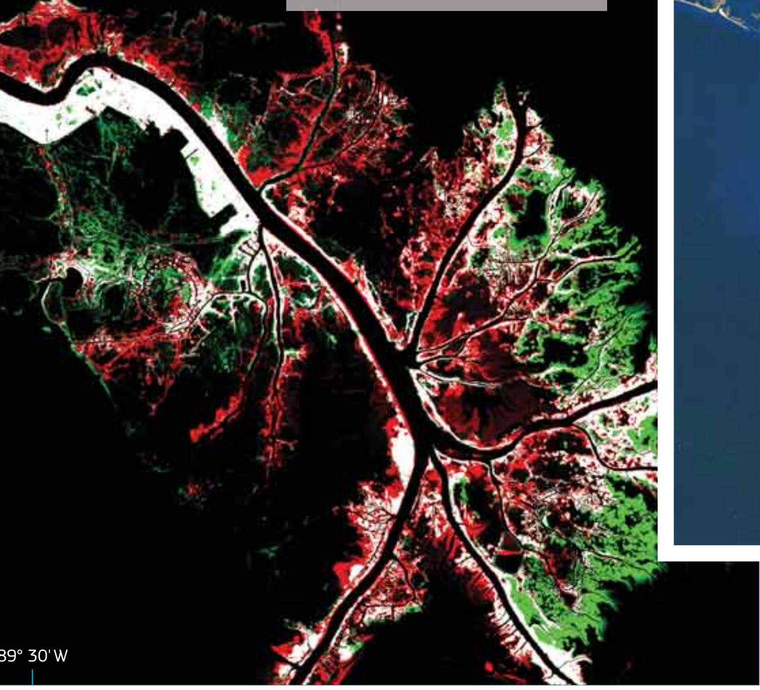


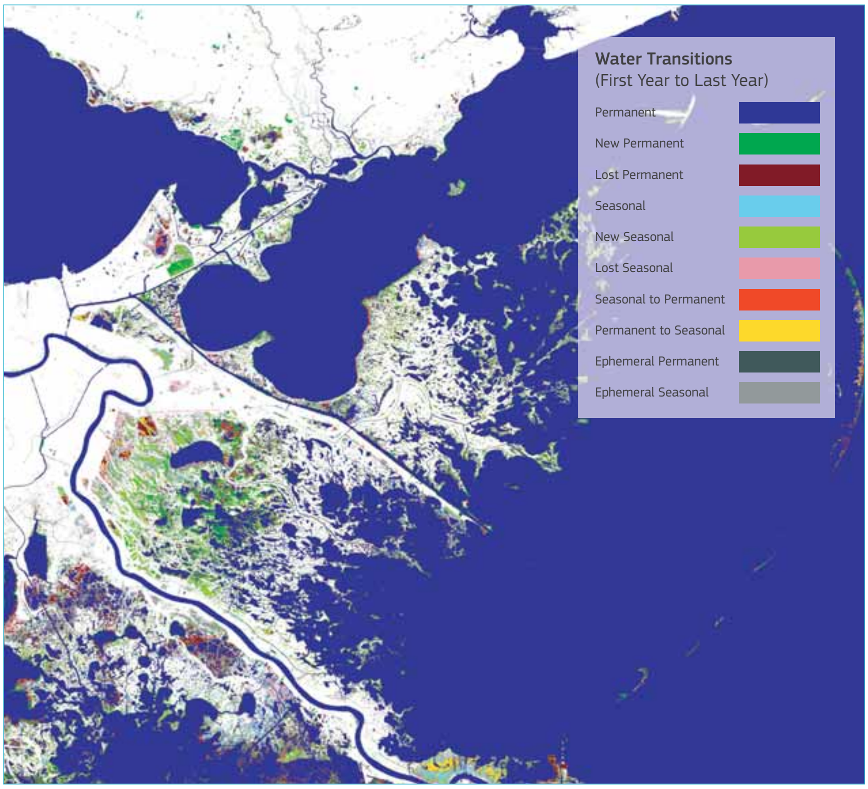
Mississippi River Delta

USA

Changes in upstream river management, including dredging, levee and dam construction, have led to a reduction in the sediment load carried by the Mississippi River and thus to the sediment discharged into the delta area. The consequences of this include coastal retreat and the drowning of delta wetland areas, which in turn are having profound negative impacts on the ecology of the region and the way of life for many people living in coastal Louisiana. Infrastructure and human activities linked to timber extraction, transport, shrimp farming, fishing, hunting, recreation and oil and gas exploration are all currently located on land that is inexorably vanishing[4].

29° 33' 00.0" N
89° 46' 12.0" W





Mississippi Delta, USA.
This Landsat 5 image from 25 March 1984 shows the Mississippi River's 'Bird's Foot Delta'. The sediment shows as the lighter blue tones (the darker the tone the lower the sediment load). Image is 76 km North-South (top to bottom).
Source: Alan Belward using Landsat 5 imagery, courtesy USGS/NASA.

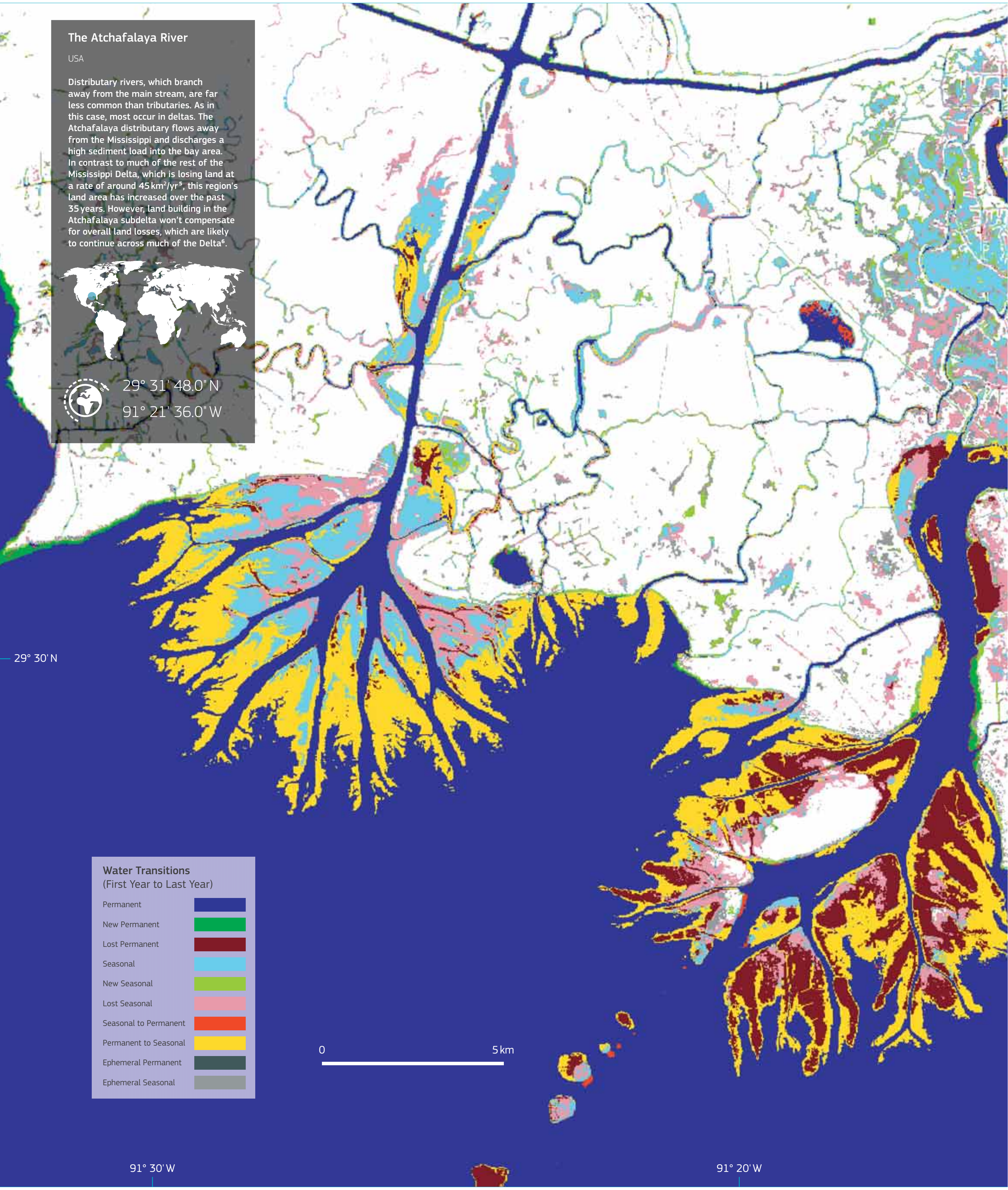
5 | The Atchafalaya River (USA)

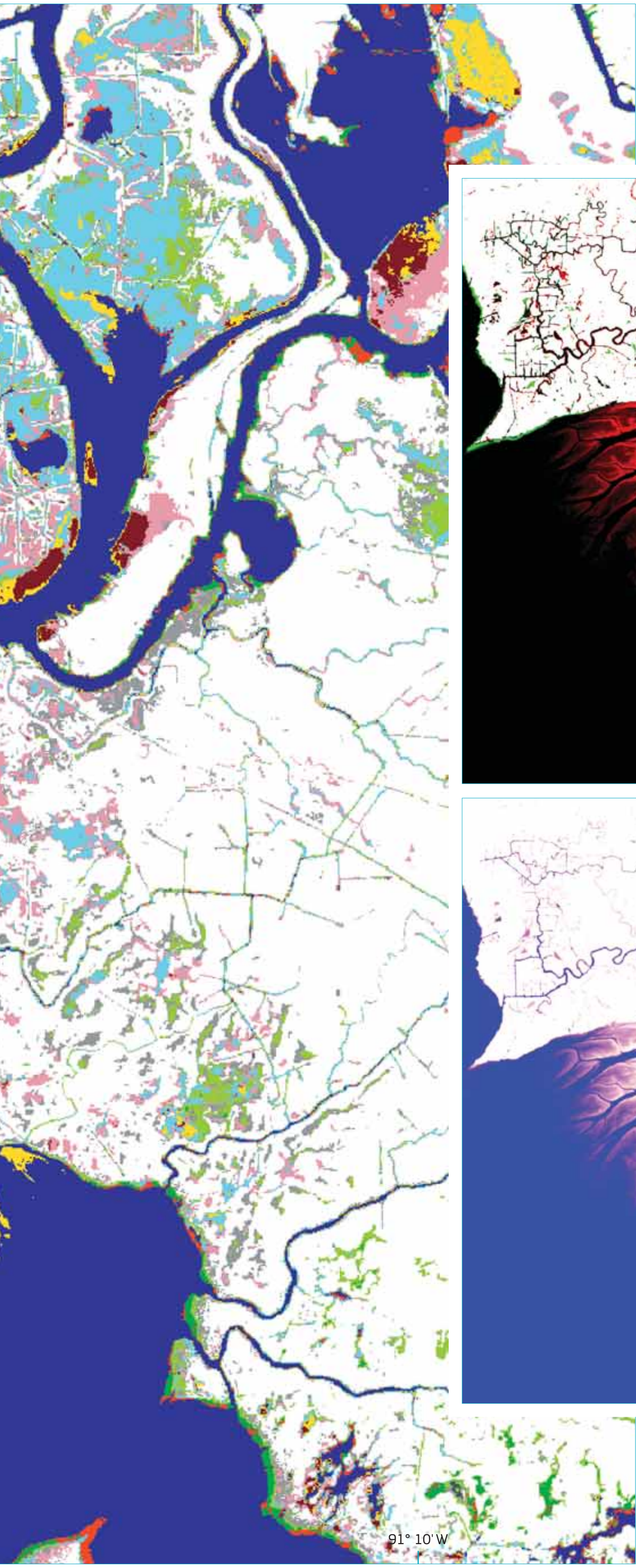
The Atchafalaya River

USA

Distributary rivers, which branch away from the main stream, are far less common than tributaries. As in this case, most occur in deltas. The Atchafalaya distributary flows away from the Mississippi and discharges a high sediment load into the bay area. In contrast to much of the rest of the Mississippi Delta, which is losing land at a rate of around 45 km^2/yr[5], this region's land area has increased over the past 35 years. However, land building in the Atchafalaya subdelta won't compensate for overall land losses, which are likely to continue across much of the Delta[6].

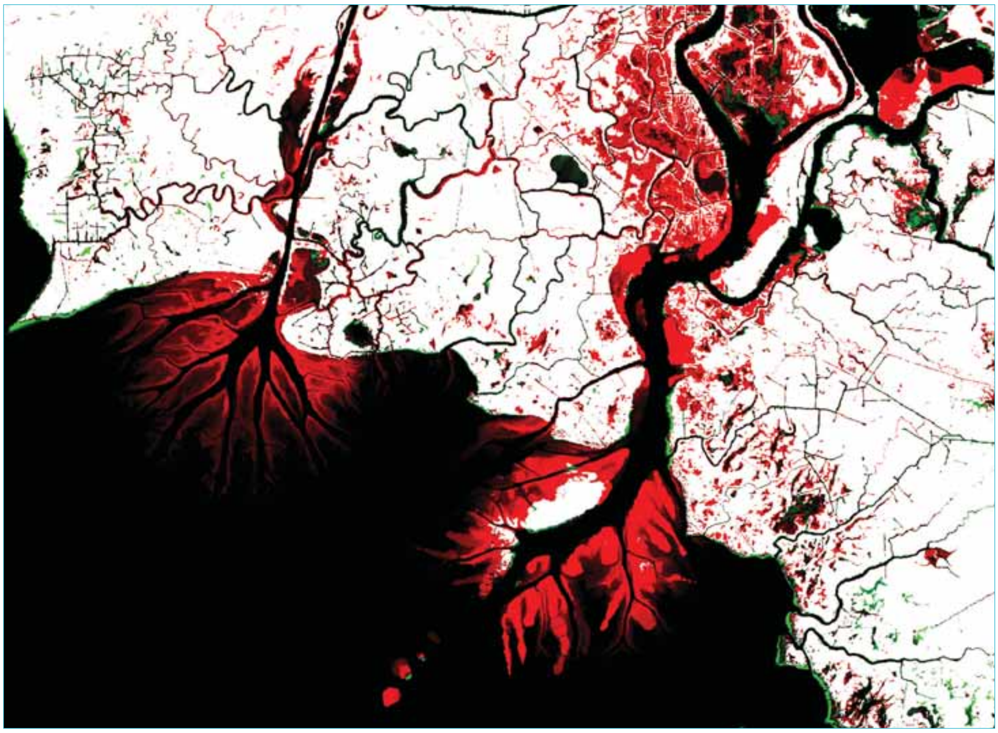
29° 31' 48.0" N
91° 21' 36.0" W

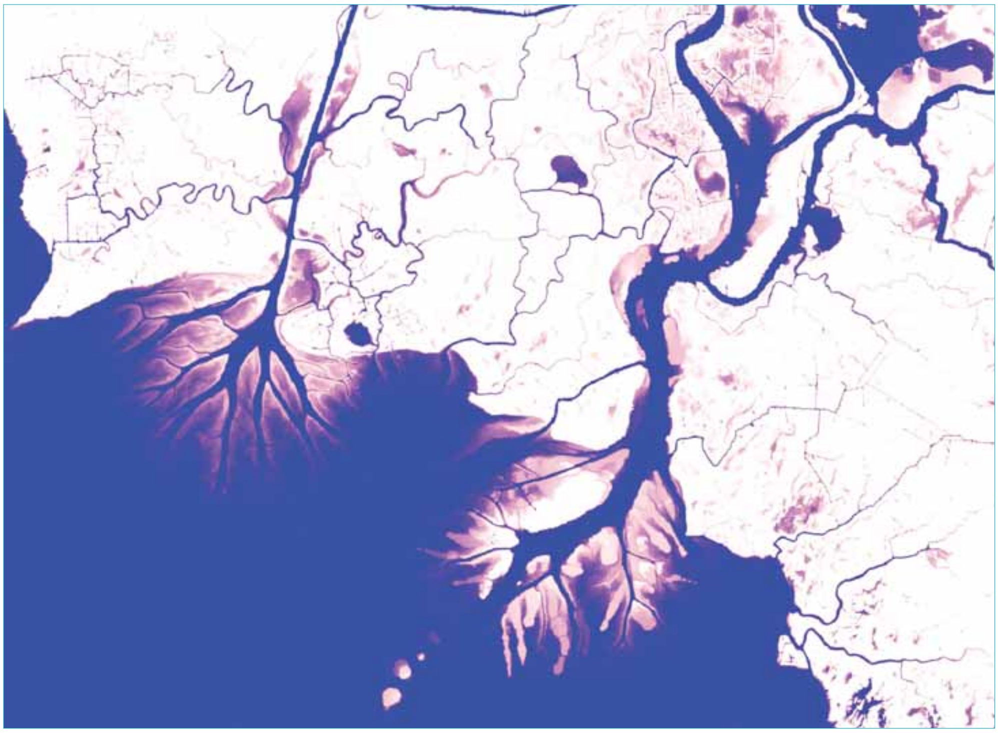




Water Occurrence Change Intensity
(1984 - 1999 to 2000 - 2018)

Decrease | No Change | Increase



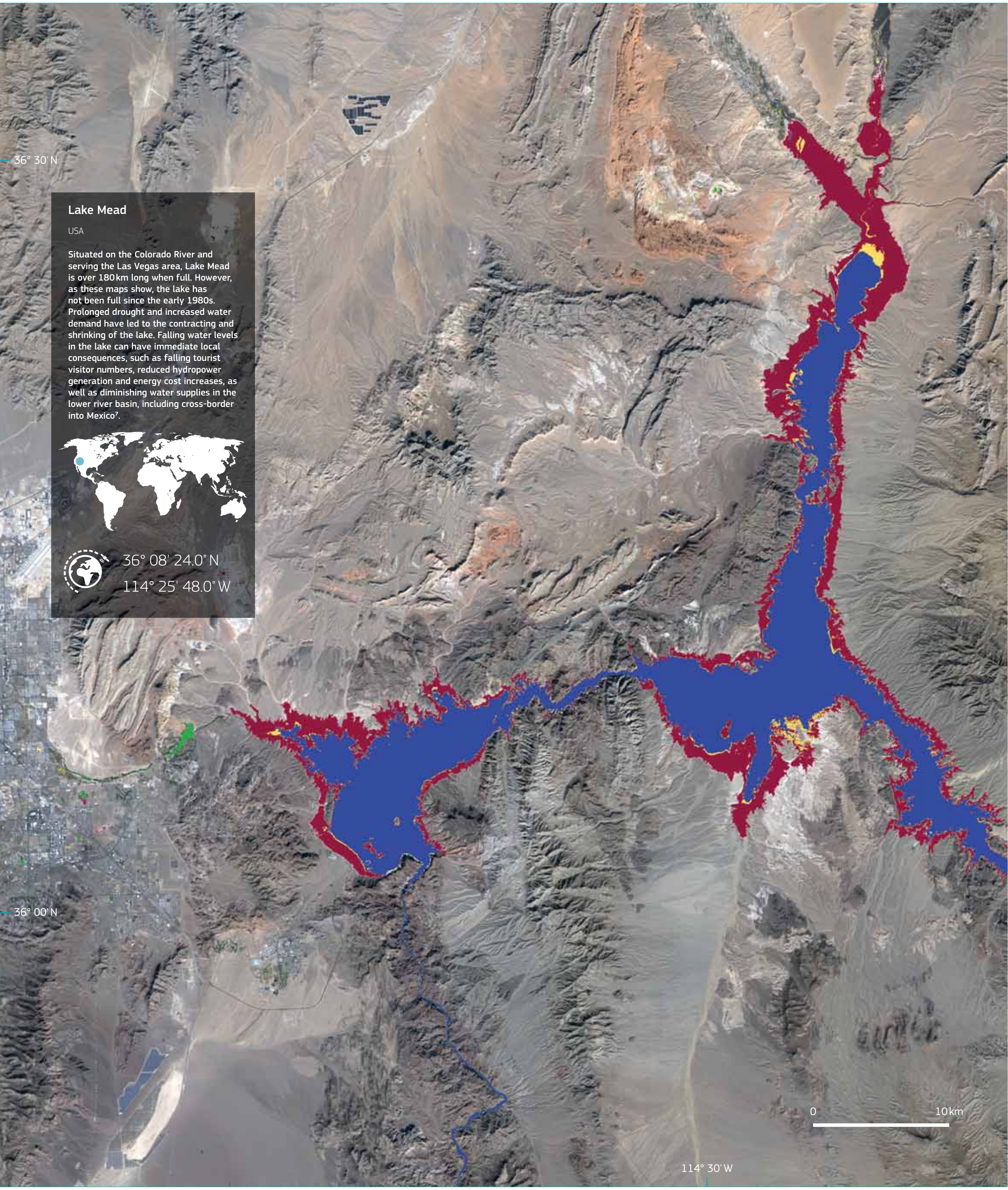


Water Occurrence
(1984 - 2018)

0% | 100%

Sometimes Water | Always Water

6 | Lake Mead (USA)

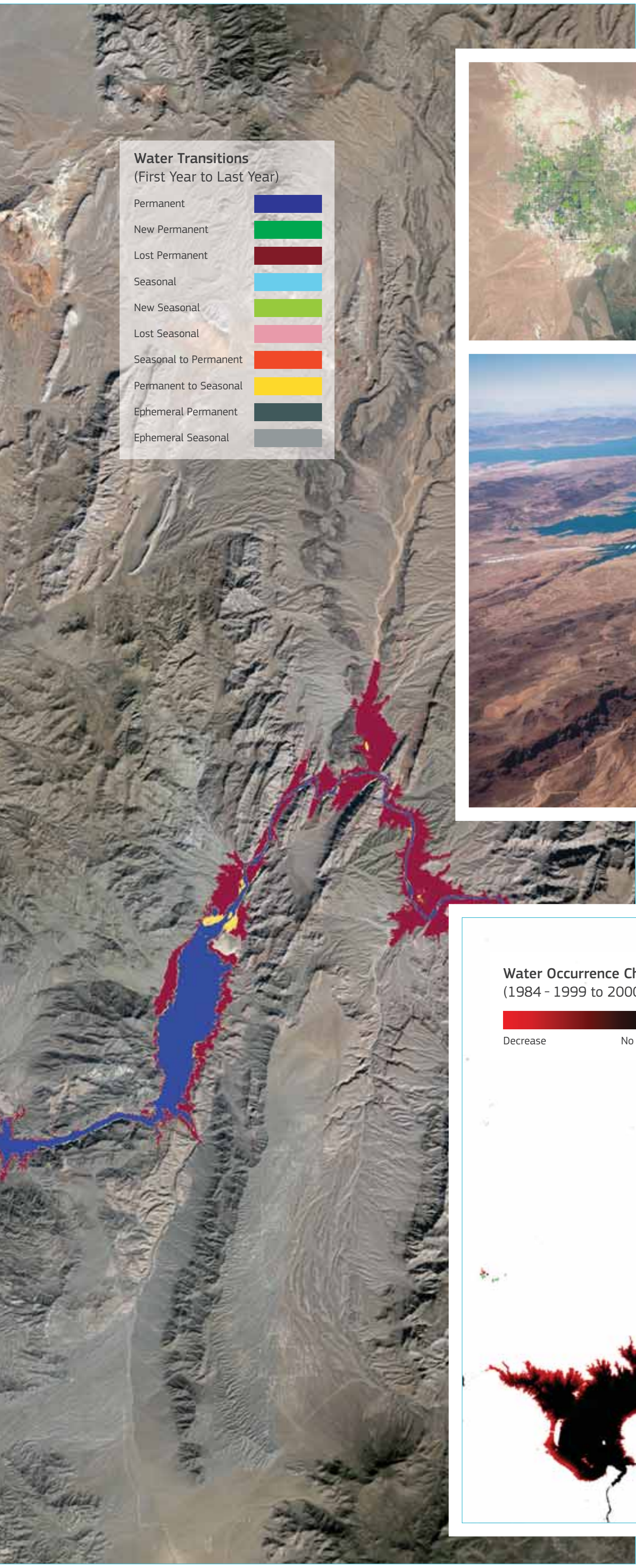


Lake Mead

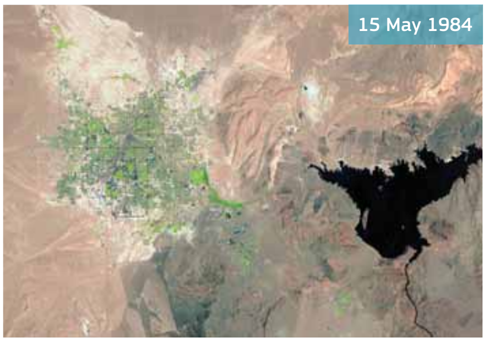
USA

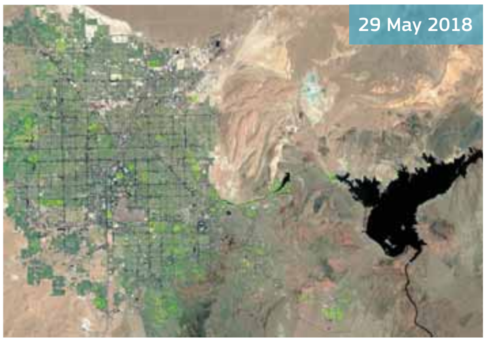
Situated on the Colorado River and serving the Las Vegas area, Lake Mead is over 180km long when full. However, as these maps show, the lake has not been full since the early 1980s. Prolonged drought and increased water demand have led to the contracting and shrinking of the lake. Falling water levels in the lake can have immediate local consequences, such as falling tourist visitor numbers, reduced hydropower generation and energy cost increases, as well as diminishing water supplies in the lower river basin, including cross-border into Mexico[7].

36° 08' 24.0" N
114° 25' 48.0" W

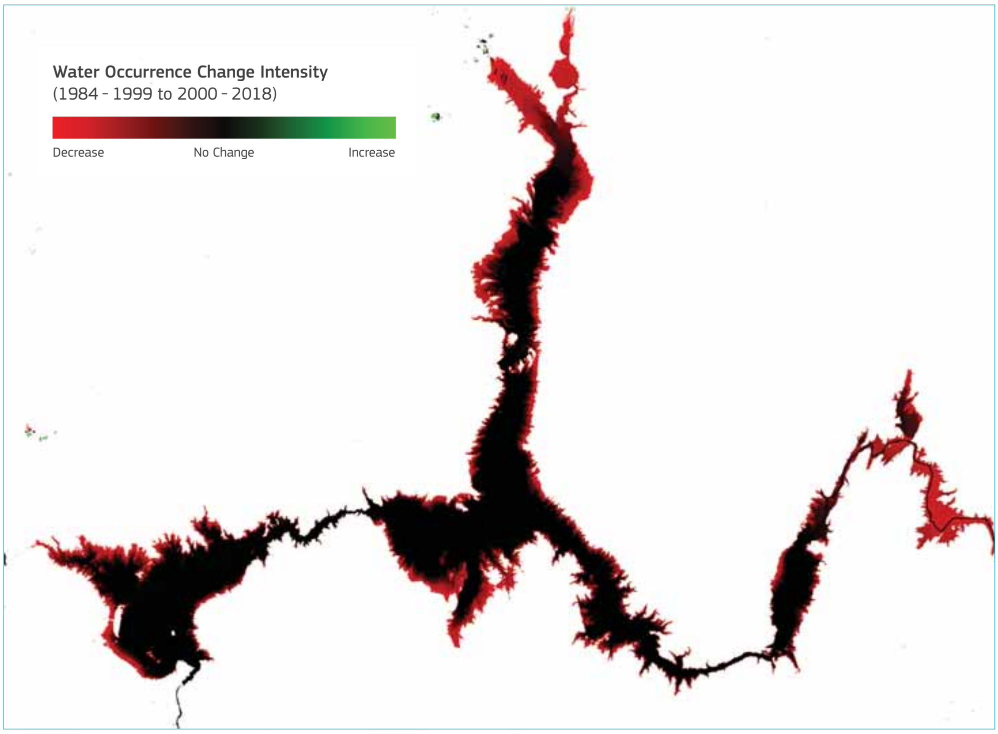


The expansion of Las Vegas vs. the contraction of Lake Mead, USA.
These two images show the expansion of the Las Vegas metropolitan area and the contraction of nearby Lake Mead that supplies the city with water. Images acquired by Landsat satellites on 15 May 1984 and 29 May 2018. Images are 45 km North-South (top to bottom).
Source: Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

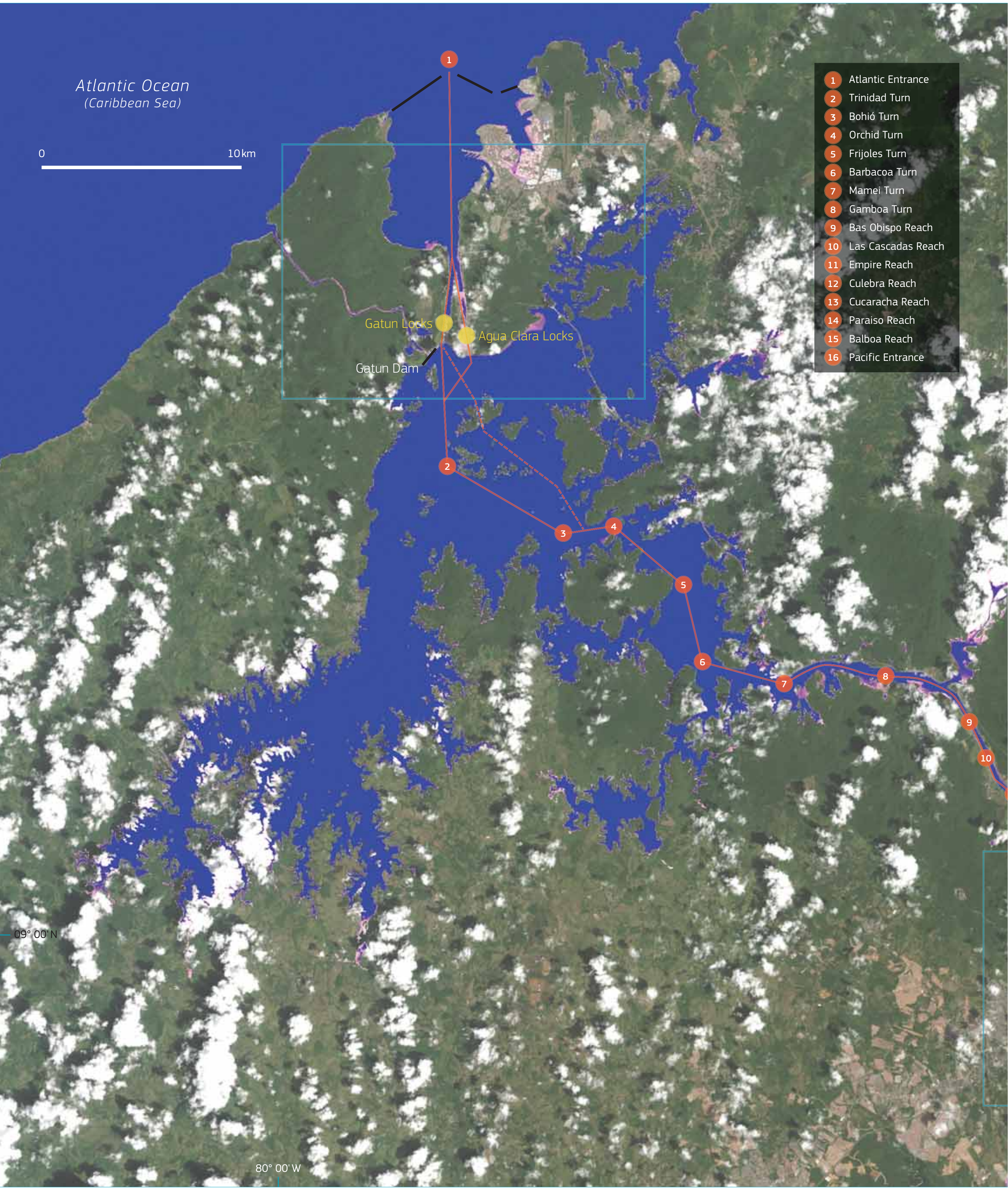




Lake Mead, Arizona/Nevada, USA.
Lake Mead, created by the damming of the Colorado River by the Hoover Dam, is the largest reservoir in the United States in terms of water capacity.
The white band clearly shows the high water level.
Source: Nikola Majksner on Unsplash.



7 | Panama Canal (Panama)



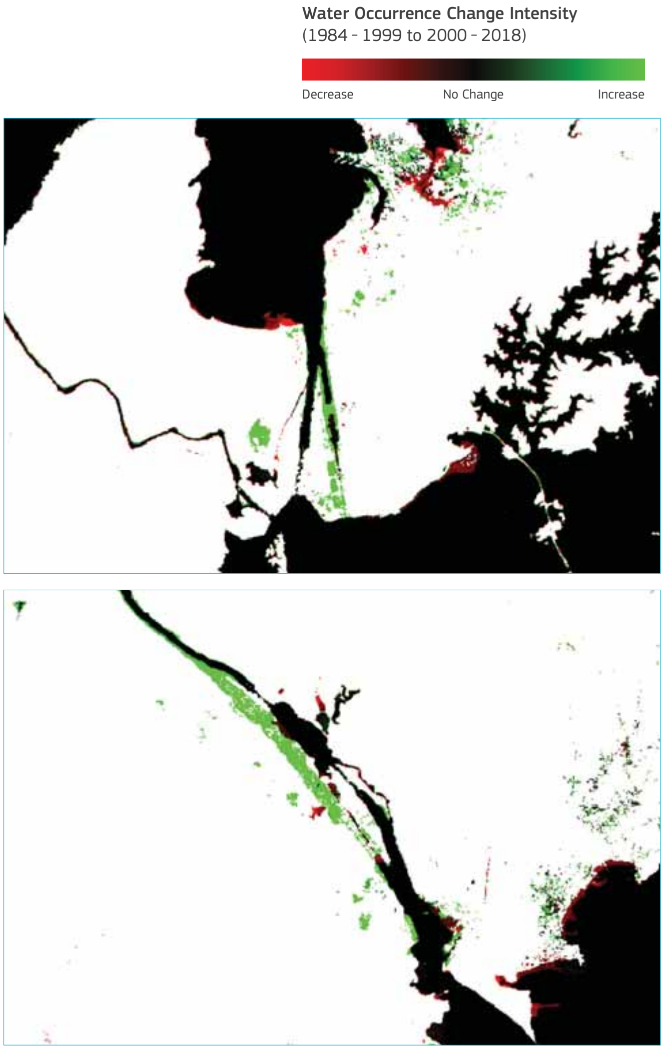
Panama Canal

Panama

Almost all the waterscape across the Panama isthmus is artificial. The pouring of concrete to form the Gatun dam on the Chagres River began in 1909, and by 1913 this modest natural waterway had become the largest artificial lake in the world. The newly created Lake Gatun was, and is, an essential part of the Panama Canal, linking the Atlantic and Pacific Oceans. Work on the canal has not stopped. The Panama Extension project, which began in 2007, saw new locks built on both the Atlantic and Pacific sides. The new locks opened in 2016 and can be seen in the surface water occurrence change maps. The construction of artificial lakes, channels and the locks flooded more than 475 km² of land, which profoundly changed its biodiversity. Subsequently, the introduction of invasive species (as part of the sport fishing use to which Lake Gatun is put) have further damaged the environment[8]. Because of its strategic and economic importance, people were largely excluded from the canal's borders, and today a corridor of intact tropical forest exists along its entire length – the only part of Central America beyond the Panama-Colombia border where forest traverses the entire isthmus[9].

09° 07' 12.0" N
79° 46' 48.0" W

A ship passing through the Agua Clara locks.
The dimensions of the Panama Canal's locks determine the maximum size to which many ships are built. These are referred to as Panamax and New Panamax vessels. Dimensions are fixed by the Panama Canal Authority, which issues regular notices to shipping (each January, or when otherwise required)[10].
Source: By Mariordo (Mario Roberto Durán Ortiz) - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=82643323



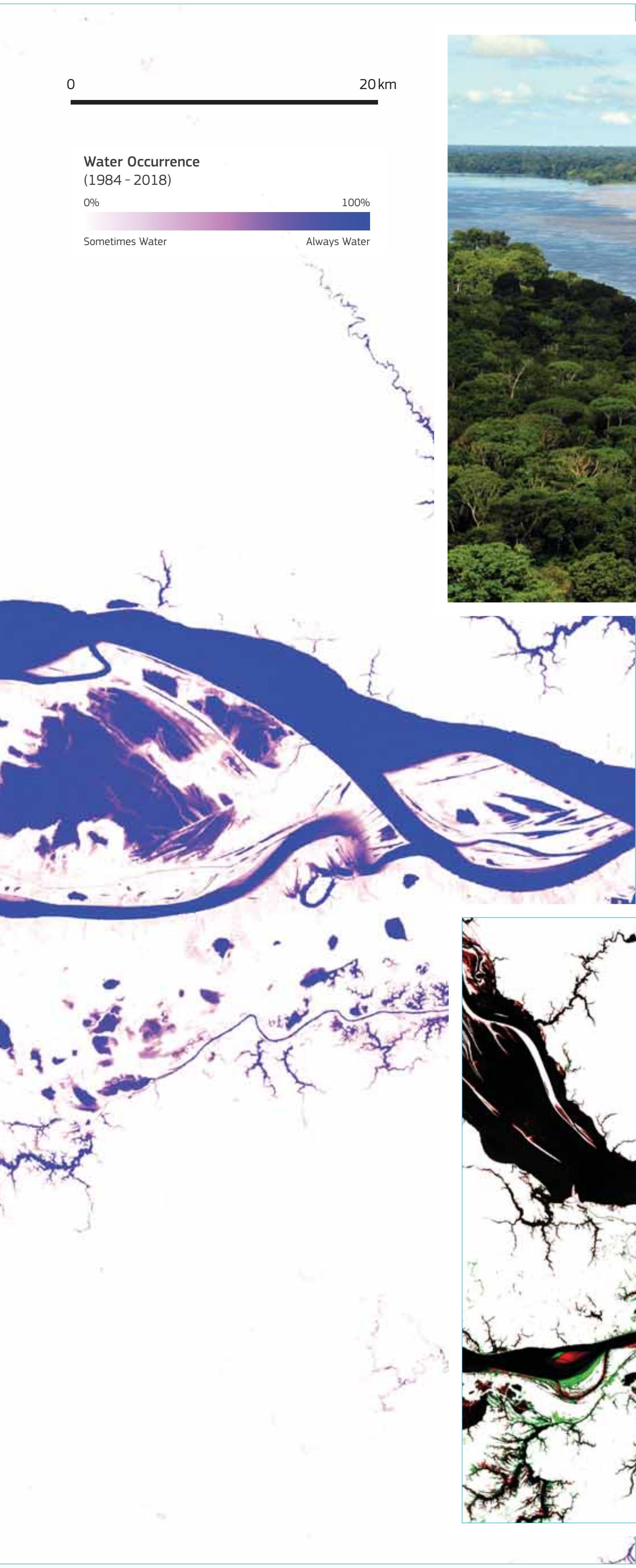
Panama Canal.
Recent lock construction at the Caribbean Sea (Agua Clara Locks) and Pacific Ocean ends of the canal can be clearly seen as light green, indicative of increasing water occurrence in the latter years of the 2000–2018 period. Three rectangular ponds designed to save water by retaining some of the water released when ships are lowered can be seen adjacent to the locks in the top inset.
Source: JRC/Google Earth Engine team.

8 | Amazon River (Brazil)

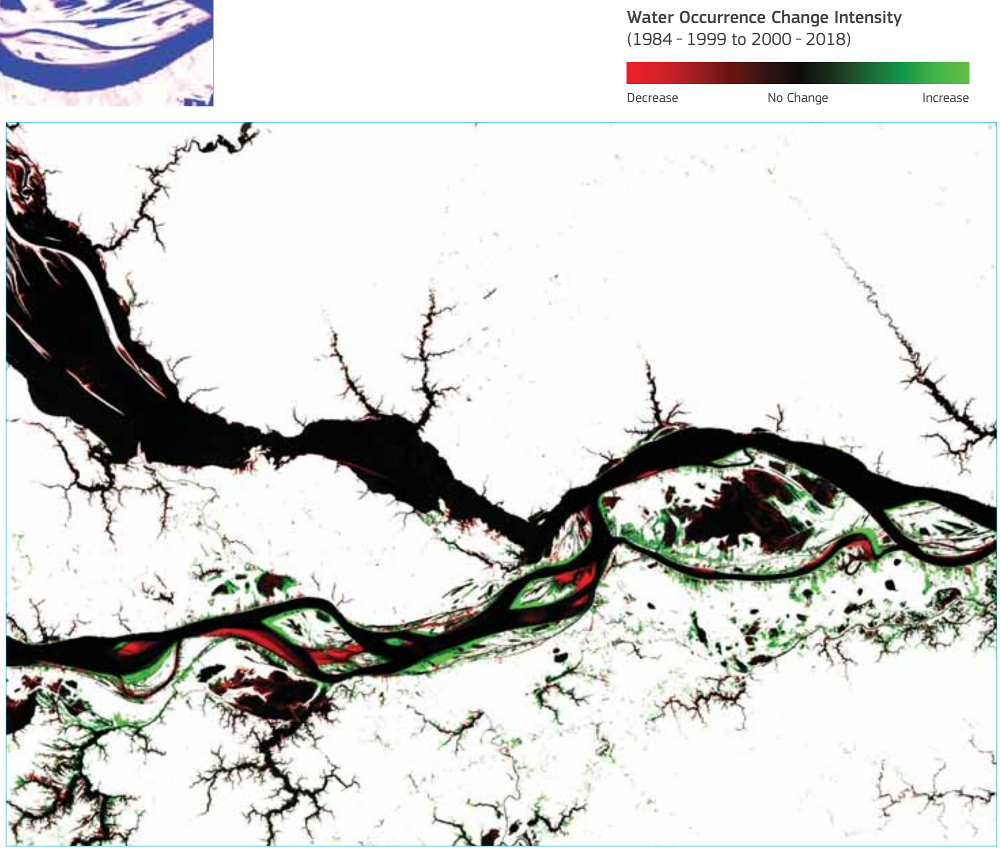
Amazon River

Brazil

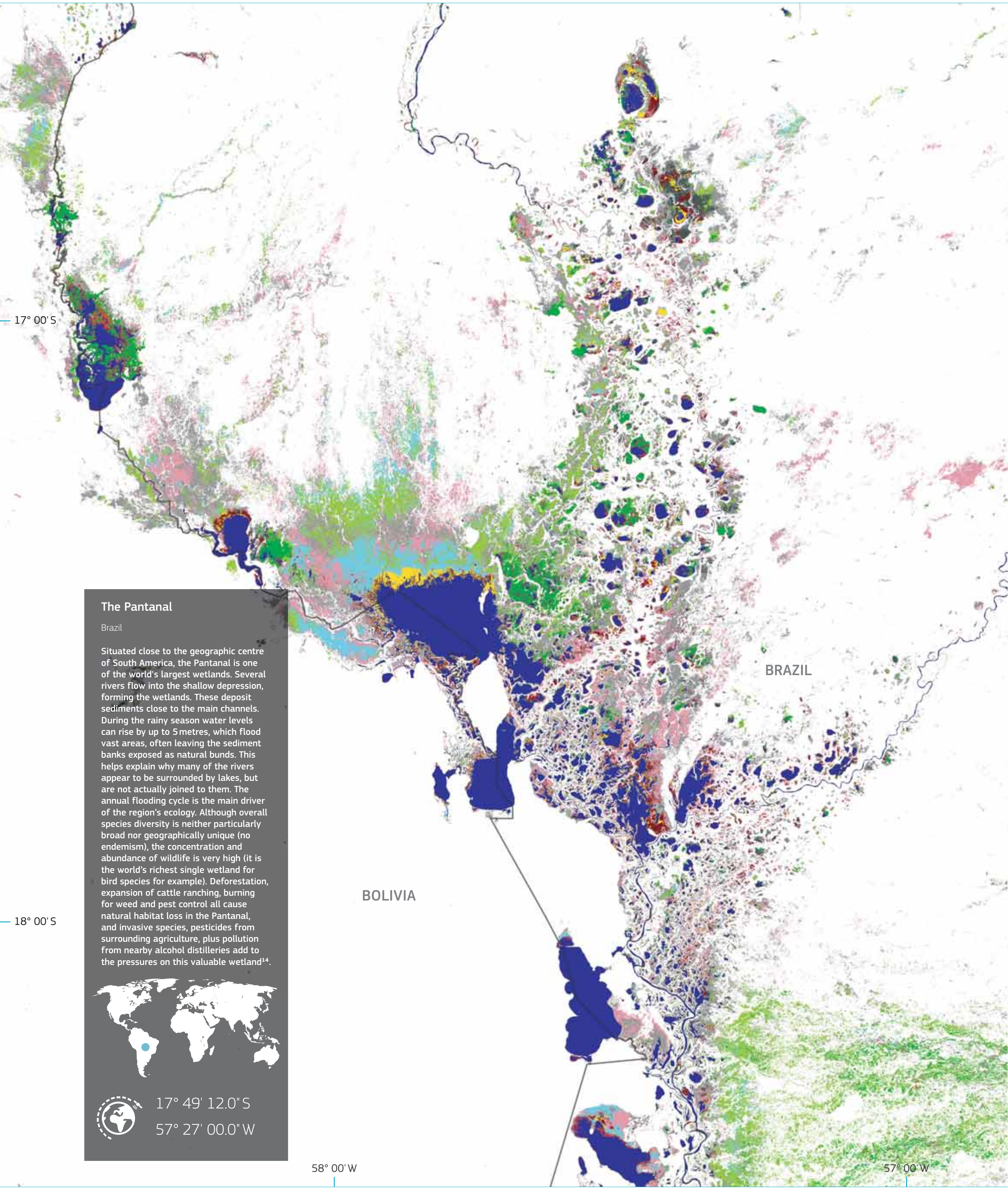
The city of Manaus sits at the confluence of the Negro and Solimões rivers that join to form the largest river on Earth, the Amazon. Although the main channels of the Negro, the Solimões (which is often called the Upper Amazon) and the Amazon are all extremely well defined as permanent waterbodies (the Amazon River is at least 11.3 million years old[11]), the numerous spits, meanders and oxbow lakes are testament to the scale of the shifting surface water dynamics. The channel of the faster flowing Solimões is particularly changeable, as seen in the water occurrence change intensity inset. Harnessing the physical differences between the two rivers' energy levels may be used to provide electricity in the future[12].



Amazon tributaries near Manaus, Brazil.
The Solimões, flowing from the Andes, has a very high sediment load (the brown water in the photograph), whilst the Negro has a higher dissolved carbon content, having flowed through much of the Amazon forest. The two rivers flow at different speeds and have different temperatures. The lighter coloured Solimões is cooler than the Negro, but flows faster. The denser waters of the Solimões flow beside and under those of the Negro, and the two rivers don't fully mix until around 100 km downstream from the confluence point[13].
Source: Neil Palmer/CIAT [CC BY-SA (https://creativecommons.org/licenses/by-sa/2.0)]



9 | The Pantanal (Brazil)

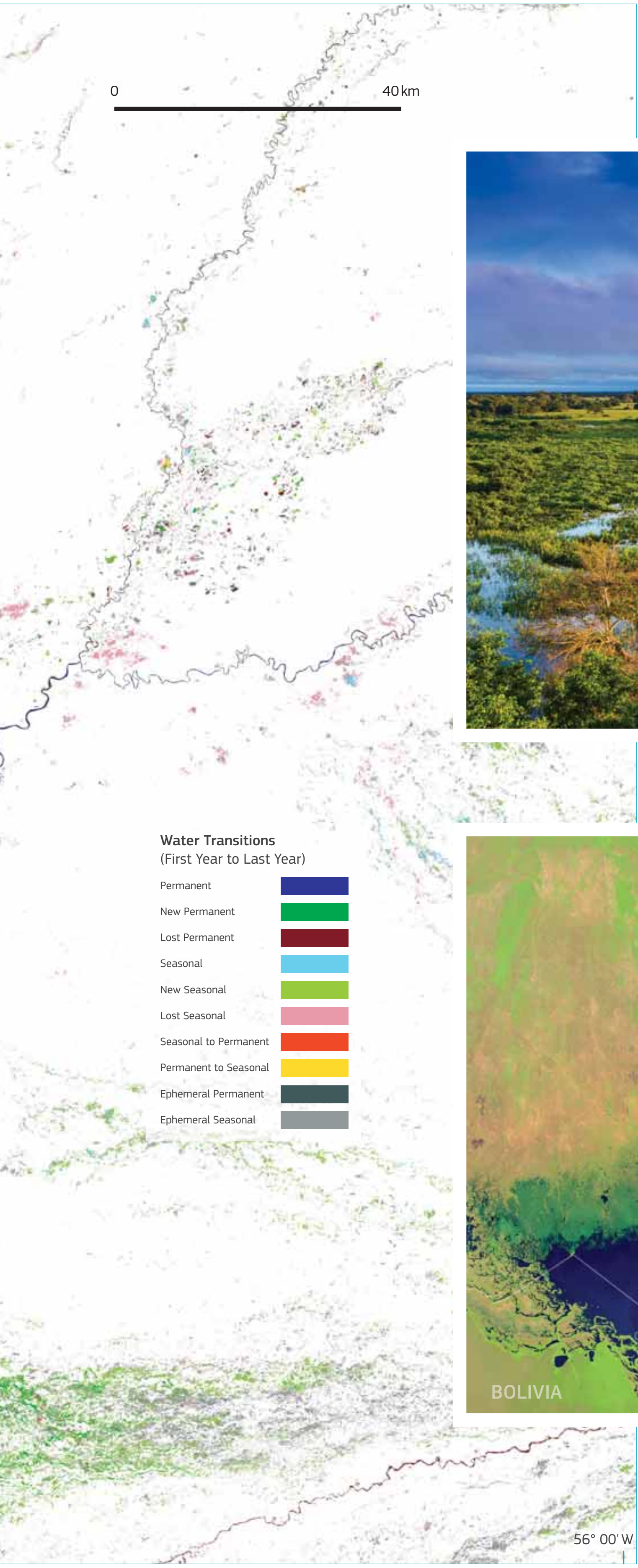


The Pantanal

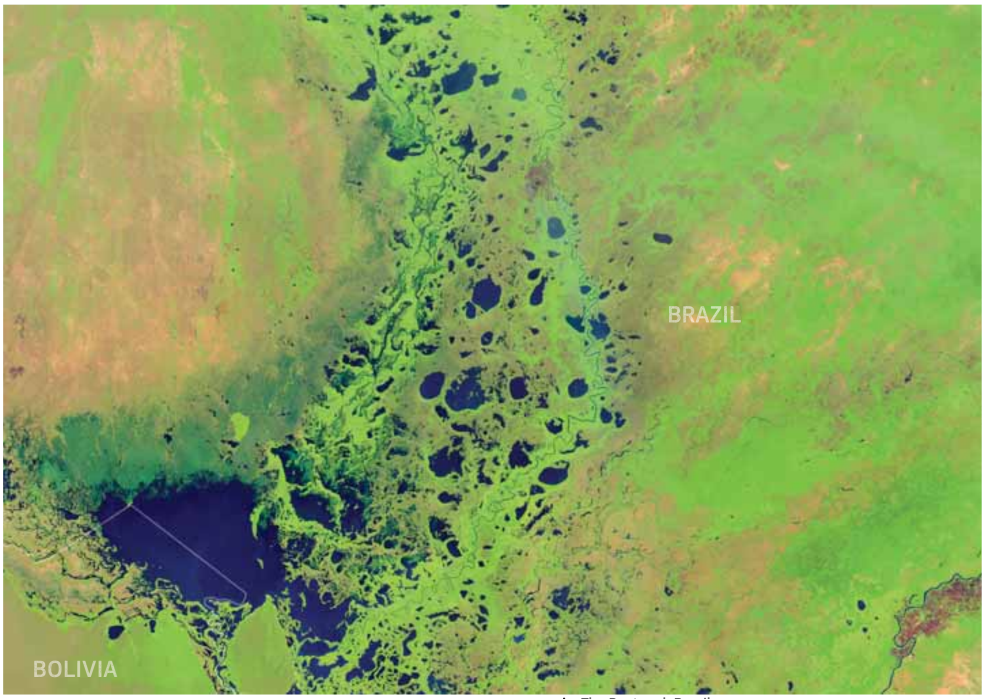
Brazil

Situated close to the geographic centre of South America, the Pantanal is one of the world's largest wetlands. Several rivers flow into the shallow depression, forming the wetlands. These deposit sediments close to the main channels. During the rainy season water levels can rise by up to 5 metres, which flood vast areas, often leaving the sediment banks exposed as natural bunds. This helps explain why many of the rivers appear to be surrounded by lakes, but are not actually joined to them. The annual flooding cycle is the main driver of the region's ecology. Although overall species diversity is neither particularly broad nor geographically unique (no endemism), the concentration and abundance of wildlife is very high (it is the world's richest single wetland for bird species for example). Deforestation, expansion of cattle ranching, burning for weed and pest control all cause natural habitat loss in the Pantanal, and invasive species, pesticides from surrounding agriculture, plus pollution from nearby alcohol distilleries add to the pressures on this valuable wetland[14].

17° 49' 12.0" S
57° 27' 00.0" W



The Pantanal, Brazil.
Typical scenery of the Pantanal, a flooded grassland and savanna ecoregion of south-central South America.
Source: Filipefrazao [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].



The Pantanal, Brazil.
Detailed view of the Pantanal straddling the border between Bolivia and Brazil. Image acquired by Landsat 8 on 28 October 2019. The image is 86 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

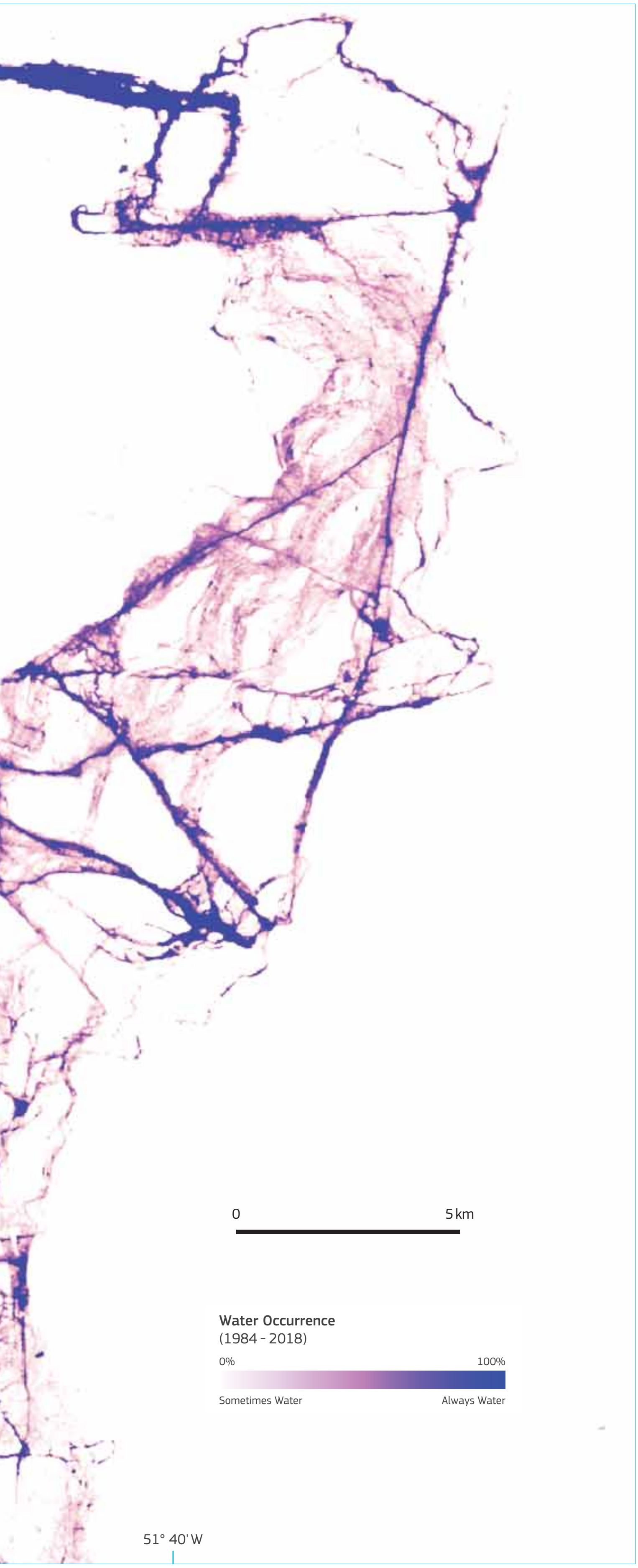
10 | The Xingu River (Brazil)

The Xingu River

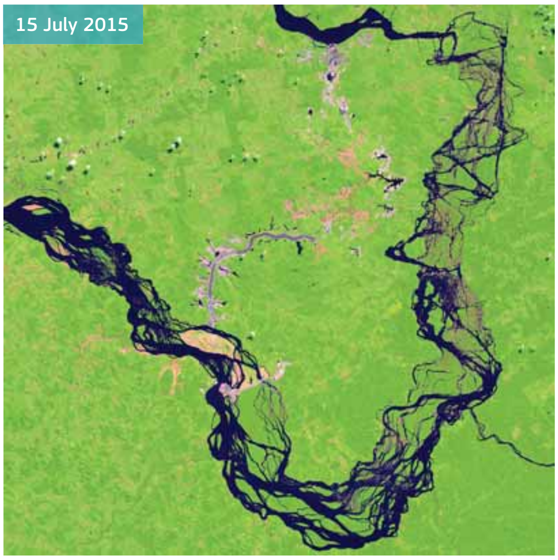
Brazil

The Xingu River, a tributary of the Amazon, was the first indigenous territory to be recognised by the Brazilian government. The river meanders for much of its length. However, just upstream of Belo Monte, it is transformed into a series of geometric shapes and sharp-angled bends and rapids as the river is constrained by the fracture and fault lines in the underlying rock. This large river bend supports a number of endemic fish species[15]. Two new lakes have formed within this major meander of the Xingu following the construction of the Belo Monte Dam between 2011 and its opening in 2016. Today the power plant's capacity of 11 223 megawatts makes it the fourth largest hydroelectric plant in the world[16]. The lakes have reduced the streamflow in the major river bend, and flooded former farmland, as well as forest. During its construction, the dam site drew many workers away from farms and ranches, which had an impact on the social fabric of communities some distance away from the dam and river too[17].

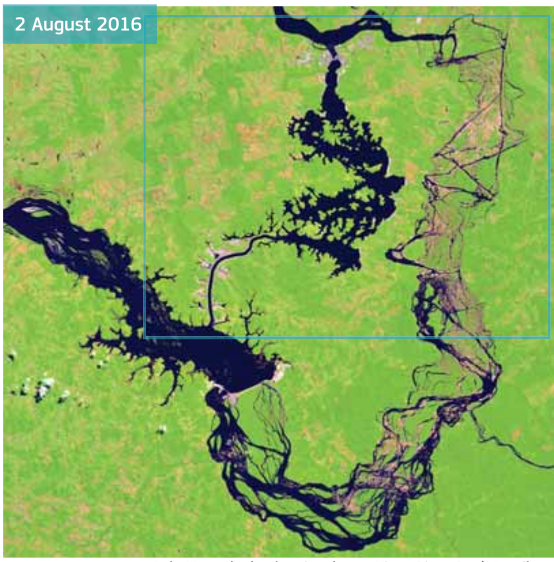
03° 13' 48.0" S
51° 39' 00.0" W



The Xingu River flows freely down to Bel Monte in a large meander, encompassing the iconic geographic flow area.



Construction of the Belo Monte hydroelectric complex is well underway.



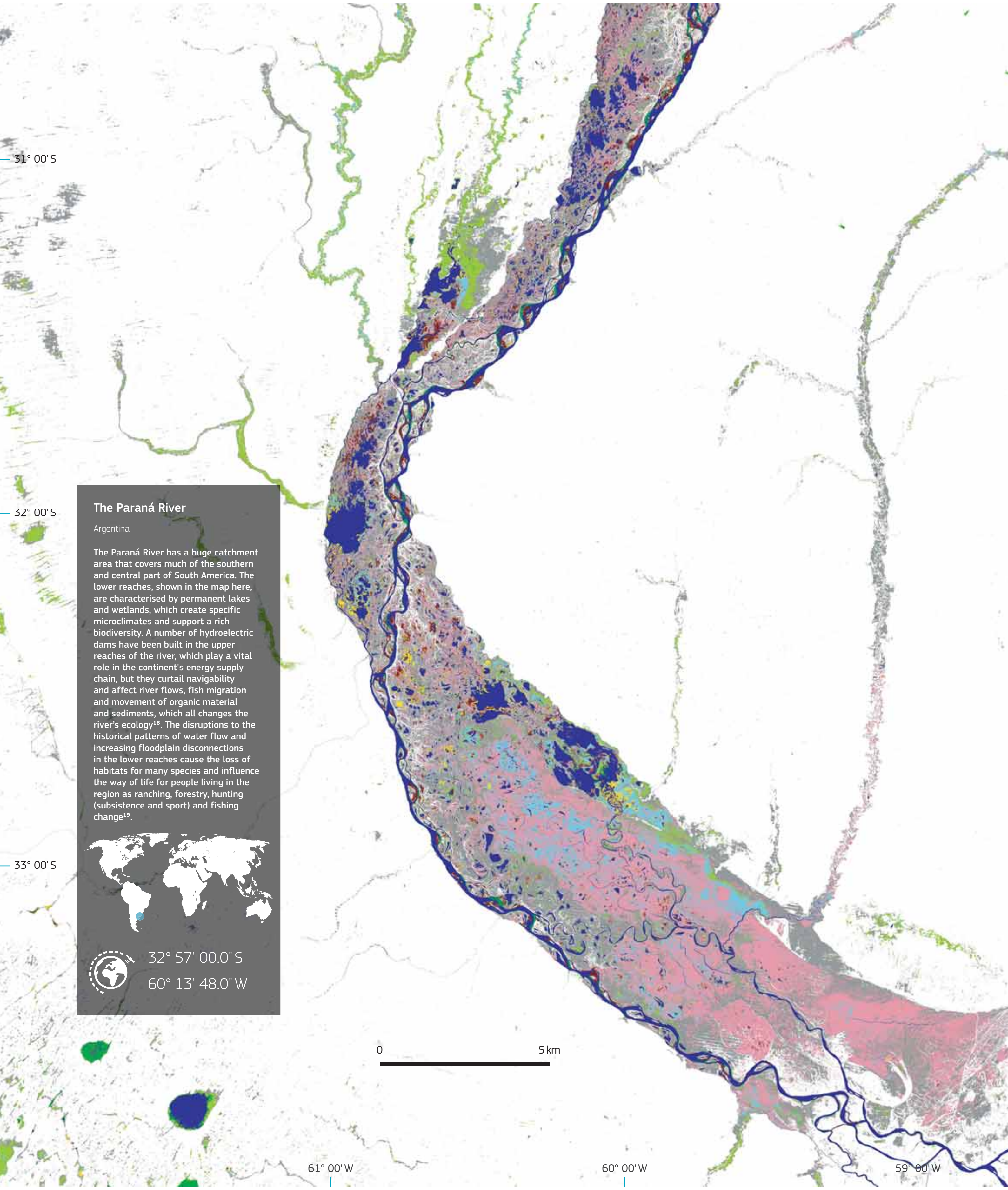
Approximate scope of main data image (Water Occurrence)

Construction has ended, the waters of the Xingu no longer flow freely, but are retained in two extensive new lakes.

Belo Monte hydroelectric scheme, Xingu River, Pará, Brazil. Landsat series showing the growth of the Belo Monte Dam, a hydroelectric dam complex on the northern part of the Xingu River. Brazil's recent rapid economic growth has provoked a huge demand for new and stable sources of energy. All images are 60 km North-South (top to bottom).

Source: All images Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

11 | The Paraná River (Argentina)



The Paraná River

Argentina

The Paraná River has a huge catchment area that covers much of the southern and central part of South America. The lower reaches, shown in the map here, are characterised by permanent lakes and wetlands, which create specific microclimates and support a rich biodiversity. A number of hydroelectric dams have been built in the upper reaches of the river, which play a vital role in the continent's energy supply chain, but they curtail navigability and affect river flows, fish migration and movement of organic material and sediments, which all changes the river's ecology[18]. The disruptions to the historical patterns of water flow and increasing floodplain disconnections in the lower reaches cause the loss of habitats for many species and influence the way of life for people living in the region as ranching, forestry, hunting (subsistence and sport) and fishing change[19].

32° 57' 00.0" S
60° 13' 48.0" W

Paraná River floodplain.
Astronaut's photo showing a 29-kilometre (18-mile) stretch of the Paraná, just downstream from Goya, Argentina.
Source: By ISS Expedition 27 crew - NASA Earth Observatory, Public Domain, https://commons.wikimedia.org/w/index.php?curid=15093216

Itaipu Dam, Paraná River, Brazil/Paraguay.
The Itaipu Dam sits well upstream of the detail shown in the water transitions map extract here. The dam, a joint undertaking of Brazil and Paraguay, is only one of many, many dams (large and small) throughout the Paraná River catchment area. Both individually and collectively, such dams have an effect on downstream hydrology, sediment loads, and ultimately on biodiversity.
Source: By Alicia Nijdam - originally posted to Flickr as Itaipu Dam. Uploaded using F2ComButton, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=9498017

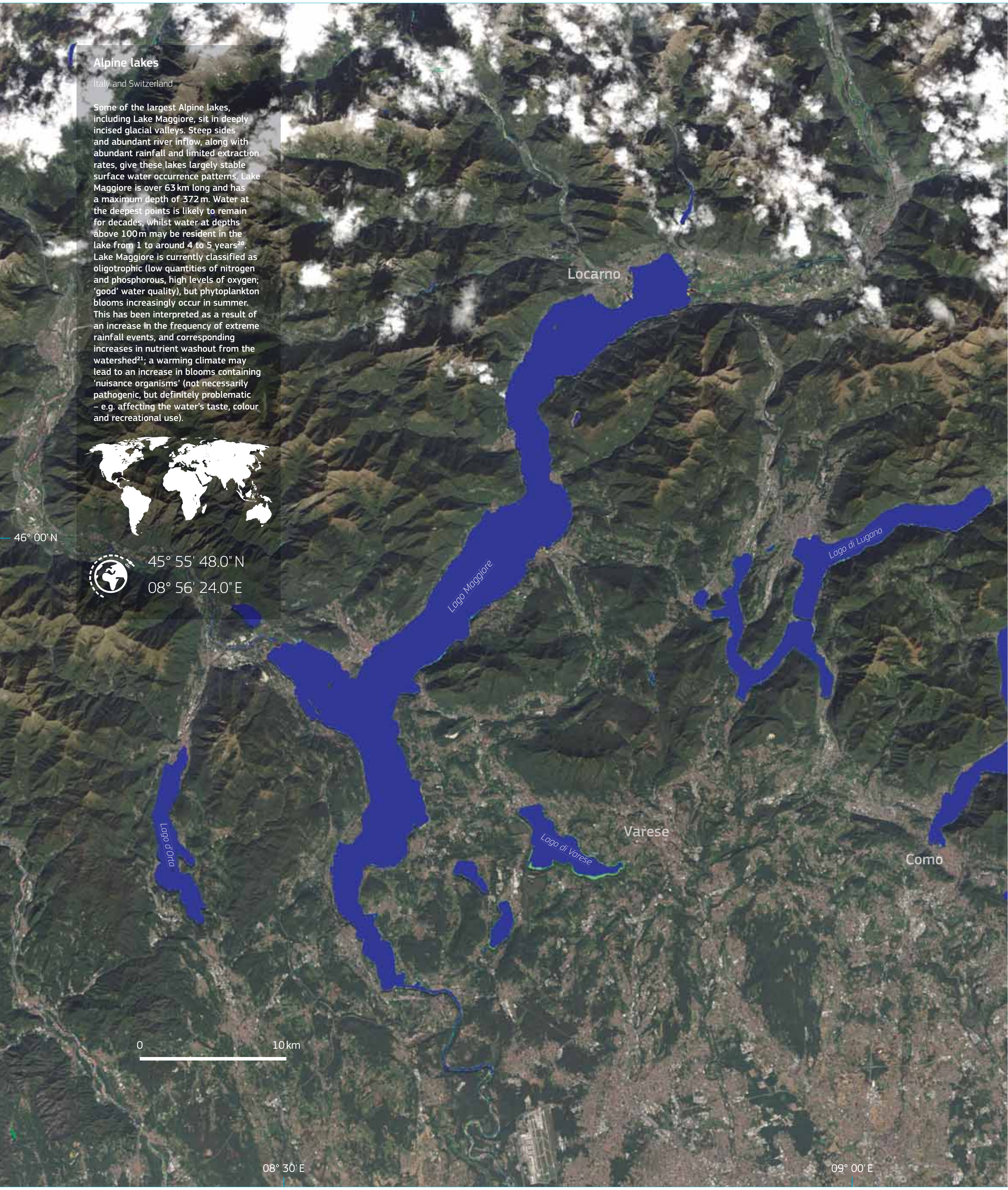
12 | Alpine lakes (Italy and Switzerland)

Alpine lakes

Italy and Switzerland

Some of the largest Alpine lakes, including Lake Maggiore, sit in deeply incised glacial valleys. Steep sides and abundant river inflow, along with abundant rainfall and limited extraction rates, give these lakes largely stable surface water occurrence patterns. Lake Maggiore is over 63 km long and has a maximum depth of 372 m. Water at the deepest points is likely to remain for decades, whilst water at depths above 100 m may be resident in the lake from 1 to around 4 to 5 years[20]. Lake Maggiore is currently classified as oligotrophic (low quantities of nitrogen and phosphorous, high levels of oxygen; 'good' water quality), but phytoplankton blooms increasingly occur in summer. This has been interpreted as a result of an increase in the frequency of extreme rainfall events, and corresponding increases in nutrient washout from the watershed[21]; a warming climate may lead to an increase in blooms containing 'nuisance organisms' (not necessarily pathogenic, but definitely problematic – e.g. affecting the water's taste, colour and recreational use).

45° 55' 48.0" N
08° 56' 24.0" E



Lake Como, viewed from Varenna, Province of Lecco, Italy.
These alpine lakes formed at the end of the last ice age, around 10 000 years ago. There have been human settlements here throughout recorded history. Tourism now flourishes, in addition to long established use as transport networks, fishing, and religious centres.
Source: Blake Kelly on Unsplash.

Hermitage of Santa Caterina del Sasso, Lake Maggiore, Italy.
This point on the lake has provided a focus for meditation and contemplation since at least the 12th Century.
Source: Gianni Careddu [CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)].

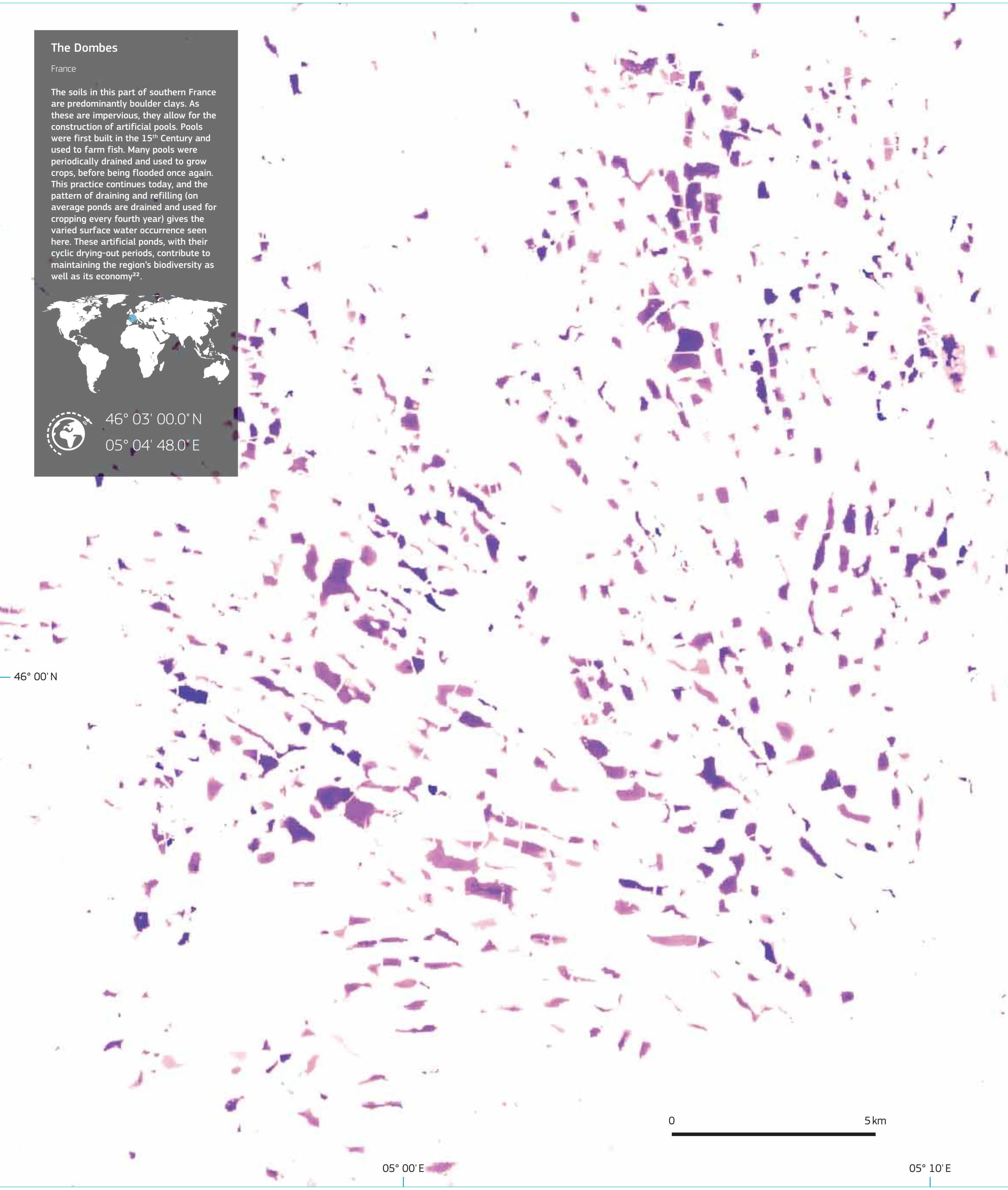
13 | The Dombes (France)

The Dombes

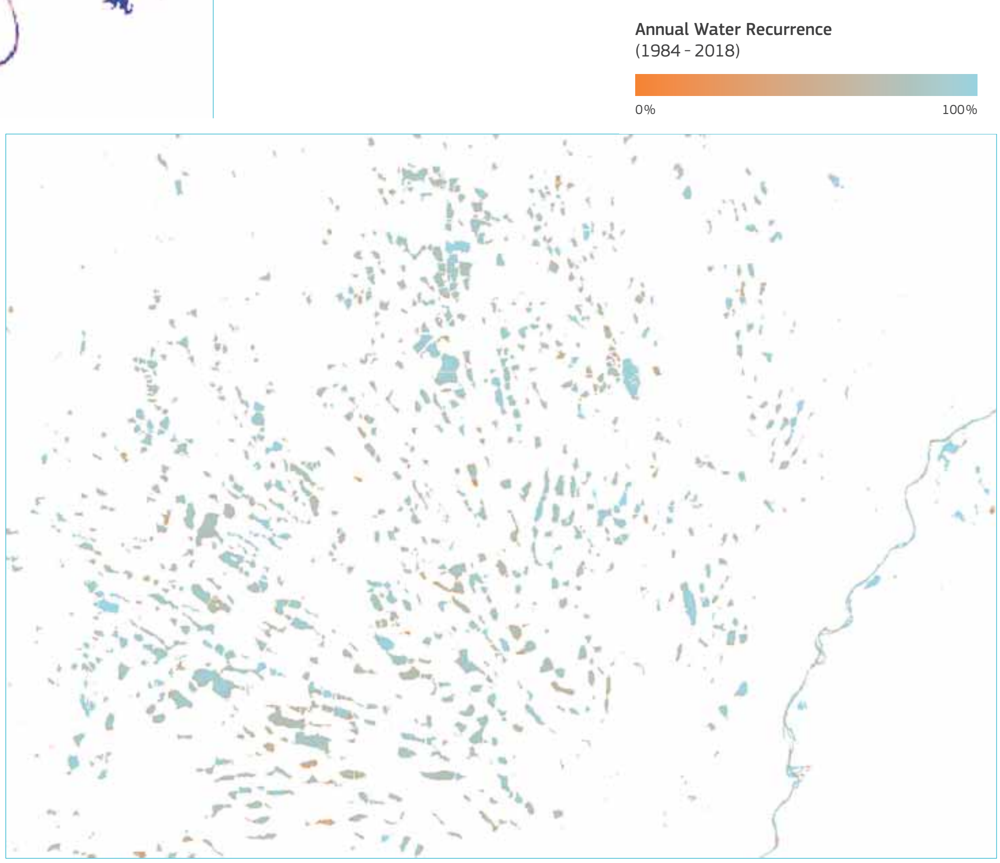
France

The soils in this part of southern France are predominantly boulder clays. As these are impervious, they allow for the construction of artificial pools. Pools were first built in the 15th Century and used to farm fish. Many pools were periodically drained and used to grow crops, before being flooded once again. This practice continues today, and the pattern of draining and refilling (on average ponds are drained and used for cropping every fourth year) gives the varied surface water occurrence seen here. These artificial ponds, with their cyclic drying-out periods, contribute to maintaining the region's biodiversity as well as its economy[22].

46° 03' 00.0" N
05° 04' 48.0" E



Working a fishpond in the Dombes.
Generally, each year fishponds are drained to obtain the fish catch, and are then refilled from other adjacent ponds. Every four years or so, the pond is left to dry out completely, rather than being immediately refilled. The dried-out pond is usually used to grow cereal crops.



Annual Water Recurrence 1984 – 2018.
Although the fish ponds are generally drained every four years or so, the pattern of repeated draining and filling is remarkably consistent. This gives rise to high recurrence rates of this alternating water/land pattern, which in turn is a major factor influencing the region's biodiversity.

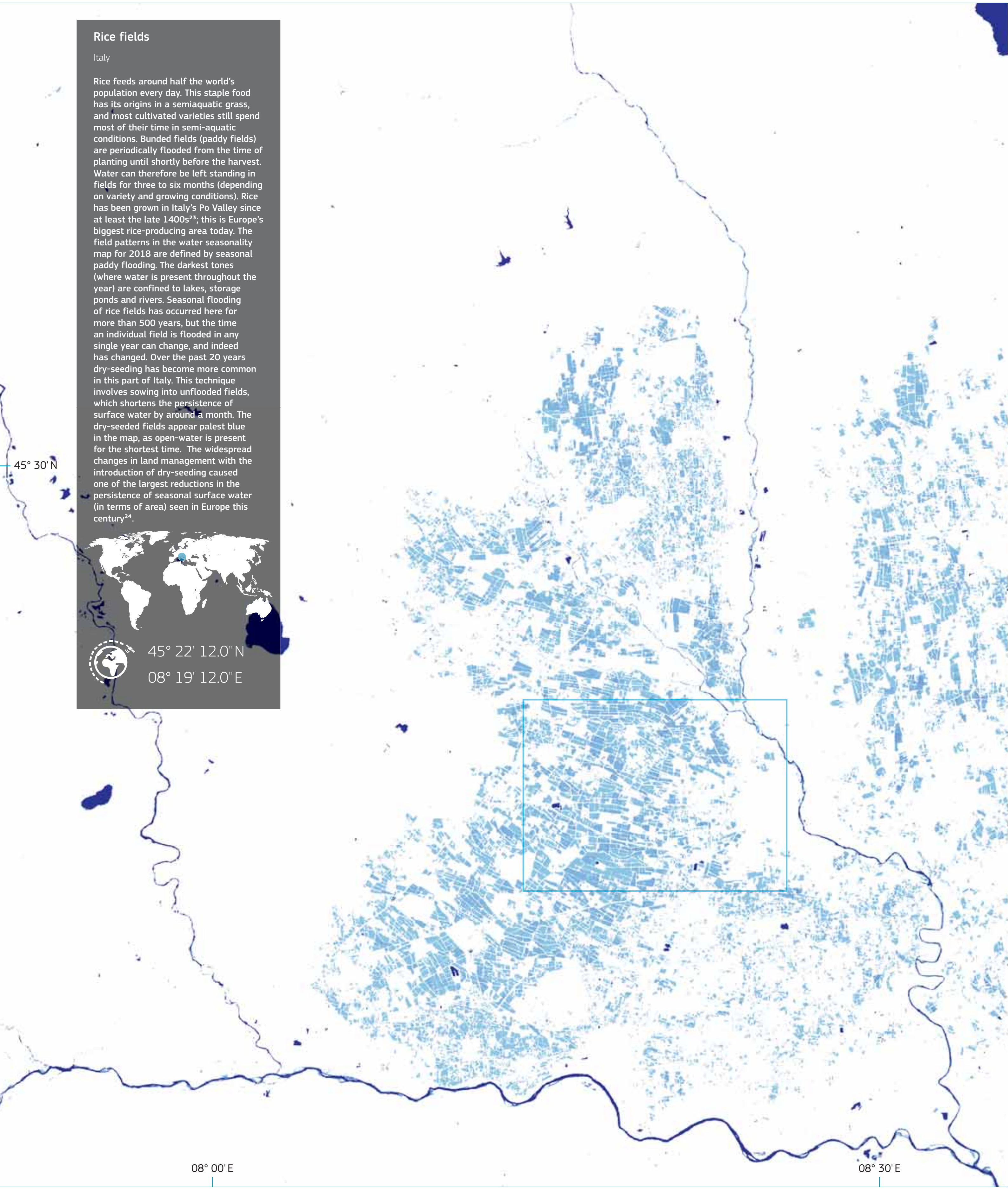
14 | Rice fields (Italy)

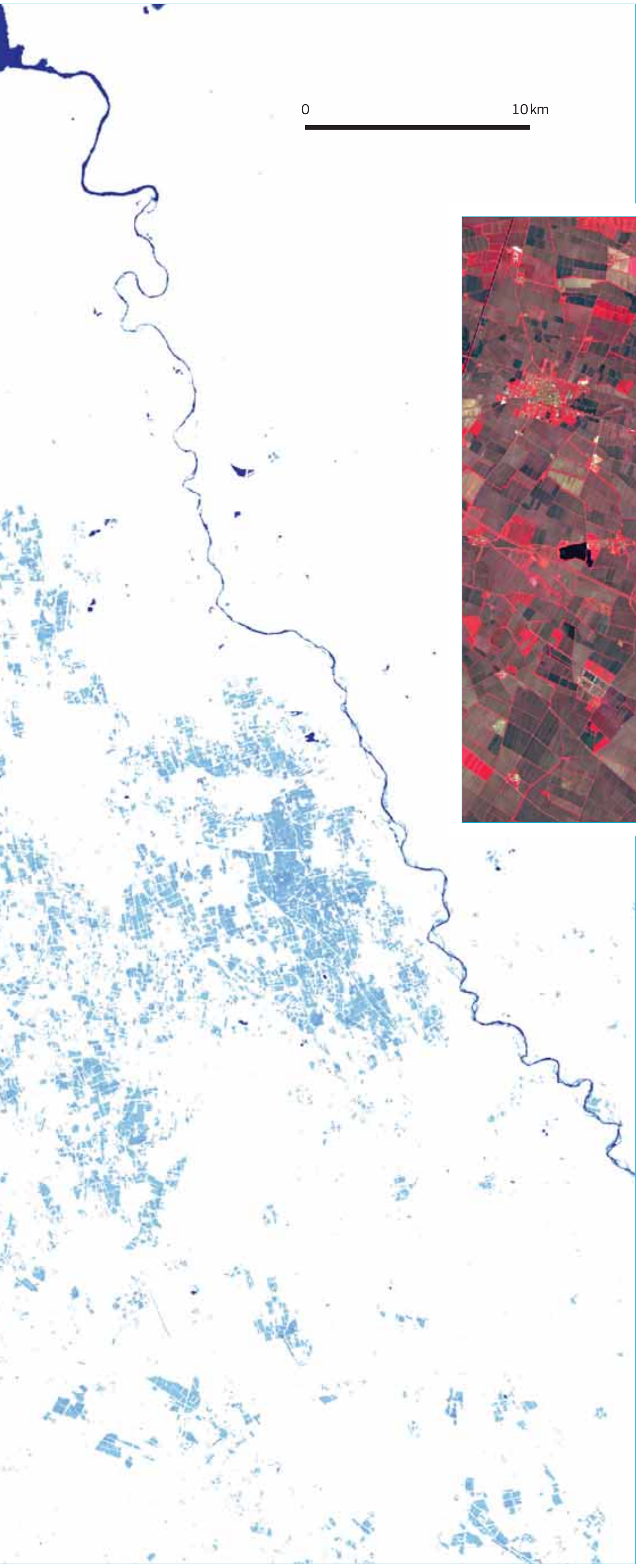
Rice fields

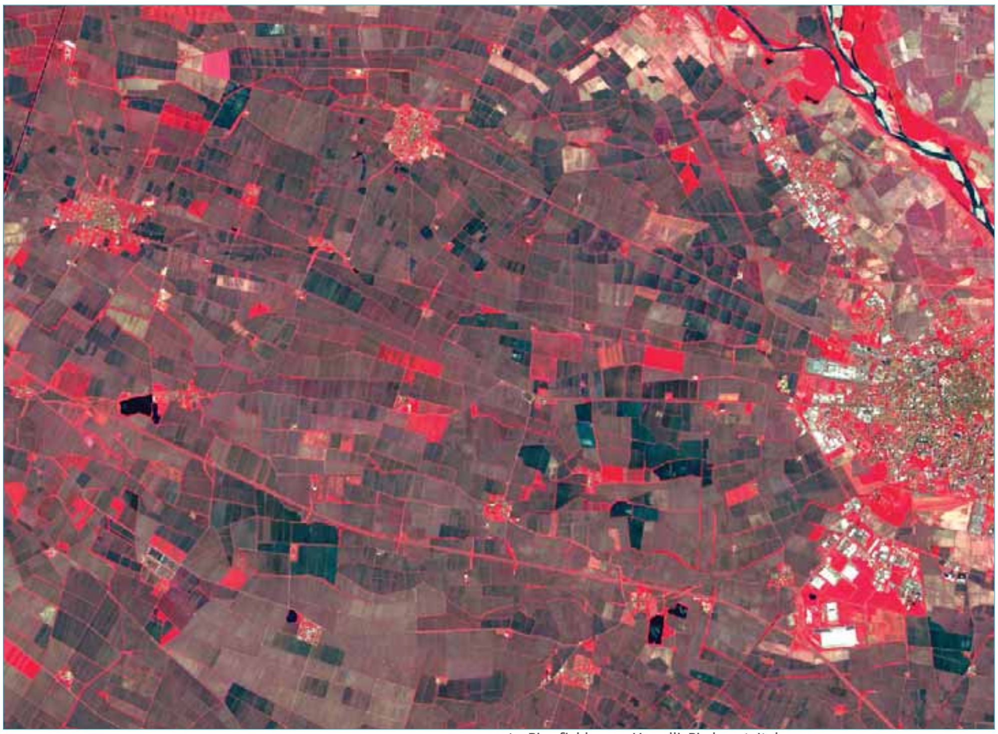
Italy

Rice feeds around half the world's population every day. This staple food has its origins in a semiaquatic grass, and most cultivated varieties still spend most of their time in semi-aquatic conditions. Bunded fields (paddy fields) are periodically flooded from the time of planting until shortly before the harvest. Water can therefore be left standing in fields for three to six months (depending on variety and growing conditions). Rice has been grown in Italy's Po Valley since at least the late 1400s[23]; this is Europe's biggest rice-producing area today. The field patterns in the water seasonality map for 2018 are defined by seasonal paddy flooding. The darkest tones (where water is present throughout the year) are confined to lakes, storage ponds and rivers. Seasonal flooding of rice fields has occurred here for more than 500 years, but the time an individual field is flooded in any single year can change, and indeed has changed. Over the past 20 years dry-seeding has become more common in this part of Italy. This technique involves sowing into unflooded fields, which shortens the persistence of surface water by around a month. The dry-seeded fields appear palest blue in the map, as open-water is present for the shortest time. The widespread changes in land management with the introduction of dry-seeding caused one of the largest reductions in the persistence of seasonal surface water (in terms of area) seen in Europe this century[24].

45° 22' 12.0" N
08° 19' 12.0" E







Rice fields near Vercelli, Piedmont, Italy.
False colour infrared image acquired by a Sentinel-2 satellite on 30 May 2019. Vigorously growing vegetation appears red in false colour images, whilst flooded rice fields with no apparent crop growth appear almost black. The purple tones are where some vegetation has grown. Urban areas appear as light grey to white. The image is around 11 km North-South (top to bottom). The approximate area of the Sentinel image is shown in the bounding box on the map.
Source: Alan Belward using Sentinel-2 imagery, courtesy EU Copernicus Programme.

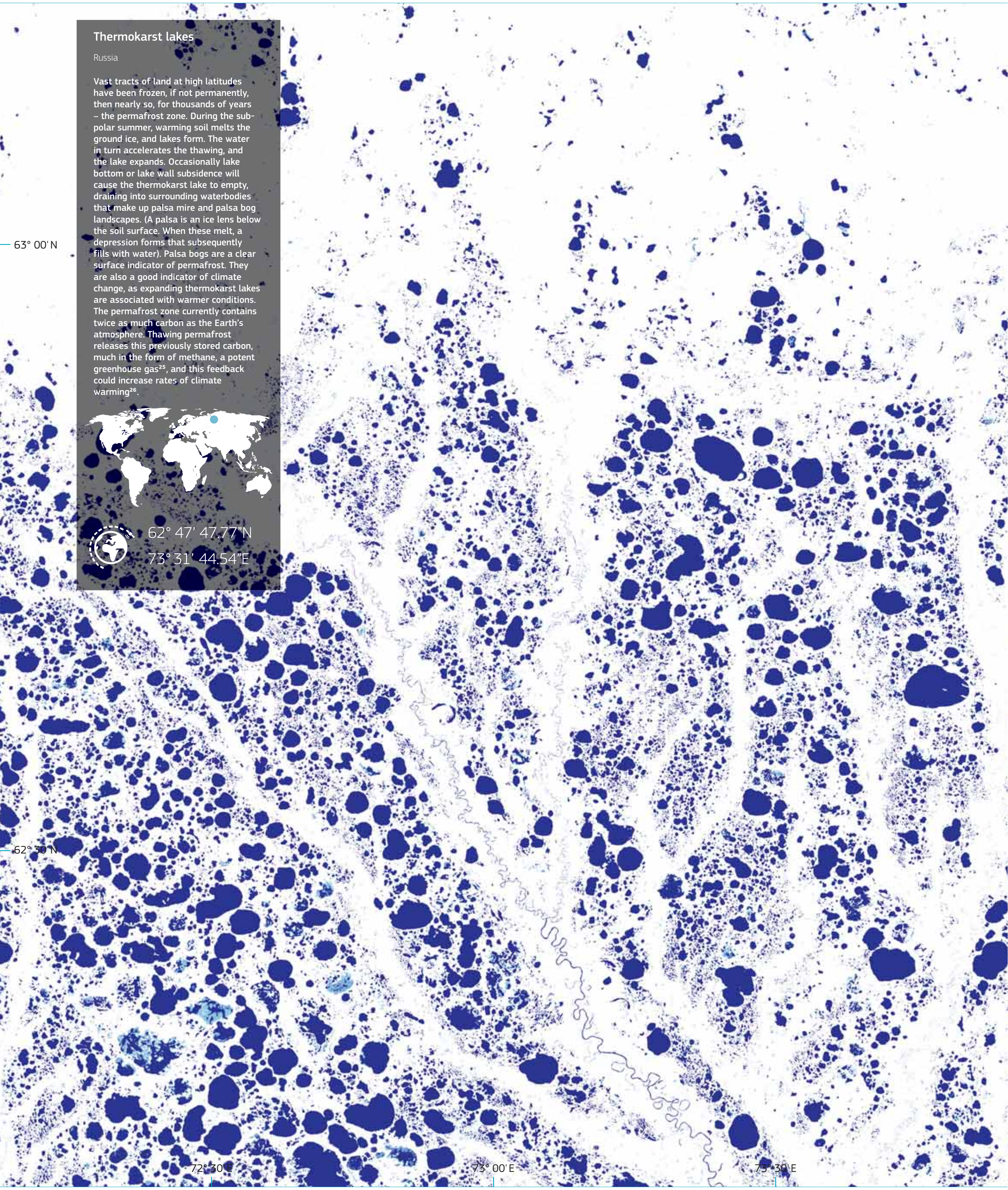
Rice fields near Livorno Ferraris, Province of Vercelli, Piedmont, Italy.
The repeated (but seasonal) flooding over many years is seen in the well-defined field patterns in the Water Seasonality map.
Source: Alan Belward.

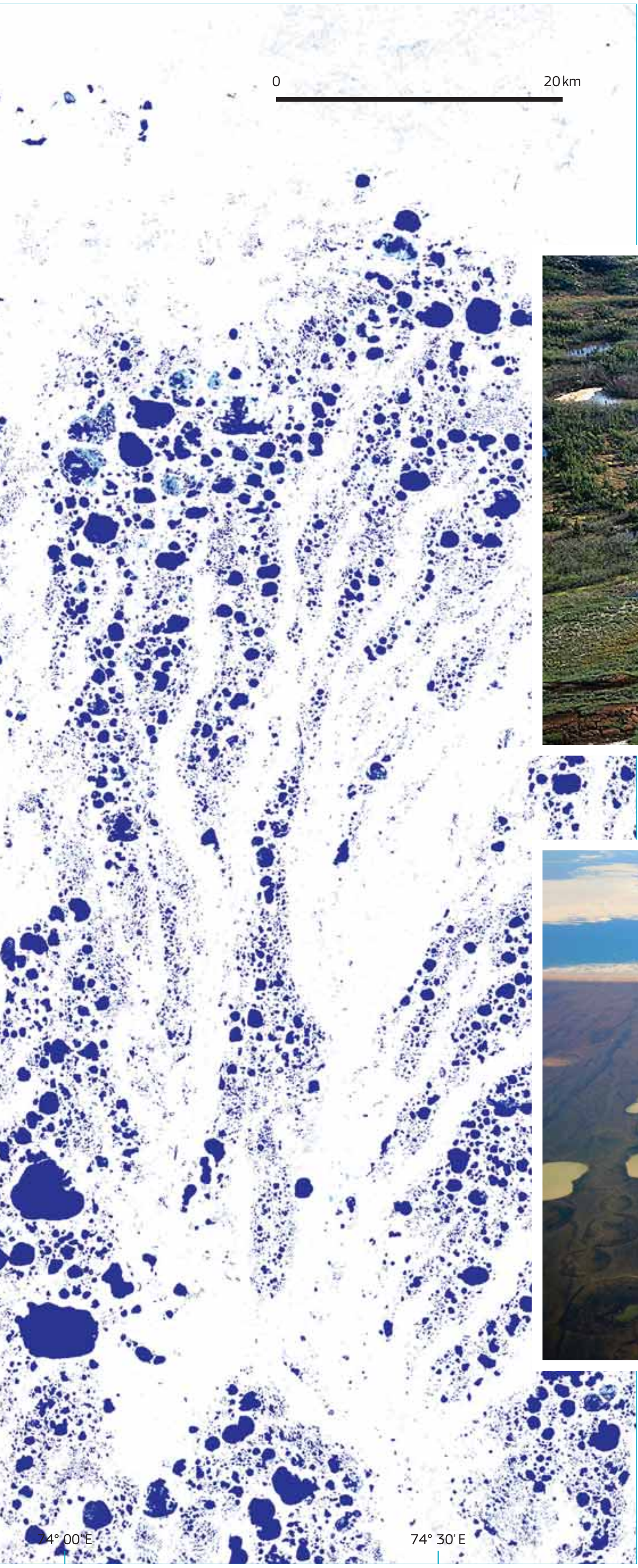
15 | Thermokarst lakes (Russia)

Thermokarst lakes

Russia

Vast tracts of land at high latitudes have been frozen, if not permanently, then nearly so, for thousands of years – the permafrost zone. During the sub-polar summer, warming soil melts the ground ice, and lakes form. The water in turn accelerates the thawing, and the lake expands. Occasionally lake bottom or lake wall subsidence will cause the thermokarst lake to empty, draining into surrounding waterbodies that make up palsa mire and palsa bog landscapes. (A palsa is an ice lens below the soil surface. When these melt, a depression forms that subsequently fills with water). Palsa bogs are a clear surface indicator of permafrost. They are also a good indicator of climate change, as expanding thermokarst lakes are associated with warmer conditions. The permafrost zone currently contains twice as much carbon as the Earth's atmosphere. Thawing permafrost releases this previously stored carbon, much in the form of methane, a potent greenhouse gas[25], and this feedback could increase rates of climate warming[26].





Palsa lakes.
A group of well developed palsas as seen from above. Ice lenses are responsible for palsa growth.

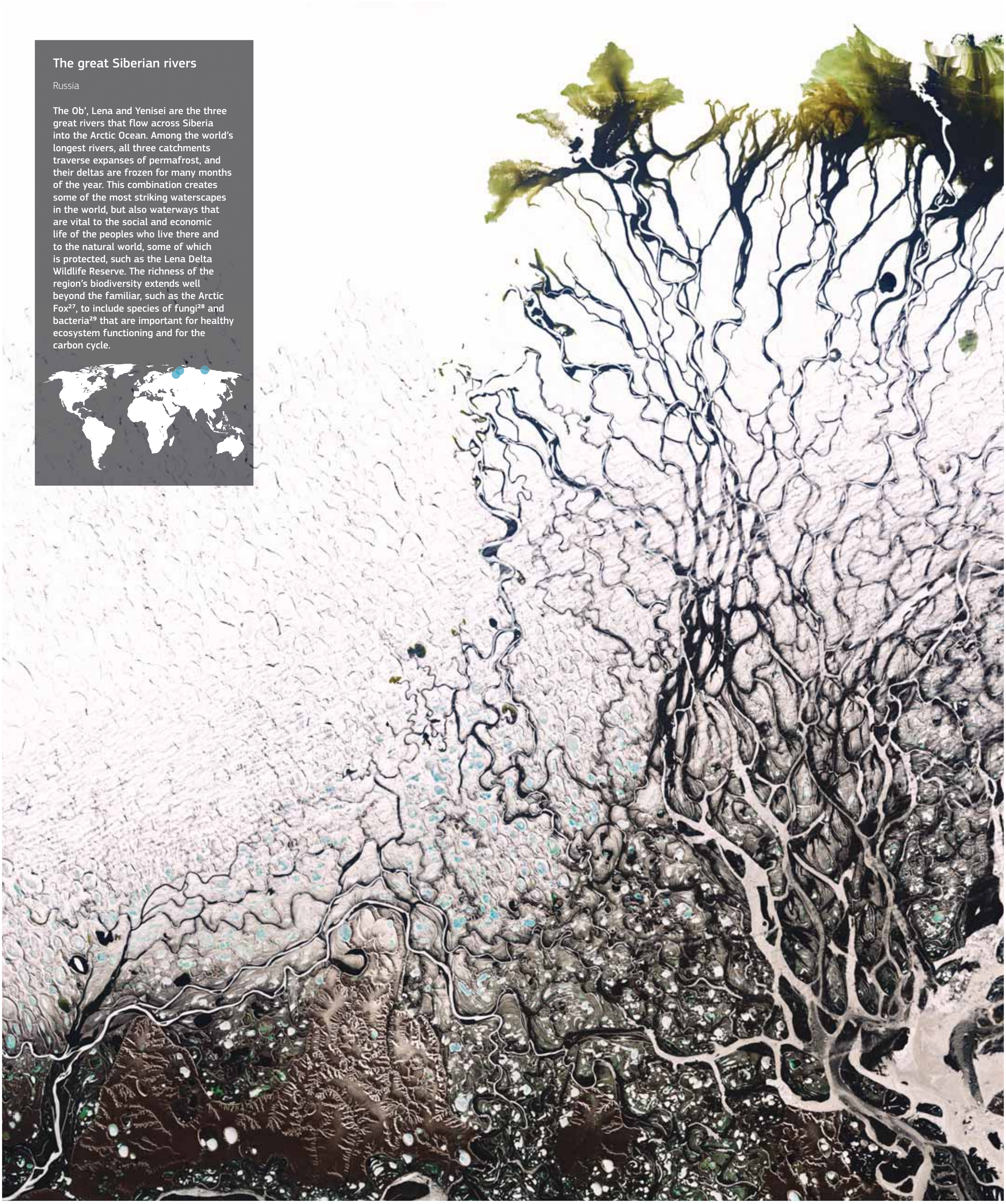
Thermokarst lakes.
Similar patterns of permafrost lakes occur across the Permafrost Zone, including North America, as seen in Hudson Bay, Canada in 2008.

16 | The great Siberian rivers (Russia)

The great Siberian rivers

Russia

The Ob', Lena and Yenisei are the three great rivers that flow across Siberia into the Arctic Ocean. Among the world's longest rivers, all three catchments traverse expanses of permafrost, and their deltas are frozen for many months of the year. This combination creates some of the most striking waterscapes in the world, but also waterways that are vital to the social and economic life of the peoples who live there and to the natural world, some of which is protected, such as the Lena Delta Wildlife Reserve. The richness of the region's biodiversity extends well beyond the familiar, such as the Arctic Fox[27], to include species of fungi[28] and bacteria[29] that are important for healthy ecosystem functioning and for the carbon cycle.



Lena Delta shakes off winter.
After seven months encased in snow and ice, the delta emerges for the short Siberian summer.
Source: Joshua Stevens using MODIS and Landsat imagery, courtesy NASA (MODIS) and USGS/NASA (Landsat).

17 | Merowe Dam (Sudan)

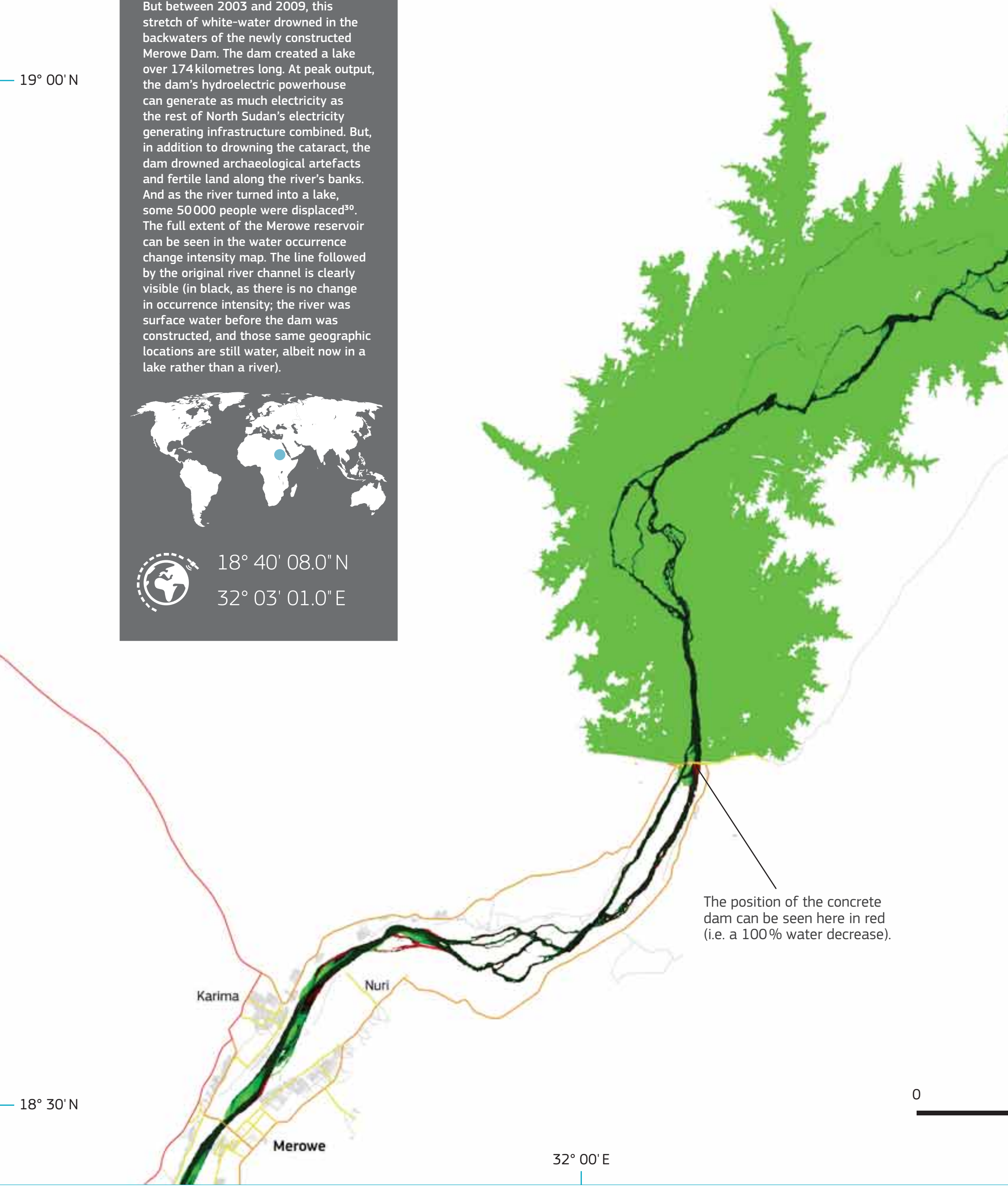
Merowe Dam, Sudan.
The Merowe site is Sudan's largest hydropower plant, with a capacity of 1 250 MW.
Source: Sudani (Public domain).

Merowe Dam

Sudan

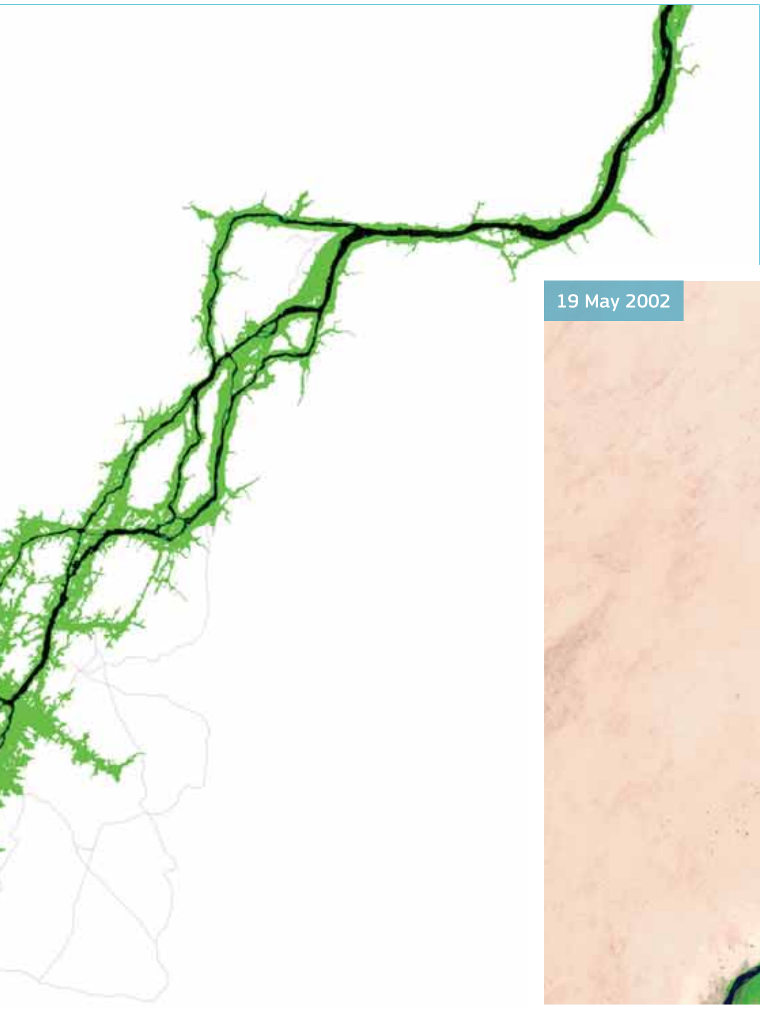
For millennia, the River Nile flowed freely across the river's six cataracts. One of these, the band of rocks and boulders crossing the river in the Manasir Desert, was one of the least navigable sections of the entire river. But between 2003 and 2009, this stretch of white-water drowned in the backwaters of the newly constructed Merowe Dam. The dam created a lake over 174 kilometres long. At peak output, the dam's hydroelectric powerhouse can generate as much electricity as the rest of North Sudan's electricity generating infrastructure combined. But, in addition to drowning the cataract, the dam drowned archaeological artefacts and fertile land along the river's banks. And as the river turned into a lake, some 50 000 people were displaced[30]. The full extent of the Merowe reservoir can be seen in the water occurrence change intensity map. The line followed by the original river channel is clearly visible (in black, as there is no change in occurrence intensity; the river was surface water before the dam was constructed, and those same geographic locations are still water, albeit now in a lake rather than a river).

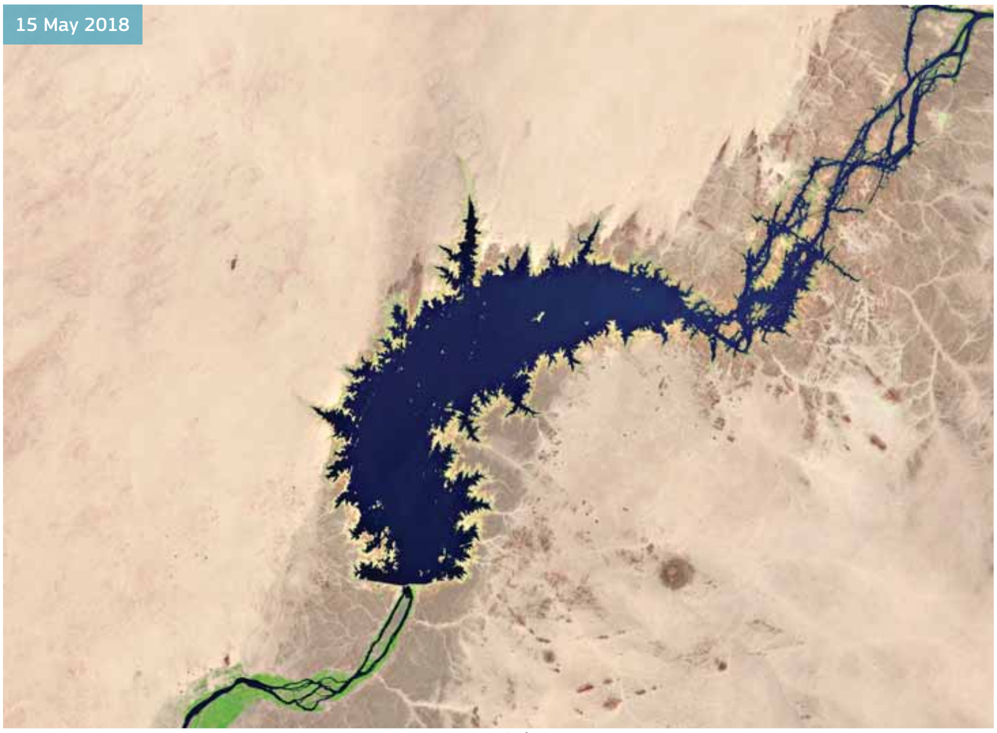
18° 40' 08.0" N
32° 03' 01.0" E



The original river channel is clearly visible in black (i.e. no change).

The position of the concrete dam can be seen here in red (i.e. a 100 % water decrease).





Relocation of people prior to flooding.
Ahead of the flooding of the Merowe Dam, the Manasir people were relocated from Dar al-Manasir, their villages were destroyed, and compensated palm trees were partly uprooted and burned to prevent them from returning.
Source: David Haberlah at the English language Wikipedia [CC BY-SA 3.0].

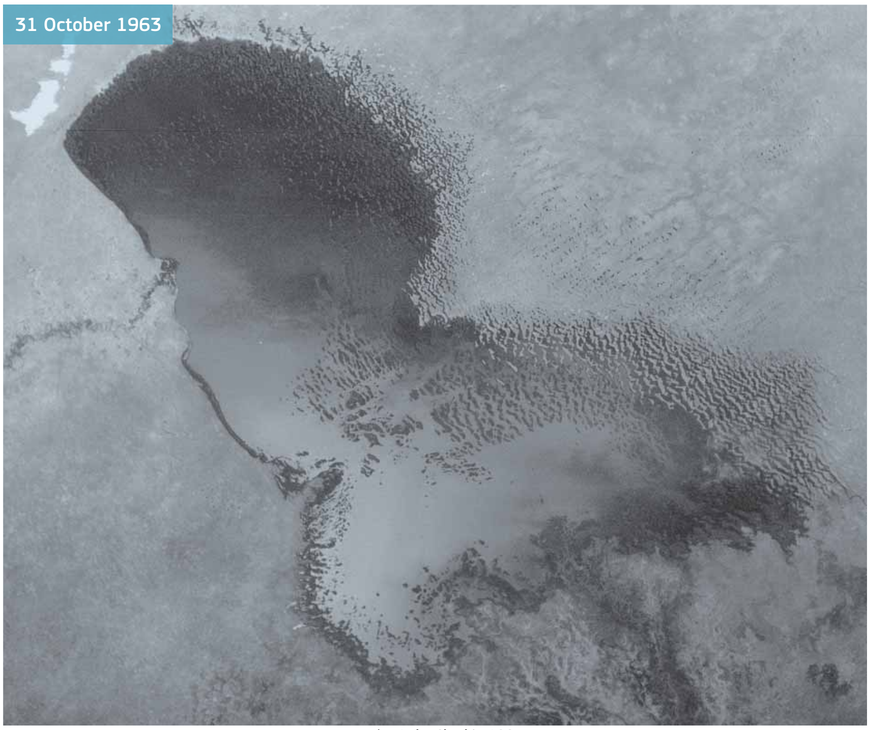
Merowe Dam, Sudan.
Top: The Nile flowing freely across the river's fourth cataract 19 May 2002.
Bottom: The Nile flows into a lake that has only existed for the past decade, 15 May 2018.
The images are 66 km North-South (top to bottom).
Source: Both images Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

18 | The Sahel, and Lake Chad (West and Central Africa)

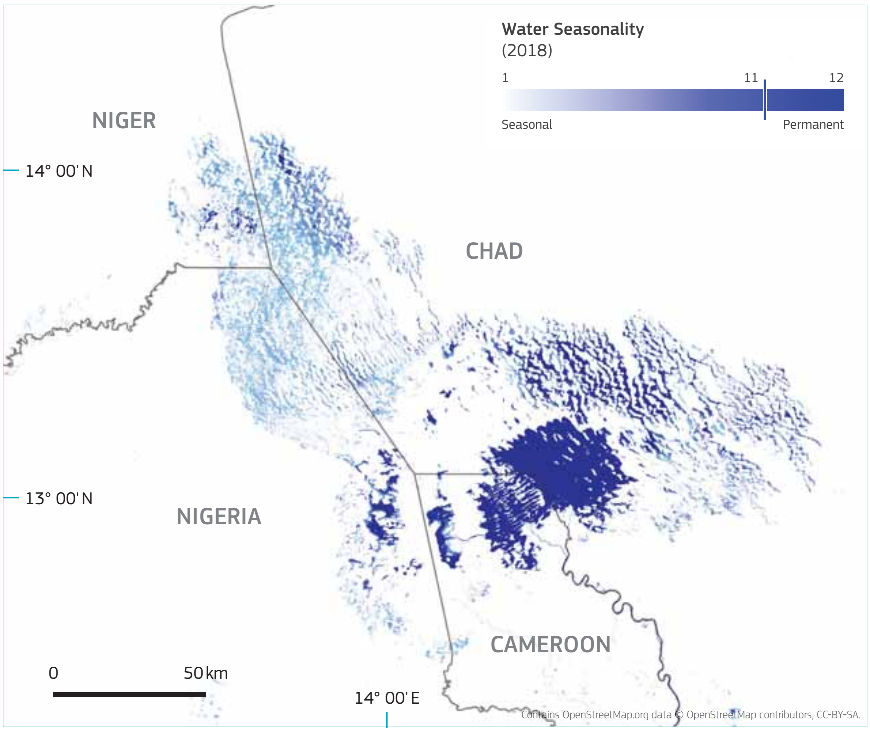
The Sahel, and Lake Chad

West and Central Africa

Pre Global Surface Water Explorer, accurate maps of surface water occurrence were particularly rare in parts of the world where surface water resources are themselves rare; mapping small (and often temporary) features over large areas is both challenging and costly. This map shows water recurrence patterns for the few lakes around the city of Tahoua, in the Sahel zone of Niger. Tahoua is one of the country's major cities, and the hinterland supports both farmers and pastoralists, but is largely devoid of surface waterbodies. Animal husbandry accounts for over 40% of agricultural GDP in the Sahel and West Africa[31]. Knowing where and when surface water resources occur, such as in the regularly appearing but seasonal waterbodies near Tahoua, allows for better use of grazing lands by enabling herders to plan the movement of cattle between watering points and to identify places where additional investment in surface water storage is needed. Increasing demand from irrigation scheme expansion and population growth reduce water availability[32]. Cimate change and associated reductions in water resources will add to pressures on pastoralists and crop-producing farmers alike, and may exacerbate conflict between the communities[33]. In places of surface water scarcity, such as the Sahel, knowing when and where water will occur can make the difference between life and death. High recurrence when mapped over 35 years means a high probability that seasonal waterbodies will return year after year – which is definitely good to know.



Lake Chad in 1963.
In the 1960s Lake Chad's open water surface covered an area of more than 24 000 km². The image is 230 km North-South (top to bottom).
Source: Jesse Allen using declassified Corona imagery, courtesy USGS.



Lake Chad Water Seasonality (2018).
Lake Chad is (still!) the largest surface waterbody in the entire Sahel (the semi-arid lands running from the Atlantic to the Red Sea along the southern border of the Sahara Desert). But today, open water covers less than 10% of the area it covered in the 1960s. The major contraction in lake size occurred due to a lack of rainfall in the 1970s[34], though increasing irrigation withdrawals have also been implicated[35]. Much of the lake basin was entirely devoid of surface water in 2018. Open water was present throughout the year in only a small part of the south basin, mainly in Cameroon and Chad. The lake is shared by Niger, Chad, Cameroon and Nigeria, and supports the livelihoods of some 20 million people. Its importance is such that plans have even been advanced (although not implemented) to refill the basin by damming the Ubangi River in the Central African Republic, and transferring the water via canals to Lake Chad[36]. This extract from the water seasonality (2018) map covers the same area as the satellite image shown above.

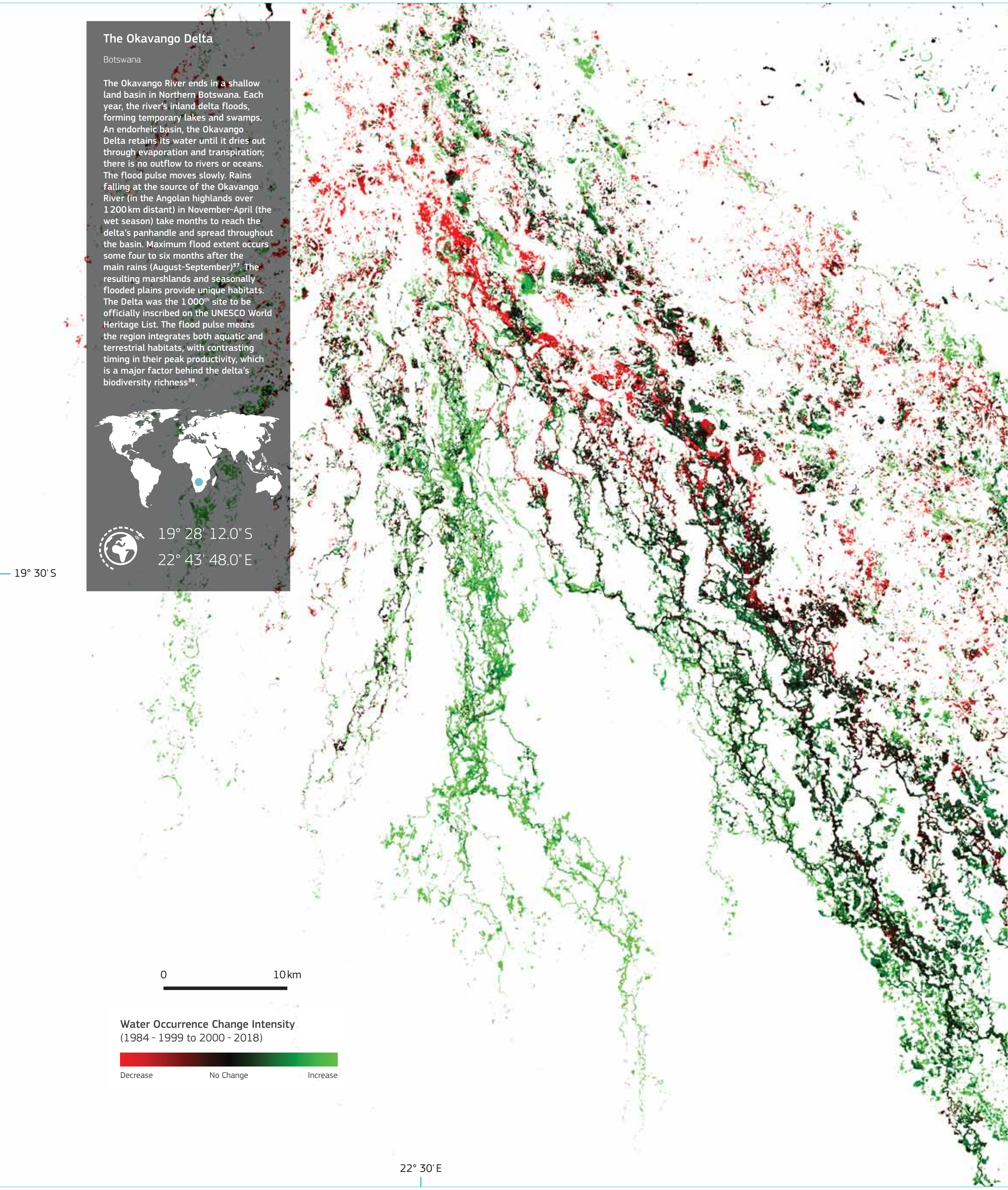
19 | The Okavango Delta (Botswana)

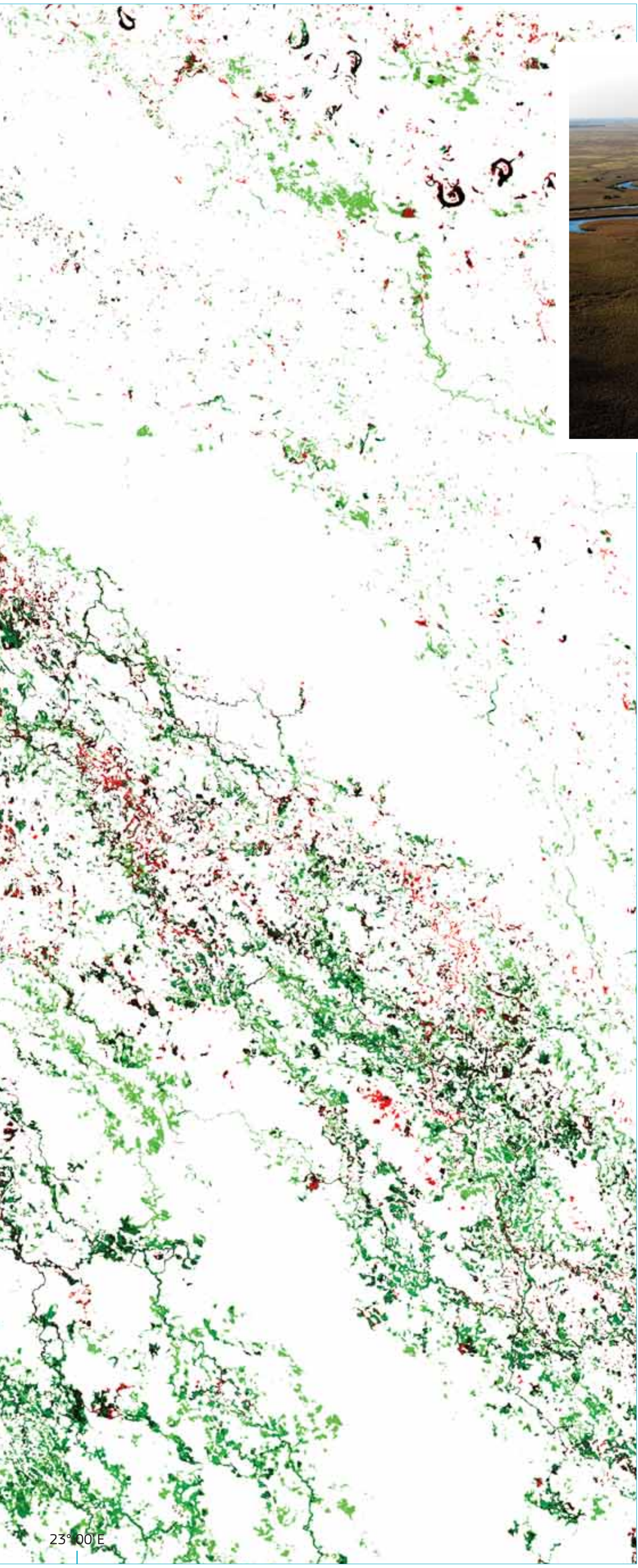
The Okavango Delta

Botswana

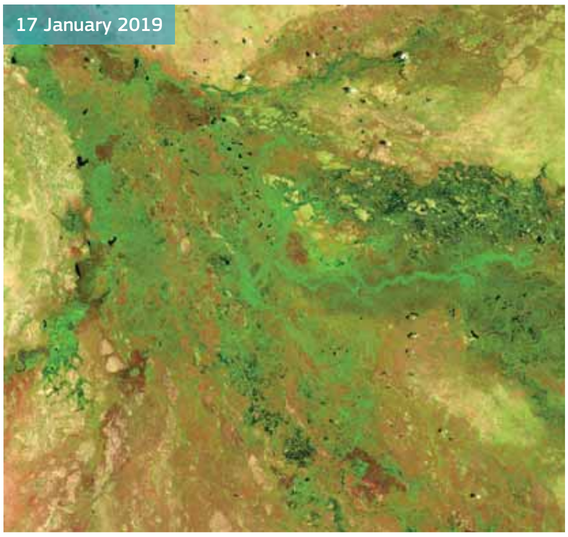
The Okavango River ends in a shallow land basin in Northern Botswana. Each year, the river's inland delta floods, forming temporary lakes and swamps. An endorheic basin, the Okavango Delta retains its water until it dries out through evaporation and transpiration; there is no outflow to rivers or oceans. The flood pulse moves slowly. Rains falling at the source of the Okavango River (in the Angolan highlands over 1 200 km distant) in November-April (the wet season) take months to reach the delta's panhandle and spread throughout the basin. Maximum flood extent occurs some four to six months after the main rains (August-September)[37]. The resulting marshlands and seasonally flooded plains provide unique habitats. The Delta was the 1 000th site to be officially inscribed on the UNESCO World Heritage List. The flood pulse means the region integrates both aquatic and terrestrial habitats, with contrasting timing in their peak productivity, which is a major factor behind the delta's biodiversity richness[38].

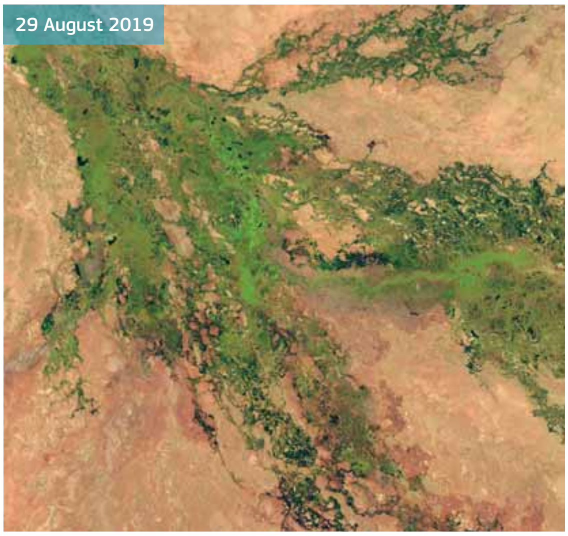
19° 28' 12.0" S
22° 43' 48.0" E





.·˙·. The Okavango Delta, Botswana.
Aerial shot of the Okavango River at Shakawe, Botswana.
Source: Wynand Uys on Unsplash.





.·˙·. **Landsat 8 images of the lower panhandle area of the Okavango Delta acquired in northern Botswana's wet and dry seasons (usually November-April and May-October repectively).**
The terrestrial habitats are at their lushest green in the wet season, whilst paradoxically the open surface water extent in the delta (the darkest tones in the image) is at its maximum during the dry season, when the surrounding land has lost its green tinge. Images are around 80 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA, wet season 17 January 2019; dry season 29 August 2019.

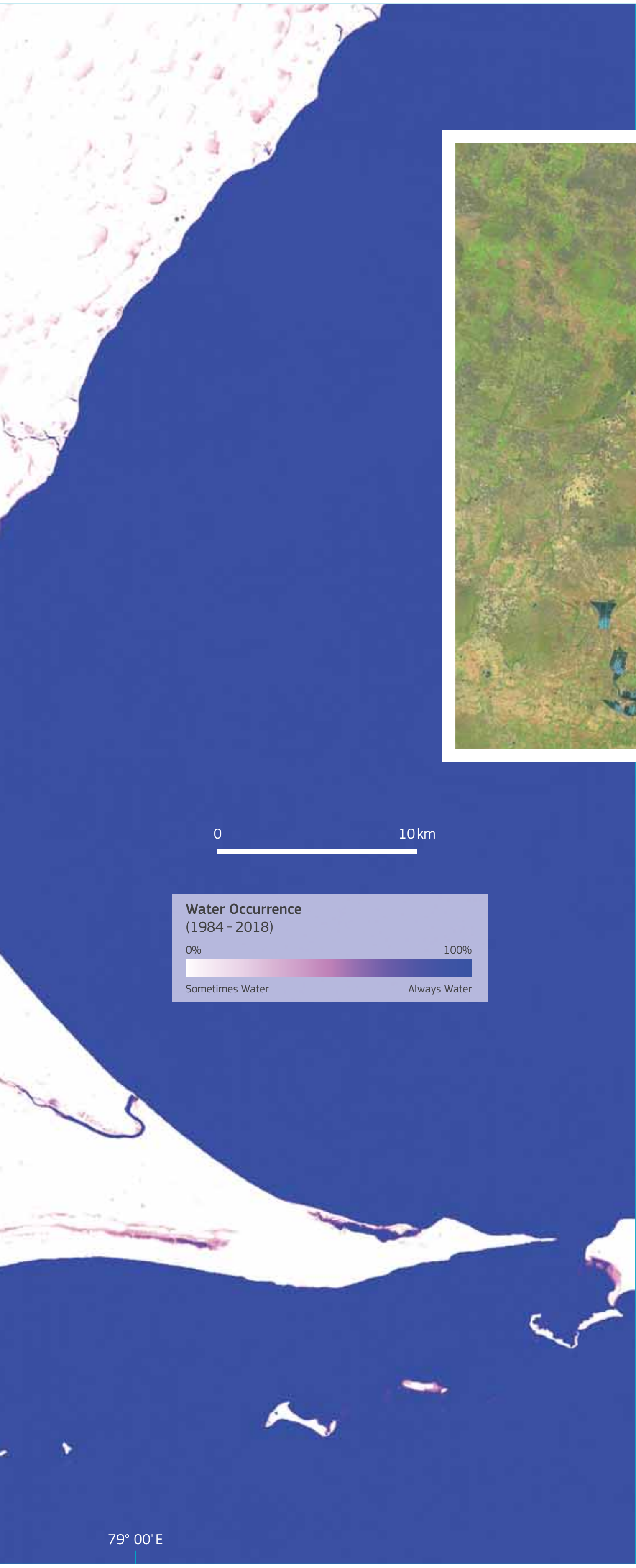
20 | Ramanathapuram (India)

Ramanathapuram

India

Earthen barriers, or bunds, constructed across the slope are used to intercept surface runoff and collect monsoon rainwater so it can be used in the following dry periods. The resulting tanks are common throughout much of rural Tamil Nadu. Most villages, and even some individual farms, have this water storage system. Some are stand-alone structures, others part of complex chains or cascades. The persistence of water in individual tanks varies for reasons including rainfall and runoff rates, evaporation rates, the permeability of the underlying soils and geology as well as local management, e.g. silting of the tank bed, bund leakages, rates of use, and release to tanks further down the chain. The tank system has been a feature of the landscape/waterscape for centuries, though numbers are declining, partly because of physical changes (such as silting), partly because alternative supplies (such as wells) are being used, and partly because the village institutions responsible for tank management are disappearing. However, tank conservation and rehabilitation is becoming increasingly important if groundwater depletion is to be avoided and to deal with changing predictability of the monsoon rains[39].

09° 21' 00.0" N
79° 78' 48.0" E



Time is the missing dimension.
The individual dams can be seen in this Landsat 8 image from 2 May 2019, but without time, the characteristic crescent shapes of the filling and emptying reservoirs behind them are not apparent. The image is 25 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

Earthen barriers, or bunds.
Whilst earthen bunds are common, some dam constructions are more substantial. Here we see the fixing of a liner over earthen barriers.
Source: Synjagu [CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0)].

21 | The Pearl River Delta (China)

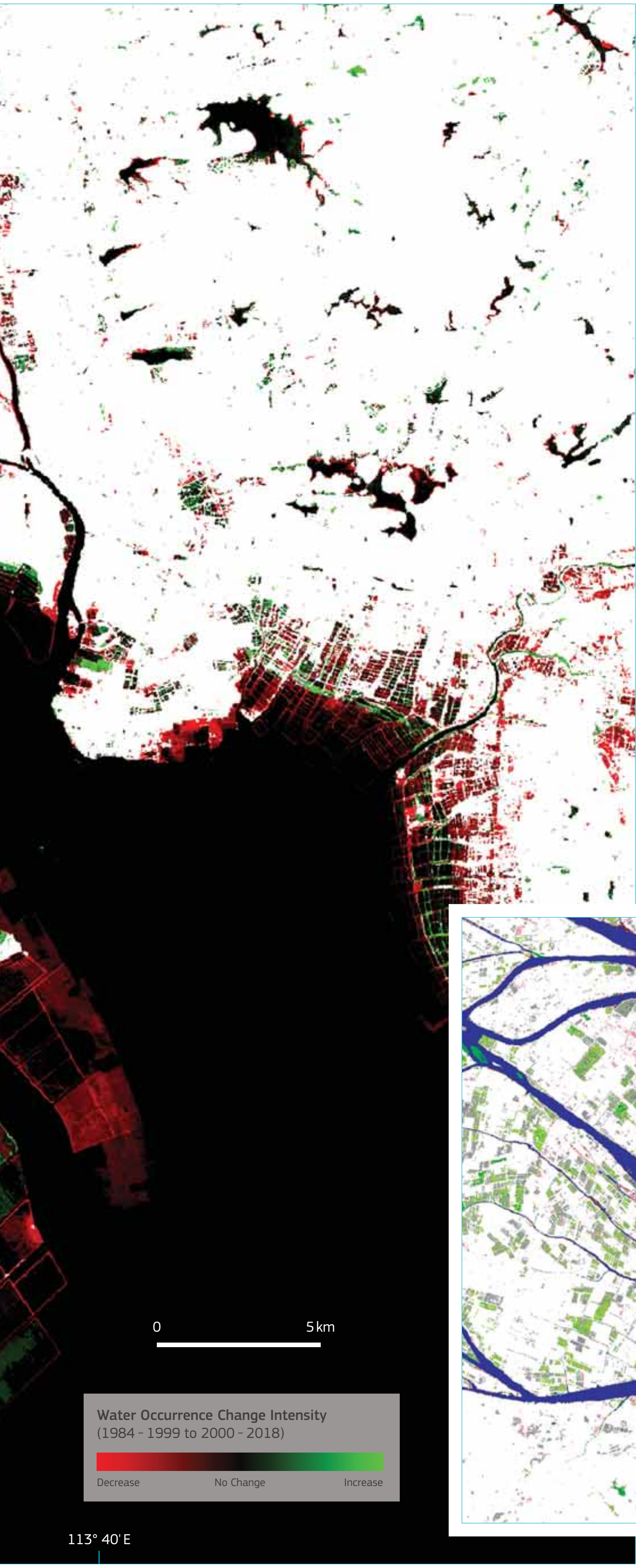
The Pearl River Delta

China

China's Pearl River Delta is now the largest contiguous urban region in the world, bordered by at least 8 cities, each of which has more than one million inhabitants. These include two megacities, Guangzhou and Shenzen, with populations over ten million people apiece. Collectively, the 8 largest cities alone were home to over 47.6 million people in 2018, and this is set to reach over 57.7 million by 2030[40]. The construction of new housing, port infrastructure and other developments have led to significant changes in the coastline over the past 35 years. The effects of land reclamation, the conversion of former paddy fields and aquaculture into urban areas, and the construction of new aquaculture along the coastal margins can all be seen in the changing patterns of water occurrence. Coastal wetlands have disappeared, indeed so too have many coastlines[41]. Complete loss of coastal wetland ecosystems due to land reclamation, and declining water quality (including from aquaculture, agriculture and urban sources) occur throughout the region, leading to widespread ecological degradation[42].

22° 43' 12.0" N

113° 33' 66.0" E

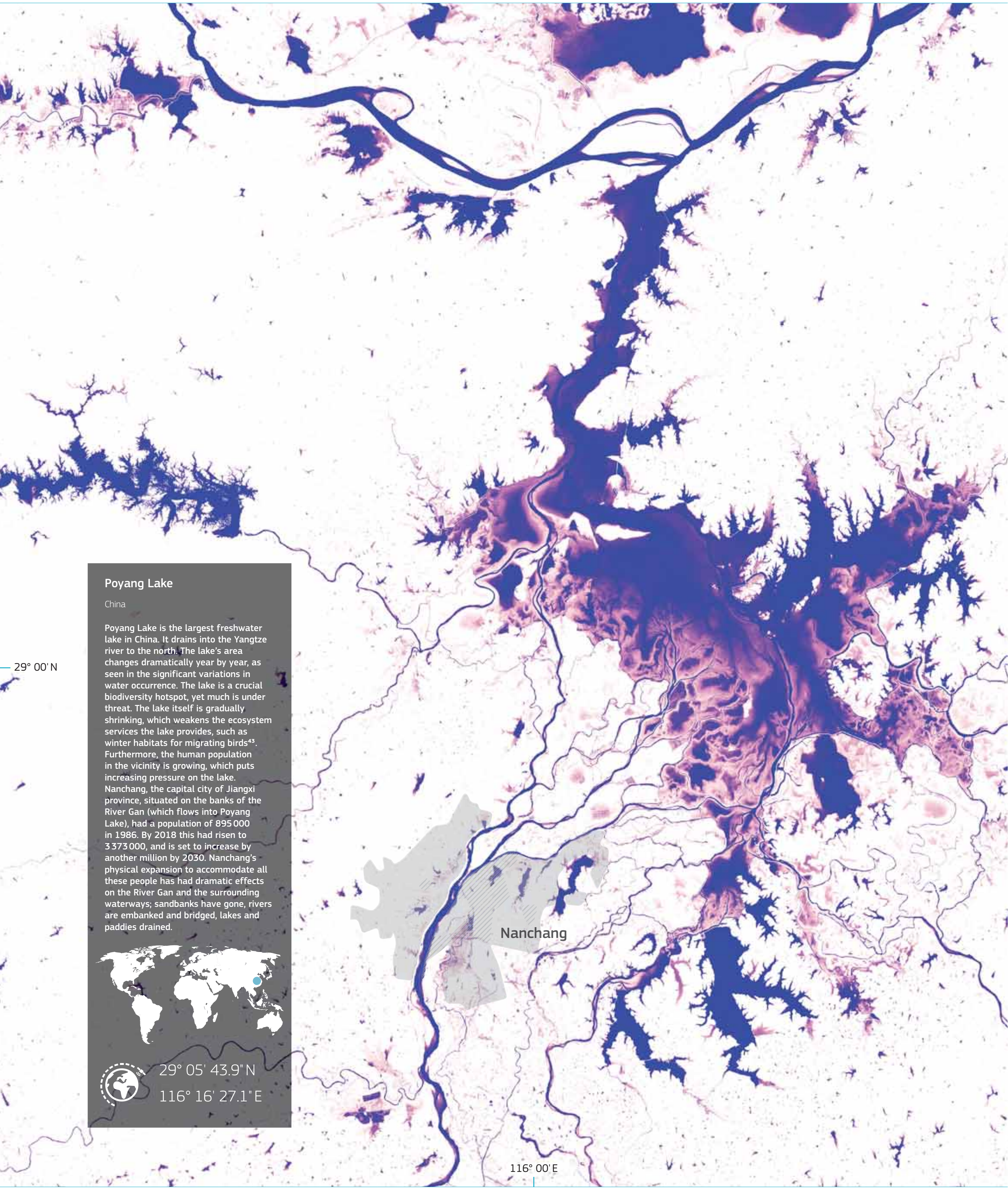


Guangzhou, China, as seen from Liede Bridge. Guangzhou is one of the world's megacities. This city, at the heart of the Pearl River Delta Economic Zone, was home to well over 12.6 million people in 2018, and this is set to rise to over 16 million by 2030.
Source: Lycheeart on Unsplash.

Water Transitions
(First Year to Last Year)

- Permanent
- New Permanent
- Lost Permanent
- Seasonal
- New Seasonal
- Lost Seasonal
- Seasonal to Permanent
- Permanent to Seasonal
- Ephemeral Permanent
- Ephemeral Seasonal

22 | Poyang Lake (China)

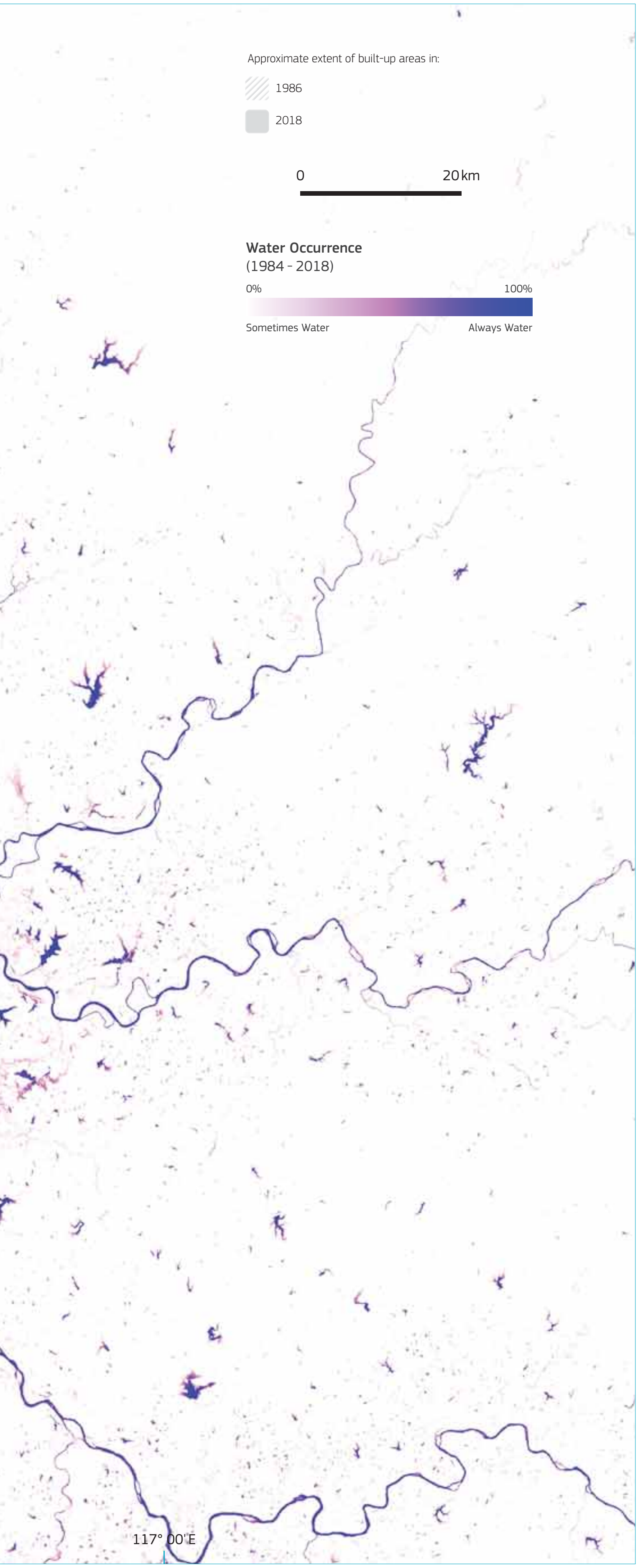


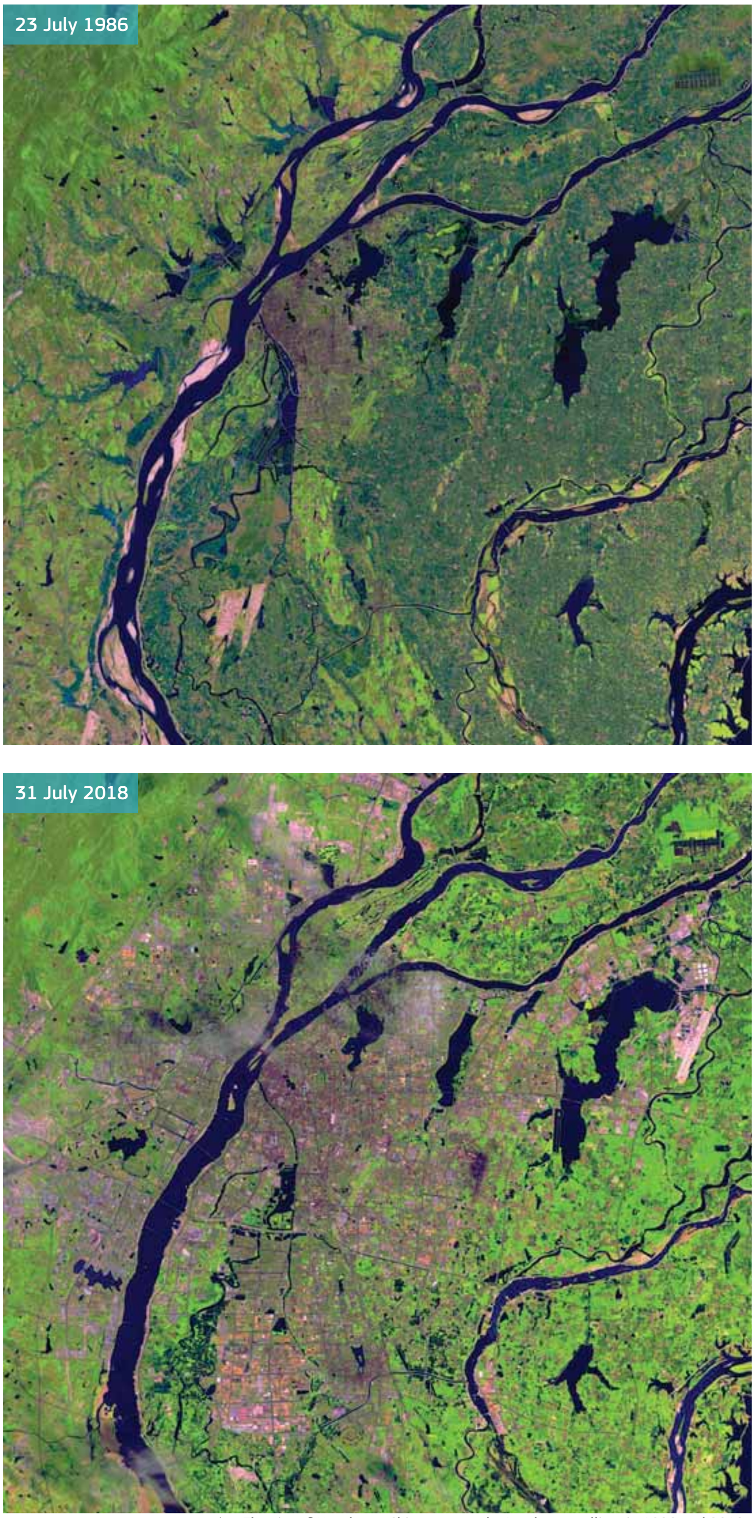
Poyang Lake

China

Poyang Lake is the largest freshwater lake in China. It drains into the Yangtze river to the north. The lake's area changes dramatically year by year, as seen in the significant variations in water occurrence. The lake is a crucial biodiversity hotspot, yet much is under threat. The lake itself is gradually shrinking, which weakens the ecosystem services the lake provides, such as winter habitats for migrating birds[43]. Furthermore, the human population in the vicinity is growing, which puts increasing pressure on the lake. Nanchang, the capital city of Jiangxi province, situated on the banks of the River Gan (which flows into Poyang Lake), had a population of 895 000 in 1986. By 2018 this had risen to 3 373 000, and is set to increase by another million by 2030. Nanchang's physical expansion to accommodate all these people has had dramatic effects on the River Gan and the surrounding waterways; sandbanks have gone, rivers are embanked and bridged, lakes and paddies drained.

29° 05' 43.9" N
116° 16' 27.1" E

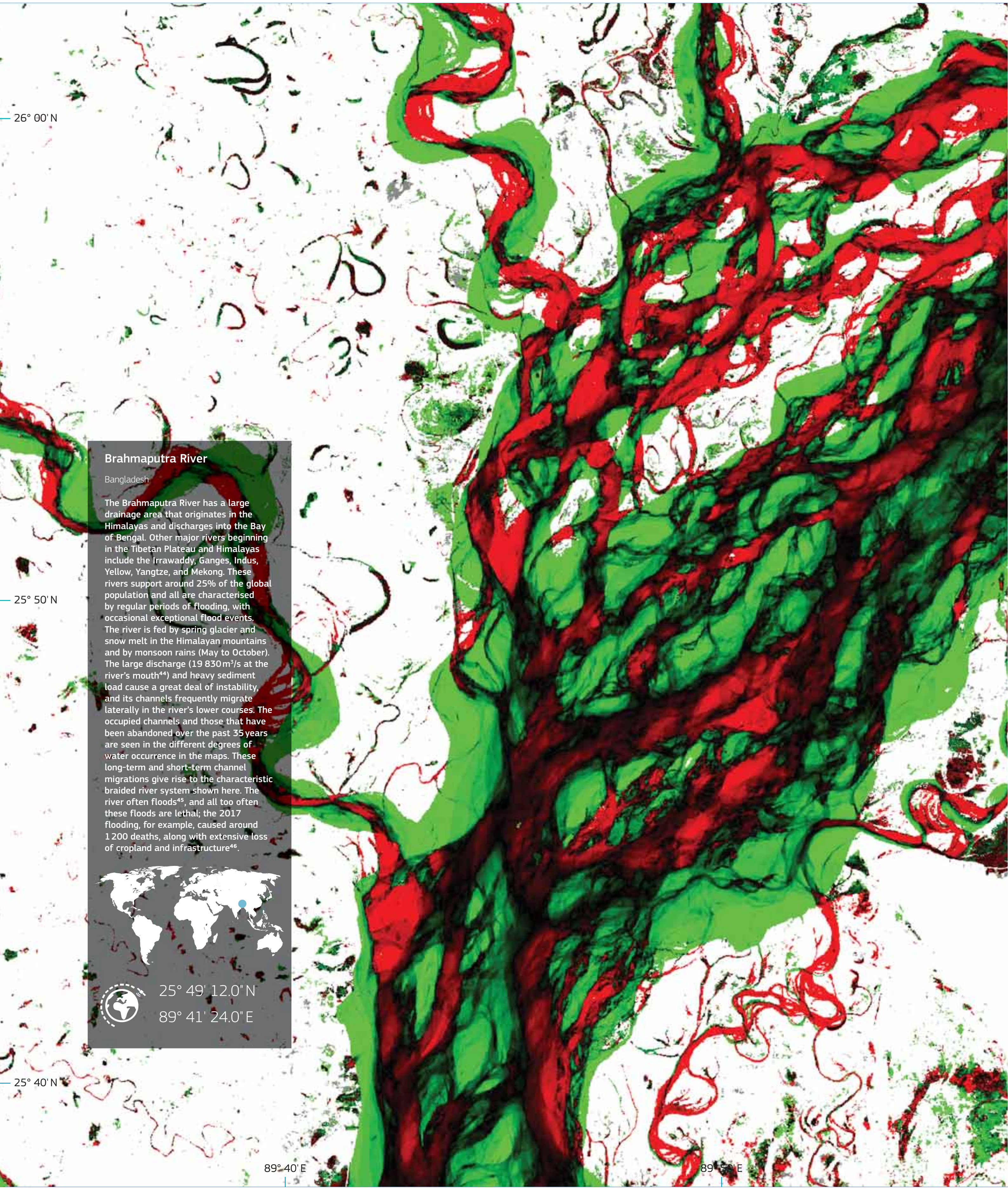




The city of Nanchang, China, as seen by Landsat satellites in 1986 and 2018. Since the 1980s, Nanchang has experienced rapid expansion of its urban infrastructure. The built-up area has increased fourfold, as agricultural land has been lost to urbanisation. The rivers and lakes play a vital part in the city's economy and transport infrastructure. As the urban area expands and more people use the waterways, water pollution prevention strategies and infrastructure become ever more important.

Source: Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

23 | Brahmaputra River (Bangladesh)

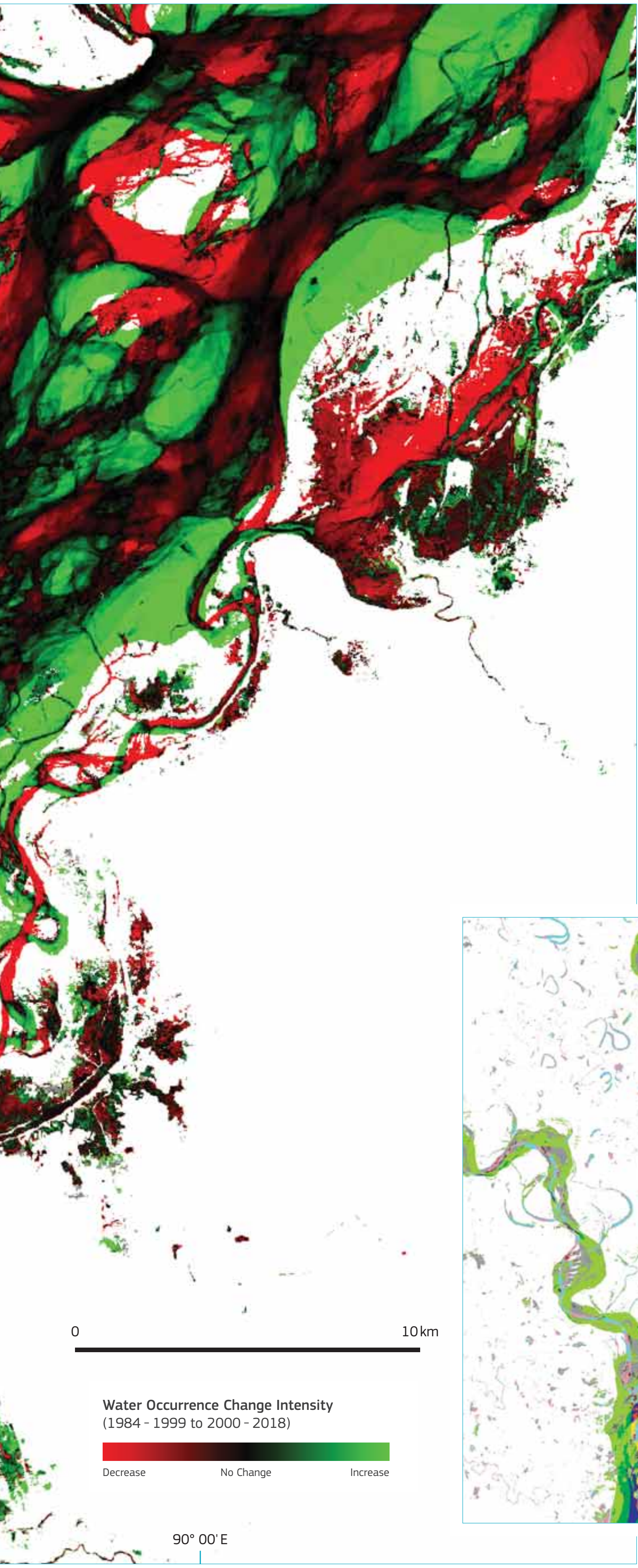


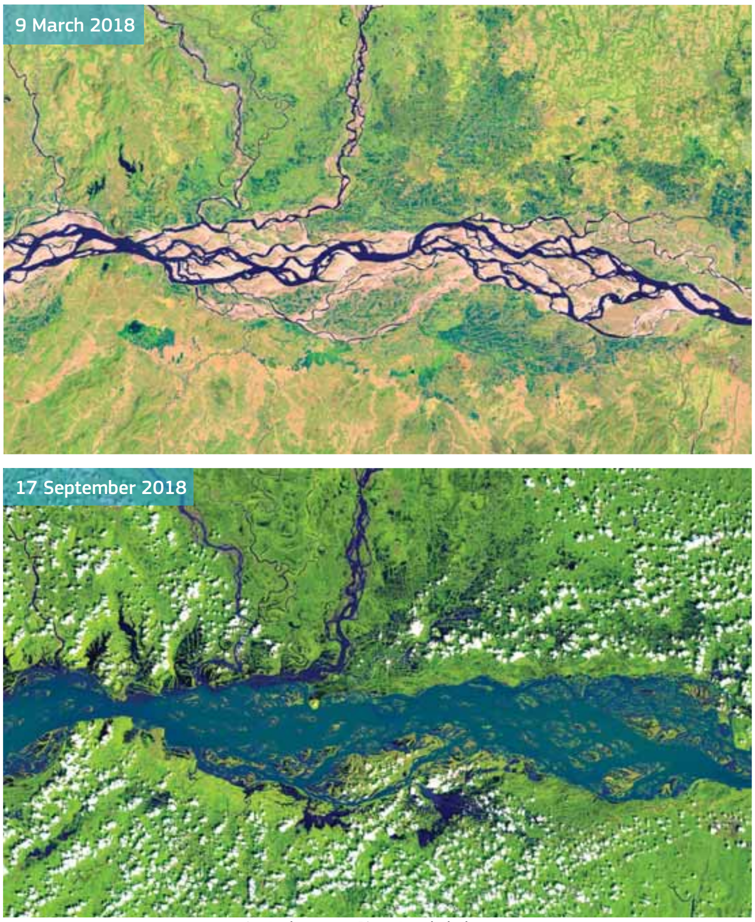
Brahmaputra River

Bangladesh

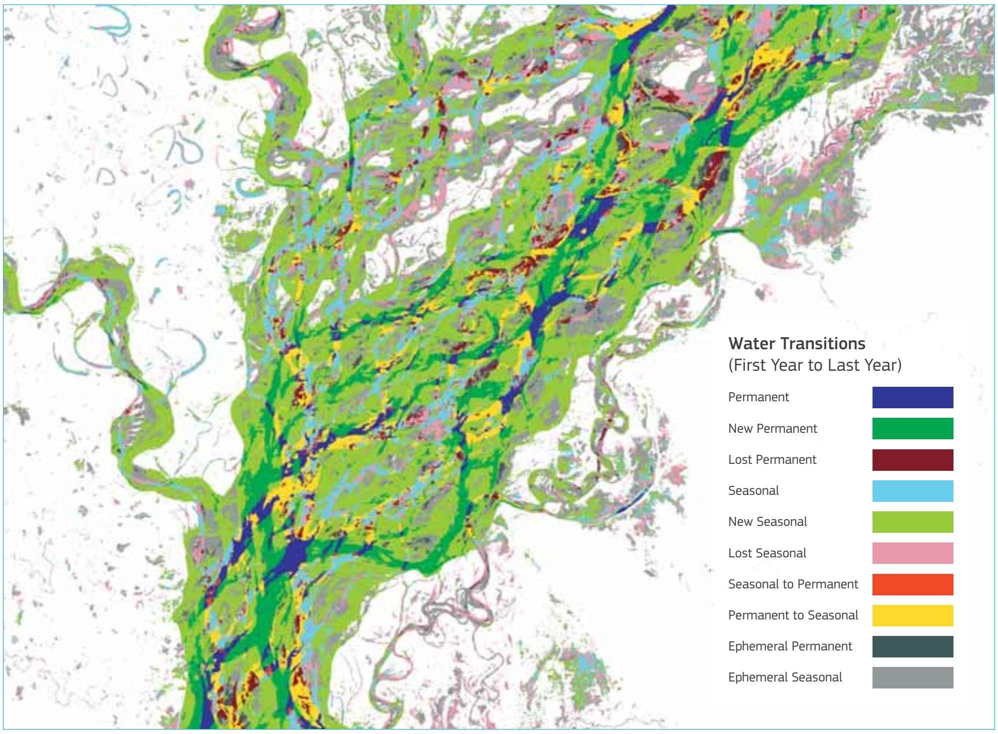
The Brahmaputra River has a large drainage area that originates in the Himalayas and discharges into the Bay of Bengal. Other major rivers beginning in the Tibetan Plateau and Himalayas include the Irrawaddy, Ganges, Indus, Yellow, Yangtze, and Mekong. These rivers support around 25% of the global population and all are characterised by regular periods of flooding, with occasional exceptional flood events. The river is fed by spring glacier and snow melt in the Himalayan mountains and by monsoon rains (May to October). The large discharge (19 830 m^3/s at the river's mouth[44]) and heavy sediment load cause a great deal of instability, and its channels frequently migrate laterally in the river's lower courses. The occupied channels and those that have been abandoned over the past 35 years are seen in the different degrees of water occurrence in the maps. These long-term and short-term channel migrations give rise to the characteristic braided river system shown here. The river often floods[45], and all too often these floods are lethal; the 2017 flooding, for example, caused around 1 200 deaths, along with extensive loss of cropland and infrastructure[46].

25° 49' 12.0" N
89° 41' 24.0" E

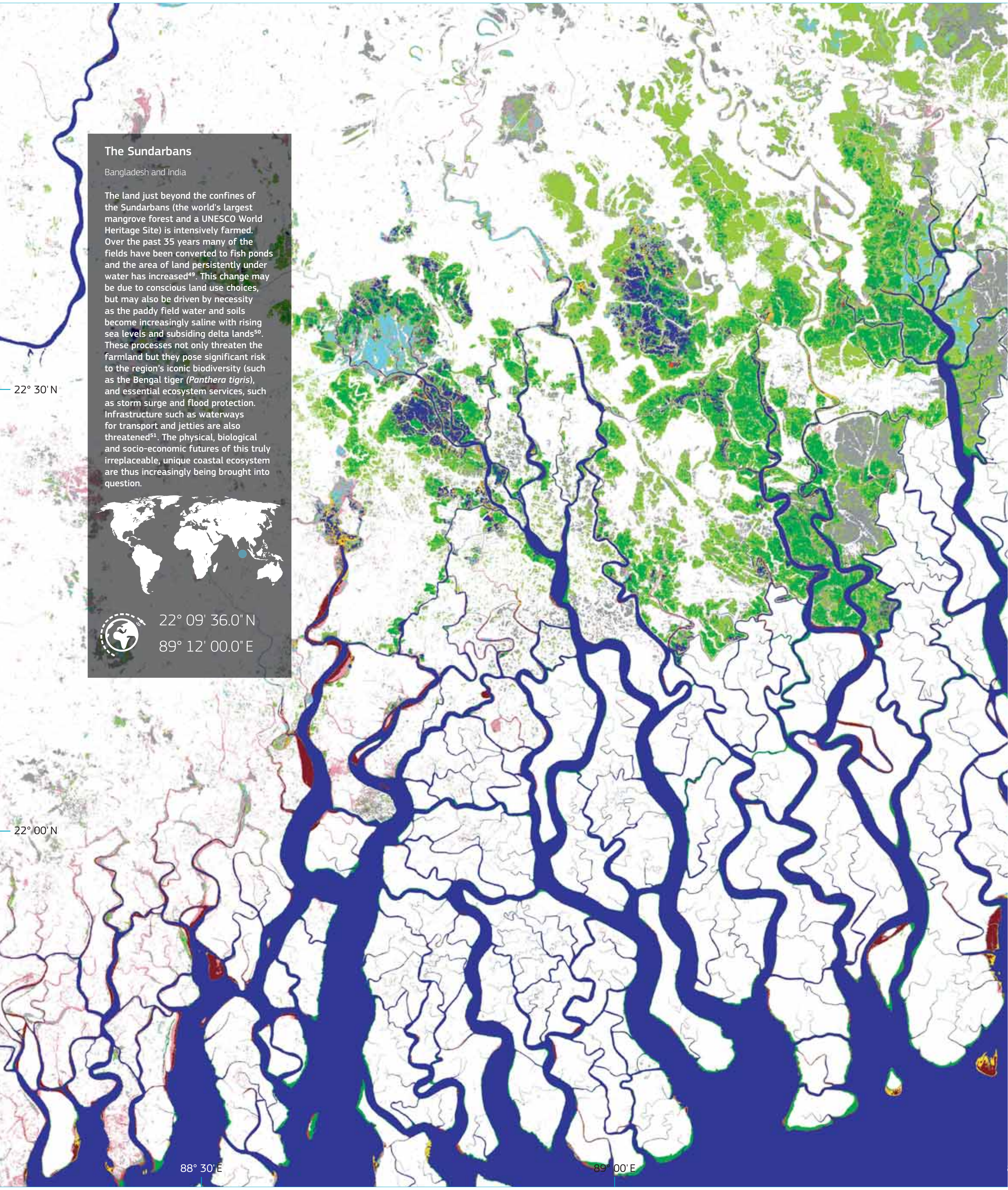




Brahmaputra River, Bangladesh.
Brahmaputra River at low water (March) and high water (September) in 2018 (Assam State, India). The Brahmaputra Valley in Assam is between 35 and 90 km wide[47], and the river's floodplain has to accommodate enormous annual changes in river width, with flooding a very common occurrence. Periodic flooding replenishes the river valley's soils, but more extreme events cause extensive loss of life and destroy millions of homes[48]. Both images are 66 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.



24 | The Sundarbans (Bangladesh and India)

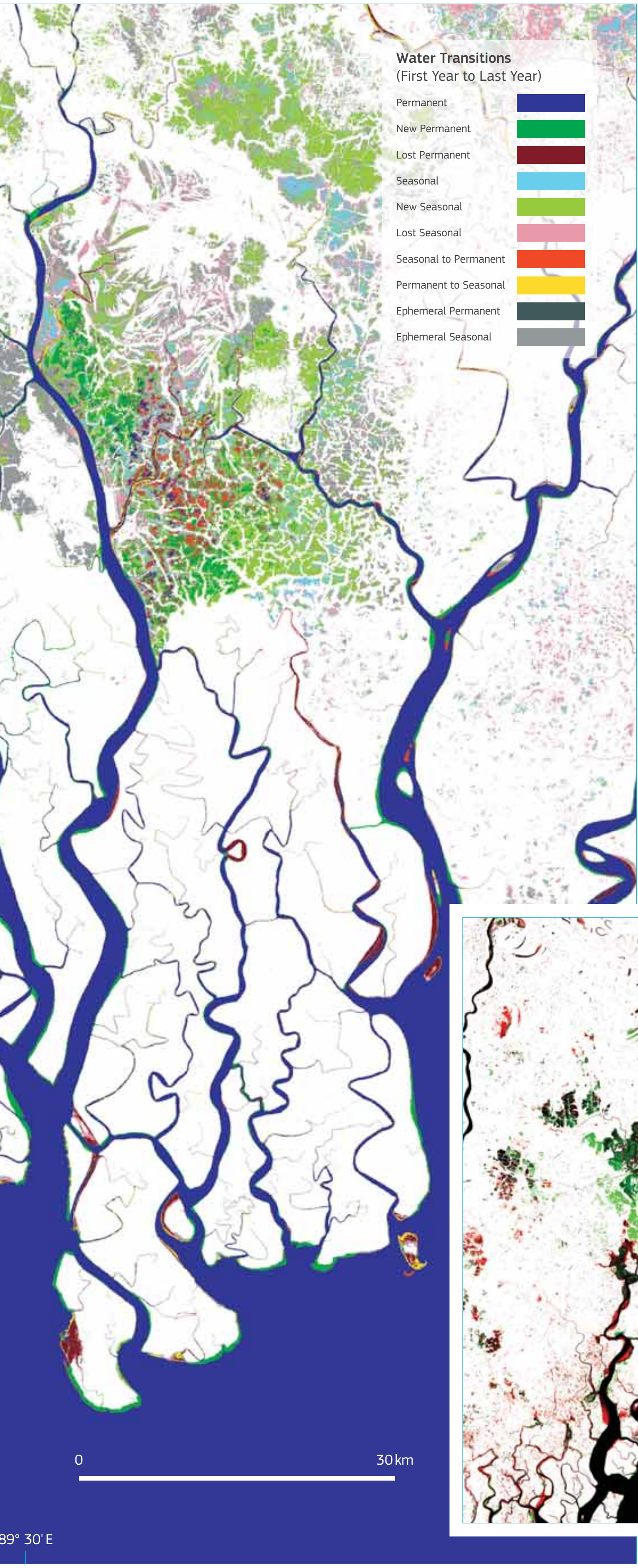


The Sundarbans

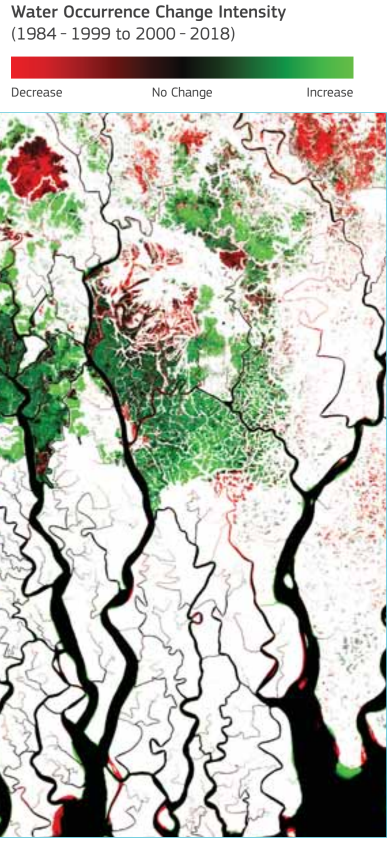
Bangladesh and India

The land just beyond the confines of the Sundarbans (the world's largest mangrove forest and a UNESCO World Heritage Site) is intensively farmed. Over the past 35 years many of the fields have been converted to fish ponds and the area of land persistently under water has increased[49]. This change may be due to conscious land use choices, but may also be driven by necessity as the paddy field water and soils become increasingly saline with rising sea levels and subsiding delta lands[50]. These processes not only threaten the farmland but they pose significant risk to the region's iconic biodiversity (such as the Bengal tiger *(Panthera tigris)*, and essential ecosystem services, such as storm surge and flood protection. Infrastructure such as waterways for transport and jetties are also threatened[51]. The physical, biological and socio-economic futures of this truly irreplaceable, unique coastal ecosystem are thus increasingly being brought into question.

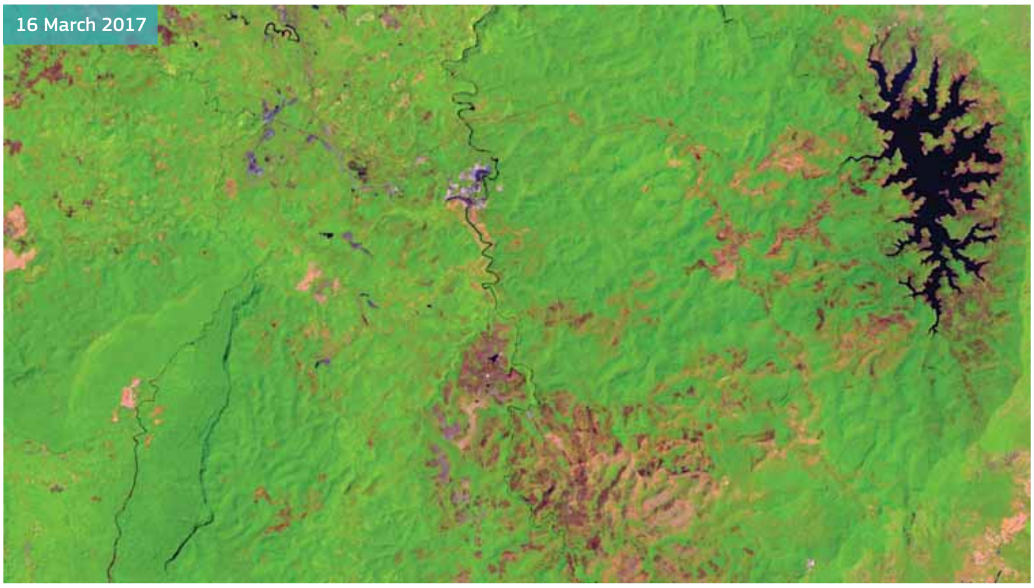
22° 09' 36.0" N
89° 12' 00.0" E



Farmhouse in the Ganges Delta.
Rising sea levels and subsidence in the delta region endanger agriculture and deny people space to live. Homes such as this are under threat from rising waters.
Source: Arne Hückelheim [CC BY-SA (https://creativecommons.org/licenses/by-sa/3.0)].



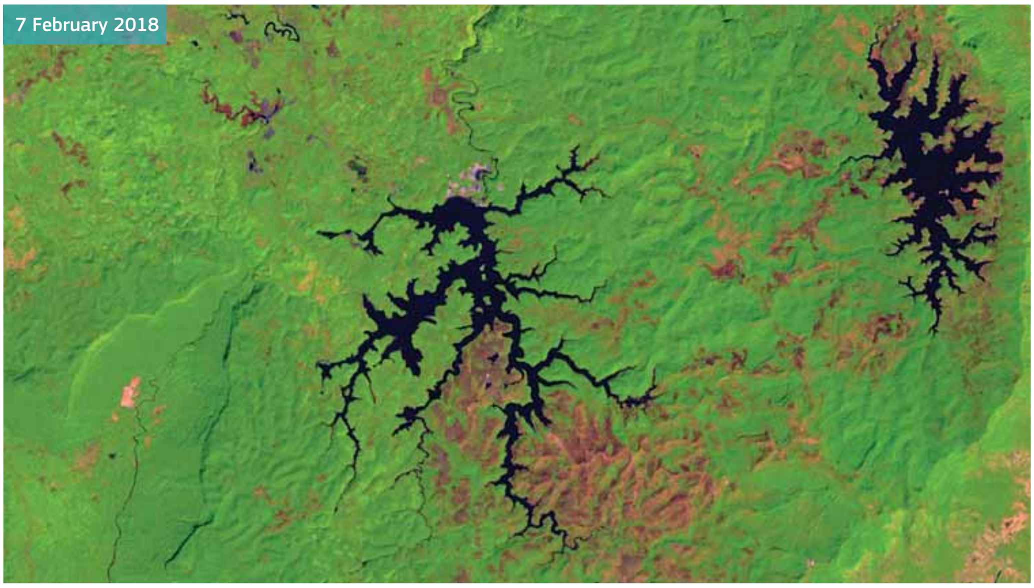
25 | Paksong Dam (Laos)



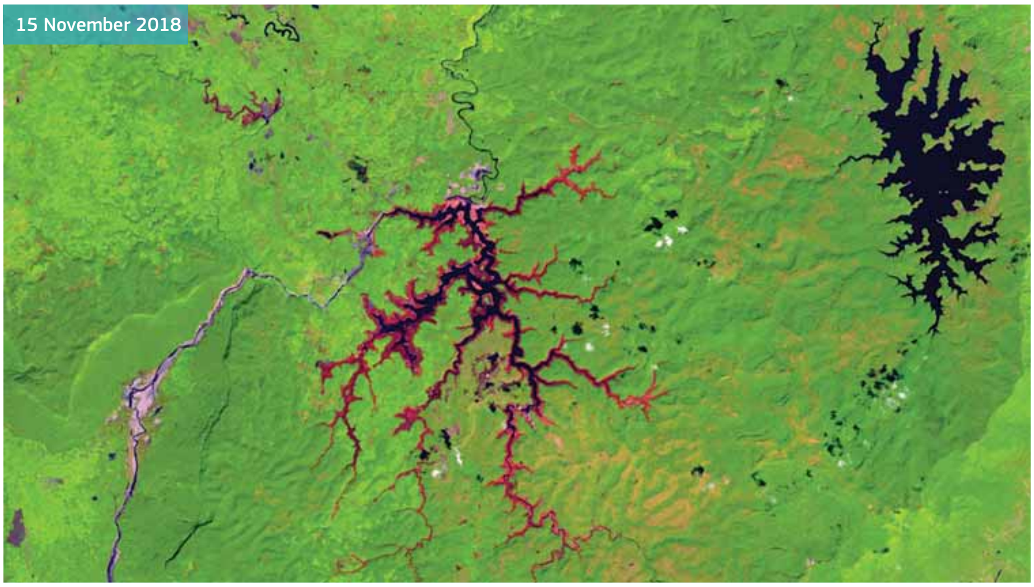
The 2018 dam collapse captured in time-lapse.

These images are all natural colour composites. Open water surfaces appear black in all images, growing vegetation shows as green, whilst senescent and very sparse vegetation appears in brown tones. The construction site, as the dam is being built, appears as light grey; it is a mixture of bare soil and concrete surfaces. This is seen in the image acquired 16 March 2017. Once the lake emptied, the freshly exposed land, now denuded of vegetation, shows as dark red and brown tones; this is seen in the image acquired on 15 November 2018. Note how much of the green vegetation along the watercourse has been washed away, and in the 15 November 2018 image appears in the same grey to lilac tones as the construction site. All images are 17.5 km North-South (top to bottom).
Source: All images Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

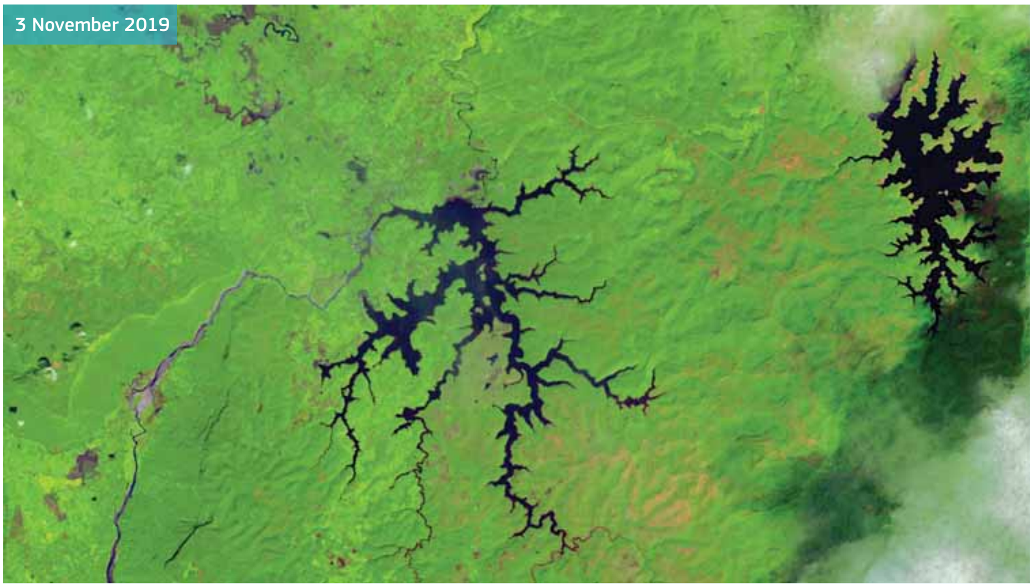
Dam building on the Xe Namnoy River, Laos, reaches its final stages.



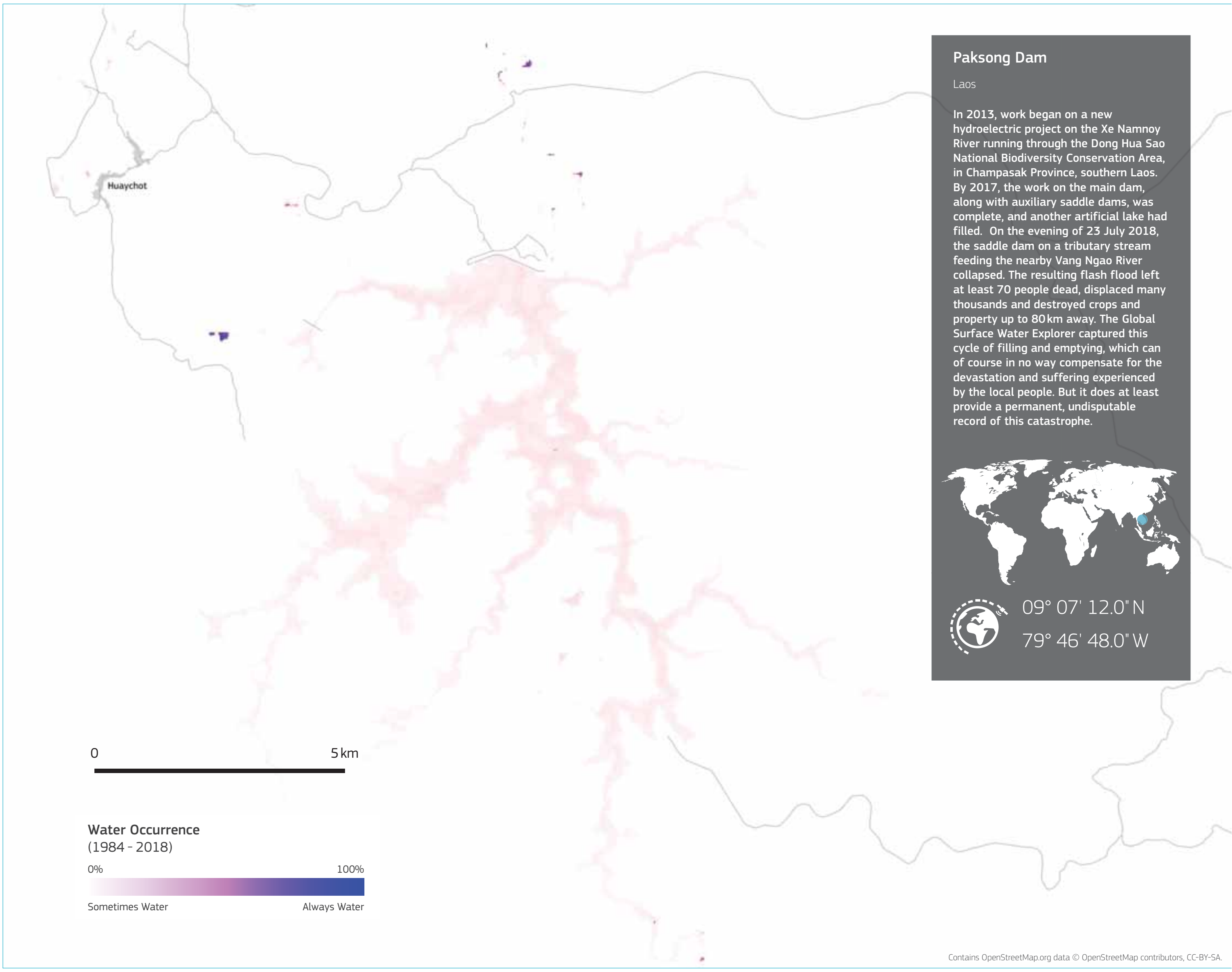
Dam construction is completed and the artificial lake feeding the Xe-Pian Xe-Namnoy Power Company Hydroelectric power station has filled.



The artificial lake has largely emptied following the catastrophic failure of one of the saddle dams. Widespread destruction of vegetation and silt deposition can be seen all along the banks of the tributary flowing from the ruined saddle dam. The area of drowned land can also be seen in the now largely empty reservoir.



One year later, a new saddle dam was built about a kilometre below the failed structure, and the lake has once more filled. The damage along the tributary river's banks is still apparent.



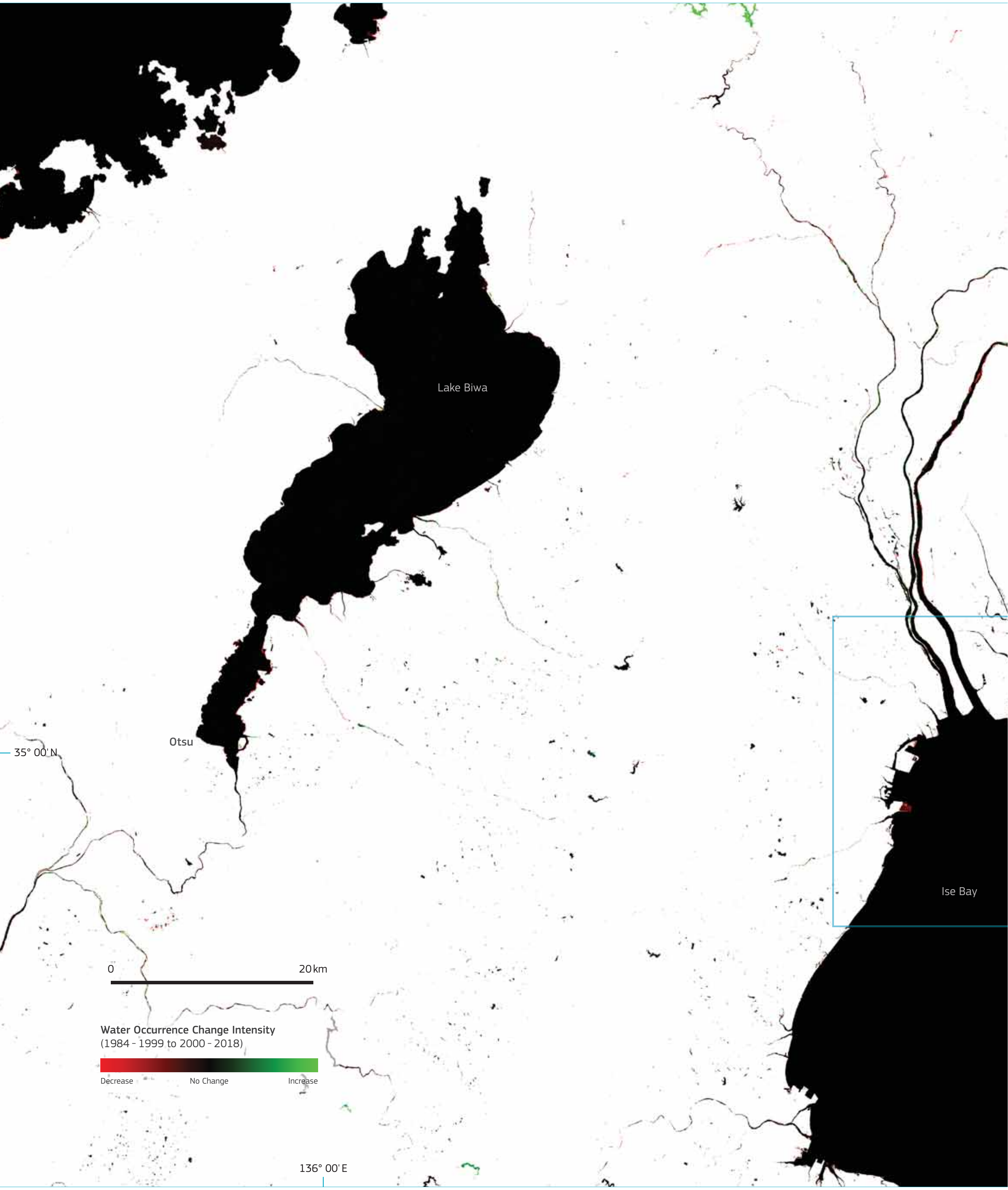
Paksong Dam

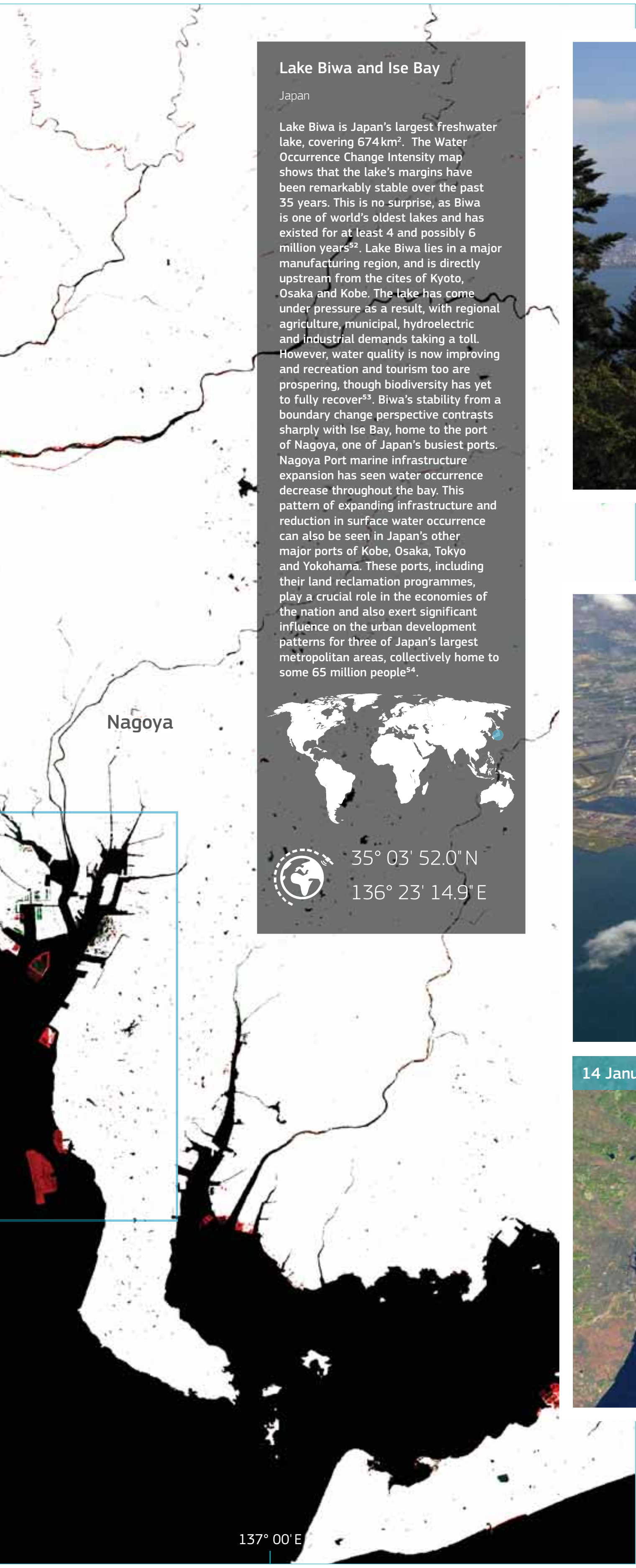
Laos

In 2013, work began on a new hydroelectric project on the Xe Namnoy River running through the Dong Hua Sao National Biodiversity Conservation Area, in Champasak Province, southern Laos. By 2017, the work on the main dam, along with auxiliary saddle dams, was complete, and another artificial lake had filled. On the evening of 23 July 2018, the saddle dam on a tributary stream feeding the nearby Vang Ngao River collapsed. The resulting flash flood left at least 70 people dead, displaced many thousands and destroyed crops and property up to 80 km away. The Global Surface Water Explorer captured this cycle of filling and emptying, which can of course in no way compensate for the devastation and suffering experienced by the local people. But it does at least provide a permanent, undisputable record of this catastrophe.

09° 07' 12.0" N
79° 46' 48.0" W

26 | Lake Biwa and Ise Bay (Japan)





Lake Biwa and Ise Bay

Japan

Lake Biwa is Japan's largest freshwater lake, covering 674 km^2. The Water Occurrence Change Intensity map shows that the lake's margins have been remarkably stable over the past 35 years. This is no surprise, as Biwa is one of world's oldest lakes and has existed for at least 4 and possibly 6 million years[52]. Lake Biwa lies in a major manufacturing region, and is directly upstream from the cites of Kyoto, Osaka and Kobe. The lake has come under pressure as a result, with regional agriculture, municipal, hydroelectric and industrial demands taking a toll. However, water quality is now improving and recreation and tourism too are prospering, though biodiversity has yet to fully recover[53]. Biwa's stability from a boundary change perspective contrasts sharply with Ise Bay, home to the port of Nagoya, one of Japan's busiest ports. Nagoya Port marine infrastructure expansion has seen water occurrence decrease throughout the bay. This pattern of expanding infrastructure and reduction in surface water occurrence can also be seen in Japan's other major ports of Kobe, Osaka, Tokyo and Yokohama. These ports, including their land reclamation programmes, play a crucial role in the economies of the nation and also exert significant influence on the urban development patterns for three of Japan's largest metropolitan areas, collectively home to some 65 million people[54].

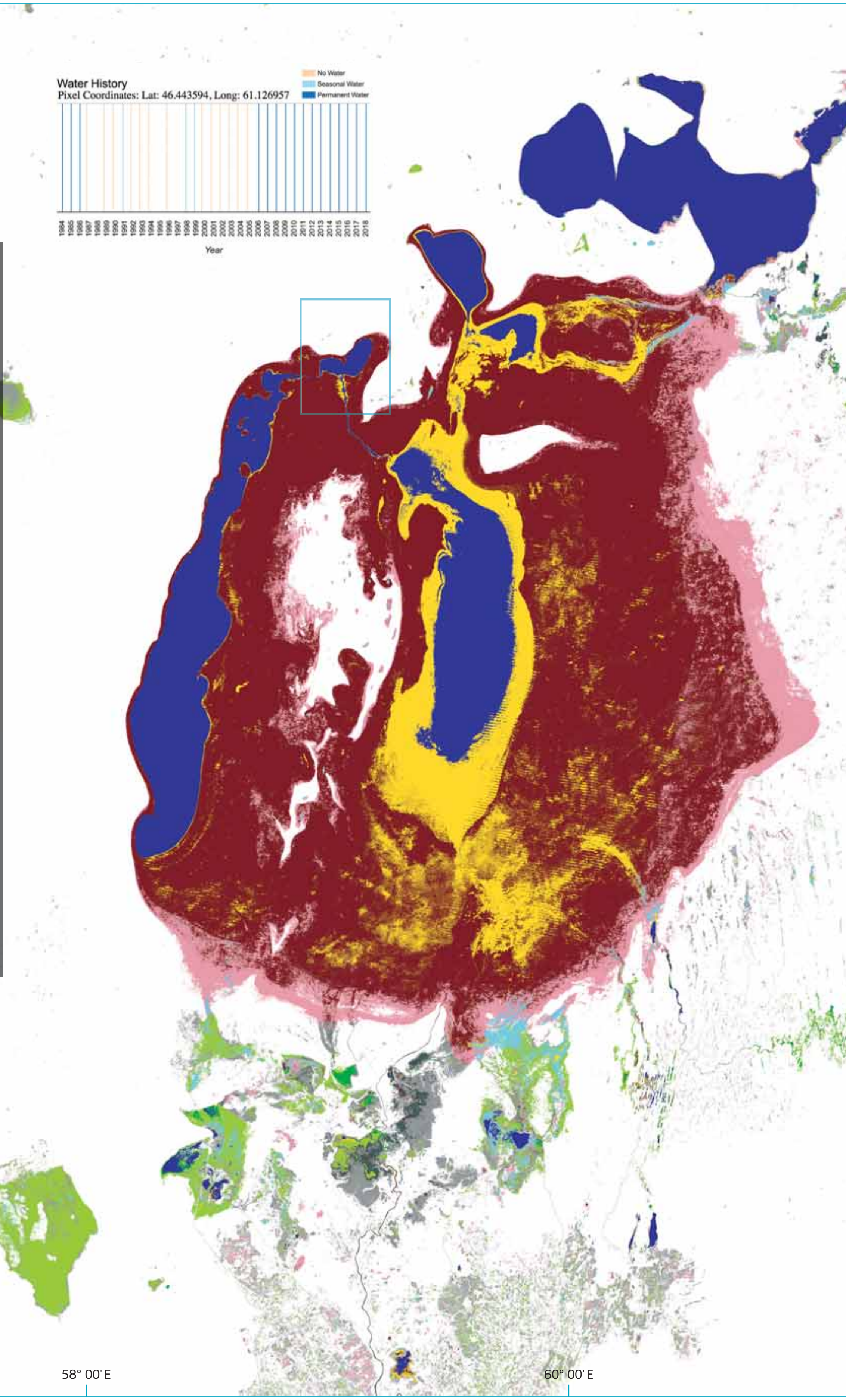
35° 03' 52.0" N
136° 23' 14.9" E

Otsu city and the southern end of Lake Biwa.
Lake Biwa lies in an important manufacturing region. Industry, agriculture and metropolitan growth have all put pressure on this ancient lake.
Source: G. P. Witteveen. This file is licensed under the Creative Commons Attribution-Share Alike 4.0 International license.

Nagoya Port in Ise Bay seen from the air and from Landsat satellites (14 January 1988, 6 January 2020).
Land reclamation has occurred throughout the bay. New infrastructure can be seen when comparing the two Landsat scenes, acquired 42 years apart. Both Landsat scenes are 32 km North-South (top to bottom). Scope of photograph indicated on the main map.
Source: 663highland [CC BY-SA (http://creativecommons.org/licenses/by-sa/3.0/)], Landsat scenes Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

Regional highlights

27 | Aral Sea (Kazakhstan and Uzbekistan)

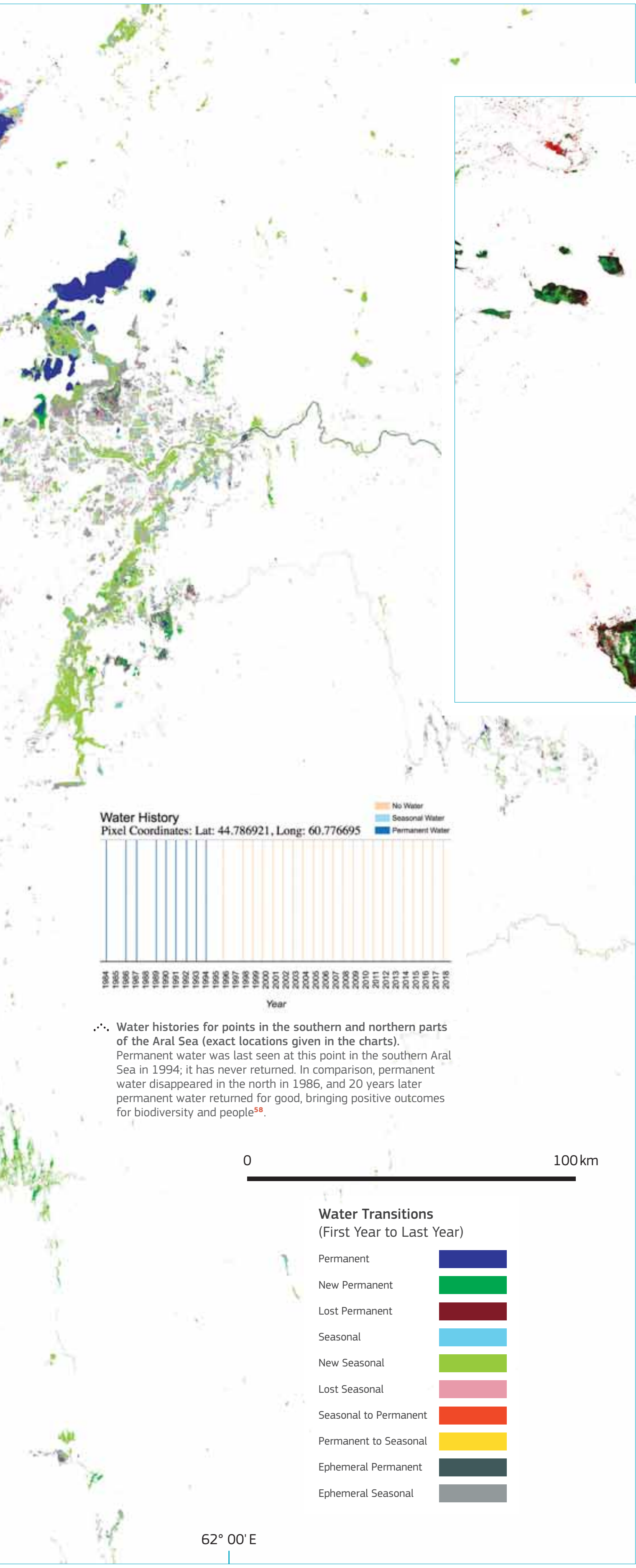


Aral Sea

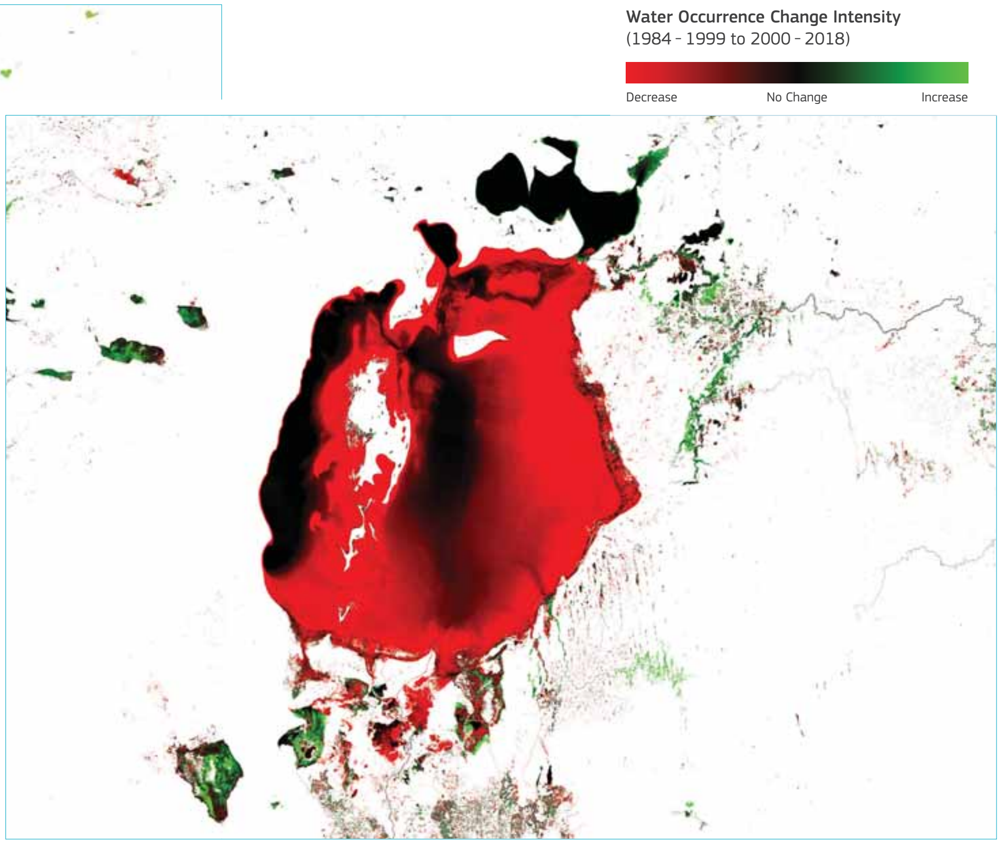
Kazakhstan and Uzbekistan

Once one of the world's largest lakes, the Aral Sea used to be fed by two main rivers, the Amu Darya and Syr Darya. By the 1960s much of the water from these was being diverted to irrigate freshly established cotton fields. As a consequence, the Aral Sea began to contract. In the early 1980s the lake was still largely one contiguous waterbody (albeit smaller than the original), but by the mid- to late-2000s it had been transformed into separate residual lakes, covering only 10 % of its former area[55]. Water loss by evaporation in this location outstrips recharge from precipitation, groundwater flow and snowmelt, so in the absence of sufficient river recharge the lake not only contracted and divided, it also increased in salinity. In some locations salinity levels reach 100 grammes/litre (on average, seawater contains 35 grammes/litre). Disappearing lake habitats and increasing salinity have led to significantly reduced biodiversity, collapse of the region's fishing industry and dust/salt storms from the newly created Aralkum desert[56]. There is some partial recovery in the north, following completion of the Kokaral dam in 2005. Water levels in the northern part of the lake are rising and salinity levels falling[57].

45° 09' 36.0" N
59° 40' 48.0" E



Water histories for points in the southern and northern parts of the Aral Sea (exact locations given in the charts).
Permanent water was last seen at this point in the southern Aral Sea in 1994; it has never returned. In comparison, permanent water disappeared in the north in 1986, and 20 years later permanent water returned for good, bringing positive outcomes for biodiversity and people[58].



Aral Sea.
Extensive water withdrawal from the Amu and Syr rivers that once fed the lake is the main cause of loss, but changes in water management, where less is abstracted and less diverted, give hope for stabilisation and partial restoration of the lake in the coming years. Approximate scope of photograph indicated on the main map.
Source: Patrick Schneider on Unsplash.

28 | High-elevation lakes (Tibetan Plateau)

High-elevation lakes

Tibetan Plateau

Lakes throughout the Tibetan Plateau, which is part of a major endorheic basin, have expanded in size over the past 35 years. The growth in surface area of such lakes has been linked to increases in annual precipitation and temperatures in the region, both of which are subsequently linked to increased run-off from accelerated snow and glacier-melt. The expanding lakes reduce the availability of grazing land, as some disappears entirely under water and some is damaged by salination caused by brackish water; the expanding lakes also threaten roads and railways[59].

31° 49' 12.0" N
88° 58' 48.0" E

Lake Nam (Namtșo), Tibetan Plateau.
Lake Nam (Namtso) is a mountain salt lake, at an elevation of 4 718 m, born in the Paleogene age as a result of Himalayan tectonic plate movements.
Source: Photo by Mèng Jia on Unsplash.

Siling Lake, Tibetan Plateau.
Siling Lake viewed by Landsat 8, 14 June 2019. The image is 88 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

29 | The Palm Islands (United Arab Emirates)

The Palm Islands

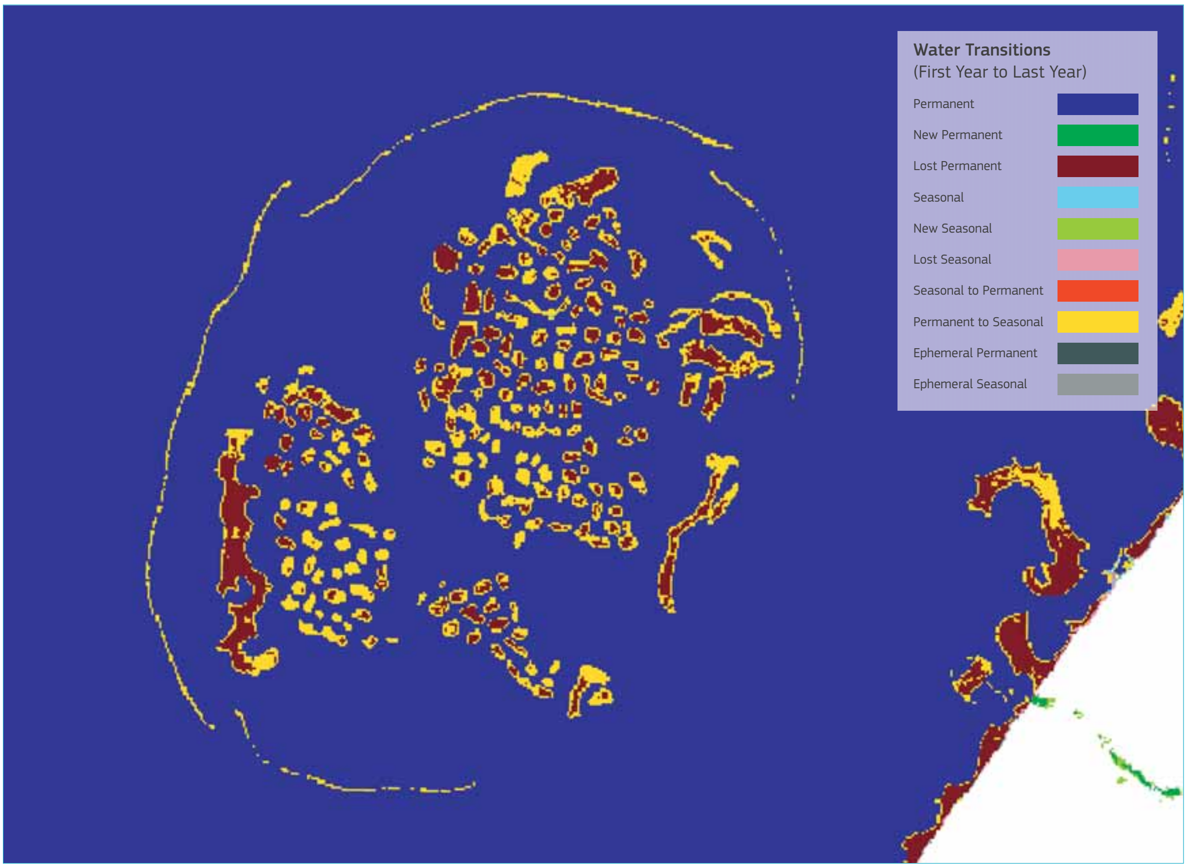
United Arab Emirates

The Palm Islands were built using millions of tonnes of rock to make breakwaters and subsequent infilling using sand dredged from the seabed. This began in 2001 and has created over 500 km of new coastline. Variations in decreasing water occurrence are indicative of the different lengths of time it took to build the islands; the brighter red tones are indicative of more recent transitions from water to land. The Palm Islands are not unique. Many countries bordering the Persian Gulf have created artificial islands, including the United Arab Emirates, Qatar, Oman, Kuwait and Bahrain. Most are constructed using the same technique as with the Palm Islands, but some are made by cutting waterways into the coast[60]. Tourism is a primary motivation for the construction, with iconic hotels (such as the Burj Al Arab, sitting on its own artificial island) offering alternatives to heritage, religious and more conventional beach tourism[61]. As a largely enclosed sea, the Persian Gulf is highly susceptible to pollution. Commonplace sources, such as oil and waste dumping from shipping, are now competing with in situ human interference in the form of artificial islands. These bring people (and their waste) into direct contact with what was exclusively a marine environment, they remove natural seabed and coastal habitats[62] and alter patterns of coastal deposition, nutrients, currents, specific heat capacity and wave movement[63]. Paradoxically, these newly built islands are at risk from rising sea levels, storm surges and extreme weather associated with climate change[64].

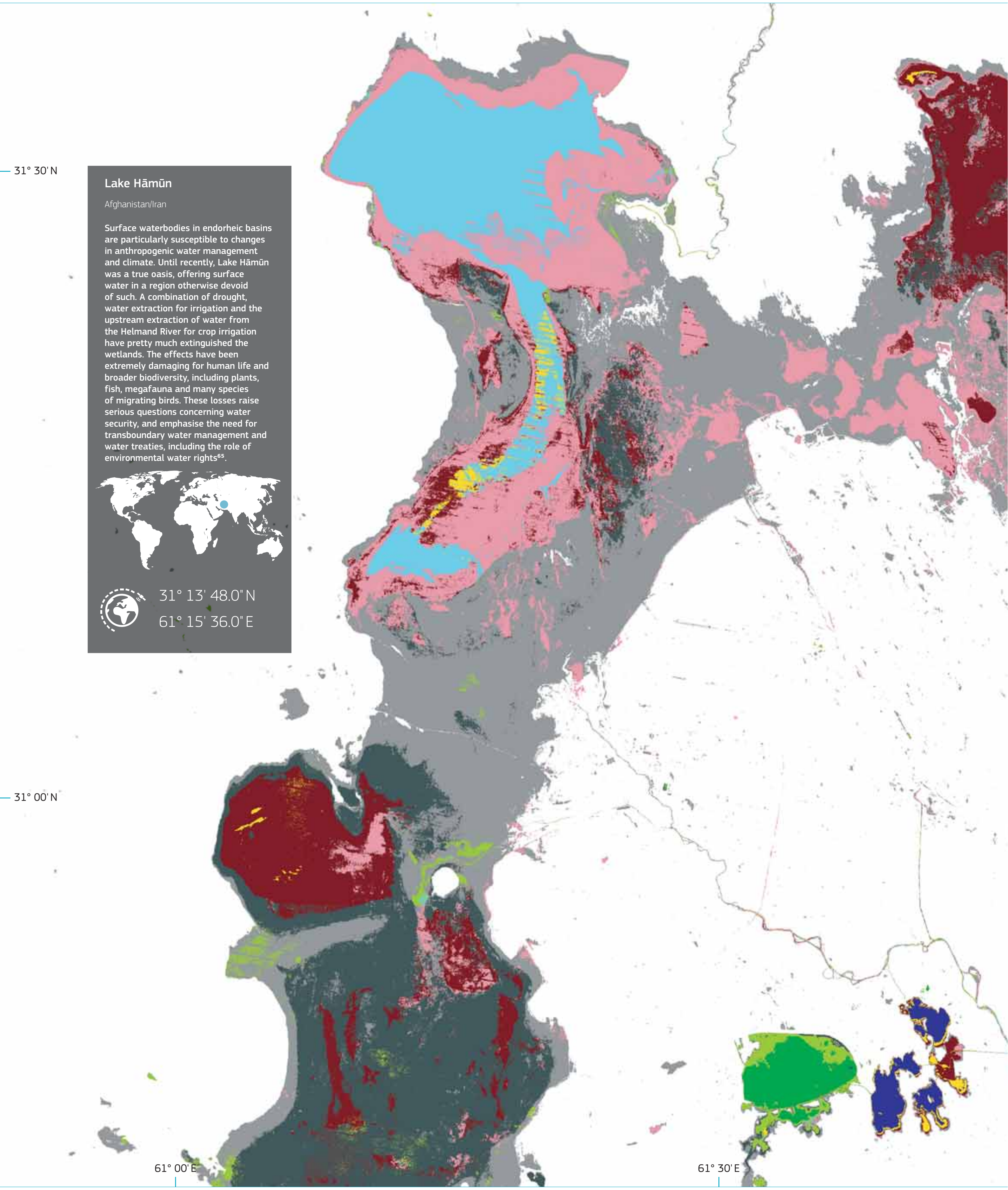
25° 06' 36.0" N
55° 07' 48.0" E

Properties fringe the artificial beach in Dubai, UAE. Luxury hotels and 'hyper-real' landscapes are part of the region's strategy to boost new forms of tourism.
Source: Christoph Schulz on Unsplash.

'The World' group of islands, Dubai, UAE.
Taken in April 2015, the image shows the newly constructed archipelago of undeveloped islands. Sand was dredged from the shallow coastal sea bed and pumped to create the islands, protected by long rock breakwaters (discontinuous to prevent stagnation) as seen in the inset below.



30 | Lake Hāmūn (Afghanistan/Iran)

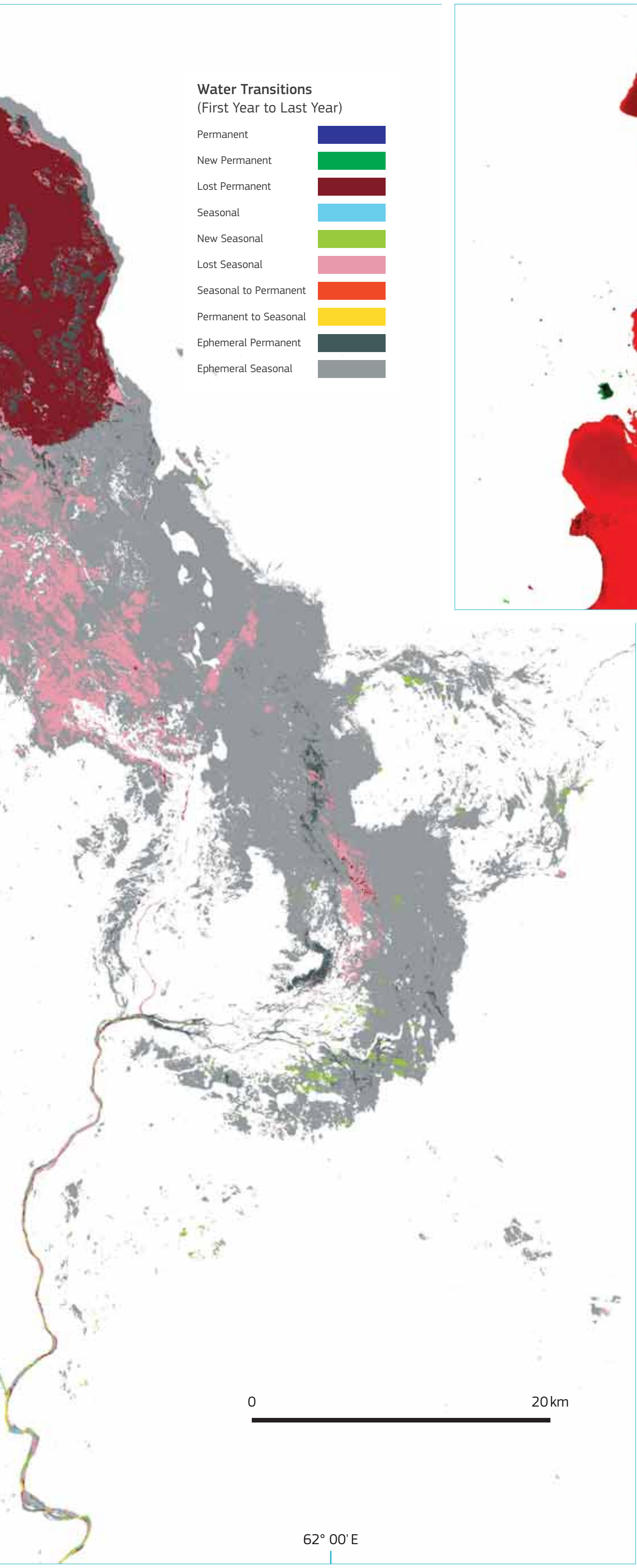


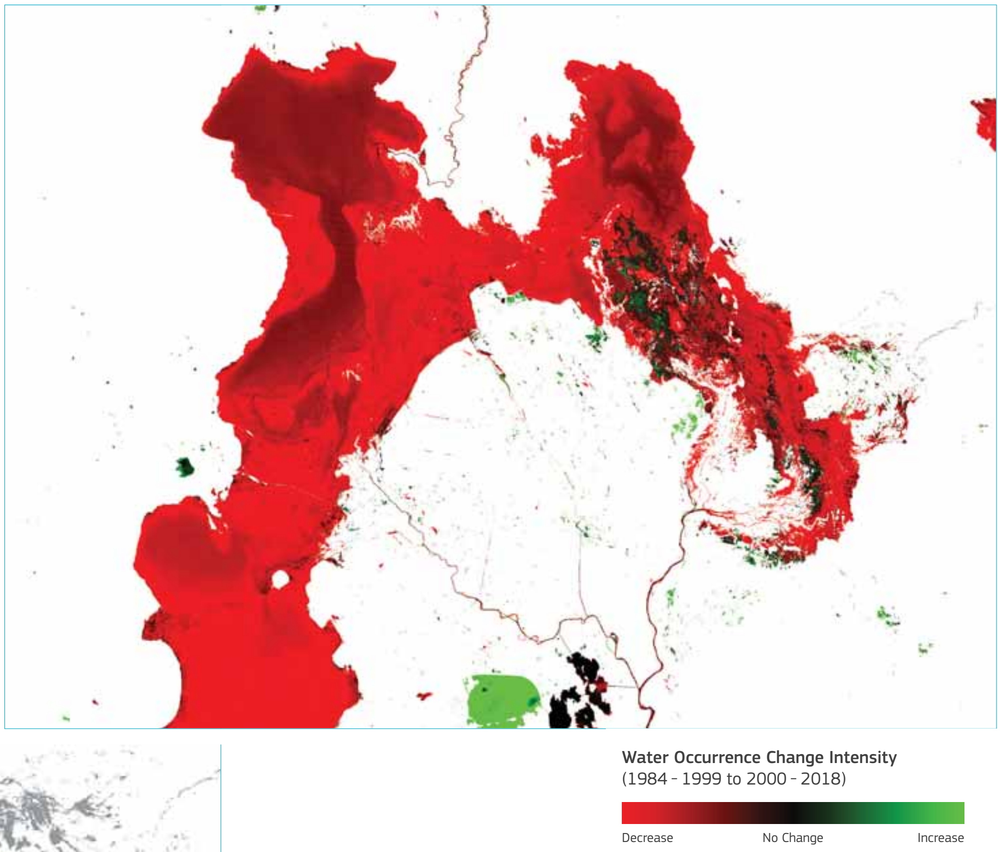
Lake Hāmūn

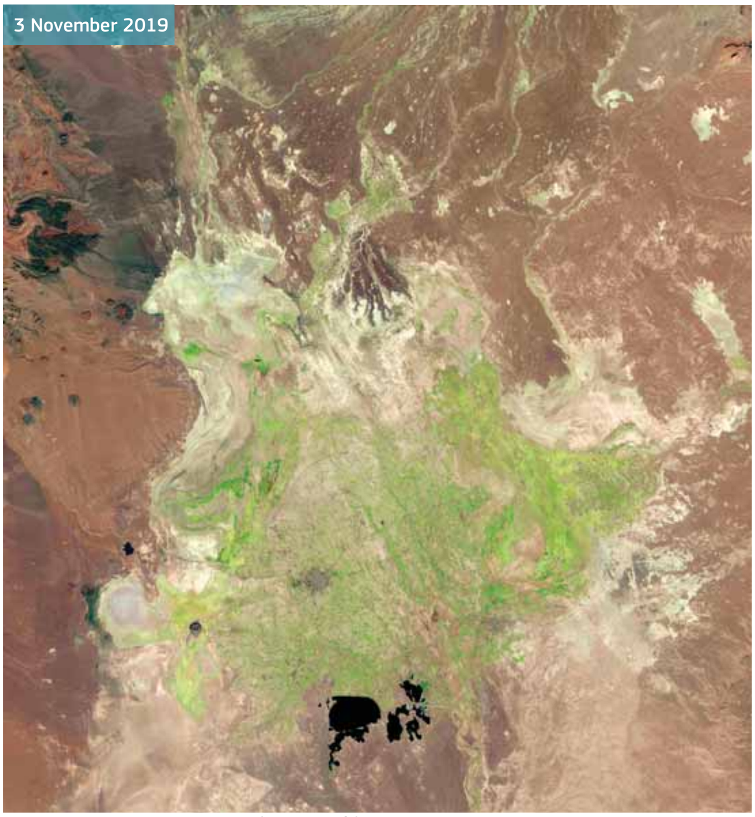
Afghanistan/Iran

Surface waterbodies in endorheic basins are particularly susceptible to changes in anthropogenic water management and climate. Until recently, Lake Hāmūn was a true oasis, offering surface water in a region otherwise devoid of such. A combination of drought, water extraction for irrigation and the upstream extraction of water from the Helmand River for crop irrigation have pretty much extinguished the wetlands. The effects have been extremely damaging for human life and broader biodiversity, including plants, fish, megafauna and many species of migrating birds. These losses raise serious questions concerning water security, and emphasise the need for transboundary water management and water treaties, including the role of environmental water rights[65].

31° 13' 48.0" N
61° 15' 36.0" E

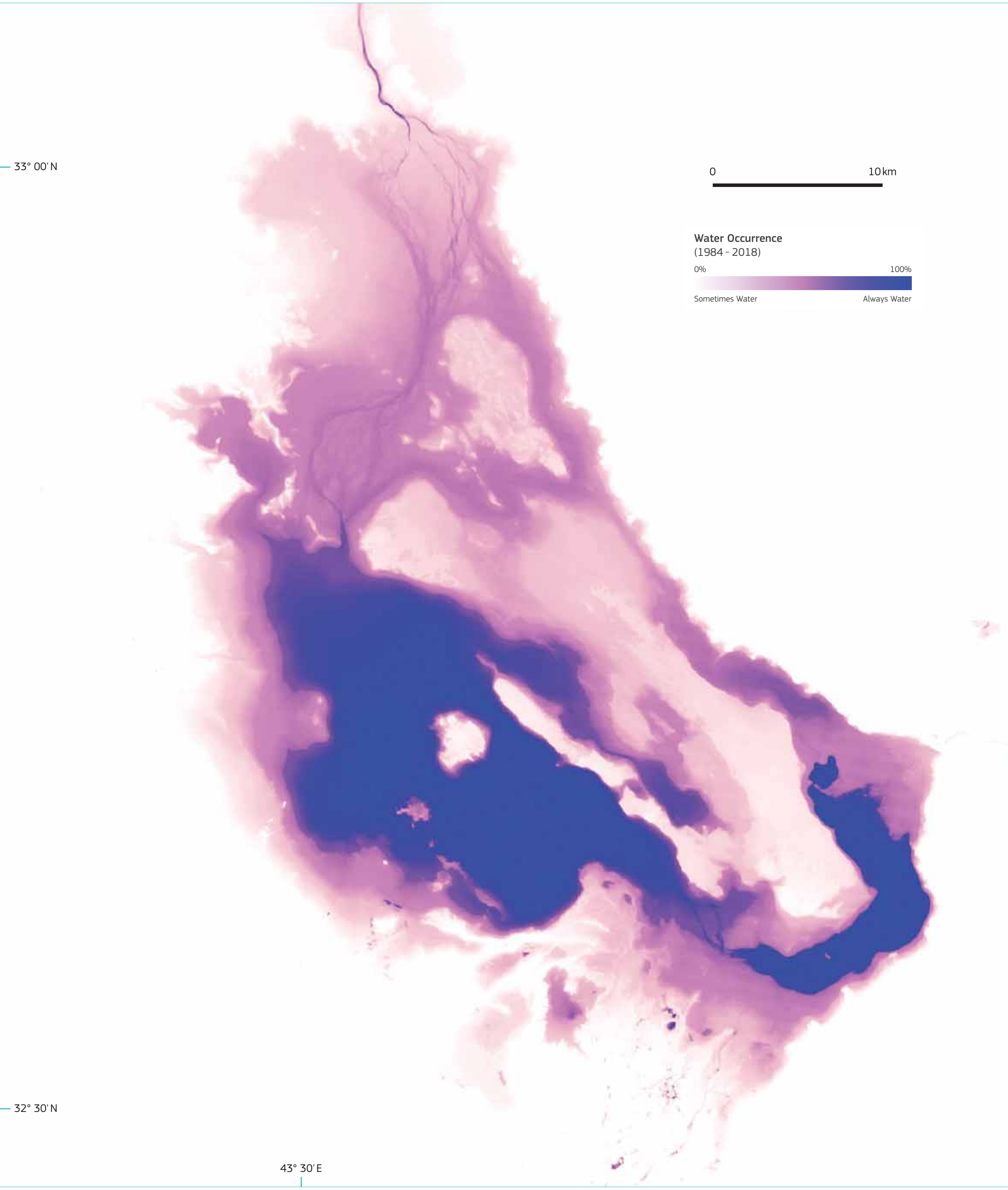






Lake Hāmūn, Afghanistan/Iran.
The dried-out bed of Lake Hāmūn, near Zabol, close to the border between Iran and Afghanistan. The only surface water visible in the scene is the black balloon shapes of the reservoir complex, seen in the lower-centre part of the scene. The image is 158 km North-South (top to bottom).
Source: Alan Belward using Landsat 8 imagery, courtesy USGS/NASA.

31 | Razzaza Lake (Iraq)

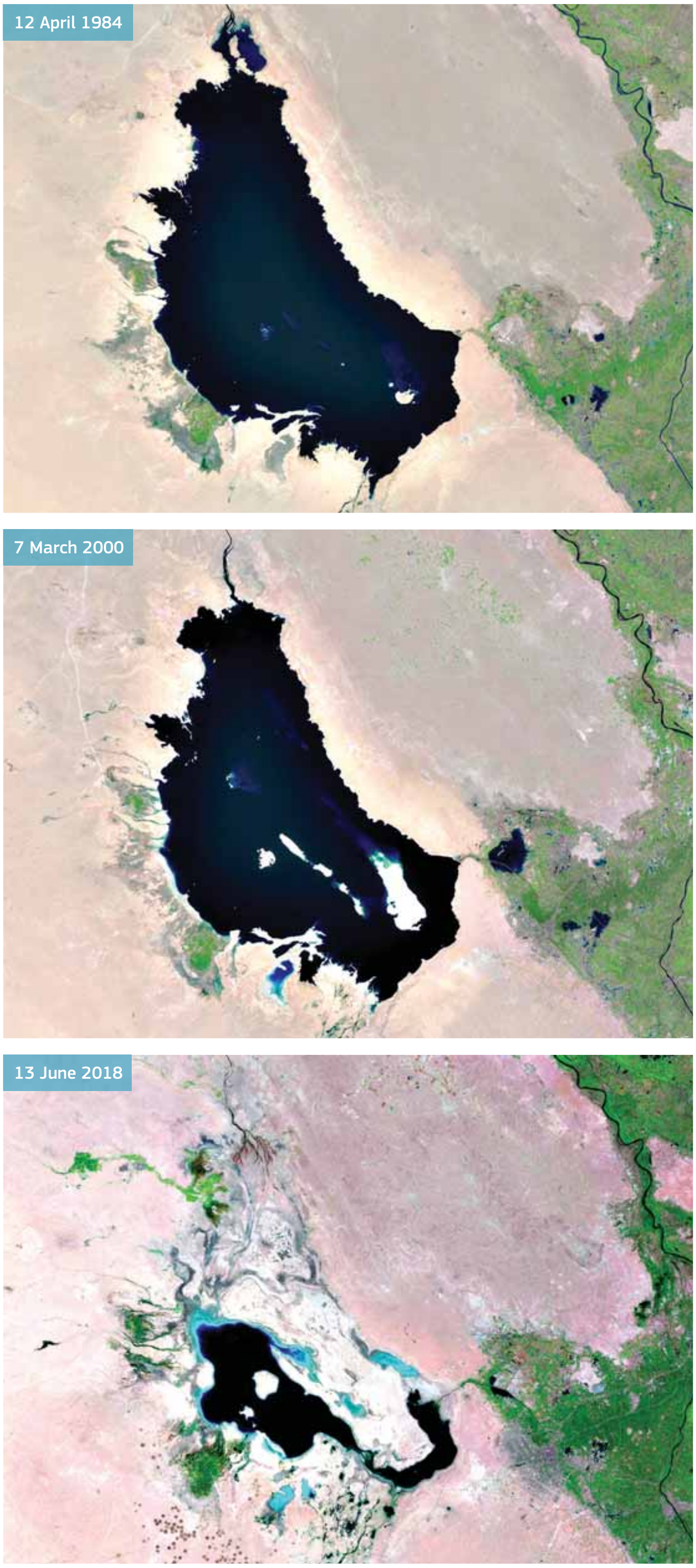


Razzaza Lake

Iraq

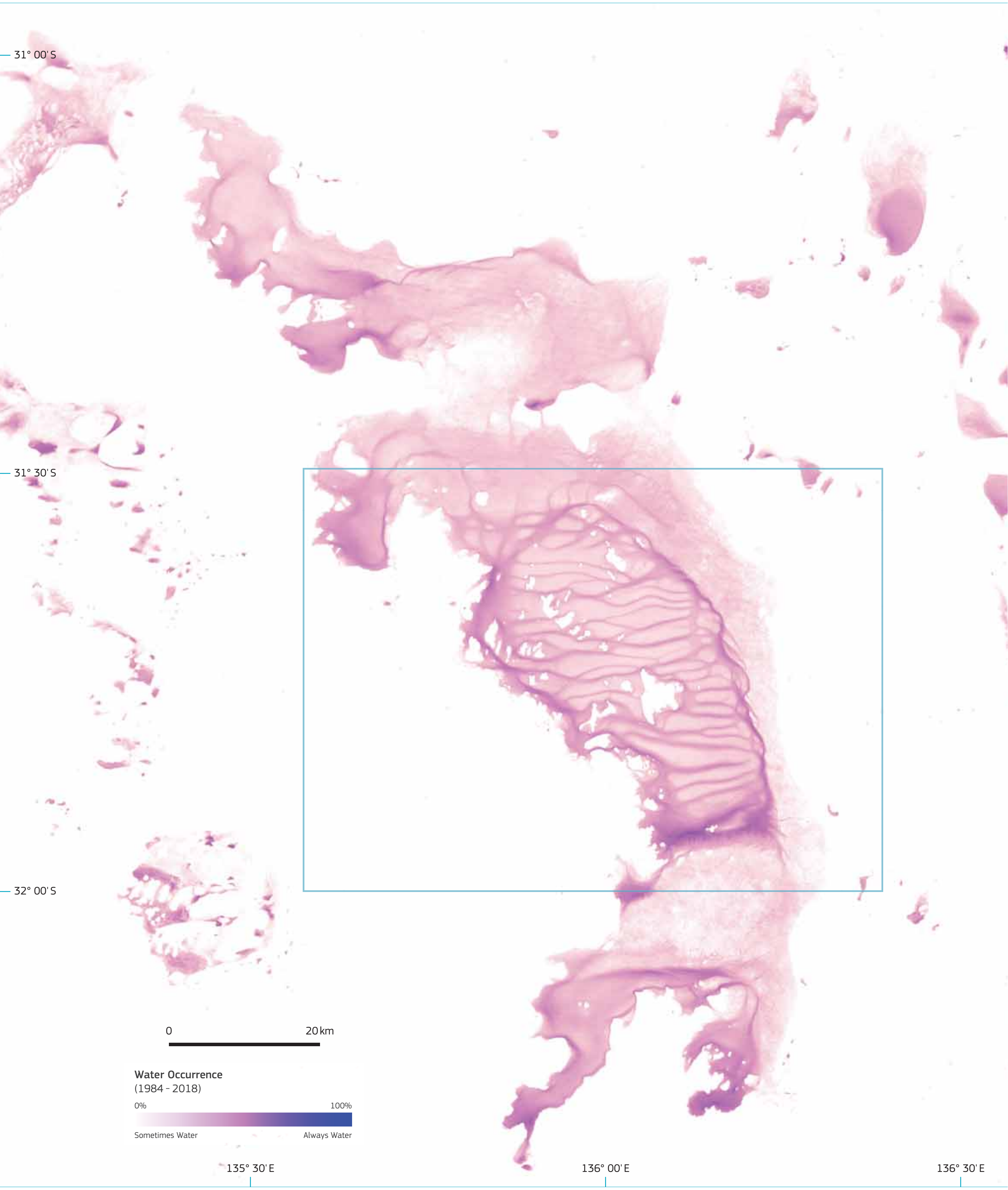
Razzaza Lake, lying to the southwest of Baghdad, is fed via a canal from its smaller northern neighbour, Lake Habbaniyah, which in turn fills from the Euphrates River. Until the early years of this century, Razzaza was Iraq's largest freshwater lake. Increased water abstraction from the Euphrates and Habbaniyah in recent years (mainly for crop irrigation) means less excess water flows onwards into Razzaza, and as a consequence the lake is rapidly drying up and becoming increasingly saline[66]. Much of the lake has vanished since 2000. The contracting lake is losing its fish stock and diversity, along with its plant and bird life. The land degradation around (and increasingly in) the lake significantly and negatively affects both biodiversity and human well-being. Livelihoods from recreation, fishing and farming are all in sharp decline with only one species of fish reported as remaining in the lake[67] - though desert fauna and flora thrive on the newly exposed land.

32° 45' 00.0" N
43° 38' 00.0" E



Contracting Razzaza Lake.
This series of three images were acquired by Landsat satellites on 12 April 1984, 7 March 2000 and 13 June 2018. Open water appears black in these satellite images. As the lake dries out, the surface water area contracts to the point that former islands are now connected to the mainland, and entirely new islands have formed. This pattern of retreat is captured fully in the accompanying water occurrence map. The images are 74 km North-South (top to bottom).
Sources: All images Alan Belward using Landsat 5 and 8 imagery, courtesy USGS/NASA.

32 | Lake Gairdner (Australia)



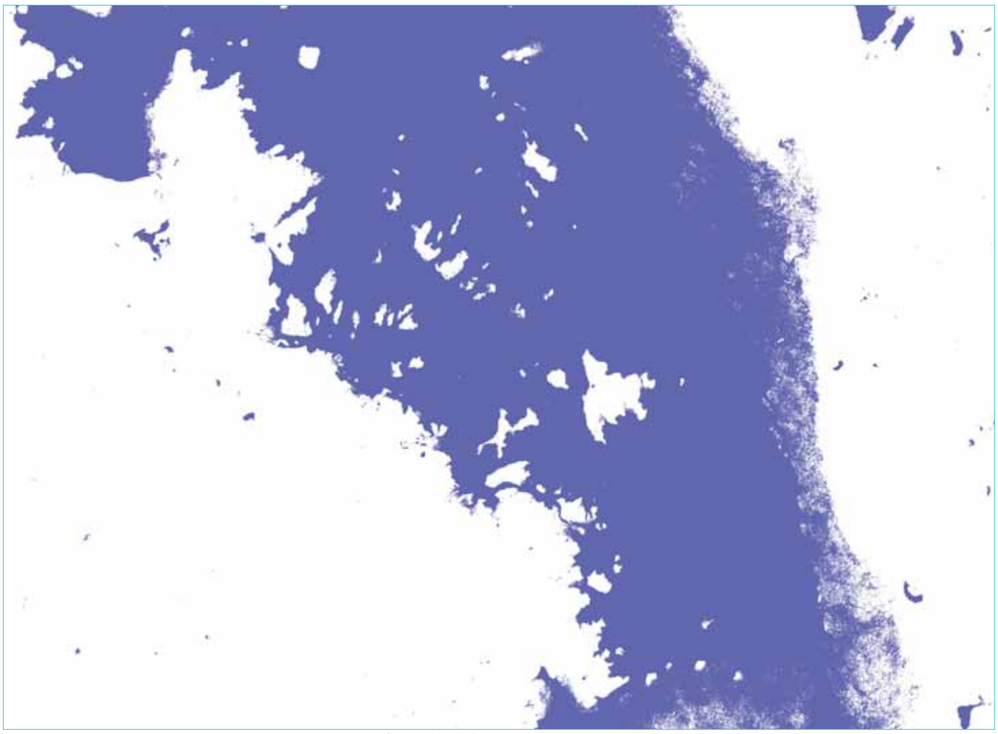
Lake Gairdner

Australia

Episodic inundations can create lakes of considerable size that only last for a season and don't appear on an annual basis, such as Lake Gairdner in Australia, which is over 150 km in length. The lake is a hotspot for bird biodiversity[68]. Plant biodiversity is relatively low[69], which is unsurprising given the arid conditions and saline nature of the lake bed. The intricate pattern of water occurrence mapped here shows how spatially complex such ephemeral flooding can be. A system of low-lying, gently rolling red sand hills creates a system of interconnected creeks. These low-lying areas are the first to fill with water following rain, and remain full for longer than surrounding higher ground. This creates the rib-like appearance of the water occurrence map. The lake contains extensive saltflats, which are used for annual motor vehicle races[70]. The region's indigenous population, the Gawler people, attach great cultural and ecological significance to water across this landscape and have the right to access and use water on and in the land[71].

31° 49' 12.0" S
136° 06' 36.0" E

Lake Gairdner, South Australia, Australia.
Lake Gairdner's extensive salt flats are used for straight line racing of cars, motorcycles and trucks during an annual 'Speed Week'. The lake also falls into the Gawler Ranges Native Title Claim Area, which assigns multiple rights to the indigenous Gawler People.
Source: Murray Foubister [CC BY-SA (https://creativecommons.org/licenses/by-sa/2.0)].

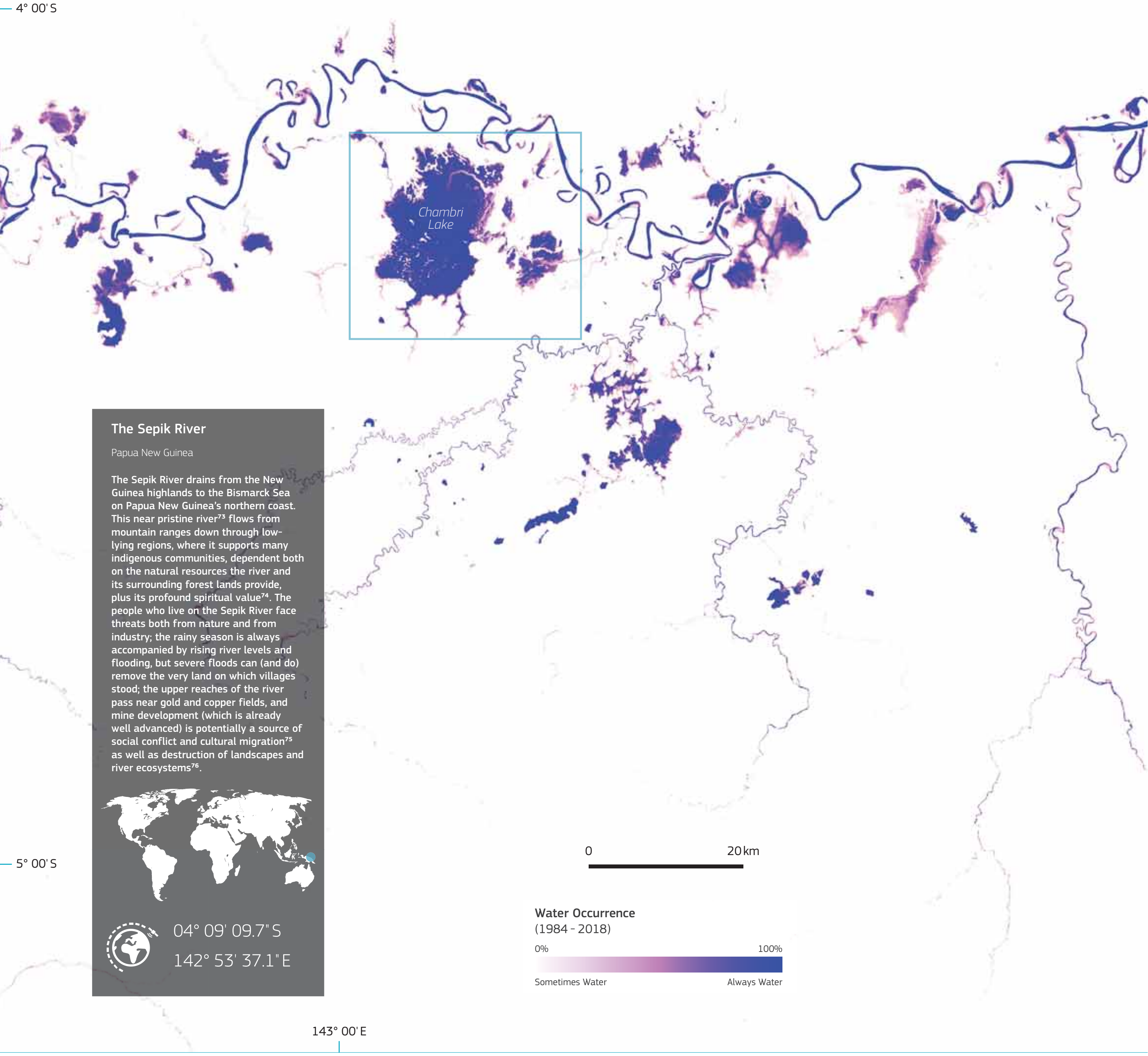


Maximum Water Extent.
Lake Gairdner fills from local drainage and never has water all year round - it is always seasonal. The lake is usually at its fullest in the cooler, wetter months of June to September, though rainfall here is among the most variable in timing, duration and intensity of any arid region in the world[72], so this is not always the case. The 'ribs' shown by the water occurrence in the main map confirm that not all the lake basin fills each year. However, the Maximum Water Extent, shown here, confirms that, over time, the entire basin does indeed fill.

33 | The Sepik River (Papua New Guinea)

Men's house (or cult house) belonging to the Crocodile Clan of the Iatmul people, Tambunum village, middle Sepik River.
Public buildings and homes are usually built on stilts to accommodate seasonal fluctuations in water levels and provide wind protection.

Female figure, dating from 19th to early 20th Century; East Sepik Province, coastal Sepik River.
The figure is made from wood, human hair, conus and nassa shell, rattan and pigment. The cultural integrity of the Sepik River's peoples is under threat from both natural and anthropogenic processes.

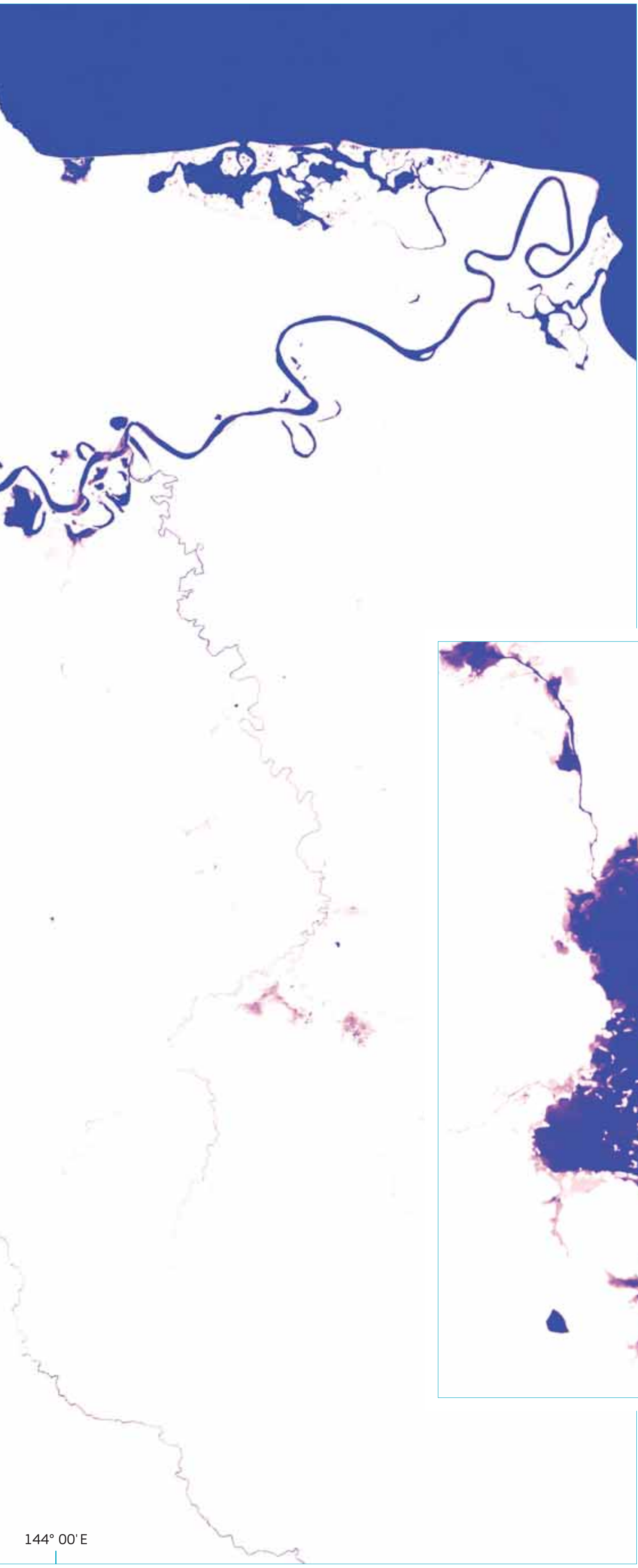


The Sepik River

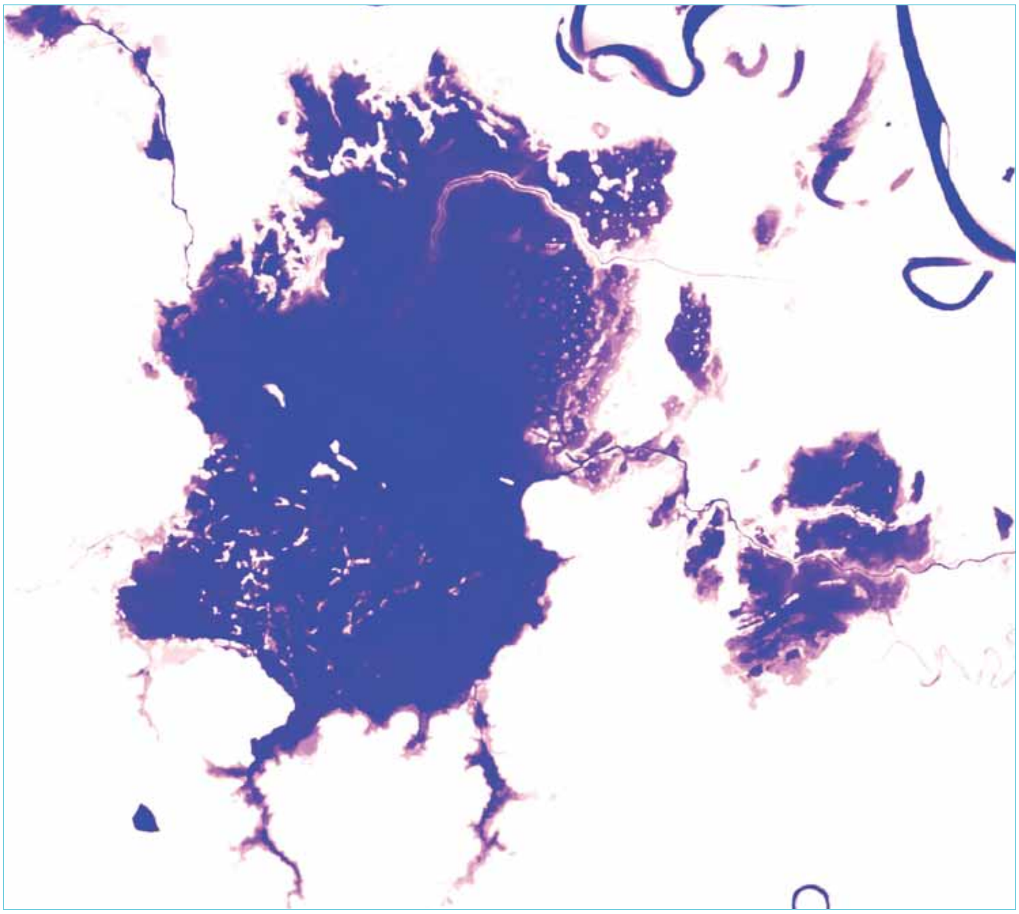
Papua New Guinea

The Sepik River drains from the New Guinea highlands to the Bismarck Sea on Papua New Guinea's northern coast. This near pristine river[73] flows from mountain ranges down through low-lying regions, where it supports many indigenous communities, dependent both on the natural resources the river and its surrounding forest lands provide, plus its profound spiritual value[74]. The people who live on the Sepik River face threats both from nature and from industry; the rainy season is always accompanied by rising river levels and flooding, but severe floods can (and do) remove the very land on which villages stood; the upper reaches of the river pass near gold and copper fields, and mine development (which is already well advanced) is potentially a source of social conflict and cultural migration[75] as well as destruction of landscapes and river ecosystems[76].

04° 09' 09.7" S
142° 53' 37.1" E



.·˙. **Housing in Yejemagwa village, Sepik River system.**
The physical environment (including seasonally fluctuating river levels) conditions the social, spiritual and economic dimensions of everyday life for the people. If the integrity and pristine state of the river changes, then so too will the way of life.
Source: Weli'mi'nakwan flickr Attribution 2.0 Generic (CC BY 2.0).



.·˙. **Chambri Lake.**
The lake supports abundant wildlife, including crocodiles. The crocodile is not only an important part of the region's biodiversity but also occupies a key role in the daily and ceremonial affairs of the people[74].

Part 5 - Conclusions

Water shapes all life on Earth, it shapes Earth's physical appearance, and we shape it.

Nature isn't going to stop affecting global surface water dynamics any time soon, and nor are humans. Earth-observing satellites have given us the capacity to study changes to our entire planet's land surface for more than 40 years. The latest generation of satellites provides even greater capacity. Matching peerless imaging capacity to advances in computing and advanced analytical techniques puts even greater knowledge concerning surface water dynamics within reach.

Clockwise from top-left:

A permanent change in environment created by river damming.
Source: Nicolas Desmangles on Unsplash.

Sentinel-1B heading for orbit to join its identical twin, Sentinel-1A, which was launched in 2014. By orbiting 180° apart, global coverage and data delivery are optimised for the Copernicus services. The mission is being used for a multitude of applications to improve everyday life and help to understand our changing planet, from tracking land subsidence to monitoring ice in polar oceans.
Source: ESA/ATG medialab.

A high altitude glacier and lake in Patagonia, Argentina.
Source: Arto Marttinen on Unsplash.

Lake Balaton's striking emerald-green colour in this Copernicus Sentinel-2 image is most likely due to its shallow (average depth 3.3 m) waters and chemical composition. It is heavy in carbonates and sulphates, and there are also around 2 000 species of algae that grow in its waters. Plans to drain the lake and use the resulting land to grow crops were proposed in the 18th and 20th centuries[1,2], but neither proposal reached fruition.
Source: contains modified Copernicus Sentinel data (2019), processed by ESA, CC BY-SA 3.0 IGO.

Conclusions

This Atlas is a snapshot in time. But mapping surface water dynamics cannot be a one-off activity. The geological time scales over which river valleys are carved and lakes fill or empty, variations in the weather as seasons come and go, and the daily ebb and flow along millions of kilometres of coastline result in truly beautiful patterns in the way water appears on our planet's land surface. The stories in this Atlas show how this beauty affects many, many aspects of our daily lives – and they show how the daily lives of 7.7 billion people affect this beauty. For better or worse, we will continue channeling, dredging, draining, damming, using and abusing surface waters. Some of the patterns revealed in this Atlas have endured for millennia and, in all likelihood, will endure for millennia to come. Others will not. New maps of surface water dynamics will be needed to record these changes.

Fortunately, the foundation of the maps in this Atlas, the Landsat program, continues to gather and provide new imagery every day, and work is already underway to harness the daily flow of terabytes of imagery from the Copernicus Sentinel-1 and Sentinel-2 satellites for water mapping.

The USGS not only collect new Landsat imagery, they are also enriching the historic archive by gathering and reprocessing old images collected at receiving stations from all around the world. This 'Landsat Global Archive Consolidation' (LGAC) has successfully recovered many thousands of scenes that were stored on magnetic tapes. The tapes go through a restoration process (principally baking them at around 60 °C for many hours) before reading them using tape-readers from the last century. These 'new-old' data are then processed to the high geometric and radiometric standards of today and added to the archive[3]. This richer historic archive will improve the time dimension in future versions of the Global Surface Water Explorer, especially for the early years.

Other improvements will come from incorporating imagery from other satellite programmes. The characteristics of the TM, ETM+ and OLI sensors mean the maps in this Atlas don't show waterbodies smaller than 30 m × 30 m. The sensors on the Sentinel-1 and -2 satellites for example, will allow us to map waterbodies down to 10 m × 10 m in size.

It still won't be possible to map waterbodies hidden by overhanging or standing vegetation, or water flowing in tunnels and under bridges, and the changes to seasonal water are still difficult to map because our planet's surface simply isn't imaged frequently enough. The extra images added to the archive through the LGAC will improve seasonal mapping to some extent, and the Sentinels also offer two avenues for improvement. Firstly, the gap between repeat overflights from Sentinel-2A and -2B is only 5 days, and secondly, Sentinel-1A and -1B are radar imaging satellites. Radar (Radio Detection and Ranging) is a technology that can 'see' through clouds, and can 'see' at high latitudes even when solar angles are very low during the winter nights (Radar satellites provide their own electromagnetic radiation, and thus are not dependent on sunlight to take images). Radar will again give us far more frequent imaging, and thus many more opportunities to capture short-term seasonal changes in the appearance of water on the Earth's surface, as well as more accurate mapping of high-latitude areas.

Copernicus Sentinel-1 Mission

Two Sentinel-1 satellites have been launched so far. 1A was launched on 3 April 2014 and 1B on 25 April 2016. Both satellites carry C-band synthetic aperture radars, which are capable of collecting imagery day or night, through clear or cloudy skies. The two satellites are in the same orbital plane and positioned such that each satellite gives a 12-day repeat cycle, whilst the two-satellite constellation provides an exact repeat cycle of 6 days at the equator. Spatial resolution depends on processing level. Typical products are released at 5 × 5 m in 80 km swaths, to 20 × 40 m in a 400 km extra-wide swath mode.

Artist's impression of Sentinel-1B.
Radar satellites, such as Sentinel-1B, provide all-weather, day and night imaging capabilities.
Source: ESA–Pierre Carril.

Copernicus Sentinel-2 Mission

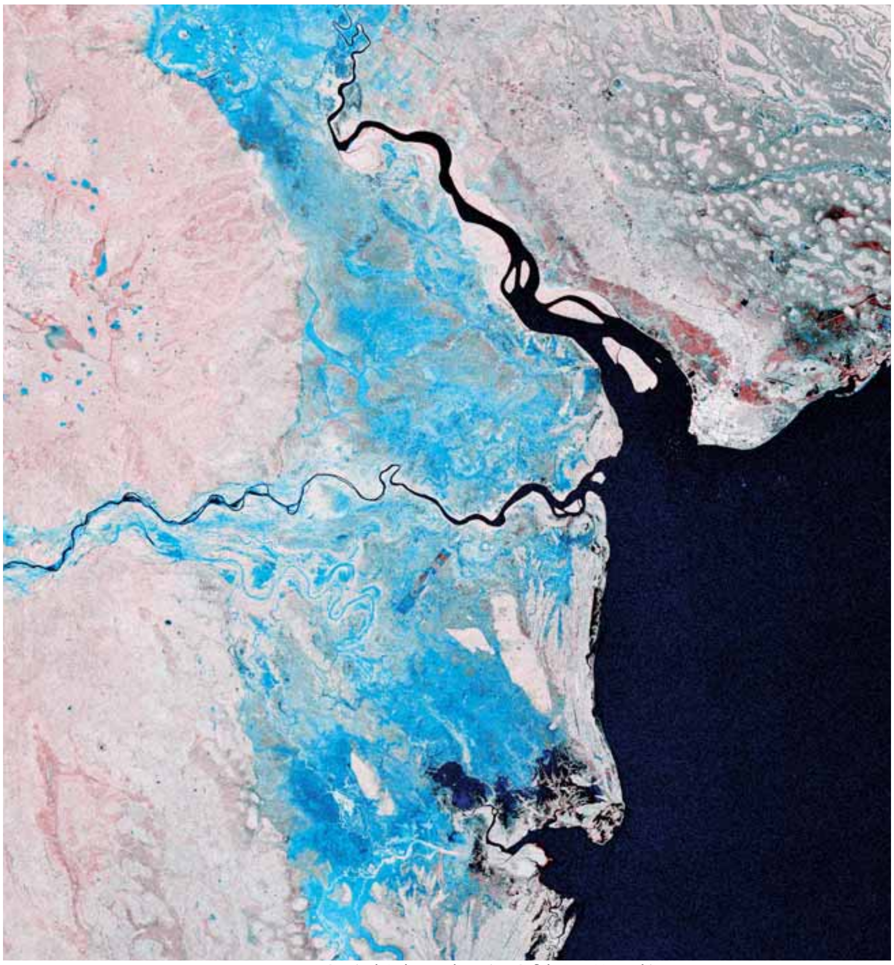
The Copernicus Sentinel-2 mission also consists of a two-satellite constellation. Sentinel-2A was launched on 23 June 2015 and -2B on 7 April 2017. Both satellites carry high resolution (up to 10 m, with a 290 km swath) optical imagers. The two satellites are again in an identical orbital plane and positioned such that each satellite gives a 10-day repeat cycle, whilst the two-satellite constellation provides an exact repeat cycle of 5 days at the equator. The 5-day revisit period is particularly valuable for following rapidly changing events on the Earth's surface, and the increased revisit period means more chances of obtaining a cloud-free image.

Artist's impression of Sentinel-2A.
Sentinel-2A provides well calibrated, high radiometric resolution multispectral measurements in 13 different wavebands, ranging from visible to shortwave infrared, at spatial resolutions from 10 to 60 m, depending on waveband.
Source: ESA–Pierre Carril.

Copernicus Programme

Copernicus (https://www.copernicus.eu/en) is the European Union's Earth Observation Programme. The Programme is coordinated and managed by the European Commission, and implemented in partnership with the European Union's Member States, the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF), EU Agencies and Mercator Océan. The programme operates via a series of dedicated services that address key issues around the atmosphere, marine, land, climate change, security and emergencies, underpinned by the Sentinel family of satellites and in situ measurements. The data and information the services and underpinning satellites produce are available on a free and open basis.

Copernicus services.
From its inception, the Copernicus Programme has been dedicated to providing European Earth Observation (EO) satellites and putting in situ networks in place that together provide data to services that deliver information and knowledge to: monitor the Earth to support environmental protection and civil protection and civil security efforts; maximise socio-economic benefits by promoting EO use in services; foster development of a competitive European space and services industry; ensure autonomous access to environmental knowledge and key technologies for EO; support and contribute to European policies and foster global initiatives[4].



Sentinel-1 change detection, Sofala Bay, Mozambique.
The ability of radar imagers, such as the Copernicus Programme's Sentinel-1A and -1B satellites, to see through clouds is particularly valuable for monitoring cloudy parts of the world. On 4 March 2019, tropical cyclone Idai made landfall on Africa's east coast and didn't fully dissipate until 21 March. The storm system caused extensive flooding in Mozambique, Zimbabwe and Malawi. This image is created by combining Sentinel-1 (VH) imagery collected during and immediately after the storm (from 15 March to 1 April 2019, with data from the same period in the preceding year (15 March to 1 April 2018). The floodwaters are shown in the lighter blue tones. The very dark blue/black tones are where water was present both before and after the flood events. The floodwaters had a devastating, even lethal, impact on people throughout the region, and caused the loss of almost a million ha of crops[1]. The image is 86 km North-South (top to bottom).
Source: Guido Lemoine using Sentinel-1 imagery, courtesy EU Copernicus Programme.

Sentinel-2 cloud-free mosaic, Lake Toba, Sumatra, Indonesia.
Lake Toba is the largest volcanic lake in the world, and Indonesia's largest lake too. It fills a caldera around 100 km long by 30 km wide belonging to a long-extinct supervolcano. The volcano's last eruption, some 74 000 years ago, was the largest explosive event the Earth has experienced in at least the past 100 000 years, and could certainly have produced decade–long harsh winter conditions (volcanic winter) with massive negative impacts on plant and animal life[5]. Sentinel-2A and -2B images gathered between 2014 and 2016 are used to create the cloud-free mosaic shown here. The image is 70 km North-South (top to bottom).
Source: Jean-François Pekel using Sentinel-2 imagery, courtesy EU Copernicus Programme.

By taking advantage of the enriched historic Landsat archive and maximising the potential of the Copernicus Programme and its Sentinel satellites, the Global Surface Water Explorer should continue to develop and move to more detailed mapping (in both geographic detail and time). The Copernicus Programme itself should continue to ensure that data and information flows freely from its Sentinel satellites, that efforts continue to turn these data into information and that cloud-processing capabilities increasingly make the processing of large volumes of geospatial data a reality. Together, such advances will ensure that the stories told in this Atlas don't come to an abrupt end, and that new stories can be told.

Appendices and References

The European Commission

The Joint Research Centre of the European Commission

The European Union

The European Union (EU) is a unique economic and political union between 27 EU countries. It began in the aftermath of the Second World War as a purely economic union and gradually evolved into an organisation spanning policy areas, from climate, environment and health to external relations and security, justice and migration.

The EU is governed by the principle of representative democracy, with citizens directly represented at Union level in the European Parliament and Member States represented in the European Council and the Council of the EU. The European Commission is the EU's politically independent executive arm, which promotes the general interest of the EU by proposing legislation to and enforcing decisions by the Parliament and the Council.

The EU is represented at the United Nations, the World Trade Organization, the G8 (Group of Eight industrialised nations) and the G20 (Group of 20).

The European Commission

The European Commission is the executive body of the EU, and is responsible for proposing legislation, verifying its implementation, and upholding the Union's treaties. Political leadership is provided by a team of 27 Commissioners (one from each EU country) – led by the Commission President, who decides who is responsible for which policy area. Each member of the College is nominated by their national government, and then appointed by the European Council after the approval of the European Parliament.

The day-to-day running of Commission business is performed by staff (specialists in domains such as law, finance, economics, science, communications and administration) working in departments known as Directorates-General (DGs). Each DG is responsible for a specific policy area. DGs develop, implement and manage EU policy, law, and funding programmes. The Commission proposes new laws, but it is the European Parliament and Council of the European Union that enact them. Service departments deal with administrative issues, and executive agencies manage programmes set up by the Commission.

The Joint Research Centre (JRC)

The Joint Research Centre (JRC) is one of the Commission's DGs. It is the Commission's science and knowledge service, carrying out research in order to provide independent scientific advice and support to EU policy.

JRC staff create, manage and make sense of knowledge, and develop innovative tools and make them available to policymakers; anticipate emerging issues that need to be addressed at EU level and understand policy environments; and collaborate with over a thousand organisations worldwide.

JRC work has a direct impact on the lives of citizens by contributing with its research outcomes to a healthy and safe environment, secure energy supplies, sustainable mobility and consumer health and safety. The JRC draws on over 60 years of scientific experience, and continually builds expertise in knowledge production and knowledge management. The organisation hosts specialist laboratories and unique research facilities, and is the workplace for thousands of scientists. The JRC has six sites in five EU countries (Brussels, Geel, Ispra, Karlsruhe, Petten and Seville).

JRC research is clustered into ten science areas: agriculture and food security; economic and monetary union; energy and transport; environment and climate change; health and consumer protection; information society; innovation and growth; nuclear safety and security; safety and security; and standards. Details can be found on https://ec.europa.eu/jrc/en/science-areas. The research is carried out through six knowledge production directorates, working alongside additional support, strategy and knowledge management directorates. See https://ec.europa.eu/jrc/en/about/jrc-in-brief for further information. The work presented in this Atlas was carried out in the Directorate for Sustainable Resources.

The Directorate for Sustainable Resources

The Joint Research Centre in Ispra (the third biggest European Commission site after Brussels and Luxembourg) is the main location of the Directorate for Sustainable Resources. The directorate is a leading exponent of environmental, economic and process modelling, geospatial statistics and information processing, and Earth observation science and applications. It has dedicated laboratory facilities, runs in situ measurement campaigns, and is engaged in education and capacity building on site and with partner institutions throughout the world.

The directorate carries out research on food and nutrition security, agricultural production, consumption and trade, the food chain, land use, land-use change, soil, water (inland and marine), forests, raw materials, fisheries, biodiversity and ecosystem services. The directorate's research highlights the threats to our existing resources and natural capital, and the role of sustainable resources in climate change mitigation and adaptation; explores alternative resource management pathways; supports the development of a sustainable bioeconomy in Europe; and provides insight into the functions of sustainable resources in achieving the Sustainable Development Goals of the UN's 2030 Agenda for Sustainable Development.

The Directorate for Sustainable Resources is located in Ispra, a small town on the shore of Lake Maggiore in northern Italy. The JRC's Ispra site is in the centre foreground, Monte Rosa, the second highest mountain in western Europe (after Mont Blanc), is the high-point on the skyline.
Source: EC-JRC.

Location of the directorates and headquarters of the JRC.
Source: EC-JRC.

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