Contents

Mapping and techniques

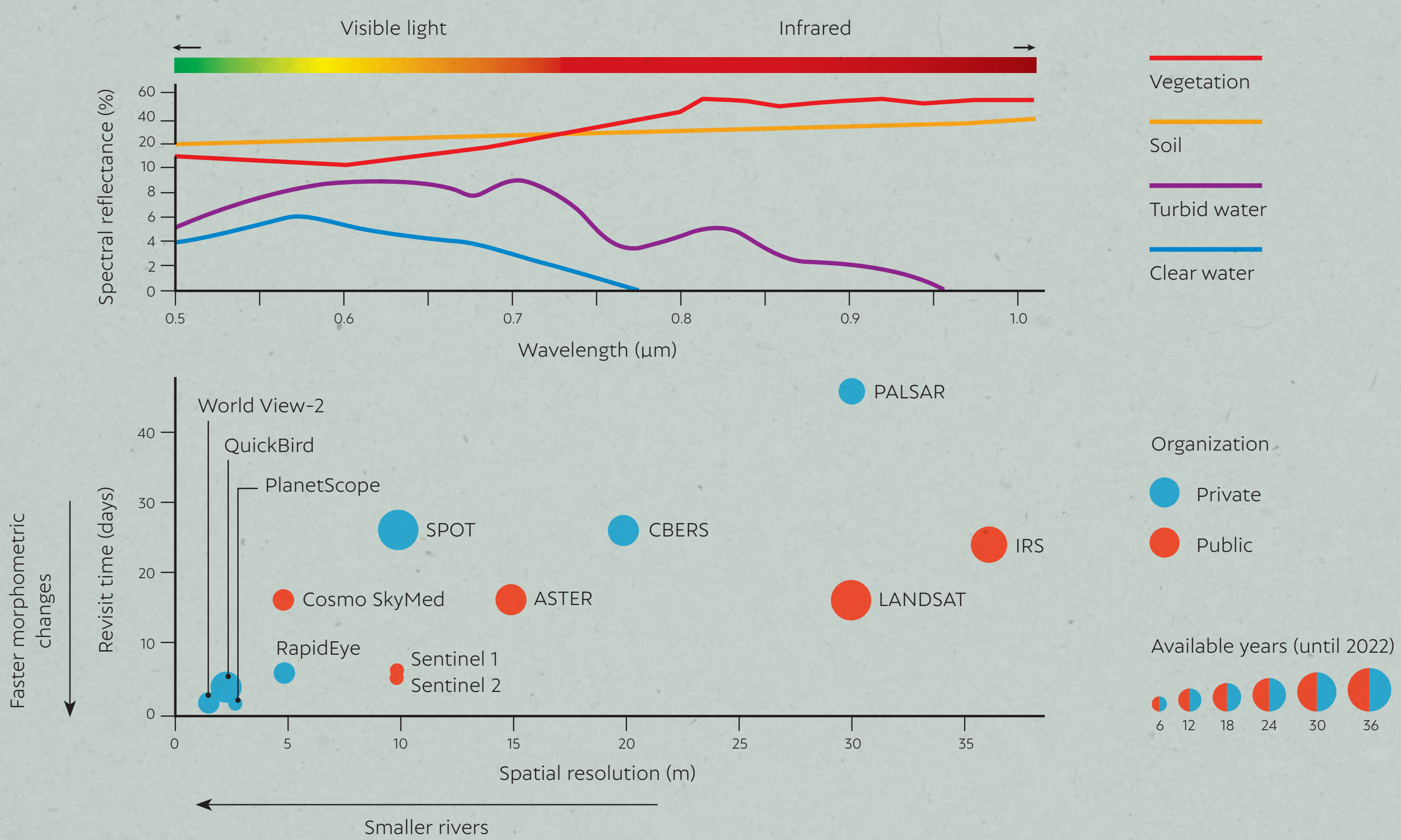
Monitoring the shape of the Earth's surface and its changes over time has been revolutionized over the past 60 years by new technologies: satellite remote sensing from space, application of light detection and ranging (LiDAR) methods, and new uses of aerial images. Combined, these now provide us with unprecedented capabilities to measure the Earth's surface and how it is changing due to natural and anthropogenic stresses.

Principles of remote sensing

Large-scale mapping of the Earth's surface is possible through the application of various remote-sensing techniques using airborne or space-borne sensors. These sensors work by detecting radiation emitted from the Earth's surface, with different sensors focusing on different regions (wavelengths) of the electromagnetic spectrum (EMS). Since the amount of radiation reflected is influenced by both the properties of the surface and the incoming radiation, different sensors can capture different

SENSING EARTH'S WATERBODIES

Different features on the Earth reflect solar radiation in distinctive ways. Earth observation satellites can measure these reflected signals at varying temporal and spatial scales.



information about surface properties. For example, conventional aerial photography, long used in mapmaking, simply utilizes light in the visible spectrum. Especially pertinent to the mapping of rivers, estuaries, and deltas is the fact that water has a highly distinctive spectral signature compared to adjacent land, making it possible to delimit water features. Compared to land, water more readily absorbs incoming solar radiation in the infrared portion of the EMS (wavelengths of 0.75–3.0 μm), but it absorbs less in the visible range (wavelengths of 0.38–0.75 μm). This means that, so long as corrections are made for the fact that water in waterbodies is rarely perfectly clear (due to the presence of suspended sediment, phytoplankton, and chlorophyll-*a*), remote detection of water features is possible using optical sensors that have at least one detecting "band" in the infrared spectrum.

Many remote-sensing techniques are based on passive sensors that rely on receiving solar radiation reflected from the Earth's surface. However, active sensors are also employed. For example, synthetic aperture radars (SARs) emit and then receive microwave radiation backscattered by the Earth's surface. The great advantage of SARs is that they can penetrate cloud cover that would otherwise limit the use of optical sensors.

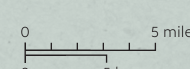
Earth images from early spy satellites

A fascinating glimpse into the shape of the Earth's surface in the 1960s comes from the 1995 release of classified images taken by reconnaissance satellites operated by the United States Central Intelligence Agency (CIA) between 1959 and 1972.

The CORONA project was rapidly advanced after a United States U-2 spy plane was shot down over the Soviet Union on May 1, 1960, and eventually consisted of eight separate satellite missions. On each mission, a space vehicle flew at altitudes of about 185 km (115 miles), capturing images on photographic film using a rotating stereo panoramic camera system. The film was developed on board the vehicle and fed into cassettes in recovery capsules that eventually descended Earthward, where the film was retrieved. Each payload consisted of an astonishing 9,600 m (31,500 ft) of 70 mm film, with the program collecting more than 800,000 images in 12 years. The images have a ground resolution of 8 m (25 ft), increasing to 2 m (6 ft) as technology improved.

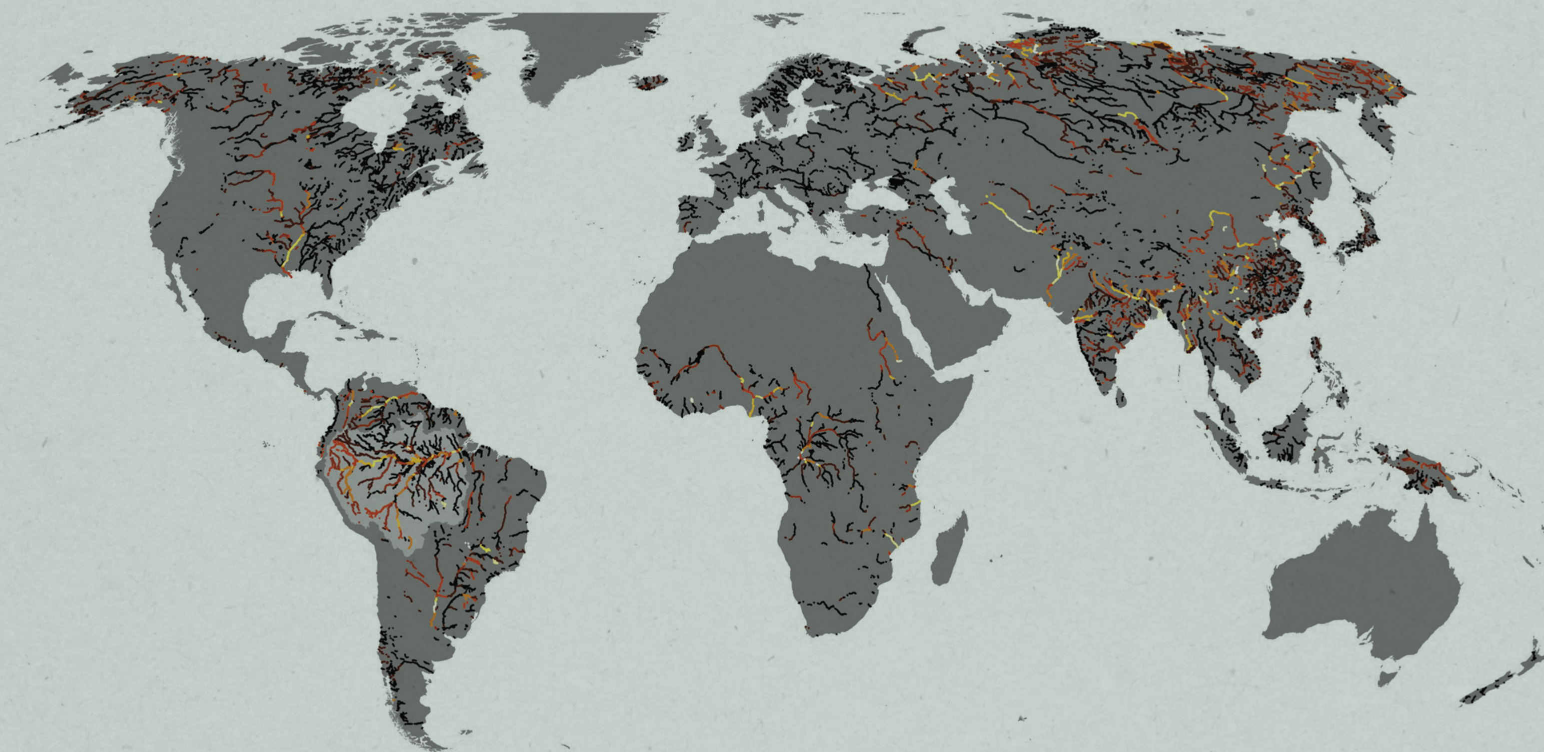
Although designed as spy satellites to record details of Russian and Chinese military operations, the CORONA archive—now declassified and available to all—provides an invaluable record of many parts of the Earth's surface in the 1960s, including its rivers, deltas, and estuaries.

Landscape change in the Nile delta
Images of the downstream terminus of the Damietta branch channel taken in 1968 (upper) by the United States CORONA spy satellite, and in 2022 (lower) by the Planet CubeSat satellite.

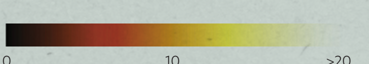


TRACKING RIVER MOTION

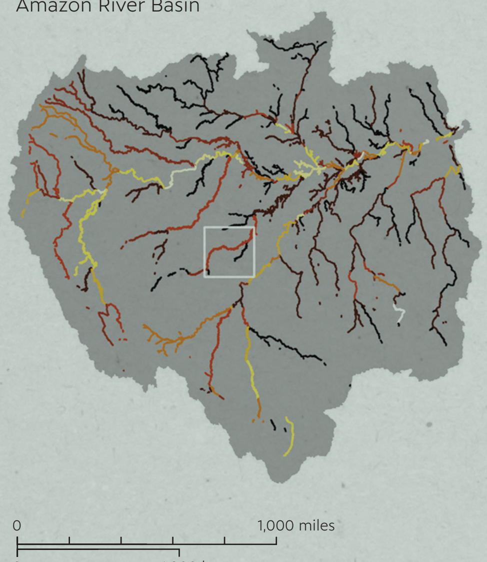
Analysis of 20 years of Landsat imagery allows river migration rates to be estimated along 370,000 km (230,000 miles) of Earth's river network. The median annual rate of channel migration is 1.52 m (5 ft), but most rivers are moving across their floodplains at slower rates. The most rapidly migrating rivers tend to be located in the Amazon Basin and parts of Asia.



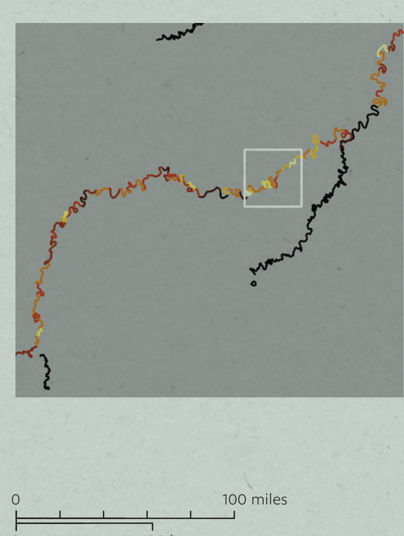
Riverbank erosion (m/yr)



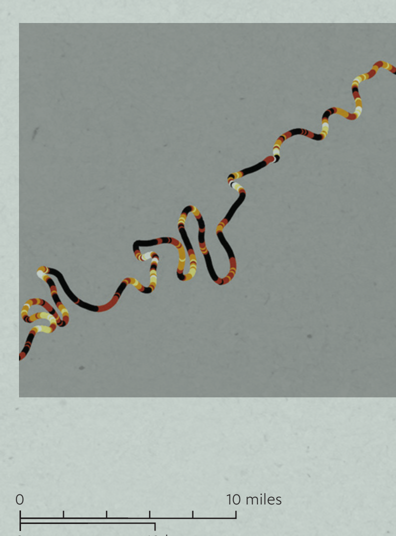
Amazon River Basin



10 km reaches



200 m nodes



Landsat: a game-changing development

The Landsat program, funded by the National Aeronautics and Space Administration (NASA), stands out as the most widely used platform for studies of the Earth's surface. The program started with the launch of Landsat 1 in 1972, followed by Landsat 5 (1984), Landsat 7 (1999), Landsat 8 (2013) and, most recently, Landsat 9 (2021). The high spatial resolution (60 m/200 ft for Landsat 4 in 1982, and 30 m/100 ft subsequently) and quality of the Landsat sensors have allowed the expansion of remote sensing—once mainly restricted to land surface changes—to numerous applications.

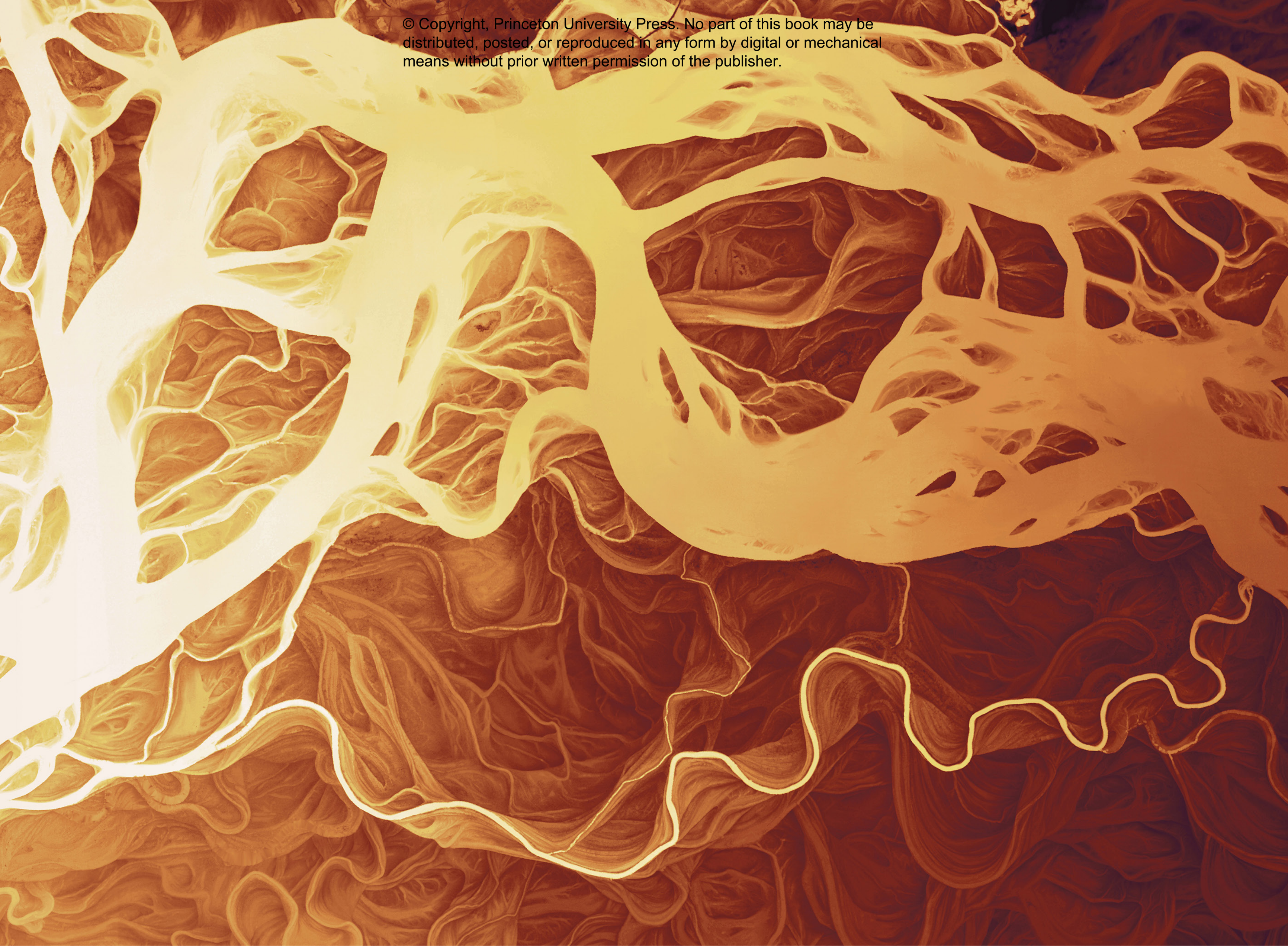
Three key factors have contributed to Landsat's status as a "game-changer." First, since 1984 the Landsat satellites have employed three different bands in the infrared spectrum: near infrared (NIR), 0.85–0.88 μm; shortwave infrared (SWIR) 1, 1.57–1.65 μm; and SWIR 2, 2.11–2.29 μm. This enables a wide variety of water-detection algorithms and indices to be developed and improved. Second, its longevity (30 m/100 ft spatial resolution imagery available continuously and globally since 1984) has made it possible for researchers to investigate how rivers, estuaries, and deltas evolve over longer timescales, even in inaccessible areas of the globe. Finally, as a government-funded programme, Landsat imagery is free for anyone, anywhere, to use, thereby contributing to an important "democratization" of Earth science.

Global digital elevation models

Maps of the elevation of the Earth's terrestrial surface have been central to advancing our knowledge of the world's landscapes. Several near-global datasets are now available, including that produced by the NASA Shuttle Radar Topography Mission (SRTM), which employed a specially modified radar system onboard the Space Shuttle *Endeavour* during an 11-day mission in February 2000. This produced a digital elevation model (DEM) of the majority of the Earth's surface on a 30 m (100 ft) grid, allowing mapping of many remote regions.

Other global DEMs are now also freely available, including the Japan-USA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and European Union Copernicus missions. These datasets, and the various products derived from them, provided an unrivaled quantitative view of the Earth's topography.

Mapping topography
Global elevation datasets, such as that from NASA's Shuttle Radar Topography Mission, have revolutionized mapping of the Earth's surface, revealing the intimate connections between topography, rivers, estuaries, and deltas. Here, topography created by mountains, geological faults, and volcanoes shapes the passage of rivers in South Island, Aotearoa New Zealand to coastal plains and the ocean.



▲ **Rivers revealed**
LiDAR-derived "bare-earth" surface image of the Yukon River and its floodplain, southeast of Fort Yukon, Alaska.

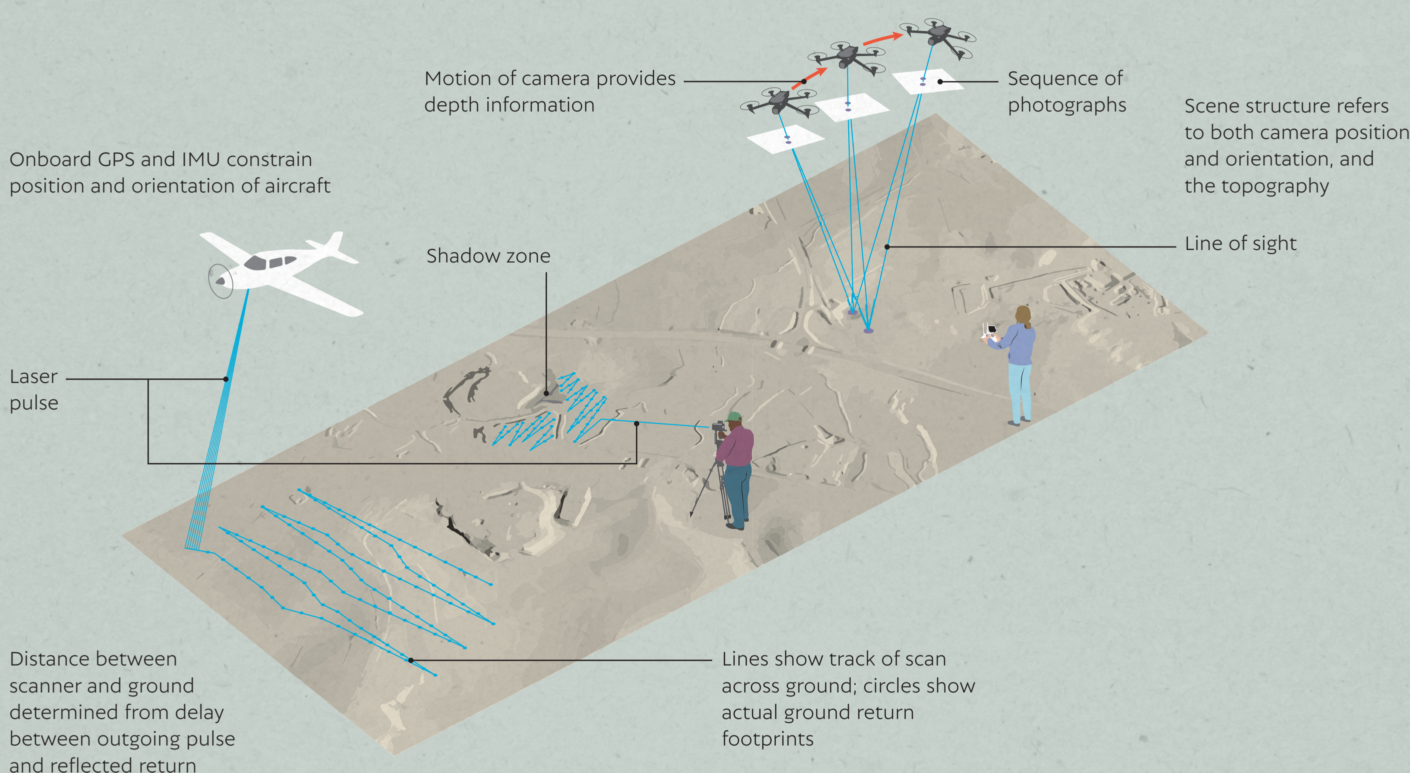
Using lasers to map the Earth's surface

The widespread adoption of light detection and ranging (LiDAR) has provided the means to map large areas of terrain accurately. LiDAR works by timing the interval required for an emitted laser pulse to be reflected back from the target to the sensor, enabling the distance between the sensor and target to be calculated. By mounting a sensor on a conventional aircraft or drone, whose location is itself accurately measured using a Global Positioning System (GPS), and by having a sensor that emits repeated pulses at extremely high frequency (in some instances up to 100 million times per second), a highly detailed (dense) "point cloud" of accurately geolocated points can be obtained. These can cover very large spatial areas, offering the means to measure surface topography in unprecedented detail.

A key feature of some LiDAR instruments is that the wavelengths of the returned laser pulse can be modified according to surface characteristics, enabling features such as vegetation that obscures the true surface of the Earth to be "removed," revealing the "hidden" detail beneath. Similarly, green-waveform LiDARs (which emit laser pulses with wavelengths in the green part of the visible spectrum) can penetrate shallow water that has good transparency, allowing submerged surfaces to be revealed (topobathymetric LiDAR).

MEASURING THE EARTH'S SURFACE

Three methods for producing high-resolution quantification of the Earth's surface: airborne LiDAR, terrestrial (ground-based) LiDAR, and aerial platform (e.g., drone) structure from motion (SfM). Abbreviations: GPS, Global Positioning System (to measure position); IMU, inertial motion unit (to measure precise three-dimensional movement of the sensor).

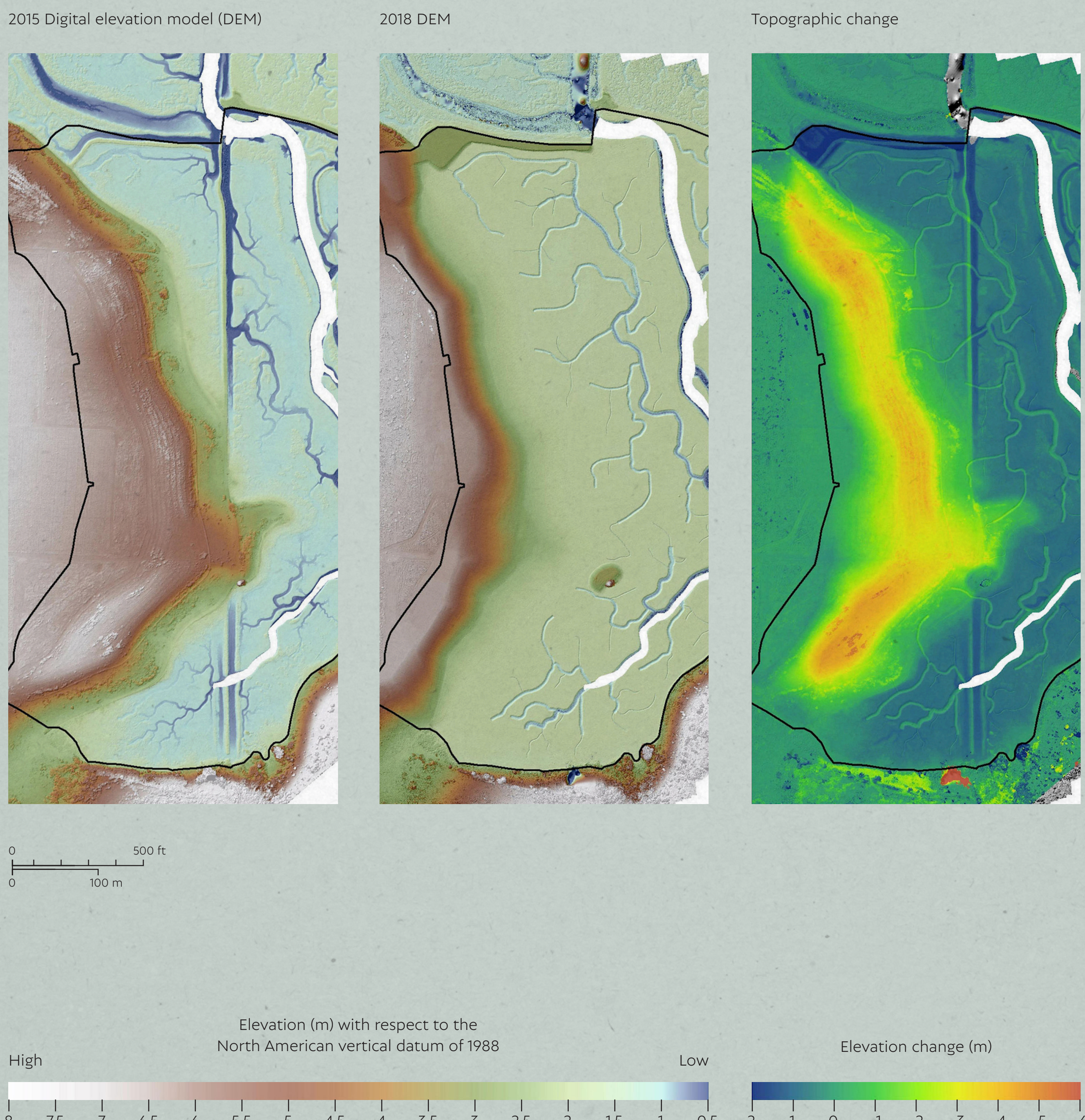


Structure from motion imaging

Stereo photogrammetry, in which overlapping aerial photographs are used to reconstruct three-dimensional models of the terrain based on the shift in apparent position of an object from one image to the other, has long been used to produce detailed terrain maps. Advances in computing power and image-processing algorithms have led to development of the "structure from motion" (SfM) technique, whereby the structure of features is tracked and quantified between multiple overlapping images. Given a known camera position in each image, and/or if the locations of distinct points marked on the ground surface are also known with a high accuracy (so-called ground-control points), features can be matched between images and used to generate a three-dimensional map of the surface. The SfM technique can thus yield a dense cloud of points that depict the height of the surface. Images may be taken from airplanes, but are increasingly being captured using unmanned aerial vehicles (drones). As such, SfM is being rapidly adopted as a low-cost but highly accurate method for measuring the morphology of Earth surface change. Although the SfM point clouds depict the surface imaged, and thus cannot measure the bare-earth surface like LiDAR, the technique is rapid and has been adopted for Earth surface research, forestry, hazard mapping, building inspections, and archeological studies.

IMAGING TOPOGRAPHIC CHANGE

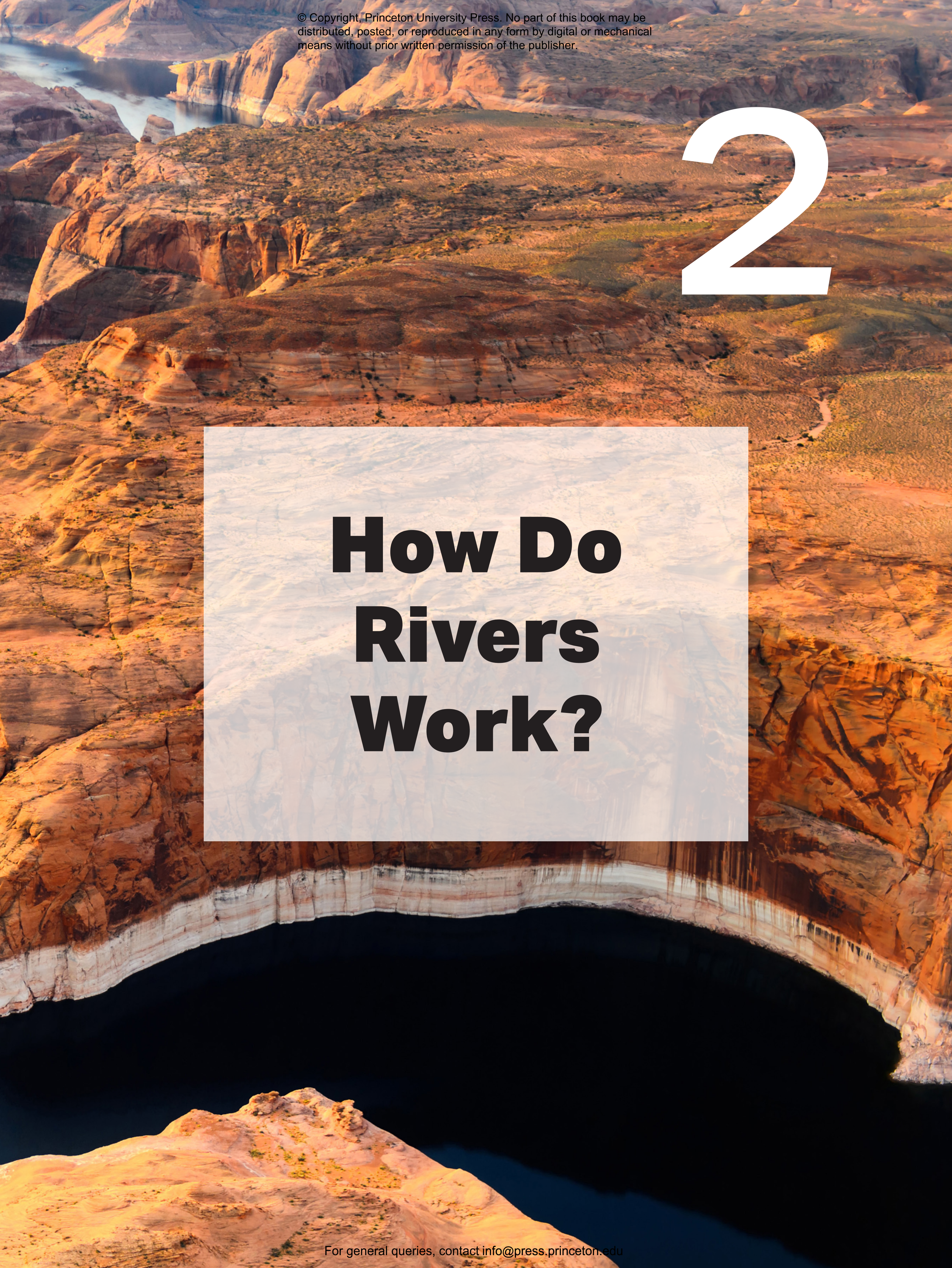
Elevation maps produced from aerial drone imagery and structure from motion (SfM) photogrammetry of the Hester Marsh restoration site, Elkhorn Slough, an estuary in central California. Maps show elevation before and after restoration of the tidal flats, which involved raising the marsh plain and tidal creeks. Quantification of topography can be vital in aiding environmental rehabilitation.



A flock of doves

Technological advances in remote sensing from space have allowed near-daily coverage of most of the Earth's surface using constellations of small CubeSat satellites, termed "doves." These small satellites are the size of a shoebox and less costly than larger satellites. While they have more limited capabilities, they can be deployed in their hundreds, may possess multiple spectral bands, and can yield images with a resolution between 5 m (16 ft) and 0.3 m (1 ft). These flocks of doves provide an unrivaled opportunity to monitor natural events such as floods, hurricanes, and landslides, and human-induced changes such as deforestation and urban expansion. The frequency and high spatial resolution of such images can be of vital use in our response to natural disasters and their management.

▶ **Flood watch**
CubeSat imaging permits the monitoring of flood extent and inundation, as here at low-water (top) and flood (bottom) states on the Sacramento River, California, February 2017.



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How Do Rivers Work?

Why do rivers flow where they do?

Rivers sculpt the Earth's surface through the erosion, transport, and deposition of sediment, creating a rich tapestry of landscapes that support immense ecological diversity and are home to billions of humans. Earth's surface topography, created by tectonics and worn down by erosion, determines the paths that rivers follow.

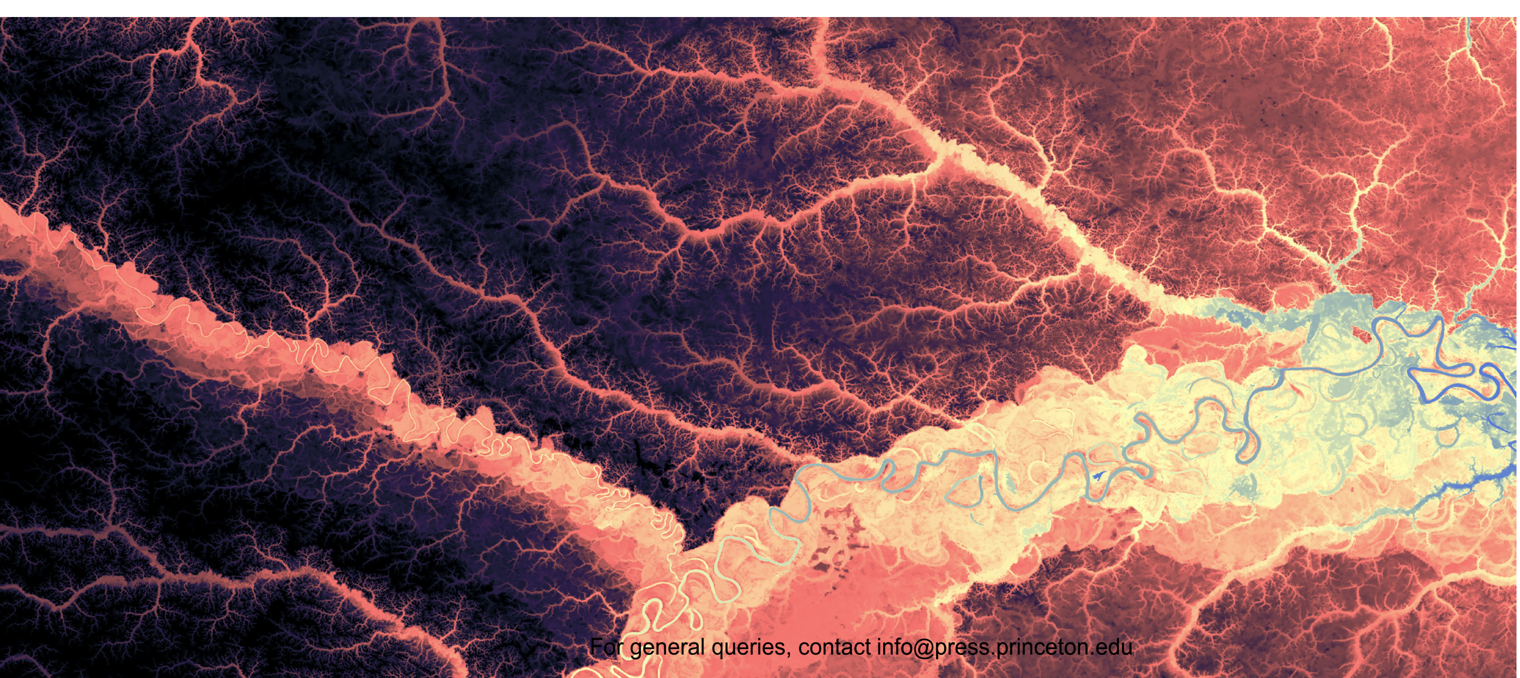
Follow a drop of water in its natural path along a river and you will always be going downhill—water acts under gravity to trace the gradient of the surface over which it is passing, from steep mountainous headwaters to low-gradient rivers that enter the ocean. This simple movement of water, and the sediment it transports, ties rivers to topography. It also provides a feedback mechanism where the longer-term erosion of the landscape takes place through the action of flowing water. Rivers thus respond to topography, seeking the steepest route, being steered around higher ground, and depositing sediment where flows decelerate.

Dendritic drainage networks

As rivers develop on a fresh surface, their channels etch a pattern, or drainage network, into the landscape that routes water from the land. Upstream channel growth takes place by erosion at the tips of the river network—a process known as headcut erosion. On a relatively uniform sloping surface, or over very long periods of time, this produces a tree-like, or dendritic, drainage network, with the branches of the river tree feeding water and sediment, via channel confluences, into ever-larger channels that eventually form the main trunk channel downstream. Dendritic drainage networks can be found on all scales, from small rivers to some of the world's largest drainage basins.

River networks thus unite channels of different size and provide ecosystem connections—for instance, as paths for the upstream migration of salmon from the ocean to small headwater streams, where they spawn and where individuals of some species then die. Their decomposing carcasses subsequently contribute food for the entire ecosystem. However, human interventions such as damming are making this natural journey far more challenging.

▼ **Intricate networks** *Dendritic networks feed water and sediment into meandering rivers and their floodplains, Amazon River Basin, Brazil. The image shows the elevation from high (black/purple) to low (yellow/blue) and is plotted from the global FABDEM terrain data.*



RIVER PATTERNS

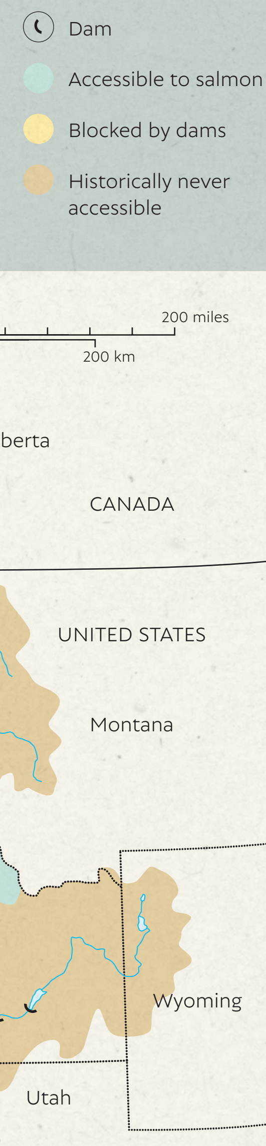
The map shows river basins of North America in different colours. The dendritic network of the mighty Mississippi River drains 41 percent of the contiguous United States. The Colorado and Columbia Rivers each drain around 8 percent of the same area with the Rio Grande collecting water from *c.* 6 percent of this land area.

Dam removal

Restoration of the Elwha River in Washington State is the largest dam-removal project in US history. It saw the removal of Glines Canyon Dam between September 2011 and August 2014. The Glines was the upper of two dams in the project; the downstream Elwha Dam was dismantled by March 2012.

HUMAN-MADE BARRIERS

Dams, such as here on the Columbia River in the United States, can fragment river networks, interrupting the migration of species such as salmon.



Upstream migration

After a long journey upstream through a river network, a female Sockeye Salmon (Oncorhynchus nerka) uses her tail to excavate a pit, or redd, in an Alaskan riverbed to lay her eggs.

River networks and controls

The development of river networks is controlled by surface topography, climate, and the level of the waterbody into which they flow. Over tens of millions of years, the uplift of mountains and movement of continents provides the template on which rivers develop.

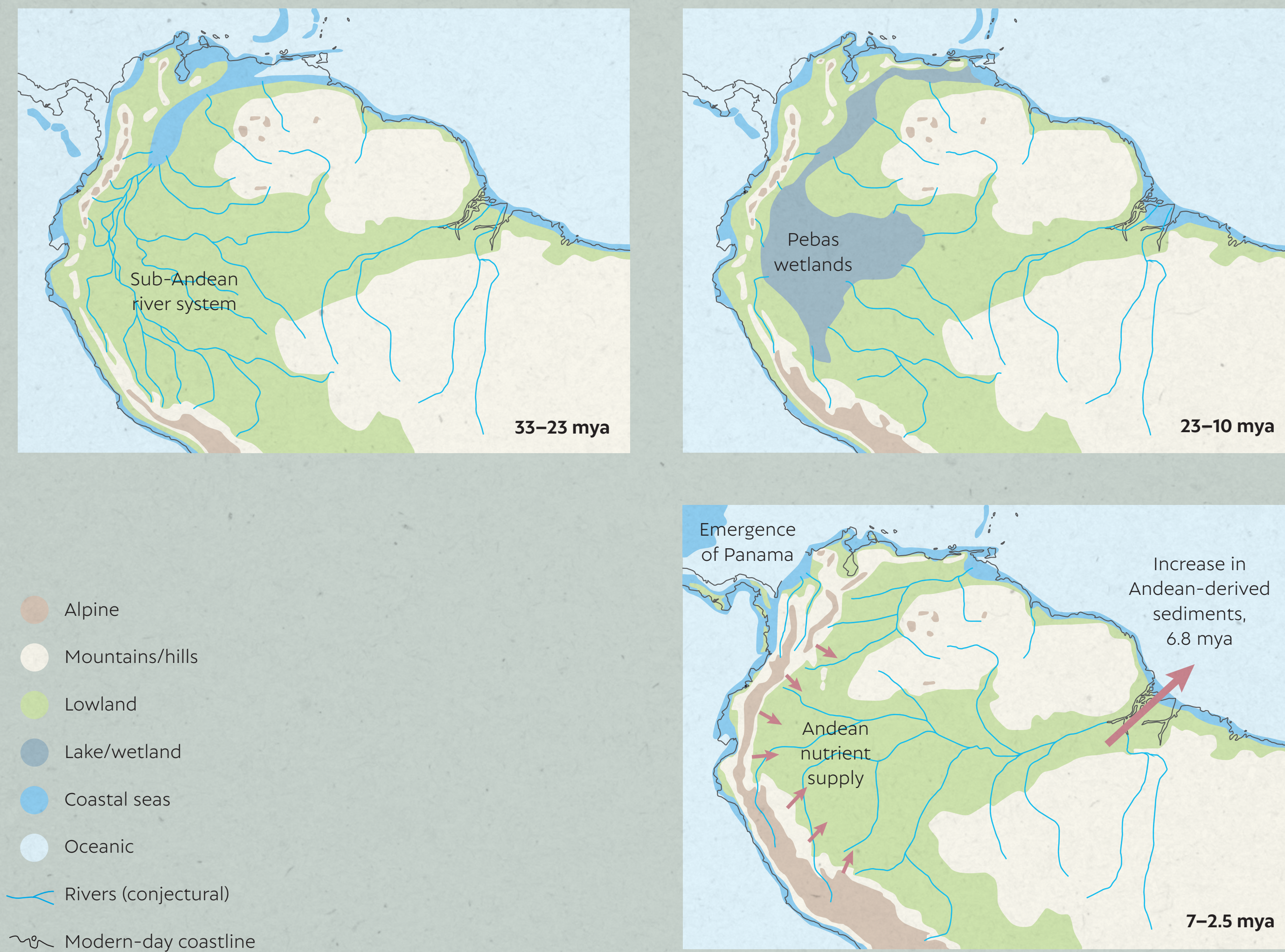
The rivers of the world act over long periods of time to erode and sculpt the landscapes over which they flow as water travels downhill in its journey from the uplands to the ocean (although some rivers terminate in inland deserts and swamps, never reaching the sea). Because rivers act as conduits for the flow of water, sediment, carbon, nutrients, and contaminants over long periods, they are also indicators of some of the long-term controls that shape our continental landscapes.

Three of the largest-scale controls are those of plate tectonics, climate, and relative sea level, which may change radically over periods ranging from thousands to hundreds of millions of years. Deciphering the pattern of river drainage networks on the Earth's surface thus helps us interpret the changes in these broadscale controls in geological deep time. In addition, the tectonic makeup and climatic character of the Earth's surface changes greatly across the globe, and the world's rivers reflect these changing attributes in their course and the pattern of their drainage networks.

Stepping down strata
A river responding to geology and topography in this false-color Landsat image: the Ugab River, Namibia. The river steps its way along, and across, topography created by folded rock strata. This topography forces rivers to run parallel to the ridges in some places, until they incise and cut across the strata, forming steps in the river planform. The river paths also take advantage of geological faults that can be seen as straight lines running northwest to southeast in some parts of the image.

REVERSAL OF THE AMAZON

Uplift of the Andes Mountains since *c.* 50 million years ago has caused the mighty Amazon River to reverse its course. It once flowed to the northwest and north, but uplift of the Andes resulted in a gradual change in surface topography, first forming the extensive Pebas wetlands and eventually causing the Amazon River to flow eastward into the Atlantic Ocean.



Tectonic controls

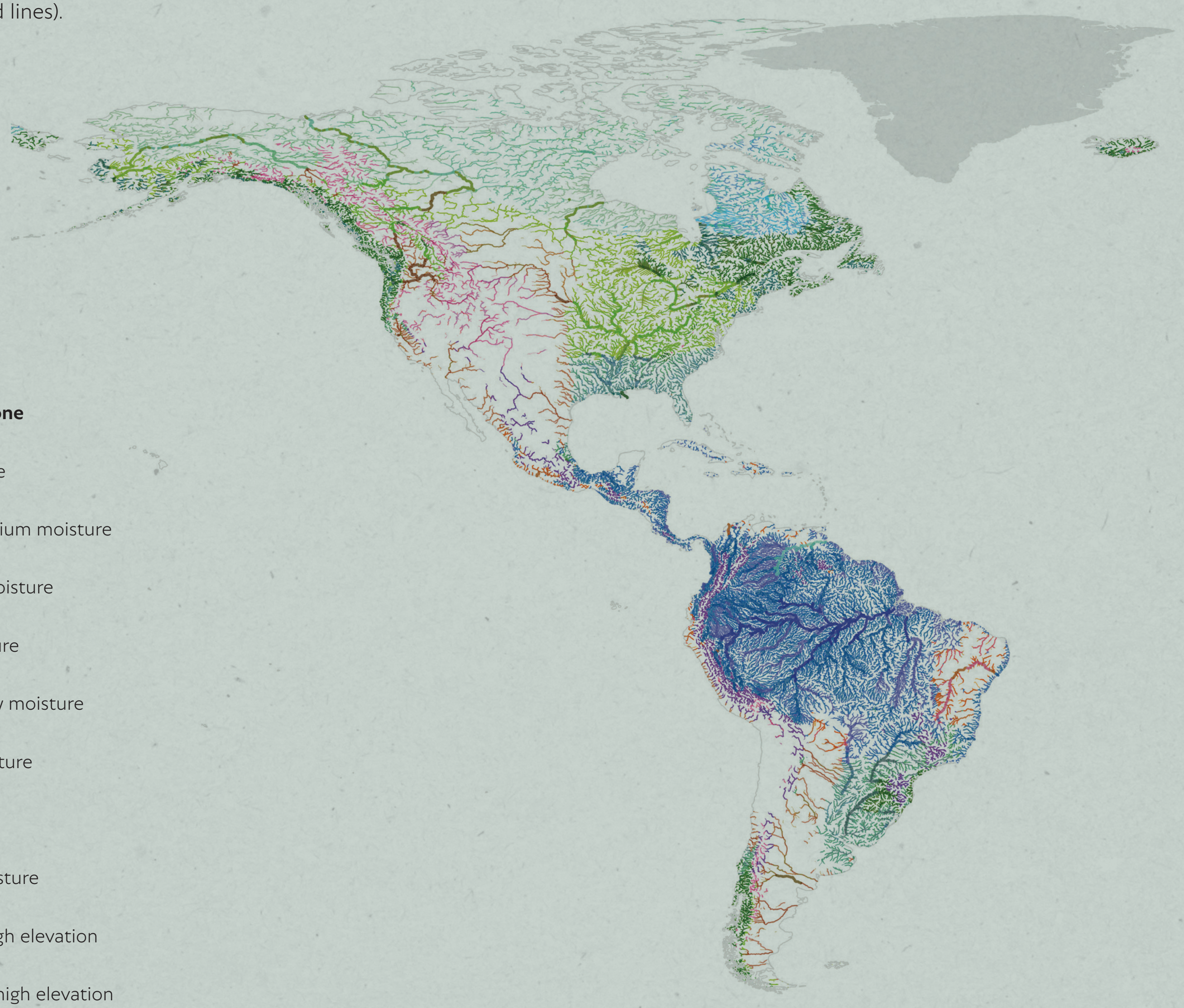
Because water follows the gradient of the land surface, the routes and patterns of riverine drainage networks reflect large-scale plate tectonics and evolution of the Earth's crust. Water is diverted by topography, such as that created by tectonic folds and faults, or incises into bedrock that is rising over millions of years due to tectonic uplift. Tectonics provide the fabric of the canvas on which the world's rivers are painted, and act as a principal control on how their drainage networks are organized. Some river networks develop rectangular or "trellis" planform patterns, whereas those draining from domed topography—for example, around volcanoes—generate river channels that run radially from the highest point. Drainage networks thus provide a sensitive record of crustal deformation, and as plate tectonics alter surface gradients through geological time, so the surface routing of rivers responds accordingly.

Climate controls

The weathering of rocks and transport of sediment are strongly influenced by climate, which helps determine the type of weathering as well as the volume of water supplied to river networks. Climate thus exerts a first-order control on the dynamics of rivers. Climate changes both spatially across the globe and temporally through geological time as the Earth has warmed and cooled.

RIVER CLASSIFICATION

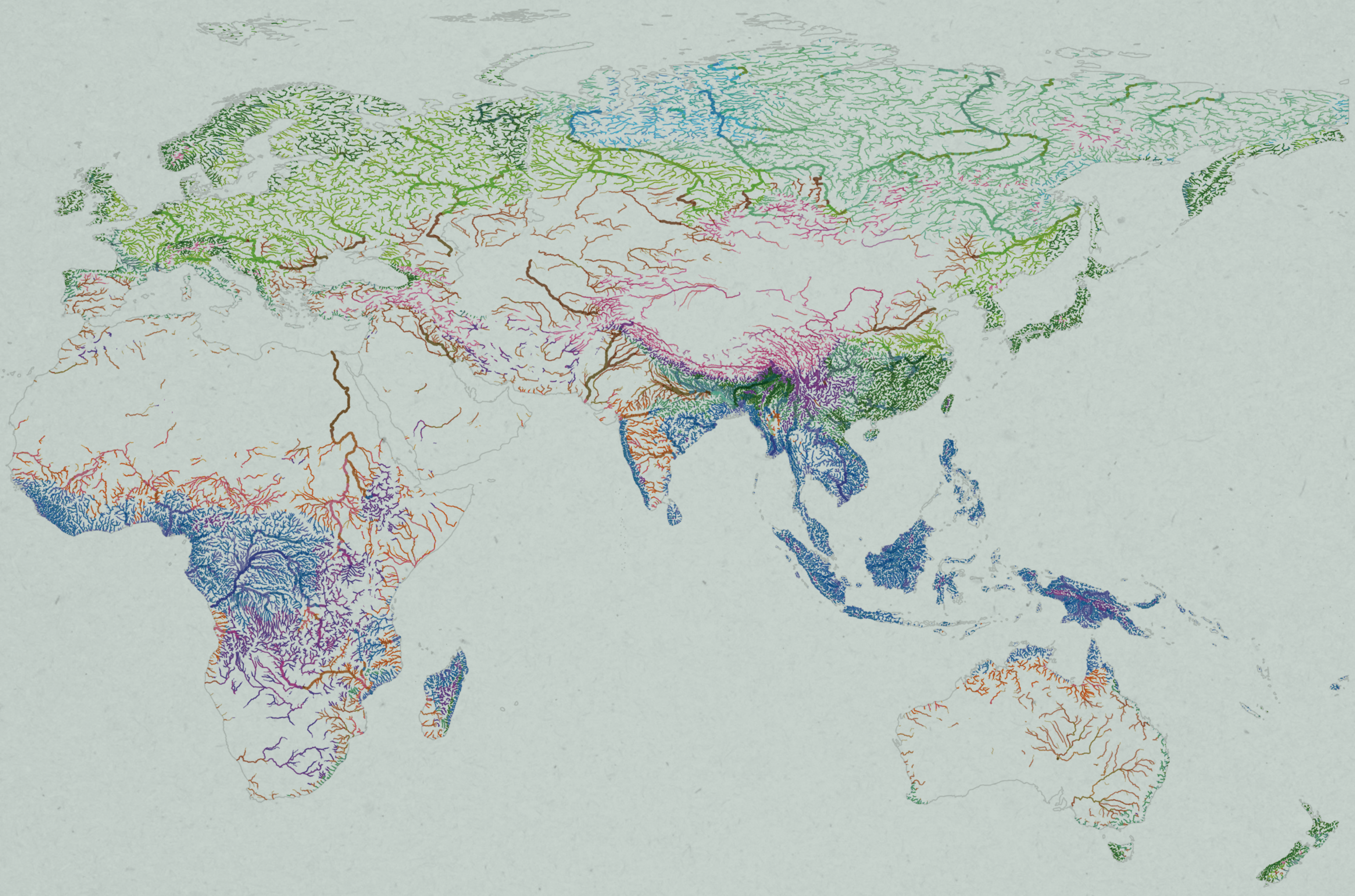
Classification of the world's rivers based on characteristics of their water flow (hydrology, shown by line thickness) and their physical and climatic controls (indicated by different-colored lines).



Physio-climatic zone

- Cold, high moisture
- Cold, low and medium moisture
- Warm, medium moisture
- Warm, high moisture
- Warm and hot, low moisture
- Very hot, low moisture
- Hot, high moisture
- Very hot, high moisture
- Cold and warm, high elevation
- Hot and very hot, high elevation

Climate has also changed as the Earth's crust has evolved through time. For example, uplift of the Himalayas, which began around 50–60 million years ago and is caused by the northward drift of the Indian tectonic plate and its collision with the Eurasian plate, has resulted in dramatic shifts in the Earth's climate, changing global circulation in the last 10 million years and leading to the onset of the Indian summer monsoons. The Himalayas are still rising today—by about 1 cm (⅔ in) per year or 10 km (6 miles) in the last million years—signifying the intense weathering and erosion that is feeding sediment to the great rivers flowing from the high mountains. Himalayan uplift and associated climate change has thus shaped both the paths of the many rivers in this region and the climate. In turn, the rivers have fed immense quantities of sediment to the oceans, forming some of the world's greatest estuaries and deltas.

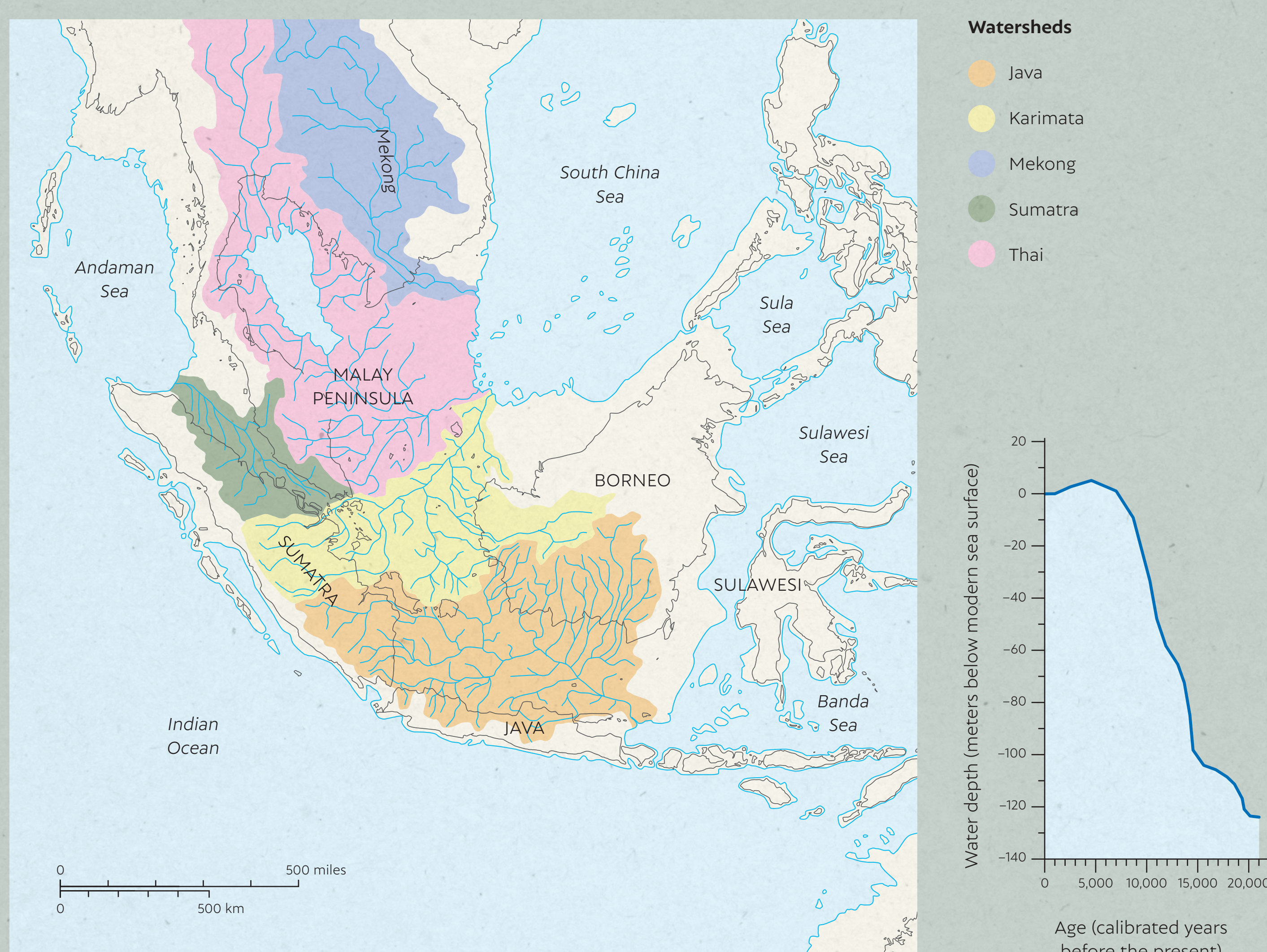


Sea-level controls

Rivers flow to lower elevations, many eventually forming estuaries and deltas as they enter the ocean. As a consequence, sea level acts as the key control on the distal end of a river system—the baselevel to which the end of the river must adjust. However, baselevel changes as sea level rises or falls—for example, absolute changes in sea level caused by melting of the ice caps or relative changes due to more local processes such as regional tectonics or land subsidence. Land subsidence in many of the world's present-day deltas (for example, caused by groundwater extraction) is exacerbating the effect of sea-level rise due to a warming climate.

OUT OF SUNDALAND

Schematic representation of the rivers of Sundaland, a vast area south of the present-day China Sea, at minimum sea level at the height of the last glacial maximum some 18,000 years ago. Rivers extended further across the continental shelf, and likely provided a home for early humans who transited across this landmass. The inset shows sea level over the last 21,000 years.



Today, we live in a world with a sea level that is relatively high in relation to the last few million years of Earth's history—as shown by the existence of many estuaries along our contemporary coastlines that represent river valleys drowned by high sea levels. Yet, at the height of the last glacial maximum around 18,000 years ago, when much water was locked up in extensive continental ice sheets, the global sea level was, on average, some 120 m (400 ft) below where it is today. As such, the distal ends of some rivers extended many tens or hundreds of kilometers further across the continental shelves and have subsequently been drowned, and buried with sediment, as sea levels have risen. Such expanded land areas at low sea level also provided routes for human dispersal and migration across the globe. Scientists speculate that one such landmass, Sundaland (between present-day Thailand, Borneo, Java, and Sumatra), once formed a region that fostered the spread of humans across the globe and was perhaps the cradle of civilization.

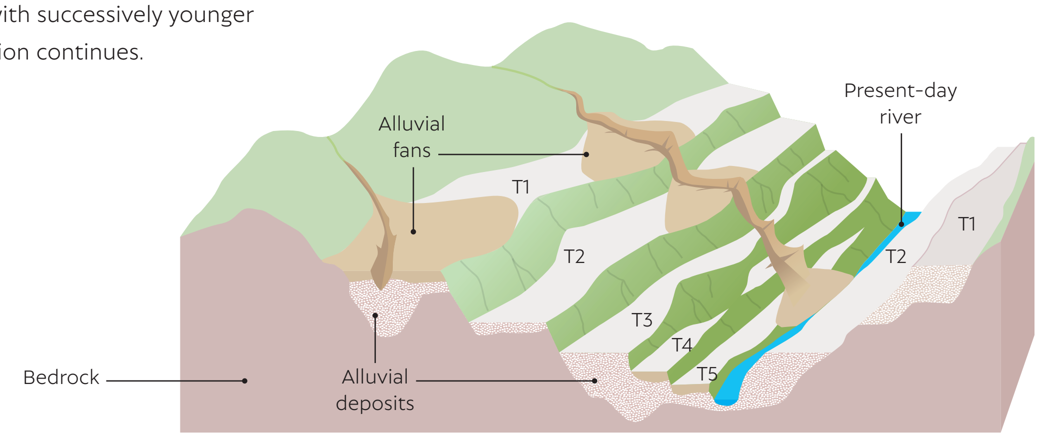
Multiple controls: river terraces

As one might expect, rivers are often shaped by a combination of controls that act over different scales in both space and time. One example is found in the common presence of river terraces within alluvial valleys. These are flat-topped benches that represent the surfaces of river floodplains that have become abandoned due to vertical incision (or aggradation) by the river. Multiple terraces are separated by steeper steps, with the oldest terraces usually at a higher elevation and more fragmented due to longer periods of incision and erosion.

River terraces may be formed by erosion into existing sediments (alluvial terraces) or bedrock (strath terraces). Incision is driven either by external factors—such as tectonic uplift, falls in baselevel, or changes in climate, which may enable the river to erode more—or due to the inherent lateral migration of river channels across their floodplains. Some terraces can be formed by sediment deposition as the bed of the river valley aggrades through time, perhaps burying older terrace fragments. These flat-topped benches may extend for long distances along a river valley, and they may occur in pairs on either side of the valley but with the top of each pair being at the same elevation. The number and elevation of terraces can thus inform us about the longer-term evolution of the river and help reveal the controls on how the alluvial valley has been sculpted through time.

TERRACE FORMATION

River terraces formed by incision of a channel into older alluvial sediments or bedrock, with successively younger terraces (T1–T5) forming as incision continues.



Weathering and erosion

For sediment to be supplied to a river, the source rocks in its upstream catchment must be weathered to yield sediment particles of many different sizes that can be transported downstream. Rock weathering occurs through a range of physical, chemical, and biological processes, all of which are strongly modulated by climate.

▼ **The power of ice**
Freeze-thaw weathering can split boulders apart, eventually yielding smaller fragments of rock to the river system.

Types of weathering

Physical weathering can involve the thermal expansion and contraction of rock surfaces (insolation), caused by daytime solar heating and nighttime cooling, producing stresses that fragment the surface. If water is present in fractures and cracks, its freezing and thawing can also split rock surfaces apart.

The presence of water in rock fissures can also create chemical change, such as the breakdown of rock by acidic water (hydrolysis) to produce clays and soluble salts, the dissolution of soluble materials such as calcium carbonate, and the oxidation of iron-rich minerals. Chemical weathering becomes more important in warmer, wetter climates, where chemical reactions can take place more easily and rapidly, and where unstable minerals such as feldspars (a very common aluminosilicate mineral) can be weathered to yield smaller grains and alteration products such as clays.

Rock weathering is also significantly influenced by biological activity. This includes the action of plant roots and, especially, that of algae and fungi, which produce organic acids that aid rock disintegration.

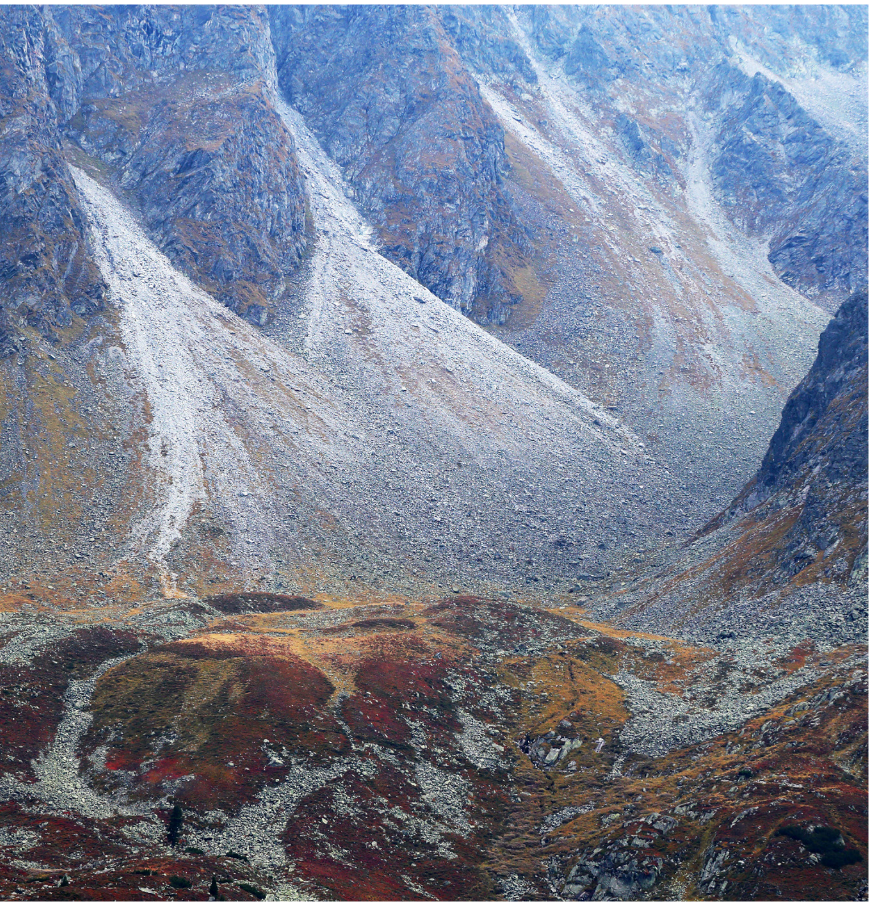
Weathering gives rise to the formation of soils, which constitute an important weathering rind on the Earth's surface that supports life. In tropical environments, weathering to a depth of up to around 30 m (100 ft) produces brick-red lateritic soils that are rich in iron and aluminum and have formed the building blocks of many architectural wonders.

Erosion

Over time, weathering thus rots unstable minerals, generating rock fragments and mineral grains for transport by water, yielding a range of elements to groundwater, producing alteration products such as clays, and progressively leaving behind the more stable minerals such as quartz (silicon dioxide) and hard, heavy minerals. Upland, mountainous terrains feed sediment into river channels by a mixture of processes, such as direct rockfalls, the slower downslope creep of material, and transport by flows of debris, mud, or water. Fan-shaped accumulations of sediment, known as alluvial fans, are deposited at breaks in slope between uplands and a lower-gradient valley floor. These can provide abundant sources of loose, unconsolidated sediment that are then eroded by the river and transported downstream. Thus begins the long journey of sediment from its erosive source to its eventual depositional 'sink', whether that be within an alluvial valley, estuary, delta, beach, or deep-sea environment.

◣ **Fanning out**
The weathering of mountains feeds sediment to alluvial fans and then into river networks.

▼ **Royal building material**
The ultimate product of tropical weathering—red iron-rich soils, called laterites—can be used as building stones, such as in the Pre Rup temple, Angkor Wat, Cambodia, which was dedicated to the Khmer King Rajendravarman in 961 or 962 CE.



Sediment transport

Water flowing over a bed of sediment exerts forces that drive different types of grain movement. Measuring such sediment transport is fundamental to understanding how rivers shift this material and estimating the changing quantities of sediment supplied to the world's estuaries and deltas.

▶ **Mobile sediment**
The mobile bed of the River Markarfljot, Iceland, is sculpted into barforms that are indicative of active sediment transport.

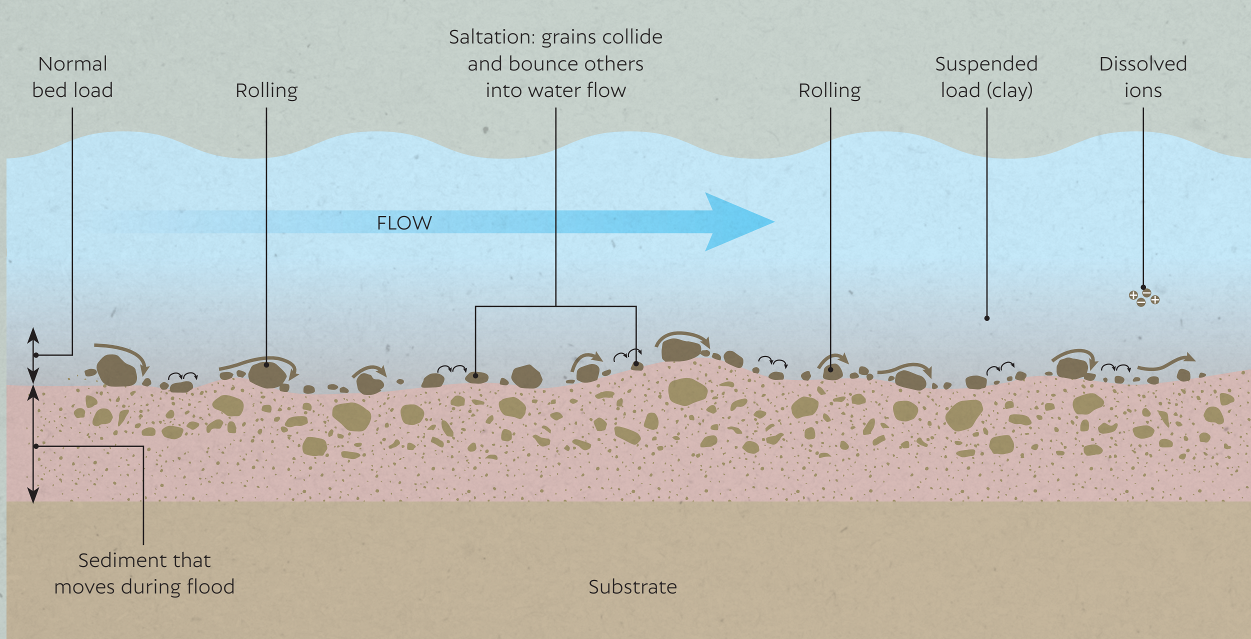
Types of sediment transport

The solid sediment particles moved along the course of a river are transported in two distinctive modes. The bedload is the portion of sediment that is transported by intermittent rolling, sliding, or "hopping" (termed saltation) of grains along or near the riverbed, typically at average speeds much less than that of the flowing water. In contrast, the suspended load comprises particles that are held aloft by turbulent eddies in the main body of the water, which move at roughly the speed of the flow and are carried along without significant contact with the riverbed.

With an abundant availability of sediment, the overall rate of sediment transport increases rapidly as flow velocity increases. The proportional split between bedload and suspended load fractions is controlled by a balance between the size of the sediment particles being transported and the rate at which sediment is mixed upward into the flow by turbulence. This means that larger particles tend to move more as bedload.

ROLLING STONES

The different modes of sediment transport in rivers.



Traditional techniques to measure sediment transport

Most sediment is therefore transported during floods, which means that measuring sediment transport can be very challenging and even dangerous. Traditional "intrusive" measurement methods typically rely on deploying sampling devices of varying designs into the flow to capture the mass, or concentration (per unit volume of water), of moving sediment; this sometimes requires major infrastructure to trap moving sediments. However, unless such sediment samplers are very carefully designed and deployed, they can alter the flow, or become rapidly infilled or fouled, meaning that they may not always provide a representative picture of the actual rate of sediment transport. Moreover, such techniques may be difficult, or impossible, to use in large or remote rivers.

New techniques for measuring sediment transport

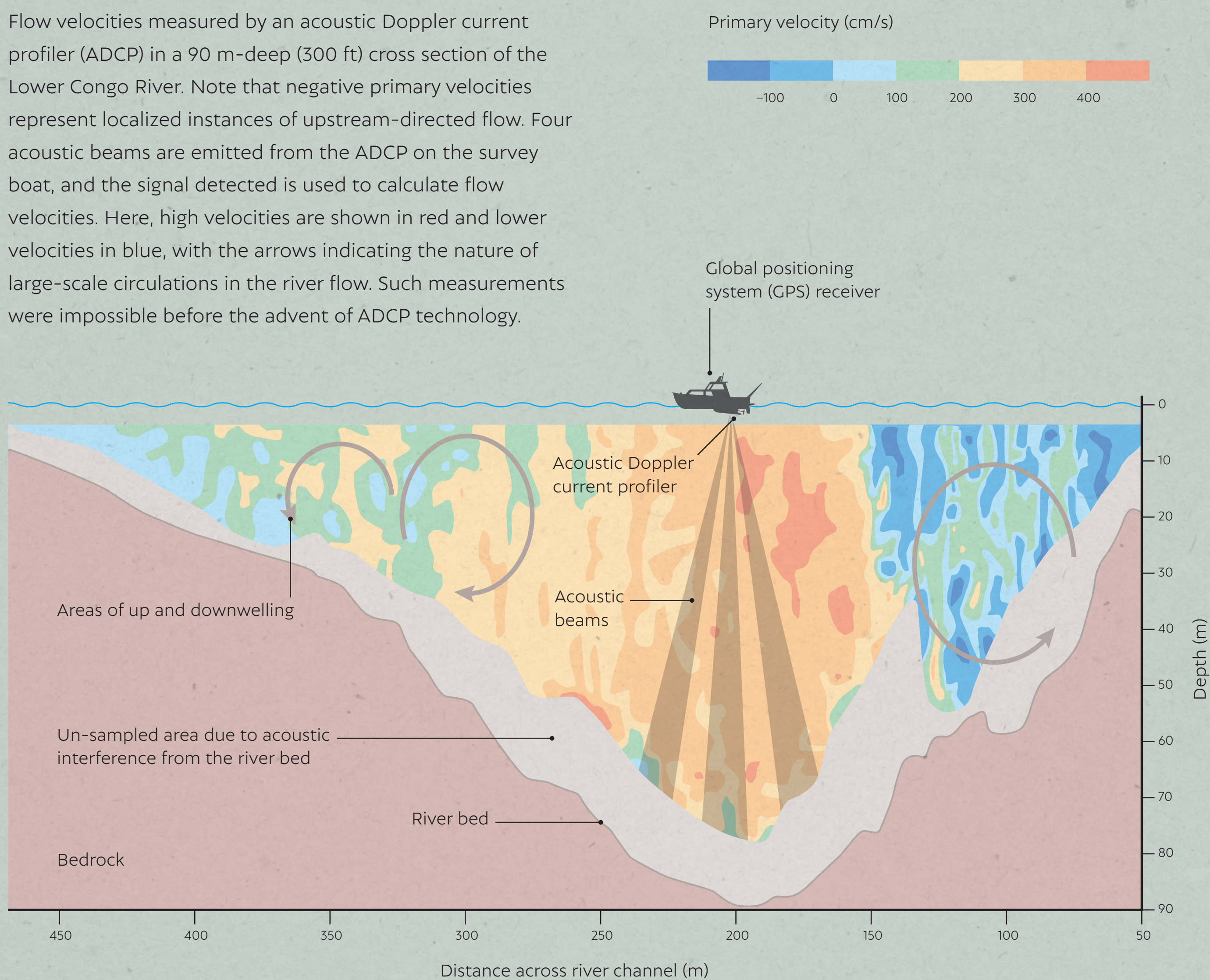
To overcome these limitations, modern measurement of sediment transport uses passive, non-intrusive techniques that rely on the principles of hydroacoustics. For example, hydrophones (underwater microphones) can monitor the noise made as grains collide and then calibrate this as a proxy measure of the intensity of bedload transport. Alternatively, sonar mapping can be used to create detailed maps of the riverbed through time, allowing the migration of sandbars to be tracked. This information can then be used to determine the rate of bulk bedload sediment motion.

The development of acoustic Doppler current profilers (ADCPs) has revolutionized the measurement of flow velocities and suspended sediment concentrations in the world's rivers, lakes, estuaries, deltas, and oceans. These instruments transmit acoustic energy into the water column from an array of transducers, with the energy backscattered to the instrument from different depths being proportional to the concentration of suspended sediment in the water column (accounting for the loss in energy due to the spread of the acoustic beams). The frequency of the backscattered sound changes due to interaction

▶ **Traditional measurement**
Measuring suspended load in the shallow North Fork Toutle River, Mount St. Helens, Washington State, using sampling bottles.

USING SOUND TO MEASURE FLOW VELOCITY

Flow velocities measured by an acoustic Doppler current profiler (ADCP) in a 90 m-deep (300 ft) cross section of the Lower Congo River. Note that negative primary velocities represent localized instances of upstream-directed flow. Four acoustic beams are emitted from the ADCP on the survey boat, and the signal detected is used to calculate flow velocities. Here, high velocities are shown in red and lower velocities in blue, with the arrows indicating the nature of large-scale circulations in the river flow. Such measurements were impossible before the advent of ADCP technology.



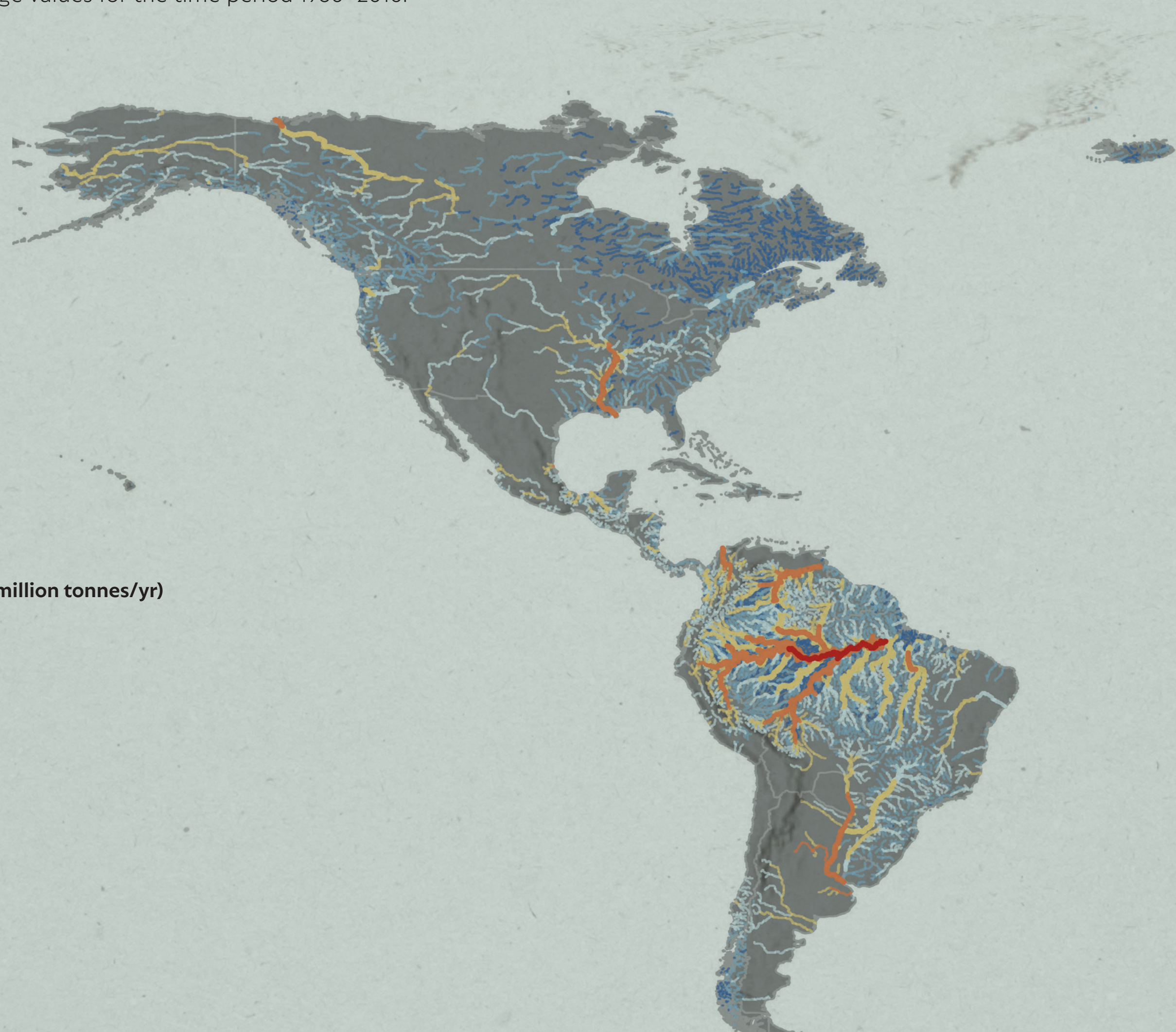
with particles in the water—the so-called Doppler shift, a phenomenon we also notice when the sound of a train changes as it approaches and then recedes from us. This frequency shift is proportional to the velocity of these particles, which are assumed to be moving at the same as the velocity of the water. In this way, ADCPs measure water velocity throughout most of the water depth. Such hydroacoustic monitoring allows measurement of both the speed of the water and the concentration of suspended sediment. We can then multiply these two measurements to calculate the flux of material being carried in suspension. Both sonars and ADCPs can be deployed from moving boats or on the riverbed, and can be used in shallow channels decimeters deep up to the world's biggest river channels. They can also be used during floods when other methods cannot be employed. Perhaps more than any other instrument, ADCPs have lifted the veil on the many secrets of water flow and sediment transport in global rivers.

Colliding rivers

Near Manaus, Brazil, the dark (blackwater) Rio Negro joins the pale sandy-colored (whitewater) Amazon River (referred to as the Solimões River in Brazil upriver of this confluence).

SPATIAL VARIABILITY

The difference in suspended sediment load in the world's large river systems (drainage areas >40,000 km^2 or 15,400 square miles, and water discharge >30 m^3/s or 1,060 ft^3/s). Data represent average values for the time period 1960–2010.

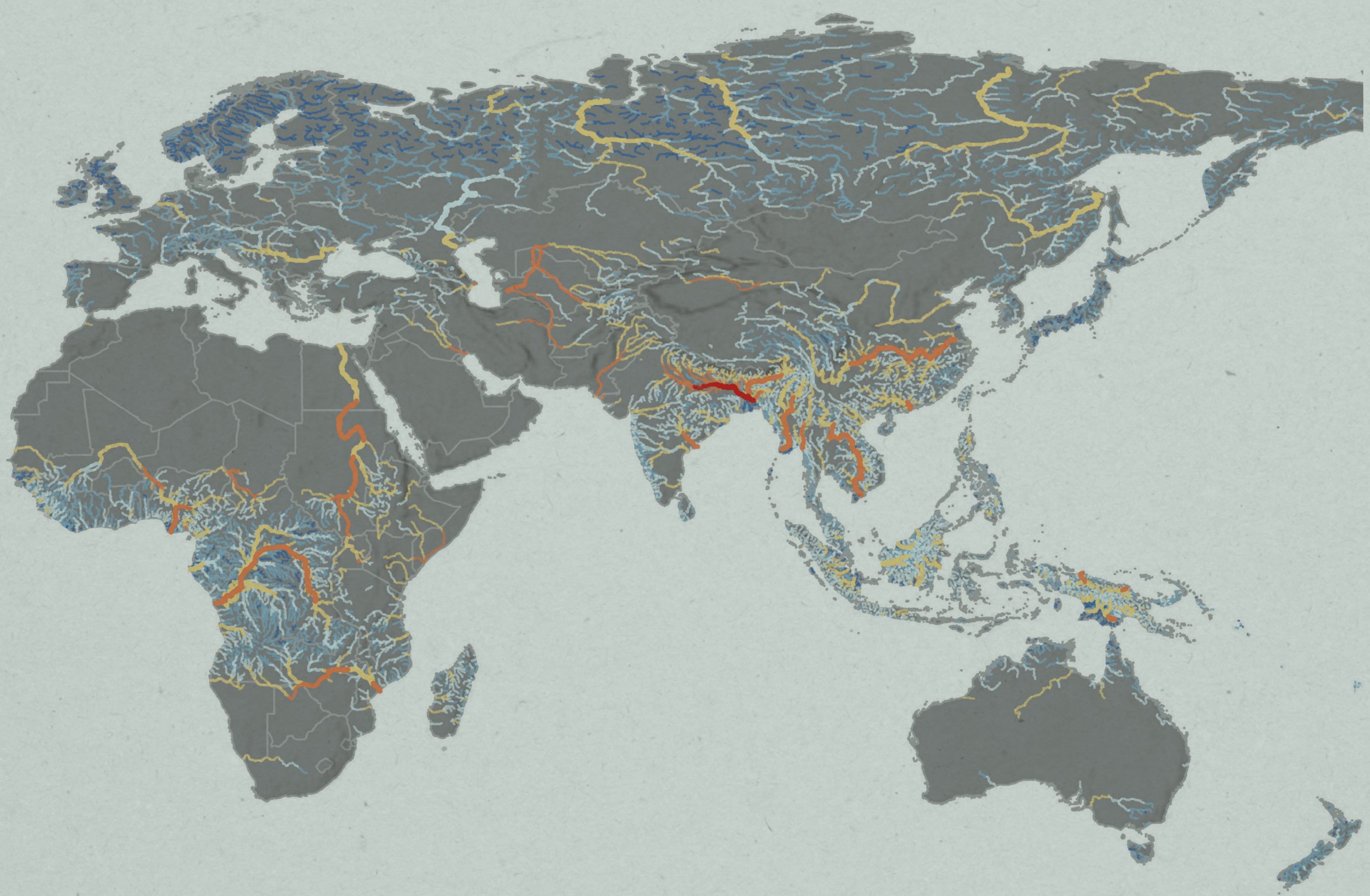


Suspended sediment (million tonnes/yr)

- 0–0.1
- 0.2–1
- 1.1–10
- 10.1–100
- 100.1–1,000
- >1,000

The challenges of measurement

Whether intrusive or non-intrusive methods are used, measuring sediment transport is both time-consuming and expensive, and on average globally there is just one suspended sediment monitoring station per 10,000 km (6,200 miles) of river length. Thus, while it is estimated that about 19 billion tonnes (21 billion tons) of sediment are discharged from the world's rivers into the oceans each year, the sparse coverage of the global sediment transport monitoring network means that this estimate is very uncertain—by around ±50 percent. Moreover, there is a very large spatial variability in the rates of suspended sediment transport through the world's rivers, with the highest values located in zones of intense rainfall that coincide with steep, tectonically active mountain regions with erodible rocks, such as in the rivers that drain the Andes, the Himalayas, and Southeast Asia.



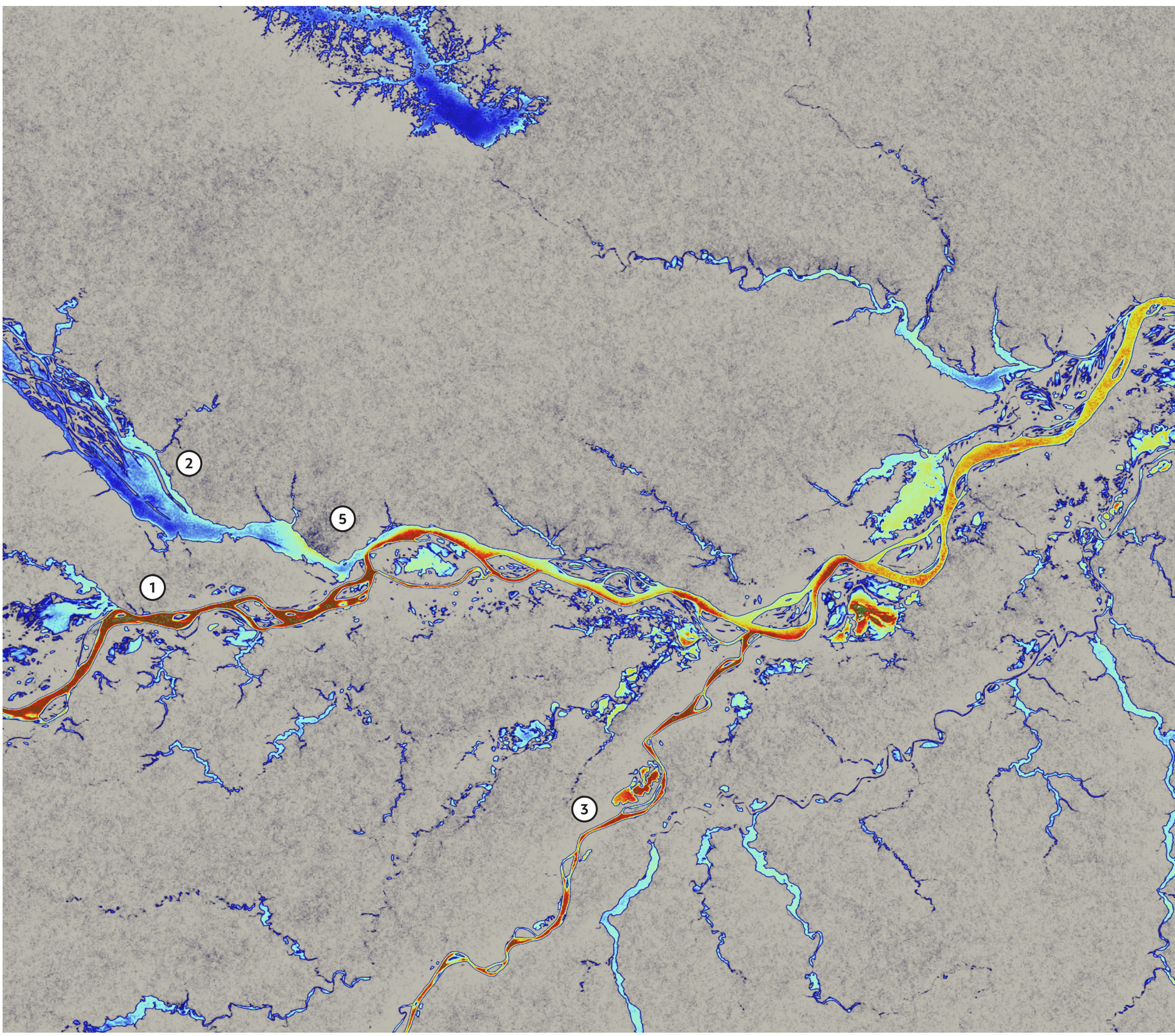
SEDIMENT CONCENTRATIONS FROM SATELLITE

Suspended sediment concentration (SSC) for part of the Amazon River for September averaged over the period 2000–2016, as measured from satellite imagery. The map illustrates differences in sediment supply from tributary channels, patterns of mixing between river flows, and higher suspended sediment concentrations in some floodplain lakes.

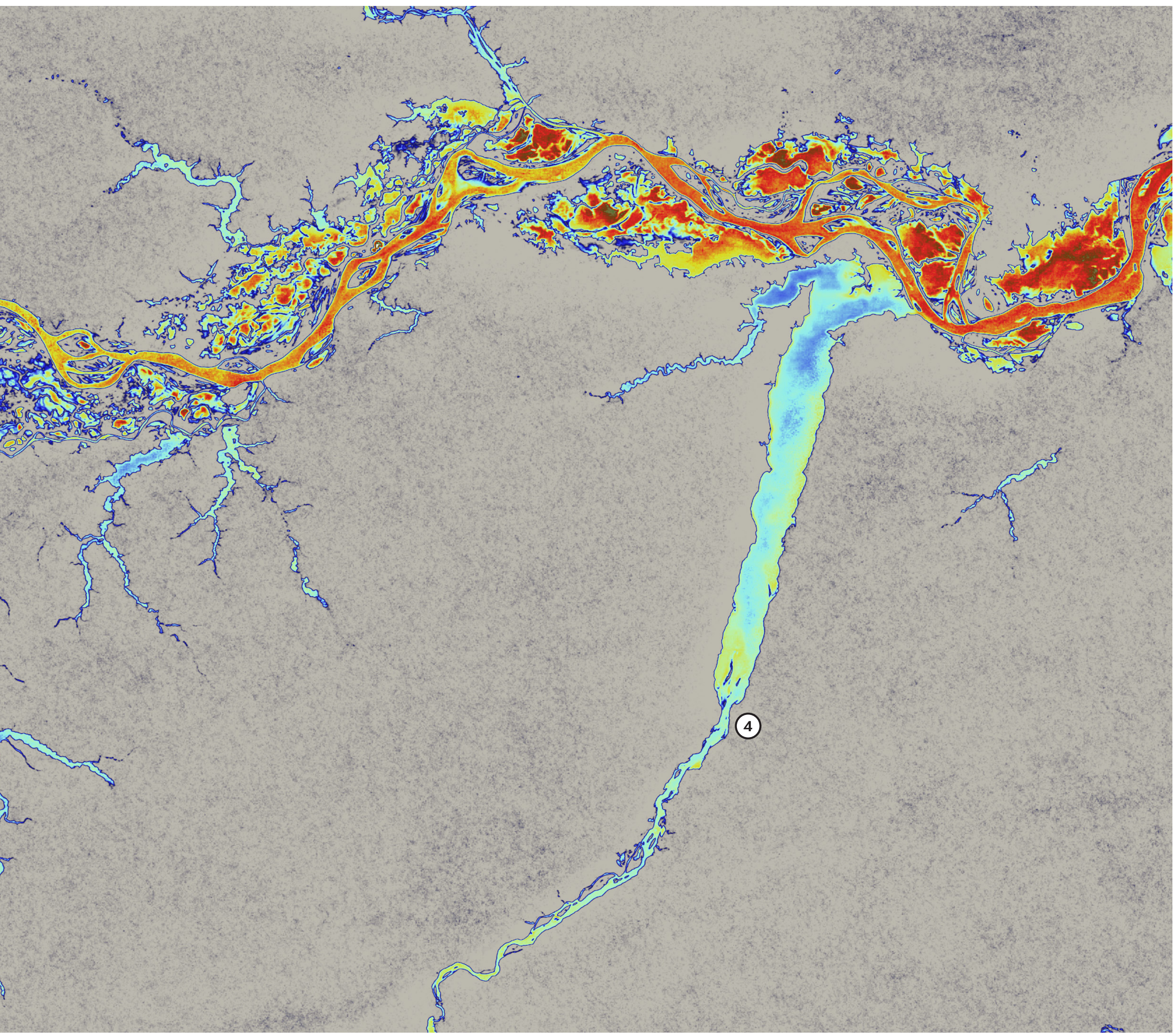
1 Rio Solimões
2 Rio Negro
3 Rio Madeira
4 Rio Tapajós
5 Manaus

0 50 miles
0 50 km

SSC, mg/L:



So, how can these challenges of monitoring sediment movement be overcome in the future? One way is to use remote sensing from satellites. The concentration of suspended sediment particles at the water's surface is known to affect the reflectance of incoming solar radiation. By using satellite sensors to measure this surface reflectance, it is now possible to estimate suspended sediment concentrations from space by calibrating this with known river samples. Such satellite-based remote sensing is offering exciting new opportunities to monitor sediment transport across large spatial scales, and on a routine basis, affording new insights into the processes by which erosion and sedimentation reshape some of Earth's most dramatic and inhospitable environments.



Carbon and nutrient flows through rivers

Besides transporting sediment particles, rivers are responsible for moving huge quantities of nutrients and carbon to the oceans. In addition, rivers and their floodplains provide regions for abundant vegetation growth, and carbon, stored as organic material, can become buried and locked into alluvial sediments.

Supplying nutrients to the oceans

Rivers are vital conveyors of nutrients and carbon from the land to the sea. Nutrients are critical to the development of plant and animal life, and are required for the growth of algae and cyanobacteria that lie at the base of the riverine food web, forming a food source for many small invertebrates and fish. However, healthy aquatic ecosystems require only modest concentrations of nutrients and, as we shall see later, pristine nutrient conditions are essentially non-existent in many rivers, estuaries, and deltas due to a range of human-sourced contaminants. The excessive enrichment of nutrients such as nitrogen and phosphorus—in a process termed eutrophication—is perhaps the Earth's most widespread issue for water quality.

Natural nutrients enter rivers through a range of processes, such as direct input from the weathering of rocks and nutrient release from soils, as well as the decomposition of riverside vegetation and aquatic organisms. Dissolved inorganic nitrogen (DIN) and phosphorus (DIP) are two of the most common and vital nutrients in rivers. Around three-quarters of these riverine nutrients reach the open ocean each year—globally, around 17 million tonnes (19 million tons) of DIN and 1.2 million tonnes (1.3 million tons) of DIP are delivered to the sea to support marine aquatic ecosystems. Some of these nutrients may become processed and changed due to biological activity in estuaries and along coasts, which act as biogeochemical buffers between rivers and the ocean.

▶ **Flood debris**
Mountain stream in flood, with large boulders, trees overhanging the channels, and fallen trees creating logjams.

(continued...)

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Note:
All rivers and lakes are listed under their specific name, e.g. River Nile is indexed under Nile River; Lake Victoria is indexed as Victoria, Lake.

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