Geomorphology

(Components & Applications)

Setsuko Singer

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Geomorphology
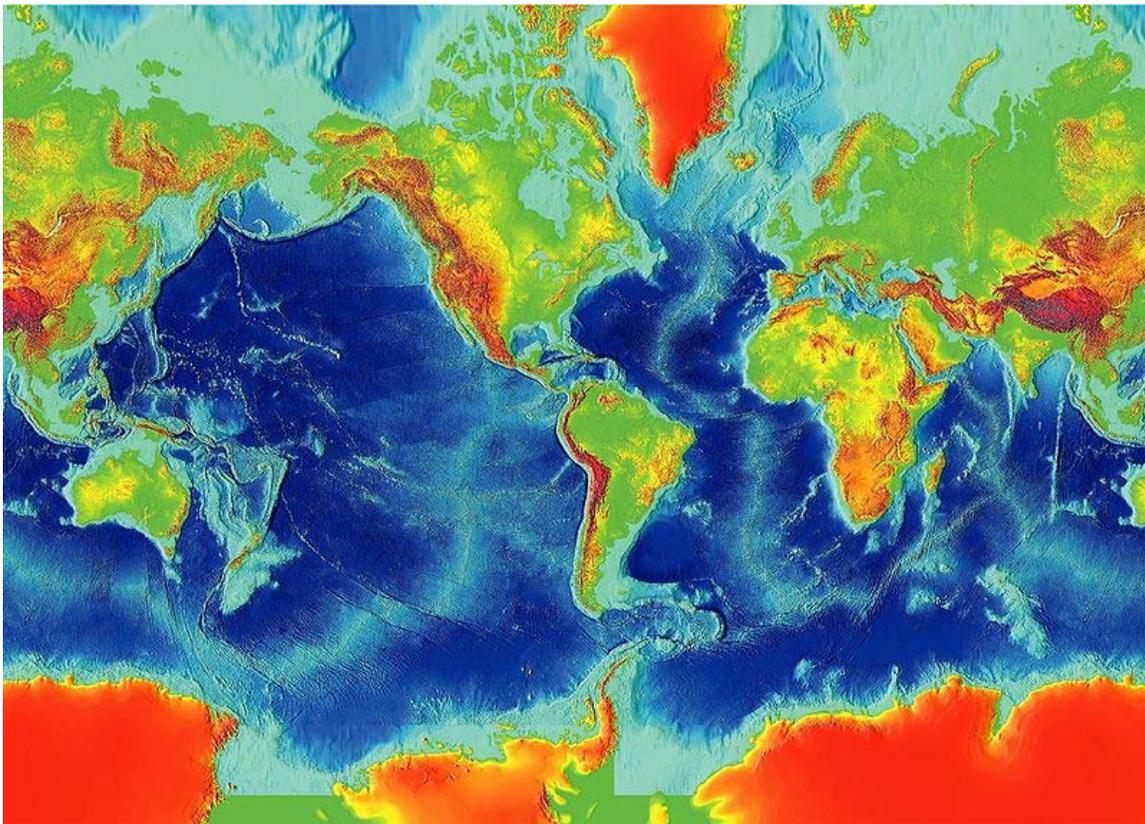
Surface of the Earth

Geomorphology is the scientific study of landforms and the processes that shape them, and more broadly, the evolution of processes controlling the topography of any planet. Geomorphologists seek to understand why landscapes look the way they do, to understand landform history and dynamics, and to predict future changes through a combination of field observation, physical experiment, and numerical modeling. Geomorphology is practiced within geography, geology, geodesy, engineering geology, archaeology, and geotechnical engineering, and this broad base of interest contributes to a wide variety of research styles and interests within the field.

The form of the Earth's surface evolves in response to a combination of natural and anthropogenic processes, and responds to the balance between processes that add material and those that remove it. Such processes may act across very many lengthscales and timescales. On the broadest scales, the landscape is built up through tectonic uplift and volcanism. Denudation occurs by erosion and mass wasting, which produces sediment that is transported and deposited elsewhere within the landscape or off the coast. On progressively smaller scales, similar ideas apply, where individual landforms evolve in response to the balance of additive (tectonic or sedimentary) and subtractive (erosive) processes. Modern geomorphology can be thought of as the study of the divergence of flux of material on a planetary surface, and as such is closely allied with sedimentology, which can equally be seen as the convergence of that flux.

Geomorphic processes are influenced by tectonics, climate, ecology, and human activity, and equally, many of these drivers can be affected by the ongoing evolution of the Earth's surface, for example, via isostasy or orographic precipitation. Many geomorphologists are particularly interested in the potential for feedbacks between climate and tectonics mediated by geomorphic processes.

Practical applications of geomorphology include hazard assessment including landslide prediction and mitigation, river control and restoration, and coastal protection.

History

With some notable exceptions (see below), geomorphology is a relatively young science, growing along with interest in other aspects of the Earth Sciences in the mid 19th century. This section provides a very brief outline of some of the major figures and events in its development.

Ancient geomorphology

Perhaps the earliest one to devise a theory of geomorphology was the polymath Chinese scientist and statesman Shen Kuo (1031-1095 AD). This was based on his observation of marine fossil shells in a geological stratum of a mountain hundreds of miles from the Pacific Ocean. Noticing bivalve shells running in a horizontal span along the cut section of a cliffside, he theorized that the cliff was once the pre-historic location of a seashore that had shifted hundreds of miles over the centuries. He inferred that the land was reshaped and formed by soil erosion of the mountains and by deposition of silt, after observing strange natural erosions of the Taihang Mountains and the Yandang Mountain near Wenzhou. Furthermore, he promoted the theory of gradual climate change over centuries of time once ancient petrified bamboos were found to be preserved underground in the dry, northern climate zone of *Yanzhou*, which is now modern day Yan'an, Shaanxi province.

Early modern geomorphology

The first use of the word geomorphology was likely to be in the German language when it appeared in Laumann's 1858 work. Keith Tinkler has suggested that the word came into general use in English, German and French after John Wesley Powell and W. J. McGee used it in the International Geological Conference of 1891.

An early popular geomorphic model was the *geographical cycle* or the *cycle of erosion*, developed by William Morris Davis between 1884 and 1899. The cycle was inspired by theories of uniformitarianism first formulated by James Hutton (1726–1797). Concerning valley forms, uniformitarianism depicted the cycle as a sequence in which a river cuts a valley more and more deeply, but then erosion of side valleys eventually flatten the terrain again, to a lower elevation. uplift could start the cycle over. Many studies in geomorphology in the decades following Davis' development of his theories sought to fit their ideas into this framework for broad scale landscape evolution, and are often today termed "Davisian". Davis' ideas have largely been superseded today, mainly due to their lack of predictive power and qualitative nature, but he remains an extremely important figure in the history of the subject.

In the 1920s, Walther Penck developed an alternative model to Davis', believing that landform evolution was better described as a balance between ongoing processes of uplift and denudation, rather than Davis' single uplift followed by decay. However, due to his relatively young death, disputes with Davis and a lack of English translation of his work his ideas were not widely recognised for many years.

These authors were both attempting to place the study of the evolution of the Earth's surface on a more generalized, globally relevant footing than had existed before. In the earlier parts of the 19th century, authors - especially in Europe - had tended to attribute the form of landscape to local climate, and in particular to the specific effects of glaciation and periglacial processes. In contrast, both Davis and Penck were seeking to emphasize the importance of evolution of landscapes through time and the generality of Earth surface processes across different landscapes under different conditions.

Quantitative geomorphology

While Penck and Davis and their followers were writing and studying primarily in Western Europe, another, largely separate, school of geomorphology was developed in the United States in the middle years of the 20th century. Following the early trailblazing work of Grove Karl Gilbert around the turn of the 20th century, a group of natural scientists, geologists and hydraulic engineers including Ralph Alger Bagnold, John Hack, Luna Leopold, Thomas Maddock and Arthur Strahler began to research the form of landscape elements such as rivers and hillslopes by taking systematic, direct, quantitative measurements of aspects of them and investigating the scaling of these measurements. These methods began to allow prediction of the past and future behavior of landscapes from present observations, and were later to develop into what today is known as the subdiscipline of *Quantitative Geomorphology*, or *Geomorphometry*.

Contemporary geomorphology

Today, the field of geomorphology encompasses a very wide range of different approaches and interests. Modern researchers aim to draw out quantitative "laws" that govern Earth surface processes, but equally, recognize the uniqueness of each landscape and environment in which these processes operate. Particularly important realizations in contemporary geomorphology include:

1) that not all landscapes can be considered as either "stable" or "perturbed", where this perturbed state is a temporary displacement away from some ideal target form. Instead, dynamic changes of the landscape are now seen as an essential part of their nature.

2) that many geomorphic systems are best understood in terms of the stochasticity of the processes occurring in them, that is, the probability distributions of event magnitudes and return times. This in turn has indicated the importance of chaotic determinism to landscapes, and that landscape properties are best considered statistically. The same processes in the same landscapes does not always lead to the same end results.

Processes

Grand Canyon, Arizona

Modern geomorphology focuses on the quantitative analysis of interconnected processes. Modern advances in geochemistry, in particular cosmochemistry, isotope geochemistry and fission track dating, have enabled us for the first time to measure the rates at which geomorphic processes occur at geologically relevant timescales. At the same time, the use of more precise physical measurement techniques, including differential GPS, remotely sensed digital terrain models and laser scanning techniques, have allowed quantification and study of these processes as they happen. Computer simulation and modeling may then be used to test our understanding of how these processes work together and through time.

Most geomorphically relevant processes can be thought of as either erosive, transportive, or some combination thereof. Depositional processes are mostly thought of as within the field of sedimentology, but also frequently considered as part of geomorphology. Weathering is the chemical and physical disruption of earth materials in place on exposure to atmospheric or near surface agents. The products of these near surface changes can subsequently be transported away by various agents of erosion.

The nature of the processes investigated by geomorphologists is strongly dependent on the landscape or landform under investigation and the time and length scales of interest. However, the following non-exhaustive list provides a flavor of the landscape elements associated with some of these.

Primary surface processes responsible for most topographic features include wind, waves, chemical dissolution, mass wasting, groundwater movement, surface water flow, glacial action, tectonism, and volcanism. Other more exotic geomorphic processes might include periglacial (freeze-thaw) processes, salt-mediated action, or extraterrestrial impact.

Fluvial processes

Fluvial is used in geography and Earth science to refer to the processes associated with rivers and streams and the deposits and landforms created by them. When the stream or rivers are associated with glaciers, ice sheets, or ice caps, the term **glaciofluvial** or **fluvioglacial** is used.

Fluvial processes comprise the motion of sediment and erosion or deposition (geology) on the river bed.

Erosion by moving water can happen in two ways. Firstly, the movement of water across the bed exerts a shear stress directly onto the bed. If the cohesive strength of the substrate is lower than the shear exerted, or the bed is composed of loose sediment which can be mobilized by such stresses, then the bed will be lowered purely by clearwater flow. However, if the river carries significant quantities of sediment, this material can act as tools to enhance wear of the bed (abrasion). At the same time the fragments themselves are ground down, becoming smaller and more rounded (attrition).

Sediment in rivers is transported as either bedload (the coarser fragments which move close to the bed) or suspended load (finer fragments carried in the water). There is also a component carried as dissolved material.

For each grain size there is a specific velocity at which the grains start to move, called *entrainment velocity*. However the grains will continue to be transported even if the velocity falls below the entrainment velocity due to the reduced (or removed) friction between the grains and the river bed. Eventually the velocity will fall low enough for the grains to be deposited. This is shown by the Hjulstrøm curve.

A river is continually picking up and dropping solid particles of rock and soil from its bed throughout its length. Where the river flow is fast, more particles are picked up than dropped. Where the river flow is slow, more particles are dropped than picked up. Areas where more particles are dropped are called alluvial or flood plains, and the dropped particles are called alluvium.

Even small streams make alluvial deposits, but it is in the flood plains and deltas of large rivers that large, geologically-significant alluvial deposits are found.

The amount of matter carried by a large river is enormous. The names of many rivers derive from the color that the transported matter gives the water. For example, the Huang He in China is literally translated "Yellow River", and the Mississippi River in the United States is also called "the Big Muddy." It has been estimated that the Mississippi River annually carries 406 million tons of sediment to the sea, the Huang He 796 million tons, and the Po River in Italy 67 million tons.

Aeolian processes

Wind-carved alcove in the Navajo Sandstone near Moab, Utah.

Aeolian (or **Eolian** or **Æolian**) processes pertain to the activity of the winds and more specifically, to the winds' ability to shape the surface of the Earth and other planets. Winds may erode, transport, and deposit materials, and are effective agents in regions with sparse vegetation and a large supply of unconsolidated sediments. Although water is a much more powerful eroding force than wind, aeolian processes are important in arid environments such as deserts.

The term is derived from the name of the Greek god, Æolus, the keeper of the winds.

Wind erosion

Wind erodes the Earth's surface by deflation (the removal of loose, fine-grained particles), by the turbulent eddy action of the wind and by abrasion (the wearing down of surfaces by the grinding action and sandblasting of windborne particles).

Regions which experience intense and sustained erosion are called deflation zones. Most aeolian deflation zones are composed of desert pavement, a sheet-like surface of rock fragments that remains after wind and water have removed the fine particles. Almost half of Earth's desert surfaces are stony deflation zones. The rock mantle in desert pavements protects the underlying material from deflation.

A dark, shiny stain, called desert varnish or rock varnish, is often found on the surfaces of some desert rocks that have been exposed at the surface for a long period of time. Manganese, iron oxides, hydroxides, and clay minerals form most varnishes and provide the shine.

Deflation basins, called blowouts, are hollows formed by the removal of particles by wind. Blowouts are generally small, but may be up to several kilometers in diameter.

Wind-driven grains abrade landforms. Grinding by particles carried in the wind creates grooves or small depressions. Ventifacts are rocks which have been cut, and sometimes polished, by the abrasive action of wind.

Sculpted landforms, called yardangs, are up to tens of meters high and kilometers long and are forms that have been streamlined by desert winds. The famous sphinx at Giza in Egypt may be a modified yardang.

Rock carved by drifting sand below Fortification Rock in Arizona (Photo by Timothy H. O'Sullivan, USGS, 1871)

Sand blowing off a crest in the Kelso Dunes of the Mojave Desert, California.

Transport

Particles are transported by winds through suspension, saltation, and creep.

Small particles may be held in the atmosphere in suspension. Upward currents of air support the weight of suspended particles and hold them indefinitely in the surrounding air. Typical winds near Earth's surface suspend particles less than 0.2 millimeters in diameter and scatter them aloft as dust or haze.

Saltation is downwind movement of particles in a series of jumps or skips. Saltation normally lifts sand-size particles no more than one centimeter above the ground, and proceeds at one-half to one-third the speed of the wind. A saltating grain may hit other grains that jump up to continue the saltation. The grain may also hit larger grains that are too heavy to hop, but that slowly creep forward as they are pushed by saltating grains. Surface creep accounts for as much as 25 percent of grain movement in a desert.

Aeolian turbidity currents are better known as dust storms. Air over deserts is cooled significantly when rain passes through it. This cooler and denser air sinks toward the desert surface. When it reaches the ground, the air is deflected forward and sweeps up surface debris in its turbulence as a dust storm.

Crops, people, villages, and possibly even climates are affected by dust storms. Some dust storms are intercontinental, a few may circle the globe, and occasionally they may engulf entire planets. When the Mariner 9 spacecraft entered its orbit around Mars in 1971, a dust storm lasting one month covered the entire planet, thus delaying the task of photo-mapping the planet's surface.

Most of the dust carried by dust storms is in the form of silt-size particles. Deposits of this windblown silt are known as loess. The thickest known deposit of loess, 335 meters, is on the Loess Plateau in China. In Europe and in the Americas, accumulations of loess are generally from 20 to 30 meters thick.

Small whirlwinds, called dust devils, are common in arid lands and are thought to be related to very intense local heating of the air that results in instabilities of the air mass. Dust devils may be as much as one kilometer high.

Dust storm approaching Spearman, Texas April 14, 1935.

A massive sand storm cloud is close to enveloping a military camp as it rolls over Al Asad, Iraq, just before nightfall on April 27, 2005.

Deposition

Wind-deposited materials hold clues to past as well as to present wind directions and intensities. These features help us understand the present climate and the forces that molded it. Wind-deposited sand bodies occur as sand sheets, ripples, and dunes.

Sand sheets are flat, gently undulating sandy plots of sand surfaced by grains that may be too large for saltation. They form approximately 40 percent of aeolian depositional surfaces. The Selima Sand Sheet, which occupies 60,000 square kilometers in southern Egypt and northern Sudan, is one of the Earth's largest sand sheets. The Selima is absolutely flat in some places; in others, active dunes move over its surface.

Wind blowing on a sand surface ripples the surface into crests and troughs whose long axes are perpendicular to the wind direction. The average length of jumps during saltation corresponds to the wavelength, or distance between adjacent crests, of the ripples. In ripples, the coarsest materials collect at the crests causing inverse grading. This distinguishes small ripples from dunes, where the coarsest materials are generally in the troughs. This is also a distinguishing feature between water laid ripples and eolian ripples.

Wind-blown sand moves up the gentle upwind side of the dune by saltation or creep. Sand accumulates at the brink, the top of the slipface. When the buildup of sand at the brink exceeds the angle of repose, a small avalanche of grains slides down the slipface. Grain by grain, the dune moves downwind.

Accumulations of sediment blown by the wind into a mound or ridge, dunes have gentle upwind slopes on the wind-facing side. The downwind portion of the dune, the lee slope, is commonly a steep avalanche slope referred to as a slipface. Dunes may have more than one slipface. The minimum height of a slipface is about 30 centimeters.

Some of the most significant experimental measurements on aeolian sand movement were performed by Ralph Alger Bagnold, a British engineer who worked in Egypt prior to World War II. Bagnold investigated the physics of particles moving through the atmosphere and deposited by wind. He recognized two basic dune types, the crescentic dune, which he called "barchan," and the linear dune, which he called longitudinal or "seif" (Arabic for "sword").

Crossbedding of sandstone near Mt. Carmel road, Zion Canyon, indicating wind action and sand dune formation prior to formation of rock (NPS photo by George A. Grant, 1929)

Mesquite Flat Dunes in Death Valley looking toward the Cottonwood Mountains from the north west arm of Star Dune (2003)

Hillslope processes

Example of mass wasting at Palo Duro Canyon, Texas

Soil, regolith, and rock move downslope under the force of gravity via creep, slides, flows, topples, and falls. Such mass wasting occurs on both terrestrial and submarine slopes, and has been observed on Earth, Mars, Venus, Titan and Iapetus.

Ongoing hillslope processes can change the topology of the hillslope surface, which in turn can change the rates of those processes. Hillslopes that steepen up to certain critical thresholds are capable of shedding extremely large volumes of material very quickly, making hillslope processes an extremely important element of landscapes in tectonically active areas.

On Earth, biological processes such as burrowing or tree throw may play important roles in setting the rates of some hillslope processes.

Glacial processes
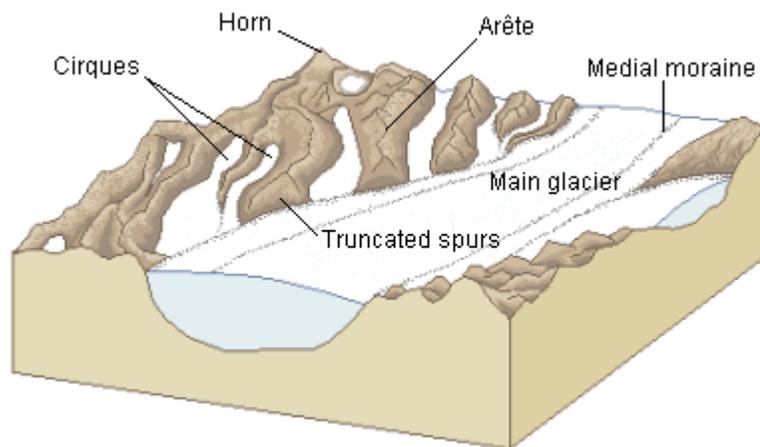
Features of a glacial landscape

Glaciers, while geographically restricted, are effective agents of landscape change. The gradual movement of ice down a valley causes abrasion and plucking of the underlying rock. Abrasion produces fine sediment, termed glacial flour. The debris transported by the glacier, when the glacier recedes, is termed a moraine. Glacial erosion is responsible for U-shaped valleys, as opposed to the V-shaped valleys of fluvial origin.

The way glacial processes interact with other landscape elements, particularly hillslope and fluvial processes, is an important aspect of Plio-Pleistocene landscape evolution and its sedimentary record in many high mountain environments. Environments that have been relatively recently glaciated but are no longer may still show elevated landscape change rates compared to those that have never been glaciated. Nonglacial geomorphic processes which nevertheless have been conditioned by past glaciation are termed paraglacial processes. This concept contrasts with periglacial processes, which are directly driven by formation or melting of ice or frost.

Tectonic processes

Tectonic effects on geomorphology can range from scales of millions of years to minutes or less. The effects of tectonics on landscape are heavily dependent on the nature of the underlying bedrock fabric that more less controls what kind of local morphology tectonics can shape. Earthquakes can, in terms of minutes, submerge large extensions creating new wetlands. Isostatic rebound can account for significant changes over thousand or hundreds of years, and allows erosion of a mountain belt to promote further erosion as mass is removed from the chain and the belt uplifts. Long-term plate tectonic dynamics give rise to orogenic belts, large mountain chains with typical lifetimes of many tens of millions of years, which form focal points for high rates of fluvial and hillslope processes and thus long-term sediment production.

Features of deeper mantle dynamics such as plumes and delamination of the lower lithosphere have also been hypothesised to play important roles in the long term (> million year), large scale (thousands of km) evolution of the Earth's topography. Both can promote surface uplift through isostasy as hotter, less dense, mantle rocks displace cooler, denser, mantle rocks at depth in the Earth.

Igneous processes

Both volcanic (eruptive) and plutonic (intrusive) igneous processes can have important impacts on geomorphology. The action of volcanoes tends to rejuvenize landscapes, covering the old land surface with lava and tephra, releasing pyroclastic material and forcing rivers through new paths. The cones built by eruptions also build substantial new topography, which can be acted upon by other surface processes.

Subsurface movement of magma also plays a role in geomorphology. Migrating melts beneath the surface can cause the inflation and deflation of the land surface, and a partially molten crustal layer beneath Tibet has even been implicated in controlling the geomorphology of the Tibetan plateau across many thousands of kilometres.

Biological processes

The interaction of living organisms with landforms, or biogeomorphologic processes, can be of many different forms, and is probably of profound importance for the terrestrial geomorphic system as a whole. Biology can influence very many geomorphic processes, ranging from biogeochemical processes controlling chemical weathering, to the influence of mechanical processes like burrowing and tree throw on soil development, to even controlling global erosion rates through modulation of climate through carbon dioxide balance. Terrestrial landscapes in which the role of biology in mediating surface processes can be definitively excluded, are extremely rare, but may hold important information for understanding the geomorphology of other planets, such as Mars.

Scales in geomorphology

Different geomorphological processes dominate at different spatial and temporal scales. Moreover, scales on which processes occur may determine the reactivity or otherwise of landscapes to changes in driving forces such as climate or tectonics. These ideas are key to the study of geomorphology today.

To help categorize landscape scales some geomorphologists might use the following taxonomy:

- 1st - Continent, ocean basin, climatic zone (~10,000,000 km^2)
- 2nd - Shield, e.g. Baltic Shield, or mountain range (~1,000,000 km^2)
- 3rd - Isolated sea, Sahel (~100,000 km^2)
- 4th - Massif, e.g. Massif Central or Group of related landforms, e.g., Weald (~10,000 km^2)
- 5th - River valley, Cotswolds (~1,000 km^2)
- 6th - Individual mountain or volcano, small valleys (~100 km^2)
- 7th - Hillslopes, stream channels, estuary (~10 km^2)
- 8th - gully, barchannel (~1 km^2)
- 9th - Meter-sized features

Chapter-2

Sediment Transport

A plume of dust blows off of the Sahara Desert and sails over Atlantic Ocean towards the Canary Islands.

Mesquite Dunes, Death Valley, California. Ripples and dunes form as a natural self-organizing response to sediment transport.

Sediment transport is the movement of solid particles (sediment), typically due to a combination of the force of gravity acting on the sediment, and/or the movement of the fluid in which the sediment is entrained. An understanding of sediment transport is typically used in natural systems, where the particles are clastic rocks (sand, gravel, boulders, etc.), mud, or clay; the fluid is air, water, or ice; and the force of gravity acts to move the particles due to the sloping surface on which they are resting. Sediment transport due to fluid motion occurs in rivers, the oceans, lakes, seas, and other bodies of water, due to currents and tides; in glaciers as they flow, and on terrestrial surfaces under the influence wind. Sediment transport due only to gravity can occur on sloping surfaces in general, including hillslopes, scarps, cliffs, and the continental shelf—continental slope boundary.

Sediment transport is important in the fields of sedimentary geology, geomorphology, civil engineering and environmental engineering. Knowledge of sediment transport is most often used to know whether erosion or deposition will occur, the magnitude of this erosion or deposition, and the time and distance over which it will occur.

Mechanisms

Sand blowing off a crest in the Kelso Dunes of the Mojave Desert, California.

Toklat River, East Fork, Polychrome overlook, Denali National Park, Alaska. This river, like other braided streams, rapidly changes the positions of its channels through processes of erosion, sediment transport, and deposition.

Aeolian

Aeolian or *eolian* (depending on the parsing of æ) is the term for sediment transport by wind. This process results in the formation of ripples and sand dunes. Typically, the size of the transported sediment is fine sand (<1 mm) and smaller, because air is a fluid with low density and viscosity, and can therefore not exert very much shear on its bed.

Aeolian sediment transport is common on beaches and in the arid regions of the world, because it is in these environments that vegetation does not prevent the presence and motion of fields of sand.

Wind-blown very fine-grained dust is capable of entering the upper atmosphere and moving across the globe. Dust from the Sahara deposits on the Canary Islands and islands in the Caribbean, and dust from the Gobi desert has deposited on the western United States. This sediment is important to the soil budget and ecology of several islands.

Deposits of fine-grained wind-blown glacial sediment are called loess.

Fluvial

In geology, physical geography, and sediment transport, fluvial processes relate to flowing water in natural systems. This encompasses rivers, streams, periglacial flows, flash floods and glacial lake outburst floods. Sediment moved by water can be larger than sediment moved by air because water has both a higher density and viscosity. In typical rivers the largest carried sediment is of sand and gravel size, but larger floods can carry cobbles and even boulders.

Fluvial sediment transport can result in the formation of ripples and dunes, in fractal-shaped patterns of erosion, in complex patterns of natural river systems, and in the development of floodplains.

Sand ripples, Laysan Beach, Hawaii. Coastal **sediment transport** results in these evenly spaced ripples along the shore. Monk seal for scale.

Coastal

Coastal sediment transport takes place in near-shore environments due to the motions of waves and currents. At the mouths of rivers, coastal sediment and fluvial sediment transport processes mesh to create river deltas.

Coastal sediment transport results in the formation of characteristic coastal landforms such as beaches and barrier islands. In coastal-fluvial systems, river deltas form.

A glacier joining the Gorner Glacier, Zermatt, Switzerland. These glaciers transport sediment and leave behind lateral moraines.

Glacial

Glaciers can carry the largest sediment, and areas of glacial deposition often contain a large number of glacial erratics, many of which are several meters in diameter.

Hillslope

In hillslope sediment transport, a variety of processes move regolith downslope. These include:

- Soil creep
- Tree throw
- Movement of soil by burrowing animals
- Slumping and landsliding of the hillslope

These processes generally combine to give the hillslope a profile that looks like a solution to the diffusion equation, where the diffusivity is a parameter that relates to the ease of sediment transport on the particular hillslope. For this reason, the tops of hills generally have a parabolic concave-down profile, which grades into a concave-up profile around valleys.

Applications

Suspended sediment from a stream emptying into a fjord (Isfjorden, Svalbard, Norway).

Sediment transport is applied to solve many environmental, geotechnical, and geological problems.

Movement of sediment is important in providing habitat for fish and other organisms in rivers. Therefore, managers of highly regulated rivers, which are often sediment-starved due to dams, are often advised to stage short floods to refresh the bed material and

rebuild bars. This is also important, for example, in the Grand Canyon of the Colorado River, to rebuild shoreline habitats also used as campsites.

Sediment discharge into a reservoir formed by a dam forms a reservoir delta. This delta will fill the basin, and eventually, either the reservoir will need to be dredged or the dam will need to be removed. Knowledge of sediment transport can be used to properly plan to extend the life of a dam.

Geologists can use inverse solutions of transport relationships to understand flow depth, velocity, and direction, from sedimentary rocks and young deposits of alluvial materials.

Flow in culverts, over dams, and around bridge piers can cause erosion of the bed. This erosion can damage the environment and expose or unsettle the foundations of the structure. Therefore, good knowledge of the mechanics of sediment transport in a built environment are important for civil and hydraulic engineers.

When suspended sediment transport is increased due to human activities, causing environmental problems including the filling of channels, it is called siltation after the grain-size fraction dominating the process.

Initiation of motion

Stress balance

For a fluid to begin transporting sediment that is currently at rest on a surface, the boundary (or bed) shear stress τ_b exerted by the fluid must exceed the critical shear stress τ_c for the initiation motion of grains at the bed. This basic criterion can be for the initiation of motion can be written as:

$$\tau_b = \tau_c.$$

This is typically represented by a comparison between a dimensionless shear stress (τ_b *) and a dimensionless critical shear stress (τ_c *). The nondimensionalization is in order to compare the driving forces of particle motion (shear stress) to the resisting forces that would make it stationary (particle density and size). This dimensionless shear stress, τ *, is called the Shields parameter and defined as:

$$\tau* = \frac{\tau}{(\rho_s - \rho)(g)(D)}.$$

And the new equation to solve becomes:

$$\tau_b * = \tau_c *.$$

The equations included here describe sediment transport for clastic, or granular sediment. They do not work for clays and muds because these types of floccular sediments do not fit the geometric simplifications in these equations, and also interact thorough electrostatic forces. They were also designed fluvial sediment transport of particles carried along in a liquid flow, such as that in a river, canal, or other open channel.

Critical shear stress

The Shields diagram empirically shows how the dimensionless critical shear stress required for the initiation of motion is a function of a particular form of the particle Reynolds number, Re_p or Reynolds number related to the particle. This allows us to rewrite the criterion for the initiation of motion in terms of only needing to solve for a specific version of the particle Reynolds number, which we call Re_p *.

$$\tau_b* = f\left(Re_p*\right)$$

This equation can then be solved by using the empirically derived Shields curve to find τ_c * as a function of a specific form of the particle Reynolds number called the boundary Reynolds number.

Particle Reynolds Number

In general, a particle Reynolds Number has the form:

$$Re_p = \frac{U_p D}{\nu}$$

Where U_p is a characteristic particle velocity, D is the grain diameter (a characteristic particle size), and ν is the kinematic viscosity, which is given by the dynamic viscosity, μ, divided by the fluid density, ρ.

$$\nu = \frac{\mu}{\rho}$$

The specific particle Reynolds number of interest is called the boundary Reynolds number, and it is formed by replacing the velocity term in the Particle Reynolds number by the shear velocity, u *, which is a way of rewriting shear stress in terms of velocity.

$$u_* = \sqrt{\frac{\tau_b}{\rho_w}} = \kappa z \frac{\partial u}{\partial z}$$

where τ_b is the bed shear stress (described below), and κ is the von Kármán constant, where

$$\kappa = 0.407.$$

The particle Reynolds number is therefore given by:

$$Re_p* = \frac{u * D}{\nu}$$

Bed shear stress

The boundary Reynolds number can be used with the Shields diagram to empirically solve the equation

$$\tau_c* = f\left(Re_p*\right),$$

which solves the right-hand side of the equation

$$\tau_b * = \tau_c *.$$

In order to solve the left-hand side, expanded as

$$\tau_b* = \frac{\tau_b}{(\rho_s - \rho)(g)(D)},$$

we must find the bed shear stress, τ_b. There are several ways to solve for the bed shear stress. First, we develop the simplest approach, in which the flow is assumed to be steady and uniform and reach-averaged depth and slope are used. Due to the difficulty of measuring shear stress *in situ*, this method is also one of the most-commonly used. This method is known as the depth-slope product.

Depth-slope product

For a river undergoing approximately steady, uniform equilibrium flow, of approximately constant depth h and slope θ over the reach of interest, and whose width is much greater than its depth, the bed shear stress is given by some momentum considerations stating that the gravity force component in the flow direction equals exactly the friction force. For a wide channel, it yields:

$$\tau_b = \rho g h \sin(\theta)$$

For shallow slopes, which are found in almost all natural lowland streams, the small-angle formula shows that $\sin(\theta)$ is approximately equal to $\tan(\theta)$, which is given by S, the slope. Rewritten with this:

$$\tau_b = \rho g h S$$

Shear velocity, velocity, and friction factor

For the steady case, by extrapolating the depth-slope product and the equation for shear velocity:

$$\tau_b = \rho g h S$$

$$u_* = \sqrt{\left(\frac{\tau_b}{\rho}\right)},$$

We can see that the depth-slope product can be rewritten as:

$$\tau_b = \rho u_*^2.$$

$u*$ is related to the mean flow velocity, $\bar{u}$, through the generalized Darcy-Weisbach friction factor, C_f, which is equal to the Darcy-Weisbach friction factor divided by 8 (for mathematical convenience). Inserting this friction factor,

$$\tau_b = \rho C_f \left(\bar{u}\right)^2.$$

Unsteady flow

For all flows that cannot be simplified as a single-slope infinite channel (as in the depth-slope product, above), the bed shear stress can be locally found by applying the Saint-Vennant equations for continuity, which consider accelerations within the flow.

Solution

Set-up

The criterion for the initiation of motion, established earlier, states that

$$\tau_b * = \tau_c *.$$

In this equation,

$$\tau* = \frac{\tau_b}{(\rho_s - \rho)(g)(D)}, \text{ and therefore}$$

$$\frac{\tau_b}{(\rho_s - \rho)(g)(D)} = \frac{\tau_c}{(\rho_s - \rho)(g)(D)}.$$

$\tau_c *$ is a function of boundary Reynolds number, a specific type of particle Reynolds number.

$$\tau_c* = f\left(Re_p*\right).$$

For a particular particle Reynolds number, $\tau_c *$ will be an emprical constant given by the Shields Curve or by another set of empirical data (depending on whether or not the grain size is uniform).

Therefore, the final equation that we seek to solve is:

$$\frac{\tau_b}{(\rho_s - \rho)(g)(D)} = f\left(Re_p*\right).$$

Solution

We make several assumptions to provide an example that will allow us to bring the above form of the equation into a solved form.

First, we assume that the a good approximation of reach-averaged shear stress is given by the depth-slope product. We can then rewrite the equation as

$$\rho ghS = 0.06(\rho_s - \rho)(g)(D).$$

Moving and re-combining the terms, we obtain:

$$hS = \frac{(\rho_s - \rho)}{\rho}(D)\left(f\left(Re_p*\right)\right) = RD\left(f\left(Re_p*\right)\right)$$

where R is the submerged specific gravity of the sediment.

We then make our second assumption, which is that the particle Reynolds number is high. This is typically applicable to particles of gravel-size or larger in a stream, and means that the critical shear stress is a constant. The Shields curve shows that for a bed with a uniform grain size,

$$\tau_c * = 0.06.$$

Later researchers have shown that this value is closer to

$$\tau_c * = 0.03$$

for more uniformly sorted beds. Therefore, we will simply insert

$$\tau_c* = f\left(Re_p*\right)$$

and insert both values at the end.

The equation now reads:

$$hS = RD\tau_c *$$

This final expression shows that the product of the channel depth and slope is equal to the Shield's criterion times the submerged specific gravity of the particles times the particle diameter.

For a typical situation, such as quartz-rich sediment $\left(\rho_s = 2650\dfrac{kg}{m^3}\right)$ in water $\left(\rho = 1000\dfrac{kg}{m^3}\right)$, the submerged specific gravity is equal to 1.65.

$$R = \frac{(\rho_s - \rho)}{\rho} = 1.65$$

Plugging this into the equation above,

$$hS = 1.65(D)\tau_c *.$$

For the Shield's criterion of $\tau_c * = 0.06$. $0.06 * 1.65 = 0.099$, which is well within standard margins of error of 0.1. Therefore, for a uniform bed,

$$hS = 0.1(D).$$

For these situations, the product of the depth and slope of the flow should be 10% of the diameter of the median grain diameter.

The mixed-grain-size bed value is $\tau_c * = 0.03$, which is supported by more recent research as being more broadly applicable because most natural streams have mixed grain sizes. Using this value, and changing D to D_50 ("50" for the 50th percentile, or the median grain size, as we are now looking at a mixed-grain-size bed), the equation becomes:

$$hS = 0.05(D_{50})$$

Which means that the depth times the slope should be about 5% of the median grain diameter in the case of a mixed-grain-size bed.

Modes of entrainment

The sediments entrained in a flow can be transported along the bed as bed load in the form of sliding and rolling grains, or in suspension as suspended load advected by the

main flow. Some sediment materials may also come from the upstream reaches and be carried downtream in the form of wash load.

Rouse number

The location in the flow in which a particle is entrained is determined by the Rouse number, which is determined by the density ρ_s and diameter d of the sediment particle, and the density ρ and kinematic viscosity ν of the fluid, determine in which part of the flow the sediment particle will be carried.

$$P = \frac{w_s}{\kappa u_*}$$

Here, the Rouse number is given by P. The term in the numerator is the (downwards) sediment the sendiment settling velocity w_s, which is discussed below. The upwards velocity on the grain is given as a product of the von Kármán constant, $\kappa = 0.407$, and the shear velocity, u_*.

The following table gives the approximate required Rouse numbers for transport as bed load, suspended load, and wash load.

Mode of Transport	Rouse Number
Initiation of motion	>7.5
Bed load	7.5>2.5
Suspended load: 50% Suspended	>1.2, <2.5
Suspended load: 100% Suspended	>0.8, <1.2
Wash load	<0.8

Settling velocity
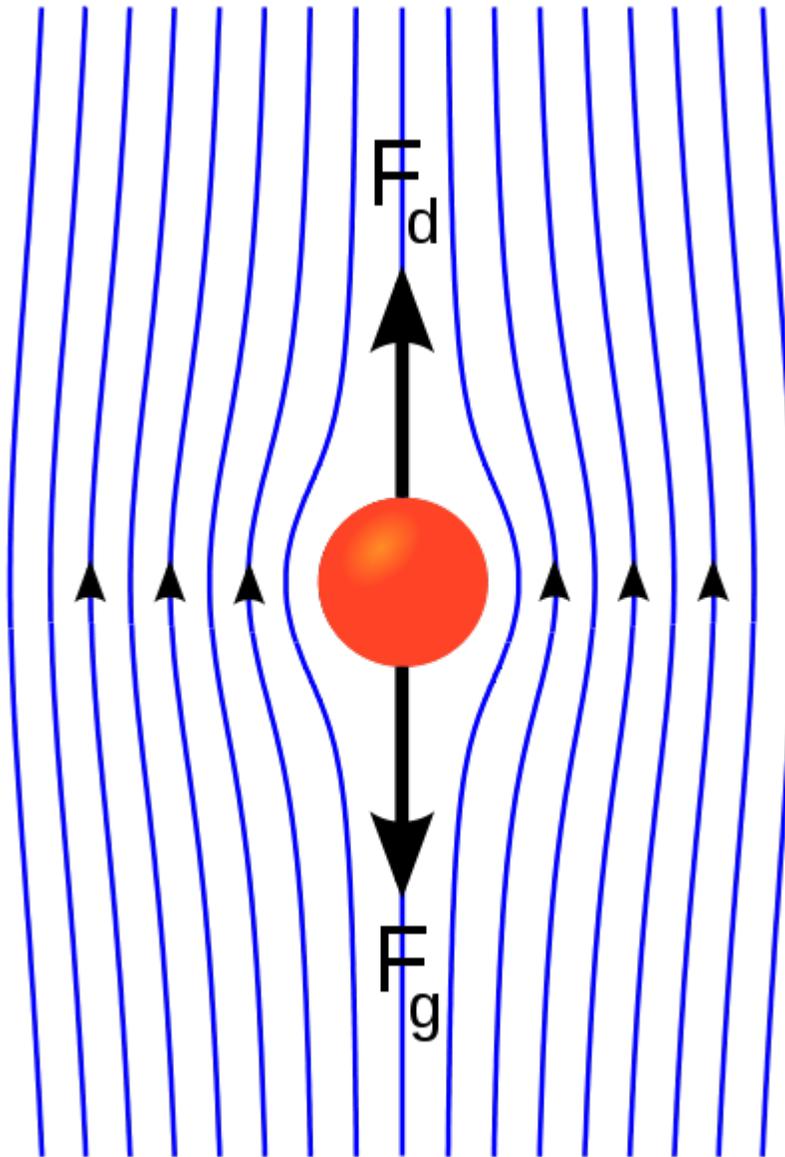
Streamlines around a sphere falling through a fluid. This illustration is accurate for laminar flow, in which the particle Reynolds number is small. This is typical for small particles falling through a viscous fluid; larger particles would result in the creation of a turbulent wake.

The settling velocity (also called the "fall velocity" or "terminal velocity") is a function of the particle Reynolds number. Generally, for small particles (laminar approximation), it can be calculated with Stokes' Law. For larger particles (turbulent particle Reynolds numbers), fall velocity is calculated with the turbulent drag law. Dietrich (1982) compiled a large amount of published data to which he empirically fit settling velocity curves. Ferguson and Church (2006) analytically combined the expressions for Stokes

flow and a turbulent drag law into a single equation that works for all sizes of sediment, and successfully tested it against the data of Dietrich. Their equation is

$$w_s = \frac{RgD^2}{C_1 \nu + (0.75 C_2 RgD^3)^{(0.5)}}.$$

In this equation w_s is the sediment settling velocity, g is acceleration due to gravity, and D is mean sediment diameter. ν is the kinematic viscosity of water, which is approximately 1.0×10^{-6} m^2/s for water at 20°C.

C_1 and C_2 are constants related to the shape and smoothness of the grains.

Constant	Smooth Spheres	Natural Grains: Sieve Diameters	Natural Grains: Nominal Diameters	Limit for Ultra-Angular Grains
C_1	18	18	20	24
C_2	0.4	1.0	1.1	1.2

The expression for fall velocity can be simplified so that it can be solved only in terms of D. We use the sieve diameters for natural grains, $g = 9.8$, and values given above for ν and R. From these parameters, the fall velocity is given by the expression:

$$w_s = \frac{16.17 D^2}{1.8 \cdot 10^{-5} + (12.1275 D^3)^{(0.5)}}$$

Transport rate
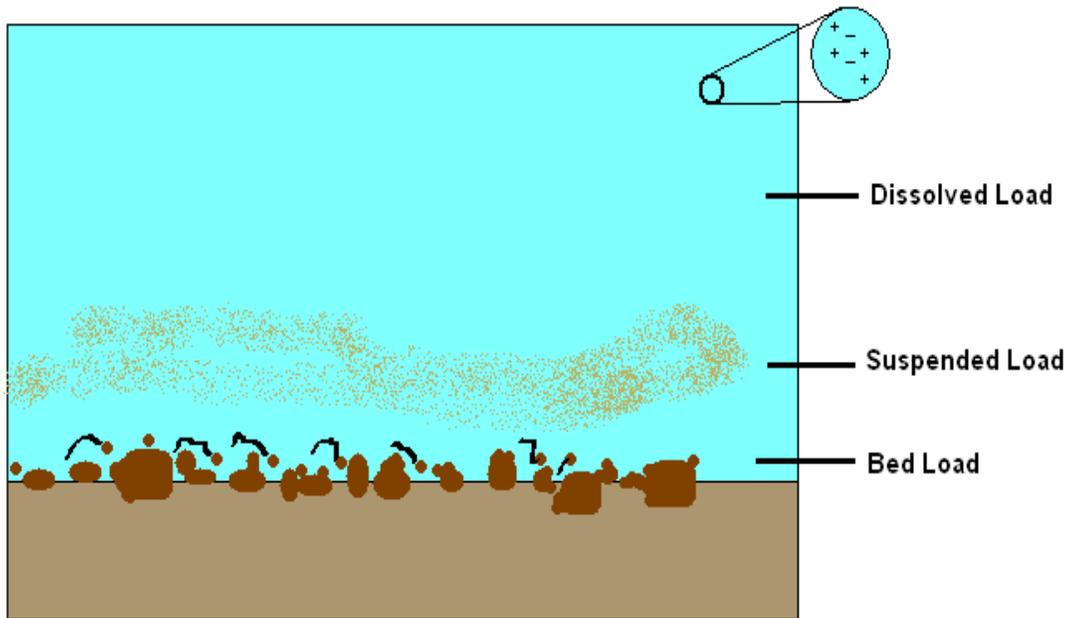
A schematic diagram of where the different types of sediment load are carried in the flow. Dissolved load is not sediment: it is composed of disassociated ions moving along with the flow. It may, however, constitute a significant proportion (often several percent, but occasionally greater than half) of the total amount of material being transported by the stream.

Formulas to calculate sediment transport rate exist for sediment moving in several different parts of the flow. These formulas are often segregated into bed load, suspended load, and wash load. They may sometimes also be segregated into bed material load and wash load.

Bed Load

Bed load moves by rolling, sliding, and hopping (or saltating) over the bed, and moves at a small fraction of the fluid flow velocity. Bed load is generally thought to constitute 5-10% of the total sediment load in a stream, making it less important in terms of mass balance. However, the bed material load (the bed load plus the portion of the suspended load which comprises material derived from the bed) is often dominated by bed load, especially in gravel-bed rivers. This bed material load is the only part of the sediment load that actively interacts with the bed. As the bed load is an important component of that, it plays a major role in controlling the morphology of the channel.

Bed load transport rates are usually expressed as being related to excess dimensionless shear stress raised to some power. Excess dimensionless shear stress is a nondimensional measure measure of bed shear stress about the threshold for motion.

$$\left(\tau_b^* - \tau_c^*\right),$$

Bed load transport rates may also be given by a ratio of bed shear stress to critical shear stress, which is equivalent in both the dimensional and nondimensional cases. This ratio is called the "transport stage" (T_s or φ) and is an important in that it shows bed shear stress as a multiple of the value of the criterion for the initiation of motion.

$$T_s = \phi = \frac{\tau_b}{\tau_c}$$

When used for sediment transport formulae, this ratio is typically raised to a power.

The majority of the published relations for bedload transport are given in dry sediment weight per unit channel width, b ("breadth"):

$$q_s = \frac{Q_s}{b}.$$

Due to the difficulty of estimating bed load transport rates, these equations are typically only suitable for the situations for which they were designed.

Notable bed load transport formulae

Meyer-Peter Müller and derivatives

The transport formula of Meyer-Peter and Müller, originally developed in 1948, was designed for well-sorted fine gravel at a transport stage of about 8. The formula uses the above nondimensionalization for shear stress,

$$\tau* = \frac{\tau}{(\rho_s - \rho)(g)(D)},$$

and Hans Einstein's nondimensionalization for sediment volumetric discharge per unit width

$$q_s* = \frac{q_s}{D\sqrt{\frac{\rho_s - \rho}{\rho}gD}} = \frac{q_s}{Re_p\nu}.$$

Their formula reads:

$$q_s* = 8 \left(\tau * - \tau *_c \right)^{3/2}.$$

Their experimentally determined value for $\tau *_c$ is 0.047, and is the third commonly used value for this (in addition to Parker's 0.03 and Shields' 0.06).

Because of its broad use, some revisions to the formula have taken place over the years that show that the coefficient on the left ("8" above) is a function of the transport stage:

$$T_s \approx 2 \rightarrow q_s* = 5.7 \left(\tau * - 0.047 \right)^{3/2}$$
$$T_s \approx 100 \rightarrow q_s* = 12.1 \left(\tau * - 0.047 \right)^{3/2}$$

The variations in the coefficient were later generalized as a function of dimensionless shear stress:

$$\begin{cases} q_s* = \alpha_s \left(\tau * - \tau_c* \right)^n \\ n = \frac{3}{2} \\ \alpha_s = 1.6 \ln \left(\tau* \right) + 9.8 \approx 9.64 \tau*^{0.166} \end{cases}$$

Wilcock and Crowe

In 2003, Peter Wilcock and Joanna Crowe (now Joanna Curran) published a sediment transport formula that works with multiple grain sizes across the sand and gravel range. Their formula works with surface grain size distributions, as opposed to older models which use subsurface grain size distributions (and thereby implicitly infer a surface grain sorting).

Their expression is more complicated than the basic sediment transport rules (such as that of Meyer-Peter and Müller) because it takes into account multiple grain sizes: this requires consideration of reference shear stresses for each grain size, the fraction of the total sediment supply that falls into each grain size class, and a "hiding function".

The "hiding function" takes into account the fact that, while small grains are inherently more mobile than large grains, on a mixed-grain-size bed, they may be trapped in deep pockets between large grains. Likewise, a large grain on a bed of small particles will be stuck in a much smaller pocket than if it were on a bed of grains of the same size. In gravel-bed rivers, this can cause "equal mobility", in which small grains can move just as easily as large ones. As sand is added to the system, it moves away from the "equal mobility" portion of the hiding function to one in which grain size again matters.

Their model is based on the transport stage, or ratio of bed shear stress to critical shear stress for the initiation of grain motion. Because their formula works with several grain sizes simultaneously, they define the critical shear stress for each grain size class, τ_{c,D_i}, to be equal to a "reference shear stress", τ_{ri}.

They express their equations in terms of a dimensionless transport parameter, W_i^* (with the " * " indicating nondimensionality and the "$_i$" indicating that it is a function of grain size):

$$W_i^* = \frac{Rgq_{bi}}{F_i u*^3}$$

q_{bi} is the volumetric bed load transport rate of size class i per unit channel width b. F_i is the proportion of size class i that is present on the bed.

They came up with two equations, depending on the transport stage, φ. For φ < 1.35:

$$W_i^* = 0.002\phi^{7.5}$$

and for $\phi \geq 1.35$:

$$W_i^* = 14 \left(1 - \frac{0.894}{\phi^{0.5}} \right)^{4.5}$$

.

This equation asymptotically reaches a constant value of W_i^* as φ becomes large.

Suspended load

Suspended load is carried in the lower to middle parts of the flow, and moves at a large fraction of the mean flow velocity in the stream.

A common characterization of suspended sediment concentration in a flow is given by the Rouse Profile. This characterization works for the situation in which sediment concentration c_0 at one particular elevation above the bed z_0 can be quantified. It is given by the expression:

$$\frac{c_s}{c_0} = \left[\frac{z\,(h - z_0)}{z_0\,(h - z)} \right]^{-P/\alpha}$$

Here, z is the elevation above the bed, c_s is the concentration of suspended sediment at that elevation, h is the flow depth, P is the Rouse number, and α relates the eddy viscosity for momentum K_m to the eddy diffusivity for sediment, which is approximately equal to one.

$$\alpha = \frac{K_s}{K_m} \approx 1$$

Experimental work has shown that α ranges from 0.93 to 1.10 for sands and silts.

Bed material load

Bed material load comprises the bed load and the portion of the suspended load that is sourced from the bed.

Three common bed material transport relations are the "Ackers-White", "Engelund-Hansen", "Yang" formulae. The first is for sand to granule-size gravel, and the second and third are for sand though Yang later expanded his formula to include fine gravel. That all of these formulae cover the sand-size range and two of them are exclusively for sand is that the sediment in sand-bed rivers is commonly moved simultaneously as bed and suspended load.

Engelund-Hansen

The bed material load formula of Engelund and Hansen is the only one to not include some kind of critical value for the initiation of sediment transport. It reads:

$$q_s* = \frac{0.05}{c_f}\tau*^{2.5}$$

where q_s* is the Einstein nondimensionalization for bed shear stress, c_f is a friction factor, and $\tau*$ is the Shields stress. The Engelund-Hansen formula is one of the few sediment transport formulae in which a threshold "critical shear stress" is absent.

Wash load

Wash load is carried within the water column as part of the flow, and therefore moves with the mean velocity of main stream. Wash load concentrations are approximately uniform in the water column, and are perfectly uniform for the endmember case in which the Rouse number is equal to 0.
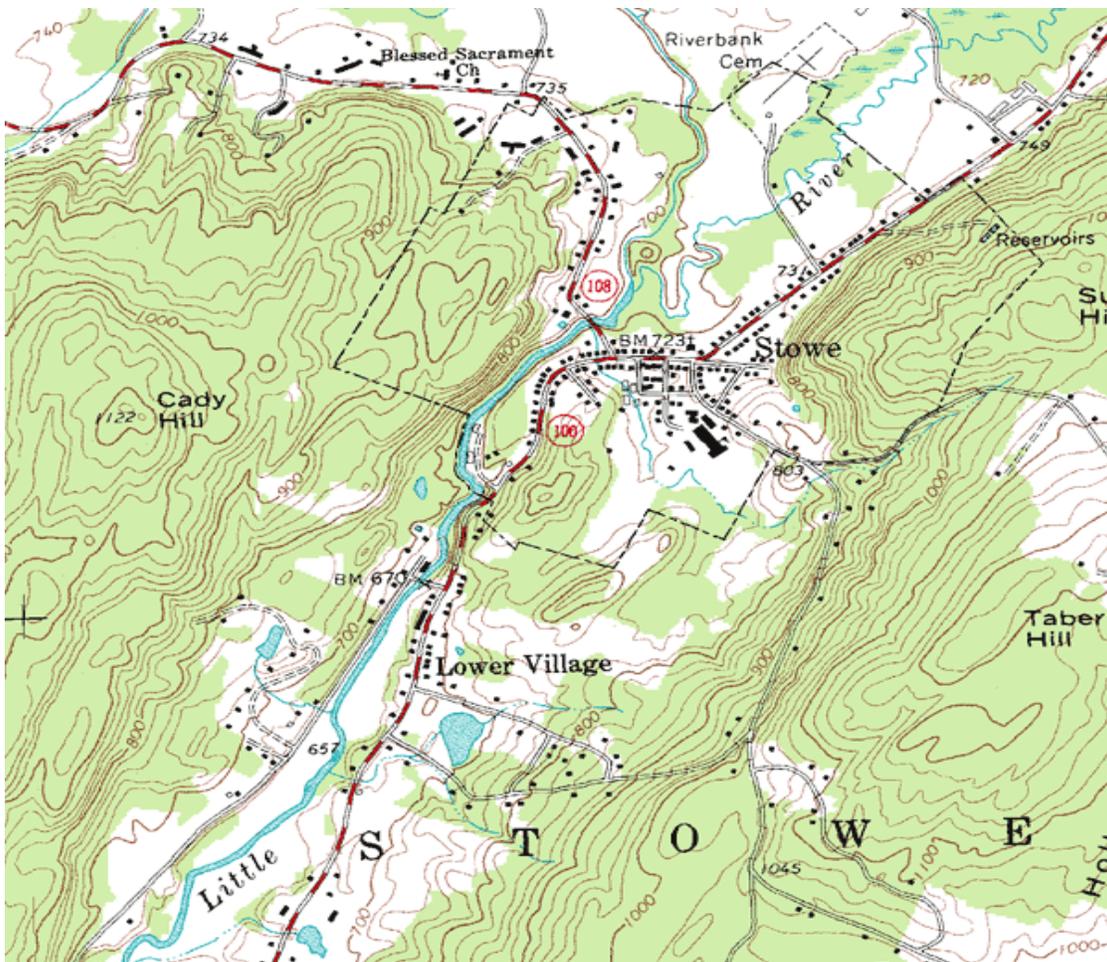
Total load

Some authors have attempted formulations for the total sediment load carried in water.

Chapter-3

Topography and Landforms

Topography

A topographic map with contour intervals

Topography is the study of Earth's surface shape and features or those of planets, moons, and asteroids. It is also the description of such surface shapes and features (especially their depiction in maps).

The topography of an area can also mean the surface shape and features themselves.

In a broader sense, topography is concerned with local detail in general, including not only relief but also vegetative and human-made features, and even local history and culture. This meaning is less common in America, where topographic maps with elevation contours have made "topography" synonymous with relief. The older sense of topography as the study of place still has currency in Europe.

For the purposes of this article, topography specifically involves the recording of relief or terrain, the three-dimensional quality of the surface, and the identification of specific landforms. This is also known as geomorphometry. In modern usage, this involves generation of elevation data in electronic form. It is often considered to include the graphic representation of the landform on a map by a variety of techniques, including contour lines, Hypsometric tints, and relief shading.

Etymology

The term topography originated in ancient Greece and continued in ancient Rome, as the detailed description of a place. The word comes from the Greek words τόπος (*topos*, place) and γραφία (*graphia*, writing). In classical literature this refers to writing about a place or places, what is now largely called 'local history'. In Britain and in Europe in general, the word topography is still sometimes used in its original sense.

Detailed military surveys in Britain (beginning in the late eighteenth century) were called Ordnance Surveys, and this term was used into the 20th century as generic for topographic surveys and maps. The earliest scientific surveys in France were called the Cassini maps after the family who produced them over four generations. The term "topographic surveys" appears to be American in origin. The earliest detailed surveys in the United States were made by the "Topographical Bureau of the Army," formed during the War of 1812. After the work of national mapping was assumed by the U.S. Geological Survey in 1878, the term topographical remained as a general term for detailed surveys and mapping programs, and has been adopted by most other nations as standard.

In the 20th century, the term topography started to be used to describe surface description in other fields where mapping in a broader sense is used, particularly in medical fields such as neurology.

Objectives

An objective of topography is to determine the position of any feature or more generally any point in terms of both a horizontal Coordinate system such as latitude and longitude, and altitude. Identifying (naming) features and recognizing typical landform patterns are also part of the field.

A topographic study may be made for a variety of reasons: military planning and geological exploration have been primary motivators to start survey programs, but detailed information about terrain and surface features is essential for the planning and construction of any major civil engineering, public works, or reclamation projects.

Techniques of topography

There are a variety of approaches to studying topograpy. Which method(s) to use depend on the scale and size of the area under study, its accessibility, and the quality of existing surveys.

Direct survey

A surveying point in Germany

Surveying helps determine accurately the terrestrial or three-dimensional space position of points and the distances and angles between them using leveling instruments such as theodolites, dumpy levels and clinometers.

Even though remote sensing has greatly speeded up the process of gathering information, and has allowed greater accuracy control over long distances, the direct survey still provides the basic control points and framework for all topographic work, whether manual or GIS-based.

In areas where there has been an extensive direct survey and mapping program (most of Europe and the Continental US, for example), the compiled data forms the basis of basic digital elevation datasets such as USGS DEM data. This data must often be "cleaned" to eliminate discrepancies between surveys, but it still forms a valuable set of information for large-scale analysis.

The original American topographic surveys (or the British "Ordnance" surveys) involved not only recording of relief, but identification of landmark features and vegetative land cover.

Remote sensing

Synthetic aperture radar image of Death Valley colored using polarimetry.

Remote sensing is the small- or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Thus, Earth observation or weather satellite collection platforms, ocean and atmospheric observing weather buoy platforms, the monitoring of a parolee via an ultrasound identification system, Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), X-radiation (X-RAY) and space probes are all examples of remote sensing. In modern usage, the term generally refers to the use of imaging sensor technologies including: instruments found in aircraft and spacecraft as well as those used in electrophysiology, and is distinct from other imaging-related fields such as medical imaging.

Overview

There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive sensors detect natural radiation that is emitted or reflected by the object or surrounding area being observed. Reflected sunlight is the most common source of radiation measured by passive sensors. Examples of passive remote sensors include film photography, infrared, charge-coupled devices, and radiometers. Active collection, on the other hand, emits energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target. RADAR is an example of active remote sensing where the time delay between emission and return is measured, establishing the location, height, speed and direction of an object.

Remote sensing makes it possible to collect data on dangerous or inaccessible areas. Remote sensing applications include monitoring deforestation in areas such as the Amazon Basin, glacial features in Arctic and Antarctic regions, and depth sounding of coastal and ocean depths. Military collection during the cold war made use of stand-off collection of data about dangerous border areas. Remote sensing also replaces costly and slow data collection on the ground, ensuring in the process that areas or objects are not disturbed.

Orbital platforms collect and transmit data from different parts of the electromagnetic spectrum, which in conjunction with larger scale aerial or ground-based sensing and analysis, provides researchers with enough information to monitor trends such as El Niño and other natural long and short term phenomena. Other uses include different areas of the earth sciences such as natural resource management, agricultural fields such as land usage and conservation, and national security and overhead, ground-based and stand-off collection on border areas.

Data acquisition techniques

The basis for multispectral collection and analysis is that of examined areas or objects that reflect or emit radiation that stand out from surrounding areas.

Applications of remote sensing data

- Conventional radar is mostly associated with aerial traffic control, early warning, and certain large scale meteorological data. Doppler radar is used by local law enforcements' monitoring of speed limits and in enhanced meteorological collection such as wind speed and direction within weather systems. Other types of active collection includes plasmas in the ionosphere). Interferometric synthetic aperture radar is used to produce precise digital elevation models of large scale terrain.
- Laser and radar altimeters on satellites have provided a wide range of data. By measuring the bulges of water caused by gravity, they map features on the seafloor to a resolution of a mile or so. By measuring the height and wave-length of ocean waves, the altimeters measure wind speeds and direction, and surface ocean currents and directions.
- Light detection and ranging (LIDAR) is well known in examples of weapon ranging, laser illuminated homing of projectiles. LIDAR is used to detect and measure the concentration of various chemicals in the atmosphere, while airborne LIDAR can be used to measure heights of objects and features on the ground more accurately than with radar technology. Vegetation remote sensing is a principal application of LIDAR.
- Radiometers and photometers are the most common instrument in use, collecting reflected and emitted radiation in a wide range of frequencies. The most common are visible and infrared sensors, followed by microwave, gamma ray and rarely, ultraviolet. They may also be used to detect the emission spectra of various chemicals, providing data on chemical concentrations in the atmosphere.
- Stereographic pairs of aerial photographs have often been used to make topographic maps by imagery and terrain analysts in trafficability and highway departments for potential routes.
- Simultaneous multi-spectral platforms such as Landsat have been in use since the 70's. These thematic mappers take images in multiple wavelengths of electro-magnetic radiation (multi-spectral) and are usually found on Earth observation satellites, including (for example) the Landsat program or the IKONOS satellite. Maps of land cover and land use from thematic mapping can be used to prospect for minerals, detect or monitor land usage, deforestation, and examine the health of indigenous plants and crops, including entire farming regions or forests.
- Within the scope of the combat against desertification, remote sensing allows to follow-up and monitor risk areas in the long term, to determine desertification factors, to support decision-makers in defining relevant measures of environmental management, and to assess their impacts.

Geodetic

- Overhead geodetic collection was first used in aerial submarine detection and gravitational data used in military maps. This data revealed minute perturbations in the Earth's gravitational field (geodesy) that may be used to determine changes in the mass distribution of the Earth, which in turn may be used for geological or hydrological studies.

Acoustic and near-acoustic

- Sonar: *passive sonar*, listening for the sound made by another object (a vessel, a whale etc); *active sonar*, emitting pulses of sounds and listening for echoes, used for detecting, ranging and measurements of underwater objects and terrain.
- Seismograms taken at different locations can locate and measure earthquakes (after they occur) by comparing the relative intensity and precise timing.

To coordinate a series of large-scale observations, most sensing systems depend on the following: platform location, what time it is, and the rotation and orientation of the sensor. High-end instruments now often use positional information from satellite navigation systems. The rotation and orientation is often provided within a degree or two with electronic compasses. Compasses can measure not just azimuth (i. e. degrees to magnetic north), but also altitude (degrees above the horizon), since the magnetic field curves into the Earth at different angles at different latitudes. More exact orientations require gyroscopic-aided orientation, periodically realigned by different methods including navigation from stars or known benchmarks.

Resolution impacts collection and is best explained with the following relationship: less resolution=less detail & larger coverage, More resolution=more detail, less coverage. The skilled management of collection results in cost-effective collection and avoid situations such as the use of multiple high resolution data which tends to clog transmission and storage infrastructure.

Data processing

Generally speaking, remote sensing works on the principle of the *inverse problem*. While the object or phenomenon of interest (the **state**) may not be directly measured, there exists some other variable that can be detected and measured (the **observation**), which may be related to the object of interest through the use of a data-derived computer model. The common analogy given to describe this is trying to determine the type of animal from its footprints. For example, while it is impossible to directly measure temperatures in the upper atmosphere, it is possible to measure the spectral emissions from a known chemical species (such as carbon dioxide) in that region. The frequency of the emission may then be related to the temperature in that region via various thermodynamic relations.

The quality of remote sensing data consists of its spatial, spectral, radiometric and temporal resolutions.

Spatial resolution
>The size of a pixel that is recorded in a raster image – typically pixels may correspond to square areas ranging in side length from 1 to 1,000 metres (3.3 to 3,300 ft).

Spectral resolution
>The wavelength width of the different frequency bands recorded – usually, this is related to the number of frequency bands recorded by the platform. Current Landsat collection is that of seven bands, including several in the infra-red spectrum, ranging from a spectral resolution of 0.07 to 2.1 μm. The Hyperion sensor on Earth Observing-1 resolves 220 bands from 0.4 to 2.5 μm, with a spectral resolution of 0.10 to 0.11 μm per band.

Radiometric resolution
>The number of different intensities of radiation the sensor is able to distinguish. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the gray scale and up to 16,384 intensities or "shades" of colour, in each band. It also depends on the instrument noise.

Temporal resolution
>The frequency of flyovers by the satellite or plane, and is only relevant in time-series studies or those requiring an averaged or mosaic image as in deforesting monitoring. This was first used by the intelligence community where repeated coverage revealed changes in infrastructure, the deployment of units or the modification/introduction of equipment. Cloud cover over a given area or object makes it necessary to repeat the collection of said location.

In order to create sensor-based maps, most remote sensing systems expect to extrapolate sensor data in relation to a reference point including distances between known points on the ground. This depends on the type of sensor used. For example, in conventional photographs, distances are accurate in the center of the image, with the distortion of measurements increasing the farther you get from the center. Another factor is that of the platen against which the film is pressed can cause severe errors when photographs are used to measure ground distances. The step in which this problem is resolved is called georeferencing, and involves computer-aided matching up of points in the image (typically 30 or more points per image) which is extrapolated with the use of an established benchmark, "warping" the image to produce accurate spatial data. As of the early 1990s, most satellite images are sold fully georeferenced.

In addition, images may need to be radiometrically and atmospherically corrected.

Radiometric correction
>gives a scale to the pixel values, e. g. the monochromatic scale of 0 to 255 will be converted to actual radiance values.

Atmospheric correction

eliminates atmospheric haze by rescaling each frequency band so that its minimum value (usually realised in water bodies) corresponds to a pixel value of 0. The digitizing of data also make possible to manipulate the data by changing gray-scale values.

Interpretation is the critical process of making sense of the data. The first application was that of aerial photographic collection which used the following process; spatial measurement through the use of a light table in both conventional single or stereographic coverage, added skills such as the use of photogrammetry, the use of photomosaics, repeat coverage, Making use of objects' known dimensions in order to detect modifications. Image Analysis is the recently developed automated computer-aided application which is in increasing use.

Object-Based Image Analysis (OBIA) is a sub-discipline of GIScience devoted to partitioning remote sensing (RS) imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scale.

Old data from remote sensing is often valuable because it may provide the only long-term data for a large extent of geography. At the same time, the data is often complex to interpret, and bulky to store. Modern systems tend to store the data digitally, often with lossless compression. The difficulty with this approach is that the data is fragile, the format may be archaic, and the data may be easy to falsify. One of the best systems for archiving data series is as computer-generated machine-readable ultrafiche, usually in typefonts such as OCR-B, or as digitized half-tone images. Ultrafiches survive well in standard libraries, with lifetimes of several centuries. They can be created, copied, filed and retrieved by automated systems. They are about as compact as archival magnetic media, and yet can be read by human beings with minimal, standardized equipment.

Data processing levels

To facilitate the discussion of data processing in practice, several processing "levels" were first defined in 1986 by NASA as part of its Earth Observing System and steadily adopted since then, both internally at NASA (e. g.,) and elsewhere (e. g.,); these definitions are:

| Level	Description
0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e. g., synchronization frames, communications headers, duplicate data) removed.
1a	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e. g., platform ephemeris) computed and appended but not applied to the Level 0 data (or if applied, in a manner that level 0 is fully recoverable from level 1a data).
1b	Level 1a data that have been processed to sensor units (e. g., radar backscatter

	cross section, brightness temperature, etc.); not all instruments have Level 1b data; level 0 data is not recoverable from level 1b data.
2	Derived geophysical variables (e. g., ocean wave height, soil moisture, ice concentration) at the same resolution and location as Level 1 source data.
3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency (e. g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc).
4	Model output or results from analyses of lower level data (i. e., variables that were not measured by the instruments but instead are derived from these measurements).

A Level 1 data record is the most fundamental (i. e., highest reversible level) data record that has significant scientific utility, and is the foundation upon which all subsequent data sets are produced. Level 2 is the first level that is directly usable for most scientific applications; its value is much greater than the lower levels. Level 2 data sets tend to be less voluminous than Level 1 data because they have been reduced temporally, spatially, or spectrally. Level 3 data sets are generally smaller than lower level data sets and thus can be dealt with without incurring a great deal of data handling overhead. These data tend to be generally more useful for many applications. The regular spatial and temporal organization of Level 3 datasets makes it feasible to readily combine data from different sources.

History

The TR-1 reconnaissance/surveillance aircraft
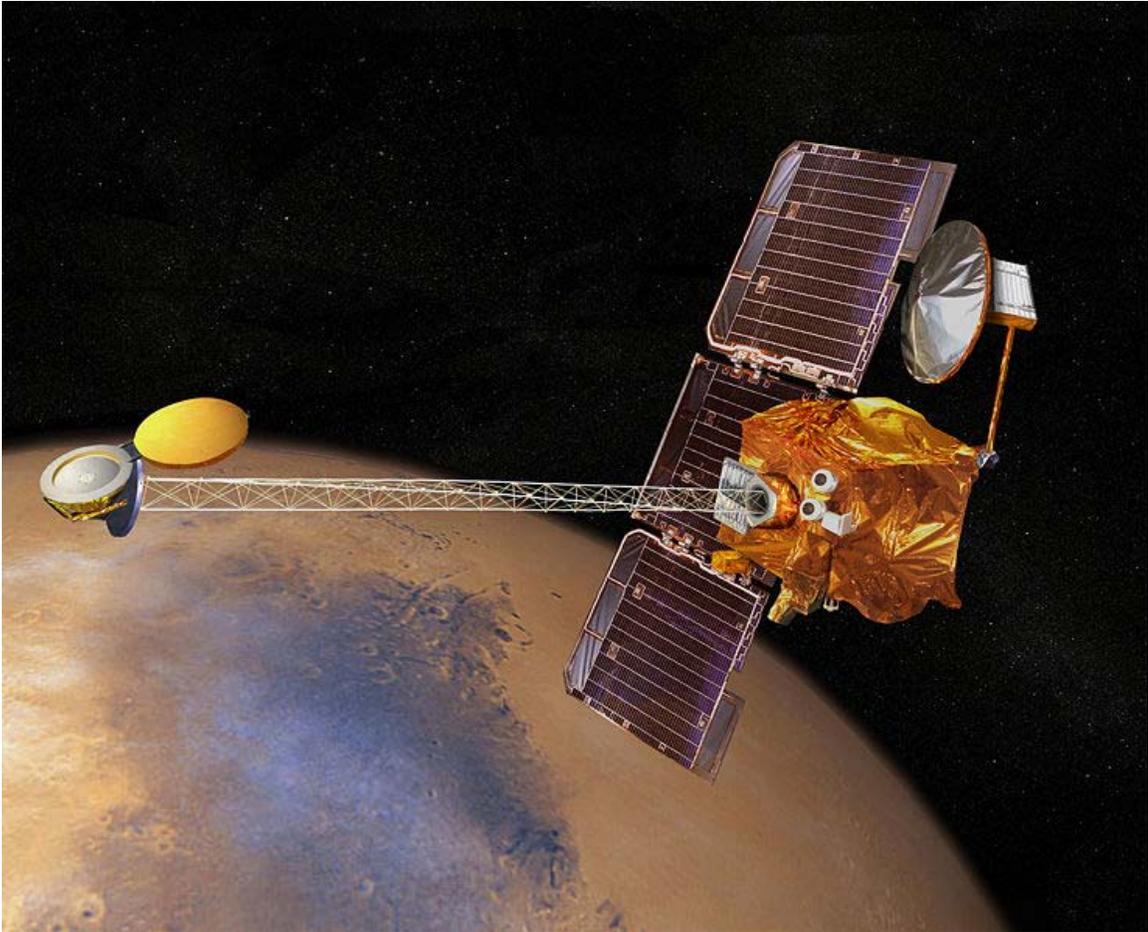
The *2001 Mars Odyssey* used spectrometers and imagers to hunt for evidence of past or present water and volcanic activity on Mars.

Beyond the primitive methods of remote sensing our earliest ancestors used (ex.: standing on a high cliff or tree to view the landscape), the modern discipline arose with the development of flight. The balloonist G. Tournachon (alias Nadar) made photographs of Paris from his balloon in 1858. Messenger pigeons, kites, rockets and unmanned balloons were also used for early images. With the exception of balloons, these first, individual images were not particularly useful for map making or for scientific purposes.

Systematic aerial photography was developed for military surveillance and reconnaissance purposes beginning in World War I and reaching a climax during the Cold War with the use of modified combat aircraft such as the P-51, P-38, RB-66 and the F-4C, or specifically designed collection platforms such as the U2/TR-1, SR-71, A-5 and the OV-1 series both in overhead and stand-off collection. A more recent development is that of increasingly smaller sensor pods such as those used by law enforcement and the military, in both manned and unmanned platforms. The advantage of this approach is that this requires minimal modification to a given airframe. Later imaging technologies would include Infra-red, conventional, doppler and synthetic aperture radar.

The development of artificial satellites in the latter half of the 20th century allowed remote sensing to progress to a global scale as of the end of the Cold War. Instrumentation aboard various Earth observing and weather satellites such as Landsat, the Nimbus and more recent missions such as RADARSAT and UARS provided global measurements of various data for civil, research, and military purposes. Space probes to other planets have also provided the opportunity to conduct remote sensing studies in extraterrestrial environments, synthetic aperture radar aboard the Magellan spacecraft provided detailed topographic maps of Venus, while instruments aboard SOHO allowed studies to be performed on the Sun and the solar wind, just to name a few examples.

Recent developments include, beginning in the 1960s and 1970s with the development of image processing of satellite imagery. Several research groups in Silicon Valley including NASA Ames Research Center, GTE and ESL Inc. developed Fourier transform techniques leading to the first notable enhancement of imagery data.

The introduction of online web services for easy access to remote sensing data in the 21st century (mainly low/medium-resolution images), like Google Earth, has made remote sensing more familiar to the big public and has popularized the science.

Remote Sensing software

Remote Sensing data is processed and analyzed with computer software, known as a remote sensing application. A large number of proprietary and open source applications exist to process remote sensing data. According to an NOAA Sponsored Research by Global Marketing Insights, Inc. the most used applications among Asian academic groups involved in remote sensing are as follows: ERDAS 36% (ERDAS IMAGINE 25% & ERMapper 11%); ESRI 30%; ITT Visual Information Solutions ENVI 17%; MapInfo 17%. Among Western Academic respondents as follows: ESRI 39%, ERDAS IMAGINE 27%, MapInfo 9%, AutoDesk 7%, ITT Visual Information Solutions ENVI 17%. Other important Remote Sensing Software packages include: TNTmips from MicroImages, PCI Geomatica made by PCI Geomatics, the leading remote sensing software package in Canada, IDRISI from Clark Labs, Image Analyst from Intergraph, and the original object based image analysis software eCognition from Definiens. Dragon/ips is one of the oldest remote sensing packages still available, and is in some cases free. Open source remote sensing software includes GRASS GIS, QGIS, OSSIM, Opticks (software) and Orfeo toolbox.and arc gis

Aerial and satellite imagery

Besides their role in photogrammetry, aerial and satellite imagery can be used to identify and delineate terrain features and more general land-cover features. Certainly they have become more and more a part of geovisualization, whether maps or GIS systems. False-color and non-visible spectra imaging can also help determine the lie of the land by delineating vegetation and other land-use information more clearly. Images can be in visible colours and in other spectrum

Photogrammetry

Photogrammetry is a measurement technique for which the co-ordinates of the points in 3D of an object are determined by the measurements made in two photographic images (or more) taken starting from different positions, usually from different passes of an aerial photography flight. In this technique, the common points are identified on each image. A line of sight (or ray) can be built from the camera location to the point on the object. It is the intersection of its rays (triangulation) which determines the relative three-dimensional position of the point. Known control points can be used to give these relative positions absolute values. More sophisticated algorithms can exploit other information on the scene known a priori (for example, symmetries in certain cases allowing the rebuilding of three-dimensional co-ordinates starting from one only position of the camera).

Radar and sonar

Satellite radar mapping is one of the major techniques of generating Digital Elevation Models (see below). Similar techniques are applied in bathymetric surveys using sonar to determine the terrain of the ocean floor. In recent years, LIDAR (**L**ight **D**etection **a**nd **R**anging), a remote sensing technique using a laser instead of radio waves, has increasingly been employed for complex mapping needs such as charting canopies and monitoring glaciers.

Forms of topographic data

Terrain is commonly modelled either using vector (triangulated irregular network or TIN) or gridded (Raster image) mathematical models. In the most applications in environmental sciences, land surface is represented and modelled using gridded models. In civil engineering and entertainment businesses, the most representations of land surface employ some variant of TIN models. In geostatistics, land surface is commonly modelled as a combination of the two signals - the smooth (spatially correlated) and the rough (noise) signal.

In practice, surveyors first sample heights in an area, then use these to produce a Digital Land Surface Model (also known as a digital elevation model). The DLSM can then be used to visualize terrain, drape remote sensing images, quantify ecological properties of a surface or extract land surface objects. Note that the contour data or any other sampled elevation datasets are not a DLSM. A DLSM implies that elevation is available continuously at each location in the study area, i.e. that the map represents a complete surface. Digital Land Surface Models should not be confused with Digital Surface Models, which can be surfaces of the canopy, buildings and similar objects. For example, in the case of surface models produces using the LIDAR technology, one can have several surfaces - starting from the top of the canopy to the actual solid earth. The difference between the two surface models can then be used to derive volumetric measures (height of trees etc).

Raw survey data

Topographic survey information is historically based upon the notes of surveyors. They may derive naming and cultural information from other local sources (for example, boundary delineation may be derived from local cadastral mapping. While of historical interest, these field notes inherently include errors and contradictions that later stages in map production resolve.

Remote sensing data

As with field notes, remote sensing data (aerial and satellite photography, for example), is raw and uninterpreted. It may contain holes (due to cloud cover for example) or inconsistencies (due to the timing of specific image captures). Most modern topographic mapping includes a large component of remotely sensed data in its compilation process.

Topographic map
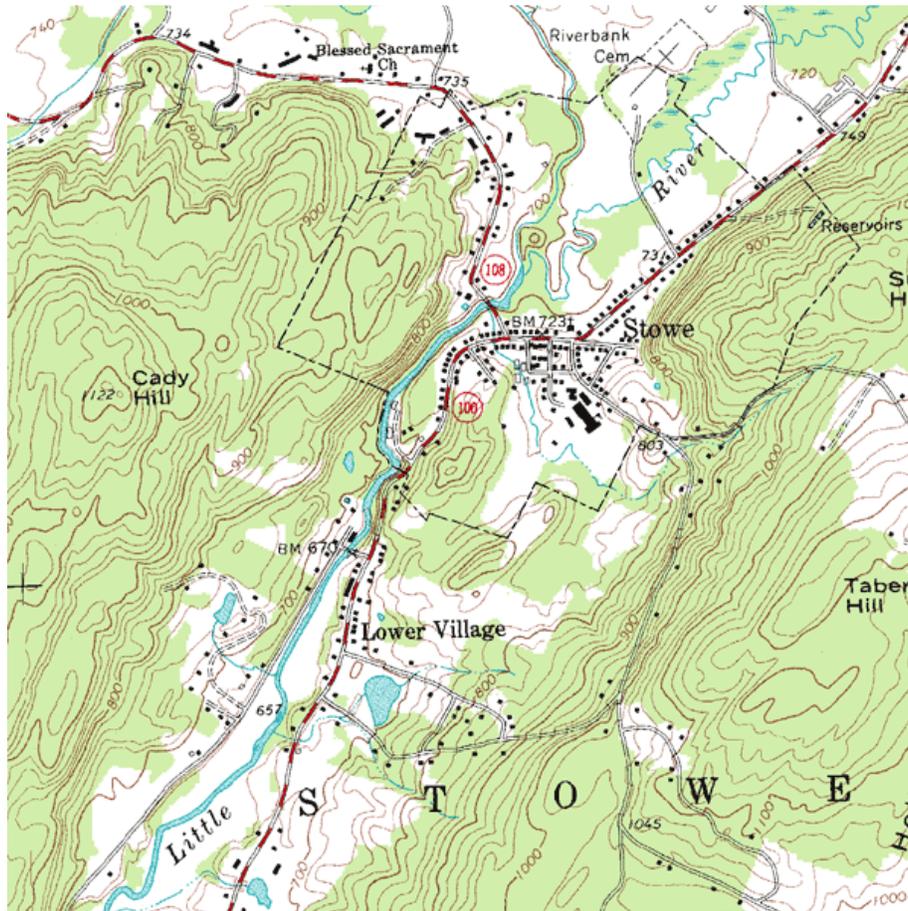
A topographic map with contour lines
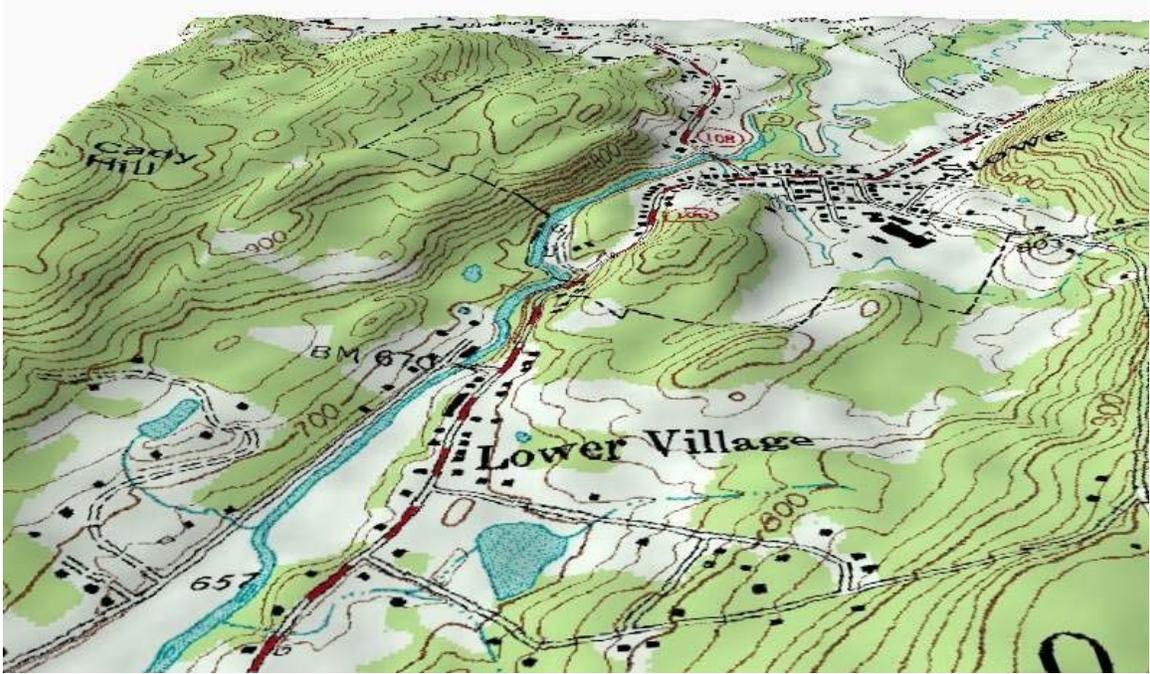
Part of the same map in a perspective shaded relief view illustrating how the contour lines follow the terrain
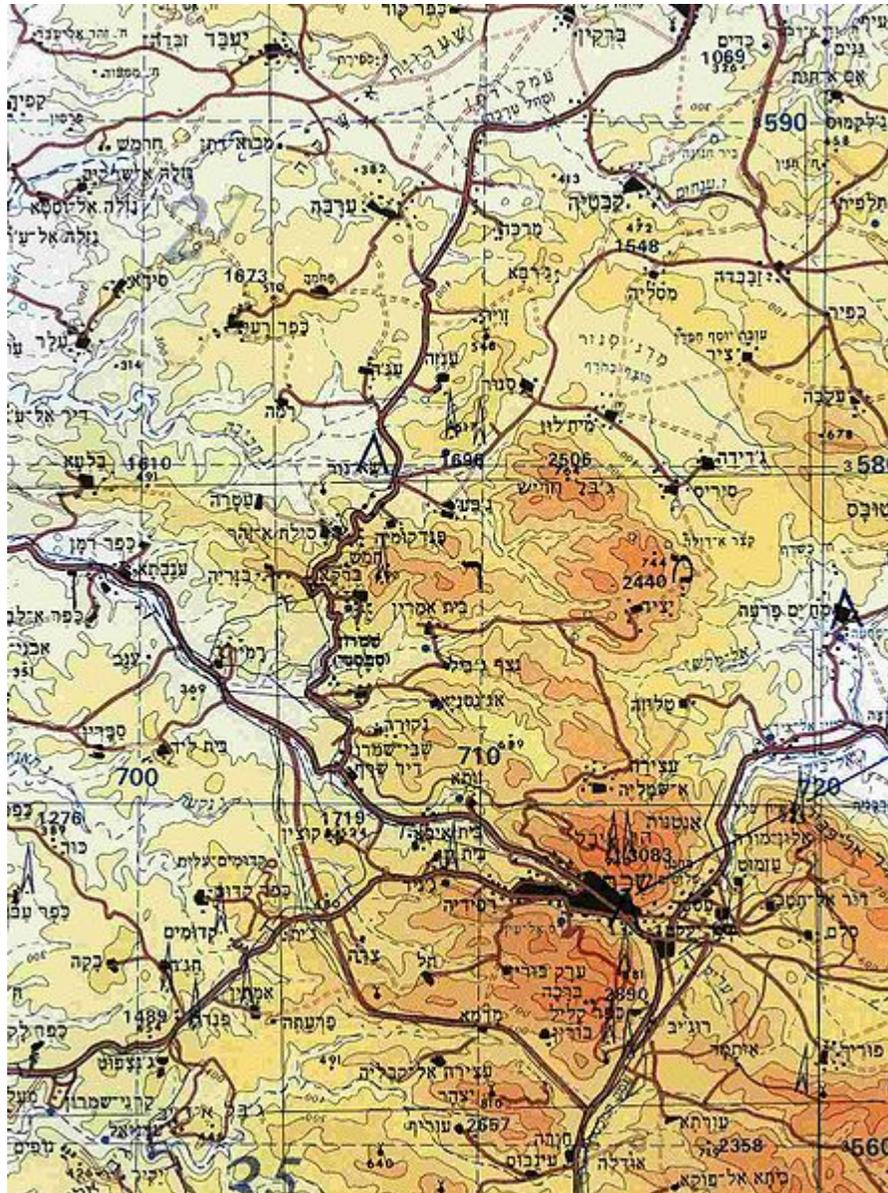
Section of topographical map of Nablus area (West Bank) with contour lines at 100-meter intervals. Heights are colour-coded

A **topographic map** is a type of map characterized by large-scale detail and quantitative representation of relief, usually using contour lines in modern mapping, but historically using a variety of methods. Traditional definitions require a topographic map to show both natural and man-made features. A topographic map is typically published as a map series, made up of two or more map sheets that combine to form the whole map.

The Canadian Centre for Topographic Information provides this definition of a topographic map:

A topographic map is a detailed and accurate graphic representation of cultural and natural features on the ground.

Other authors define topographic maps by contrasting them with another type of map; they are distinguished from smaller-scale "chorographic maps" that cover large regions, "planimetric maps" that do not show elevations, and "thematic maps" that focus on specific topics.

However, in the vernacular and day to day world, the representation of relief (contours) is popularly held to define the genre, such that even small-scale maps showing relief are commonly (and erroneously, in the technical sense) called "topographic".

The study or discipline of topography, while interested in relief, is actually a much broader field of study which takes into account all natural and man made features of terrain.

History

Topographic maps are based on topographical surveys. Performed at large scales, these surveys are called topographical in the old sense of topography, showing a variety of elevations and landforms. This is in contrast to older cadastral surveys, which primarily show property and governmental boundaries. The first multi-sheet topographic map series of an entire country, the *Carte géométrique de la France*, was completed in 1789. Topographic surveys were prepared by the military to assist in planning for battle and for defensive emplacements (thus the name and history of the United Kingdom's Ordnance Survey). As such, elevation information was of vital importance.

As they evolved, topographic map series became a national resource in modern nations in planning infrastructure and resource exploitation. In the United States, the national map-making function which had been shared by both the Army Corps of Engineers and the Department of the Interior migrated to the newly created United States Geological Survey in 1879, where it has remained since.

Uses

Topographic maps have multiple uses in the present day: any type of geographic planning or large-scale architecture; earth sciences and many other geographic disciplines; mining and other earth-based endeavours; and recreational uses such as hiking or, in particular, orienteering, which uses highly detailed maps in its standard requirements.

Map conventions

The various features shown on the map are represented by conventional signs or symbols. For example, colors can be used to indicate a classification of roads. These signs are

usually explained in the margin of the map, or on a separately published characteristic sheet.

Topographic maps are also commonly called *contour maps* or *topo maps*. In the United States, where the primary national series is organized by a strict 7.5 minute grid, they are often called *topo quads* or quadrangles.

Topographic maps conventionally show topography, or land contours, by means of contour lines. Contour lines are curves that connect contiguous points of the same altitude (isohypse). In other words, every point on the marked line of 100 m elevation is 100 m above mean sea level.

These maps usually show not only the contours, but also any significant streams or other bodies of water, forest cover, built-up areas or individual buildings (depending on scale), and other features and points of interest.

Today, topographic maps are prepared using photogrammetric interpretation of aerial photography, LIDAR and other Remote sensing techniques. Older topographic maps were prepared using traditional surveying instruments.

Publishers of national topographic map series

Most countries have some sort of national mapping program. Those listed below are only a small selection. Several commercial vendors supply international topographic map series.

Australia

The National Mapping Information Group of Geoscience Australia is the Australian Government's national mapping agency. It provides topographic maps and data to meet the needs of the sustainable development of the nation. The Office of Spatial Data Management provides an online free map service MapConnect. These topographic maps of scales 1:250,000 and 1:100,000 are available in printed form from the Sales Centre. 1:50,000 and 1:25,000 maps are produced in conjunction with the Department of Defence.

Canada

The Centre for Topographic Information produces topographic maps of Canada at scales of 1:50,000 and 1:250,000. They are known as the National Topographic System (NTS). A government proposal to discontinue publishing of all hardcopy or paper topographic maps in favor of digital-only mapping data was shelved in 2006 after intense public opposition.

Denmark

The National Survey and Cadastre of Denmark is responsible for producing topographic and nautical geodata of Denmark, Greenland and the Faroe Islands.

Finland

The National Land Survey of Finland produces the Topographic Database (accuracy 1:5000-1:10 000) and publishes topographic maps of Finland at 1:25,000 and 1:50,000. In addition topographics maps can be viewed by using a free map service MapSite

France

The Institut Géographique National (IGN) produces topographic maps of France at 1:25,000 and 1:50,000. In addition, topographic maps are freely accessible online, through the Géoportail website.

Germany

In principle, each federal state *(Bundesland)* is in charge of producing the official topographic maps. In fact, the maps between 1:5,000 and 1:100,000 are produced and published by the land surveying offices of each federal state, the maps between 1:200,000 and 1:1,000,000 by a federal office - the Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt am Main.

Greece

Topographic maps for general use are available at 1:50,000 and 1:100,000 from the *Hellenic Military Geographical Service (HMGS)*. They use a national projection system called EGSA'87, which is a Transverse Mercatorial Projection mapping Greece in one zone. A few areas are also available at 1:25,000. Some private firms sell topographic maps of national parks based on HMGS topography.

India

The Survey of India is responsible for all topographic control, surveys and mapping of India.

Japan

The Geographical Survey Institute of Japan is responsible for base mapping of Japan. Standard map scales are 1:25,000, 1:50,000, 1:200,000 and 1:500,000

New Zealand

Land Information New Zealand is the government agency responsible for providing up-to-date topographic mapping. LINZ topographic maps cover all of New Zealand, offshore islands, some Pacific Islands and the Ross Sea Region. The standard issue *NZTopo* map series was published September 2009 at 1:50,000 (NZTopo50), and 1:250,000 (NZTopo250). Vector data from the New Zealand Topographic Database (NZTopo) is also available.

Pakistan

The responsibility for topographic mapping and aerial photography lies with the Surveyor General of Pakistan [SGP]. Established in 1947, the Survey of Pakistan (SOP) is based in Rawalpindi with a number of regional offices distributed at urban centers throughout Pakistan. SGP is a civil organization which, for security reasons, is headed by a Surveyor General and works under the strict control of Army General Headquarters (GHQ). Colonel C.A.K. Innes-Wilson, a Royal Engineers officer who joined the Survey of India which mapped the subcontinent, was the first Surveyor General of Pakistan.

All departments which require topographic maps make their request to SGP and many are permanently registered with it for mapping and aerial photographs procurement. The SOP performs these functions under the auspices of the Ministry of Defence (MOD). Organisationally, the SOP is overseen by the Surveyor General (SG) who is a direct military appointee and a senior uniformed officer. The SG reports directly to the Secretary of Defence. Under the SG are two Deputy SG's (I and II) who manage the operational departments of the agency and a Senior Technical Advisor. These departments are divided into Regional Directorates for Topographic Mapping including the Northern region centred in Peshawar, Eastern region (Lahore), Western region (Quetta) and finally, the Southern region in Karachi. Responsibility for fields surveys and the maintenance/update of topographic maps are sub-divided according to these geographic areas.

Three other operational directorates exist within the SOP which include the Directorate of Photogrammetry (Rawalpindi), Directorate of Printing and Map Publications (Rawalpindi) and the Directorate of the Survey Training Institute (Islamabad). The Photogrammetry Directorate is responsible for the commissioning and flying of aerial photography, followed by map interpretation and production from these source data.

Spain

The Instituto Geográfico Nacional (IGN) is responsible for the official topographic maps. It does use six scales that cover all the Spanish territory: 1:25,000, 1:50,000, 1:200,000, 1:500,000, 1:1,000,000 and 1:2,000,000. The commonest scale is the first one, which utilizes the UTM system.

South Africa

The Chief Directorate: National Geo-spatial Information (CD:NGI) is responsible for the official, definitive, national topographic mapping and control network system of South Africa. The CD:NGI provides a range of maps, aerial photography, survey services and computer data products for government departments, commerce, planning, administrative, educational, management and leisure use.

Switzerland

Swisstopo (the Federal Office of Topography) produces topographic maps of Switzerland at seven different scales.

United Kingdom

The Ordnance Survey (OS) produces topographic map series covering the United Kingdom at 1:25,000 and 1:50,000 scales. The 1:25,000 scale is known as the "Explorer" series, and include an "OL" (Outdoor Leisure) sub-series for areas of special interest to hikers and walkers. It replaced the "Pathfinder" series, which was less colourful and covered a smaller area on each map. The 1:50,000 scale is known as the "Landranger" and carries a distinctive pink cover. More detailed mapping as fine as 1:10000 cover some parts of the country. The 1:25K and 1:50K metric scales are easily coordinated with standard romer scales on currently available compasses and plotting tools. The Ordnance Survey maintains a mapping database from which they can print specialist maps at virtually any scale.

United States

The United States Geological Survey (USGS), a civilian Federal agency, produces several national series of topographic maps which vary in scale and extent, with some wide gaps in coverage, notably the complete absence of 1:50,000 scale topographic maps or their equivalent. The largest (both in terms of scale and quantity) and best-known topographic series is the 7.5-minute, 1:24,000 scale, quadrangle — a non-metric scale virtually unique to the United States.
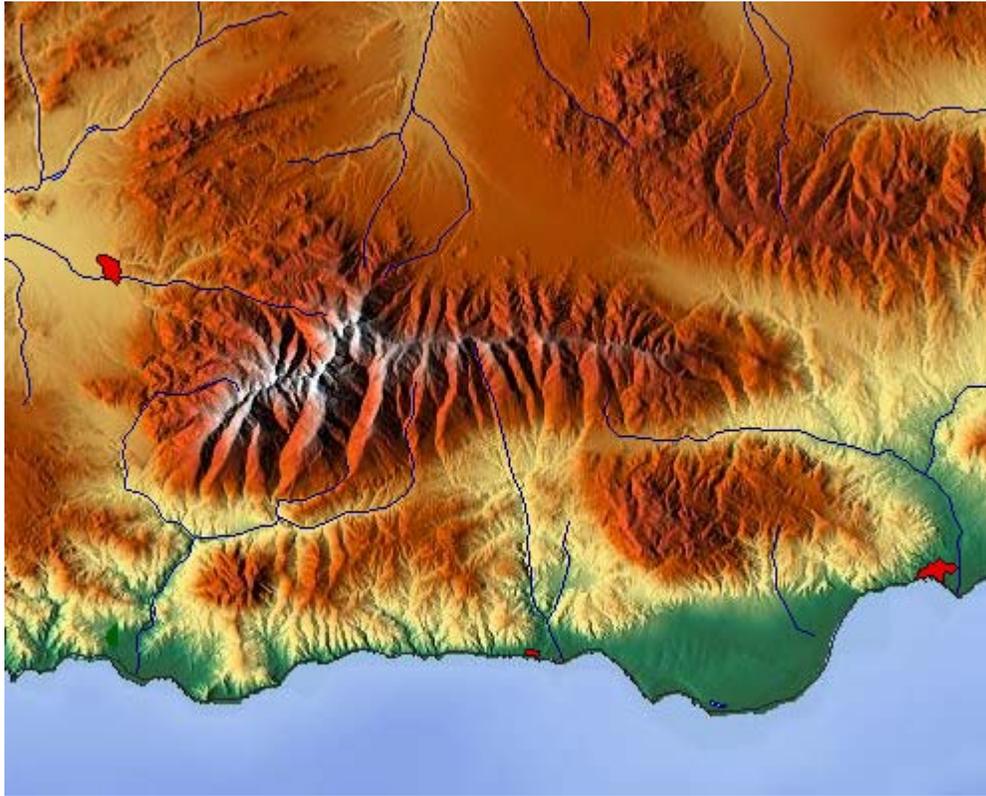
Digital elevation model

MTM -05/277 E: Tithonium Chasma (3 X Vertical Exaggeration)
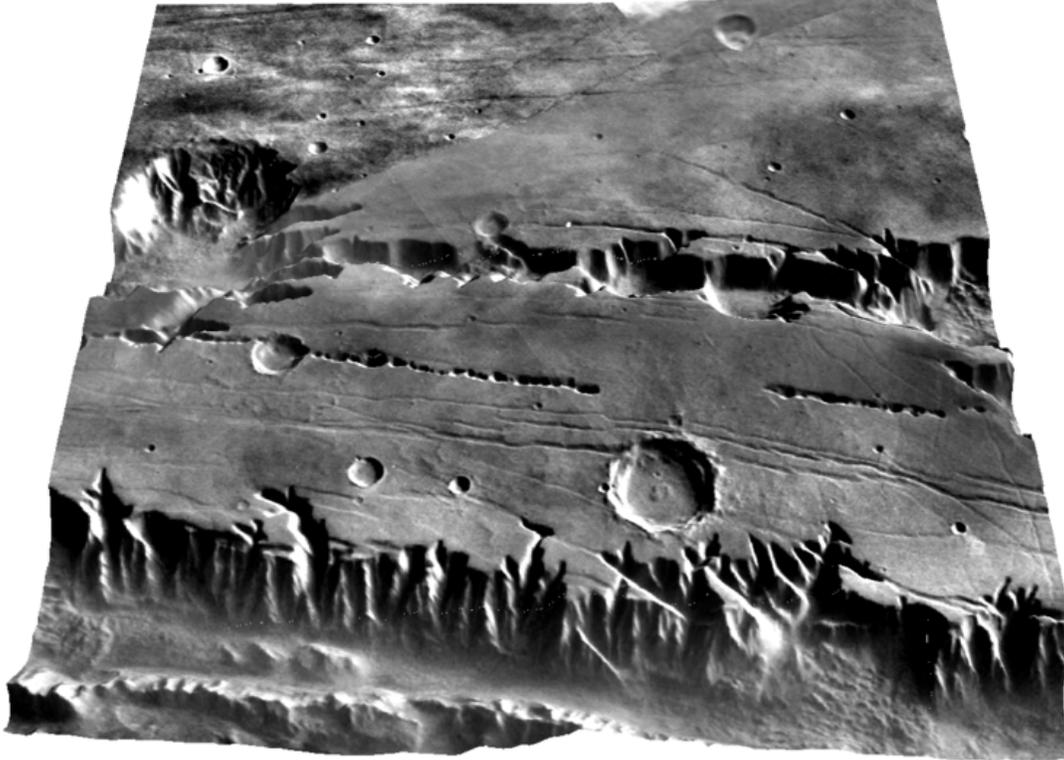
3D rendering of a DEM of Tithonium Chasma on Mars

A **digital elevation model** (**DEM**) is a digital representation of ground surface topography or terrain. It is also widely known as a **digital terrain model** (**DTM**). A DEM can be represented as a raster (a grid of squares) or as a triangular irregular network. DEMs are commonly built using remote sensing techniques, but they may also be built from land surveying. DEMs are used often in geographic information systems, and are the most common basis for digitally-produced relief maps.

Production

Relief map Sierra Nevada

Digital elevation models may be prepared in a number of ways, but they are frequently obtained by remote sensing rather than direct survey. One powerful technique for generating digital elevation models is interferometric synthetic aperture radar: two passes of a radar satellite (such as RADARSAT-1 or TerraSAR-X), or a single pass if the satellite is equipped with two antennas (like the SRTM instrumentation), suffice to generate a digital elevation map tens of kilometers on a side with a resolution of around ten meters. Alternatively, other kinds of stereoscopic pairs can be employed using the digital image correlation method, where two optical images acquired with different angles taken from the same pass of an airplane or an Earth Observation Satellite (such as the HRS instrument of SPOT5 or the VNIR band of ASTER).

In 1986, the SPOT 1 satellite provided the first usable elevation data for a sizeable portion of the planet's landmass, using two-passes stereoscopic correlation. Later, further data were provided by the European Remote-Sensing Satellite (ERS) using the same method, the Shuttle Radar Topography Mission using single-pass SAR and the ASTER instrumentation on the Terra satellite using double-pass stereo pairs.

Older methods of generating DEMs often involve interpolating digital contour maps that may have been produced by direct survey of the land surface; this method is still used in

mountain areas, where interferometry is not always satisfactory. Note that the contour line data or any other sampled elevation datasets (by GPS or ground survey) are not DEMs, but may be considered digital terrain models. A DEM implies that elevation is available continuously at each location in the study area.

The quality of a DEM is a measure of how accurate elevation is at each pixel (absolute accuracy) and how accurately is the morphology presented (relative accuracy). Several factors play an important role for quality of DEM-derived products:

* terrain roughness;
* sampling density (elevation data collection method);
* grid resolution or pixel size;
* interpolation algorithm;
* vertical resolution;
* terrain analysis algorithm;

Methods for obtaining elevation data used to create DEMs

* Real Time Kinematic GPS
* stereo photogrammetry
* LIDAR
* Topographic maps
* Theodolite or total station
* Doppler radar
* Focus variation
* Inertial surveys

Uses

Common uses of DEMs include:

* Extracting terrain parameters
* Modeling water flow or mass movement (for example avalanches and landslides)
* Creation of relief maps
* Rendering of 3D visualizations.
* 3d flight planning
* Creation of physical models (including raised-relief maps)
* Rectification of aerial photography or satellite imagery.
* Reduction (terrain correction) of gravity measurements (gravimetry, physical geodesy).
* Terrain analyses in geomorphology and physical geography
* Geographic Information Systems (GIS)
* Engineering and infrastructure design
* Global positioning systems (GPS)

- Line-of-sight analysis
- Base mapping
- Flight simulation
- Precision farming and forestry
- Surface analysis
- Intelligent transportation systems (ITS)
- Auto safety / Advanced Driver Assistance Systems (ADAS)

Differences between DEMs and DSMs

A *digital elevation model* - also sometimes called a *digital terrain model* (DTM) - generally refers to a representation of the Earth's surface (or subset of this), excluding features such as vegetation, buildings, bridges, etc. The DEM often comprises much of the raw dataset, which may have been acquired through techniques such as photogrammetry, LiDAR, IfSAR, land surveying, etc. A *digital surface model* (DSM) on the other hand includes buildings, vegetation, and roads, as well as natural terrain features. The DEM provides a so-called bare-earth model, devoid of landscape features. While a DSM may be useful for landscape modeling, city modeling and visualization applications, a DEM is often required for flood or drainage modeling, land-use studies, geological applications, and much more.

Sources

A free DEM of the whole world called GTOPO30 (30 arcsecond resolution, approx. 1 km) is available, but its quality is variable and in some areas it is very poor. A much higher quality DEM from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument of the Terra satellite is also freely available for 99% of the globe, and represents elevation at a 30 meter resolution. A similarly high resolution was previously only available for the United States territory under the Shuttle Radar Topography Mission (SRTM) data, while most of the rest of the planet was only covered in a 3 arc-second resolution (around 90 meters). The limitation with the GTOPO30 and SRTM datasets is that they cover continental landmasses only, and SRTM does not cover the polar regions and has mountain and desert no data (void) areas. SRTM data, being derived from radar, represents the elevation of the first-reflected surface — quite often tree tops. So, the data are not necessarily representative of the ground surface, but the top of whatever is first encountered by the radar. Submarine elevation (known as bathymetry) data is generated using ship-mounted depth soundings. The SRTM30Plus dataset (used in NASA World Wind) attempts to combine GTOPO30, SRTM and bathymetric data to produce a truly global elevation model. A novel global DEM of postings lower than 12m and a height accuracy of less than 2m is expected being genetated by the TanDEM-X satellite mission which started in July 2010.

The most usual grid (raster) is between 50 and 500 meters. In gravimetry e.g., the primary grid may be 50 m, but is switched to 100 or 500 meters in distances of about 5 or 10 kilometers.

Many national mapping agencies produce their own DEMs, often of a higher resolution and quality, but frequently these have to be purchased, and the cost is usually prohibitive to all except public authorities and large corporations. DEMs are often a product of National LIDAR Dataset programs.

Free DEMs are also available for Mars: the MEGDR, or Mission Experiment Gridded Data Record, from the Mars Global Surveyor's Mars Orbiter Laser Altimeter (MOLA) instrument; and NASA's Mars Digital Terrain Model (DTM).

United States

The US Geological Survey produces the National Elevation Dataset, a seamless DEM for the contiguous United States, Hawaii and Puerto Rico based on 7.5' topographic mapping. As of the beginning of 2006, this replaces the earlier DEM tiled format (one DEM per USGS topographic map).

Topological modeling

A geographic information system (GIS) can recognize and analyze the spatial relationships that exist within digitally stored spatial data. These topological relationships allow complex spatial modelling and analysis to be performed. Topological relationships between geometric entities traditionally include adjacency (what adjoins what), containment (what encloses what), and proximity (how close something is to something else).

- reconstitute a sight in synthesized images of the ground,
- determine a trajectory of overflight of the ground,
- calculate surfaces or volumes,
- trace topographic profiles,

Topography in other fields

Topography has been applied to different science fields. In neuroscience, the neuroimaging discipline uses techniques such as EEG topography for brain mapping. In ophthalmology, corneal topography is used as a technique for mapping the surface curvature of the cornea.
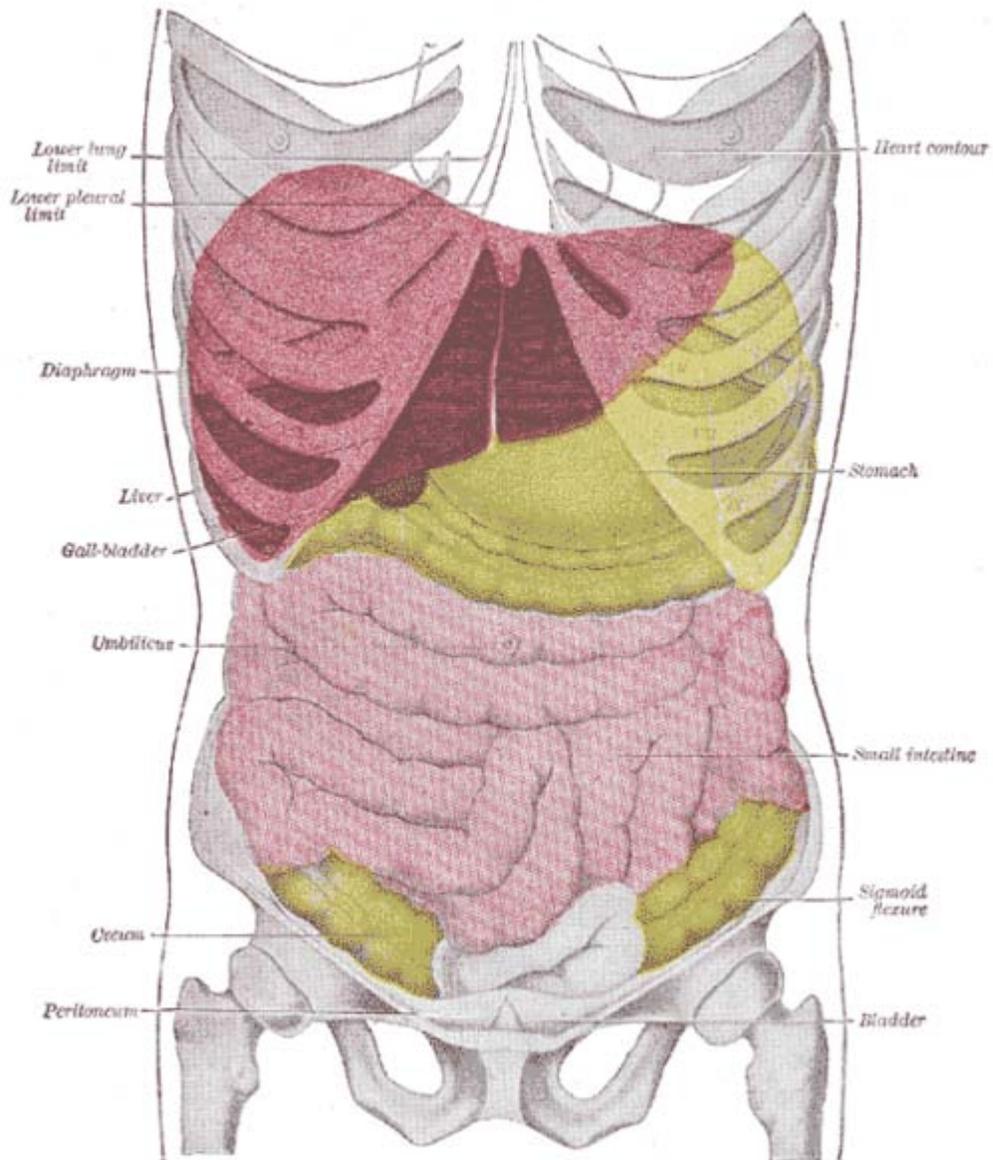
Topography of thoracic and abdominal viscera

In human anatomy, topography is superficial human anatomy.

In mathematics the concept of topography is used to indicate the patterns or general organization of features on a map or as a term referring to the pattern in which variables (or their values) are distributed in a space.

Landform

This panorama in Great Smoky Mountains National Park has the readily identifiable **physical features** of a rolling plain, actually part of a broad valley, distant foothills, and a backdrop of the old much weathered Appalachian mountain range.

In the earth sciences and geology sub-fields, a **landform** or **physical feature** comprises a geomorphological unit, and is largely defined by its surface form and location in the landscape, as part of the terrain, and as such, is typically an element of topography. Landform elements also include seascape and oceanic waterbody interface features such as bays, peninsulas, seas and so forth, including sub-aqueous terrain features such as submersed mountain ranges, volcanoes, and the great ocean basins.

Physical characteristics

Landforms are categorised by characteristic physical attributes such as elevation, slope, orientation, stratification, rock exposure, and soil type.

Gross *physical features or landforms* include intuitive elements such as berms, mounds, hills, ridges, cliffs, valleys, rivers, peninsulas and numerous other structural and size-scaled (i.e. ponds vs. lakes, hills vs. mountains) elements including various kinds of inland and oceanic waterbodies and sub-surface features.

Hierarchy of classes

Oceans and continents exemplify the highest-order landforms. Landform elements are parts of a high-order landforms that can be further identified and systematically given a cohesive definition such as hill-tops, shoulders, saddles, foreslopes and backslopes.

Some generic landform elements including: pits, peaks, channels, ridges, passes, pools and plains, may be extracted from a digital elevation model using some automated techniques where the data has been gathered by modern satellites and stereoscopic aerial surveillance cameras. Until recently, compiling the data found in such data sets required time consuming and expensive techniques of many man-hours.

Terrain (or *relief*) is the third or vertical dimension of *land surface*. Topography is the study of terrain, although the word is often used as a synonym for relief itself. When relief is described underwater, the term bathymetry is used. In cartography, many different techniques are used to describe relief, including contour lines and TIN (Triangulated irregular network).

Elementary landforms (segments, facets, relief units) are the smallest homogeneous divisions of the land surface, at the given scale/resolution. These are areas with relatively homogenous morphometric properties, bounded by lines of discontinuity. A plateau or a hill can be observed at various scales ranging from few hundred meters to hundreds of kilometers. Hence, the spatial distribution of landforms is often scale-dependent as is the case for soils and geological strata.

A number of factors, ranging from plate tectonics to erosion and deposition, can generate and affect landforms. Biological factors can also influence landforms— for example, note the role of vegetation in the development of dune systems and salt marshes, and the work of corals and algae in the formation of coral reefs.

Landforms do not include man-made features, such as canals, ports and many harbors; and geographic features, such as deserts, forests, grasslands, and impact craters.

Many of the terms are not restricted to refer to features of the planet Earth, and can be used to describe surface features of other planets and similar objects in the Universe. Examples are mountains, polar caps, and valleys, which are found on all of the terrestrial planets.

Chapter-4

Drainage Basin & System
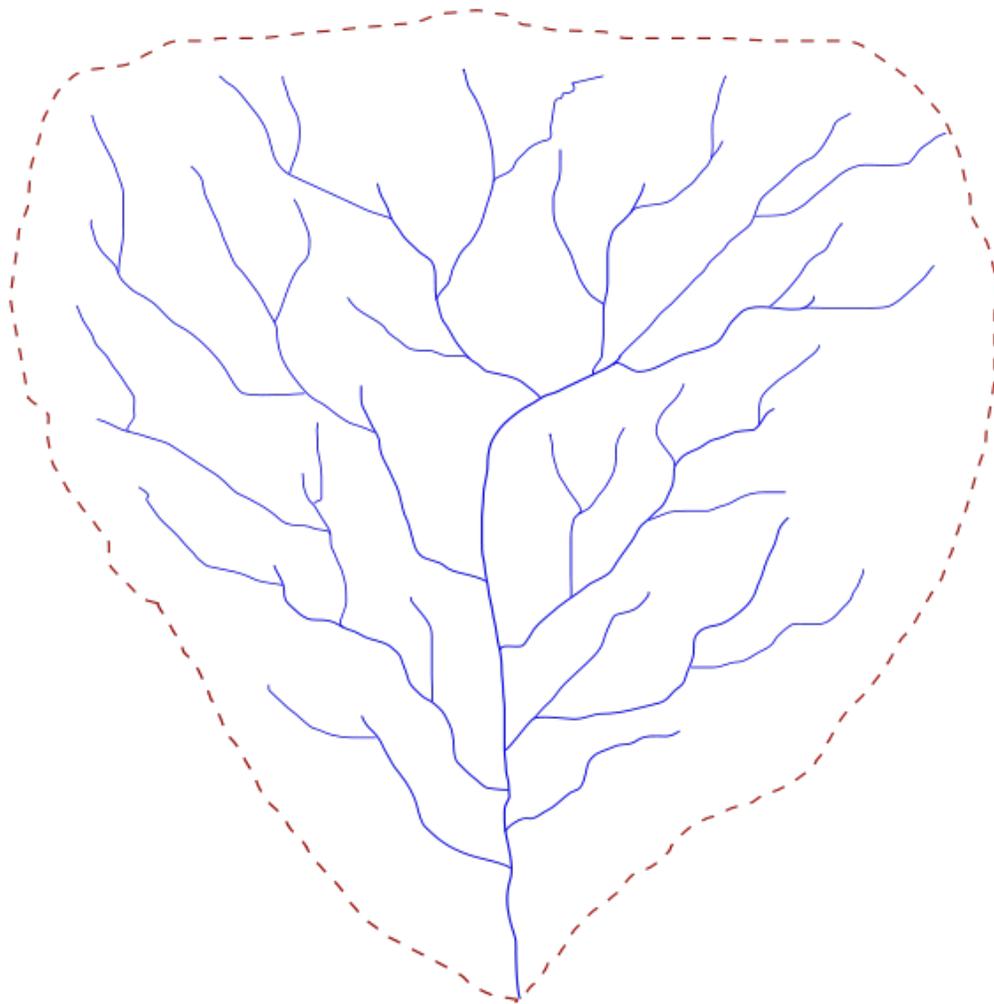
Example of a drainage basin. The dashed line is the main water divide of the hydrographic basin

A **drainage basin** is an extent or area of land where water from rain and melting snow or ice drains downhill into a body of water, such as a river, lake, reservoir, estuary, wetland, sea or ocean. The drainage basin includes both the streams and rivers that convey the water as well as the land surfaces from which water drains into those channels, and is separated from adjacent basins by a drainage divide.

The drainage basin acts as a funnel by collecting all the water within the area covered by the basin and channelling it into a waterway. Each drainage basin is separated topographically from adjacent basins by a geographical barrier such as a ridge, hill or mountain, which is known as a water divide.

Other terms that are used to describe a drainage basin are **catchment**, **catchment area**, **catchment basin**, **drainage area**, **river basin**, **water basin** and **watershed**. In the technical sense, a watershed refers to a divide that separates one drainage area from another drainage area. However, in the United States and Canada, the term is often used to mean a drainage basin or catchment area itself. Drainage basins drain into other drainage basins in a hierarchical pattern, with smaller **sub-drainage basins** combining into larger drainage basins.

The United States Environmental Protection Agency launched the website Watershed Central for the US public to exchange information and locate resources needed to restore local drainage basins in that country.

Major drainage basins of the world

Map
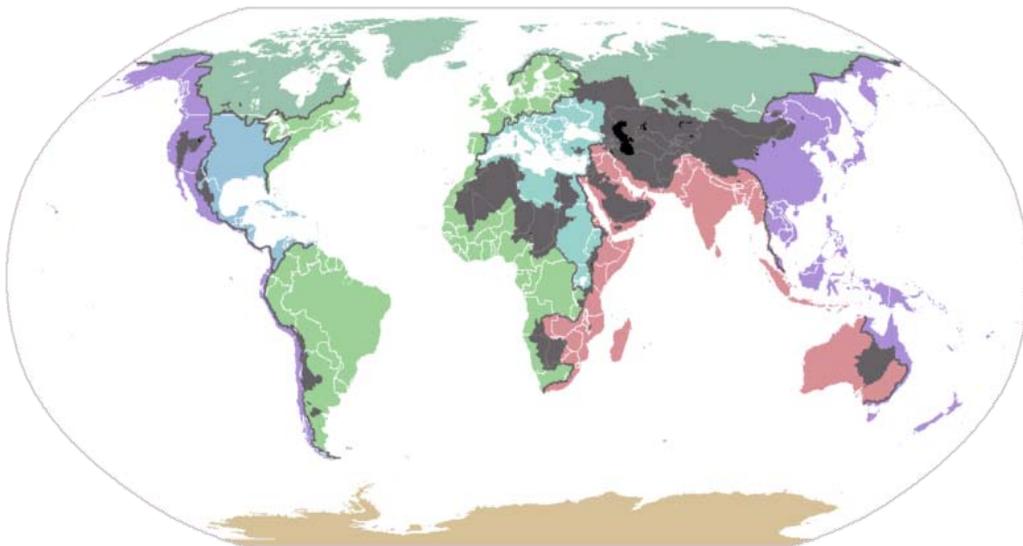
Drainage basins of the principal oceans and seas of the world. Grey areas are endorheic basins that do not drain to the ocean.

Ocean basins

There are numerous drainage basins throughout the world in all sorts of places. The following is a list of some of the major ones:

- About 47% of all land in the world drains to the Atlantic Ocean. In North America, it directly drains the Saint Lawrence River and Great Lakes basins, the Eastern Seaboard of the United States, the Canadian Maritimes, and most of Newfoundland and Labrador. It also directly drains nearly all of South America east of the Andes, most of Western and Central Europe, and the greatest portion of western Sub-Saharan Africa. The three major mediterranean seas of the world also flow to the Atlantic:
    - The American Mediterranean Sea (the Caribbean Sea and Gulf of Mexico) basin includes most of the American interior between the Appalachian and Rocky Mountain ranges, a small part of the Canadian provinces of Alberta and Saskatchewan, eastern Central America, the islands of the Caribbean and the Gulf, and a small part of northern South America.
    - The European Mediterranean Sea basin includes much of northern Africa, east-central Africa (through the Nile), southern, central, and eastern Europe, Turkey, and the coastal areas of Israel, Lebanon, and Syria.
    - The Arctic Ocean basin drains most of Western and Northern Canada east of the Continental Divide, the north shore of Alaska and parts of North Dakota, South Dakota, Minnesota, and Montana in the United States, the north shore of the Scandinavian peninsula in Europe, and much of central and northern Russia.
- Just over 13% of the land in the world drains to the Pacific Ocean. Its basin includes much of China, southeastern Russia, Japan, Korea, most of Indonesia and Malaysia, the Philippines, all of the Pacific Islands, the northeast coast of Australia, and the western parts of Canada, the United States (including most of Alaska), Central America, and South America.
- The Indian Ocean's drainage basin also comprises about 13% of Earth's land. It drains the eastern coast of Africa, the coasts of the Red Sea and the Persian Gulf, the Indian subcontinent, Burma, and most of Australia.
- The Southern Ocean drains Antarctica. Antarctica comprises approximately eight percent of the Earth's land.

Largest river basins

The three largest river basins (by area), from largest to smallest, are the Amazon basin, the Congo basin, and the Mississippi basin. The three rivers that drain the most water, from most to least, are the Amazon, Congo, and Ganges Rivers.

Endorheic drainage basins

NASA photo of the endorheic Tarim Basin

Endorheic basin showing waterflow input into Üüreg Nuur

An **endorheic basin** is a closed drainage basin that retains water and allows no outflow to other bodies of water such as rivers or oceans. Normally, water that has accrued in a drainage basin eventually flows out through rivers or streams on Earth's surface or by underground diffusion through permeable rock, ultimately ending up in the oceans. However, in an endorheic basin, rain (or other precipitation) that falls within it does not flow out but may only leave the drainage system by evaporation and seepage. The bottom of such a basin is typically occupied by a salt lake or salt pan. Endorheic basins are also called **internal drainage systems**.

Endorheic regions, in contrast to exorheic regions which flow to the ocean in geologically defined patterns, are closed hydrologic systems. Their surface waters drain to inland terminal locations where the water evaporates or seeps into the ground, having no access to discharge into the sea. Endorheic water bodies include some of the largest lakes in the world, such as the Aral Sea and the Caspian Sea, the world's largest saline body of water cut off from the ocean.

Endorheic lakes

Endorheic lakes are bodies of water that do not flow into the sea. Most of the water falling on earth finds its way to the oceans through a network of rivers, lakes and wetlands. However, there is a class of water bodies that are located in closed or endorheic watersheds where the topography prevents their drainage to the oceans. These endorheic watersheds (containing water in rivers or lakes that form a balance of surface inflows, evaporation and seepage) are often called terminal lakes or sink lakes.

Endorheic lakes are usually in the interior of a body mass, far from an ocean. Their watersheds are often confined by natural geologic land formations such as a mountain range, cutting off water access to the ocean. The inland water flows into dry watersheds where the water evaporates, leaving a high concentration of minerals and other inflow erosion products. Over time this input of erosion products can cause the endorheic lake to become relatively saline (a "salt lake"). Since the main outflow pathways of these lakes are chiefly through evaporation and seepage, endorheic lakes are usually more sensitive to environmental pollutants inputs than water bodies that have access to oceans.

Occurrence

Endorheic regions can occur in any climate but are most commonly found in hot desert locations. In areas where rainfall is higher, riparian erosion will generally carve drainage channels (particularly in times of flood), or cause the water level in the terminal lake to rise until it finds an outlet, breaking the enclosed endorheic hydrological system's geographical barrier and opening it to the surrounding terrain. The Black Sea was likely such a lake, having once been an independent hydrological system before the Mediterranean Sea broke through the terrain separating the two.

Endorheic regions tend to be far inland with their boundaries defined by mountains or other geological features that block their access to oceans. Since the inflowing water can evacuate only through seepage or evaporation, dried minerals or other products collect in the basin, eventually making the water saline and also making the basin vulnerable to pollution. Continents vary in their concentration of endorheic regions due to conditions of geography and climate. Australia has the highest percentage of endorheic regions at 21 percent while North America has the least at 5 percent. Approximately 18 percent of the earth's land drains to endorheic lakes or seas, the largest of these land areas being the interior of Asia.

In deserts, water inflow is low and loss to solar evaporation high, drastically reducing the formation of complete drainage systems. Closed water flow areas often lead to the concentration of salts and other minerals in the basin. Minerals leached from the surrounding rocks are deposited in the basin, and left behind when the water evaporates. Thus endorheic basins often contain extensive salt pans (also called salt flats, salt lakes, alkali flats, dry lake beds or playas). These areas tend to be large, flat hardened surfaces and are sometimes used for aviation runways or land speed record attempts, because of their extensive areas of perfectly level terrain.

Both permanent and seasonal endorheic lakes can form in endorheic basins. Some endorheic basins are essentially stable, climate change having reduced precipitation to the degree that a lake no longer forms. Even most permanent endorheic lakes change size and shape dramatically over time, often becoming much smaller or breaking into several smaller parts during the dry season. As humans have expanded into previously uninhabitable desert areas, the river systems that feed many endorheic lakes have been altered by the construction of dams and aqueducts. As a result many endorheic lakes in developed or developing countries have contracted dramatically, resulting in increased salinity, higher concentrations of pollutants, and the disruption of ecosystems.

Notable endorheic basins and lakes
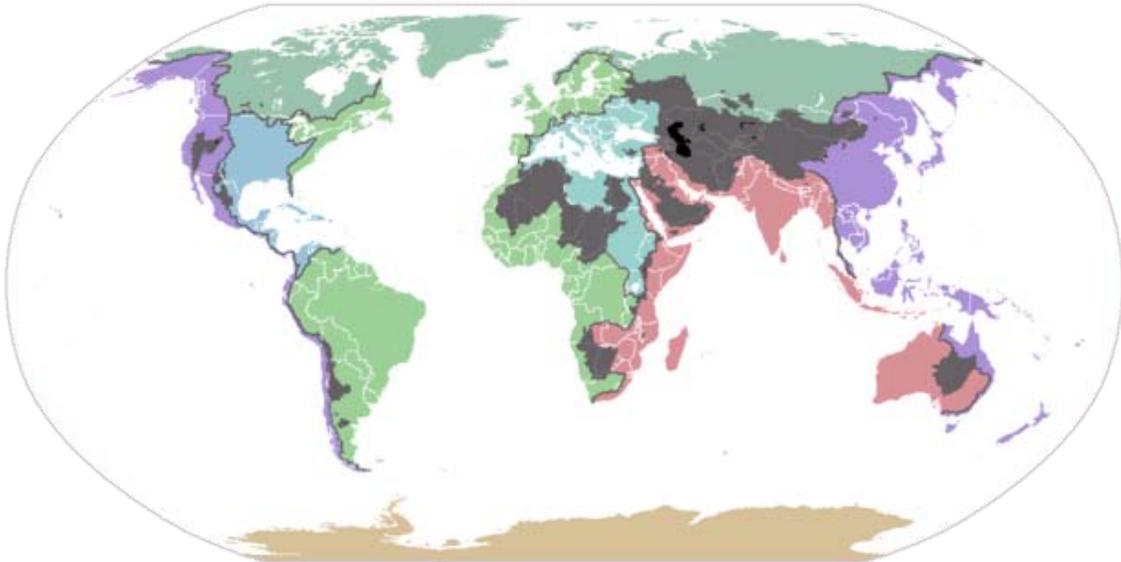
Major endorheic basins of the world. Basins are shown in dark gray; major endorheic lakes are shown in black.

Antarctica

Endorheic lakes in Antarctica are located in the McMurdo Dry Valleys, Victoria Land, Antarctica, the largest ice-free area in Antarctica.

- Don Juan Pond in Wright Valley is fed by groundwater from a rock glacier and remains unfrozen throughout the year.
- Lake Vanda in Wright Valley has a perennial ice cover, the edges of which melt in the summer allowing flow from the longest river in Antarctica, the Onyx River. The lake is over 70 m deep and is hypersaline.
- Lake Bonney is in Taylor Valley and has a perennial ice over and two lobes separated by the Bonney Riegel. The lake is fed by glacial melt and discharge from Blood Falls. Its unique glacial history has resulted in a hypersaline brine in the bottom waters and fresh water at the surface.
- Lake Hoare, in Taylor Valley, is the freshest of the Dry Valley lakes receiving its melt almost exclusively from the Canada Glacier. The lake has an ice cover and forms a moat during the Austral summer.
- Lake Fryxell, in adjacent to the Ross Sea in Taylor Valley. The lake has an ice cover and receives its water from numerous glacial meltwater streams for approximately 6 weeks out of the year. Its salinity increases with depth.

Caspian Sea, a giant inland basin
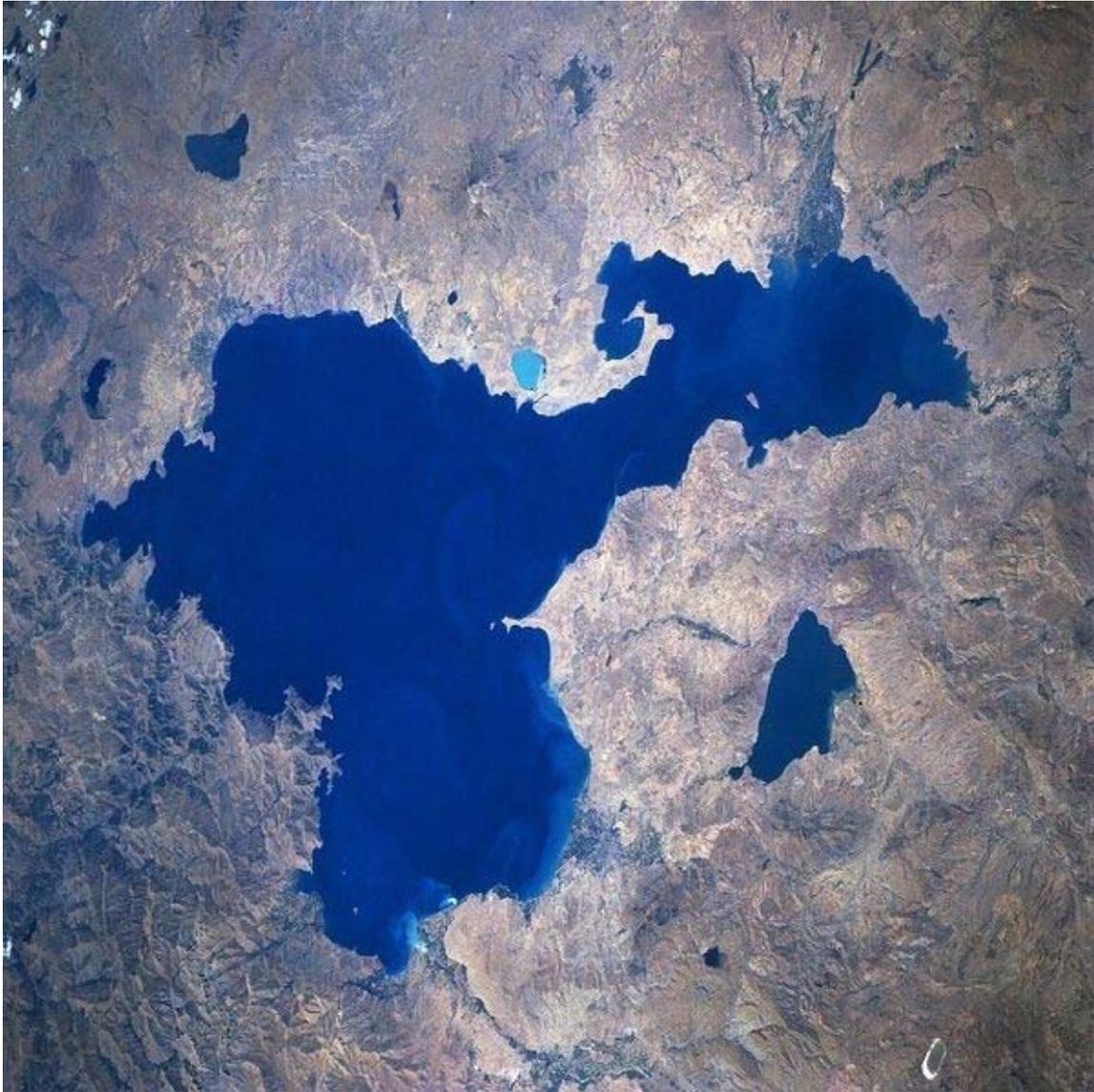
Lake Van, Turkey

Much of western and Central Asia is a single, giant inland basin. It contains several lakes, including:

- The Central Asian Internal Drainage Basin, the largest of the three major basins covering Mongolia.
- The Caspian Sea, the largest lake on Earth. In fact, a large part of Eastern Europe drained by the Volga River also belongs to its basin.
- The Aral Sea, whose tributary rivers have been diverted, leading to a dramatic shrinkage of the lake. The resulting ecological disaster has brought the plight faced by internal drainage basins to public attention.
- Lake Balkhash (Kazakhstan)

- Lop Nur Basin, in the southeastern portion of Xinjiang Uygur Autonomous Region in northwestern China
- Issyk-Kul, Son-Kul and Chatyr-Kul lakes in Kyrgyzstan
- Qaidam Basin in Qinghai Province, China
- Sistan Basin covering areas of Iran and Afghanistan
- Tarim Basin in Xinjiang Uyghur Autonomous Region
- Uvs Nuur basin, Mongolia, Tuvan Republic of Russia
- The Dead Sea, the lowest surface point on Earth and one of its saltiest bodies of water, lies between Israel and Jordan.
- Sambhar Lake in Rajasthan, north-western India, is also the terminal point of an endorheic basin.
- Lake Van in Turkey is one of the world's largest endorheic lakes.
- Sabkhat al-Jabbul extensive salt flats and 100 km^2 lake in Syria.
- Solar Lake, Sinai, near the Israeli-Egypt border.

Australia

Australia, being very dry and having exceedingly low runoff ratios due to its ancient soils, has a great prominence of variable, endorheic drainages. The most important are:

- Lake Eyre Basin, which drains into the highly variable Lake Eyre and includes Lake Frome.
- Lake Torrens, to the west of the Flinders Ranges in South Australia.
- Lake Corangamite, a highly saline crater lake in western Victoria.
- Lake George, formerly connected to the Murray-Darling Basin

A false-colour satellite photo of Australia's Lake Eyre
Image credit: *NASA's Earth Observatory*

Africa

- Lake Turkana in Kenya, whose basin includes the Omo River of Ethiopia
- The Okavango Delta, an endorheic inland delta in the Kalahari Desert of Botswana
- Lake Ngami in Botswana
- Lake Chad (between Chad and Cameroon), fed by the Chari and Logon rivers
- Etosha pan in Namibia's Etosha National Park
- Qattara Depression in Egypt
- Chott Melrhir in Algeria

- Lake Chilwa in Malawi
- Afar Depression in Eritrea, Ethiopia and Djibouti
- The Rift Valley lakes Abijatta, Chew Bahir, and Shala
- Chott el Djerid in Tunisia
- Lake Mweru Wantipa in Zambia

North and Central America

A unusually wet winter creates a lake at Badwater in Death Valley National Park, 2005
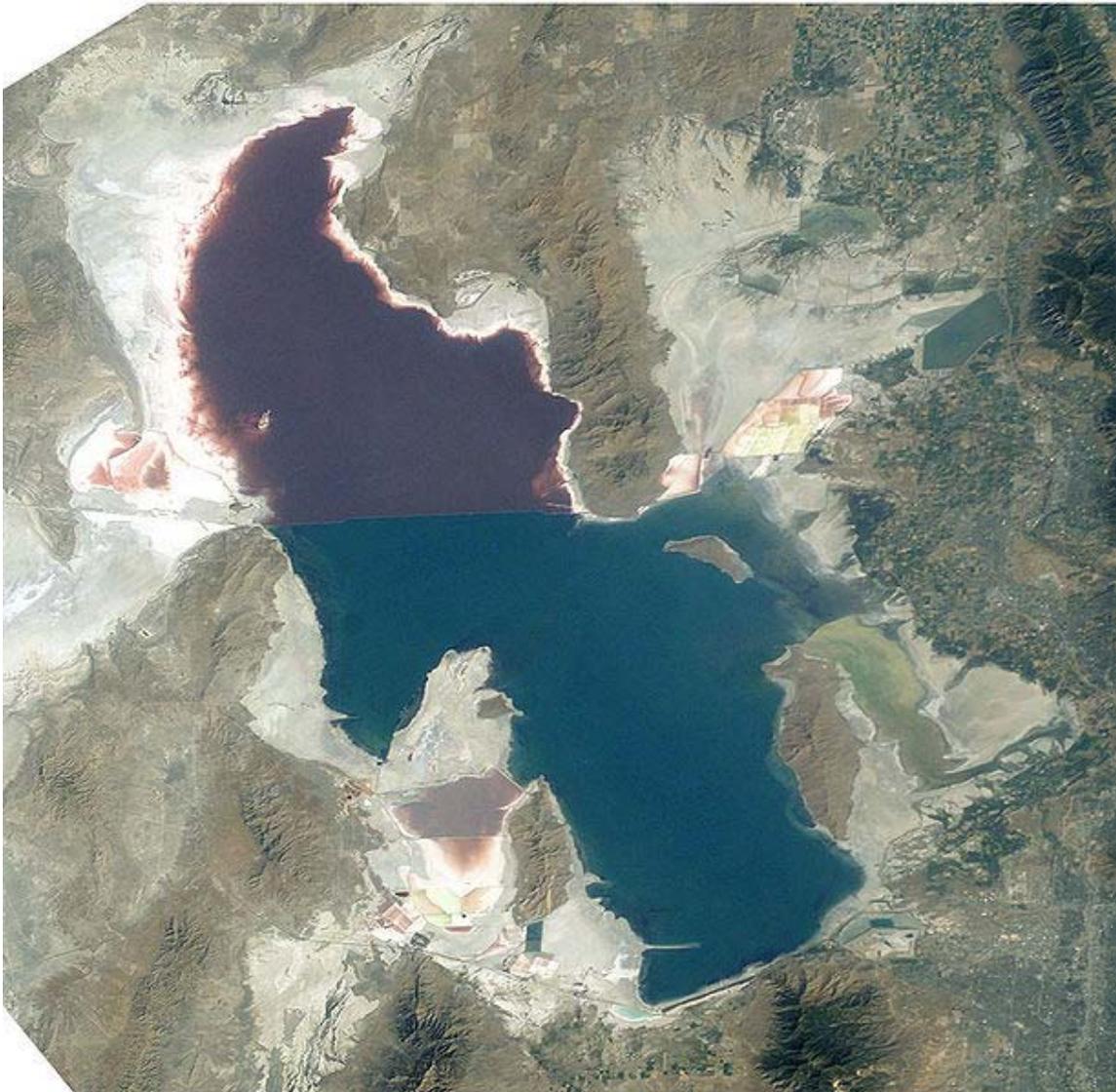
Great Salt Lake, Satellite photo (2003) after five years of drought

- Lago de Atitlán, in the highlands of Guatemala;
- Bolsón de Mapimí, in northern Mexico
- Crater Lake in Oregon
- Devils Lake (North Dakota)
- Devil's Lake (Wisconsin)
- The Great Basin, which covers much of Nevada and Utah, includes:
  - The Black Rock Desert in Nevada, location of the Thrust2 and ThrustSSC landspeed record runs, and the annual home to the Burning Man festival
  - Death Valley in California and Nevada, the lowest land point in the United States
  - Groom Dry Lake in Nevada, location of Area 51

- o Utah's Great Salt Lake, the largest terminal lake in the Western Hemisphere
  - o Salton Sea in California, a lake accidentally recreated in 1905 when irrigation canals ruptured, filling a desert endorheic basin and recreating an ancient saline sea
  - o Utah's Sevier Lake
  - o Pyramid Lake in Nevada
  - o Mono Lake in California
- The Great Divide Basin in Wyoming, a small endorheic basin that straddles the Continental Divide of the Americas.
- Guzmán Basin, in northern Mexico and the southwestern United States;
- Little Manitou Lake in Saskatchewan
- New Mexico has a number of desert endorheic basins including:
  - o The Tularosa Basin, a rift valley;
  - o Zuni Salt Lake, a maar;
  - o The Mimbres River Basin, in Grant County, NM;
- Rogers Lake, at Edwards Air Force Base in California
- Tulare Lake, an endorheic basin at the southern end of the San Joaquin Valley fed by the Kings River, Tule River and Kaweah River; since the late 19th century the lake bed has been reclaimed and used as farmland, though it occasionally floods when rainfall is especially heavy
- The Valley of Mexico. In Pre-Columbian times, the Valley was substantially covered with five lakes, including Lake Texcoco, Lake Xochimilco, and Lake Chalco.

Many small lakes and ponds in North Dakota and Manitoba are endorheic; some of them have salt encrustations along their shores.

Europe

- Neusiedlersee/Fertő tó in Austria and Hungary
- Lake Trasimeno in Italy
- Lake Velence in Hungary
- Lake Prespa between Albania, Greece and the Republic of Macedonia
- Rahasane turlough, in County Galway, Republic of Ireland, is the county's largest and covers about 2.5 square kilometres.

All these lakes are drained, however, either through manmade canals or via karstic phenomena. Minor additional endorheic lakes exist throughout the Mediterranean countries Spain (e.g. Laguna de Gallocanta), Italy, Cyprus (Larnaca and Akrotiri salt lakes) and Greece.

South America
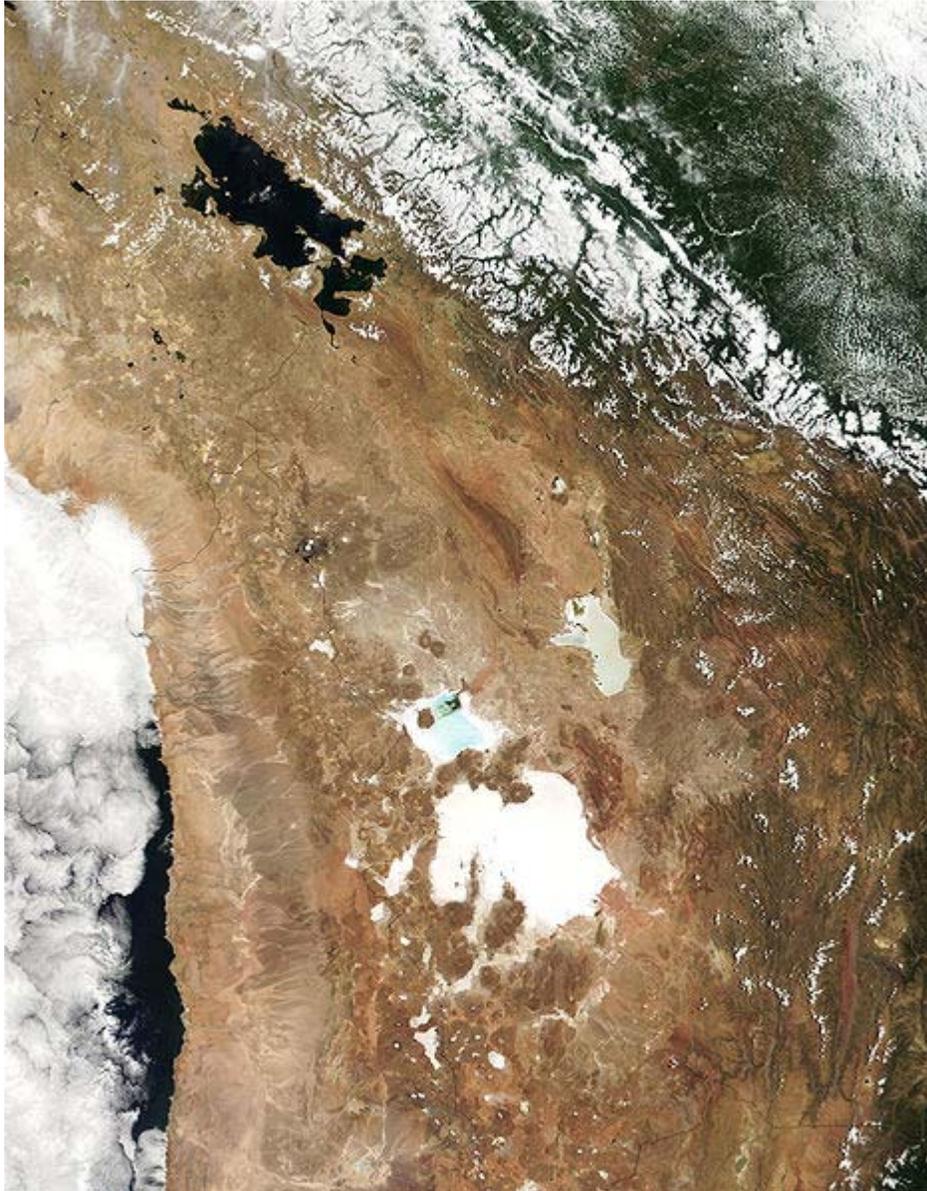
MODIS image from November 4, 2001 showing Lake Titicaca, the Salar de Uyuni, and the Salar de Coipasa. These are all parts of the Altiplano

- Altiplano basin, one of the largest and second highest in the world.
- Lake Valencia (Spanish: Lago de Valencia) the second largest lake in Venezuela.
- Salar de Atacama, Atacama Desert, Chile (although close to the Altiplano it is not part of it)
- Northwest Pampas Basins in the Dry Pampas of Argentina
- Southwest Pampas Basins in the Dry Pampas of Argentina
- Meseta Somuncura in the Patagonia region of Argentina

Ancient

Some of the Earth's ancient endorheic systems include:

- The Black Sea, until its merger with the Mediterranean
- The Mediterranean Sea itself and all its tributary basins, during its Messinian desiccation (5 m.y. BP aprox.) as it became disconnected from the Atlantic Ocean.
- Lake Lahontan in the western US
- Ebro and Duero basins, draining most of northern Spain during the Neogene and perhaps Pliocene.
- Lake Bonneville (Utah)

Importance of drainage basins

Geopolitical boundaries

Drainage basins have been historically important for determining territorial boundaries, particularly in regions where trade by water has been important. For example, the English crown gave the Hudson's Bay Company a monopoly on the fur trade in the entire Hudson Bay basin, an area called Rupert's Land. Today, bioregional democracy can include agreements of states in a particular drainage basin to defend it. One example of this is the Great Lakes Commission.

Hydrology

Drainage basin of the Ohio River, part of the Mississippi River drainage basin.

In hydrology, the drainage basin is a logical unit of focus for studying the movement of water within the hydrological cycle, because the majority of water that discharges from the basin outlet originated as precipitation falling on the basin. A portion of the water that enters the groundwater system beneath the drainage basin may flow towards the outlet of another drainage basin because groundwater flow directions do not always match those of their overlying drainage network. Measurement of the discharge of water from a basin may be made by a stream gauge located at the basin's outlet.

Rain gauge data is used to measure total precipitation over a drainage basin, and there are different ways to interpret that data. If the gauges are many and evenly distributed over an area of uniform precipitation, using the arithmetic mean method will give good results. In the Thiessen polygon method, the watershed is divided into polygons with the rain gauge in the middle of each polygon assumed to be representative for the rainfall on the area of land included in its polygon. These polygons are made by drawing lines between

gauges, then making perpendicular bisectors of those lines form the polygons. The isohyetal method involves contours of equal precipitation are drawn over the gauges on a map. Calculating the area between these curves and adding up the volume of water is time consuming.

Geomorphology

Drainage basins are the principal hydrologic unit considered in fluvial geomorphology. A drainage basin is the source for water and sediment that moves through the river system and reshapes the channel.

Ecology

The Mississippi River drains the largest area of any U.S. river, much of it agricultural regions. Agricultural runoff and other water pollution that flows to the outlet is the cause of the dead zone in the Gulf of Mexico.

Drainage basins are important elements to consider also in ecology. As water flows over the ground and along rivers it can pick up nutrients, sediment, and pollutants. Like the water, they get transported towards the outlet of the basin, and can affect the ecological processes along the way as well as in the receiving water source.

Modern usage of artificial fertilizers, containing nitrogen, phosphorus, and potassium, has affected the mouths of watersheds. The minerals will be carried by the watershed to the mouth and accumulate there, disturbing the natural mineral balance. This can cause eutrophication where plant growth is accelerated by the additional material.

Resource management

Because drainage basins are coherent entities in a hydrological sense, it has become common to manage water resources on the basis of individual basins. In the U.S. state of Minnesota, governmental entities that perform this function are called watershed districts. In New Zealand, they are called catchment boards. Comparable community groups based

in Ontario, Canada, are called conservation authorities. In North America this function is referred to as watershed management. In Brazil, the National Policy of Water Resources, regulated by Act n° 9.433 of 1997, establishes the drainage basin as territorial division of Brazilian water management.

Catchment factors

The catchment is the most significant factor determining the amount or likelihood of flooding.

Catchment factors are: topography, shape, size, soil type and land use (paved or roofed areas). Catchment topography and shape determine the time taken for rain to reach the river, while catchment size, soil type and development determine the amount of water to reach the river.

Topography

Topography determines the speed with which the runoff will reach a river. Clearly rain that falls in steep mountainous areas will reach the river faster than flat or gently sloping areas.

Shape

Shape will contribute to the speed with which the runoff reaches a river. A long thin catchment will take longer to drain than a circular catchment.

Size

Size will help determine the amount of water reaching the river, as the larger the catchment the greater the potential for flooding.

Soil type

Soil type will help determine how much water reaches the river. Certain soil types such as sandy soils are very free draining and rainfall on sandy soil is likely to be absorbed by the ground. However, soils containing clay can be almost impermeable and therefore rainfall on clay soils will run off and contribute to flood volumes. After prolonged rainfall even free draining soils can become saturated, meaning that any further rainfall will reach the river rather than being absorbed by the ground.

Land use

Land use can contribute to the volume of water reaching the river, in a similar way to clay soils. For example, rainfall on roofs, pavements and roads will be collected by rivers with almost no absorption into the groundwater.

## *Drainage system (geomorphology)*

In geomorphology, a **drainage system** is the pattern formed by the streams, rivers, and lakes in a particular drainage basin. They are governed by the topography of the land, whether a particular region is dominated by hard or soft rocks, and the gradient of the land. Geomorphologists and hydrologists often view streams as being part of drainage basins. A drainage basin is the topographic region from which a stream receives runoff, throughflow, and groundwater flow. Drainage basins are divided from each other by topographic barriers called a watershed. A watershed represents all of the stream tributaries that flow to some location along the stream channel. The number, size, and shape of the drainage basins found in an area varies and the larger the topographic map, the more information on the drainage basin is available.
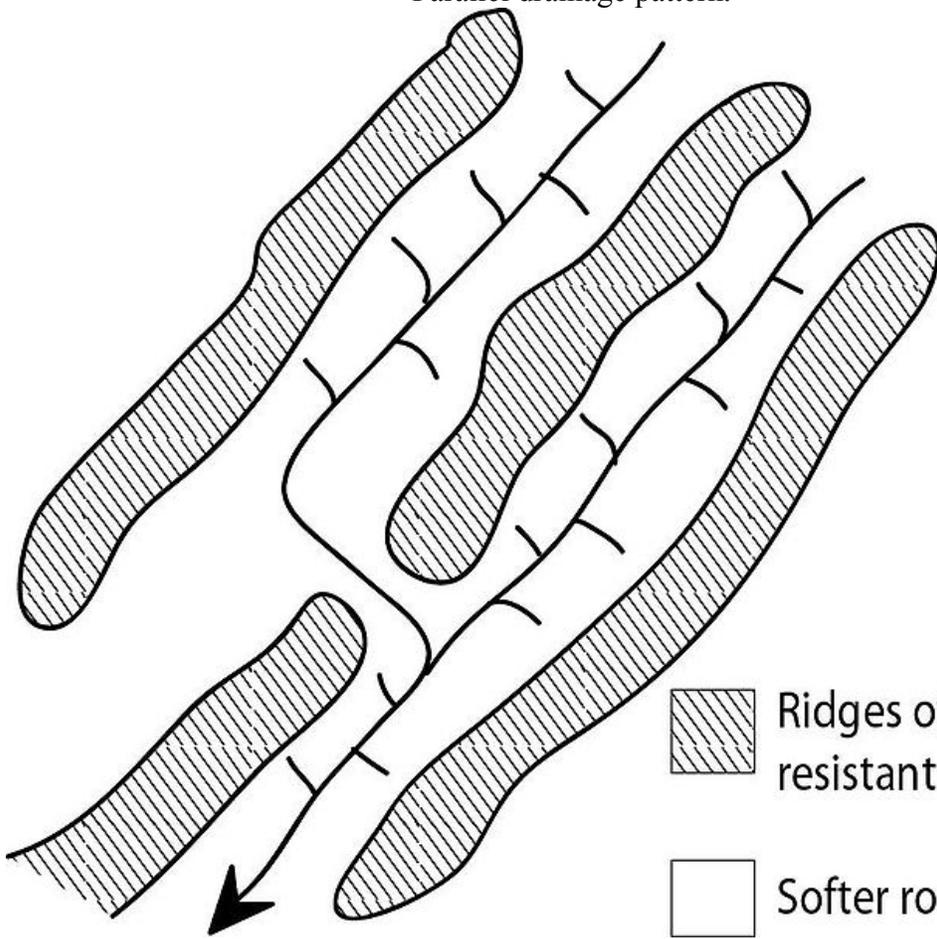
Types of drainage system

Drainage systems can fall into one of several categories, depending on the topography and geology of the land:
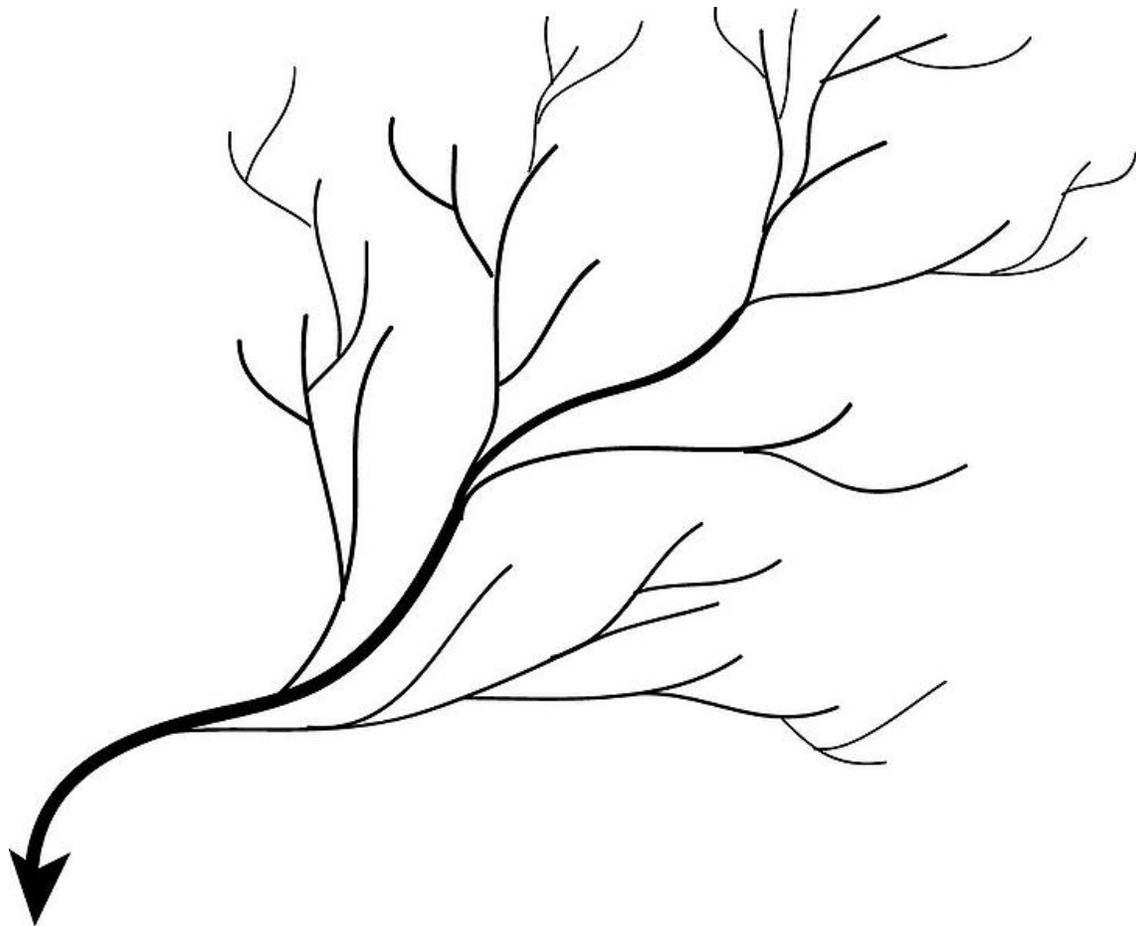
Dendritic drainage pattern.
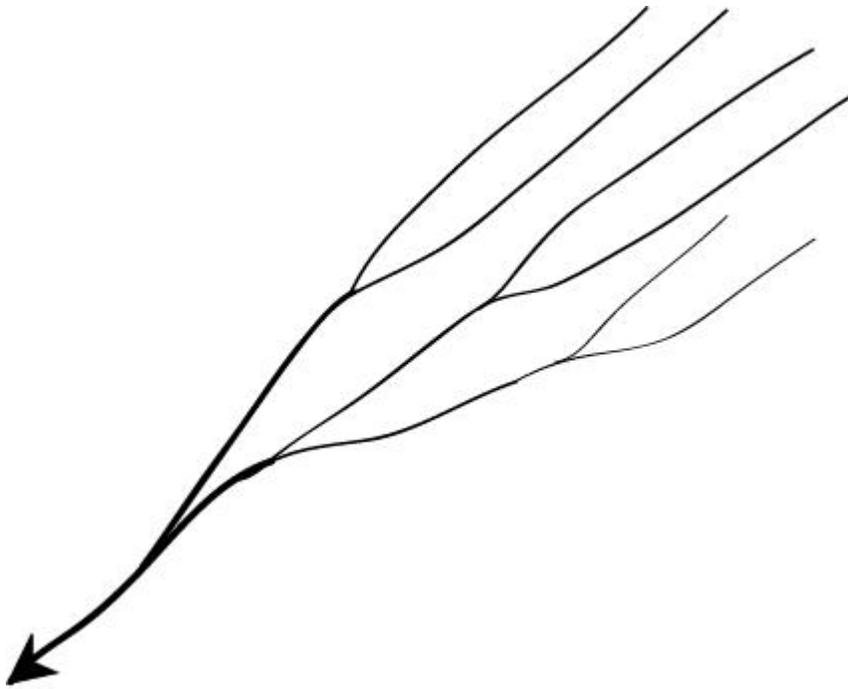
Parallel drainage pattern.

Ridges of resistant rock

Softer rock

Trellis drainage pattern.

Dendritic drainage system

Dendritic drainage systems are the most common form of drainage system. In a dendritic system, there are many contributing streams (analogous to the twigs of a tree), which are then joined together into the tributaries of the main river (the branches and the trunk of the tree, respectively). They develop where the river channel follows the slope of the terrain. Dendritic systems form in V-shaped valleys; as a result, the rock types must be impervious and non-porous.

Parallel drainage system

A parallel drainage system is a pattern of rivers caused by steep slopes with some relief. Because of the steep slopes, the streams are swift and straight, with very few tributaries, and all flow in the same direction. This system forms on uniformly sloping surfaces, for example, rivers flowing southeast from the Aberdare Mountains in Kenya.

Trellis drainage system

The geometry of a trellis drainage system is similar to that of a common garden trellis used to grow vines. As the river flows along a strike valley, smaller tributaries feed into it from the steep slopes on the sides of mountains. These tributaries enter the main river at approximately 90 degree angles, causing a trellis-like appearance of the drainage system. Trellis drainage is characteristic of folded mountains, such as the Appalachian Mountains in North America.

Rectangular drainage system

Rectangular drainage develops on rocks that are of approximately uniform resistance to erosion, but which have two directions of jointing at approximately right angles. The joints are usually less resistant to erosion than the bulk rock so erosion tends to preferentially open the joints and streams eventually develop along the joints. The result is a stream system in which streams consist mainly of straight line segments with right angle bends, and tributaries join larger streams at right angles.

Radial drainage system

In a radial drainage system the streams radiate outwards from a central high point. Volcanos usually display excellent radial drainage. Other geological features on which radial drainage commonly develops are domes and laccoliths. On these features the drainage may exhibit a combination of radial and annular patterns.

Deranged drainage system

A deranged drainage system is a drainage system in drainage basins where there is no coherent pattern to the rivers and lakes. It happens in areas where there has been much geological disruption. The classic example is the Canadian Shield. During the last ice

age, the topsoil was scraped off, leaving mostly bare rock. The melting of the glaciers left land with many irregularities of elevation, and a great deal of water to collect in the low points, explaining the large number of lakes which are found in Canada. The watersheds are young and are still sorting themselves out. Eventually the system will stabilize.
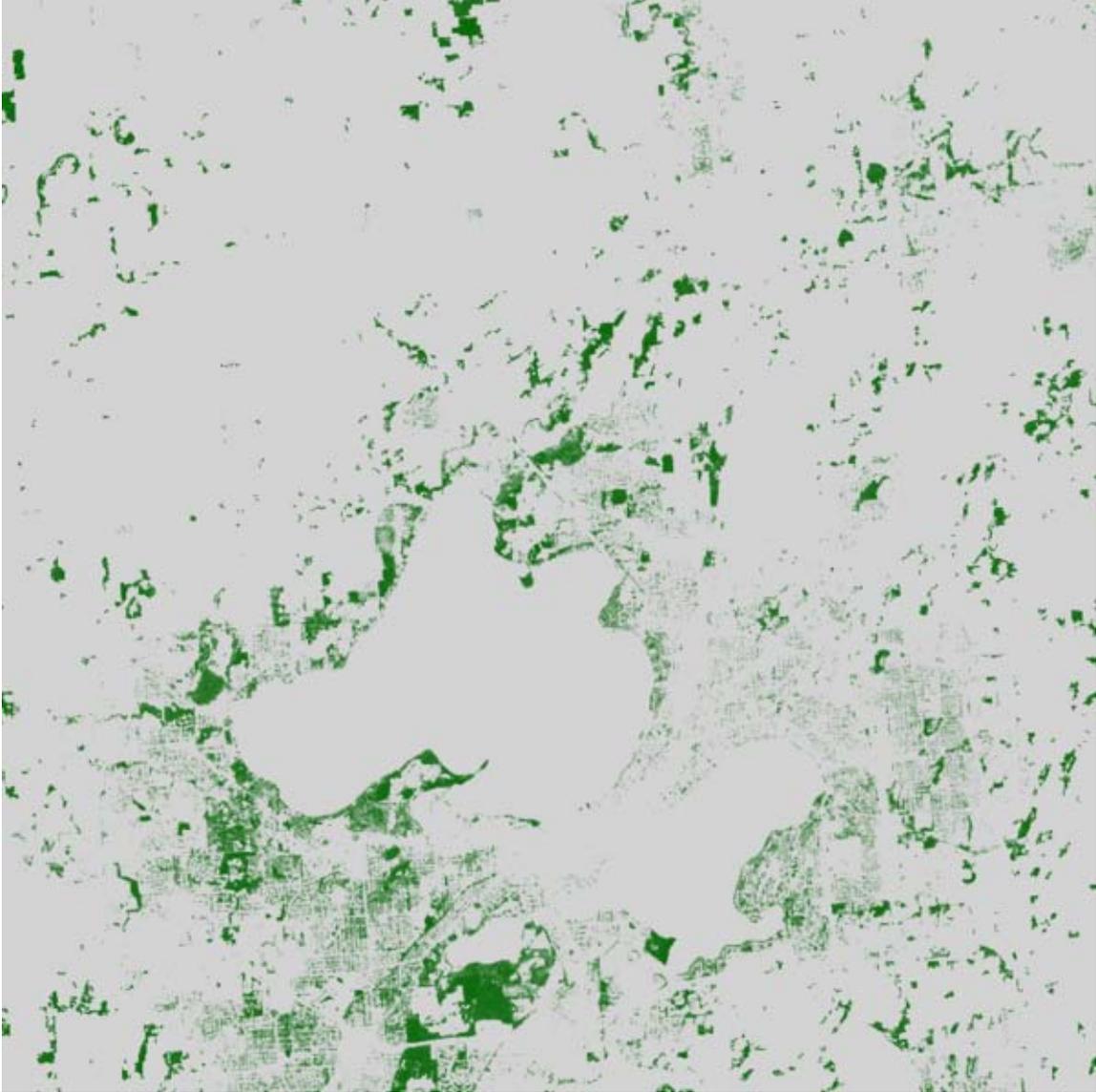
Chapter-5

Landscape Ecology
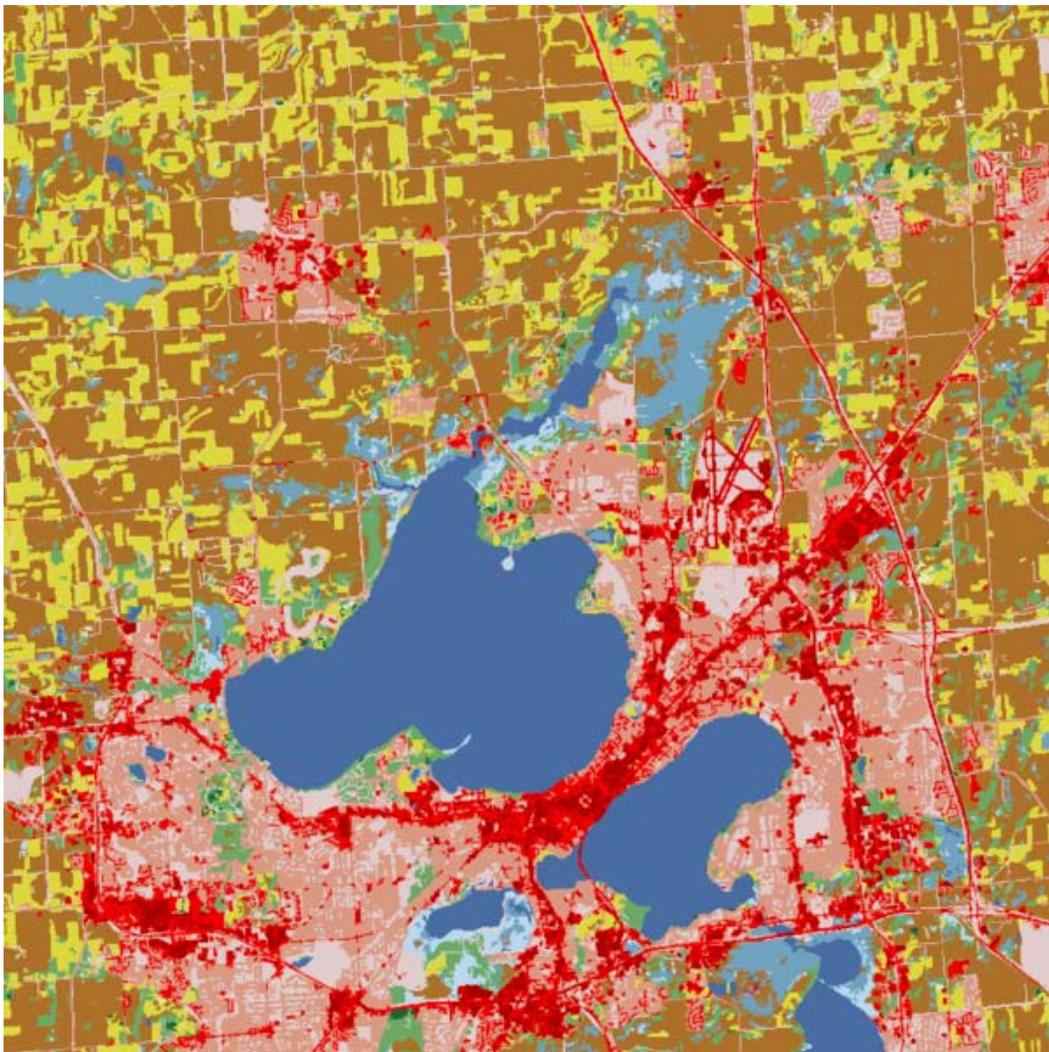
Land cover surrounding Madison, WI. Fields are colored yellow and brown, water is colored blue, and urban surfaces are colored red.
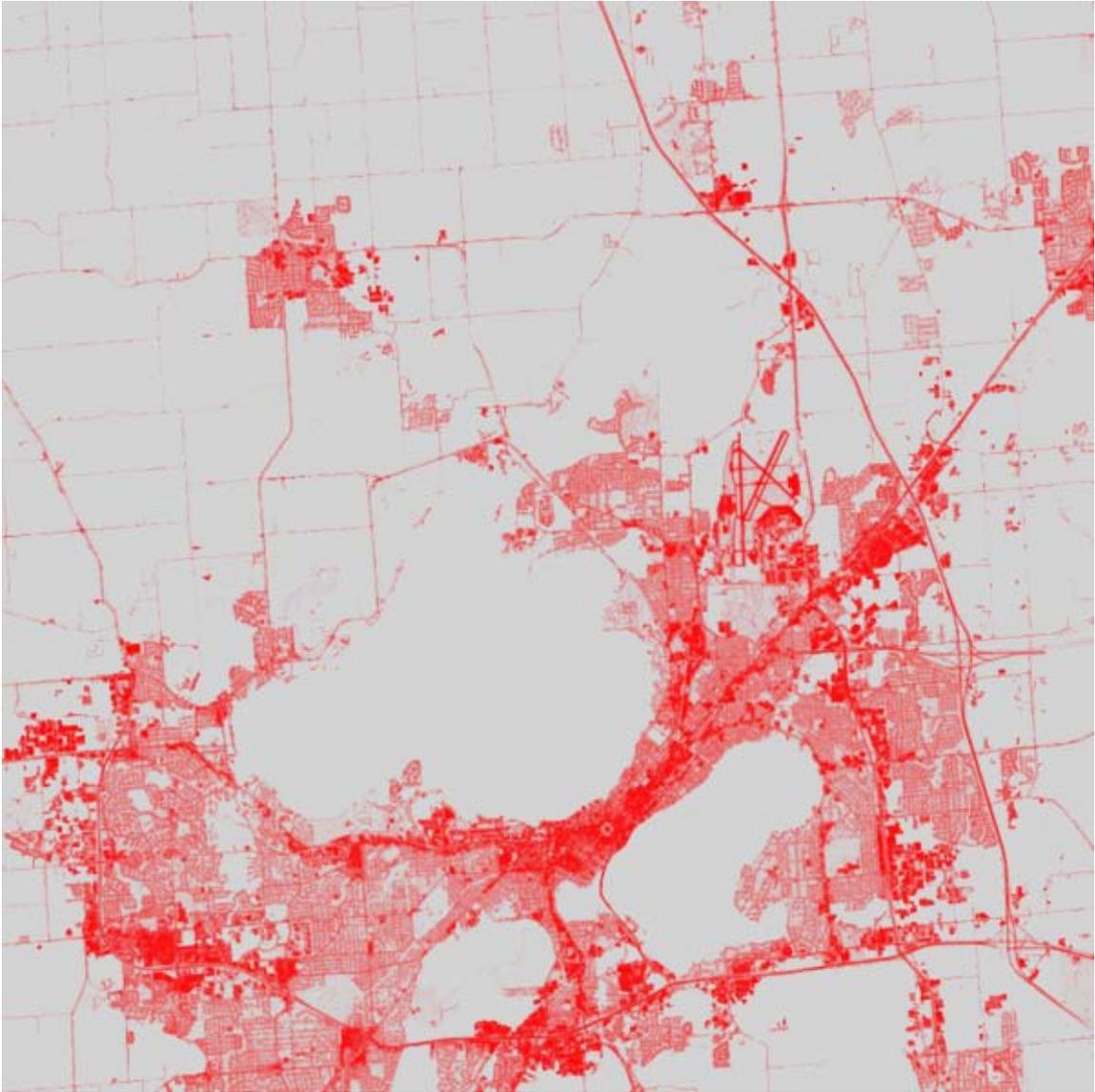
Impervious surfaces surrounding Madison, WI

Canopy cover surrounding Madison, WI

Landscape ecology is the science of studying and improving the relationship between spatial pattern of urban development and ecological processes on a multitude of landscape scales and organisational levels. As a highly interdisciplinary enterprise, landscape ecology integrates biophysical and analytical approaches with humanistic and holistic perspectives across natural and social sciences. Landscapes are spatially heterogeneous geographic areas characterized by diverse interacting patches or ecosystems, ranging from relatively natural terrestrial and aquatic systems such as forests, grasslands and lakes to human-dominated environments including agricultural and urban settings. The most salient characteristics of landscape ecology are its emphasis on the relationship among pattern, process and scale and its focus on broad-scale ecological and environmental issues. These necessitate the coupling between biophysical and socioeconomic sciences. Key research topics in landscape ecology include ecological

flows in landscape mosaics, land use and land cover change, scaling, relating landscape pattern analysis with ecological processes, and landscape conservation and sustainability (Wu & Hobbs 2002).

Terminology

The term *landscape ecology* was coined by Carl Troll, a German geographer, in 1939. He developed this terminology and many early concepts of landscape ecology as part of his early work, which consisted of applying aerial photograph interpretation to studies of interactions between environment and vegetation.

Explanation

Heterogeneity is the measure of how different parts of a landscape are from one another. Landscape ecology looks at how this spatial structure affects organism abundance at the landscape level, as well as the behavior and functioning of the landscape as a whole. This includes studying the influence of pattern, or the internal order of a landscape, on process, or the continuous operation of functions of organisms. Landscape ecology also includes geomorphology as applied to the design and architecture of landscapes. Geomorphology is the study of how geological formations are responsible for the structure of a landscape.

History

Evolution of theory

One central landscape ecology theory originated from MacArthur & Wilson's *The Theory of Island Biogeography*. This work considered the biodiversity on islands as the result of competing forces of colonization from a mainland stock and stochastic extinction. The concepts of island biogeography were generalized from physical islands to abstract patches of habitat by Levins' metapopulation model. This generalization spurred the growth of landscape ecology by providing conservation biologists a new tool to assess how habitat fragmentation affects population viability. Recent growth of landscape ecology owes much to the development of geographic information systems (GIS) and the availability of large-extent habitat data (e.g. remotely sensed datasets).

Development as a discipline

Landscape ecology developed in Europe from historical planning on human-dominated landscapes. Concepts from general ecology theory were integrated in North America. While general ecology theory and its sub-disciplines focused on the study of more homogenous, discrete community units organized in a hierarchical structure (typically as ecosystems, populations, species, and communities), landscape ecology built upon heterogeneity in space and time. It frequently included human-caused landscape changes in theory and application of concepts.

By 1980, landscape ecology was a discrete, established, discipline. It was marked by the organization of the International Association for Landscape Ecology (IALE) in 1982. Landmark book publications defined the scope and goals of the discipline, including Naveh and Lieberman and Forman and Godron. Forman wrote that although study of "the ecology of spatial configuration at the human scale" was barely a decade old, there was strong potential for theory development and application of the conceptual framework. Today, theory and application of landscape ecology continues to develop through a need for innovative applications in a changing landscape and environment. Landscape ecology relies on advanced technologies such as remote sensing, GIS, and models. There has been associated development of powerful quantitative methods to examine the interactions of patterns and processes. An example would be determining the amount of carbon present in the soil based on landform over a landscape, derived from GIS maps, vegetation types, and rainfall data for a region.

Relationship to ecological theory

Landscape ecology theory may be slightly outside of the "classical and preferred domain of scientific disciplines" because of the large, heterogeneous areas of study. However, general ecology theory is central to landscape ecology theory in many aspects. Landscape ecology consists of four main principles: the development and dynamics of spatial heterogeneity, interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and the management of spatial heterogeneity. The main difference from traditional ecological studies, which frequently assume that systems are spatially homogenous, is the consideration of spatial patterns.

Important terms in Landscape ecology

Landscape ecology not only created new terms, but also incorporated existing ecological terms in new ways. Many of the terms used in landscape ecology are as interconnected and interrelated as the discipline itself. *Landscape* can be defined as an area containing two or more ecosystems in close proximity.

Scale and heterogeneity (incorporating composition, structure, and function)

A main concept in landscape ecology is *scale*. Scale represents the real world as translated onto a map, relating distance on a map image and the corresponding distance on earth. Scale is also the spatial or temporal measure of an object or a process, or amount of spatial resolution. Components of scale include composition, structure, and function, which are all important ecological concepts. Applied to landscape ecology, *composition* refers to the number of patch types (see below) represented on a landscape and their relative abundance. For example, the amount of forest or wetland, the length of forest edge, or the density of roads can be aspects of landscape composition. *Structure* is determined by the composition, the configuration, and the proportion of different patches across the landscape, while *function* refers to how each element in the landscape interacts

based on its life cycle events. *Pattern* is the term for the contents and internal order of a heterogeneous area of land.

A landscape with structure and pattern implies that it has spatial *heterogeneity*, or the uneven distribution of objects across the landscape. Heterogeneity is a key element of landscape ecology that separates this discipline from other branches of ecology.

Patch and mosaic

Patch dynamics is a conceptual approach to ecosystem and habitat analysis that emphasizes dynamics of heterogeneity within a system (i.e. that each area of an ecosystem is made up of a mosaic of small 'sub-ecosystems').

Diverse patches of habitat created by natural disturbance regimes are seen as critical to maintenance of diversity (ecology). A *habitat patch* is any discrete area that is used by a species for breeding or obtaining other resources. They have a definite shape and spatial configuration, or heterogeneity.

Mosaics are the patterns within landscapes that are composed of smaller elements, such as individual forest stands, shrubland patches, highways, farms, or towns.

Patches and mosaics

Historically, due to the short time scale of human observation, mosaic landscapes were perceived to be static. This focus centered around the idea that the status of a particular population, community, or ecosystem could be understood by studying a particular patch within a mosaic. However, this perception ignored the conditions that interact with, and connect patches. In 1979, Bormann and Likens coined the phrase *shifting mosaic* to describe the theory that landscapes change and fluctuate, and are in fact dynamic. This is related to the battle of cells that occurs in a Petri dish.

Patch dynamics refers to the concept that all landscapes are dynamic. There are three states that a patch can exist in: *potential*, *active*, and *degraded*. Patches in the *potential* state are transformed into active patches through colonization of the patch by dispersing species arriving from other *active* or *degrading* patches. Patches are transformed from the *active* state to the *degraded* state when the patch is abandoned, and patches change from *degraded* to *potential* through a process of recovery.

Logging, fire, farming, and reforestation can all contribute to the process of colonization, and can effectively change the shape of the patch. *Patch dynamics* also refers to changes in the structure, function, and composition of individual patches that can, for example, effect the rate of nutrient cycling.

Patches are also linked, although separated from other patches, migration occurs from one patch to another. This migration maintains the population of some patches, and can

be the mechanism by which some plant species spread. This implies that ecological systems within landscapes are open, rather than closed and isolated. (Pickett, 2006)

Conservation efforts

Recognizing the patch dynamics within a system is needed for conservation (ecology) efforts to succeed. Successful conservation includes understanding how a patch changes and predicting how they will be affected by external forces. These externalities include natural effects, such as land use, disturbance, restoration, and succession, and the effects of human activities. In a sense, conservation is the active maintenance of patch dynamics (Pickett, 2006).

Boundary and edge

Landscape patches have a boundary between them which can be defined or fuzzy. The zone composed of the edges of adjacent ecosystems is the *boundary*. *Edge* means the portion of an ecosystem near its perimeter, where influences of the adjacent patches can cause an environmental difference between the interior of the patch and its edge. This edge effect includes a distinctive species composition or abundance. For example, when a landscape is a mosaic of perceptibly different types, such as a forest adjacent to a grassland, the edge is the location where the two types adjoin. In a continuous landscape, such as a forest giving way to open woodland, the exact edge location is fuzzy and is sometimes determined by a local gradient exceeding a threshold, such as the point where the tree cover falls below thirty-five percent.

Ecotones, ecoclines, and ecotopes

Ecotone

Reed beds are a common form of lakeside ecotone. The beds tend to accumulate organic matter which is then colonised by trees, forcing the reeds further into the lake.
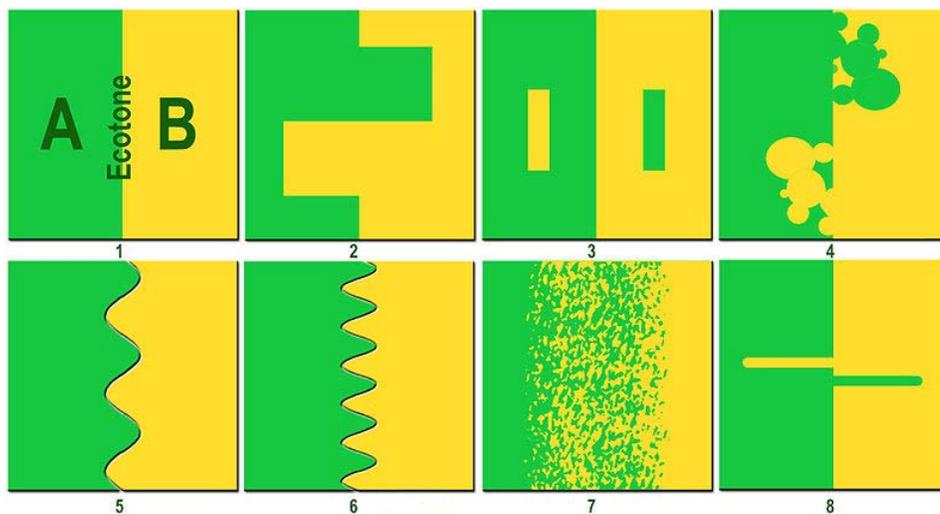

Fig.1 & 2 show simple ecotones with equal and homogeneous surfaces in both cases. Fig.3 shows an inclusion of each medium in the other, creating multiple ecotones, which

are shown in a more complex form in figure 4. Fig. 5 & 6 show the edges of forests or banks treated in such a way as to lengthen the ecotone considerably without excessively modifying the environment. Fig.7 shows a common interpenetration of mediums (such as that found at the edge of a forest). Fig.8 shows an ecotone that could have been formed by an animal modifying its environment.

An **ecotone** is a transition area between two adjacent but different plant communities, such as forest and grassland. It may be narrow or wide, and it may be local (the zone between a field and forest) or regional (the transition between forest and grassland). An ecotone may appear on the ground as a gradual blending of the two communities across a broad area, or it may manifest itself as a sharp boundary line.

The word ecotone was coined from a combination of *eco*(logy) plus *-tone*, from the Greek *tonos* or tension – in other words, a place where ecologies are in tension.

Formation

Changes in the physical environment may produce a sharp boundary, as in the example of the interface between areas of forest and cleared land (Krummholz). Elsewhere, a more gradually blended interface area will be found, where species from each community will be found together as well as unique local species. Mountain ranges often create such ecotones, due to the wide variety of climatic conditions experienced on their slopes. They may also provide a boundary between species due to the obstructive nature of their terrain. Mont Ventoux in France is a good example, marking the boundary between the flora and fauna of northern and southern France. Most wetlands are ecotones.

Plants in competition extend themselves on one side of the ecotone as far as their ability to maintain themselves allows. Beyond this competitors of the adjacent community take over. As a result the ecotone represents a shift in dominance. Ecotones are particularly significant for mobile animals, as they can exploit more than one set of habitats within a short distance. The ecotone contains not only species common to the communities on both sides; it may also include a number of highly adaptable species that tend to colonize such transitional areas. This can produce an edge effect along the boundary line, with the area displaying a greater than usual diversity of species.

The phenomenon of increased variety of plants as well as animals at the community junction is called the "edge effect" and is essentially due to a locally broader range of suitable environmental conditions or ecological niches.

Ecotones and ecoclines

An ecotone is often associated with an ecocline: a "physical transition zone" between two systems. The ecotone and ecocline concepts are sometimes confused: an ecocline can signal an ecotone chemically (ex: pH or salinity gradient), or microclimatically (hydrothermal gradient) between two ecosystems.

In contrast:

- an ecocline is a variation of the physicochemical environment dependent of one or two physico-chemical factors of life, and thus presence/absence of certain species. An ecoline can be a thermocline, chemocline (chemical gradient), halocline (salinity gradient) or pycnocline (variations in density of water induced by temperature or salinity).
- an ecotone describes a variation in species prevalence and is often not strictly dependent a major physical factor separating an ecosystem from another, with resulting habitat variability. An ecotone is often unobtrusive and harder to measure.

An *ecocline* is another type of landscape boundary, but it is a gradual and continuous change in environmental conditions of an ecosystem or community. Ecoclines help explain the distribution and diversity of organisms within a landscape because certain organisms survive better under certain conditions, which change along the ecocline. They contain heterogeneous communities which are considered more environmentally stable than those of ecotones.

An *ecotope* is a spatial term representing the smallest ecologically-distinct unit in mapping and classification of landscapes. Relatively homogeneous, they are spatially-explicit landscape units used to stratify landscapes into ecologically distinct features. They are useful for the measurement and mapping of landscape structure, function, and change over time, and to examine the effects of disturbance and fragmentation.

Disturbance and fragmentation

Disturbance is an event that significantly alters the pattern of variation in the structure or function of a system. *Fragmentation* is the breaking up of a habitat, ecosystem, or land-use type into smaller parcels. Disturbance is generally considered a natural process. Fragmentation causes land transformation, an important process in landscapes as development occurs.

An important consequence of repeated, random clearing (whether by natural disturbance or human activity) is that contiguous cover can break down into isolated patches. This happens when the area cleared exceed a critical level, which means that landscapes exhibit two phases: connected and disconnected.

Landscape ecology theory

Landscape ecology theory stresses the role of human impacts on landscape structures and functions. It also proposes ways for restoring degraded landscapes. Landscape ecology explicitly includes humans as entities that cause functional changes on the landscape. Landscape ecology theory includes the landscape stability principle, which emphasizes

the importance of landscape structural heterogeneity in developing resistance to disturbances, recovery from disturbances, and promoting total system stability. This principle is a major contribution to general ecological theories which highlight the importance of relationships among the various components of the landscape. Integrity of landscape components helps maintain resistance to external threats, including development and land transformation by human activity. Analysis of land use change has included a strongly geographical approach which has led to the acceptance of the idea of multifunctional properties of landscapes. There are still calls for a more unified theory of landscape ecology due to differences in professional opinion among ecologists and its interdisciplinary approach (Bastian 2001).

An important related theory is hierarchy theory, which refers to how systems of discrete functional elements operate when linked at two or more scales. For example, a forested landscape might be hierarchically composed of drainage basins, which in turn are composed of local ecosystems, which are in turn composed of individual trees and gaps. Recent theoretical developments in landscape ecology have emphasized the relationship between pattern and process, as well as the effect that changes in spatial scale has on the potential to extrapolate information across scales. Several studies suggest that the landscape has critical thresholds at which ecological processes will show dramatic changes, such as the complete transformation of a landscape by an invasive species with small changes in temperatures which favors the invasive's habitat requirements.

Landscape ecology application

Research directions

Developments in landscape ecology illustrate the important relationships between spatial patterns and ecological processes. These developments incorporate quantitative methods that link spatial patterns and ecological processes at broad spatial and temporal scales. This linkage of time, space, and environmental change can assist managers in applying plans to solve environmental problems. The increased attention in recent years on spatial dynamics has highlighted the need for new quantitative methods that can analyze patterns, determine the importance of spatially explicit processes, and develop reliable models. Multivariate analysis techniques are frequently used to examine landscape level vegetation patterns. Studies use statistical techniques, such as cluster analysis, canonical correspondence analysis (CCA), or detrended correspondence analysis (DCA), for classifying vegetation. Gradient analysis is another way to determine the vegetation structure across a landscape or to help delineate critical wetland habitat for conservation or mitigation purposes (Choesin and Boerner 2002).

Climate change is another major component in structuring current research in landscape ecology. Ecotones, as a basic unit in landscape studies, may have significance for management under climate change scenarios, since change effects are likely to be seen at ecotones first because of the unstable nature of a fringe habitat. Research in northern regions has examined landscape ecological processes, such as the accumulation of snow, melting, freeze-thaw action, percolation, soil moisture variation, and temperature regimes

through long-term measurements in Norway. The study analyzes gradients across space and time between ecosystems of the central high mountains to determine relationships between distribution patterns of animals in their environment. Looking at where animals live, and how vegetation shifts over time, may provide insight into changes in snow and ice over long periods of time across the landscape as a whole.

Other landscape-scale studies maintain that human impact is likely the main determinant of landscape pattern over much of the globe. Landscapes may become substitutes for biodiversity measures because plant and animal composition differs between samples taken from sites within different landscape categories. Taxa, or different species, can "leak" from one habitat into another, which has implications for landscape ecology. As human land use practices expand and continue to increase the proportion of edges in landscapes, the effects of this leakage across edges on assemblage integrity may become more significant in conservation. This is because taxa may be conserved across landscape levels, if not at local levels.

Relationship to other disciplines

Landscape ecology has been incorporated into a variety of ecological subdisciplines. For example, a recent development has been the more explicit consideration of spatial concepts and principles into the study of lakes, streams and wetlands in the field of landscape limnology. In addition, landscape ecology has important links to application-oriented disciplines such as agriculture and forestry. In agriculture, landscape ecology has introduced new options for the management of environmental threats brought about by the intensification of agricultural practices. Agriculture has always been a strong human impact on ecosystems. In forestry, from structuring stands for fuelwood and timber to ordering stands across landscapes to enhance aesthetics, consumer needs have affected conservation and use of forested landscapes. Landscape forestry provides methods, concepts, and analytic procedures for landscape forestry. Finally, landscape ecology has been cited as a contributor to the development of fisheries biology as a distinct biological science discipline, and is frequently incorporated in study design for wetland delineation in hydrology.