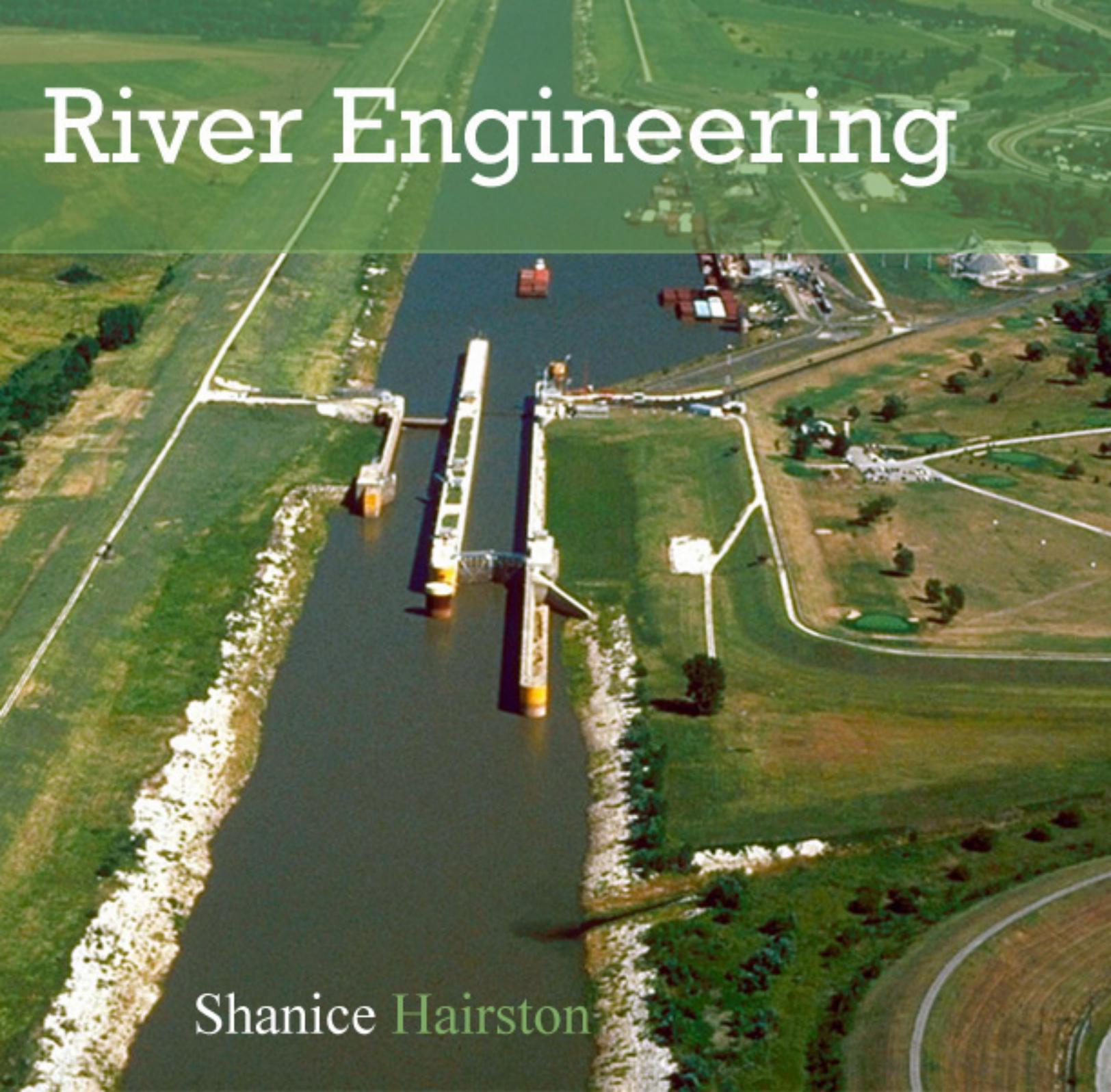


River Engineering

An aerial photograph of a river system featuring a dam and two locks. The river flows from the top of the frame towards the bottom. The dam is a long, low structure with a spillway on the left side. Two locks are situated downstream of the dam, each with a vertical gate. The surrounding landscape is a mix of green fields and brownish soil. In the background, there are some buildings and a road. The sky is not visible.

Shanice Hairston

First Edition, 2012

ISBN 978-81-323-4397-4

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Published by:

White Word Publications

4735/22 Prakashdeep Bldg,

Ansari Road, Darya Ganj,

Delhi - 110002

Email: info@wtbooks.com

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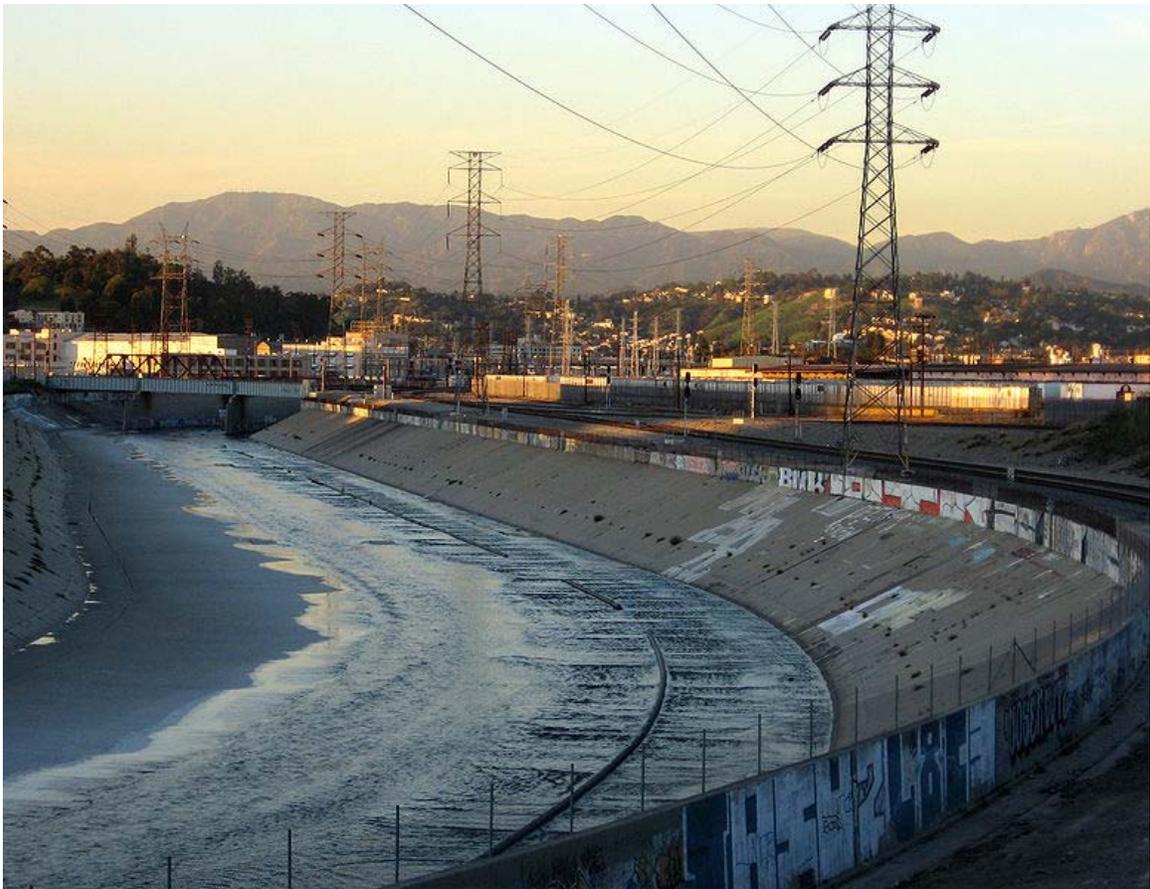
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Chapter 1

River Engineering



The Los Angeles River is extensively channelized with concrete embankments.

River engineering is the process of planned human intervention in the course, characteristics or flow of a river with the intention of producing some defined benefit. People have intervened in the natural course and behaviour of rivers since before recorded history - to manage the water resources, to protect against flooding or to make passage along or across rivers easier. From Roman times, rivers have been used as a

source of hydropower. From the late 20th century, river engineering has had environmental concerns broader than immediate human benefit and some river engineering projects have been concerned exclusively with the restoration or protection of natural characteristics and habitats.

Hydromodification is a term which encompasses the systematic response to alterations to riverine and non-riverine water bodies such as coastal waters (estuaries and bays) and lakes. The U.S. Environmental Protection Agency (EPA) has defined hydromodification as the "alteration of the hydrologic characteristics of coastal and non-coastal waters, which in turn could cause degradation of water resources." River engineering has often resulted in unintended systematic responses.

The river engineering discipline now strives to repair hydromodified degradations and account for potential systematic response to planned alterations by considering fluvial geomorphology. Fluvial geomorphology is the study of how rivers change their form over time. Fluvial geomorphology is the cumulation of a number of sciences including open channel hydraulics, sediment transport, hydrology, physical geology, and riparian ecology. River engineering attempts to understand fluvial geomorphology, implement a physical alteration, and maintain public safety.

Characteristics of rivers

The size of rivers above any tidal limit and their average freshwater discharge are proportionate to the extent of their basins and the amount of rain which, after falling over these basins, reaches the river channels in the bottom of the valleys, by which it is conveyed to the sea.

The basin of a river is the expanse of country bounded by a watershed (called a "divide" in North America) over which rainfall flows down towards the river traversing the lowest part of the valley, whereas the rain falling on the far slope of the watershed flows away to another river draining an adjacent basin. River basins vary in extent according to the configuration of the country, ranging from the insignificant drainage areas of streams rising on high ground very near the coast and flowing straight down into the sea, up to immense tracts of great continents, where rivers rising on the slopes of mountain ranges far inland have to traverse vast stretches of valleys and plains before reaching the ocean. The size of the largest river basin of any country depends on the extent of the continent in which it is situated, its position in relation to the hilly regions in which rivers generally arise and the sea into which they flow, and the distance between the source and the outlet into the sea of the river draining it.

The rate of flow of rivers depends mainly upon their fall, also known as the gradient or slope. When two rivers of different sizes have the same fall, the larger river has the quicker flow, as its retardation by friction against its bed and banks is less in proportion to its volume than is the case with the smaller river. The fall available in a section of a river approximately corresponds to the slope of the country it traverses; as rivers rise close to the highest part of their basins, generally in hilly regions, their fall is rapid near

their source and gradually diminishes, with occasional irregularities, until, in traversing plains along the latter part of their course, their fall usually becomes quite gentle. Accordingly, in large basins, rivers in most cases begin as torrents with a very variable flow, and end as gently flowing rivers with a comparatively regular discharge.

The irregular flow of rivers throughout their course forms one of the main difficulties in devising works for mitigating inundations or for increasing the navigable capabilities of rivers. In tropical countries subject to periodical rains, the rivers are in flood during the rainy season and have hardly any flow during the rest of the year, whilst in temperate regions, where the rainfall is more evenly distributed throughout the year, evaporation causes the available rainfall to be much less in hot summer weather than in the winter months, so that the rivers fall to their low stage in the summer and are very liable to be in flood in the winter. In fact, with a temperate climate, the year may be divided into a warm and a cold season, extending from May to October and from November to April in the Northern hemisphere respectively; the rivers are low and moderate floods are of rare occurrence during the warm period, and the rivers are high and subject to occasional heavy floods after a considerable rainfall during the cold period in most years. The only exceptions are rivers which have their sources amongst mountains clad with perpetual snow and are fed by glaciers; their floods occur in the summer from the melting of snow and ice, as exemplified by the Rhône above the Lake of Geneva, and the Arve which joins it below. But even these rivers are liable to have their flow modified by the influx of tributaries subject to different conditions, so that the Rhone below Lyon has a more uniform discharge than most rivers, as the summer floods of the Arve are counteracted to a great extent by the low stage of the Saône flowing into the Rhone at Lyon, which has its floods in the winter when the Arve, on the contrary, is low.

Another serious obstacle encountered in river engineering consists in the large quantity of detritus they bring down in flood-time, derived mainly from the disintegration of the surface layers of the hills and slopes in the upper parts of the valleys by glaciers, frost and rain. The power of a current to transport materials varies with its velocity, so that torrents with a rapid fall near the sources of rivers can carry down rocks, boulders and large stones, which are by degrees ground by attrition in their onward course into shingle, gravel, sand and silt, simultaneously with the gradual reduction in fall, and, consequently, in the transporting force of the current. Accordingly, under ordinary conditions, most of the materials brought down from the high lands by torrential water courses are carried forward by the main river to the sea, or partially strewn over flat alluvial plains during floods; the size of the materials forming the bed of the river or borne along by the stream is gradually reduced on proceeding seawards, so that in the Po River in Italy, for instance, pebbles and gravel are found for about 140 miles below Turin, sand along the next 100 miles, and silt and mud in the last 110 miles.

Methods

Improvements can be divided into those that are aimed at improving the flow of the river, particularly in flood conditions, and those that aim to hold back the flow, primarily for navigation purposes, although power generation is often an important factor. The former

is known in the US as *channelization* and the latter is generally referred to as *canalization*.

Channelization



Channelized stream in Georgia. Courtesy: U.S. Fish & Wildlife Service

Reducing the length of the channel by substituting straight cuts for a winding course is the only way in which the (effective) fall can be increased. This involves some loss of capacity in the channel as a whole, and in the case of a large river with a considerable flow it is very difficult to maintain a straight cut owing to the tendency of the current to erode the banks and form again a sinuous channel. Even if the cut is preserved by protecting the banks, it is liable to produce changes shoals and raise the flood-level in the channel just below its termination. Nevertheless, where the available fall is exceptionally small, as in land originally reclaimed from the sea, such as the English Fenlands, and where, in consequence, the drainage is in a great measure artificial, straight channels have been formed for the rivers. Because of the perceived value in protecting these fertile, low-lying lands from inundation, additional straight channels have also been provided for the discharge of rainfall, known as drains in the fens. Even extensive modification of the course of a river combined with an enlargement of its channel often produces only a limited reduction in flood damage. Consequently, such floodworks are only commensurate with the expenditure involved where significant assets (such as a town) are under threat. Additionally, even when successful, such floodworks may simply move

the problem further downstream and threaten some other town. Recent floodworks in Europe have included restoration of natural floodplains and winding courses, so that floodwater is held back and released more slowly.

The removal of obstructions, natural or artificial (e.g., trunks of trees, boulders and accumulations of gravel) from a river bed furnishes a simple and efficient means of increasing the discharging capacity of its channel. Such removals will consequently lower the height of floods upstream. Every impediment to the flow, in proportion to its extent, raises the level of the river above it so as to produce the additional artificial fall necessary to convey the flow through the restricted channel, thereby reducing the total available fall.

Human intervention sometimes inadvertently modifies the course or characteristics of a river, for example by introducing obstructions such as mining refuse, sluice gates for mills, fish-traps, unduly wide piers for bridges and solid weirs. By impeding flow these measures can raise the flood-level upstream. Regulations for the management of rivers may include stringent prohibitions with regard to pollution, requirements for enlarging sluice-ways and the compulsory raising of their gates for the passage of floods, the removal of fish traps, which are frequently blocked up by leaves and floating rubbish, reduction in the number and width of bridge piers when rebuilt, and the substitution of movable weirs for solid weirs.

By installing gauges in a fairly large river and its tributaries at suitable points, and keeping continuous records for some time of the heights of the water at the various stations, the rise of the floods in the different tributaries, the periods they take in passing down to definite stations on the main river, and the influence they severally exercise on the height of the floods at these places, can be ascertained. With the help of these records, and by observing the times and heights of the maximum rise of a particular flood at the stations on the various tributaries, the time of arrival and height of the top of the flood at any station on the main river can be predicted with remarkable accuracy two or more days beforehand. By communicating these particulars about a high flood to places on the lower river, weir-keepers are enabled to fully open the movable weirs beforehand to permit the passage of the flood, and riparian inhabitants receive timely warning of the impending inundation.

Where portions of a riverside town are situated below the maximum flood-level, or when it is important to protect land adjoining a river from inundations, the overflow of the river must be diverted into a flood-dam or confined within continuous embankments on both sides. By placing these embankments somewhat back from the margin of the river-bed, a wide flood-channel is provided for the discharge of the river as soon as it overflows its banks, whilst leaving the natural channel unaltered for the ordinary flow. Low embankments may be sufficient where only exceptional summer floods have to be excluded from meadows. Occasionally the embankments are raised high enough to retain the floods during most years, whilst provision is made for the escape of the rare, exceptionally high floods at special places in the embankments, where the scour of the issuing current is guarded against, and the inundation of the neighboring land is least

injurious. In this manner, the increased cost of embankments raised above the highest flood-level of rare occurrence is avoided, as is the danger of breaches in the banks from an unusually high flood-rise and rapid flow, with their disastrous effects.

Effects

A most serious objection to the formation of continuous, high embankments along rivers bringing down considerable quantities of detritus, especially near a place where their fall has been abruptly reduced by descending from mountain slopes onto alluvial plains, is the danger of their bed being raised by deposit, producing a rise in the flood-level, and necessitating a raising of the embankments if inundations are to be prevented.

Longitudinal sections of the Po River, taken in 1874 and 1901, show that its bed was materially raised during this period from the confluence of the Ticino to below Caranella, despite the clearance of sediment effected by the rush through breaches. Therefore, the completion of the embankments, together with their raising, would only eventually aggravate the injuries of the inundations they have been designed to prevent, as the escape of floods from the raised river must occur sooner or later.

In the UK, problems of flooding of domestic properties around the turn of the 21st century have been blamed on inadequate planning controls which have permitted development on floodplains. This exposes the properties on the floodplain to flood, and the substitution of concrete for natural strata speeds the run-off of water, which increases the danger of flooding downstream. In the Midwestern United States and the Southern United States the term for this measure is *channelization*. Much of it was done under the auspices or overall direction of the United States Army Corps of Engineers. One of the most heavily channelized areas in the United States is West Tennessee, where every major stream with one exception (the Hatchie River) has been partially or completely channelized.

Advantages

Channelization of a stream may be undertaken for several reasons. One is to make a stream more suitable for navigation or for navigation by larger vessels with deep draughts. Another is to restrict water to a certain area of a stream's natural bottom lands so that the bulk of such lands can be made available for agriculture. A third reason is flood control, with the idea of giving a stream a sufficiently large and deep channel so that flooding beyond those limits will be minimal or nonexistent, at least on a routine basis. One major reason is to reduce natural erosion; as a natural waterway curves back and forth, it usually deposits sand and gravel on the inside of the corners where the water flows slowly, and cuts sand, gravel, subsoil, and precious topsoil from the outside corners where it flows rapidly due to a change in direction. Unlike sand and gravel, the topsoil that is eroded does not get deposited on the inside of the next corner of the river. It simply washes away. Channelization of a waterway by straightening it prevents the water from changing directions randomly, and net erosion is greatly reduced.

Disadvantages

Channelization has several predictable and negative effects. One of them is loss of wetlands. Wetlands are an excellent habitat for many forms of wildlife, and additionally serve as a "filter" for much of the world's surface fresh water. Another is the fact that channelized streams are almost invariably straightened. For example, the channelization of Florida's Kissimmee River has been cited as a cause contributing to the loss of wetlands. This straightening causes the streams to flow more rapidly, which can, in some instances, vastly increase soil erosion. It can also increase flooding downstream from the channelized area, as larger volumes of water traveling more rapidly than normal can reach choke points over a shorter period of time than they otherwise would, with a net effect of flood control in one area coming at the expense of greatly aggravated flooding in another. In addition, studies have shown that stream channelization results in declines of river fish populations. A 1971 study of the Chariton River in northern Missouri, United States, found that the channelized section of the river contained only 13 species of fish, whereas the natural segment of the stream was home to 21 species of fish. The biomass of fish able to be caught in the dredged segments of the river was 80 percent less than in the natural parts of the same stream. This loss of fish diversity and abundance is thought to occur because of reduction in habitat, elimination of riffles and pools, greater fluctuation of stream levels and water temperature, and shifting substrates. The rate of recovery for a stream once it has been dredged is extremely slow, with many streams showing no significant recovery 30 to 40 years after the date of channelization.

Modern policy

For the reasons cited above, in recent years stream channelization has been greatly curtailed in the U.S., and in some instances even partially reversed. The United States Government now has in place a "no net loss of wetlands" policy that means that stream channelization in one place has to be offset by the creation of new wetlands in another, a process known as "mitigation." The major agency involved in the enforcement of this policy is the same Army Corps of Engineers which for so long was the primary promoter of wide-scale channelization. Often, in the instances where channelization is permitted, boulders may be installed in the bed of the new channel so that water velocity is slowed, and channels may be deliberately curved as well. In 1990 the U.S. Congress gave the Army Corps a specific mandate to include environmental protection in its mission, and in 1996 it authorized the Corps to undertake restoration projects. The U.S. Clean Water Act regulates certain aspects of channelization by requiring non-Federal entities (i.e. state and local governments, private parties) to obtain permits for dredging and filling operations. Permits are issued by the Army Corps with EPA participation.

This new policy also has its critics, however. Farmers who are losing land to soil erosion as channelized streams cease to be maintained feel particularly aggrieved. Not only are they losing their valuable property to erosion, the erosion ends up in the stream or river, and contributes to decreased water quality. They also point out that if such policies had been in place in the U.S. at the time of white settlement, the country probably would never have become a leader in world agriculture and a net exporter of food.

Channelization critics respond that this is immaterial, as we are no longer living in the era of initial settlement.

Canalization of rivers



A channelized section of the Floyd River in Sioux City, Iowa



A channelized section of the South Fork of the Crow River in Meeker County, Minnesota



An early large channelization was performed by Johann Gottfried Tulla on the Upper Rhine.

Rivers whose discharge is liable to become quite small at their low stage, or which have a somewhat large fall, as is usual in the upper part of rivers, cannot be given an adequate depth for navigation purely by works which regulate the flow; their ordinary summer level has to be raised by impounding the flow with weirs at intervals across the channel, while a lock has to be provided alongside the weir, or in a side channel, to provide for the passage of vessels. A river is thereby converted into a succession of fairly level reaches rising in steps up-stream, providing still-water navigation comparable to a canal; but it differs from a canal in the introduction of weirs for keeping up the water-level, in the provision for the regular discharge of the river at the weirs, and in the two sills of the locks being laid at the same level instead of the upper sill being raised above the lower one to the extent of the rise at the lock, as usual on canals.

Canalization secures a definite available depth for navigation; and the discharge of the river generally is amply sufficient for maintaining the impounded water level, as well as providing the necessary water for locking. Navigation, however, is liable to be stopped during the descent of high floods, which in many cases rise above the locks; and it is necessarily arrested in cold climates on all rivers by long, severe frosts, and especially by ice. Many small rivers, like the Thames above its tidal limit, have been rendered navigable by canalization, and several fairly large rivers have thereby provided a good

depth for vessels for considerable distances inland. Thus the canalized Seine has secured a navigable depth of 10 1/2 feet from its tidal limit up to Paris, a distance of 135 miles, and a depth of 6 3/4 feet up to Montereau, 62 miles higher up.

Regulation works (flow and depth control)

As rivers flow onward towards the sea, they experience a considerable diminution in their fall, and a progressive increase in the basin which they drain, owing to the successive influx of their various tributaries. Thus, their current gradually becomes more gentle and their discharge larger in volume and less subject to abrupt variations; and, consequently, they become more suitable for navigation. Eventually, large rivers, under favorable conditions, often furnish important natural highways for inland navigation in the lower portion of their course, as, for instance, the Rhine, the Danube and the Mississippi. River engineering works are only required to prevent changes in the course of the stream, to regulate its depth, and especially to fix the low-water channel and concentrate the flow in it, so as to increase as far as practicable the navigable depth at the lowest stage of the water level.

Engineering works to increase the navigability of rivers can only be advantageously undertaken in large rivers with a moderate fall and a fair discharge at their lowest stage, for with a large fall the current presents a great impediment to up-stream navigation, and there are generally great variations in water level, and when the discharge becomes very small in the dry season. it is impossible to maintain a sufficient depth of water in the low-water channel.

The possibility to secure uniformity of depth in a river by lowering the shoals obstructing the channel depends on the nature of the shoals. A soft shoal in the bed of a river is due to deposit from a diminution in velocity of flow, produced by a reduction in fall and by a widening of the channel, or to a loss in concentration of the scour of the main current in passing over from one concave bank to the next on the opposite side. The lowering of such a shoal by dredging merely effects a temporary deepening, for it soon forms again from the causes which produced it. The removal, moreover, of the rocky obstructions at rapids, though increasing the depth and equalizing the flow at these places, produces a lowering of the river above the rapids by facilitating the efflux, which may result in the appearance of fresh shoals at the low stage of the river. Where, however, narrow rocky reefs or other hard shoals stretch across the bottom of a river and present obstacles to the erosion by the current of the soft materials forming the bed of the river above and below, their removal may result in permanent improvement by enabling the river to deepen its bed by natural scour.

The capability of a river to provide a waterway for navigation during the summer or throughout the dry season depends on the depth that can be secured in the channel at the lowest stage. The problem in the dry season is the small discharge and deficiency in scour during this period. A typical solution is to restrict the width of the low-water channel, concentrate all of the flow in it, and also to fix its position so that it is scoured out every year by the floods which follow the deepest part of the bed along the line of the strongest

current. This can be effected by closing subsidiary low-water channels with dikes across them, and narrowing the channel at the low stage by low-dipping cross dikes extending from the river banks down the slope and pointing slightly up-stream so as to direct the water flowing over them into a central channel.

Estuarine works

The needs of navigation may also require that a stable, continuous, navigable channel is prolonged from the navigable river to deep water at the mouth of the estuary. The interaction of river flow and tide needs to be modeled by computer or using scale models, moulded to the configuration of the estuary under consideration and reproducing in miniature the tidal ebb and flow and fresh-water discharge over a bed of very fine sand, in which various lines of training walls can be successively inserted. The models should be capable of furnishing valuable indications of the respective effects and comparative merits of the different schemes proposed for works.

Chapter 2

Lock (Water Transport)



Canal locks in England.



Canal lock in the Noordoostpolder, Netherlands.



Canal lock and weir complex in Grave, Netherlands.



Bardney lock, River Witham, UK.



Lock One, Trent-Severn Waterway, Ontario, Canada



Lock in river Neckar, Heidelberg, Germany

A **lock** is a device for raising and lowering boats between stretches of water of different levels on river and canal waterways. The distinguishing feature of a lock is a fixed chamber in which the water level can be varied; whereas in a caisson lock, a boat lift, or on a canal inclined plane, it is the chamber itself (usually then called a caisson) that rises and falls.

Locks are used to make a river more easily navigable, or to allow a canal to take a reasonably direct line across land that is not level.

Pound lock

A **pound lock** is a type of lock that is used almost exclusively nowadays on canals and rivers. A pound lock has a chamber (the pound) with gates at both ends that control the level of water in the pound. In contrast, an earlier design with a single gate was known as a flash lock.

Indirect evidence suggests that pound locks may have been used in antiquity by the Ptolemaic Greeks and the Romans.

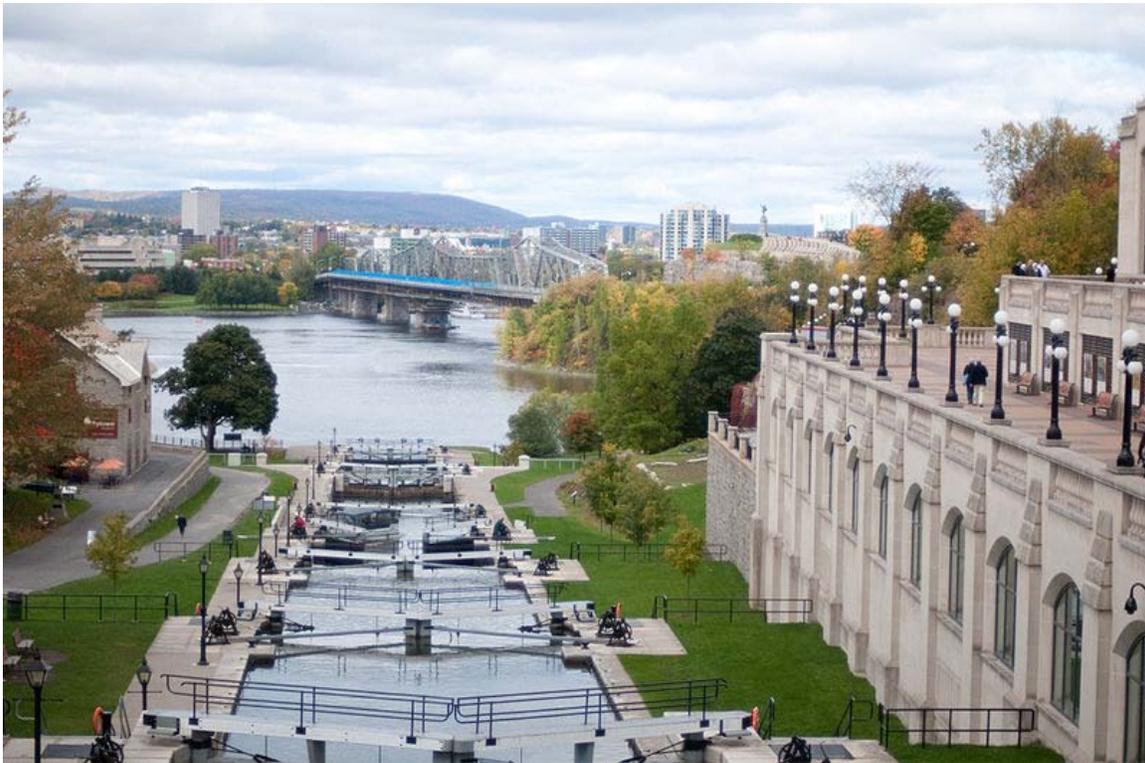
Pound locks were used in ancient China during the Song Dynasty (960–1279 AD), having been pioneered by the government official and engineer Qiao Weiyo in 984. They replaced earlier double slipways that had caused trouble and are mentioned by the Chinese polymath Shen Kuo (1031–1095) in his book *Dream Pool Essays* (published in 1088), and fully described in the Chinese historical text *Song Shi* (compiled in 1345):

The distance between the two locks was rather more than 50 paces, and the whole space was covered with a great roof like a shed. The gates were 'hanging gates'; when they were closed the water accumulated like a tide until the required level was reached, and then when the time came it was allowed to flow out.

The water level could differ by 4 or 5 feet at each lock and in the Grand Canal the level was raised in this way by 138 feet (42 m).

In medieval Europe a type of pound lock was first built in 1373 at Vreeswijk, Netherlands. This pound lock serviced many ships at once in a large basin, yet the true pound lock (i.e. one for a small basin) came in 1396 with the one built at Damme near Bruges. A famous civil engineer of pound locks in Europe was the Italian Bertola da Novate (c. 1410-1475), who constructed 18 of them on the Naviglio di Bereguardo (part of the Milan canal system sponsored by Francesco Sforza) between the years 1452 and 1458.

Use of locks in river navigations



Locks on the Rideau Canal near Parliament Hill, Ottawa, Canada

A lock is required when a stretch of river is made navigable by bypassing an obstruction such as a rapid, dam, or mill weir — because of the change in river level across the obstacle.

In large scale river navigation improvements, weirs and locks are used together. A weir will increase the depth of a shallow stretch, and the required lock will either be built in a gap in the weir, or at the downstream end of an artificial *cut* which bypasses the weir and perhaps a shallow stretch of river below it. A river improved by these means is often called a Waterway or River Navigation.

The lowest lock on a navigable river separates the tidal and non-tidal stretches. Sometimes a river is made entirely non-tidal by constructing a *sea lock* directly into the estuary.

In more advanced river navigations, more locks are required.

- Where a longer cut bypasses a circuitous stretch of river, the upstream end of the cut will often be protected by a *flood lock*.
- The longer the cut, the greater the difference in river level between start and end of the cut, so that a very long cut will need additional locks along its length. At this point, the cut is, in effect, a *canal*.

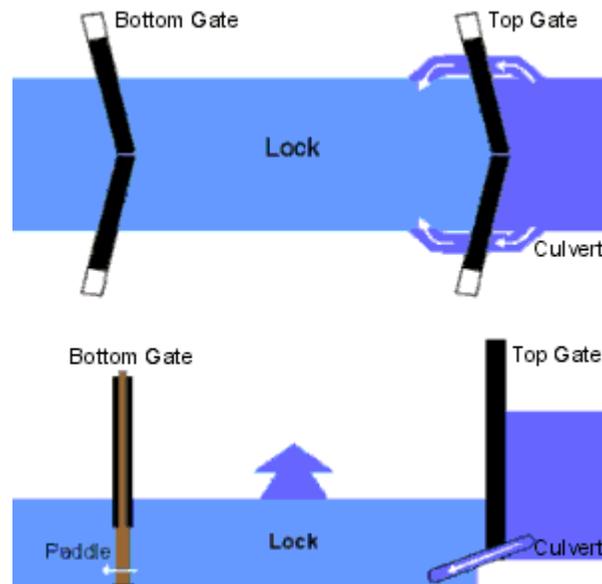
Use of locks in canals



Locks of the Panama Canal during construction, 1913.

Early completely artificial canals, across fairly flat countryside, would get round a small hill or depression by simply detouring (*contouring*) around it. As engineers became more ambitious in the types of country they felt they could overcome, locks became essential to effect the necessary changes in water level without detours that would be completely uneconomic both in building costs and journey time. Later still, as construction techniques improved, engineers became more willing to barge directly through and across obstacles by constructing long tunnels, cuttings, aqueducts or embankments, or to construct even more technical devices such as inclined planes or boat lifts. However, locks continued to be built to supplement these solutions, and are an essential part of even the most modern navigable waterways.

Basic construction and operation



A plan and side view of a generic, empty canal lock. A lock chamber separated from the rest of the canal by an upper pair and a lower pair of mitre gates. The gates in each pair close against each other at an 18° angle to approximate an arch against the water pressure on the "upstream" side of the gates when the water level on the "downstream" side is lower.

All pound locks have three elements:

- A watertight *chamber* connecting the upper and lower canals, and large enough to enclose one or more boats. The position of the chamber is fixed, but its water level can vary.
- A *gate* (often a pair of "pointing" half-gates) at each end of the chamber. A gate is opened to allow a boat to enter or leave the chamber; when closed, the gate is watertight.
- A set of *lock gear* to empty or fill the chamber as required. This is usually a simple valve (traditionally, a flat panel (paddle) lifted by manually winding a rack and pinion mechanism) which allows water to drain into or out of the chamber; larger locks may use pumps.

The principle of operating a lock is simple. For instance, if a boat travelling downstream finds the lock already full of water:

- The entrance gates are opened and the boat sails in.
- The entrance gates are closed.
- A valve is opened, this lowers the boat by draining water from the chamber.
- The exit gates are opened and the boat sails out.

If the lock were empty, the boat would have had to wait 5 to 10 minutes while the lock was filled. For a boat travelling upstream, the process is reversed; the boat enters the empty lock, and then the chamber is filled by opening a valve that allows water to enter the chamber from the upper level. The whole operation will usually take between 10 and 20 minutes, depending on the size of the lock and whether the water in the lock was originally set at the boat's level.

Boaters approaching a lock are usually pleased to meet another boat coming towards them, because this boat will have just exited the lock on their level and therefore set the lock in their favour — saving about 5 to 10 minutes. However, this is not true for staircase locks, where it is quicker for boats to go through in convoy.

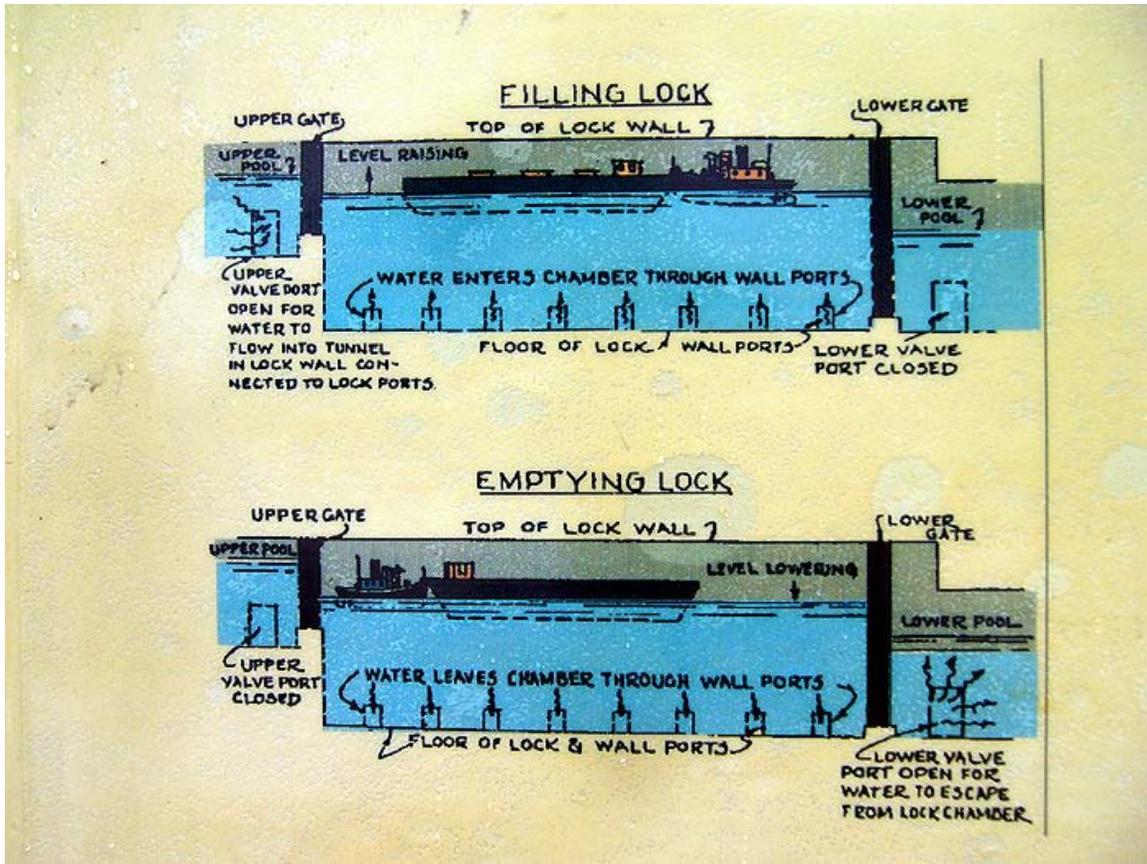


Operation of a canal lock

1-3. Boat enters 'empty' lock

4. Bottom gates are closed, bottom paddles closed, top paddles opened, lock starts to fill

5. Lock is filling with water, lifting boat to the higher level



Lock operation

Details and terminology

For simplicity, this section describes a basic type of lock, with a pair of gates at each end of the chamber and simple rack and pinion paddles raised manually by means of a detachable windlass operated by the boat's shore crew. This type can be found all over the world, but the terminology here is that used on the British canals. A subsequent section explains common variations.

Rise

The change in water-level effected by the lock. The two deepest locks on the English canal system are Bath deep lock on the Kennet and Avon Canal and Tuel Lane Lock on the Rochdale Canal, which both have a rise of nearly 20 feet (6.1 m). Both locks are amalgamations of two separate locks, which were combined when the canals were restored to accommodate changes in road crossings. The deepest "as-built" locks in England are considered to be Etruria Top Lock on the Trent and Mersey Canal or Somerton Deep Lock on the Oxford Canal, both of which have a rise of about 14 ft (4.3 m). Again, sources vary as to which is the deepest and in any case Etruria has been deepened over the years to accommodate subsidence. A more typical (English) rise would be 7–12 feet (though even shallower ones can be encountered).

Pound

The level stretch of water between two locks (also known as a *reach*).

Chamber

The main feature of a lock. It is a watertight (masonry, brick, steel or concrete) enclosure which can be sealed off from the pounds at either end by means of *gates*. The chamber may be the same size (plus a little manoeuvring room) as the largest vessel for which the waterway was designed; sometimes larger, to allow more than one such vessel at a time to use the lock. The chamber is said to be "full" when the water level is the same as in the upper pound; and "empty" when the level is the same as in the lower pound. (If the lock has no water in it at all, perhaps for maintenance work, it might also be said to be empty, but less-confusing terms for this are "drained" or "de-watered".)

Cill



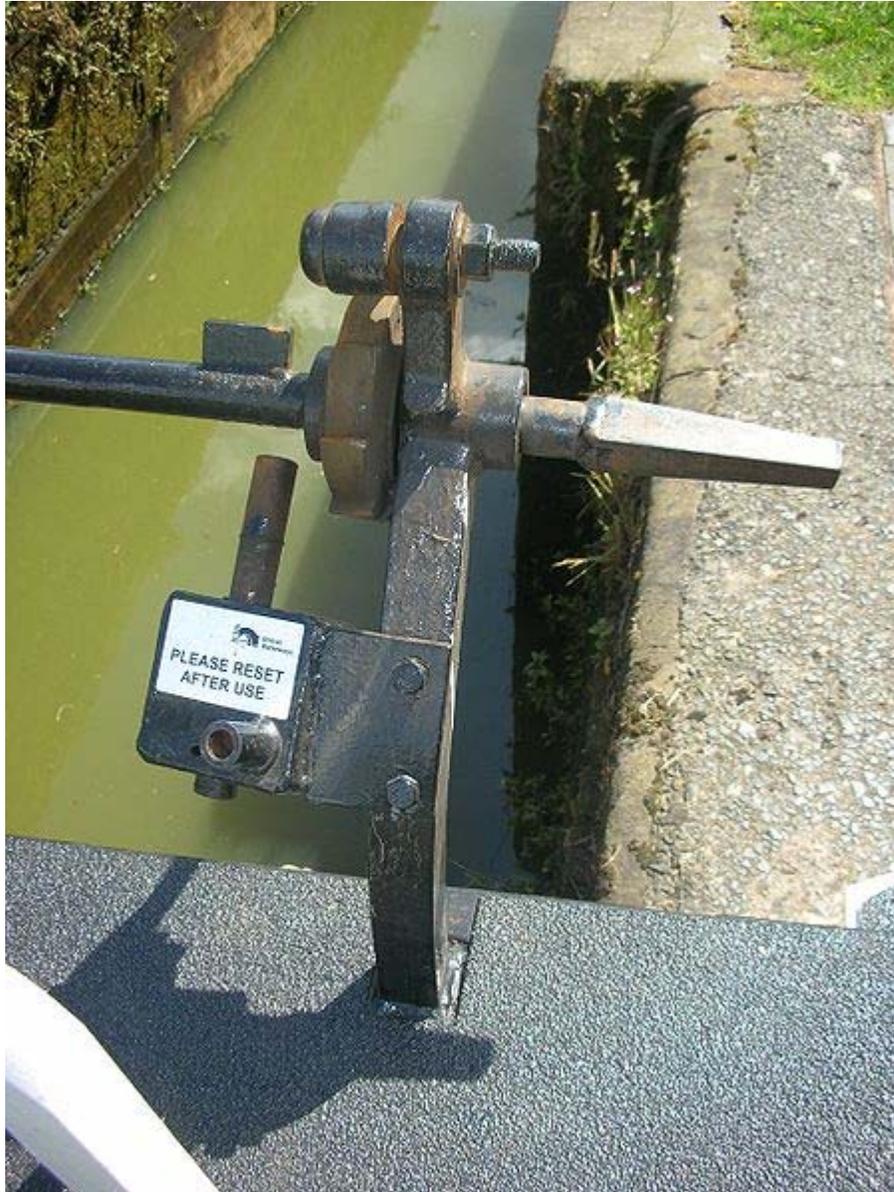
The cill exposed in the deep Pont de Flandre lock on the Canal Saint-Denis, Paris



Top gate of a lock, showing the balance beams and paddle winding gear



200-year-old paddle gear on the Wiener Neustädter Kanal, Austria



Water conservation gear on the Birmingham Canal Navigations

A narrow horizontal ledge protruding a short way into the chamber from below the upper gates. Allowing the rear of the boat to "hang" on the cill is the main danger one is warned to guard against when descending a lock, and the position of the forward edge of the cill is usually marked on the lock side by a white line. The edge of the cill is usually curved, protruding less in the centre than at the edges. In some locks, there is a piece of oak about 9" thick which protects the solid part of the lock cill. On the Oxford Canal it is called a Babbie; on the Grand Union Canal it is referred to as the cill Bumper.

Gates

Gates are the watertight doors which seal off the chamber from the upper and lower pounds. Each end of the chamber is equipped with a gate, or pair of half-gates, made of oak or elm (or now sometimes steel). The most common arrangement, usually called *mitre gates*, was invented in 1440 in Italy by Philippe Marie Visconti. When closed, a pair meet at an angle like a chevron pointing upstream and only a very small difference in water-level is necessary to squeeze the closed gates securely together. This reduces any leaks from between them and prevents their being opened until water levels have equalised. If the chamber is not completely full, the top gate is secure; and if the chamber is not completely empty, the bottom gate is secure (in normal operation, therefore, the chamber cannot be open at both ends). A lower gate is taller than an upper gate, because the upper gate only has to be tall enough to close off the upper pound, while the lower gate has to be able to seal off a full chamber. *The upper gate is as tall as the canal is deep, plus a little more for the balance beam, winding mechanism, etc.; the lower gate's height equals the upper gate plus the lock's rise.*

Balance beam

A *balance beam* is the long arm projecting from the landward side of the gate over the towpath. As well as providing leverage to open and close the heavy gate, the beam also balances the (non-floating) weight of the gate in its socket, and so allows the gate to swing more freely.

Paddle

A *paddle* – sometimes known as a *slacker*, *clough*, or (in American English) *wicket* – is the simple valve by which the lock chamber is filled or emptied. The paddle itself is a sliding wooden (or nowadays plastic) panel which when "lifted" (slid up) out of the way allows water to either enter the chamber from the upper pound or flow out to the lower pound. A *gate paddle* simply covers a hole in the lower part of a gate; a more sophisticated *ground paddle* blocks an underground culvert. There can be up to 8 paddles (two gate paddles and two ground paddles at both upper and lower ends of the chamber) but there will often be fewer. For a long period since the 1970s it has been British Waterways policy not to provide gate paddles in replacement top gates if two ground paddles exist. The reason for this has been safety, since it is possible for an ascending boat to be swamped by the water from a carelessly lifted gate paddle. However, this makes the locks slower to operate and has been blamed in some places for causing congestion. Since the late 1990s the preferred method has been to retain the gate paddles and fit 'baffles' across them to minimise the risk of inundation.

Winding gear or paddle gear

The mechanism which allows paddles to be lifted (opened) or lowered (closed). Typically, a square-section stub emerges from the housing of the winding gear. This is the axle of a sprocket ("pinion") which engages with a toothed bar ("rack") attached by

rodding to the top of the paddle. A member of the boat's shore crew engages the square socket of their *windlass* onto the end of the axle and turns the windlass perhaps a dozen times. This rotates the pinion and lifts the paddle. A pawl engages with the rack to prevent the paddle from dropping inadvertently while being raised, and to keep it raised when the windlass is removed, so that the operator can attend to other paddles. Nowadays it is considered discourteous and wasteful of water to leave a paddle open after a boat has left the lock, but in commercial days it was normal practice. To lower a paddle the pawl must be disengaged and the paddle wound down with the windlass. Dropping paddles by knocking the pawl off can cause damage to the mechanism – the paddle gear is typically made of cast iron and can shatter or crack when dropped from a height. In areas where water-wastage due to vandalism is a problem, (for example the Birmingham Canal Navigations), paddle mechanisms are commonly fitted with vandal-proof locks (nowadays rebranded *water conservation devices*) which require the boater to employ a key before the paddle can be lifted. The keys are officially known as "water conservation keys", but boaters usually refer to them as *T-keys*, from their shape, *handcuff key* because the original locks, fitted on the Leeds and Liverpool Canal, resembled handcuffs, *Leeds and Liverpool Keys* after that canal, or simply *Anti-Vandal Keys*.

Hydraulic paddle gear

During the 1980s British Waterways began to introduce a hydraulic system for operating paddles, especially those on bottom gates, which are the heaviest to operate. A metal cylinder about a foot in diameter was mounted on the balance beam and contained a small oil-operated hydraulic pump. A spindle protruded from the front face and was operated by a windlass in the usual way, the energy being transferred to the actual paddle by small bore pipes. The system was widely installed and on some canals it became very common. There turned out to be two serious drawbacks. It was much more expensive to install and maintain than traditional gear and went wrong more frequently, especially once the vandals learned to cut the pipes. Even worse, it had a safety defect, in that the paddle once in the raised position could not be dropped in an emergency, but had to be wound down, taking a good deal longer. These factors led to the abandonment of the policy in the late 1990s, but examples of it survive all over the system, as it is usually not removed until the gates need replacing, which happens about every twenty years.

Windlass ("lock key")

A windlass (also known as a 'lock handle', 'iron' or simply 'key') is a detachable crank used for opening lock paddles (the word does not refer to the winding mechanism itself).

The simplest windlass is made from an iron rod of circular section, about half an inch in diameter and two feet long, bent to make an L-shape with legs of slightly different length. The shorter leg is called the handle, and the longer leg is called the arm. Welded to the end of the arm is a square, sometimes tapered, socket of the correct size to fit onto the spindle protruding from lock winding gear.

- **Socket:** Traditionally, windlasses had a single socket, designed for a particular canal. When undertaking a journey through several canals with different lock-gear spindle sizes it was necessary to carry several different windlasses. A modern windlass usually has two sockets for use on different canals: the smaller is for the British Waterways standard spindle, fitted in the early 1990s almost everywhere, the larger for the gear on the Grand Union Canal north of Napton Junction, which they were unable to convert.
- **Handle:** The handle is long enough for a two-handed grip and is far enough from the socket to give enough leverage to wind the paddle up or down. There may be a freely-rotating sleeve around the handle to protect the tender hands of a novice boater from the blisters which can be caused by the friction of a rough iron handle turning against soft skin.
- **Arm:** A "long throw" windlass has a longer arm so that the handle is further from the socket to give a greater leverage on stiffer paddles. If the throw is *too long* then the user, winding a gate paddle, risks barking their knuckles against the balance beam when the handle is at the lowest point of its arc. A sophisticated modern windlass may have an adjustable-length arm.
- **Materials :** Early windlasses were individually hand forged from a single piece of wrought iron by a blacksmith. More modern techniques include casting of iron or bronze, drop forging and (the most common technique) welding. Some boatmen had their windlasses 'silvered' (or chrome plated) for increased comfort and to prevent rusting. Windlasses are now only rarely plated, but a popular modern choice of metal is aluminium, whose smooth and rustproof surface has the same advantages of longevity and blister-reduction, and is also very light. One type of these, the Dunton Double, has only a single eye, but by clever tapering it will operate either size of spindle.

"Turning" a lock

This can simply mean emptying a full lock or filling an empty one (*We entered the lock, and it only took us five minutes to turn it*). It is used more often to refer to a lock being filled or emptied while you are not in it (*The lock was turned for us by a boat coming the other way*) and particularly when there is no boat in it at all (*The lock was set for us, but the crew of the boat coming the other way turned it before we got there*).

"Lock Mooring"

This was a commonly used method of navigating into a lock by a barge traveling upstream. The barge would be directed to the slack water to one side of the lock gates and as the volume of water decreases as the lock empties the barge or boat is effectively sucked out of the slack water into the path of the lock gates. The effort required to navigate the barge or boat into the mouth of the lock is therefore substantially reduced.

Variations



A series of photos of the Canadian Locks in Sault Ste. Marie to illustrate a drop of about 22 ft (7 m) in a lock.

Not all locks work exactly as described above, and the terminology changes, too ...

- Single gates on narrow canals (locks approx. 7 feet / 2.1 m wide)
 - On most English narrow canals, the upper end of the chamber is closed by a single gate the full width of the lock. This was cheaper to construct and is quicker to operate with a small crew, as only one gate needs to be opened.
 - Some narrow locks (e.g. on Birmingham Canal Navigations) go even further. They have single gates at the lower end also. This speeds up passage, even though single lower gates are heavy (heavier than a single upper gate, because the lower gate is taller) and the lock has to be longer (a lower gate opens INTO the lock, it has to pass the bow or stern of an enclosed boat, and a single gate has a wider arc than two half-gates).
 - A few narrow locks imitate wide locks in having paired gates at both ends (e.g. Bosley, on the Macclesfield Canal)
- Steel Gates. Steel gates and/or balance beams are frequently used nowadays, although all-wooden versions are still fitted where appropriate.
 - Swinging gates: Even very large steel-gated locks still can use essentially the same swinging gate design as small 250-year-old locks on the English

canals. On English canals, steel gates usually have wooden mitre posts as this gives a better seal.

- Sliding gates: Some low-head locks use sliding steel gates.
 - Guillotine gates: Some locks have vertically moving steel gates — these are quite common on river navigations in East Anglia. Sometimes just one of the pairs of swinging gates is replaced by a guillotine: for instance at Salterhebble Locks, where space to swing the balance beams of bottom gates of the lowest lock was restricted by bridge widening. On the River Nene most locks have this arrangement as in time of flood the top mitre gates are chained open and the bottom guillotines lifted so that the lock chamber acts as an overflow sluice. Guillotine gates are also used on the downstream side of larger locks such as the 23m Bollène lock on the River Rhône, the aperture being large enough for a boat to travel under it.
 - Vertically-rotating gates: Gates which, when open, lie flat on the canal bed and which close by lifting (London Flood Barrier).
 - Rotating-sector gates. Some of these work very like traditional swinging gates, but with each gate in the form of a sector of a cylinder. They close by rotating out from the lock wall and meeting in the centre of the chamber. Water is let in or out by opening the gates slightly: there are no paddles or other lock gear. The lock at Limehouse Basin, which gives access to the River Thames, is an example. A dramatically-large one can be seen at the Rotterdam flood defences (huge flood gates). There is a different type at the sea lock on the Ribble Link: this is a rising sector gate, which has a horizontal axis: the gate drops to the bed of the river to allow boats to pass.
- Alternate paddle gear
 - Some manually-operated paddles do not require a detachable handle (windlass) because they have their handles ready-attached.
 - On the Leeds and Liverpool Canal there is a variety of different lock gear. Some paddles are raised by turning what is in effect a large horizontal wing nut (butterfly nut) lifting a screw-threaded bar attached to the top of the paddle. Others are operated by lifting a long wooden lever, which operates a wooden plate which seals the culvert. These are known locally as "jack cloughs". Bottom gate paddles are sometimes operated by a horizontal ratchet which also slides a wooden plate sideways, rather than the more common vertical lift. Many of these idiosyncratic paddles have been "modernised" and they are becoming rare.
 - On the Calder and Hebble Navigation, some paddle gear is operated by repeatedly inserting a *Calder and Hebble Handspike* (length of 4" by 2" hardwood) into a ground-level slotted wheel and pushing down on the handspike to rotate the wheel on its horizontal axis.
 - On some parts of the Montgomery Canal bottom paddles are used in place of side paddles. Rather than passing into the lock through a culvert around the side of the lock gate, the water flows through a culvert in the bottom of the canal. The paddle slides horizontally over the culvert.

- Lock keepers. Some locks are operated (or at least supervised) by professional lock keepers. This is particularly true on commercial waterways, or where locks are large or have complicated features that the average leisure boater may not be able to operate successfully. For instance, although the Thames above Teddington (England) is almost entirely a leisure waterway, the locks are usually staffed. Only recently have boaters been allowed limited access to the hydraulic gear to operate the locks when the keeper is not present.
- Powered operation. On large modern canals, especially very large ones such as ship canals, the gates and paddles are too large to be hand operated, and are operated by hydraulic or electrical equipment. Even on smaller canals, some gates and paddles are electrically operated, particularly if the lock is regularly staffed by professional lock keepers. On the River Thames below Oxford all the locks are staffed and powered. Powered locks are usually still filled by gravity, though some very large locks use pumps to speed things up.
- Fish Ladders. The construction of weirs on rivers obstructs the passage of both fish and ships. Some fish such as trout and salmon go upstream to spawn. Measures such as a fish ladder are often taken to counteract this.
- Weigh lock. A weigh lock is a specialized canal lock designed to determine the weight of barges in order to assess toll payments based upon the weight and value of the cargo carried.

Special cases

Lock flights



Flight of locks, Bratch, Staffordshire and Worcestershire Canal



The flight of 16 locks at Caen Hill on the Kennet and Avon Canal

Loosely, a flight of locks is simply a series of locks in close-enough proximity to be identified as a single group. For many reasons, a flight of locks is preferable to the same number of locks spread more widely: crews are put ashore and picked up once, rather than multiple times; transition involves a concentrated burst of effort, rather than a continually-interrupted journey; a lock keeper may be stationed to help crews through the flight quickly; and where water is in short supply, a single pump can recycle water to the top of the whole flight. The need for a flight may be purely determined by the lie of the land, but it is possible to purposely group locks into flights by using cuttings or embankments to "postpone" the height change. Examples: Caen Hill locks, Devizes.

"Flight" is not synonymous with "Staircase". A set of locks is only a staircase if successive lock chambers share a gate (i.e. do not have separate top and bottom gates with a pound between them). Most flights are not staircases, because each chamber is a separate lock (with its own upper and lower gates), there is a navigable pound (however short) between each pair of locks, and the locks are operated in the conventional way.

However, some flights include (or consist entirely of) staircases. On the Grand Union (Leicester) Canal, the Watford flight consists of a four-chamber staircase and three separate locks; and the Foxton flight consists entirely of two adjacent 5-chamber staircases.

Staircase locks



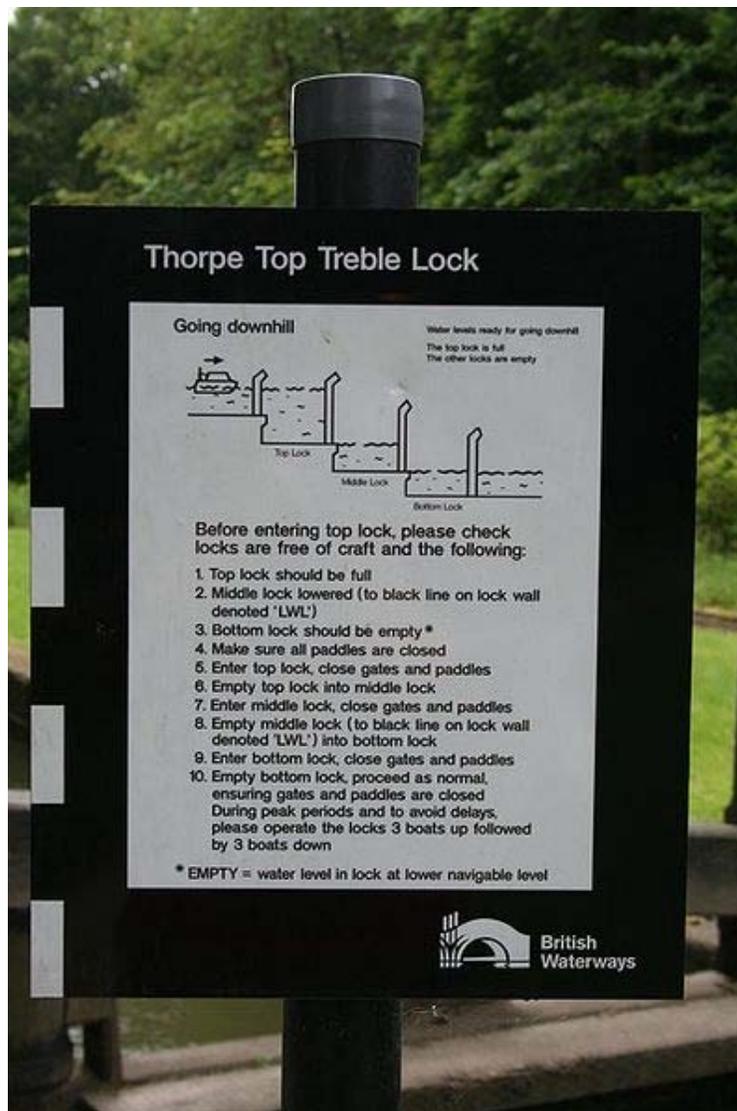
Staircase of five locks, dating from 1774, at Bingley, England

When a very steep gradient has to be climbed, a lock staircase is used. There are two types of staircase. A "real" staircase can be thought of as a "compressed" flight, where the intermediate pounds have disappeared, and the upper gate of one lock is also the lower gate of the one above it. However, it is incorrect to use the terms *staircase* and *flight* interchangeably: because of the "loss" of the intermediate pounds, operating a staircase is very different from operating a flight. It can be more useful to think of a staircase as a single lock with intermediate levels (the top gate is a normal top gate, and the intermediate gates are all as tall as the bottom gate). As there is no intermediate pound, a chamber can only be filled by emptying the one above, or emptied by filling the one below: thus the whole staircase has to be full of water (except for the bottom chamber) before a boat starts to ascend, or empty (except for the top chamber) before a boat starts to descend. By building a pair of such lock sets (one used to climb and the other to descend) these difficulties are avoided, as well as enabling a greater traffic volume and reduced wait times.

In an "apparent" staircase the chambers still have common gates, except in the case of Bratch Locks on the Staffordshire and Worcestershire Canal, but the water does not pass directly from one chamber to the next, going instead via side ponds. This means it is not necessary to ensure that the flight is full or empty before starting.

Examples of famous "real" staircases in England include Bingley and Grindley Brook. Two-rise staircases are more common: Snakeholme Lock and Struncheon Hill Lock on the Drifffield Navigation were converted to staircase locks after low water levels hindered navigation over the bottom cill at all but the higher tides — the new bottom chamber rises just far enough to get the boat over the original lock cill. In China, the recently completed Three Gorges Dam includes a double five-step staircase for large ships, and a ship lift for vessels of less than three thousand metric tons. Examples of "apparent" staircases include Foxton Locks and Watford Locks on the Leicester Branch of the Grand Union.

The absence of intermediate pounds in a "real" staircase of locks causes the staircase to use more water to transfer boats between levels than an ordinary flight does. An "apparent" staircase does not suffer from this problem and indeed this is the main reason for their design.



Instructions for descent of treble staircase, Chesterfield Canal

Operation of a staircase is more involved than a flight. Inexperienced boaters may find operating staircase locks difficult. The key worries (apart from simply being paralysed with indecision) are either sending down more water than the lower chambers can cope with (flooding the towpath, or sending a tidal wave along the canal) or completely emptying an intermediate chamber (although this shows that a staircase lock can be used as an emergency dry dock). To avoid these mishaps, it is usual to have the whole staircase empty before starting to descend, or full before starting to ascend, apart from the initial chamber.

One striking difference in using a staircase of either type (compared with a single lock, or a flight) is the best sequence for letting boats through. In a single lock (or a flight with room for boats to pass) it is obvious that boats should ideally alternate in direction. In a staircase, however, it is quicker for a boat to follow a previous one going in the same direction. Partly for this reason staircase locks such as Grindley Brook, Foxton, Watford and Bratch are supervised by lock-keepers, at least during the main cruising season and the normal rule they apply is to alternate as many boats up, followed by down as there are chambers in the flight.

As with a flight, it is possible on a broad canal for more than one boat to be in a staircase at the same time, but managing this without waste of water requires expertise. On English canals, a staircase of more than two chambers is usually staffed: the lock keeper at Bingley (looking after both the "5-rise" and the "3-rise") has worked there for more than 20 years and ensures that there are no untoward events and that boats are moved through as speedily and efficiently as possible. Such expertise permits miracles of boat balletics: it is possible for boats travelling in opposite directions to pass each other halfway up the staircase by moving sideways around each other; or at peak times, to have all the chambers full simultaneously with boats travelling in the same direction.

Doubled, paired or twinned locks

Locks can be built in parallel (i.e. side by side). This can be called *doubling, pairing, or twinning*. There are several examples (in this case called "double locks") on the Trent and Mersey Canal north of Harecastle Tunnel. Doubling gives advantages in speed: avoiding hold-ups at busy times; or increasing the chance of a boat finding a lock set in its favour. Also, there can be water savings: the locks may be of different sizes, so that a small boat does not need to empty a large lock; or each lock may be able to act as a side pond (water-saving basin) for the other. In this latter case, the word used is usually "twinned": here indicating the possibility of saving water by synchronising the operation of the chambers so that some water from the emptying chamber helps to fill the other. This facility has long been withdrawn on the English canals, although the disused paddle gear can sometimes be seen, as at Hillmorton on the Oxford Canal.

The once-famous staircase at Lockport, New York was also a doubled set of locks. Five twinned locks allowed east- and west-bound boats to climb/descend the 60 feet (18 m) Niagara Escarpment — a considerable engineering feat in the nineteenth century. While

Lockport today has two large steel locks, half of the old twin stair acts as a spillway and can still be seen (without lock gates).

Other meanings: These terms can also (in different places or to different people) mean either a two-chamber staircase (e.g. Turner Wood Double Locks on the Chesterfield Canal: the same canal has a three-rise staircase called Thorpe Low Treble locks), or just a flight of two locks (as at Thornhill Double Locks on the Calder and Hebble Navigation). Also, "double lock" (less often, "twin lock") is often used by novices on the English canals to mean a wide (14 ft) lock, presumably because it is "double" the width of a narrow lock, and allows two narrow boats going in the same direction to "double up". These are properly known as broad locks.

Stop locks



Lifford lane guillotine lock, Kings Norton, Birmingham between the Stratford-upon-Avon Canal and the Worcester and Birmingham Canal

A "stop" lock is a (very) low-rise lock built at the junction of two (rival) canals to prevent water from passing between them.

During the competitive years of the English waterways system, an established canal company would often refuse to allow a connection from a newer, adjacent one. This situation created the Worcester Bar in Birmingham, where goods had to be transhipped between boats on rival canals only feet apart.

Where a junction was built, either because the older canal company saw an advantage in a connection, or where the new company managed to insert a mandatory connection into its Act of Parliament, then the old company would seek to protect (and even enhance) its water supply. Normally, they would specify that, at the junction, the newer canal must be at a higher level than their existing canal. Even though the drop from the newer to the older canal might only be a few inches, the difference in levels still required a lock — called a **stop lock**, because it was to stop water flowing continuously between the newer canal and the older, lower one. The lock would be under the control of the new company, and the gates would, of course, "point" uphill - towards the newer canal. This would protect the water supply of the newer canal, but would nevertheless "donate" a lockful of water to the older company every time a boat went through. In times of excess water, of course, the lock "bywash" would continuously supply water to the lower canal.

When variable conditions meant that a higher water level in the new canal could not be guaranteed, then the older company would also build a stop lock (under its own control, with gates pointing towards its own canal) which could be closed when the new canal was low. This resulted in a sequential pair of locks, with gates pointing in opposite directions: one example was at Hall Green near Kidsgrove, where the southern terminus of the Macclesfield Canal joined the Hall Green Branch of the earlier Trent and Mersey Canal. The four gate stop lock near Kings Norton Junction, between the Stratford-upon-Avon Canal and the Worcester and Birmingham Canal was replaced in 1914 by a pair of guillotine lock gates which stopped the water flow regardless of which canal was higher. These gates have been permanently open since nationalisation.

Many stop locks were removed or converted to a single gate after nationalisation in 1948. Hall Green stop lock remains, but as a single lock: the extra lock was removed because the lowering of the T&M's summit pound (to improve Harecastle Tunnel's "air draught" — its free height above the water level) meant that the T&M would always be lower than the Macclesfield. The Hall Green Branch is now considered to be an extension of the Macclesfield Canal, which now meets the T&M at Hardings Wood Junction (just short of the Harecastle Tunnel north portal).

It should be noted that the "new canal must be higher" rule is not cast-iron. For instance: the very shallow lock at Atherley Junction, where the 1835 Birmingham and Liverpool canal (now part of the Shropshire Union Canal) met the older (1772) Staffordshire and Worcestershire Canal. The Nicholson guide shows that a boater coming south down the "Shroppie" locks UP before turning N or S onto the to the older S&W - so the Shroppie (the newer canal) gains a small lockful of water each time a boat passes. However, the

gain is tiny since the level difference is so small that it is sometimes possible to open both gates at once.

Round locks



Agde Round Lock

There are several examples where locks have been built to a round plan, with more than two exits from the lock chamber, each serving a different water level. Thus the lock serves both as a way of changing levels, but also as a junction. The circular plan of the lock allows boats to rotate within the lock, in order to line up with the appropriate exit gate.

The best known example of such a round lock is the Agde Round Lock on the Canal du Midi in France. This both serves as a lock on the main line of the canal, and also allow access to the Hérault River.

A second French round lock can be found in the form of the, now disused, Ecluse des Lorraines, connecting the Canal latéral à la Loire with the River Allier.

Drop locks



Dalmuir drop lock.

A drop lock allows a short length of canal to be lowered temporarily while a boat passes under an obstruction such as a low bridge. During canal restoration, a drop lock may be mooted where it is impractical or prohibitively expensive to remove or raise a structure that was built after the canal was closed (and where re-routing the canal is not possible).

A drop lock can consist of two conventional lock chambers leading to a sump pound, or a single long chamber incorporating the sump - although the term properly applies only to the second case. As the pounds at either end of the structure are at the same height, the lock can only be emptied either by allowing water to run to waste from the sump to a lower stream or drain, or (less wastefully) by pumping water back up to the canal. Particularly in the two-chamber type, there would be a need for a bypass culvert, to allow water to move along the interrupted pound and so supply locks further down the canal. In the case of the single-chamber type, this can be achieved by keeping the lock full and leaving the gates open whilst not in use.

Whilst the concept has been suggested in a number of cases, the only example in the world of a drop lock that has actually been constructed is at Dalmuir on the Forth and Clyde Canal in Scotland. This lock, of the single chamber type, was incorporated during the restoration of the canal, to allow the replacement of a swing bridge (on a busy A road)

by a fixed bridge, and so answer criticisms that the restoration of the canal would cause frequent interruptions of the heavy road traffic. It can be emptied by pumping - but as this uses a lot of electricity the method used when water supplies are adequate is to drain the lock to a nearby burn. A series of pictures showing the operation of the lock can be seen here. A similar arrangement is due to be built as part of the Droitwich Canal restoration.

Flood locks

A *flood lock* is to prevent a river from flooding a connected waterway. It is typically installed where a canal leaves a river. At normal river levels, the lock gates are left open, and the height of the canal is allowed to rise and fall with the height of the river.

However, if the river floods beyond a safe limit for the canal, then the gates are closed (and an extra lock created) until the river drops again. Since this is a true lock it is possible for boats to leave the canal for the flooded river despite the difference in water levels (though this is not likely to be wise) or (more sensibly) to allow boats caught out on the flood to gain refuge in the canal.

Note that if the canal is simply a navigation cut connecting two stretches of the same river, the flood lock will be at the **upstream** end of the cut (the downstream end will have a conventional lock).

Flood locks which have been used only as flood *gates* are often incapable of reverting to their former purpose without refurbishment. That is, where only outer gates are ever closed (probably because a waterway is not a true commercial one, and therefore there is no financial imperative for a boat to venture out onto a flooded river) inner gates soon suffer from lack of maintenance. A good example is on the Calder and Hebble Navigation, where structures referred to in the boating guides as "Flood Locks" are clearly only capable of being used for flood-prevention, not for "penning" boats to or from the river in flood.

Flood gates



Bi-directional flood gates on the canal Schoten-Dessel, Belgium.

A *flood gate* or "stop gate" is the cheaper equivalent of a flood lock. Only one set of gates exist, and so when the river is higher than the canal, the gates are closed and navigation ceases. These are quite common in the French inland waterways system. Flood gates may also be used to sub-divide long canal pounds or protect, in case of bank collapse, the surrounding area if this is lower than the water level of the canal. They are commonly found at the ends of long embankments and at aqueducts. These gates are often overlooked because they lack balance beams and are only a little higher than normal canal level.

Bi-directional gates and locks



Bi-directional gates at one chamber end of a tidal lock (located in Veurne on the canal Nieuwpoort - Duinkerke).

Where a lock is tidal (i.e. one side of the lock has water whose level varies with the tide) or where a canal meets a river whose level may vary, the water on the tidal or river side (the "downstream" side) may rise above the water on the normal "upper" side. The "upstream" pointing doors will then fail to do their job, and will simply drift open. To prevent water flowing the wrong way through the lock, there will need to be at least one set of gates pointing in the "wrong" direction. If it is desirable that boats can use the lock in these circumstances, then there needs to be a full set of gates pointing towards the tidal or river side. The usual method is to have gates pointing in opposite directions at both ends of the chamber (alternatively, the "paired stop lock" arrangement of two separate sequential locks pointing in opposite directions would work here — but would require an extra chamber). If navigation is not required (or impossible) at one "extreme" (e.g. allow navigation above mid-tide, but just prevent the canal emptying at low tide) then it is only necessary to have one set of bi-directional gates.

Sea locks

A lock connecting a canal or river directly with the estuary (or beach). All sea locks are tidal.



Sea lock at Bude, Cornwall

Tidal locks

Loosely, any lock connecting tidal with non-tidal water. This includes a lock between a tidal river and the non-tidal reaches; or between a tidal river and a canal; or a sea lock. However, the term usually refers specifically to a lock whose method of operation is affected by the *state* of the tide. Examples:

- *A canal joining a river whose levels are always lower than the canal.* All that is needed is an ordinary lock, with the gates pointing up the canal. The lock is used normally so long as the tide is high enough to float boats through the lower gates. If near low tide the lock becomes unusable, then the gates can be barred (and simply become a "reverse flood gate", holding water in the canal). This arrangement also applies to some sea locks (e.g. Bude Canal).
- *A canal joining a river which is normally below it, but which can rise above it (at very high tides, or after heavy rain).* One pair of gates can be made bidirectional, i.e. the inward-pointing gates would be supplemented by a pair pointing out to the river. When the river is higher than the canal, the normal gates would just drift open, but the additional pair of gates can be closed to protect the canal, and prevent navigation to the river. In effect, we have simply added a flood gate.
- *As above, but where it is safe to navigate even when the river is higher than the canal.* The lock will be fully bidirectional (two pairs of oppositely pointing gates at each end) to allow boats to pass at any normal river levels. At extreme low or

high tides unsuitable for navigation, the appropriate sets of gates are barred to prevent passage.

Very large locks



Barges at a lock on the Mississippi River

The world's largest lock is the Berendrecht Lock giving access to the Port of Antwerp in Belgium. The lock is 500 metres (1,640 ft) long, and 68 metres (223 ft) wide and drops 13.5 m, and has four sliding lock gates. The size of locks cannot be compared without considering the difference in water level that they are designed to operate under. For example, the Bollène lock on the River Rhône has a fall of at least 23 m and the Oskemen Lock on the Irtysh River in Kazakhstan has a drop of 42 m. The total volume of water to be considered in any lock equals the product of its length, breadth and the difference in water levels. Lock staircases are used in an attempt to reduce the total volume of water required in relation to the amount of useful work done. The useful work done relates to the weight of the vessel and the height it is lifted. When a vessel is lowered the consumption of potential energy of the water consumed is considered. An alternative to locks is a boat lift; facilities of this type, e.g. the Anderton boat lift or the Strépy-Thieu

boat lift in Belgium, do not rely on the consumption of water as the primary power source, are powered by motors and are designed to consume a minimum amount of water.

The Welland Canal is a ship canal in Canada, that runs 42 km (27.0 miles) from Port Colborne, Ontario on Lake Erie to Port Weller, Ontario on Lake Ontario. A major part of the St. Lawrence Seaway, the canal allows ships to avoid Niagara Falls by traversing the Niagara Escarpment.

Approximately 40,000,000 tonnes of cargo is carried through the Welland Canal annually by over 3,000 ocean and lake vessels. It allows goods from notable cities like Toronto, Detroit, Cleveland and Chicago along with other heavily industrialized areas of the United States and Canada to be shipped via ocean-going vessels for international delivery.

The completion of the Welland Canal made the Trent-Severn Waterway (which links Lake Ontario with Lake Huron) all but obsolete as a commercial traffic route for Great Lakes navigation.

The canal's Lake Erie (southern) terminus, at Port Colborne, is 99.5 m (326.5 feet) higher in elevation than the Lake Ontario (northern) terminus at Port Weller. The canal comprises eight lift locks, each 24.4 m (80 ft) wide by 233.5 m (766 ft) long. Due to the Garden City Skyway, the maximum ship height allowed is 35.5 m (116.5 ft). All other crossings are movable bridges (lift or Bascule) or tunnels. The maximum permissible vessel length is 225.5 m (740 ft). It takes ships an average of 11 hours to traverse the canal's length.

The 29 locks on the Mississippi River are typically 600 feet (180 m) long while tug and barge combinations are as much as 1,200 feet (360 m) long consisting of as many as 15 barges and one tug. In these cases, some of the barges are locked through, using partially opened lock valves to create a current to pull the un-powered barges out of the lock where they are tied up to wait the rest of the barges and the tug to pass through the lock. It can take as much as an hour and a half to pass the lock.

Hiram M. Chittenden Locks

In November 2004 one of the Hiram M. Chittenden Locks (better known locally as the "Ballard Locks" in reference to the Seattle neighborhood they are located in) was emptied for maintenance, as seen in the pictures below. This provided an opportunity to visualize how a lock works without the water obscuring the bottom of the lock. For reference, the picture far left shows the lock in operation, with a tug and a barge (loaded with sand and gravel) waiting for the gates to open. In the bottom left corner of the picture may be seen the cut-out in the side wall that contains the gate when open.

The lock has three pairs of gates, one pair at each end and one pair in the middle so that half the length of the lock can be used when the whole length is not required, thus saving water. The barely-visible person walking along the bottom of the lock in the second

picture gives an indication of the vast size of this lock. In both pictures of the end gates, the string of penstock openings are visible along the sides at the bottom. The water entering and leaving the lock flows by gravity through these openings. It requires around 15 minutes to fill or empty the lock.



Hiram M. Chittenden Locks: tug and barge in lock when full.



Lock emptied for maintenance – low water end of the lock.



Lock emptied for maintenance – centre pair of gates.



Lock emptied for maintenance – high water end of the lock.

History and development

Dams and weirs

In ancient times river transport was common, but rivers were often too shallow to carry anything but the smallest boats. Ancient people discovered that rivers could be made to carry larger boats by making dams to raise the water level. The water behind the dam deepened until it spilled over the top creating a weir. The water was then deep enough to carry larger boats. This dam building was repeated along the river, until there were "steps" of deep water.

Flash locks

The development of dams and weirs created the problem of how to get the boats between these "steps" of water. An early and crude way of doing this was by means of a flash lock. A flash lock consisted essentially of a small opening in the dam, which could be quickly opened and closed. On the Thames in England, this was closed with vertical posts (known as rimers) against which boards were placed to block the gap.

When the gap was opened, a torrent of water would spill out, carrying a "downstream" boat with it, or allowing an "upstream" boat to be manhauled or winched through against the flow. When the boat was through, the opening would be quickly closed again. The "gate" could also be opened to release a 'flash' downstream to enable grounded boats to get off shoals, hence the name.

This system was used extensively in Ancient China and in many other parts of the world. But this method was dangerous and many boats were sunk by the torrent of water. Since this system necessarily involved lowering the level in the pound, it was not popular with millers who depended on a full head of water to operate their equipment. This led to constant battles, both legal and physical, between the navigation and milling interests, with rivers being closed to navigation if there was any shortage of water. It was mainly this conflict which led to the adoption of the pound lock in medieval China, as this means that relatively little water is consumed by navigation.

Staunch

A more sophisticated device was the staunch or water gate, consisting of a gate (or pair of mitred gates) which could be closed (and held shut by water pressure) when the river was low, in order to float vessels over upstream shallows at times of low water. However, the whole upstream head of water had to be drained (by some auxiliary method approaching modern sluices) before the a boat could pass. Accordingly they were not used where the obstacle to be passed was a mill weir.

Pound lock



Model of early river pound lock, constructed in Lankheet water park, Netherlands

The natural extension of the Stauch was to provide an upper gate (or pair of gates) to form an intermediate "pound" which was all that need be emptied when a boat passed through. This type of lock, called a pound lock was known in Imperial China, Medieval Europe, and possibly the Romans as indirect evidence suggests. *Note the change in terminology: on a British Canal, it is the section of canal **between** locks that is called a pound.*



The turf-sided Monkey Marsh Lock on the Kennet & Avon Canal at Thatcham

Turf-sided lock

A turf-sided lock is an early form of canal lock design that uses earth banks to form the lock chamber, subsequently attracting grasses and other vegetation, instead of the now more familiar and widespread brick, stone, or concrete lock wall constructions. This early lock design was most often used on river navigations in the early 1700s before the advent of canals. The sides of the turf-lock are sloping so, when full, the lock is quite wide. Consequently, this type of lock needs more water to operate than vertical-sided brick- or stone-walled locks. On British canals and waterways most turf-sided locks have been subsequently rebuilt in brick or stone, and so only a few good examples survive, such as at Garston Lock, and Monkey Marsh Lock, on the Kennet and Avon Canal.

Use of water

The main problem caused by locks is that, each time a lock goes through one fill-empty cycle, a lockful of water (tens or hundreds of thousands of gallons) is released to the lower pound. In over-simplistic terms: on a canal where only one boat will fit into a lock, a boat travelling from the summit pound to the lowest pound is accompanied on its journey by one 'personal' lockful of water. A boat going the other way also transfers a lockful of water from the summit pound to the lowest pound. To prevent the canal from

running dry, some method must be used to ensure that the water supply at the canal summit is constantly replenished at the rate that the water is being drained downwards. This is, of course much more of a problem on an artificial canal crossing a watershed than on a river navigation.

Design

When planning a canal, the designer will attempt to build a summit level with a large reservoir, or one supplied by an artificial watercourse from a distant source, or one as long as possible (to act as its own reservoir) or which cuts across as many springs or rivers as possible (or all of these).

Pumping

Where it is clear that natural supply will not be sufficient to replenish the summit level at the rate that water will be used (or to allow for unexpected periods of drought) the designer may plan for water to be back-pumped back up to the summit from lower down. Such remedies may of course be installed later, when poor planning becomes apparent, or when there is an unforeseeable increase in traffic or dearth of rain. On a smaller scale, some local pumping may be required at particular points (water is continually recycled through some locks on the Kennet and Avon canal).

Water saving basins



Disused side pond at Atherstone on the Coventry Canal, England

A way of reducing the water used by a lock is to give it one or multiple reservoirs, whose levels are intermediate between the upper and lower pounds. These reservoirs can store the water drained from the lock as a boat descends, and release it to fill the next time a boat ascends. This saves half the amount of water lost downhill in each fill-empty cycle. Generally these reservoirs are called "saving basins", or, in England, "side ponds".

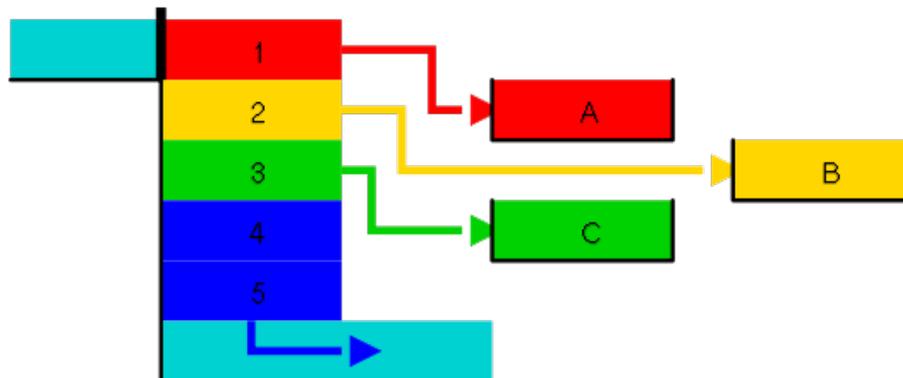


Diagram of water saving basins (descending)

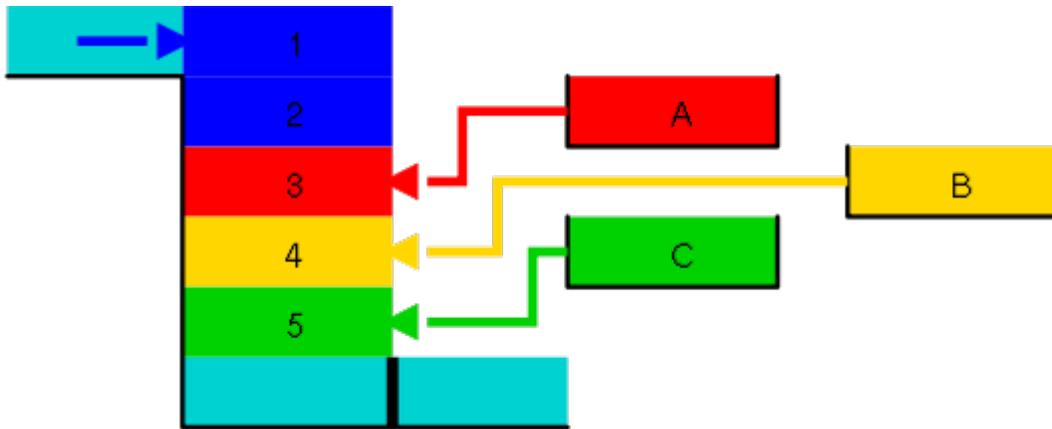


Diagram of water saving basins (ascending)

For example the Hindenburg-lock (in Hannover, Germany, built 1919-1928) has two lock chambers of 225 m length, each of which would use 42,000 m³ of water for a full locking cycle. Due to the use of 10 water saving basins, only 10,500 m³ of water are used. A more recent example is the Rhine–Main–Danube Canal with 13 *saving locks* out of a total of 16 locks.

Water saving basins are incorporated in proposals to augment the capacity of the Panama Canal, but the scheme is controversial because the mixing of salt and fresh water in the basins will allow brackish water into Gatun Lake, a source of drinking water and a wildlife reserve.



Map showing extended intermediate ponds at Caen Hill locks

On English canals, these reservoirs are called *side ponds*. They were installed on the Grand Union Canal and the Coventry Canal, amongst others. They are now out of use, and in some cases have been filled in, because British Waterways considered that it was too easy to misuse them and flood the surrounding area. On some flights of locks with short intermediate ponds, the ponds are extended sideways — in effect to provide a reservoir to ensure that the pond does not run dry (in case, for instance, the lock below

leaks more than the lock above). These extended intermediate pounds are sometimes confused with side ponds.

Alternatives

As well as the "static" approaches mentioned earlier (various types of contouring, excavating, and spanning), there were many ingenious "dynamic" solutions, mostly variations on the boat lift or the inclined plane. These tend to be more expensive to install and operate, but offer faster transit and waste less water.

Inclined plane

An inclined plane consists of a cradle (to hold a barge) or caisson (a box full of water in which a barge can float) which moves on rails sideways up a slope from one waterway to the other. Since the box is "wet" (filled with water), Archimedes' principle ensures that the caisson always weighs the same, regardless of the size of boat being carried (or even if it contains only water). This makes for easy counterbalancing by a fixed weight or by a second caisson. The motive power may be steam or hydraulic, or may come from overbalancing the top caisson with extra water from the upper waterway.

There are no working waterway inclined planes in the UK at the moment, but the remains of a famous one can be seen at Foxton in Leicestershire on the Leicester arm of the Grand Union Canal. The plane enabled wide-beam boats to bypass the flight of ten narrow locks, but failure to make improvements at the other end of the arm and high running costs led to its early demise. There are plans to restore it, and some funding has been obtained.

Marine railway



Big Chute Marine Railway in the Trent-Severn Waterway, Ontario, Canada

A marine railway is similar to a canal inclined plane in that it moves boats up or down a slope on rails. However, the vessel is carried "dry" (in a carrying frame, or cradle) rather than in a water-filled caisson. The principle is based on the patent slip, used for hauling vessels out of the water for maintenance.

In operation, a boat is navigated into the carrying frame, which has been lowered into the water. The boat is secured to the cradle, possibly by raising slings under the hull using hydraulics, and the cradle is hauled out of the water and up the hill with a cable. At the top of the slope, the cradle is lowered into the upper waterway, and the boat released. As the boat is not floating, Archimedes' principle does not apply, so the weight lifted or lowered by the device varies - making counterbalancing (by dead weights or a second boat carriage) more difficult.

In some locations, notably the Big Chute Marine Railway on the Trent-Severn Waterway, in Ontario, Canada, a marine railway was installed as a temporary measure at the planned site of a flight of conventional locks. In this and several other cases, the locks were never built, and the marine railway continued to serve on a permanent basis.

Boat lift

The Falkirk Wheel, the world's first rotating boat lift, acts as the centrepiece of the restoration of the Forth and Clyde and Union Canals. The spectacular "Wheel" presents the 21st century's solution to replacing a flight of locks which formerly connected the canals and which were filled-in in 1930. The Falkirk Wheel was the winning design in a competition to design a new lock. Visitors can now take a boat trip on the Wheel and be lifted over 100 feet (30 m) in a few minutes compared to the time it took when the original lock staircase operated.

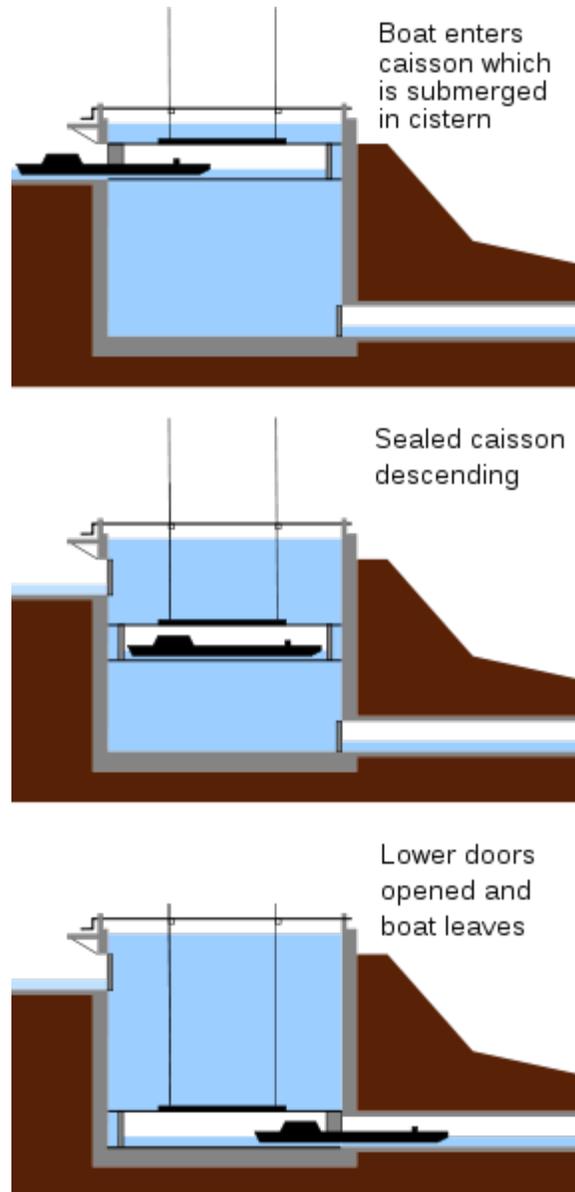
The Victorian Anderton Boat Lift, the world's first vertical boat lift, linking the Trent and Mersey Canal and the River Weaver in Cheshire, has recently been restored. The world's highest boat lift of Strépy-Thieu in Belgium raises or lowers 1,350 tonnes boats by 73.15 metres.

Another famous derivative is the Peterborough lift lock which is a boat lift located on the Trent Canal in the city of Peterborough, Ontario, Canada and is Lock 21 on the Trent-Severn Waterway.

The dual lifts are the highest hydraulic boat lifts in the world, rising 19.8 m (65 ft). This was a considerable accomplishment when conventional locks usually only had a 2 m (7 ft) rise. Each lift has a capacity of 1,300 tonnes.

The basins are 140 feet (43 m) long, 33 feet (10 m) wide and 9 feet 10 inches (3.0 m) deep. The vertical distance lifted is 65 feet (20 m). The Trent-Severn has another similar lift lock at Kirkfield, with basins of the same dimension, but which lifts over a smaller vertical distance.

Caisson lock



Operation of caisson lock

Around 1800 the use of caisson locks was proposed by Robert Weldon for the Somerset Coal Canal in England. In this **underwater** lift, the chamber was 80 ft long and 60 ft (18 m) deep and contained a completely enclosed wooden box big enough to take a barge. This box moved up and down in the 60 ft (18.2 m) deep pool of water. Apart from inevitable leakage, the water never left the chamber, and using the lock wasted no water. Instead, the boat entered the box and was sealed in by the door closing behind it, and the box itself was moved up or down through the water. When the box was at the bottom of the chamber, it was under almost 60 feet (18 m) of water – at a pressure of three atmospheres, in total. One of these "locks" was built and demonstrated to the Prince Regent (later George IV), but it had various engineering problems and the design was not

put into use on the Coal Canal. However, in about 1817 the Regents Canal Company built one of these locks at the site of the present-day Camden Lock, north London. Here the motivation was, again, water supply problems. Even though the change in level is much lower than that would have been the case in Somerset, the system was soon replaced by conventional locks. No commercially successful example has ever been built.

Diagonal lock

This new concept in lock design has yet to be installed on any waterway. The proposal is for a long tube of reinforced concrete, of a size to accommodate the boats being lifted, to be built on the slope between the upper and lower levels. The bottom of the tube is sealed with a strong watertight door, but there is a single pair of conventional lock gates at the top, installed a boat's length from the far wall of the tube. The change in level is achieved by filling the tube with water from the top pound, or by draining. The vessel floats on the surface of the water, with a guide float or pontoon, shaped to fit the tube, floating alongside to keep it clear of the walls. Side ponds, piped from the main tube, are incorporated to save water. In replacing a traditional flight or staircase of locks, a considerable time saving is anticipated. It differs from the discredited caisson lock design in that the boat does not have to be carried in a submerged chamber.

The "Diagonal Lock Advisory Group" has identified several sites in Britain where the new design could be installed, either on new waterways or canals under restoration. Projects under consideration include the restoration of the Lancaster Canal to Kendal and the proposed new branch of the Grand Union Canal between Bedford and Milton Keynes



Three Gorges Dam model view. A pair of five locking steps is at center with a ship lift to the left

A combined system - the Three Gorges Dam

At the Three Gorges Dam on the Yangtze River (Chang Jiang) in China there are two stair-steps of five large ship locks (each 300 m long and 35 m wide) for ten thousand ton ships. In addition to this there will be a boat lift (a large elevator) capable of moving a three thousand ton ship vertically in one motion. The locks and the boat lift provide a total lift of up to 113 m.

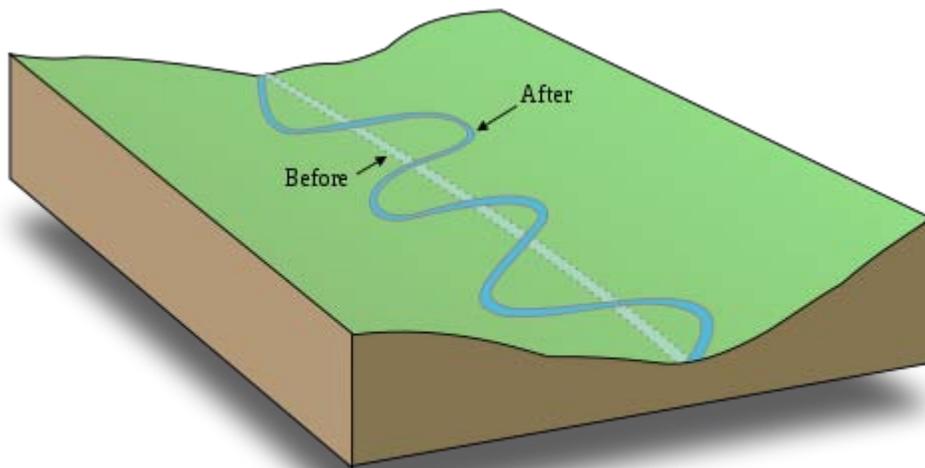
Ship sizes named after locks

Locks restrict the maximum size of ship able to pass through, some key canals have given rise to the name of standard ship sizes:

- Panamax
- Seawaymax

Chapter 3

Meander



A hypothetical stream bed following a tilted valley. The maximum gradient is along the down-valley axis represented by a hypothetical straight channel. Meanders develop, which lengthen the course of the stream, decreasing the gradient.



Meanders of the *Rio Cauto* at Guamo Embarcadero, Cuba.



White River (Washington)

A **meander** in general is a bend in a sinuous watercourse. A meander is formed when the moving water in a stream erodes the outer banks and widens its valley. A stream of any volume may assume a *meandering* course, alternatively eroding sediments from the outside of a bend and depositing them on the inside. The result is a *snaking* pattern as the stream meanders back and forth across its down-valley axis. When a meander gets cut off from the main stream, an oxbow lake is formed. Over time meanders migrate downstream, sometimes in such a short time as to create civil engineering problems for local municipalities attempting to maintain stable roads and bridges.

There is not yet full consistency or standardization of scientific terminology used to describe watercourses. A variety of symbols and schemes exist. Parameters based on

mathematical formulae or numerical data vary as well, depending on the database used by the theorist. Unless otherwise defined in a specific scheme "meandering" and "sinuosity" here are synonymous and mean any repetitious pattern of bends, or waveforms. In some schemes, "meandering" applies only to rivers with exaggerated circular loops or secondary meanders; that is, meanders on meanders.

Sinuosity is one of the channel types that a stream may assume over all or part of its course. All streams are sinuous at some time in their geologic history over some part of their length.

Origin of term

The term derives from a river, located in present-day Turkey, and known to the ancient Greeks as (*Μαίανδρος*) Maiandros or Maeander, characterised by a very convoluted path along the lower reach. As such, even in Classical Greece the name of the river had become a common noun meaning anything convoluted and winding, such as decorative patterns or speech and ideas, as well as the geomorphological feature. Strabo said: "... its course is so exceedingly winding that everything winding is called meandering."

The Meander River is located, south of Izmir, east of the ancient Greek town of Miletus, now, Milet, Turkey. It flows through a graben in the Menderes Massif, but has a flood plain much wider than the meander zone in its lower reach. In the Turkish name, the Büyük Menderes River, Menderes is from "Meander". Meanders are also formed as a result of deposition and erosion.

Meander geometry



Meanders of the Potomac River at Little Orleans, Maryland

The technical description of a meandering watercourse is termed meander geometry or meander planform geometry. It is characterized as an irregular waveform. Ideal waveforms, such as a sine wave, are one line thick, but in the case of a stream the width must be taken into consideration. The bankfull width is the distance across the bed at an average cross-section at the full-stream level, typically estimated by the line of lowest vegetation.

As a waveform the meandering stream follows the down-valley axis, a straight line fitted to the curve such that the sum of all the amplitudes measured from it is zero. This axis represents the overall direction of the stream.

At any cross-section the River/stream is following the sinuous axis, the centerline of the bed. Two consecutive crossing points of sinuous and down-valley axes define a meander loop. The meander is two consecutive loops pointing in opposite transverse directions. The distance of one meander along the down-valley axis is the meander length or wavelength. The maximum distance from the down-valley axis to the sinuous axis of a loop is the meander width or amplitude. The course at that point is the apex.

In contrast to sine waves, the loops of a meandering stream are more nearly circular. The curvature varies from a minimum at the apex to infinity at a crossing point (straight line), also called an inflection, because the curvature changes direction in that vicinity. The

radius of the loop is considered to be the straight line perpendicular to the down-valley axis intersecting the sinuous axis at the apex. As the loop is not ideal, additional information is needed to characterize it. The orientation angle is the angle between sinuous axis and down-valley axis at any point on the sinuous axis.



Concave bank and convex bank, Great Ouse Relief Channel, England.

A loop at the apex has an outer or convex bank and an inner or concave bank. The meander belt is defined by an average meander width measured from outer bank to outer bank instead of from centerline to centerline. If there is a flood plain it extends beyond the meander belt. The meander is then said to be free - it can be found anywhere in the flood plain. If there is no flood plain the meanders are fixed.

Various mathematical formulae relate the variables of the meander geometry. As it turns out some numerical parameters can be established, which appear in the formulae. The waveform depends ultimately on the characteristics of the flow but the parameters are independent of it and apparently are caused by geologic factors. In general the meander length is 10-14 times, with an average 11 times, the fullbank channel width and 3 to 5 times, with an average of 4.7 times, the radius of curvature at the apex. This radius is 2-3 times the channel width.

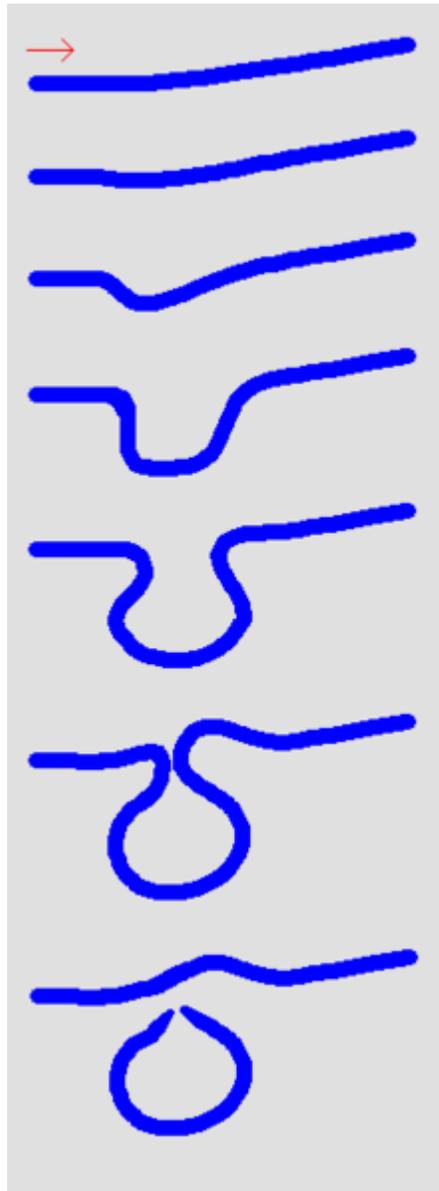


Meander of the River Cuckmere in Southern England

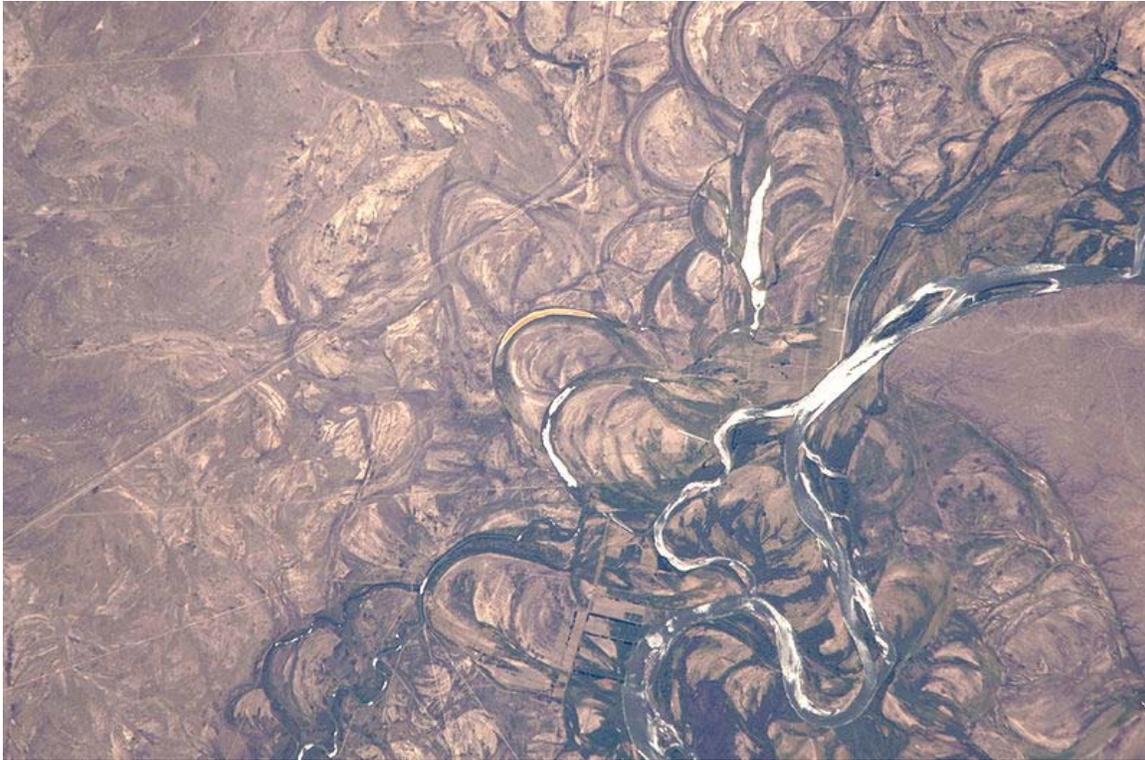
A meander has a depth pattern as well. The cross-overs are marked by riffles, or shallow beds, while at the apices are pools. In a pool direction of flow is downward, scouring the bed material. The major volume, however, flows more slowly on the inside of the bend where, due to decreased velocity, it deposits sediment.

The line of maximum depth, or channel, is the thalweg or thalweg line. It is typically designated the borderline when rivers are used as political borders. The thalweg hugs the outer banks and returns to center over the riffles. The meander arc length is the distance along the thalweg over one meander. The river length is the length along the centerline.

Formation



Life history of a meander



Spectacular meander scars, oxbow lakes and abandoned meanders in the broad flood plain of the Rio Negro, Argentina. 2010 astronaut photo from ISS.

Meander formation is a result of natural factors and processes. The waveform configuration of a stream is constantly changing. Once a channel begins to follow a sinusoidal path the amplitude and concavity of the loops increase dramatically due to the effect of helical flow sweeping dense eroded material towards the inside of the bend, and leaving the outside of the bend unprotected and therefore vulnerable to accelerated erosion, forming a positive feedback loop. In the words of Elizabeth A. Wood:

... this process of making meanders seems to be a self-intensifying process ... in which greater curvature results in more erosion of the bank, which results in greater curvature ...

Flow of a fluid around a bend is vortex flow in order to conserve angular momentum. The speed of flow on the outside of the bend is fastest, and on the inside of the bend is slowest. The water surface is also super-elevated towards the outside of the bend, so on the floor of the channel the water pressure is greater on the outside of the bend than on the inside of the bend. This pressure gradient drives a cross-current towards the inside of the bend. The cross-current along the floor of the channel is part of the secondary flow and sweeps dense eroded material towards the inside of the bend. The cross-current then rises to the surface near the inside of the bend and, moving near the surface, flows towards the outside of the bend, forming a helical flow. The greater the curvature of the bend, and the faster the flow, the stronger is the cross-current and the stronger the sweeping of dense eroded material along the floor of the channel towards the inside bank.

The question of formation is why streams of any size become sinuous in the first place. There are a number theories, not necessarily mutually exclusive.

Stochastic theory

The stochastic theory can take many forms but one of the most general statements is that of Scheidegger:

The meander train is assumed to be the result of the stochastic fluctuations of the direction of flow due to the random presence of direction-changing obstacles in the river path.

Given a flat smooth, tilted artificial surface, rainfall runs off it in sheets, but even in that case adhesion of water to the surface and cohesion of drops produce rivulets at random. Natural surfaces are rough and erodible to different degrees. The result of all the physical factors acting at random is channels that are not straight, which then progressively become sinuous. Even channels that appear to be straight have a sinuous thalweg that leads eventually to a sinuous channel.

Equilibrium theory

In the equilibrium theory, meanders decrease the stream gradient until an equilibrium between the erodibility of the terrain and the transport capacity of the stream is reached. A mass of water descending must give up potential energy, which, given the same velocity at the end of the drop as at the beginning, is removed by interaction with the material of the stream bed. The shortest distance; that is, a straight channel, results in the highest energy per unit of length, disrupting the banks more, creating more sediment and aggrading the stream. The presence of meanders allows the stream to adjust the length to an equilibrium energy per unit length in which the stream carries away all the sediment that it produces.

Geomorphic/Morphotectonic theory

Geomorphic refers to the surface structure of the terrain. Morphotectonic means having to do with the deeper, or tectonic (plate) structure of the rock. The features included under these categories are not random and guide streams into non-random paths. They are predictable obstacles that instigate meander formation by deflecting the stream. For example, the stream might be guided into a fault line (morphotectonic).

Associated landforms

Erosion Mechanics



The depositional slip off slope is on the left whilst there is a small river cliff to the right. River Ashes Hollow, UK.

Most meanders occur in the region of a river channel with shallow gradients, a well-developed floodplain, and cohesive floodplain material. Deposition of sediment occurs on the inner edge, because the secondary flow of the river sweeps and rolls sand, rocks and other submerged objects across the bed of the river towards the inside radius of the river bend, creating a slip-off slope called a point bar. Erosion is greater on the outside of the bend where the soil is not protected by deposits of sand and rocks. The current on the outside bend is more effective in eroding the unprotected soil, and the inside bend receives steadily increasing deposits of sand and rocks, and the meander tends to grow in the direction of the outside bend, forming a small cliff called a cut bank. This can be seen in areas where willows grow on the banks of rivers; on the inside of meanders, willows are often far from the bank, whilst on the outside of the bend, the roots of the willows are often exposed and undercut, eventually leading the trees to fall into the river. This demonstrates the river's movement. Slumping usually occurs on the concave sides of the banks resulting in mass movements such as slides.

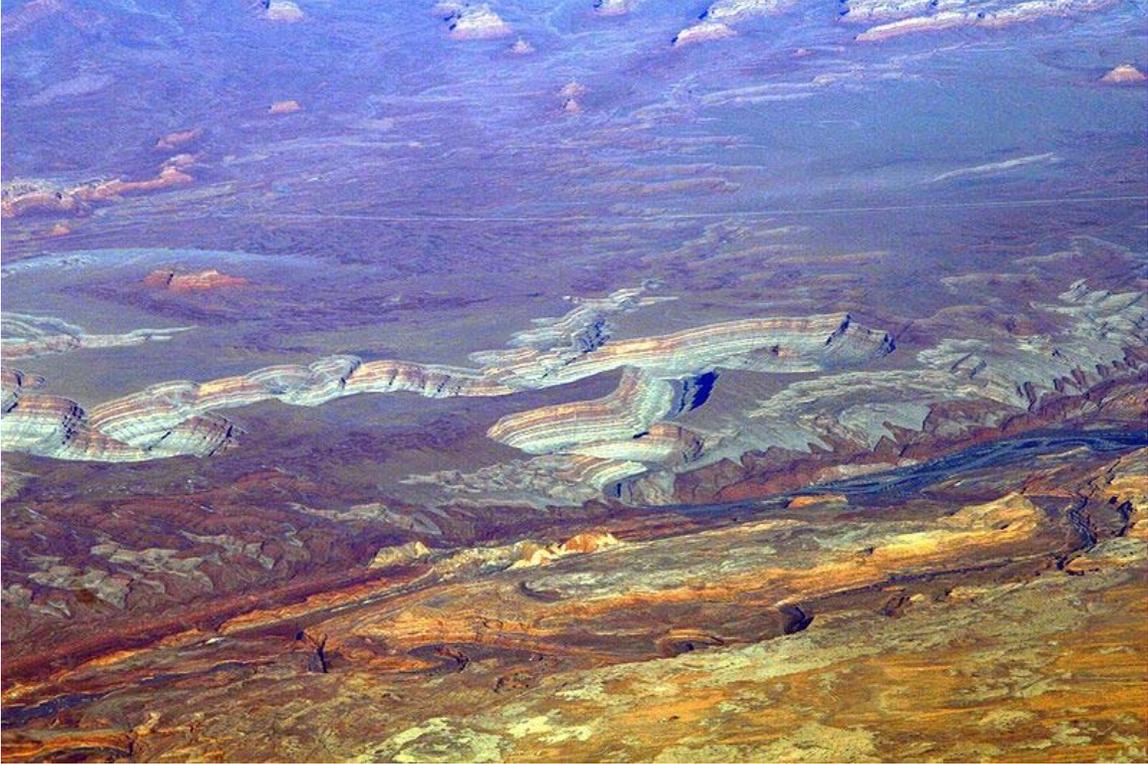
Deposits

Incised meanders



Glen Canyon, USA

If the slope of an established meandering stream is suddenly increased it will resume downward erosion – this happens when the base level of the stream is reduced, for example due to tectonic uplift of the region, a global fall in sea-level, collapse of a moraine-dammed lake downstream, or by capture of the stream by a steeper one. As the stream erodes downwards, its established meandering pattern will remain as a deep valley known as an *incised meander* or *entrenched meander*. Rivers in the Colorado Plateau and streams in the Ozark Plateau are noted for these incised meanders.



Goosenecks of the San Juan River, SE Utah. Note cut-off meander at right center.

Oxbow lakes

Oxbow lakes are created when growing meanders intersect each other and cut off a meander loop, leaving it without an active cutting stream. Over a period of time, these oxbow lakes tend to dry out or fill in with sediments.

Abandoned meander

Sometimes an incised meander is cut off, similar to an oxbow lake. The resulting landform is known as an **abandoned meander**. In the southwest United States it is also known as a **rincon**. One dramatic example, on Lake Powell, is called "The Rincon."

Scroll-bars



Meanders, scroll-bars and oxbow lakes in the Songhua River

Scroll-bars are a result of continuous lateral migration of a meander loop that creates an asymmetrical ridge and swale topography on the inside of the bends. The topography is generally parallel to the meander and is related to migrating bar forms and back bar chutes which carve sediment out from the outside of the curve and deposit sediment in the slower flowing water on the inside of the loop, in a process called lateral accretion. Scroll-bar sediments are characterized by cross-bedding and a pattern of fining upward. These characteristics are a result of the dynamic river system, where larger grains are transported during high energy flood events and then gradually die down, depositing smaller material with time (Batty 2006). Deposits for meandering rivers are generally

homogeneous and laterally extensive unlike the more heterogeneous braided river deposits. There are two distinct patterns of scroll-bar depositions; the eddy accretion scroll bar pattern and the point-bar scroll pattern. When looking down the river valley they can be distinguished because the point-bar scroll patterns are convex and the eddy accretion scroll bar patterns are concave. Scroll bars often look lighter at the tops of the ridges and darker in the swales. This is because the tops can be shaped by wind, either adding fine grains or by keeping the area unvegetated, while the darkness in the swales can be attributed to silts and clays washing in during high water periods. This added sediment in addition to water that catches in the swales is in turn a favorable environment for vegetation that will also accumulate in the swales.

Derived quantities

The meander ratio or sinuosity index is a means of quantifying how much a river or stream meanders (how much its course deviates from the shortest possible path). It is calculated as the length of the stream divided by the length of the valley. A perfectly straight river would have a meander ratio of 1 (it would be the same length as its valley), while the higher this ratio is above 1, the more the river meanders.

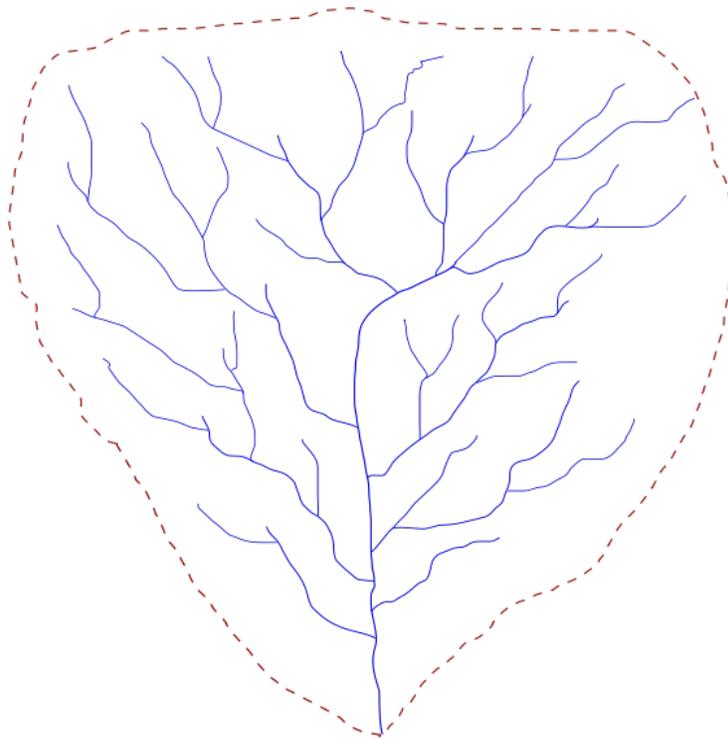
Sinuosity indices are calculated from the map or from an aerial photograph measured over a distance called the reach, which should be at least 20 times the average fullbank channel width. The length of the stream is measured by channel, or thalweg, length over the reach, while the bottom value of the ratio is the downvalley length or air distance of the stream between two points on it defining the reach.

The sinuosity index plays a part in mathematical descriptions of streams. The index may need to be elaborated because the valley may meander as well; i.e., the downvalley length is not identical to the reach. In that case the valley index is the meander ratio of the valley while the channel index is the meander ratio of the channel. The channel sinuosity index is the channel length divided by the valley length and the standard sinuosity index is the channel index divided by the valley index. Distinctions may become even more subtle.

Sinuosity Index has a non-mathematical utility as well. Streams can be placed in categories arranged by it; for example, when the index is between 1 to 1.5 the river is sinuous, but if between 1.5 and 4, then meandering. The index is a measure also of stream velocity and sediment load, those quantities being maximized at an index of 1 (straight).

Chapter 4

Drainage Basin



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 surface water from rain and melting snow or ice converges to a single point, usually the exit of the basin, where the waters join another waterbody, such as a river, lake, reservoir, estuary, wetland, sea, or ocean. In closed drainage basins the water converges to a single point inside the basin, known as a sink, which may be a permanent lake, dry lake, or a point where surface water is lost underground. 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 to a single point. 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.

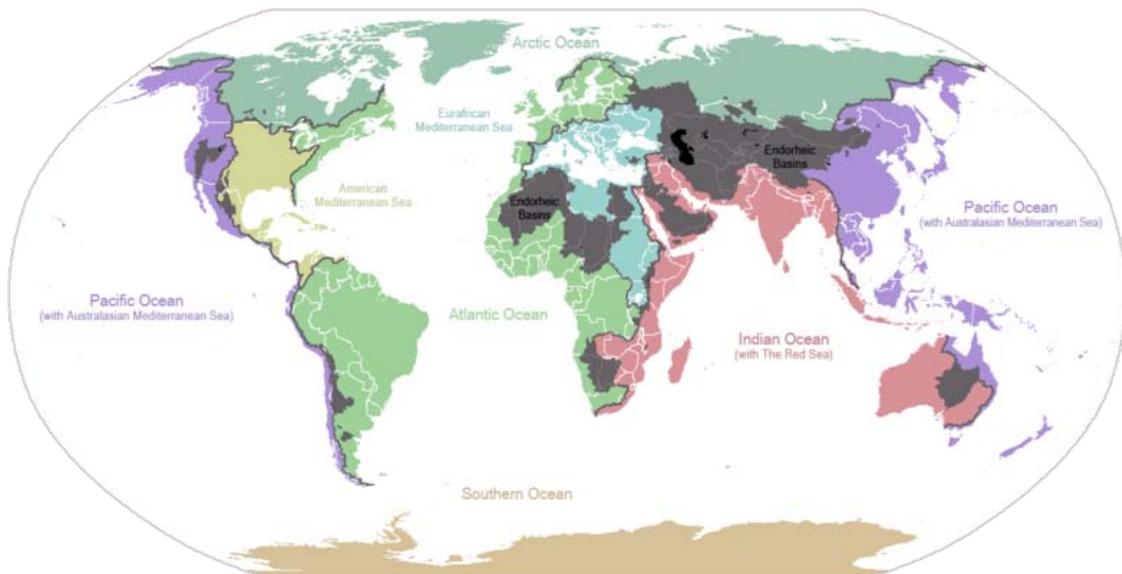
Other terms that are used to describe a drainage basin are **catchment**, **catchment area**, **catchment basin**, **drainage area**, **river basin**, **water basin** and **watershed**. In the technical sense, a watershed refers to a divide that separates one drainage area from another drainage area. 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.

Drainage basins are similar but not identical to hydrologic units, which are drainage areas delineated so as to nest into a multi-level hierarchical drainage system. Hydrologic units are designed to allow multiple inlets, outlets, or sinks. In a strict sense, all watersheds are hydrologic units but not all hydrologic units are watersheds.

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 354 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, surface water drains to the Atlantic via the Saint Lawrence River and Great Lakes basins, the Eastern Seaboard of the United States, the Canadian Maritimes, and most of Newfoundland and Labrador. Nearly all of South America east of the Andes also drains to the Atlantic, as does 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



Endorheic basin in Central Asia

Endorheic drainage basins are inland basins that do not drain to an ocean. Around 18% of all land drains to endorheic lakes or seas or sinks. The largest of these consists of much of the interior of Asia, and drains into the Caspian Sea and the Aral Sea. Other endorheic regions include the Great Basin in the United States, much of the Sahara Desert, the watershed of the Okavango River (Kalahari Basin), highlands near the African Great Lakes, the interiors of Australia and the Arabian Peninsula, and parts in Mexico and the Andes. Some of these, such as the Great Basin, are not single drainage basins but collections of separate, adjacent closed basins.

In endorheic bodies of standing water where evaporation is the primary means of water loss, the water is typically more saline than the oceans. An extreme example is the Dead Sea.

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.

Chapter 5

Riparian Zone



A well preserved riparian strip on a tributary to Lake Erie.

A **riparian zone** or **riparian area** is the interface between land and a river or stream. **Riparian** is also the proper nomenclature for one of the fifteen terrestrial biomes of the earth. Plant habitats and communities along the river margins and banks are called riparian vegetation, characterized by hydrophilic plants. Riparian zones are significant in ecology, environmental management, and civil engineering because of their role in soil conservation, their habitat biodiversity, and the influence they have on fauna and aquatic ecosystems, including grassland, woodland, wetland or even non-vegetative. In some regions the terms **riparian woodland**, **riparian forest**, **riparian buffer zone**, or

riparian strip are used to characterize a riparian zone. The word "riparian" is derived from Latin *ripa*, meaning river bank. The riparian is an important feature of a wetland because it allows us to gain an insight of its health.

Characteristics

Riparian zones may be natural or engineered for soil stabilization or restoration. These zones are important natural biofilters, protecting aquatic environments from excessive sedimentation, polluted surface runoff and erosion. They supply shelter and food for many aquatic animals and shade that is an important part of stream temperature regulation. When riparian zones are damaged by construction, agriculture or silviculture, biological restoration can take place, usually by human intervention in erosion control and revegetation. If the area adjacent to a watercourse has standing water or saturated soil for as long as a season, it is normally termed a wetland because of its hydric soil characteristics. Because of their prominent role in supporting a diversity of species, riparian zones are often the subject of national protection in a Biodiversity Action Plan.

Research shows riparian zones are instrumental in water quality improvement for both surface runoff and water flowing into streams through subsurface or groundwater flow. Particularly the attenuation of nitrate or denitrification of the nitrates from fertilizer in this buffer zone is important. Riparian zones can play a role in lowering nitrate contamination in surface runoff from agricultural fields, which runoff would otherwise damage ecosystems and human health. The use of wetland riparian zones shows a particularly high rate of removal of nitrate entering a stream and thus has a place in agricultural management.

Roles and functions

Riparian zones dissipate stream energy. The meandering curves of a river, combined with vegetation and root systems, dissipate stream energy, which results in less soil erosion and a reduction in flood damage. Sediment is trapped, reducing suspended solids to create less turbid water, replenish soils, and build stream banks. Pollutants are filtered from surface runoff which enhances water quality via biofiltration.

The riparian zones also provide wildlife habitat, increase biodiversity, and provide wildlife corridors, enabling aquatic and riparian organisms to move along river systems avoiding isolated communities. They can provide forage for wildlife and livestock.

They provide native landscape irrigation by extending seasonal or perennial flows of water. Nutrients from terrestrial vegetation (e.g. plant litter and insect drop) is transferred to aquatic food webs. The vegetation surrounding the stream helps to shade the water, mitigating water temperature changes. The vegetation also contributes wood debris to streams which is important to maintaining geomorphology.

From a social aspect, riparian zones contribute to nearby property values through amenity and views, and they improve enjoyment for footpaths and bikeways through supporting

foreshoreway networks. Space is created for riparian sports including fishing, swimming and launching for vessels and paddlecraft.

The riparian zone acts as a sacrificial erosion buffer to absorb impacts of factors including climate change, increased runoff from urbanisation and increased boatwake without damaging structures located behind a setback zone.

Role in logging

The protection of riparian zones is often a consideration in logging operations. The undisturbed soil, soil cover, and vegetation provide shade, plant litter, woody material, and reduce the delivery of soil eroded from the harvested area. Factors such as soil types and root structures, climatic conditions and above ground vegetative cover impact the effectiveness of riparian buffering.

Vegetation



Riparian zone along Trout Creek in the Trout Creek Mountains; part of the Burns Bureau of Land Management District in southeastern Oregon. The creek provides critical habitat for trout.

The assortment of riparian zone trees varies from those of wetlands and typically consists of plants that either are emergent aquatic plants, or herbs, trees and shrubs that thrive in proximity to water.

North America

Water's edge

Herbaceous Perennial:

- *Peltandra virginica* - Arrow Arum
- *Sagittaria lancifolia* - Arrowhead
- *Carex stricta* - Tussock Sedge
- *Iris virginica* - Southern Blue Flag Iris

Inundated Riparian zone

Herbaceous Perennial:

- *Sagittaria latifolia* - Duck Potato
- *Scirpus validus* - Softstem Bulrush
- *Scorpus americanus* - Three-square Bulrush
- *Eleocharis quadrangulata* - Square-stem Spikerush
- *Eleocharis obusa* - Spikerush

Eastern

Typical riparian zone trees in eastern North America include:

- *Populus deltoides* - Eastern Cottonwood
- *Acer saccharinum* - Silver Maple
- *Acer negundo* - Boxelder Maple
- *Ulmus americana* - American Elm
- *Platanus occidentalis* - American Sycamore
- *Juglans cinerea* - Butternut
- *Juglans nigra* - Black Walnut
- *Salix nigra* - Black Willow
- *Betula nigra* - River Birch
- *Fraxinus pennsylvanica* - Green Ash
- *Gleditsia triacanthos* - Honey Locust
- *Tilia americana* - Basswood

Western

In western North America and the Pacific Coast the riparian vegetation includes:

Riparian trees

- *Sequoia sempervirens* - Coast Redwood
- *Thuja plicata* - Western Redcedar
- *Abies grandis* - Grand Fir

- *Picea sitchensis* - Sitka Spruce
- *Chamaecyparis lawsoniana* - Port Orford-cedar
- *Taxus brevifolia* - Pacific Yew
- *Populus fremontii* - Fremont Cottonwood
- *Populus trichocarpa* - Black Cottonwood
- *Platanus racemosa* - California Sycamore
- *Alnus rhombifolia* - White Alder
- *Alnus rubra* - Red Alder
- *Acer macrophyllum* - Big-leaf Maple
- *Fraxinus latifolia* - Oregon ash
- *Prunus emarginata* - Bitter Cherry
- *Salix lasiolepis* - Arroyo Willow
- *Salix lucida* - Pacific Willow
- *Quercus agrifolia* - Coast live oak
- *Quercus garryana* - Garry oak
- *Populus tremuloides* - Quaking Aspen
- *Umbellularia californica* - California Bay Laurel
- *Cornus nuttallii* - Pacific Dogwood

Riparian shrubs

- *Acer circinatum* - Vine Maple
- *Ribes spp.* - Gooseberries and Currants
- *Rosa pisocarpa* - Swamp Rose or Cluster Rose
- *Symphoricarpos albus* - Snowberry
- *Spiraea douglasii* - Douglas spirea
- *Rubus spp.* - Blackberries, Raspberries, Thimbleberry, Salmonberry
- *Rhododendron occidentale* - Western Azalea
- *Oplopanax horridus* - Devil's Club
- *Oemleria cerasiformis* - Indian Plum, Osoberry
- *Lonicera involucrata* - Twinberry
- *Cornus stolonifera* - Red-osier Dogwood
- *Salix spp.* - Willows

Other plants

- *Polypodium* - Polypody Ferns
- *Polystichum* - Sword Ferns
- *Woodwardia* - Giant Chain Ferns
- *Pteridium* - Goldback Ferns
- *Dryopteris* - Wood Ferns
- *Adiantum* - Maidenhair Ferns
- *Carex spp.* - Sedges
- *Juncus spp.* - Rushes
- *Festuca californica* - California Fescue bunchgrass
- *Leymus condensatus* - Giant Wildrye bunchgrass

- *Melica californica* - California Melic bunchgrass
- *Mimulus spp.* - Monkeyflower and varieties
- *Aquilegia spp.* - Columbine

Asia

In Asia there are different types of riparian vegetation, but the interactions between hydrology and ecology are similar as occurs in other geographic areas.

- *Carex spp.* - Sedges
- *Juncus spp.* - Rushes

Australia

Typical riparian vegetation in Temperate New South Wales, Australia include:

- *Acacia melanoxylon* - Blackwood
- *Acacia pravissima* - Ovens Wattle
- *Acacia rubida* - Red Stem Wattle
- *Bursaria lasiophylla* - Blackthorn
- *Callistemon citrinus* - Crimson Bottlebrush
- *Callistemon sieberi* - River Bottlebrush
- *Casuarina cunninghamiana* - River She-Oak
- *Eucalyptus bridgesiana* - Apple Box
- *Eucalyptus camaldulensis* - River Red Gum
- *Eucalyptus melliodora* - Yellow Box
- *Eucalyptus viminalis* - Manna Gum
- *Kunzea erocoides* - Burgan
- *Leptospermum obovatum* - River Tea-Tree
- *Melaleuca ericifolia* - Swamp Paperbark

Central Europe

Typical riparian zone trees in Central Europe include:

- *Acer campestre* - Field Maple
- *Acer pseudoplatanus* - Sycamore Maple
- *Alnus glutinosa* - Black Alder
- *Carpinus betulus* - European Hornbeam
- *Fraxinus excelsior* - European Ash
- *Juglans regia* - Persian Walnut
- *Malus sylvestris* - European Wild Apple
- *Populus alba* - White Poplar
- *Populus nigra* - Black Poplar
- *Quercus robur* - Pedunculate Oak
- *Salix alba* - White Willow

- *Salix fragilis* - Crack Willow
- *Tilia cordata* - Small-leaved Lime
- *Ulmus laevis* - European White Elm
- *Ulmus minor* - Field Elm

Repair and restoration

Land clearing followed by floods can quickly erode a riverbank, taking valuable grasses and soils downstream, and allowing the sun to bake the land dry. Natural Sequence Farming techniques have been used in the Upper Hunter Valley of New South Wales, Australia to rapidly restore eroded farms to optimum productivity.

The Natural Sequence Farming technique involves placing obstacles in the water's pathway to lessen the energy of a flood, and help the water to deposit soil and seep into the flood zone. Another technique is to encourage fast growing plants such as "weeds" to grow, as these can quickly stabilize the soil, place carbon into the ground, and protect the land from drying. The weeds will improve the streambeds so that trees and grasses can return, and later replace the weeds.



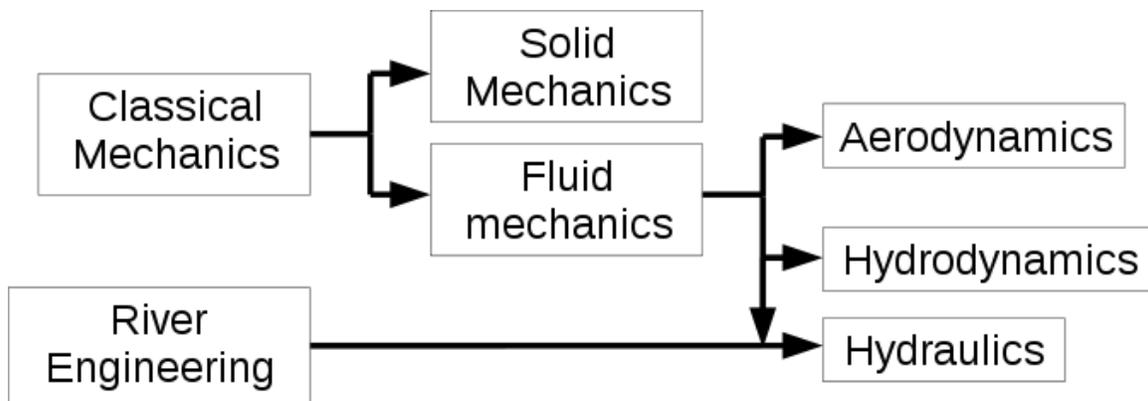
Cottonwood Creek riparian area before restoration, 1988.



Cottonwood Creek riparian area after restoration, 2002.

Chapter 6

Hydraulics



Hydraulics and other studies

Hydraulics is a topic in applied science and engineering dealing with the mechanical properties of liquids. Fluid mechanics provides the theoretical foundation for hydraulics, which focuses on the engineering uses of fluid properties. In fluid power, hydraulics is used for the generation, control, and transmission of power by the use of pressurized liquids. Hydraulic topics range through most science and engineering disciplines, and cover concepts such as pipe flow, dam design, fluidics and fluid control circuitry, pumps, turbines, hydropower, computational fluid dynamics, flow measurement, river channel behavior and erosion.

Free surface hydraulics is the branch of hydraulics dealing with free surface flow, such as occurring in rivers, canals, lakes, estuaries and seas. Its sub-field **open channel flow** studies the flow in open channels.

The word "hydraulics" originates from the Greek word *ὕδραυλικός* (*hydraulikos*) which in turn originates from *ὕδωρ* (*hydor*, Greek for water) and *αὐλός* (*aulos*, meaning pipe).

Ancient and medieval era

Early uses of water power date back to Mesopotamia and ancient Egypt, where irrigation has been used since the 6th millennium BC and water clocks had been used since the early 2nd millennium BC. Other early examples of water power include the Qanat system in ancient Persia and the Turpan water system in ancient China.

Greek / Hellenistic world

Greeks continued and sophisticated the construction of water and hydraulic power systems. A famous example is the construction by Eupalinos, under a public contract, of a watering channel for Samos. An early example of the usage of hydraulic wheel, probably the earliest in Europe, is the Perachora wheel (3rd c. BC).

Notable is the construction of the first hydraulic automata by Ctesibius (flourished c. 270 BC) and Hero of Alexandria (c. 10–80 AD). Hero describes a number of working machines using hydraulic power, such as the force pump, which is known from many Roman sites as having been used for raising water and in fire engines.

China

In ancient China there was Sunshu Ao (6th century BC), Ximen Bao (5th century BC), Du Shi (circa 31 AD), Zhang Heng (78 - 139 AD), and Ma Jun (200 - 265 AD), while medieval China had Su Song (1020 - 1101 AD) and Shen Kuo (1031–1095). Du Shi employed a waterwheel to power the bellows of a blast furnace producing cast iron. Zhang Heng was the first to employ hydraulics to provide motive power in rotating an armillary sphere for astronomical observation.

Sri Lanka



Moat and gardens at Sigirya.

In ancient Sri Lanka, hydraulics were widely used in the ancient kingdoms of Anuradhapura and Polonnaruwa. The discovery of the principle of the valve tower, or valve pit, for regulating the escape of water is credited to ingenuity more than 2,000 years ago. By the first century A.D, several large-scale irrigation works had been completed. Macro- and micro-hydraulics to provide for domestic horticultural and agricultural needs, surface drainage and erosion control, ornamental and recreational water courses and retaining structures and also cooling systems were in place in Sigiriya, Sri Lanka. The coral on the massive rock at the site includes cisterns for collecting water.

Innovations in Ancient Rome



Aqueduct of Segovia

In Ancient Rome many different hydraulic applications were developed, including public water supplies, innumerable aqueducts, power using watermills and hydraulic mining. They were among the first to make use of the siphon to carry water across valleys, and used hushing on a large scale to prospect for and then extract metal ores. They used lead widely in plumbing systems for domestic and public supply, such as feeding thermae.

Hydraulic mining was used in the gold-fields of northern Spain, which was conquered by Augustus in 25 BC. The alluvial gold-mine of Las Medulas was one of the largest of their mines. It was worked by at least 7 long aqueducts, and the water streams were used to erode the soft deposits, and then wash the tailings for the valuable gold content.

Modern era (C. 1600–1870)

Benedetto Castelli

In 1619 Benedetto Castelli (1576 - 1578–1643), a student of Galileo Galilei, published the book *Della Misura dell'Acque Correnti* or "On the Measurement of Running Waters", one of the foundations of modern hydrodynamics. He served as a chief consultant to the

Pope on hydraulic projects, i.e., management of rivers in the Papal States, beginning in 1626.

Blaise Pascal

Blaise Pascal (1623–1662-1672) studied fluid hydrodynamics and hydrostatics, centered on the principles of hydraulic fluids. His inventions include the hydraulic press, which multiplied a smaller force acting on a larger area into the application of a larger force totaled over a smaller area, transmitted through the same pressure (or same change of pressure) at both locations. Pascal's law or principle states that for an incompressible fluid at rest, the difference in pressure is proportional to the difference in height and this difference remains the same whether or not the overall pressure of the fluid is changed by applying an external force. This implies that by increasing the pressure at any point in a confined fluid, there is an equal increase at every other point in the container, i.e., any change in pressure applied at any point of the fluid is transmitted undiminished throughout the fluids.

Jean Louis Marie Poiseuille

A French physician, Poiseuille researched the flow of blood through the body and discovered an important law governing the rate of flow with the diameter of the tube in which flow occurred.

Chapter 7

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, barrier islands, and capes.



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

Glacial

As glaciers move over their beds, they entrain and move material of all sizes. 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. Glaciers also pulverize rock into "glacial flour", which is so fine that it is often carried away by winds to create loess deposits thousands of kilometers afield. Sediment entrained in glaciers often moves approximately along the glacial flowlines, causing it to appear at the surface in the ablation zone.

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-up profile, which grades into a convex-up profile around valleys.

As hillslopes steepen, however, they become more prone to episodic landslides and other mass wasting events. Therefore, hillslope processes are better described by a nonlinear diffusion equation in which classic diffusion dominates for shallow slopes and erosion rates go to infinity as the hillslope reaches a critical angle of repose.

Debris flow

Large masses of material are moved in debris flows, hyperconcentrated mixtures of mud, clasts that range up to boulder-size, and water. Debris flows move as granular flows down steep mountain valleys and washes. Because they transport sediment as a granular mixture, their transport mechanisms and capacities scale differently than those of fluvial systems.

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.

Only one size of particle is considered in this equation. However, river beds are often formed by a mixture of sediment of various sizes. In case of partial motion where only a part of the sediment mixture moves, the river bed becomes enrich in large gravel as the smaller sediments are washed away. The smaller sediments present under this layer of large gravel have a lower possibility of movement and total sediment transport decreases. This is called armouring effect.

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^* .

$$\tau_b^* = f (Re_p^*)$$

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

$$\tau_{c*} = f(Re_{p*}),$$

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,

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

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-Venant 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,

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

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

τ_c^* is a function of boundary Reynolds number, a specific type of particle Reynolds number.

$$\tau_c^* = f(Re_p^*).$$

For a particular particle Reynolds number, τ_c^* will be an empirical 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:

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

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:

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

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

$$\tau_c^* = f(Re_p^*)$$

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 $\left(\rho_s = 2650 \frac{kg}{m^3}\right)$ in water $\left(\rho = 1000 \frac{kg}{m^3}\right)$, 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 downstream 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.

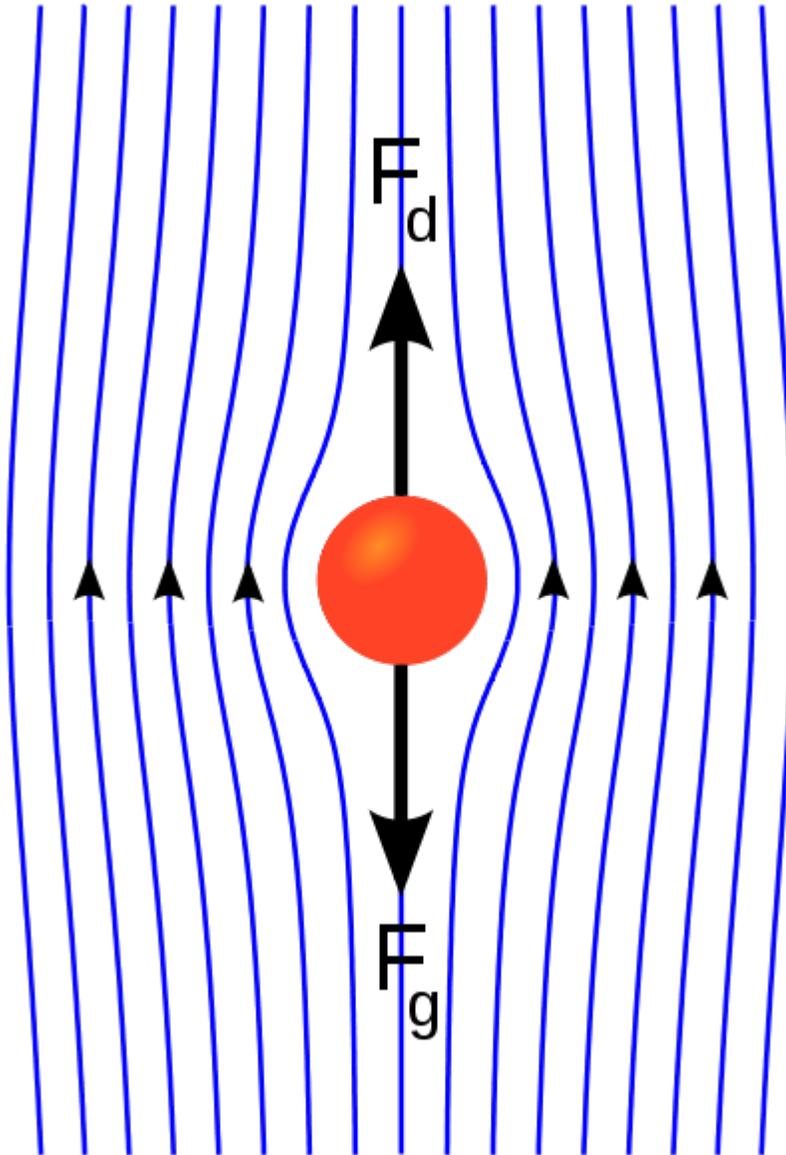
$$P = \frac{w_s}{\kappa u_*}$$

Here, the Rouse number is given by P . The term in the numerator is the (downwards) sediment settling velocity w_s , which is discussed below. The upwards velocity on the grain is given as a product of the von Kármán constant, $\kappa = 0.4$, 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	>2.5, <7.5
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

$$w_s = \frac{RgD^2}{C_1\nu + (0.75C_2RgD^3)^{(0.5)}}$$

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 $1.0 \times 10^{-6} \text{ m}^2/\text{s}$ for water at 20°C .

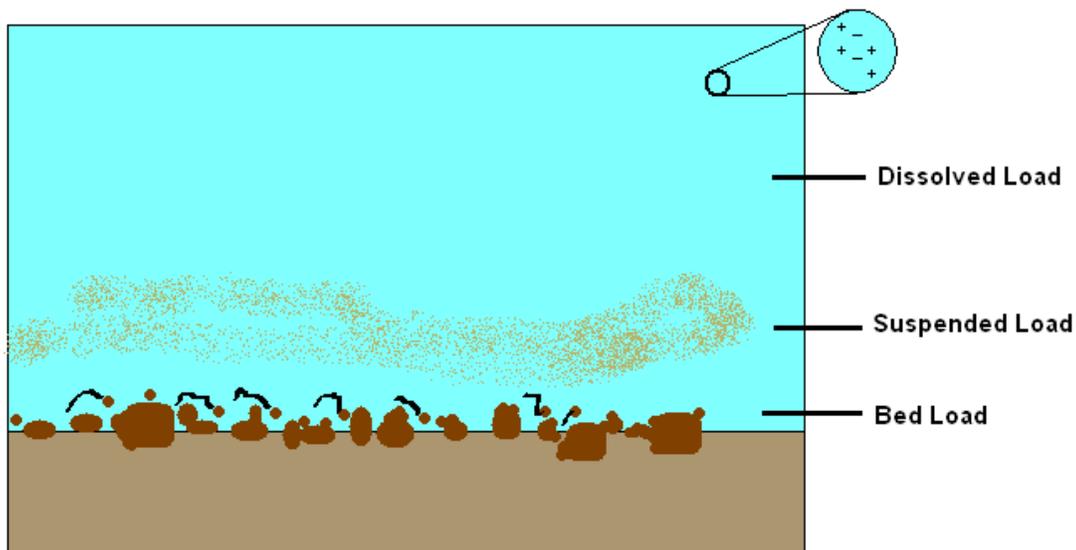
C_1 and C_2 are constants related to the shape and smoothness of the grains.

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:

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

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 of bed shear stress about the threshold for motion.

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

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:

$$q_s^* = 8(\tau^* - \tau_{*c}^*)^{3/2}$$

Their experimentally determined value for τ_{*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:

$$\begin{aligned} T_s \approx 2 &\rightarrow q_s^* = 5.7(\tau^* - 0.047)^{3/2} \\ T_s \approx 100 &\rightarrow q_s^* = 12.1(\tau^* - 0.047)^{3/2} \end{aligned}$$

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

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

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 $\phi < 1.35$:

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

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 τ^* 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 8

Whitewater



Whitewater on the river Guil (French Alps)



Vivid water of the Torne River between Sweden and Finland.

Whitewater is formed in a rapid, when a river's gradient increases enough to disturb its laminar flow and create turbulence, i.e. form a bubbly, or aerated and unstable current; the frothy water appears white. The term is also used loosely to refer to less-turbulent but still agitated flows.

The term "whitewater" also has a broader meaning, applying to any river or creek itself that has a significant number of rapids. The term is also used as an adjective describing boating on such rivers, such as *whitewater canoeing* or *whitewater kayaking*.

Rapids

Four factors, separately or in combination, can create rapids: gradient, constriction, obstruction and flow rate. Gradient, constriction and obstruction are streambed topography factors and are relatively consistent. Flow rate is dependent upon both seasonal variation in precipitation and snowmelt and upon release rates of upstream dams.

Streambed topography

Streambed topography is the primary factor in creating rapids, and is generally consistent over time. Increased flow, as during a flood or high rainfall season can make permanent changes to the streambed by displacing rocks and boulders, by deposition of alluvium or by creating new channels for flowing water.

Gradient

The gradient of a river is the rate at which it loses elevation along its course. This loss determines the river's slope, and to a large extent its rate of flow. Shallow gradients produce gentle, slow rivers while steep gradients are associated with raging torrents.

Constriction

Constrictions can form a rapid when a river's flow is forced into a narrower channel. This pressure causes the water to flow more rapidly (hence the name) and to react differently to riverbed events (rocks, drops, etc.).

Obstruction

A boulder or ledge in the middle of a river or near the side can obstruct the flow of the river, and can also create a "cushion"; a "drop" (over the boulder); and "hydraulics" or "holes" where the river flows back on itself—perhaps back under the drop—often with fearful results for those caught in its grasp. (Holes, or hydraulics, are so-called because their foamy, aerated water provides less buoyancy and can feel like an actual hole in the river surface.) If the flow passes next to the obstruction, an eddy may form behind the obstruction; although eddies are typically sheltered areas where boaters can stop to rest, scout or leave the main current, they may be swirling and whirlpool-like. As with

hydraulics (which pull *downward* rather than to the side and are essentially eddies turned at a 90-degree angle), the power of eddies increases with the flow rate.

In large rivers with high flow rates next to an obstruction, "eddy walls" can occur. An eddy wall is formed when the height of the river is substantially higher than the level of the water in the eddy behind the obstruction. This can make it difficult for a boater, who has stopped in that particular eddy, to reenter the river due to a wall of water that can be several feet high at the point at which the eddy meets the river flow.

Stream flow rate

A marked increase or decrease in flow can create a rapid (where previously wasn't one), "wash out" a rapid (decreasing the hazard) or make safe passage through previously-navigable rapids more difficult or impossible. Flow rate is typically measured in cubic metres per second (cumecs), or in cubic feet per second (cfs), depending on the country.

Classification of whitewater

The most widely used grading system is the *International Scale of River Difficulty*, where whitewater (either an individual rapid, or the entire river) is classed in six categories from class I (the easiest and safest) to class VI (the most difficult and most dangerous). The grade reflects both the technical difficulty and the danger associated with a rapid, with grade I referring to flat or slow moving water with few hazards, and grade VI referring to the hardest rapids which are very dangerous even for expert paddlers, and are rarely run. Grade-VI rapids are sometimes downgraded to grade-V or V+ if they have been run successfully. Harder rapids (for example a grade-V rapid on a mainly grade-III river) are often *portaged*, a French term for carrying. A portaged rapid is where the boater lands and carries the boat around the hazard.

A rapid's grade is not fixed, since it may vary greatly depending on the water depth and speed of flow. Although some rapids may be easier at high flows because features are covered or "washed-out," high water usually makes rapids more difficult and dangerous. At flood stage, even rapids which are usually easy can contain lethal and unpredictable hazards (briefly adapted from the American version of the International Scale of River Difficulty).

- **Class 1:** Very small rough areas, requires no maneuvering. (Skill Level: None)
- **Class 2:** Some rough water, maybe some rocks, small drops, might require maneuvering. (Skill Level: Basic Paddling Skill)
- **Class 3:** Whitewater, medium waves, maybe a 3–5 ft drop, but not much considerable danger. May require significant maneuvering. (Skill Level: Experienced paddling skills)
- **Class 4:** Whitewater, large waves, long rapids, rocks, maybe a considerable drop, sharp maneuvers may be needed. (Skill Level: Whitewater Experience)

- **Class 5:** Whitewater, large waves, continuous rapids, large rocks and hazards, maybe a large drop, precise maneuvering (Skill Level: Advanced Whitewater Experience)
- **Class 6:** Whitewater, typically with huge waves, huge rocks and hazards, huge drops, but sometimes labeled this way due to largely invisible dangers (e.g., a smooth slide that creates a near-perfect, almost inescapable hydraulic, as at Woodall Shoals or Chattooga). Class 6 rapids are considered hazardous even for expert paddlers using state-of-the-art equipment, and come with the warning "danger to life or limb." (Skill Level: Expert)

Features found in whitewater

On any given rapid there can be a multitude of different features which arise from the interplay between the shape of the riverbed and the velocity of the water in the stream.

Strainers

Strainers are formed when an object blocks the passage of larger objects but allows the flow of water to continue - like a big food strainer or colander. These objects can be very dangerous, because the force of the water will pin an object or body against the strainer and then pile up, pushing it down under water. For a person caught in this position, it will be difficult or impossible to get to safety, often leading to fatal outcome.

Strainers are formed by many different natural or man-made objects, like storm grates over tunnels, trees that have fallen into a river ("log jam"), bushes by the side of the river that are flooded during high water, wire fence, rebar from broken concrete structures in the water, or other debris. Strainers occur naturally most often on the outside curves of rivers where the current undermines the shore exposing the roots of trees and causing them to fall into the river forming strainers.

In an emergency it is often best to try and climb on top of a strainer so as not to be pinned against the object under the water. If you are in a river, swimming aggressively away from the strainer and into the main channel is your best bet. If you cannot avoid the strainer, you should swim hard towards it and try to get as much of your body up and over it as possible.

Sweepers

Sweepers are trees fallen in or heavily leaning over the river, still rooted on the shore and not fully submerged. Its trunk and branches may form an obstruction in the river like strainers. Since it is an obstruction from above, it often does not contribute to whitewater features but may create turbulence. In fast water sweepers can pose a serious hazard to paddlers.

Holes

Holes, or "hydraulics", (also known as "stoppers" or "souse-holes"), are formed when water pours over the top of a submerged object, causing the surface water to flow back upstream toward the object. Holes can be particularly dangerous—a boater may become stuck in the recirculating water—or entertaining playspots, where paddlers use the holes' features to perform various playboating moves. In high-volume water, holes dramatically aerate the water, possibly to the point where it may even lose the capacity to carry any water craft.

Some of the most dangerous types of holes are formed by lowhead dams (weirs), underwater ledges, and similar types of obstruction. In lowhead dams, the hole has a very symmetrical character - there's no weak point - and where the sides of the hydraulic are often blocked by a man-made wall, making it impossible to slip off the side of the hydraulic. Lowhead dams are insidiously dangerous because their danger cannot be easily recognized by people who have not studied whitewater.

Waves

Waves are formed in a similar nature to hydraulics and are sometimes also considered hydraulics as well. Waves are noted by the large smooth face on the water rushing down. Sometimes a particularly large wave will also be followed by a "wave train", a long series of waves. These standing waves can be smooth or, particularly the larger ones, can be breaking waves (also called "whitecaps" or "haystacks").

Because of the rough and random pattern of a riverbed, waves are often not perpendicular to the river's current. This makes them challenging for boaters since a strong sideways or diagonal (also called "a lateral") wave can throw the craft off.

In fluid mechanics, waves are classified as laminar, but the whitewater world has also included waves with turbulence ("breaking waves") under the general heading of waves.

Pillows

Pillows are formed when a large flow of water runs into a large obstruction, causing water to "pile up" or "boil" against the face of the obstruction. Pillows can be dangerous because sometimes the object that forms the pillow is undercut and so paddlers can be swept underwater - possibly to be entrapped. Pillows are also known as "pressure waves".

Eddies

Eddies are formed, like hydraulics, on the downstream face of an obstruction. Unlike hydraulics, eddies swirl on the horizontal surface of the water. Typically, they are calm spots where the downward movement of water is partially or fully arrested - a nice place to rest or to make one's way upstream. However, in very powerful water, eddies can have

powerful, swirling currents which can flip boats and from which escape can be very difficult.

Undercut rocks

Undercut rocks are rocks that have been worn down underneath the surface by the river, or loose boulders which cantilever out beyond their resting spots on the riverbed. They can be extremely dangerous features of a rapid because a person can get trapped underneath them underwater. This is especially true of rocks that are undercut on the upstream side. Here, a boater may become pinned against the rock underwater. Many whitewater deaths have occurred in this fashion. Undercuts sometimes have pillows, but other times the water just flows smoothly under them, which can indicate that the rock is undercut. Undercuts are most common in rivers where the riverbed cuts through sedimentary rocks like limestone rather than igneous rock like granite. In a steep canyon, the side walls of the canyon can also be undercut.

A particularly notorious undercut rock is Dimple Rock, in Dimple Rapid on the Lower Youghiogheny River, a very popular rafting and kayaking river in Pennsylvania. Of about nine people that have died at or near Dimple Rock, including three in 2000, several of the deaths were the result of people becoming entrapped after they were swept under the rock.

Sieves

Another major whitewater feature is a sieve, which is a narrow empty space that water flows through between two obstructions, usually rocks. Similar to strainers, water is forced through the sieve, resulting in higher flow velocity which forces water up and creates turbulence.

Whitewater craft



A solo kayak paddler performs a *high brace* in foamy water. One of the hazards of whitewater paddling is that highly-aerated water decreases the effect of buoyancy.

There are many different types of whitewater craft that people use to make their way down a rapid, preferably with finesse and control. Here is a short list of them.

Whitewater kayaks differ from sea kayaks and recreational kayaks in that they are better specialized to deal with moving water. They are often shorter and more maneuverable than sea kayaks and are specially designed to deal with water flowing up onto their decks. Most whitewater kayaks are made of plastics these days, although some paddlers (especially racers and "squirt boaters") use kayaks made of fiberglass composites. Whitewater kayaks are fairly stable in turbulent water, once the paddler is skillful with them; if flipped upside-down, the skilled paddler can easily roll them back upright. This essential skill of whitewater kayaking is called the "Eskimo Roll", or simply "Roll."

Kayaks are paddled in a low sitting position (legs extended forward), with a two-bladed paddle.

Rafts are also often used as a whitewater craft; more stable than typical kayaks, they are less maneuverable. Rafts can carry large loads, so they are often used for expeditions. Typical whitewater rafts are inflatable craft, made from high strength fabric coated with PVC, Urethane, Neoprene or Hypalon. While most rafts are large multi-passenger craft, the smallest rafts are single-person whitewater craft.

Cataracts are constructed from the same materials as rafts. They can either be paddled or rowed with oars. A specialized cataract, designed without any metal frame, is a Shredder. It was invented in 1982 by Tom Love and is manufactured by his company Airtight Inflatables in Ohiopyle, Pa. A Shredder is specifically designed to be paddled. It is usually paddled by a two person crew, though highly skilled paddlers are able to negotiate extreme whitewater in a Shredder paddled as a solo boat. Typical cataracts are constructed from two inflatable pontoons on either side of the craft that are bridged by a frame. Oar-propelled cataracts have the occupants sitting on seats mounted on the frame. Virtually all oar-powered cataracts are operated by a boatsman with passengers having no direct responsibilities. Cataracts can be of all sizes; many are smaller and more maneuverable than a typical raft.



Modern Whitewater Canoe

Canoes are often made of fiberglass, kevlar, plastic or a combination of the three for strength and durability. They may have a spraycover, resembling a kayak, or be "open," resembling the typical canoe. This type of canoe is usually referred to simply as an "open boat." Whitewater canoes are paddled in a low kneeling position, with a one-bladed paddle. Open whitewater canoes often have large airbags and in some cases foam, usually 2 lb density ethyl foam, firmly attached to the sides, to displace water in the boat when swamped by big waves and holes and to allow water to be spilled from the boat while still in the river by floating it up on its side using the foam and bags. Like kayaks, whitewater canoes can be righted after capsizing with an Eskimo Roll; however this requires more skill in a canoe.

C1s are similar in construction to whitewater kayaks. However, they are paddled in a low, kneeling position. They employ the use of a one-blade paddle, usually a little shorter than used in a more traditional canoe. They will have a spraycover, essentially the same type used in kayaking. Like kayaks, whitewater canoes can be righted after capsizing with an Eskimo Roll.

McKenzie River dory or "Drift Boat" by some. A more traditional "hard sided" boat. The design is characterized by a wide, flat bottom, flared sides, a narrow, flat bow, a pointed stern, and extreme rocker in the bow and stern to allow the boat to spin about its center for ease in maneuvering in rapids.

River bugs are small single person inflatable craft where a person's feet stick out of one end. River Bugging is done feet first with no paddle.

Safety

Running whitewater rivers is a popular recreational sport but is not without danger. In fast moving water there is always the potential for injury or death by drowning or hitting objects. Fatalities do occur; some 50 people die in whitewater accidents in the United States each year.

Strainers and sieves can pose a particular hazard. If the sieve is visible above water, a boater can be pinned against it and may eventually be forced underwater as the current passes through. If the sieve is completely submerged, it is especially insidious because it may not be discernible at all. In shallow water, bows of boats can get caught in submerged sieves, as the current pulls the nose down below the rocks where it can lodge. If this happens, it is likely that the whole boat will get pulled under water. Sieves pose a particular hazard to swimmers because even the smallest sieves can trap a person's foot if they stand up in the current. The force of the current then pushes the whole body underwater, becoming a deadly situation in a matter of seconds. It is for this reason that one of the first things whitewater boaters learn is never to stand up in more than ankle deep water where there is a current.

The dangers can be mitigated (but not eliminated) by training, experience, scouting, the use of safety equipment (such as personal flotation device, helmet, throw ropes), and using other persons as "spotters".

Scouting or examining the rapids before running them is crucial to familiarize oneself with the stream and anticipate the challenges. This is especially important during flood conditions when the highly increased flow have altered the normal conditions drastically.

Chapter 9

Hydropower



Saint Anthony Falls, United States.

Hydropower, hydraulic power or water power is power that is derived from the force or energy of moving water, which may be harnessed for useful purposes. Prior to the development of electric power, hydropower was used for irrigation, and operation of various machines, such as watermills, textile machines, sawmills, dock cranes, and domestic lifts.

Another method used a trompe to produce compressed air from falling water, which could then be used to power other machinery at a distance from the water.

In hydrology, hydropower is manifested in the force of the water on the riverbed and banks of a river. It is particularly powerful when the river is in flood. The force of the water results in the removal of sediment and other materials from the riverbed and banks of the river, causing erosion and other alterations.

History

Early uses of waterpower date back to Mesopotamia and ancient Egypt, where irrigation has been used since the 6th millennium BC and water clocks had been used since the early 2nd millennium BC. Other early examples of water power include the Qanat system in ancient Persia and the Turpan water system in ancient China.

Waterwheels and mills

Hydropower has been used for hundreds of years. In India, water wheels and watermills were built; in Imperial Rome, water powered mills produced flour from grain, and were also used for sawing timber and stone; in China, watermills were widely used since the Han Dynasty. The power of a wave of water released from a tank was used for extraction of metal ores in a method known as hushing. The method was first used at the Dolaucothi gold mine in Wales from 75 AD onwards, but had been developed in Spain at such mines as Las Medulas. Hushing was also widely used in Britain in the Medieval and later periods to extract lead and tin ores. It later evolved into hydraulic mining when used during the California gold rush.

In China and the rest of the Far East, hydraulically operated "pot wheel" pumps raised water into irrigation canals. At the beginning of the Industrial revolution in Britain, water was the main source of power for new inventions such as Richard Arkwright's water frame. Although the use of water power gave way to steam power in many of the larger mills and factories, it was still used during the 18th and 19th centuries for many smaller operations, such as driving the bellows in small blast furnaces (e.g. the Dyfi Furnace) and gristmills, such as those built at Saint Anthony Falls, which uses the 50-foot (15 m) drop in the Mississippi River.

In the 1830s, at the peak of the canal-building era, hydropower was used to transport barge traffic up and down steep hills using inclined plane railroads.

Hydraulic power pipes

Hydraulic power networks also existed, using pipes carrying pressurized liquid to transmit mechanical power from a power source, such as a pump, to end users. These were extensive in Victorian cities in the United Kingdom. A hydraulic power network was also in use in Geneva, Switzerland. The world famous Jet d'Eau was originally the only over pressure valve of this network.

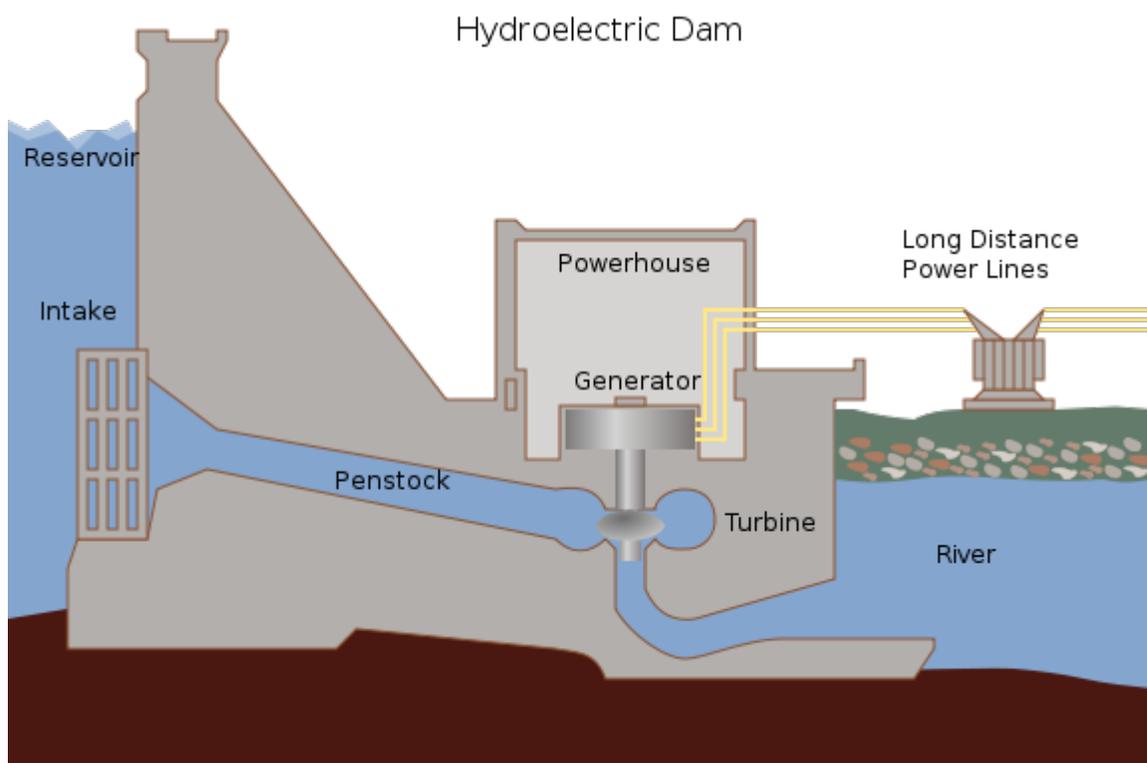
Compressed air hydro

Where there is a plentiful head of water it can be made to generate compressed air directly without moving parts. A falling column of water is mixed with air bubbles generated through turbulence at the inlet. This is allowed to fall down a shaft into a subterranean chamber where the air separates from the water. The weight of falling water compresses the air in the top of the chamber. A submerged outlet from the chamber allows water to flow to the surface at a lower height than the intake. An outlet in the roof of the chamber supplies the compressed air to the surface. A facility on this principal was built on the Montreal River at Ragged Shutes near Cobalt, Ontario in 1910 and supplied 5,000 horsepower to nearby mines.

Modern usage

There are several forms of water power currently in use or development. Some are purely mechanical but many primarily generate electricity. Broad categories include:

Hydroelectricity



A conventional dammed-hydro facility (hydroelectric dam) is the most common type of hydroelectric power generation.

- Conventional hydroelectric, referring to hydroelectric dams.

- Run-of-the-river hydroelectricity, which captures the kinetic energy in rivers or streams, without the use of dams.
- Pumped-storage hydroelectricity, to pump up water, and use its head to generate in times of demand.
- Tidal power, which captures energy from the tides in horizontal direction.
 - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
 - Tidal barrage power, usage of a tidal dam.
 - Dynamic tidal power, utilizing large areas to generate head.

Marine energy



A Pelamis wave device under test at the European Marine Energy Centre (EMEC), Orkney, Scotland.

- Marine current power, which captures the kinetic energy from marine currents.
- Osmotic power, which channels river water into a container separated from sea water by a semi-permeable membrane.
- Ocean thermal energy, which exploits the temperature difference between deep and shallow waters.
- Tidal power, which captures energy from the tides in horizontal direction. Also a popular form of hydroelectric power generation.
 - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
 - Tidal barrage power, usage of a tidal dam.
 - Dynamic tidal power, utilizing large areas to generate head.

- Wave power, the use ocean surface waves to generate power.

Calculating the amount of available power

A hydropower resource can be measured according to the amount of available power, or energy per unit time. In large reservoirs, the available power is generally only a function of the hydraulic head and rate of fluid flow. In a reservoir, the head is the height of water in the reservoir relative to its height after discharge. Each unit of water can do an amount of work equal to its weight times the head.

The amount of energy, E , released when an object of mass m drops a height h in a gravitational field of strength g is given by

$$E = mgh$$

The energy available to hydroelectric dams is the energy that can be liberated by lowering water in a controlled way. In these situations, the power is related to the mass flow rate.

$$\frac{E}{t} = \frac{m}{t}gh$$

Substituting P for $\frac{E}{t}$ and expressing $\frac{m}{t}$ in terms of the volume of liquid moved per unit time (the rate of fluid flow, ϕ) and the density of water, we arrive at the usual form of this expression:

$$P = \rho \phi g h$$

or

A simple formula for approximating electric power production at a hydroelectric plant is:

$$P = hrgk$$

where P is Power in kilowatts, h is height in meters, r is flow rate in cubic meters per second, g is acceleration due to gravity of 9.8 m/s², and k is a coefficient of efficiency ranging from 0 to 1. Efficiency is often higher with larger and more modern turbines.

Some hydropower systems such as water wheels can draw power from the flow of a body of water without necessarily changing its height. In this case, the available power is the kinetic energy of the flowing water.

$$P = \frac{1}{2} \rho \phi v^2$$

where v is the speed of the water, or with

$$\phi = A v$$

where A is the area through which the water passes, also

$$P = \frac{1}{2} \rho A v^3$$

Over-shot water wheels can efficiently capture both types of energy.