Hydraulic and River Engineering

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First Edition, 2012

ISBN 978-81-323-0938-3

Published by:
Academic Studio
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

Chapter 1

Hydraulic Engineering

Hydraulic Flood Retention Basin (HFRB)

View from Church Span Bridge, Bern, Switzerland

Riprap lining a lake shore

Hydraulic engineering as a sub-discipline of civil engineering is concerned with the flow and conveyance of fluids, principally water and sewage. One feature of these systems is the extensive use of gravity as the motive force to cause the movement of the fluids. This area of civil engineering is intimately related to the design of bridges, dams, channels, canals, and levees, and to both sanitary and environmental engineering.

Hydraulic engineering is the application of fluid mechanics principles to problems dealing with the collection, storage, control, transport, regulation, measurement, and use of water . Before beginning a hydraulic engineering project, one must figure out how much water is involved. The hydraulic engineer is concerned with the transport of sediment by the river, the interaction of the water with its alluvial boundary, and the occurrence of scour and disposition.

Fundamental Principles

A few examples of the fundamental principles of hydraulic engineering include fluid mechanics, fluid flow, behavior of real fluids, hydrology, pipelines, open channel hydraulics, mechanics of sediment transport, physical modeling, hydraulic machines, and drainage hydraulics.

Fluid Mechanics

Fundamentals of Hydraulic Engineering defines hydrostatics as the study of fluids at rest. Fluids at rest indicate that there exists a force, known as pressure, that acts upon its surroundings. This pressure, measured in N/m^2, is not constant throughout the body of fluid. Pressure, p, in a given body of fluid, increases with an increase in depth. Where the upward force on a body acts on the base and can be found by equation:

$$p=\rho gy$$

where,

ρ = density of water
g = specific gravity
y = depth of the body of liquid

Rearranging this equation gives you the "pressure head" $p/\rho g = y$. Four basic devices for finding pressure are a piezometer, manometer, differential manometer, Bourdon gauge, as well as an inclined manometer.

As Prasuhn states:

> On undisturbed submerged bodies, pressure acts along all surfaces of a body in a liquid, causing equal perpendicular forces in the body to act against the pressure of the liquid. This reaction is known as equilibrium. More advanced applications of pressure are that on plane surfaces, curved surfaces, dams, and quadrant gates, just to name a few.

Behavior of Real Fluids

1. Real and Ideal fluids

The main difference between an ideal fluid and a real fluid is that for ideal flow $p^1=p^2$ and for real flow $p^1>p^2$.

2. Viscous Flow

A viscous fluid will deform continuously under a shear force, whereas an ideal fluid doesn't deform.

3. Laminar Flow and Turbulence

The various effects of disturbance on a viscous flow are stable, transition and unstable.

Bernouilli's equation: $p/\rho g + u^2/2g = p_A/\rho g + u_A^2/2g = p_B/\rho g + u_B^2/2g$

where $p_B > p_A$

4. Boundary Layer

Assuming a flow is bounded on one side only, and that a rectilinear flow passing over a stationary flat plate which lies parallel to the flow, the flow just upstream of the plate has a uniform velocity. As the flow comes into contact with the plate, the layer of fluid actually 'adheres' to a solid surface. There is then a considerable shearing action between the layer of fluid on the plate surface and the second layer of fluid. The second layer is therefore forced to decelerate (though it is not quite brought to rest), creating a shearing action with the third layer of fluid, and so on. as the fluid passes further along the plate, the zone in which shearing action occurs tends to spread further outwards. this zone is known as the 'boundary layer'. The flow outside the boundary layer is free of shear and viscous-related forces so it is assumed to act like an ideal fluid. The flow inside the layer can be either viscous or turbulent, depending on Reynolds number.

Applications

Common topics of design for hydraulic engineers include hydraulic structures such as dams, levees, water distribution networks, water collection networks, sewage collection networks, storm water management, sediment transport, and various other topics related to transportation engineering and geotechnical engineering. Equations developed from the principles of fluid dynamics and fluid mechanics are widely utilized by other engineering disciplines such as mechanical, aeronautical and even traffic engineers.

Related branches include hydrology and rheology while related applications include hydraulic modeling, flood mapping, catchment flood management plans, shoreline management plans, estuarine strategies, coastal protection, and flood alleviation.

History

Earliest uses of hydraulic engineering were to irrigate crops and dates back to the Middle East and Africa. Controlling the movement and supply of water for growing food has been used for many thousands of years. One of the earliest hydraulic machines, the water clock was used in the early 2nd millennium BC. Other early examples of using gravity to move water include the Qanat system in ancient Persia and the very similar Turpan water system in ancient China as well as irrigation canals in Peru.

In ancient China, hydraulic engineering was highly developed, and engineers constructed massive canals with levees and dams to channel the flow of water for irrigation, as well as locks to allow ships to pass through. Sunshu Ao is considered the first Chinese hydraulic engineer. Another important Hydraulic Engineer in China, Ximen Bao was credited of starting the practice of large scale canal irrigation during the Warring States Period (481 BC-221 BC), even today hydraulic engineers remain a respectable position in China. Before becoming President, Hu Jintao was a hydraulic engineer and holds an engineering degree from Tsinghua University

Eupalinos of Megara, was an ancient Greek engineer who built the Tunnel of Eupalinos on Samos Island in the 6th century BC, an important feat of both civil and hydraulic engineering. The civil engineering aspect of this tunnel was the fact that it was dug from both ends which required the diggers to maintain an accurate path so that the two tunnels met and that the entire effort maintained a sufficient slope to allow the water to flow.

Hydraulic engineering was highly developed in Europe under the aegis of the Roman Empire where it was especially applied to the construction and maintenance of aqueducts to supply water to and remove sewage from their cities. In addition to supplying the needs of their citizens they used hydraulic mining methods to prospect and extract alluvial gold deposits in a technique known as hushing, and applied the methods to other ores such as those of tin and lead.

Further advances in hydraulic engineering occurred in the Muslim world between the 8th to 16th centuries, during what is known as the Islamic Golden Age. Of particular importance was the 'water management technological complex' which was central to the Islamic Green Revolution and, by extension, a precondition for the emergence of modern technology. The various components of this 'toolkit' were developed in different parts of the Afro-Eurasian landmass, both within and beyond the Islamic world. However, it was in the medieval Islamic lands where the technological complex was assembled and standardized, and subsequently diffused to the rest of the Old World. Under the rule of a single Islamic Caliphate, different regional hydraulic technologies were assembled into "an identifiable water management technological complex that was to have a global impact." The various components of this complex included canals, dams, the *qanat* system from Persia, regional water-lifting devices such as the *noria, shaduf* and screwpump from Egypt, and the windmill from Islamic Afghanistan. Other original Islamic developments included the *saqiya* with a flywheel effect from Islamic Spain, the reciprocating suction pump and crankshaft-connecting rod mechanism from Iraq, the geared and hydropowered water supply system from Syria, and the water purification methods of Islamic chemists.

Modern times

In many respects the fundamentals of hydraulic engineering haven't changed since ancient times. Liquids are still moved for the most part by gravity through systems of canals and aqueducts, though the supply reservoirs may now be filled using pumps. The need for water has steadily increased from ancient times and the role of the hydraulic engineer is a critical one in supplying it. For example, without the efforts of people like William Mulholland the Los Angeles area would not have been able to grow as it has because it simply doesn't have enough local water to support its population. The same is true for many of our worlds largest cities. In much the same way, the central valley of California could not have become such an important agricultural region without effective water management and distribution for irrigation.

In a somewhat parallel way to what happened in California the creation of the Tennessee Valley Authority(TVA) brought work and prosperity to the South by building dams to generate cheap electricity and control flooding in the region, making rivers navigable and generally modernizing life the region.

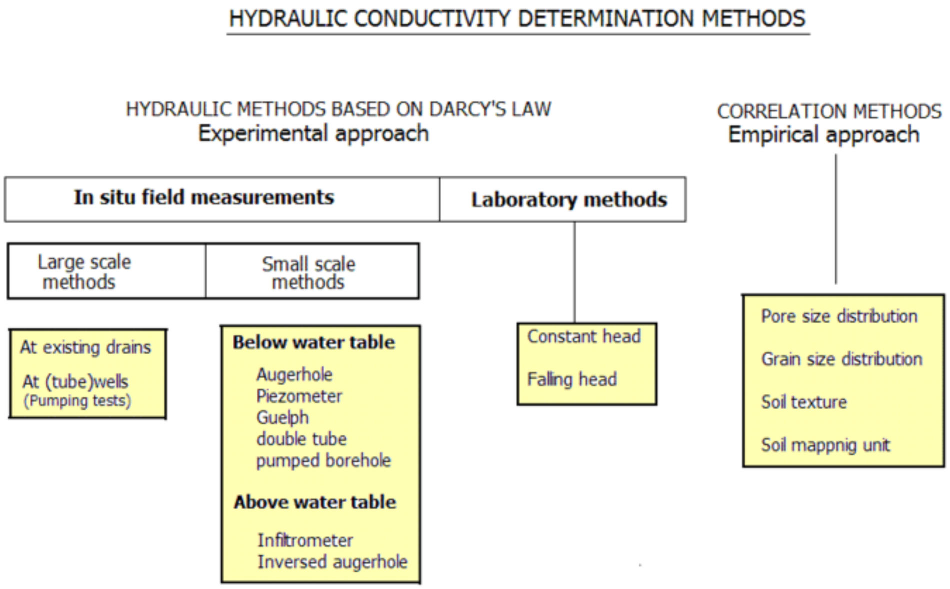
The modern hydraulic engineer uses the same kinds of computer-aided design (CAD) tools as many of the other engineering disciplines while also making use of technologies like computational fluid dynamics to perform the calculations to accurately predict flow characteristics, GPS mapping to assist in locating the best paths for installing a system and laser-based surveying tools to aid in the actual construction of a system.

Chapter 2

Hydraulic Conductivity

Hydraulic conductivity, symbolically represented as K, is a property of vascular plants, soil or rock, that describes the ease with which water can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation. Saturated hydraulic conductivity, K_{sat}, describes water movement through saturated media.

Methods of determination



Overview of determination methods

There are two broad categories of determining hydraulic conductivity:

- *Empirical* approach by which the hydraulic conductivity is correlated to soil properties like pore size and particle size (grain size) distributions, and soil texture
- *Experimental* approach by which the hydraulic conductivity is determined from hydraulic experiments using Darcy's law

The experimental approach is broadly classified into:

- Laboratory tests using soil samples subjected to hydraulic experiments
- *Field tests* (on site, in situ) that are differentiated into:
    - small scale field tests, using observations of the water level in cavities in the soil
    - large scale field tests, like pump tests in wells or by observing the functioning of existing horizontal drainage systems.

The small scale field tests are further subdivided into:

- infiltration tests in cavities *above* the water table
- slug tests in cavities *below* the water table

Estimation by empirical approach

Estimation from grain size

Shepherd derived an empirical formula for approximating hydraulic conductivity from grain size analyses:

$$K = a(D_{10})^b$$

where

a and b are empirically derived terms based on the soil type, and
D_{10} is the diameter of the 10 percentile grain size of the material

Note: Shepherd's Figure 3 clearly shows the use of D_{50}, not D_{10}, measured in mm. Therefore the equation should be $K = a(D_{50})^b$. His figure shows different lines for materials of different types, based on analysis of data from others with D_{50} up to 10 mm.

Pedotransfer function

A pedotransfer function (PTF) is a specialized empirical estimation method, used primarily in the soil sciences, however has increasing use in hydrogeology. There are many different PTF methods, however, they all attempt to determine soil properties, such as hydraulic conductivity, given several measured soil properties, such as soil particle size, and bulk density.

Determination by experimental approach

There are relatively simple and inexpensive laboratory tests that may be run to determine the hydraulic conductivity of a soil: constant-head method and falling-head method.

Laboratory methods

Constant-head method

The constant-head method is typically used on granular soil. This procedure allows water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen is measured over a period of time. By knowing the quantity Q of water measured, length L of specimen, cross-sectional area A of the specimen, time t required for the quantity of water Q to be discharged, and head h, the hydraulic conductivity can be calculated:

$$Q = Avt$$

where v is the flow velocity. Using Darcy's Law:

$$v = Ki$$

and expressing the hydraulic gradient i as:

$$i = \frac{h}{L}$$

where h is the difference of hydraulic head over distance L, yields:

$$Q = \frac{AKht}{L}$$

Solving for K gives:

$$K = \frac{QL}{Ath}$$

Falling-head method

The falling-head method is totally different than the constant head methods in its initial setup; however, the advantage to the falling-head method is that can be used for both fine-grained and coarse-grained soils. The soil sample is first saturated under a specific head condition. The water is then allowed to flow through the soil without maintaining a constant pressure head.

$$K = \frac{2.3aL}{At} \log\left(\frac{h_1}{h_2}\right)$$

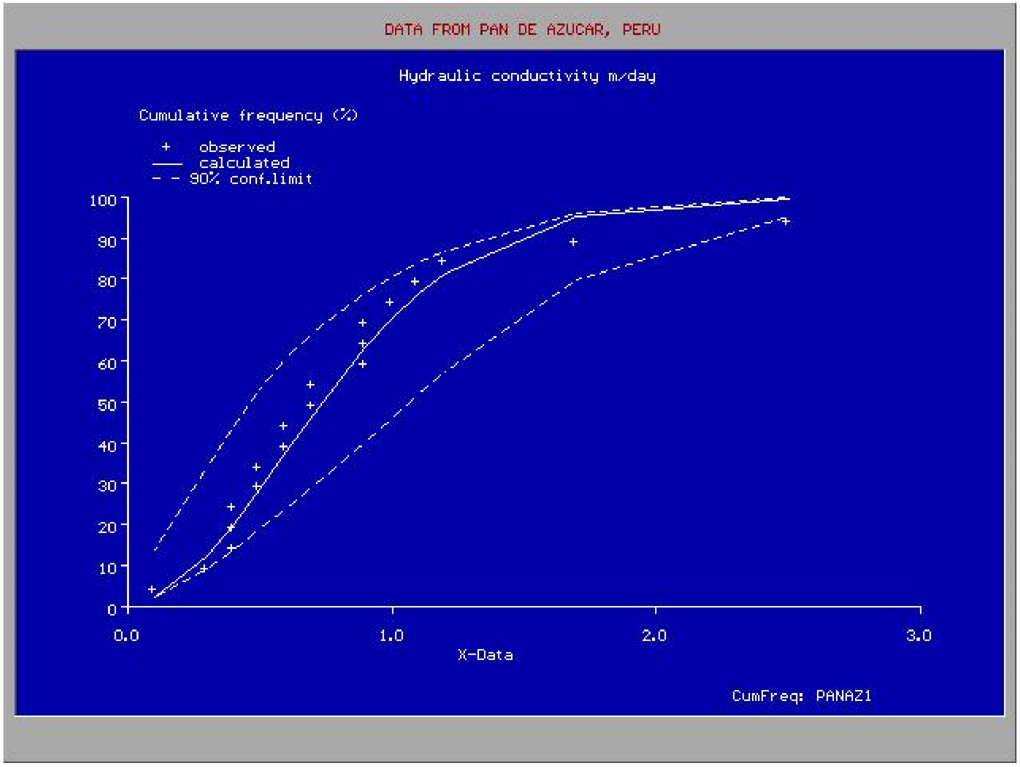
In-situ (field) methods

Augerhole method

There are also in-situ methods for measuring the hydraulic conductivity in the field. When the water table is shallow, the augerhole method, a slug test, can be used for determining the hydraulic conductivity below the water table.
The method was developed by Hooghoudt (1934) in The Netherlands and introduced in the US by Van Bavel en Kirkham (1948).
The method uses the following steps:

1. an augerhole is perforated into the soil to below the water table
2. water is bailed out from the augerhole
3. the rate of rise of the water level in the hole is recorded
4. the K-value is calculated from the data as :

$K_h = C\,(Ho-Ht)\,/\,t$



Cumulative frequency distribution (lognormal) of hydraulic conductivity (X-data) where: K_h = horizontal saturated hydraulic conductivity (m/day), H = depth of the waterlevel in the hole relative to the water table in the soil (cm), Ht = H at time t, Ho = H at time t = 0, t = time (in seconds) since the first measurement of H as Ho, and F is a factor depending on the geometry of the hole:

$$F = 4000r / h'(20+D/r)(2-h'/D)$$

where: r = radius of the cylindrical hole (cm), h' is the average depth of the water level in the hole relative to the water table in the soil (cm) , found as $h'=(Ho+Ht)/2$, and D is the depth of the bottom of the hole relative to the water table in the soil (cm).

The picture shows a large variation of K-values measured with the augerhole method in an area of 100 ha. The ratio between the highest and lowest values is 25. The cumulative frequency distribution is lognormal and was made with the CumFreq program.

Related magnitudes

Transmissivity

An aquifer may consist of *n* soil layers. The *transmissivity* for horizontal flow (T_i) of the *i − th* soil layer with a *saturated* thickness d_i and horizontal hydraulic conductivity Kh_i is:

$$T_i = Kh_i\, d_i$$

Transmissivity is directly proportional to horizontal hydraulic conductivity (Kh_i) and thickness (d_i). Expressing Kh_i in m/day and d_i in m, the transmissivity (T_i) is found in units m^2/day.
The transmissivity is a measure of how much water can be transmitted horizontally, such as to a pumping well.

> *Transmissivity* should not be confused with the similar word transmittance used in optics, meaning the fraction of incident light that passes through a sample.

The total transmissivity (Tt) of the aquifer is :

$$Tt = \Sigma\, T_i = \Sigma\, Kh_i\, d_i$$

where Σ signifies the summation over all layers: i= 1, 2, 3, . . .n
The *apparent* horizontal hydraulic conductivity (Kh_A) of the aquifer is:

$$Kh_A = Tt / Dt$$

where Dt is the total thickness of the aquifer: Dt= $\Sigma\, d_i$, with i= 1, 2, 3, . . .n

The transmissivity of an aquifer can be determined from pumping tests.

Influence of the water table

When a soil layer is above the water table, it is not saturated and does not contribute to the transmissivity. When the soil layer is entirely below the water table, its saturated thickness corresponds to the thickness of the soil layer itself. When the water table is inside a soil layer, the saturated thickness corresponds to the distance of the water table to the bottom of the layer. As the water table may behave dynamically, this thickness may change from place to place or from time to time, so that the transmissivity may vary accordingly.

In a semi-confined aquifer, the water table is found within a soil layer with a negligibly small transmissivity, so that changes of the total transmissivity (Dt) resulting from changes in the level of the water table are negligibly small.

When pumping water from an unconfined aquifer, where the water table is inside a soil layer with a significant transmissivity, the water table may be drawn down whereby the transmissivity reduces and the flow of water to the well diminishes.

Resistance

The *resistance* to vertical flow (R_i) of the $i - th$ soil layer with a *saturated* thickness d_i and vertical hydraulic conductivity Kv_i is:

$$R_i = d_i / Kv_i$$

Expressing Kv_i in m/day and d_i in m, the resistance (R_i) is expressed in days.

The total resistance (Rt) of the aquifer is :

$$Rt = \Sigma R_i = \Sigma d_i / Kv_i$$

where Σ signifies the summation over all layers: $i= 1, 2, 3, \ldots n$

The *apparent* vertical hydraulic conductivity (Kv_A) of the aquifer is:

$$Kv_A = Dt / Rt$$

where Dt is the total thickness of the aquifer: $Dt = \Sigma d_i$, with $i= 1, 2, 3, \ldots n$

The resistance plays a role in aquifers where a sequence of layers occurs with varying horizontal permeability so that horizontal flow is found mainly in the layers with high horizontal permeability while the layers with low horizontal permeability transmit the water mainly in a vertical sense.

Anisotropy

When the horizontal and vertical hydraulic conductivity (Kh_i and Kv_i) of the $i - th$ soil layer differ considerably, the layer is said to be anisotropic with respect to hydraulic conductivity.

When the *apparent* horizontal and vertical hydraulic conductivity (Kh_A and Kv_A) differ considerably, the aquifer is said to be anisotropic with respect to hydraulic conductivity.

An aquifer is called *semi-confined* when a saturated layer with a relatively small horizontal hydraulic conductivity (the semi-confining layer or aquitard) overlies a layer with a relatively high horizontal hydraulic conductivity so that the flow of groundwater in the first layer is mainly vertical and in the second layer mainly horizontal.
The resistance of a semi-confining toplayer of an aquifer can be determined from pumping tests.
When calculating flow to drains or to a well field in an aquifer with the aim to control the water table, the anisotropy is to be taken into account, otherwise the result may be erroneous.

Relative properties

Because of their high porosity and permeability, sand and gravel aquifers have higher hydraulic conductivity than clay or unfractured granite aquifers. Sand or gravel aquifers would thus be easier to extract water from (e.g., using a pumping well) because of their high transmissivity, compared to clay or unfractured bedrock aquifers.

Hydraulic conductivity has units with dimensions of length per time (e.g., m/s, ft/day and (gal/day)/ft^2); transmissivity then has units with dimensions of length squared per time. The following table gives some typical ranges (illustrating the many orders of magnitude which are likely) for *K* values.

Hydraulic conductivity (*K*) is one of the most complex and important of the properties of aquifers in hydrogeology as the values found in nature:

- range over many orders of magnitude (the distribution is often considered to be lognormal),
- vary a large amount through space (sometimes considered to be randomly spatially distributed, or stochastic in nature),
- are directional (in general *K* is a symmetric second-rank tensor; e.g., vertical *K* values can be several orders of magnitude smaller than horizontal *K* values),
- are scale dependent (testing a m^3 of aquifer will generally produce different results than a similar test on only a cm^3 sample of the same aquifer),
- must be determined indirectly through field pumping tests, laboratory column flow tests or inverse computer simulation, (sometimes also from grain size analyses), and
- are very dependent (in a non-linear way) on the water content, which makes solving the unsaturated flow equation difficult. In fact, the variably saturated *K* for a single material varies over a wider range than the saturated *K* values for all types of materials.

Ranges of values for natural materials

Table of saturated hydraulic conductivity (*K*) values found in nature

Values are for typical fresh groundwater conditions — using standard values of viscosity and specific gravity for water at 20°C and 1 atm.

<table>
<tr><td>*K* (cm/s)</td><td>10^{2}</td><td>10^{1}</td><td>$10^{0}=1$</td><td>10^{-1}</td><td>10^{-2}</td><td>10^{-3}</td><td>10^{-4}</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td><td>10^{-8}</td><td>10^{-9}</td><td>10^{-10}</td></tr>
<tr><td>*K* (ft/day)</td><td>10^{5}</td><td>10,000</td><td>1,000</td><td>100</td><td>10</td><td>1</td><td>0.1</td><td>0.01</td><td>0.001</td><td>0.0001</td><td>10^{-5}</td><td>10^{-6}</td><td>10^{-7}</td></tr>
<tr><td>Relative Permeability</td><td colspan="4">Pervious</td><td colspan="4">Semi-Pervious</td><td colspan="5">Impervious</td></tr>
<tr><td>Aquifer</td><td colspan="5">Good</td><td colspan="4">Poor</td><td colspan="4">None</td></tr>
<tr><td>Unconsolidated Sand & Gravel</td><td colspan="2">Well Sorted Gravel</td><td colspan="3">Well Sorted Sand or Sand & Gravel</td><td colspan="4">Very Fine Sand, Silt, Loess, Loam</td><td colspan="4"></td></tr>
<tr><td>Unconsolidated Clay & Organic</td><td colspan="4"></td><td colspan="2">Peat</td><td colspan="3">Layered Clay</td><td colspan="4">Fat / Unweathered Clay</td></tr>
<tr><td>Consolidated Rocks</td><td colspan="4">Highly Fractured Rocks</td><td colspan="3">Oil Reservoir Rocks</td><td colspan="2">Fresh Sandstone</td><td colspan="2">Fresh Limestone, Dolomite</td><td colspan="2">Fresh Granite</td></tr>
</table>

Chapter 3

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 widespread availability of commercial 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.

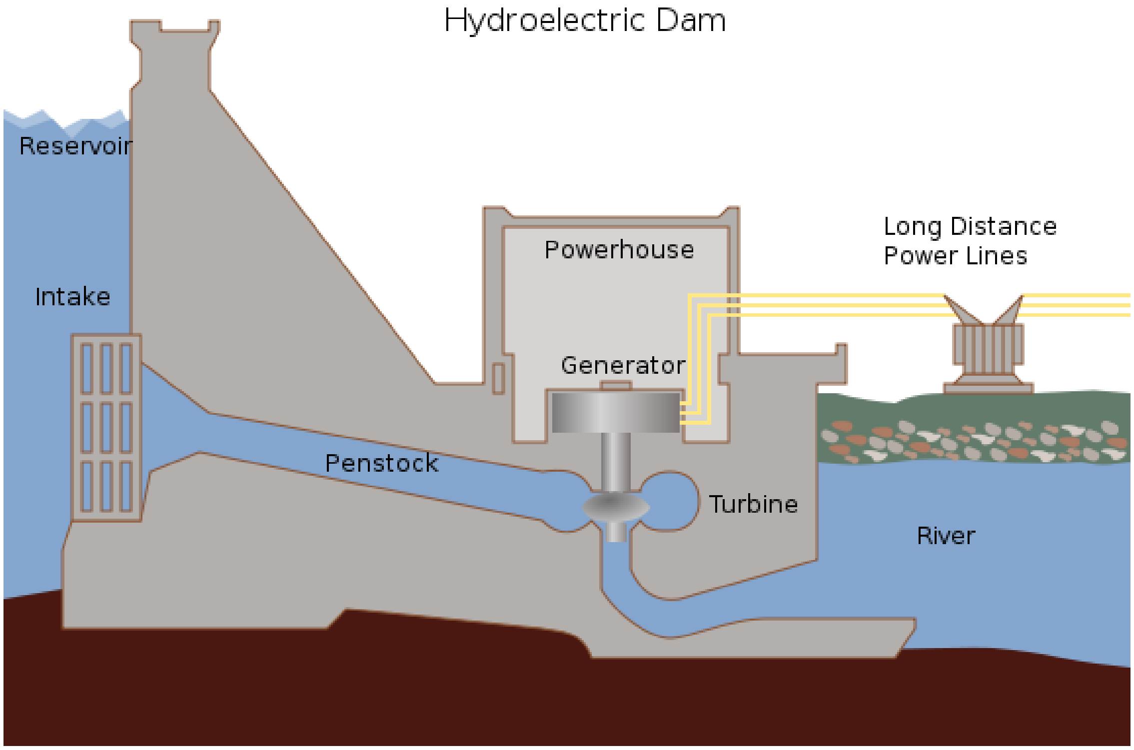
Compressed air hydro

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 $^E/_t$ and expressing $^m/_t$ 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.

Chapter 4

Hydraulic Mining

Hydraulic mining, or **hydraulicking**, is a form of mining that uses high-pressure jets of water to dislodge rock material or move sediment. In the placer mining of gold or tin, the resulting water-sediment slurry is directed through sluice boxes to remove the gold.

Precursor - ground sluicing

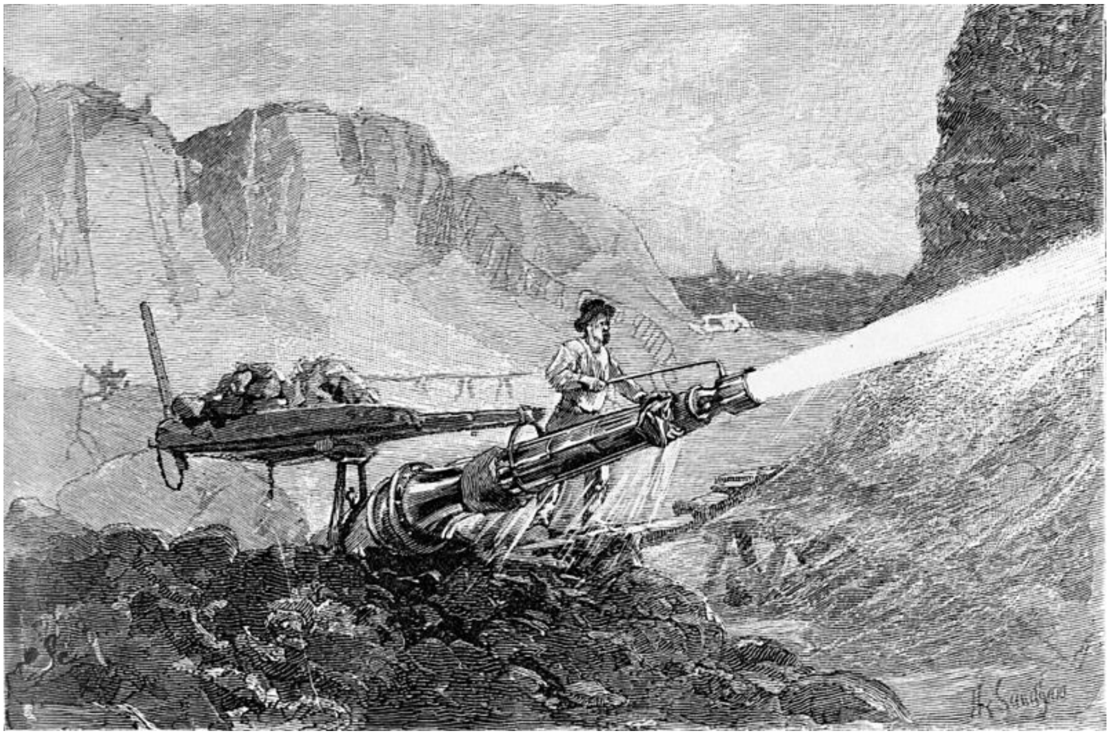
Hydraulicking had its precursor in the millennia-old practice of ground sluicing, also known as "hushing", in which surface streams of water were diverted so as to erode gold-bearing gravels. The Romans used ground sluicing to remove overburden and then gold-bearing debris in Las Médulas of Spain, and Dolaucothi in Britain. The method was also used in Elizabethan Britain for developing lead, tin and copper mines.

Panoramic view of Las Médulas

Roman era

Water was used on a large scale by Roman engineers in the first centuries BC and AD when the Roman empire was expanding rapidly in Europe. Using a process later known as hushing, the Romans stored a large volume of water in a reservoir immediately above the area to be mined; the water was then quickly released. The resulting wave of water removed overburden and exposed bedrock. Gold veins in the bedrock were then worked using a number of techniques, and water power was used again to remove debris. The remains at Las Medulas and in surrounding areas show badland scenery on a gigantic scale owing to hydraulicking of the rich alluvial gold deposits. Las Medulas is now a UNESCO World Heritage site. The site shows the remains of at least seven large aqueducts of up to 30 miles in length feeding large supplies of water into the site. The gold-mining operations were described in vivid terms by Pliny the Elder in his Naturalis Historia published in the first century AD. Pliny was a procurator in Hispania Terraconensis in the 70's and must have witnessed for himself the operations. The use of hushing has been confirmed by field survey and archaeology at Dolaucothi in South Wales, the only known Roman gold mine in Britain.

California hydraulicking



Hydraulic mining for gold in California, from *The Century Magazine* January 1883

The modern form of hydraulicking, using jets of water directed under very high pressure through hoses and nozzles at gold-bearing upland paleogravels, was first used by Edward Matteson near Nevada City, California in 1853 during the California Gold Rush. Matteson used canvas hose which was later replaced with crinoline hose by the 1860s. In

California, hydraulic mining often brought water from higher locations for long distances to holding ponds several hundred feet above the area to be mined. Insofar as California hydraulic mining exploited primarily river gravels, it was one form of placer mining, that is, working of alluvium (river sediments).

Gold miners excavate an eroded bluff with jets of water at a placer mine in Dutch Flat, California sometime between 1857 and 1870.

Early placer miners in California discovered that the more gravel they could process, the more gold they were likely to find. Instead of working with pans, sluice boxes, long toms, and rockers, miners collaborated to find ways to process larger quantities of gravel more rapidly. Hydraulic mining became the largest-scale, and most devastating, form of placer mining. Water was redirected into an ever-narrowing channel, through a large canvas hose, and out through a giant iron nozzle, called a "monitor." The extremely high pressure stream was used to wash entire hillsides through enormous sluices.

By the early 1860s, while hydraulic mining was at its height, small-scale placer mining had largely exhausted the rich surface placers, and the mining industry turned to hard rock (called quartz mining in California) or hydraulic mining, which required larger organizations and much more capital. By the mid-1880s, it is estimated that 11 million ounces of gold (worth approximately US$7.5 billion at mid-2006 prices) had been recovered by hydraulic mining in the California Gold Rush.

Environmental consequences

A man leans over a wooden sluice. Rocks line the outside of the wood boards that create the sluice.

While generating millions of dollars in tax revenues for the state and supporting a large population of miners in the mountains, hydraulic mining had a devastating effect on riparian natural environment and agricultural systems in California. Millions of tons of earth and water were delivered to mountain streams that fed rivers flowing into the Sacramento Valley. Once the rivers reached the relatively flat valley, the water slowed, the rivers widened, and the sediment was deposited in the floodplains and river beds causing them to rise, shift to new channels, and overflow their banks, causing major flooding, especially during the spring melt.

Cities and towns in the Sacramento Valley experienced an increasing number of devastating floods, while the rising riverbeds made navigation on the rivers increasingly difficult. Perhaps no other city experienced the boon and the bane of gold mining as much as Marysville. Situated at the confluence of the Yuba and Feather rivers, Marysville was the final "jumping off" point for miners heading to the northern foothills to seek their fortune. Steamboats from San Francisco, carrying miners and supplies, navigated up the Sacramento River, then the Feather River to Marysville where they would unload their passengers and cargo. Marysville eventually constructed a complex levee system to protect the city from floods and sediment. Hydraulic mining greatly exacerbated the problem of flooding in Marysville and shoaled the waters of the Feather River so severely that few steamboats could navigate from Sacramento to the Marysville docks.

The spectacular eroded landscape left at the site of hydraulic mining can be viewed at Malakoff Diggins State Historic Park in Nevada County, California. A similar landscape can be seen at Las Médulas in northern Spain, where Roman engineers ground sluiced the rich gold alluvial deposits of the river Sil. Pliny the Elder mentions in his Naturalis Historia that Spain had encroached on the sea and local lakes as a result of ground sluicing operations.

Legal ramifications

Vast areas of farmland in the Sacramento Valley were deeply buried by the mining sediment. Frequently devastated by flood waters, farmers demanded an end to hydraulic mining. In the most renowned legal fight of farmers against miners, the farmers sued the hydraulic mining operations and the landmark case of *Edwards Woodruff v. North Bloomfield Mining and Gravel Company* made its way to the United States District Court in San Francisco where Judge Lorenzo Sawyer decided in favor of the farmers in 1884, declaring that hydraulic mining was “a public and private nuisance” and enjoining its operation in areas tributary to navigable streams and rivers. Hydraulic mining was recommenced after 1893 when the United States Congress passed the Camminetti Act which allowed such mining if sediment detention structures were constructed. This led to a number of operations above brush dams and log crib dams. Most of the water-delivery infrastructure had been destroyed by an 1891 flood, so this later stage of mining was carried on at a much smaller scale in California.

Beyond California

The Oriental Claims near Omeo, Australia were mined between the 1850s and 1900s; hydraulic sluicing left man-made cliffs up to 30 metres (98 ft) high such as seen here throughout the area

Lee Moor china clay pit in Devon showing hydraulic mining

Although often associated with California due to its adoption and widespread use there, the technology was exported widely, to Oregon (Jacksonville in 1856), Colorado (Clear Creek, Central City and Breckenridge in 1860), Montana (Bannack in 1865), Arizona (Lynx Creek in 1868), Idaho (Idaho City in 1863), South Dakota (Deadwood in 1876), Alaska, British Columbia (Canada), and overseas. It was used extensively in Dahlonega, Georgia and continues to be used in developing nations, often with devastating environmental consequences. The devastation caused by this method of mining caused Edwin Carter, the "Log Cabin Naturalist," to switch from mining to collecting wildlife specimens from 1875-1900 in Breckenridge, Colorado, USA.

Hydraulic mining was also used during the Australian gold rushes where it was called hydraulic sluicing. One notable location was at the Oriental Claims near Omeo in

Victoria where it was used between the 1850s and early 1900s, with abundant evidence of the damage still being visible today.

Hydraulic mining was used extensively in the Central Otago Gold Rush that took place in the 1860s in the South Island of New Zealand, where it was also known as *sluicing*.

Starting in the 1870s, hydraulic mining became a mainstay of alluvial tin mining on the Malay Peninsula.

Hydraulicking was formerly used in Polk County, Florida to mine phosphate rock.

Hydraulic mining is the principal way that kaolinite clay is mined in Cornwall and Devon, in South-West England.

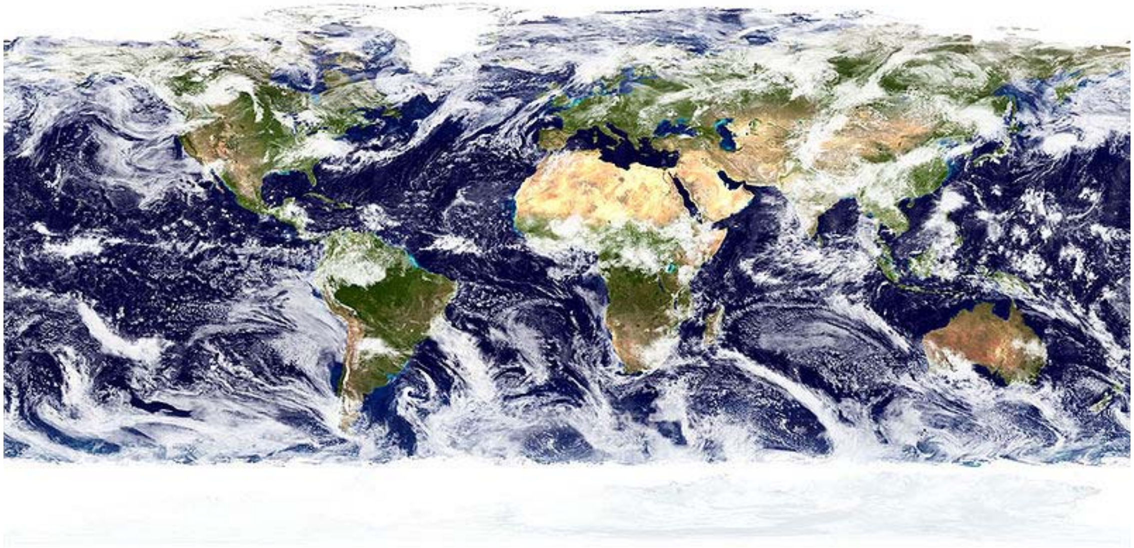
In addition to its use in true mining, hydraulic mining can be used as an excavation technique, principally to demolish hills. For example, the Denny Regrade in Seattle was largely accomplished by hydraulic mining.

Underground hydraulic mining

High-pressure water jets have also been used in the underground mining of coal, to break up the coal seam and wash the resulting coal slurry toward a collection point.

Chapter 5

Hydrology



Water covers 70% of the Earth's surface.

Hydrology is the study of the movement, distribution, and quality of water throughout the Earth, including the hydrologic cycle, water resources and environmental watershed sustainability. A practitioner of hydrology is a hydrologist, working within the fields of either earth or environmental science, physical geography, geology or civil and environmental engineering.

Domains of hydrology include hydrometeorology, surface hydrology, hydrogeology, drainage basin management and water quality, where water plays the central role. Oceanography and meteorology are not included because water is only one of many important aspects.

Hydrological research can inform environmental engineering, policy and planning.

The term *hydrology* is from Greek: ὕδωρ, *hydōr*, "water"; and λόγος, *logos*, "study".

History of hydrology

Hydrology has been a subject of investigation and engineering for millennia. For example, about 4000 B.C. the Nile was dammed to improve agricultural productivity of previously barren lands. Mesopotamian towns were protected from flooding with high earthen walls. Aqueducts were built by the Greeks and Ancient Romans, while the History of China shows they built irrigation and flood control works. The ancient Sinhalese used hydrology to build complex irrigation Works in Sri Lanka, also known for invention of the Valve Pit which allowed construction of large reservoirs, anicuts and canals which still function.

Marcus Vitruvius, in the first century B.C., described a philosophical theory of the hydrologic cycle, in which precipitation falling in the mountains infiltrated the Earth's surface and led to streams and springs in the lowlands. With adoption of a more scientific approach, Leonardo da Vinci and Bernard Palissy independently reached an accurate representation of the hydrologic cycle. It was not until the 17th century that hydrologic variables began to be quantified.

Pioneers of the modern science of hydrology include Pierre Perrault, Edme Mariotte and Edmund Halley. By measuring rainfall, runoff, and drainage area, Perrault showed that rainfall was sufficient to account for flow of the Seine. Marriotte combined velocity and river cross-section measurements to obtain discharge, again in the Seine. Halley showed that the evaporation from the Mediterranean Sea was sufficient to account for the outflow of rivers flowing into the sea.

Advances in the 18th century included the Bernoulli piezometer and Bernoulli's equation, by Daniel Bernoulli, the Pitot tube. The 19th century saw development in groundwater hydrology, including Darcy's law, the Dupuit-Thiem well formula, and Hagen-Poiseuille's capillary flow equation.

Rational analyses began to replace empiricism in the 20th century, while governmental agencies began their own hydrological research programs. Of particular importance were Leroy Sherman's unit hydrograph, the infiltration theory of Robert E. Horton, and C.V. Theis's Aquifer test/equation describing well hydraulics.

Since the 1950s, hydrology has been approached with a more theoretical basis than in the past, facilitated by advances in the physical understanding of hydrological processes and by the advent of computers and especially Geographic Information Systems (GIS).

Hydrologic cycle

The central theme of hydrology is that water circulates throughout the Earth through different pathways and at different rates. The most vivid image of this is in the evaporation of water from the ocean, which forms clouds. These clouds drift over the land and produce rain. The rainwater flows into lakes, rivers, or aquifers. The water in lakes, rivers, and aquifers then either evaporates back to the atmosphere or eventually flows back to the ocean, completing a cycle. Water changes its state of being several times throughout this cycle.

Overview

Branches of hydrology

Chemical hydrology is the study of the chemical characteristics of water.
Ecohydrology is the study of interactions between organisms and the hydrologic cycle.
Hydrogeology is the study of the presence and movement of ground water.
Hydroinformatics is the adaptation of information technology to hydrology and water resources applications.
Hydrometeorology is the study of the transfer of water and energy between land and water body surfaces and the lower atmosphere.
Isotope hydrology is the study of the isotopic signatures of water.
Surface hydrology is the study of hydrologic processes that operate at or near Earth's surface.
Drainage basin management covers water-storage, in the form of reservoirs, and flood-protection.
Water quality includes the chemistry of water in rivers and lakes, both of pollutants and natural solutes.

Related topics

Oceanography is the more general study of water in the oceans and estuaries.
Meteorology is the more general study of the atmosphere and of weather, including precipitation as snow and rainfall.
Limnology is the study of lakes. It covers the biological, chemical, physical, geological, and other attributes of all inland waters (running and standing waters, both fresh and saline, natural or man-made).

Applications of hydrology

- Determining the water balance of a region.
- Determining the agricultural water balance.
- Designing riparian restoration projects.
- Mitigating and predicting flood, landslide and drought risk.
- Real-time flood forecasting and flood warning.
- Designing irrigation schemes and managing agricultural productivity.
- Part of the hazard module in catastrophe modeling.
- Providing drinking water.
- Designing dams for water supply or hydroelectric power generation.
- Designing bridges.
- Designing sewers and urban drainage system.
- Analyzing the impacts of antecedent moisture on sanitary sewer systems.
- Predicting geomorphological changes, such as erosion or sedimentation.

- Assessing the impacts of natural and anthropogenic environmental change on water resources.
- Assessing contaminant transport risk and establishing environmental policy guidelines.

Hydrologic measurements

Measurement is fundamental for assessing water resources and understanding the processes involved in the hydrologic cycle. Because the hydrologic cycle is so diverse, hydrologic measurement methods span many disciplines: including soils, oceanography, atmospheric science, geology, geophysics and limnology, to name a few. Here, hydrologic measurement methods are organized by hydrologic sub-disciplines. Each of these subdisciplines is addressed briefly with a practical discussion of the methods used to date and a bibliography of background information.

Quantifying groundwater flow and transport

- Aquifer characterization
    - Flow direction
        - Piezometer - groundwater pressure and, by inference, groundwater depth (see: aquifer test)
        - Conductivity, storativity, transmisivity
        - Geophysical methods

- Vadose zone characterization
    - Infiltration
        - Infiltrometer - infiltration
    - Soil moisture
        - Capacitance probe-soil moisture
        - Time domain reflectometer - soil moisture
        - Tensiometer - soil moisture
        - Solute sampling
        - Geophysical methods

Quantifying surface water flow and transport

- Direct and indirect discharge measurements
    - Stream gauge - stream flow (see: discharge (hydrology))
    - Tracer techniques
    - Chemical transport
    - Sediment transport and erosion
    - Stream-aquifer exchange

Quantifying exchanges at the land-atmosphere boundary

- Precipitation

  - Bulk rain events
    - Disdrometer - precipitation characteristics
    - Radar - cloud properties, rain rate estimation, hail and snow detection
    - Rain gauge - rain and snowfall
    - Satellite - rainy area identification, rain rate estimation, land-cover/land-use, soil moisture
    - Sling psychrometer - humidity
  - Snow, hail and ice
  - Dew, mist and fog
- Evaporation
  - from water surfaces
  - Evaporation -Symon's evaporation pan
  - from plant surfaces
  - through the boundary layer
- Transpiration
  - Natural ecosystems
  - Agronomic ecosystems
- Momentum
- Heat flux
  - Energy budgets

Uncertainty analyses
Remote sensing of hydrologic processes

- Land based sensors
- Airborne Sensors
- Satellite sensors

Water quality

- Sample collection
- In-situ methods
- Physical measurements (includes sediment concentration)
- Collection of samples to quantify Organic Compounds
- Collection of samples to quantify Inorganic Compounds
- Analysis of aqueous Organic Compounds
- Analysis of aqueous Inorganic Compounds
- Microbiological sampling and analysis

Integrating measurement and modeling

- Budget analyses
- Parameter estimation
- Scaling in time and space
- Data assimilation

Hydrologic prediction

Observations of hydrologic processes are used to make predictions of the future behaviour of hydrologic systems (water flow, water quality). One of the major current concerns in hydrologic research is "Prediction in Ungauged Basins" (PUB), i.e. in basins where no or only very few data exist.

Statistical hydrology

By analysing the statistical properties of hydrologic records, such as rainfall or river flow, hydrologists can estimate future hydrologic phenomena, assuming the characteristics of the processes remain unchanged.

These estimates are important for engineers and economists so that proper risk analysis can be performed to influence investment decisions in future infrastructure and to determine the yield reliability characteristics of water supply systems. Statistical information is utilised to formulate operating rules for large dams forming part of systems which include agricultural, industrial and residential demands.

Hydrologic modeling

Hydrologic models are simplified, conceptual representations of a part of the hydrologic cycle. They are primarily used for hydrologic prediction and for understanding hydrologic processes. Two major types of hydrologic models can be distinguished:

- Models based on data. These models are black box systems, using mathematical and statistical concepts to link a certain input (for instance rainfall) to the model output (for instance runoff). Commonly used techniques are regression, transfer functions, and system identification. The simplest of these models may be linear models, but it is common to deploy non-linear components to represent some general aspects of a catchment's response without going deeply into the real physical processes involved. An example of such an aspect is the well-known behaviour that a catchment will respond much more quickly and strongly when it is already wet than when it is dry.

- Models based on process descriptions. These models try to represent the physical processes observed in the real world. Typically, such models contain representations of surface runoff, subsurface flow, evapotranspiration, and channel flow, but they can be far more complicated. These models are known as deterministic hydrology models. Deterministic hydrology models can be subdivided into single-event models and continuous simulation models.

Recent research in hydrologic modeling tries to have a more global approach to the understanding of the behaviour of hydrologic systems to make better predictions and to face the major challenges in water resources management.

Hydrologic transport

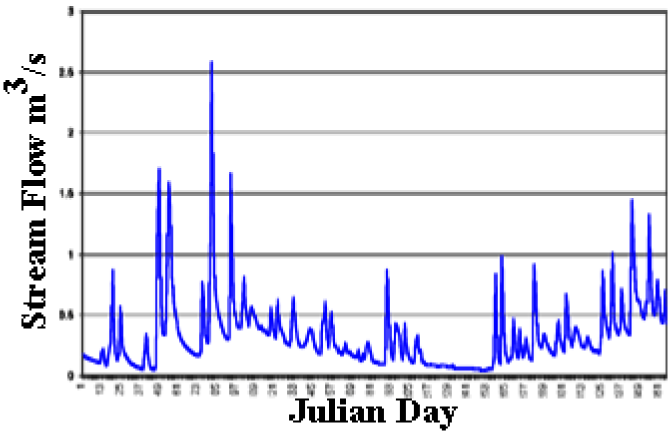
Water movement is a significant means by which other material, such as soil or pollutants, are transported from place to place. Initial input to receiving waters may arise from a point source discharge or a line source or area source, such as surface runoff. Since the 1960s rather complex mathematical models have been developed, facilitated by the availability of high speed computers. The most common pollutant classes analyzed are nutrients, pesticides, total dissolved solids and sediment.

Chapter 6

Hydrograph

A **hydrograph** is a graph showing changes in the discharge of a river over a period of time.

It can also refer to a graph showing the volume of water reaching a particular outfall, or location in a sewerage network, related to time. Hydrographs are commonly used in the design of sewerage, more specifically, the design of surface water sewerage systems and combined systems.



Stream hydrograph. Increases in stream flow follow rainfall or snowmelt. The gradual decay in flow after the peaks reflects diminishing supply from groundwater.

Terminology

The discharge is measured at a certain point in a river and is typically time variant.

- **Rising limb:** The rising limb of hydrograph, also known as concentration curve represents the increase in discharge due to the gradual building up of storage in channels and over the catchment surface.

- **Recession limb:** The recession limb extends from the point of inflection at the end of the crest segment to the commencement of the natural groundwater flow (baseflow). It represents the withdrawal of water from the storage built up in the basin during the earlier phases of the hydrograph.
- **Peak discharge:** the highest point on the hydrograph when there is the greatest amount of water in the river
- **Lag time:** Lag time is the amount of time it takes from when precipitation falls within the river basin to when it reaches the river.
- **Discharge:** volume of water in a river at a given time

Types of hydrograph can include:

- Storm hydrographs
- Flood hydrographs
- Annual hydrographs aka regimes
- Direct Runoff Hydrograph
- Effective Runoff Hydrograph

Surface water hydrography

In surface water hydrology, a hydrograph is a time record of the discharge of a stream, river or watershed outlet. Rainfall is typically the main input to a watershed and the streamflow is often considered the output of the watershed; a hydrograph is a representation of how a watershed responds to rainfall. They are used in hydrology and water resources planning.

A watershed's response to rainfall depends on a variety of factors which affect the shape of a hydrograph:

- Watershed topography and geology (i.e. bedrock permeability)
- The area of a basin receiving rainfall
- Land-use (e.g. agriculture, urban development, forestry operations)
- Drainage density
- Duration of rainfall and precipitation intensity and type
- Evapotranspiration rates
- River geometrics
- The season
- Vegetation type and cover
- River conditions (e.g. dams)
- Initial conditions (e.g. the degree of saturation of the soil and aquifers)
- Soil permeability and thickness

A hydrograph is often compared to a hyetograph of the watershed.

Unit Hydrograph

A **unit hydrograph** is used to more easily represent the effect of rainfall in a particular basin. It is a hypothetical unit response of the watershed to a unit input of rainfall. This allows easy calculation of the response to any arbitrary input (rainfall), by simply performing a convolution between the rain input and the unit hydrograph output.

An **instantaneous unit hydrograph** is a further refinement of the concept; for an IUH, the input rainfall is assumed to all take place at a discrete point in time (obviously, this isn't the case for actual rainstorms). Making this assumption can greatly simplify the analysis involved in constructing a unit hydrograph, and it is necessary for the creation of a **geomorphologic instantaneous unit hydrograph**.

The creation of a GIUH is possible given nothing more than topologic data for a particular drainage basin. In fact, only the number of streams of a given order, the mean length of streams of a given order, and the mean land area draining directly to streams of a given order are absolutely required (and can be estimated rather than explicitly calculated if necessary). It is therefore possible to calculate a GIUH for a basin without any data about stream height or flow, which may not always be available.

Factors affecting the hydrograph

- Soil Saturation is dependant on previous rainfall, or otherwise known as Antecedent rainfall.
- The surroundings; Rural or Urban (Could be less impermeable surface, or the surface type could vary)
- Vegetation type (Deforestation and amount of interception)
- Steepness of surrounding land, or 'relief' land
- Drainage density (Number of tributaries)
- Geology (Rock Type; Impermeable=flashier hydrographs. Or Permeable)
- Season dependant; Very dry weather creates a crust on the river bed. Wet winters create increase in discharge.
- Soil Type (Clay, sand etc.) Clay would create a flashy hydrograph, but there could be a continium between the two.
- Shape of drainage basin (circular or elongated).
- Precipitation (distribution of rainfall rates and locations)

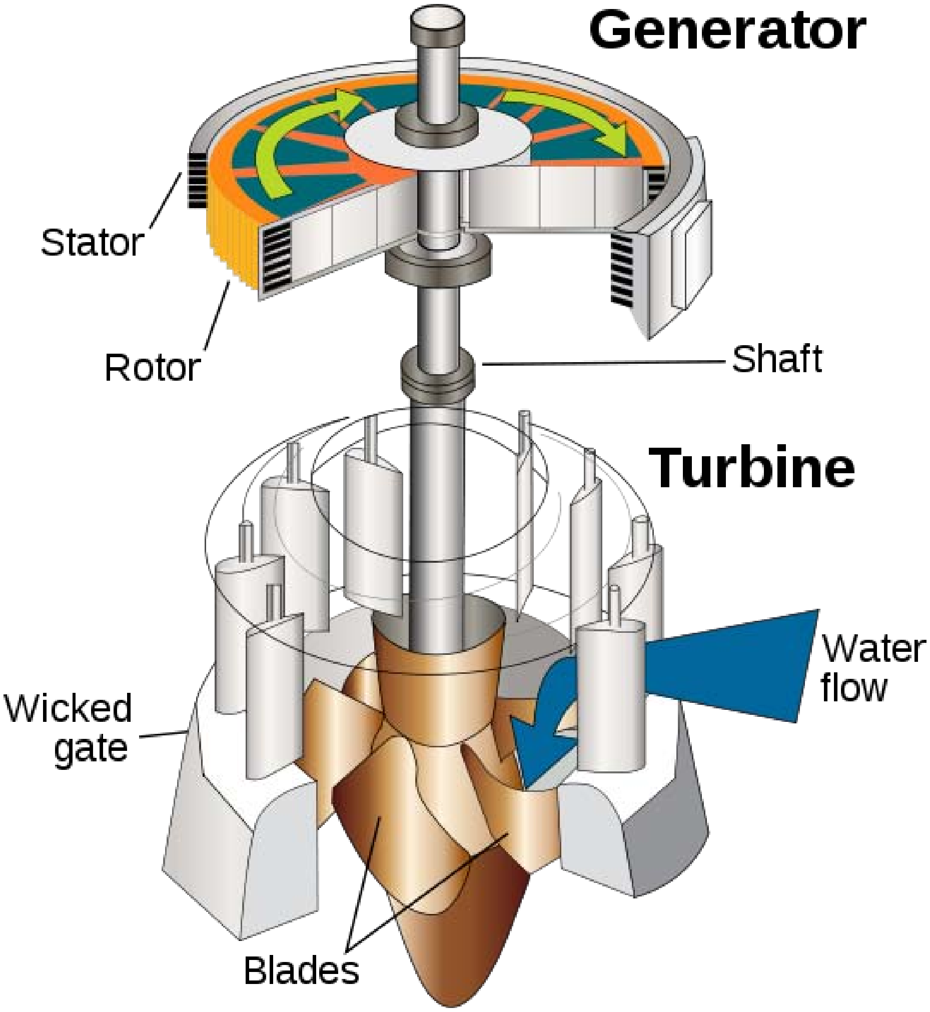
Subsurface hydrology hydrograph

In subsurface hydrology (hydrogeology), a hydrograph is a record of the water level (the observed hydraulic head in wells screened across an aquifer).

Typically, a hydrograph is recorded for monitoring of heads in aquifers during non-test conditions (e.g., to observe the seasonal fluctuations in an aquifer). When an aquifer test is being performed, the resulting observations are typically called drawdown, since they are subtracted from pre-test levels and often only the change in water level is dealt with.

Chapter 7

Water Turbine



Kaplan turbine and electrical generator cut-away view.

The runner of the small water turbine

A **water turbine** is a rotary engine that takes energy from moving water.

Water turbines were developed in the 19th century and were widely used for industrial power prior to electrical grids. Now they are mostly used for electric power generation. They harness a clean and renewable energy source.

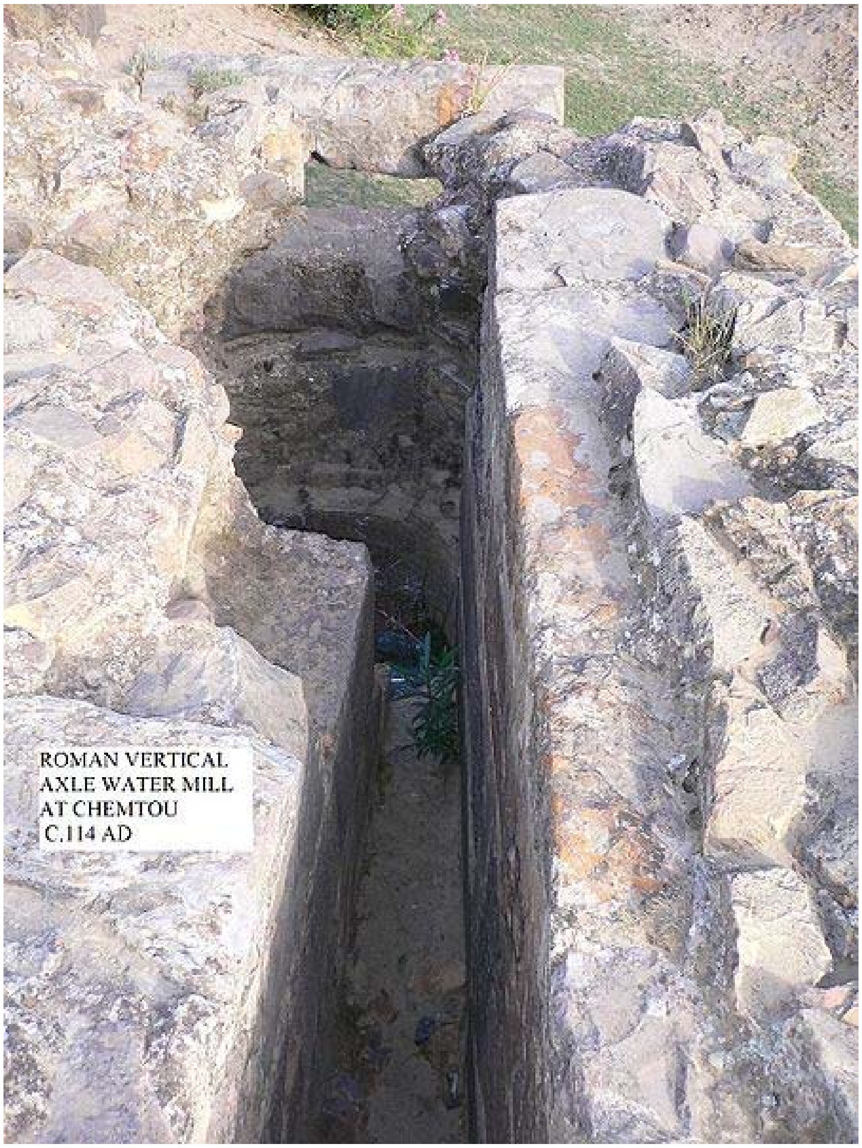
History

Water wheels have been used for thousands of years for industrial power. Their main shortcoming is size, which limits the flow rate and head that can be harnessed. The migration from water wheels to modern turbines took about one hundred years. Development occurred during the Industrial revolution, using scientific principles and methods. They also made extensive use of new materials and manufacturing methods developed at the time.

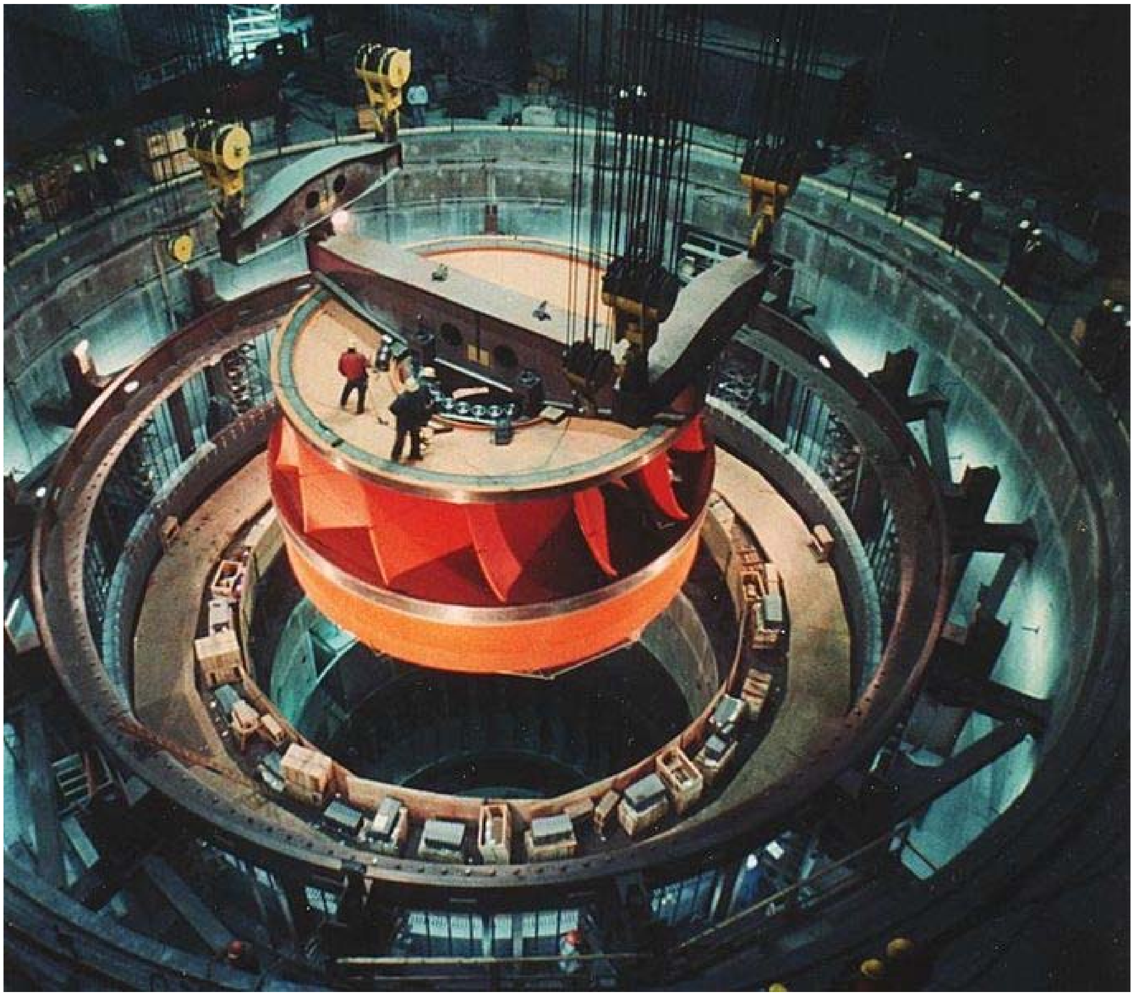
Swirl

The word turbine was introduced by the French engineer Claude Bourdin in the early 19th century and is derived from the Latin word for "whirling" or a "vortex". The main difference between early water turbines and water wheels is a swirl component of the water which passes energy to a spinning rotor. This additional component of motion allowed the turbine to be smaller than a water wheel of the same power. They could process more water by spinning faster and could harness much greater heads. (Later, impulse turbines were developed which didn't use swirl).

Time line



Roman turbine mill at Chemtou, Tunisia. The tangential water inflow of the millrace made the submerged horizontal wheel in the shaft turn like a true turbine.



A Francis turbine runner, rated at nearly one million hp (750 MW), being installed at the Grand Coulee Dam, United States.

A propeller-type runner rated 28,000 hp (21 MW)

The earliest known water turbines date to the Roman Empire. Two helix-turbine mill sites of almost identical design were found at Chemtou and Testour, modern-day Tunisia, dating to the late 3rd or early 4th century AD. The horizontal water wheel with angled blades was installed at the bottom of a water-filled, circular shaft. The water from the mill-race entered tangentially the pit, creating a swirling water column which made the fully submerged wheel act like a true turbine.

Ján Andrej Segner developed a reactive water turbine in the mid-18th century. It had a horizontal axis and was a precursor to modern water turbines. It is a very simple machine that is still produced today for use in small hydro sites. Segner worked with Euler on some of the early mathematical theories of turbine design.

In 1820, Jean-Victor Poncelet developed an inward-flow turbine.

In 1826, Benoit Fourneyron developed an outward-flow turbine. This was an efficient machine (~80%) that sent water through a runner with blades curved in one dimension. The stationary outlet also had curved guides.

In 1844, Uriah A. Boyden developed an outward flow turbine that improved on the performance of the Fourneyron turbine. Its runner shape was similar to that of a Francis turbine.

In 1849, James B. Francis improved the inward flow reaction turbine to over 90% efficiency. He also conducted sophisticated tests and developed engineering methods for water turbine design. The Francis turbine, named for him, is the first modern water turbine. It is still the most widely used water turbine in the world today. The Francis turbine is also called a radial flow turbine, since water flows from the outer circumference towards the centre of runner.

Inward flow water turbines have a better mechanical arrangement and all modern reaction water turbines are of this design. As the water swirls inward, it accelerates, and transfers energy to the runner. Water pressure decreases to atmospheric, or in some cases subatmospheric, as the water passes through the turbine blades and loses energy.

Around 1890, the modern fluid bearing was invented, now universally used to support heavy water turbine spindles. As of 2002, fluid bearings appear to have a mean time between failures of more than 1300 years.

Around 1913, Viktor Kaplan created the Kaplan turbine, a propeller-type machine. It was an evolution of the Francis turbine but revolutionized the ability to develop low-head hydro sites.

A new concept

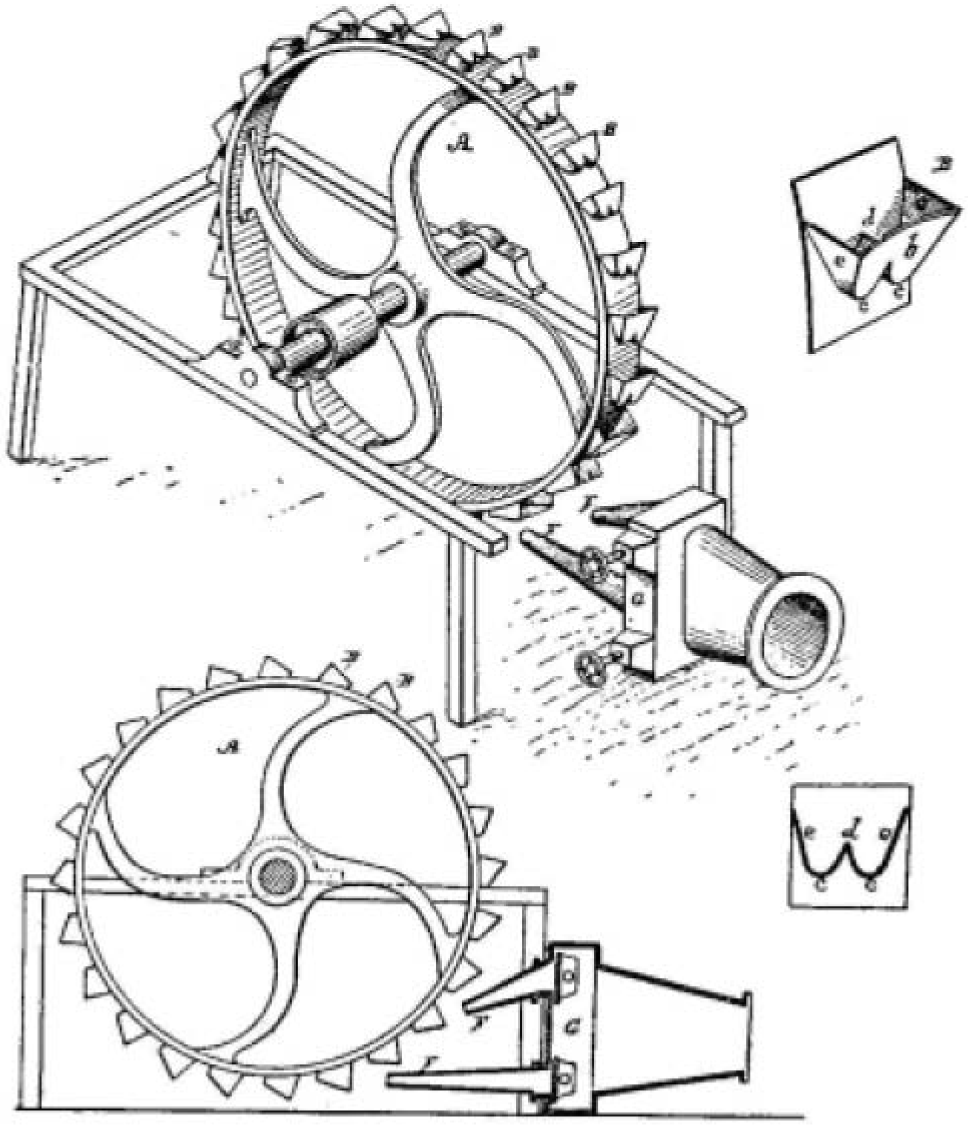


Figure from Pelton's original patent (October 1880)

All common water machines until the late 19th century (including water wheels) were basically reaction machines; water *pressure* head acted on the machine and produced work. A reaction turbine needs to fully contain the water during energy transfer.

In 1866, California millwright Samuel Knight invented a machine that took the impulse system to a new level. Inspired by the high pressure jet systems used in hydraulic mining in the gold fields, Knight developed a bucketed wheel which captured the energy of a free jet, which had converted a high head (hundreds of vertical feet in a pipe or penstock) of water to kinetic energy. This is called an impulse or tangential turbine. The water's velocity, roughly twice the velocity of the bucket periphery, does a u-turn in the bucket and drops out of the runner at low velocity.

In 1879, Lester Pelton(1829-1908), experimenting with a Knight Wheel, developed a double bucket design, which exhausted the water to the side, eliminating some energy loss of the Knight wheel which exhausted some water back against the center of the wheel. In about 1895, William Doble improved on Pelton's half-cylindrical bucket form with an elliptical bucket that included a cut in it to allow the jet a cleaner bucket entry. This is the modern form of the Pelton turbine which today achieves up to 92% efficiency. Pelton had been quite an effective promoter of his design and although Doble took over the Pelton company he did not change the name to Doble because it had brand name recognition.

Turgo and Crossflow turbines were later impulse designs.

Theory of operation

Flowing water is directed on to the blades of a turbine runner, creating a force on the blades. Since the runner is spinning, the force acts through a distance (force acting through a distance is the definition of work). In this way, energy is transferred from the water flow to the turbine

Water turbines are divided into two groups; reaction turbines and impulse turbines.

The precise shape of water turbine blades is a function of the supply pressure of water, and the type of impeller selected.

Reaction turbines

Reaction turbines are acted on by water, which changes pressure as it moves through the turbine and gives up its energy. They must be encased to contain the water pressure (or suction), or they must be fully submerged in the water flow.

Newton's third law describes the transfer of energy for reaction turbines.

Most water turbines in use are reaction turbines and are used in low (<30m/98 ft) and medium (30-300m/98–984 ft)head applications. In reaction turbine pressure drop occurs in both fixed and moving blades.

Impulse turbines

Impulse turbines change the velocity of a water jet. The jet pushes on the turbine's curved blades which changes the direction of the flow. The resulting change in momentum (impulse) causes a force on the turbine blades. Since the turbine is spinning, the force acts through a distance (work) and the diverted water flow is left with diminished energy.

Prior to hitting the turbine blades, the water's pressure (potential energy) is converted to kinetic energy by a nozzle and focused on the turbine. No pressure change occurs at the turbine blades, and the turbine doesn't require a housing for operation.

Newton's second law describes the transfer of energy for impulse turbines.

Impulse turbines are most often used in very high (>300m/984 ft) head applications .

Power

The power available in a stream of water is;

$$P = \eta \cdot \rho \cdot g \cdot h \cdot \dot{q}$$

where:

- P = power (J/s or watts)
- η = turbine efficiency
- ρ = density of water (kg/m³)
- g = acceleration of gravity (9.81 m/s²)
- h = head (m). For still water, this is the difference in height between the inlet and outlet surfaces. Moving water has an additional component added to account for the kinetic energy of the flow. The total head equals the *pressure head* plus *velocity head*.

- $\dot{q}$= flow rate (m³/s)

Pumped storage

Some water turbines are designed for pumped storage hydroelectricity. They can reverse flow and operate as a pump to fill a high reservoir during off-peak electrical hours, and then revert to a turbine for power generation during peak electrical demand. This type of turbine is usually a Deriaz or Francis in design.

Efficiency

Large modern water turbines operate at mechanical efficiencies greater than 90%.

Types of water turbines

Various types of water turbine runners. From left to right: Pelton Wheel, two types of Francis Turbine and Kaplan Turbine

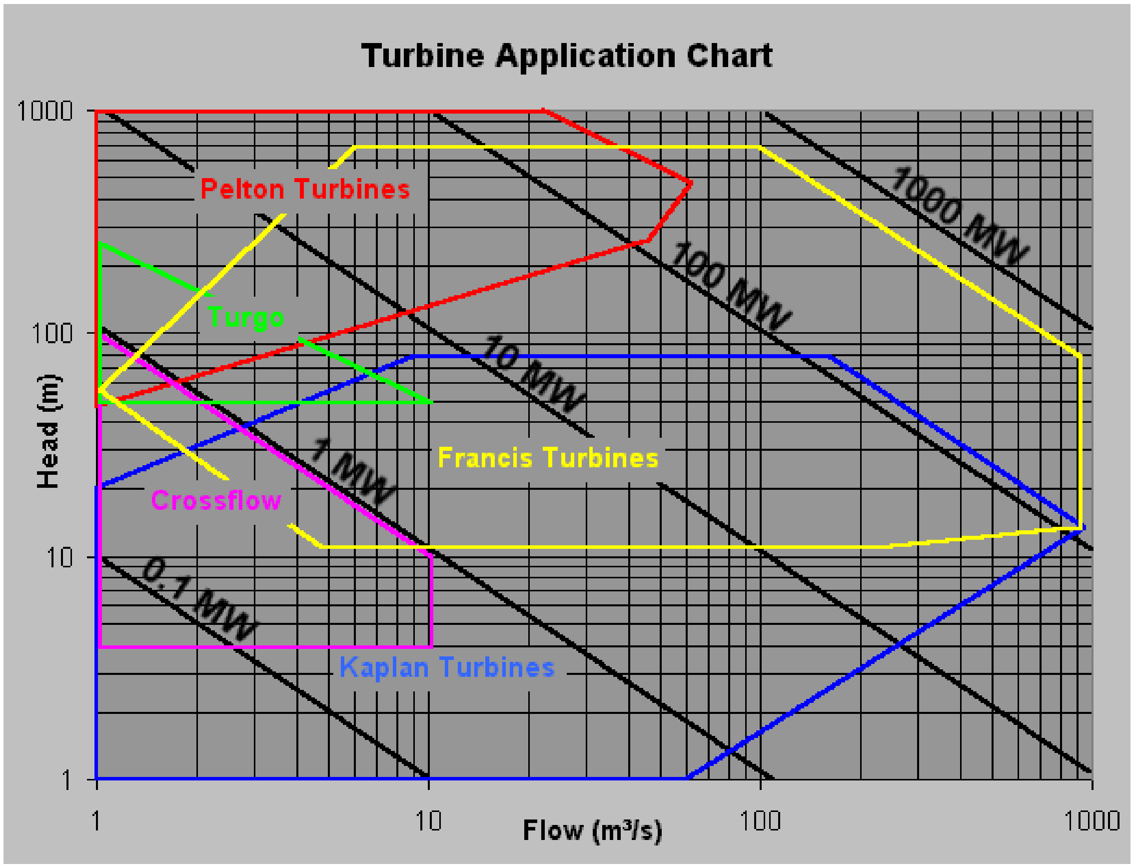
Reaction turbines:

- Francis
- Kaplan, Propeller, Bulb, Tube, Straflo
- Tyson, Gorlov (Freeflow types)

Impulse turbine

- Pelton
- Turgo
- Michell-Banki (also known as the Crossflow or Ossberger turbine)

Design and application



Turbine selection is based mostly on the available water head, and less so on the available flow rate. In general, impulse turbines are used for high head sites, and reaction turbines are used for low head sites. Kaplan turbines with adjustable blade pitch are well-adapted to wide ranges of flow or head conditions, since their peak efficiency can be achieved over a wide range of flow conditions.

Small turbines (mostly under 10 MW) may have horizontal shafts, and even fairly large bulb-type turbines up to 100 MW or so may be horizontal. Very large Francis and Kaplan machines usually have vertical shafts because this makes best use of the available head, and makes installation of a generator more economical. Pelton wheels may be either vertical or horizontal shaft machines because the size of the machine is so much less than the available head. Some impulse turbines use multiple water jets per runner to increase specific speed and balance shaft thrust.

Typical range of heads

• Hydraulic wheel turbine	$0.2 < H < 4$ (H = head in m)
• Archimedes' screw turbine	$1 < H < 10$
• Kaplan	$2 < H < 40$
• Francis	$10 < H < 350$

• Pelton	$50 < H < 1300$
• Turgo	$50 < H < 250$

Specific speed

The specific speed n_s of a turbine characterizes the turbine's shape in a way that is not related to its size. This allows a new turbine design to be scaled from an existing design of known performance. The specific speed is also the main criteria for matching a specific hydro site with the correct turbine type. The specific speed is the speed with which the turbine turns for a particular discharge Q, with unit head and thereby is able to produce unit power.

Affinity laws

Affinity Laws allow the output of a turbine to be predicted based on model tests. A miniature replica of a proposed design, about one foot (0.3 m) in diameter, can be tested and the laboratory measurements applied to the final application with high confidence. Affinity laws are derived by requiring similitude between the test model and the application.

Flow through the turbine is controlled either by a large valve or by wicket gates arranged around the outside of the turbine runner. Differential head and flow can be plotted for a number of different values of gate opening, producing a hill diagram used to show the efficiency of the turbine at varying conditions.

Runaway speed

The **runaway speed** of a water turbine is its speed at full flow, and no shaft load. The turbine will be designed to survive the mechanical forces of this speed. The manufacturer will supply the runaway speed rating.

Maintenance

A Francis turbine at the end of its life showing cavitation pitting, fatigue cracking and a catastrophic failure. Earlier repair jobs that used stainless steel weld rods are visible.

Turbines are designed to run for decades with very little maintenance of the main elements; overhaul intervals are on the order of several years. Maintenance of the runners and parts exposed to water include removal, inspection, and repair of worn parts.

Normal wear and tear includes pitting from cavitation, fatigue cracking, and abrasion from suspended solids in the water. Steel elements are repaired by welding, usually with stainless steel rods. Damaged areas are cut or ground out, then welded back up to their original or an improved profile. Old turbine runners may have a significant amount of stainless steel added this way by the end of their lifetime. Elaborate welding procedures may be used to achieve the highest quality repairs.

Other elements requiring inspection and repair during overhauls include bearings, packing box and shaft sleeves, servomotors, cooling systems for the bearings and generator coils, seal rings, wicket gate linkage elements and all surfaces.

Environmental impact

Water turbines are generally considered a clean power producer, as the turbine causes essentially no change to the water. They use a renewable energy source and are designed to operate for decades. They produce significant amounts of the world's electrical supply.

Historically there have also been negative consequences, mostly associated with the dams normally required for power production. Dams alter the natural ecology of rivers, potentially killing fish, stopping migrations, and disrupting peoples' livelihoods. For example, American Indian tribes in the Pacific Northwest had livelihoods built around salmon fishing, but aggressive dam-building destroyed their way of life. Dams also cause less obvious, but potentially serious consequences, including increased evaporation of water (especially in arid regions), build up of silt behind the dam, and changes to water temperature and flow patterns. Some people believe that it is possible to construct hydropower systems that divert fish and other organisms away from turbine intakes without significant damage or loss of power; historical performance of diversion structures have been poor. In the United States, it is now illegal to block the migration of fish, for example the endangered great white sturgeon in North America, so fish ladders must be provided by dam builders. The actual performance of fish ladders is often poor.

Chapter 8

Drainage

Deep inside a Sydney drain in New South Wales

Drainage is the natural or artificial removal of surface and sub-surface water from an area. Many agricultural soils need drainage to improve production or to manage water supplies.

History

Early history

The ancient Indus systems of sewerage and drainage that were developed and used in cities throughout the civilization were far more advanced than any found in contemporary urban sites in the Middle East and even more efficient than those in some areas of modern Pakistan and India today. All houses in the major cities of Harappa and Mohenjodaro had access to water and drainage facilities. Waste water was directed to covered drains, which lined the major streets.

Drainage in the 19th century

Tank Stream, a historical drain in the City of Sydney

From the 1881 *Household Cyclopedia*:

This operation is always best performed in spring or summer, when the ground is dry. Main drains ought to be made in every part of the field where a cross-cut or open drain was formerly wanted; they ought to be cut four feet (1.2 m) deep, upon an average. This completely secures them from the possibility of being damaged by the treading of horses or cattle, and being so far below the small drains, clears the water finely out of them. In every situation, pipe-turfs for the main drains, if they can be had, are preferable. If good stiff clay, a single row of pipe-turf; if sandy, a double row. When pipe-turf cannot be got conveniently, a good wedge drain may answer well, when the subsoil is a strong, stiff clay; but if the subsoil be only moderately so, a thorn drain, with couples below, will do still better; and if the subsoil is very sandy, except pipes can be had, it is in vain to attempt under-draining the fiel d by any other method. It may be necessary to mention here that the size of the main drains ought to be regulated according to the length and declivity of the run, and t eihther it can be he quantity of water to be carried off by them.

It is always safe, however, to have the main drains large, and plenty of them; for economy here seldom turns out well.

Having finished the main drains, proceed next to make a small drain in every furrow of the field if the ridges formerly have not been less than fifteen feet (4.6 m) wide. But if that should be the case, first level the ridges, and make the drains in the best direction, and at such a distance from each other as may be thought necessary. If the water rises well in the bottom of the drains, they ought to be cut three feet (1 m) deep, and in this ease would dry the field sufficiently well, although they were from twenty-five to thirty feet (8 to 10 m) asunder; but if the water does not draw well to the bottom of the drains, two feet (0.6 m) will be a sufficient deepness for the pipe-drain, and two and a half feet (1 m) for the wedge drain. In no case ought they to be shallower where the field has been previously leveled. In this instance, however, as the surface water is carried off chiefly by the water sinking immediately into the top of the drains, it will be necessary to have the drains much nearer each other—say from fifteen to twenty feet (4.6 to 6 m). If the ridges are more than fifteen feet (4.6 m) wide, however broad and irregular they may be, follow invariably the line of the old furrows, as the best direction for the drains; and, where they are high-gathered ridges, from twenty to twenty-four inches will be a sufficient depth for the pipe-drain, and from twenty-four to thirty inches for the wedge-drain. Particular care should be taken in connecting the small and main drains together, so that the water may have a gentle declivity, with free access into the main drains.

When the drains are finished, the ridges are cleaved down upon the drains by the plough; and where they had been very high formerly, a second clearing may be given; but it is better not to level the ridges too much, for by allowing them to retain a little of their former shape, the ground being lowest immediately where the drains are, the surface water collects upon the top of the drains; and, by shrinking into them, gets freely away. After the field is thus finished, run the new ridges across the small drains, making them about ten feet (3 m) broad, and continue afterwards to plough the field in the same manner as dry land.

It is evident from the above method of draining that the expense will vary very much, according to the quantity of main drains necessary for the field, the distance of the small drains from each other, and the distance the turf is to be carried.

The advantage resulting from under-draining, is very great, for besides a considerable saving annually of water furrowing, cross cutting, etc., the land can often be ploughed and sown to advantage, both in the spring and in the fall of the year, when otherwise it would be found quite impracticable; every species of drilled crops, such as beans, potatoes, turnips, etc., can be cultivated successfully; and every species, both of green and white crops, is less apt to fail in wet and untoward seasons.

Wherever a burst of water appears in any particular spot, the sure and certain way of getting quit of such an evil is to dig hollow drains to such a depth below the surface as is required by the fall or level that can be gained, and by the quantity of water expected to proceed from the burst or spring. Having ascertained the extent of water to be carried off, taken the necessary levels, and cleared a mouth or loading passage for the water, begin the drain at the extremity next to that leader, and go on with the work till the top of the spring is touched, which probably will accomplish the intended object. But if it should not be completely accomplished, run off from the main drain with such a number of branches as may be required to intercept the water, and in this way disappointment will hardly be experienced. Drains, to be substantially useful, should seldom be less than three feet (1 m) in depth, twenty or twenty four inches thereof to be close packed with stones or wood, according to circumstances. The former are the best materials, but in many places are not to be got in sufficient quantities; recourse therefore, must often be made to the latter, though not so effectual or durable.

It is of vast importance to fill up drains as fast as they are dug out; because, if left open for any length of time, the earth is not only apt to fall in but the sides get into a broken, irregular state, which cannot afterwards be completely rectified. A proper covering of straw or sod should be put upon the top of the materials, to keep the surface earth from mixing with them; and where wood is the material used for filling up, a double degree of attention is necessary, otherwise the proposed improvement may be effectually frustrated.

The pit method of draining is a very effectual one, if executed with judgment. When it is sufficiently ascertained where the bed of water is deposited, which can easily be done by boring with an auger, sink a pit into the place of a size which will allow a man freely to work within its bounds. Dig this pit of such a depth as to reach the bed of the water meant to be carried off; and when this depth is attained, which is easily discerned by the rising of the water, fill up the pit with great land-stones and carry off the water by a stout drain to some adjoining ditch or mouth, whence it may proceed to the nearest river.

Current practices

A plastic flexible drainpipe, used to drain water from the roof of a residential house or building

Modern drainage systems incorporate geotextile filters that retain and prevent fine grains of soil from passing into and clogging the drain. Geotextiles are synthetic textile fabrics specially manufactured for civil and environmental engineering applications. Geotextiles are designed to retain fine soil particles while allowing water to pass through. In a typical drainage system they would be laid along a trench which would then be filled with coarse granular material: gravel, sea shells, stone or rock. The geotextile is then folded over the top of the stone and the trench is then covered by soil. Groundwater seeps through the geotextile and flows within the stone to an outfall. In high groundwater conditions a perforated plastic (PVC or PE) pipe is laid along the base of the drain to increase the volume of water transported in the drain.

Green Drain

Enzymatic drain cleaners can be a safer alternative to chemical drain cleaners, and are easier on the environment. They use bacteria or enzymes, which naturally feed on organic waste, such as hair and food waste that often block drains. These tiny organisms, then digest the waste and to recreate beneficial bacteria and enzymes throughout the septic system. In fact, drain cleaners enzyme originally used to clean septic tanks and sewage. Enzymatic drain cleaners are better for the environment because they prevent hazardous chemicals that may leak into soil and water from spreading. .

Alternatively, prefabricated plastic drainage systems made of HDPE called SmartDitch, often incorporating geotextile, coco fiber or rag filters can be considered. The use of these materials has become increasingly more common due to their ease of use which eliminates the need for transporting and laying stone drainage aggregate which is invariably more expensive than a synthetic drain and concrete liners.

Over the past 30 years geotextile and PVC filters have become the most commonly used soil filter media. They are cheap to produce and easy to lay, with factory controlled properties that ensure long term filtration performance even in fine silty soil conditions.

21st century alternatives

Seattle's Public Utilities created a pilot program called Street Edge Alternatives (SEA Streets) Project. The project focuses on designing a system "to provide drainage that more closely mimics the natural landscape prior to development than traditional piped systems". The streets are characterized by ditches along the side of the roadway, with plantings designed throughout the area. An emphasis on non curbed sidewalks allows water to flow more freely into the areas of permeable surface on the side of the streets. Because of the plantings the run off water from the urban area does not all directly go into the ground but can also be absorbed into the surrounding environment. According to the monitoring by Seattle Public Utilities, they report at 99 percent reduction of storm water leaving the drainage project

Drainage in construction

Piping being placed for a sink

The civil engineer or site engineer is responsible for drainage in construction projects. They set out from the plans all the roads, Street gutters, drainage, culverts and sewers involved in construction operations. During the construction of the work on site he/she will set out all the necessary levels for each of the previously mentioned factors.

Site engineers work alongside architects and construction managers, supervisors, planners, quantity surveyors, the general workforce, as well as subcontractors. Typically, most jurisdictions have some body of drainage law to govern to what degree a landowner can alter the drainage from his parcel.

Reasons for artificial drainage

An agricultural drainage channel outside Magome, Japan after a heavy rain. Note that protuberances create turbulent water, preventing sediment from settling in the channel.

Wetland soils may need drainage to be used for agriculture. In the northern USA and Europe, glaciation created numerous small lakes which gradually filled with humus to make marshes. Some of these were drained using open ditches and trenches to make mucklands, which are primarily used for high value crops such as vegetables.

The largest project of this type in the world has been in process for centuries in the Netherlands. The area between Amsterdam, Haarlem and Leiden was, in prehistoric times swampland and small lakes. Turf cutting (Peat mining), subsidence and shoreline erosion gradually caused the formation of one large lake, the Haarlemmermeer, or lake of Haarlem. The invention of wind powered pumping engines in the 15th century permitted drainage of some of the marginal land, but the final drainage of the lake had to await the design of large, steam powered pumps and agreements between regional authorities. The elimination of the lake occurred between 1849 and 1852, creating thousands of km² of new land.

Coastal plains and river deltas may have seasonally or permanently high water tables and must have drainage improvements if they are to be used for agriculture. An example is the flatwoods citrus-growing region of Florida. After periods of high rainfall, drainage pumps are employed to prevent damage to the citrus groves from overly wet soils. Rice production requires complete control of water, as fields need to be flooded or drained at different stages of the crop cycle. The Netherlands has also led the way in this type of drainage, not only to drain lowland along the shore, but actually pushing back the sea until the original nation has been greatly enlarged.

In moist climates, soils may be adequate for cropping with the exception that they become waterlogged for brief periods each year, from snow melt or from heavy rains. Soils that are predominantly clay will pass water very slowly downward, meanwhile plant roots suffocate because the excessive water around the roots eliminates air movement through the soil.

Other soils may have an impervious layer of mineralized soil, called a hardpan or relatively impervious rock layers may underlie shallow soils. Drainage is especially important in tree fruit production. Soils that are otherwise excellent may be waterlogged for a week of the year, which is sufficient to kill fruit trees and cost the productivity of the land until replacements can be established. In each of these cases appropriate drainage carries off temporary flushes of water to prevent damage to annual or perennial crops.

Drier areas are often farmed by irrigation, and one would not consider drainage necessary. However, irrigation water always contains minerals and salts, which can be concentrated to toxic levels by evapotranspiration. Irrigated land may need periodic flushes with excessive irrigation water and drainage to control soil salinity.

A typical drain in Bankstown, New South Wales.

Chapter 9

Reservoir

The Jhonghua Dam on the Dahan River in Taoyuan County, Taiwan.

A **reservoir** (etymology from French *réservoir* a "storehouse) or an **artificial lake** is used to store water. Reservoirs may be created in river valleys by the construction of a dam or may be built by excavation in the ground or by conventional construction techniques such a brickwork or cast concrete.

The term reservoir may also be used to describe underground reservoirs such as an oil or water well.

Types

Valley dammed reservoir

Lake Vyrnwy Reservoir. The dam spans the Vyrnwy Valley and was the first large stone dam built in the United Kingdom.

Stocks Reservoir in Lancashire, England.

A dam constructed in a valley relies on the natural topography to provide most of the basin of the reservoir. Dams are typically located at a narrow part of a valley downstream of a natural basin. The valley sides act as natural walls with the dam located at the narrowest practical point to provide strength and the lowest practical cost of construction. In many reservoir construction projects people have to be moved and re-housed, historical artifacts moved or rare environments relocated. Examples include the temples of Abu Simbel (which were moved before the construction of the Aswan Dam to create Lake Nasser from the Nile in Egypt) and the re-location of the village of Capel Celyn during the construction of Llyn Celyn.

Construction of a reservoir in a valley will usually necessitate the diversion of the river during part of the build often through a temporary tunnel or by-pass channel.

In hilly regions reservoirs are often constructed by enlarging existing lakes. Sometimes in such reservoirs the new top water level exceeds the watershed height on one or more of the feeder streams such as at Llyn Clywedog in Mid Wales. In such cases additional side dams are required to contain the reservoir.

Where the topography is poorly suited to a single large reservoir, a number of smaller reservoirs may be constructed in a chain such as in the River Taff valley where the three reservoirs Llwyn-on Reservoir, Cantref Reservoir and Beacons Reservoir form a chain up the valley.

Bank-side reservoir

Where water is taken from a river of variable quality or quantity, bank-side reservoirs may be constructed to store the water pumped or siphoned from the river. Such reservoirs are usually built partly by excavation and partly by the construction of a complete encircling bund or embankment which may exceed 6 km in circumference. Both the floor of the reservoir and the bund must have an impermeable lining or core, often made of puddled clay. The water stored in such reservoirs may have a residence time of several months during which time normal biological processes are able to substantially reduce many contaminants and almost eliminate any turbidity. The use of bank-side reservoirs also allows a water abstraction to be closed down for extended period at times when the river is unacceptably polluted or when flow conditions are very low due to drought. The London water supply system is one example of the use of bank-side storage for all the water taken from the River Thames and River Lee with many large reservoirs such as Queen Mary Reservoir visible along the approach to London Heathrow Airport.

Service reservoir

Service reservoirs store fully treated potable water close to the point of distribution. Many service reservoirs are constructed as water towers, often as elevated structures on concrete pillars where the landscape is relatively flat. Other service reservoirs are entirely underground, especially in more hilly or mountainous country. In the United Kingdom, Thames Water has many underground reservoirs in London built in the 1800s by the Victorians, most of which are lined with brick. Honor Oak Reservoir, which was completed in 1909, is believed to one of the largest of this type in Europe. The roof is supported on large brick pillars and arches and the outside surface is grassed over.

Service reservoirs perform several functions including ensuring sufficient head of water in the water distribution system and providing hydraulic capacitance in the system to even out peak demand from consumers enabling the treatment plant to run at optimum efficiency. Large service reservoirs can also be managed to so that energy costs in pumping are reduced by concentrating refilling activity at times of day when power costs are low.

History

Five thousand years ago, the craters of extinct volcanoes in Arabia were used as reservoirs by farmers for their irrigation water.

Dry climate and water scarcity in India led to early development of water management techniques, including the building of a reservoir at Girnar in 3000 BC. Artificial lakes dating to the 5th century BC have been found in ancient Greece. An artificial lake in present-day Madhya Pradesh province of India, constructed in the 11th century, covered 650 square metres (7,000 sq ft).

In Sri Lanka large reservoirs have been created by ancient Sinhalese kings in order to save the water for irrigation. The famous Sri Lankan king Parākramabāhu I of Sri Lanka stated " do not let a drop of water seep into the ocean without benefiting mankind ". He created the reservoir named Parakrama Samudra(sea of King Parakrama), which has astonished archaeologists.

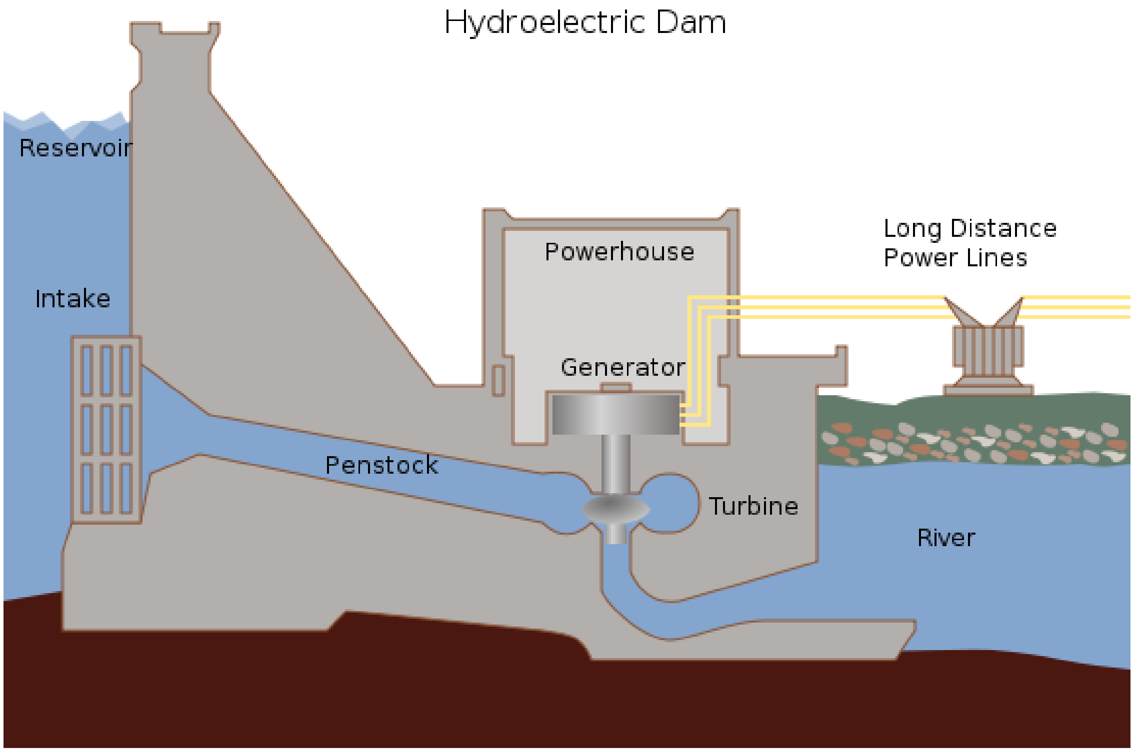
Uses

Direct water supply

Gibson Reservoir, Montana

Many dammed river reservoirs and most bank-side reservoirs are used to provide the raw water feed to a water treatment plant which delivers drinking water through water mains. The reservoir does not simply hold water until it is needed; it can also be the first part of the water treatment process. The time the water is held for before it is released is known as the *retention time*. This is a design feature that allows particles and silts to settle out, as well as time for natural biological treatment using algae, bacteria and zooplankton that naturally live within the water. However natural limnological processes in temperate climate lakes produces temperature stratification in the water body which tends to partition some elements such as manganese and phosphorus into deep, cold anoxic water during the summer months. In the autumn and winter the lake becomes fully mixed again. During drought conditions, it is sometimes necessary to draw down the cold bottom water and the elevated levels of manganese in particular can cause problems in water treatment plants.

Hydroelectricity



Hydroelectric dam in cross section.

A reservoir generating hydroelectric includes turbines connected to the retained water body by large diameter pipes. These generating sets may be at the base of the dam or some distance away. Some reservoirs generating hydro-electricity use pumped re-charge in which a high level reservoir is filled with water using high performance electric pumps at times when electricity demand is low and then uses this stored water to generate electricity by releasing the stored water into a low level reservoir when electricity demand is high. Such systems are called pump storage schemes.

Controlling watercourses

Reservoirs can be used in a number of ways to control how water flows through downstream waterways.

> **Downstream water supply** - water may be released from an upland reservoir so that it can be abstracted for drinking water lower down the system, sometimes hundred of miles further down downstream

Irrigation - water in an irrigation reservoir may be released into networks of canals for use in farmlands or secondary water systems. Irrigation may also be supported by reservoirs which maintain river flows allowing water to be abstracted for irrigation lower down the river.

Flood control - also known as an "*attenuation*" or "*balancing*" reservoir, flood control reservoirs collect water at times of very high rainfall, then release it slowly over the course of the following weeks or months. Some of these reservoirs are constructed across the river line with the onward flow controlled by an orifice plate. When river flow exceeds the capacity of the orifice plate water builds behind the dam but as soon as the flow rate reduces the water behind the dam slowly releases until the reservoir is empty again. In some cases such reservoirs only function a few times in a decade and the land behind the reservoir may be developed as community or recreational land. A new generation of balancing dams are being developed to combat the climatic consequences of climate change. They are called "Flood Detention Reservoirs". Because these reservoirs will remain dry for long periods, there may be a risk of the clay core drying out reducing its structural stability. Recent developments include the use of composite core fill made from recycled materials as an alternative to clay.

Canals - Where a natural watercourse's water is not available to be diverted into a canal, a reservoir may be built to guarantee the water level in the canal; for example, where a canal climbs to cross a range of hills through locks.

Recreational-only Kupferbach reservoir near Aachen/Germany.

Recreation - water may be released from a reservoir to artificially create or supplement white-water conditions for kayaking and other white-water sports. On salmonid rivers special releases (in Britain called *freshets*) are made to encourage natural migration behaviours in fish and to provide a variety of fishing conditions for anglers.

Flow balancing

Occasionally reservoirs are used to balance the flow in highly managed systems, taking in water during high flows and releasing it again during low flows. In order for this to work without pumping requires careful control of water levels using adjustable sluices. One example of this is Llyn Tegid in North Wales. This is a natural lake whose level was raised by a low dam and into which the River Dee flows or discharges depending upon flow conditions at the time as part of the River Dee regulation system. This mode of operation is a form of hydraulic capacitance in the river system.

Recreation

The water bodies provided by many reservoirs often allow some recreational uses such as fishing, boating, and other activities. Special rules may apply for the safety of the public and to protect the quality of the water and the ecology of the surrounding area. Many reservoirs now support and encourage less informal and less structured recreation such as natural history, bird watching, landscape painting, walking and hiking and often provide information boards and interpretation material to encourage responsible use.

Operation

Water falling as rain upstream of the reservoir together with any groundwater emerging as springs is stored in the reservoir. Any excess water can be spilled via a specifically designed spillway. Stored water may be piped by gravity for use as drinking water, to generate hydro-electricity or to maintain river flows to support downstream uses. Occasionally reservoirs can be managed to retain high rain-fall events to prevent or reduce downstream flooding. Some reservoirs support several uses and the operating rules may be complex.

Spillway of Llyn Brianne dam in Wales.

Most modern reservoirs have a specially designed draw-off tower that can discharge water from the reservoir at different levels both to access water as the reservoir draws down but also to allow water of a specific quality to be discharged into the downstream river as compensation water.

The operators of many upland or in-river reservoirs have obligations to release water into the downstream river to maintain river quality, support fisheries, maintain downstream industrial uses. maintain recreational use or for a range of other requirements. Such releases are known as *compensation water*.

Terminology

The terminology for reservoirs varies from country to country. In most of the world reservoir areas are expressed in km^2 whilst in the USA acres are commonly used. For volume either m^3 or km^3 are widely used with acre feet used in the USA.

The capacity, volume or storage of a reservoir is usually divided into distinguishable areas. *Dead* or *inactive* storage refers to water in a reservoir that cannot be drained by gravity through a dam's outlet works, spillway or power plant intake and can only be pumped out. Dead storage allows sediments to settle which improves water quality and also creates hydraulic head along with an area for fish during low levels. *Active* or *live* storage is the portion of the reservoir that can be utilized for flood control, power production, navigation and downstream releases. In addition, a reservoir's *flood control capacity* is the amount of water it can regulate during flooding. The *surcharge capacity* is the capacity of the reservoir above the spillway crest that cannot be regulated.

In the United States the water below the normal maximum level of a reservoir is called the *conservation pool*.

In the UK *top water level* describes the reservoir full state whist *fully drawn down* describes the minimum retained volume.

Modelling reservoir management

There is a wide variety of software for modelling reservoirs, from the specialist Dam Safety Program Management Tools (DSPMT) to the relatively simple WAFLEX, to integrated models like the Water Evaluation And Planning system (WEAP) that place reservoir operations in the context of system-wide demands and supplies.

Safety

In many countries large reservoirs are closely regulated to try and prevent or minimise failures of containment.

Whilst much of the effort is directed at the dam and its associated structures as the weakest part of the overall structure, the aim of such controls is to prevent an uncontrolled release of water from the reservoir. Reservoir failures can generate huge increases in flow down a river valley with the potential to wash away towns and villages and cause considerable loss of life such as the devastation following the failure of containment at Llyn Eigiau which killed 17 people.

A notable case of reservoirs being used as an instrument of War involved the British Royal Air Force Dambusters raid on Germany in World War II (codenamed "Operation Chastise"), in which three German reservoir dams were selected to be breached in order to impact on German infrastructure and manufacturing and power capabilities deriving from the Ruhr and Eder rivers. The economic and social impact was derived from the enormous volumes of previously stored water that swept down the valleys wreaking destruction. This raid later became the basis for several films.

Environmental impact

Whole life environmental impact

All reservoirs will have a monetary cost/benefit assessment made before construction to see if the project is worth proceeding with. However, such analysis can often omit the environmental impacts of dams and the reservoirs that they contain. Some impacts such as the greenhouse gas production associated with concrete manufacture are relatively easy to estimate. Other impact on the natural environment and social and cultural effects can be more difficult to assess and to weigh in the balance but identification and quantification of these issues are now commonly required in major construction projects in the developed world

Climate change

Depending upon the circumstances, a reservoir built for hydro-electricity generation can either reduce or increase the net production of greenhouse gases. An **increase** can occur if plant material in the flooded areas decays in an anaerobic environment releasing (methane and carbon dioxide). This apparently counter intuitive position arises because much carbon is released as methane which is approximately 8 time more potent as a greenhouse gas than carbon dioxide

A study for the National Institute for Research in the Amazon found that Hydroelectric reservoirs release a large pulse of carbon dioxide from above-water decay of trees left standing in the reservoirs, especially during the first decade after closing. This elevates the global warming impact of the dams to levels much higher than would occur by generating the same power from fossil fuels. According to the World Commission on Dams report (Dams And Development), when the reservoir is relatively large and no prior clearing of forest in the flooded area was undertaken, greenhouse gas emissions from the reservoir could be higher than those of a conventional oil-fired thermal generation plant. For instance, In 1990, the impoundment behind the Balbina Dam in Brazil(inaugurated in 1987) had over 20 times the impact on global warming than would generating the same power from fossil fuels, due to the large area flooded per unit of electricity generated.

A **decrease** can occur if the dam is used in place of traditional power generation, since electricity produced from hydroelectric generation does not give rise to any flue gas emissions from fossil fuel combustion (including sulfur dioxide, nitric oxide and carbon monoxide from coal). The Tucurui dam in Brazil (closed in 1984) had only 0.4 times the impact on global warming than would generating the same power from fossil fuels.

Biology

Dams can produce a block for migrating fish, trapping them in one area, producing food and a habitat for various water-birds. They can also flood various ecosystems on land and may cause extinctions.

Human Impact

Dams can severely reduce the amount of water from reaching countries downstream of them, causing water stress between the countries, e.g. the Sudan and Egypt, which damages farming businesses in the downstream countries, and reduces drinking water.

Farms and villages, e.g. Ashopton can be flooded by the creation of reservoirs, ruining many livelihoods. For this very reason, worldwide 80 million people have had to be forcibly relocated due to dam construction.

Limnology

The limnology of reservoirs has many similarities to that of lakes of equivalent size. There are however significant differences. Many reservoirs experience considerable variations in level producing significant areas that are intermittently underwater or dried out. This greatly limits the productivity or the water margins and limits the number of species able to survive in these conditions.

Upland reservoirs tend to have a much shorter residence time than natural lakes and this can lead to more rapid cycling of nutrients through the water body so that they are more quickly lost to the system. This may be seen as a mismatch between water chemistry and water biology with a tendency for the biological component to be more oligotrophic than the chemistry would suggest.

Conversely, lowland reservoirs drawing water from nutrient rich rivers, may show exaggerated eutrophic characteristics because the residence time in the reservoir is much greater than in the river and the biological systems have a much greater opportunity to utilise the available nutrients.

Deep reservoirs with multiple level draw off towers can discharge deep cold water into the downstream river greatly reducing the size of any hypolimnion. This in turn can reduce the concentrations of phosphorus released during any annual mixing event and may therefore reduce productivity.

The Dams in front of reservoirs act as knickpoints-the energy of the water falling from them reduces and deposition is a result below the Dams.

Earthquakes

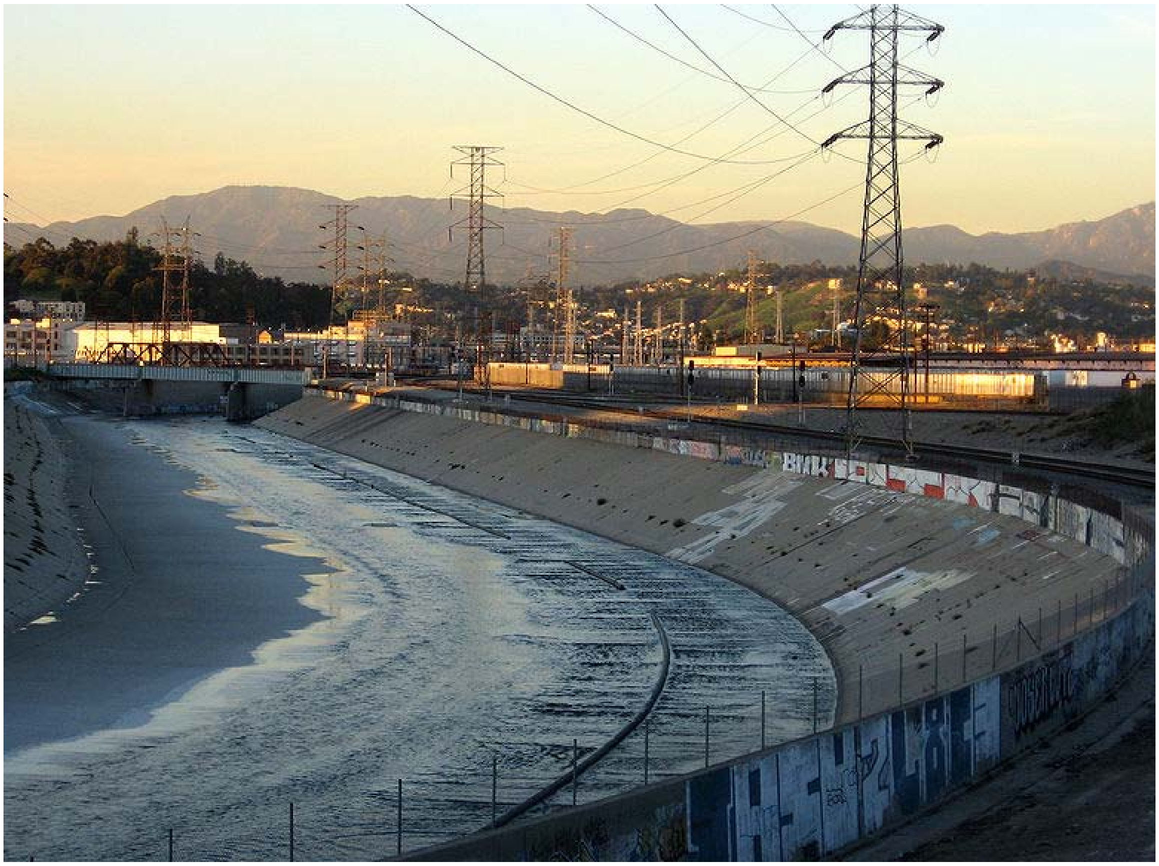
Large reservoirs have been indicated as contributing to earthquakes, due to changes in loading and/or the height of the water table.

Micro climate

Reservoirs may change the local micro-climate increasing humidity and reducing extremes of temperature. Such effects are claimed by some South Australian winerys as increasing the quality of the wine production.

Chapter 10

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 11

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.

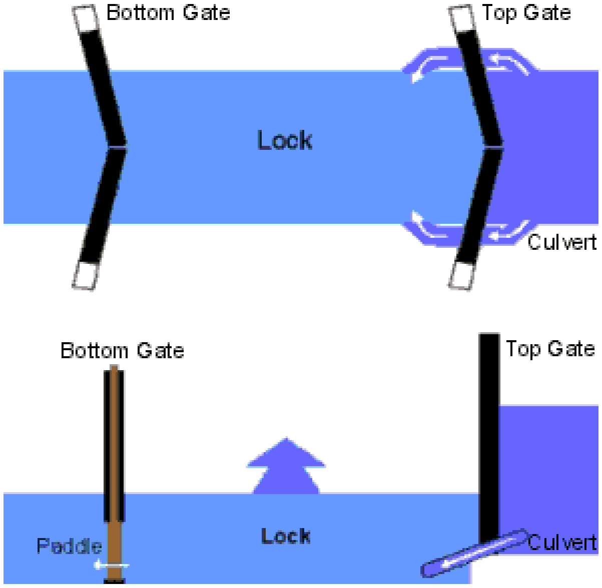
- Where a longer cut bypasses a circuitous stretch of river, the upstream end of the cut will often be protected by a *flood lock*.
- The longer the cut, the greater the difference in river level between start and end of the cut, so that a very long cut will need additional locks along its length. At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

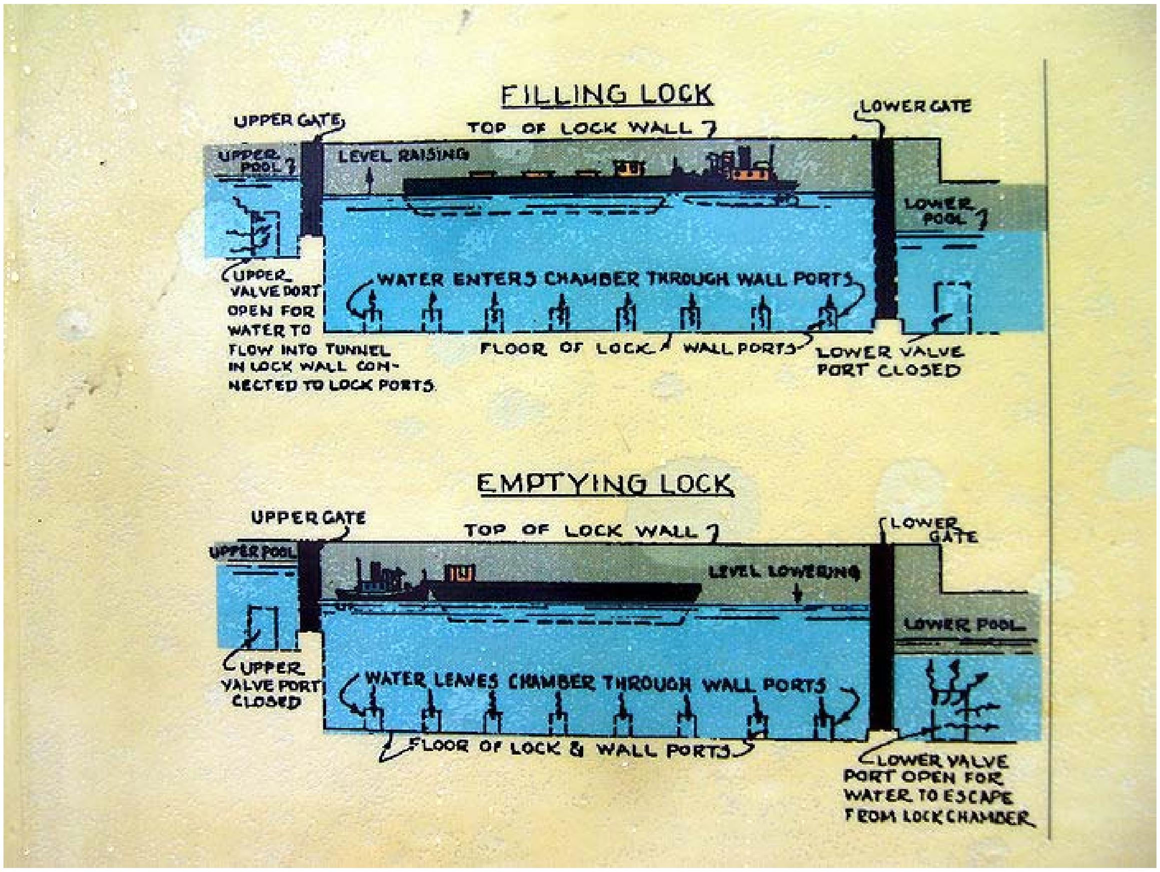
The principle of operating a lock is simple. For instance, if a boat travelling downstream finds the lock already full of water:

- 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

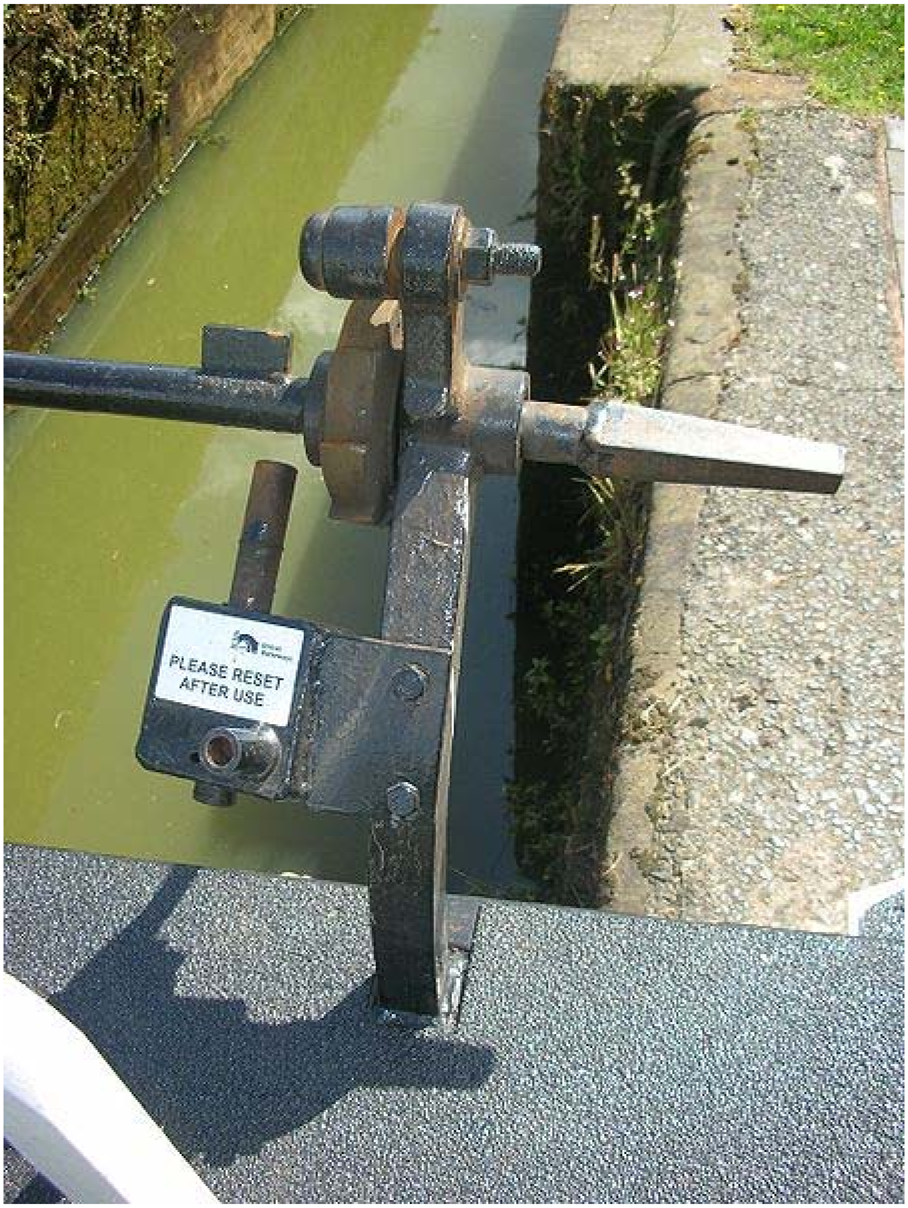
The main feature of a lock. It is a watertight (masonry, brick, steel or concrete) enclosure which can be sealed off from the pounds at either end by means of *gates*. The chamber may be the same size (plus a little manoeuvring room) as the largest vessel for which the waterway was designed; sometimes 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

How to use Bratch Locks

Bratch Locks are a flight, not a staircase. Before you enter the locks please make sure no one has already started from the opposite direction.

Going up the flight

1. Enter bottom lock.
2. Start to fill bottom lock using Blue paddles.
3. At the same time open Red paddles on middle lock. Do not open any gates until water levels have equalised.
4. Repeat procedure to move boat from middle lock to top lock.

Water will enter and leave the side pounds automatically. During heavy usage craft will be worked three up and three down in rotation. This saves time.

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

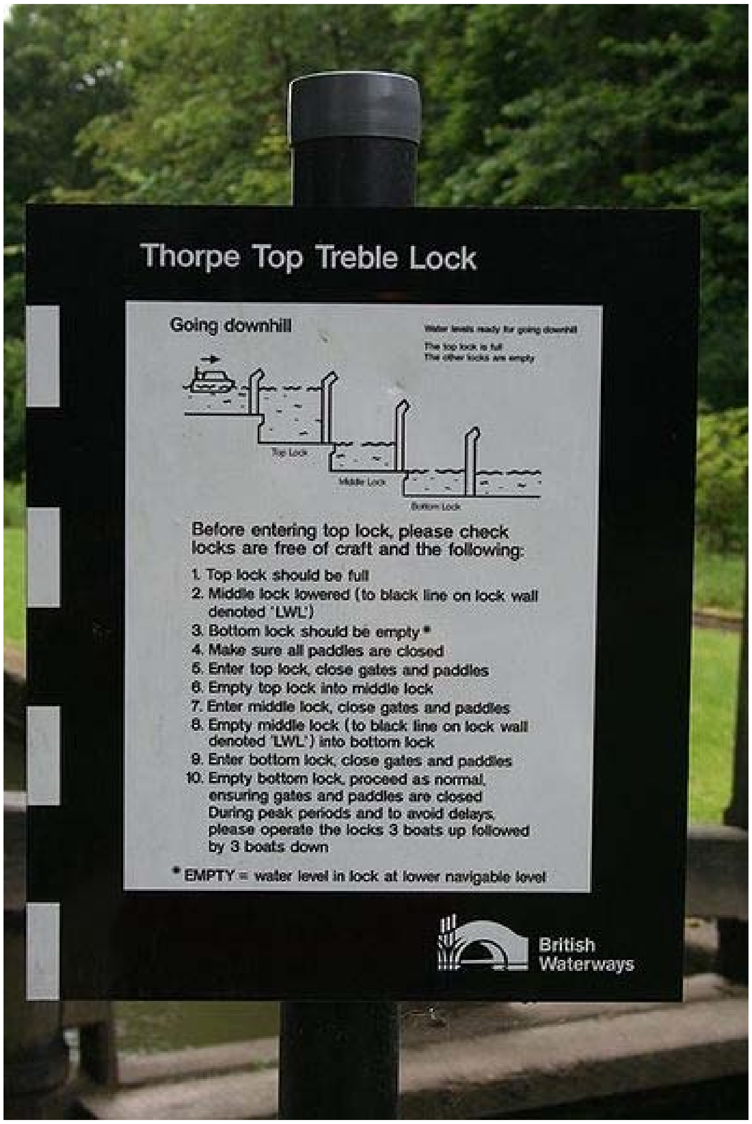
Staircase of five locks, dating from 1774, at Bingley, England

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 Driffield 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.



Thorpe Top Treble Lock

Going downhill

Water levels ready for going downhill
The top lock is full
The other locks are empty

Before entering top lock, please check locks are free of craft and the following:

1. Top lock should be full
2. Middle lock lowered (to black line on lock wall denoted 'LWL')
3. Bottom lock should be empty*
4. Make sure all paddles are closed
5. Enter top lock, close gates and paddles
6. Empty top lock into middle lock
7. Enter middle lock, close gates and paddles
8. Empty middle lock (to black line on lock wall denoted 'LWL') into bottom lock
9. Enter bottom lock, close gates and paddles
10. Empty bottom lock, proceed as normal, ensuring gates and paddles are closed
During peak periods and to avoid delays, please operate the locks 3 boats up followed by 3 boats down

* EMPTY = water level in lock at lower navigable level

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

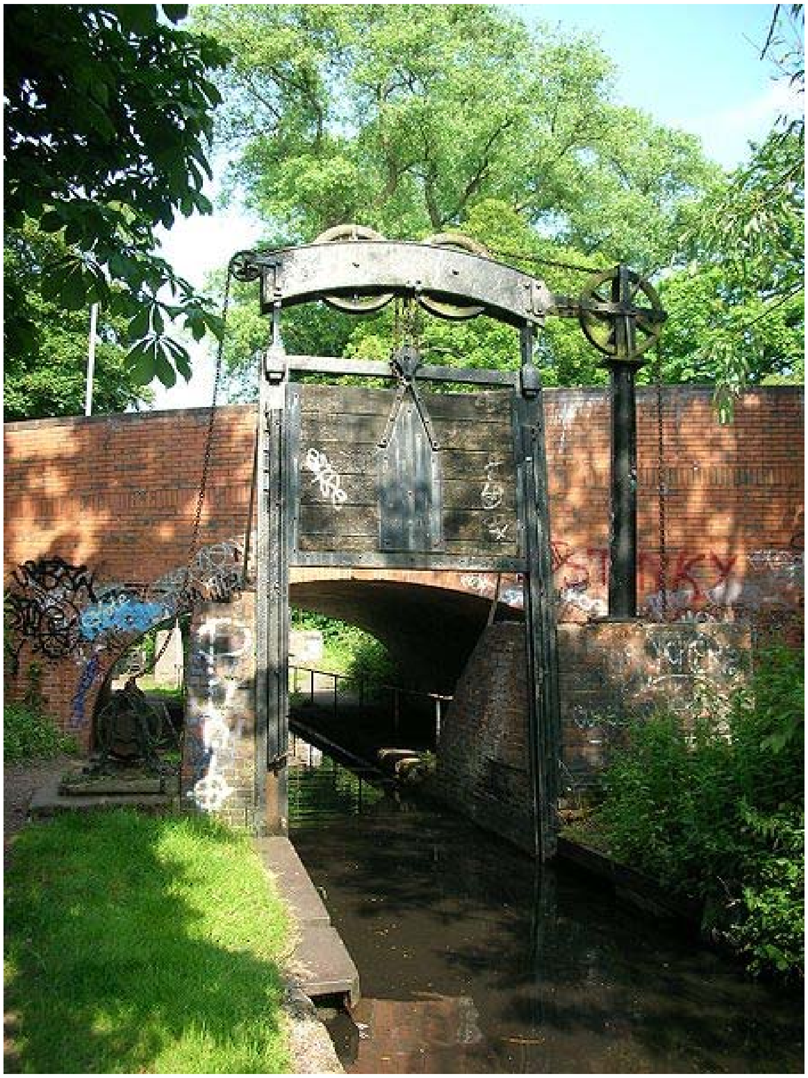
Locks can be built in parallel (i.e. side by side). This can be called *doubling, pairing, or twinning*. There are several examples (in this case called "double locks") on the Trent and Mersey Canal north of Harecastle Tunnel. Doubling gives advantages in speed: avoiding hold-ups at busy times; or increasing 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 transshipped 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 Autherley 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 supples 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 Staunch 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".

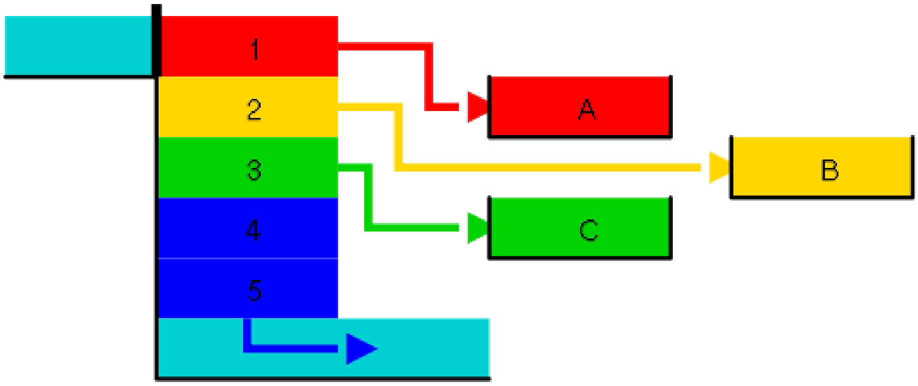


Diagram of water saving basins (descending)

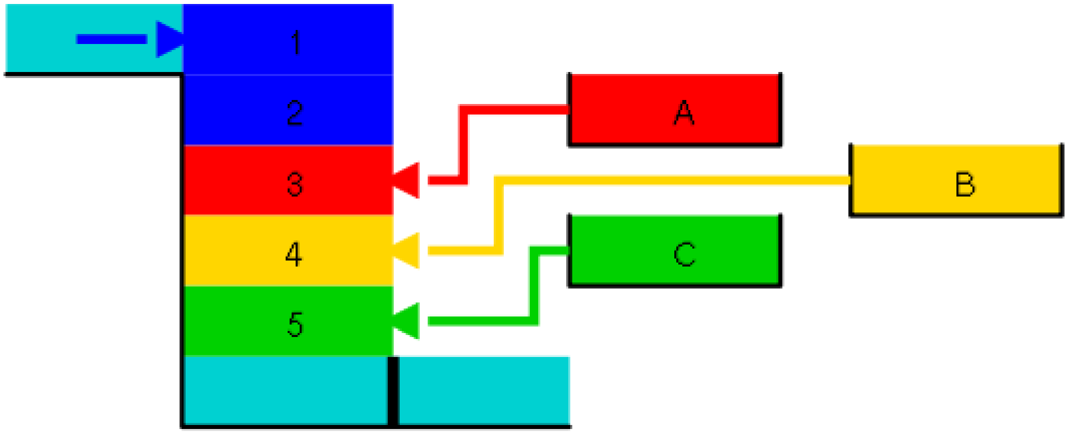
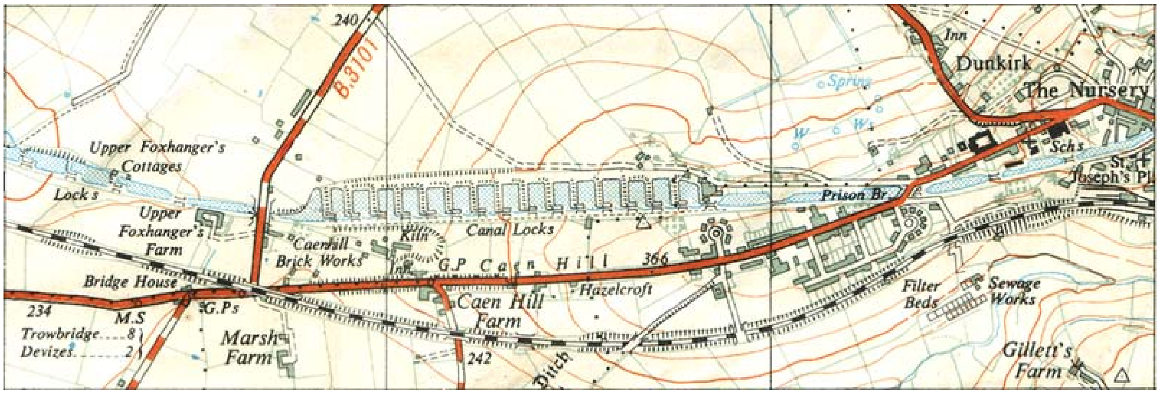


Diagram of water saving basins (ascending)

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 pounds 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 pounds, the pounds are extended sideways — in effect to provide a reservoir to ensure that the pound 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.

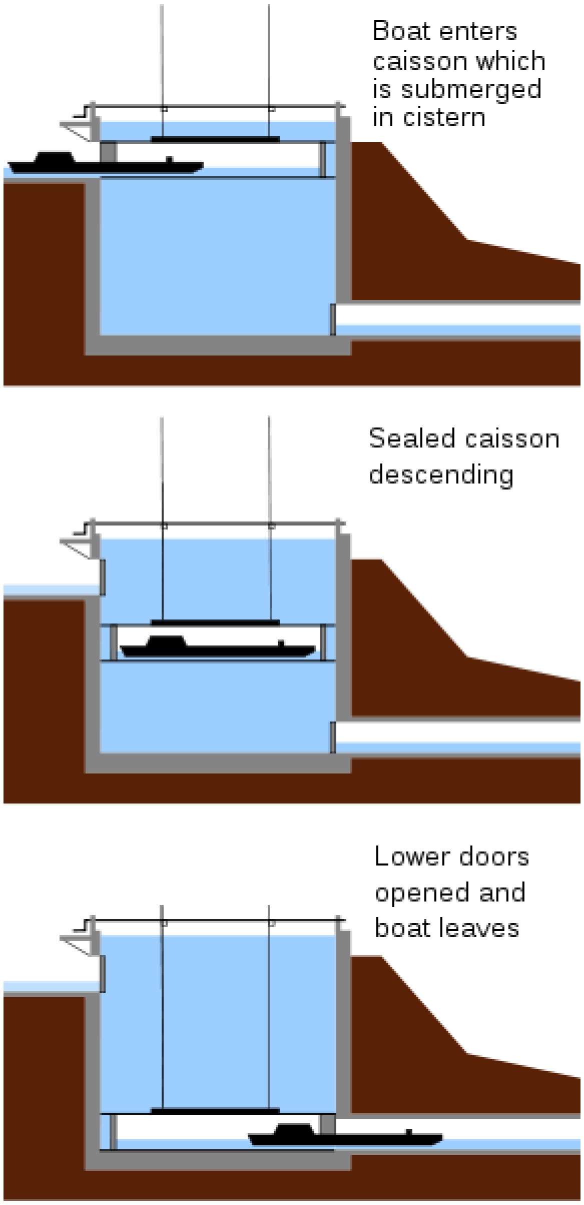
The Victorian Anderton Boat Lift, the world's first vertical boat lift, linking the Trent and Mersey Canal and the River Weaver in Cheshire, has recently been restored. The world's highest boat lift of Strépy-Thieu in Belgium raises or lowers 1,350 tonnes boats by 73.15 metres.

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.

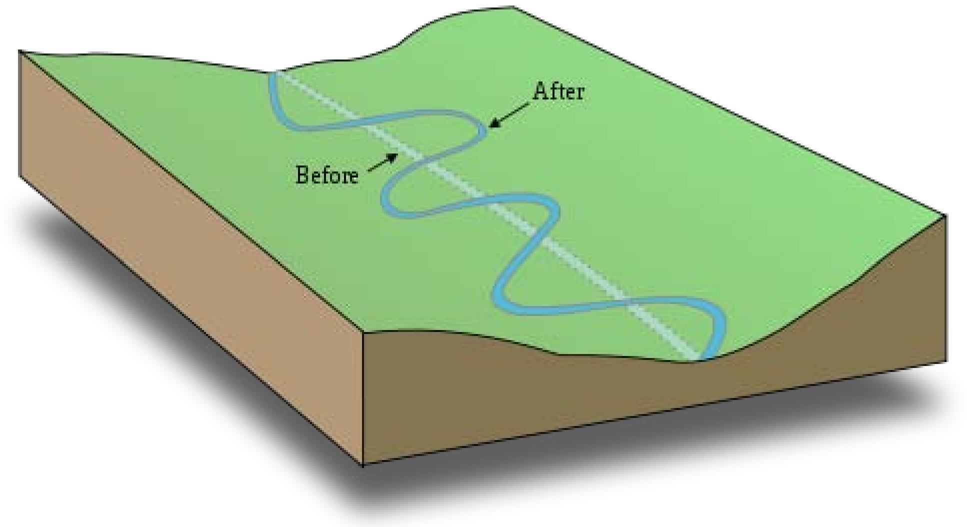
Ship sizes named after locks

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 12

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.

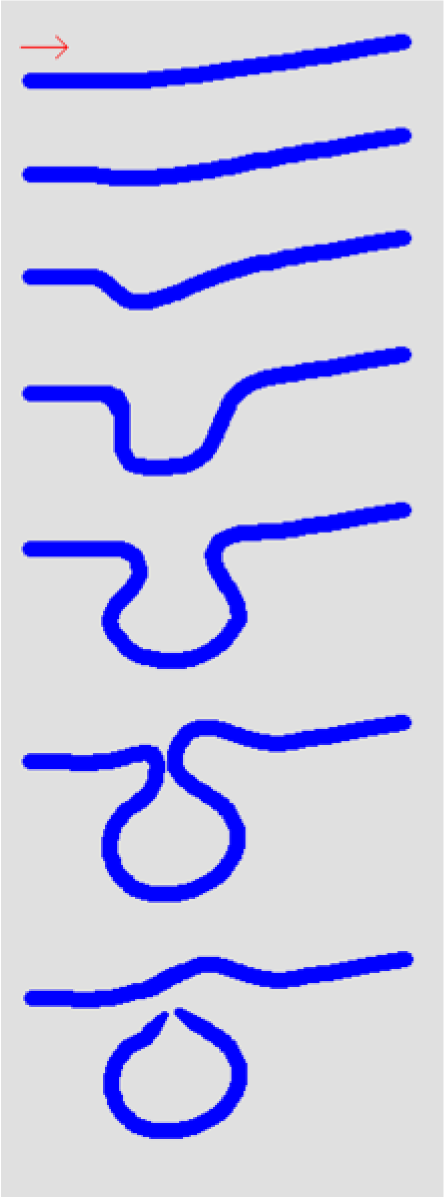
Various mathematical formulae relate the variables of the meander geometry. As it turns out some numerical parameters can be established, which appear in the formulae. The waveform depends ultimately on the characteristics of the flow but the parameters are independent of it and apparently are caused 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

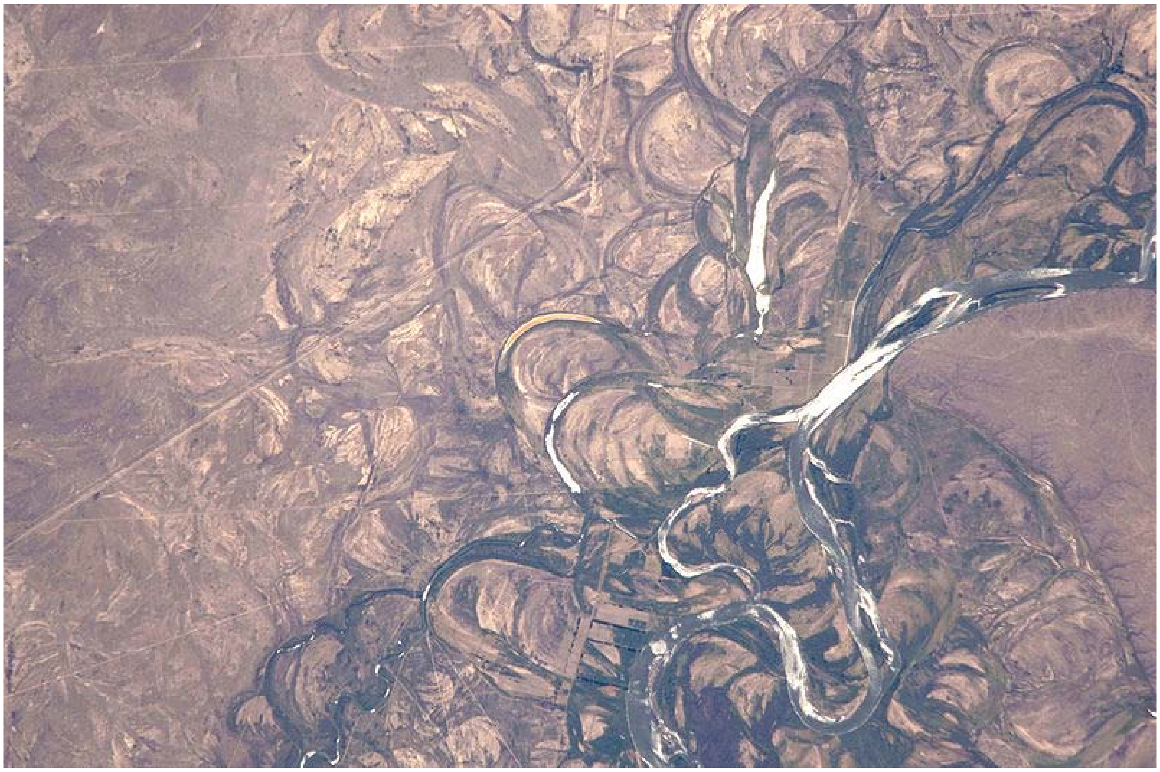
A meander has a depth pattern as well. The cross-overs are marked by riffles, or shallow beds, while at the apices are pools. In a pool direction of flow is downward, scouring the bed material. The major volume, however, flows more slowly on the inside of the bend where, due to decreased velocity, it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

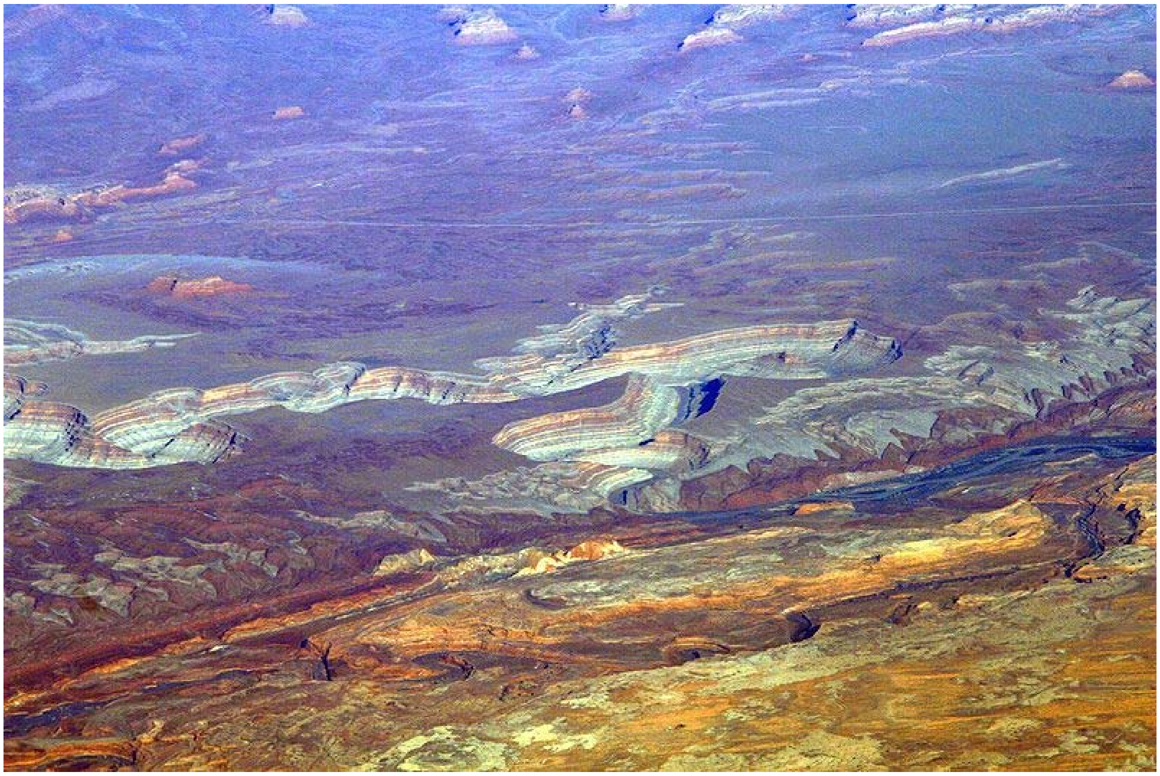
Most meanders occur in the region of a river channel with shallow gradients, a well-developed floodplain, and cohesive floodplain material. Deposition of sediment occurs on the inner edge, because the secondary flow of the river sweeps and rolls sand, rocks and other submerged objects across the bed 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.

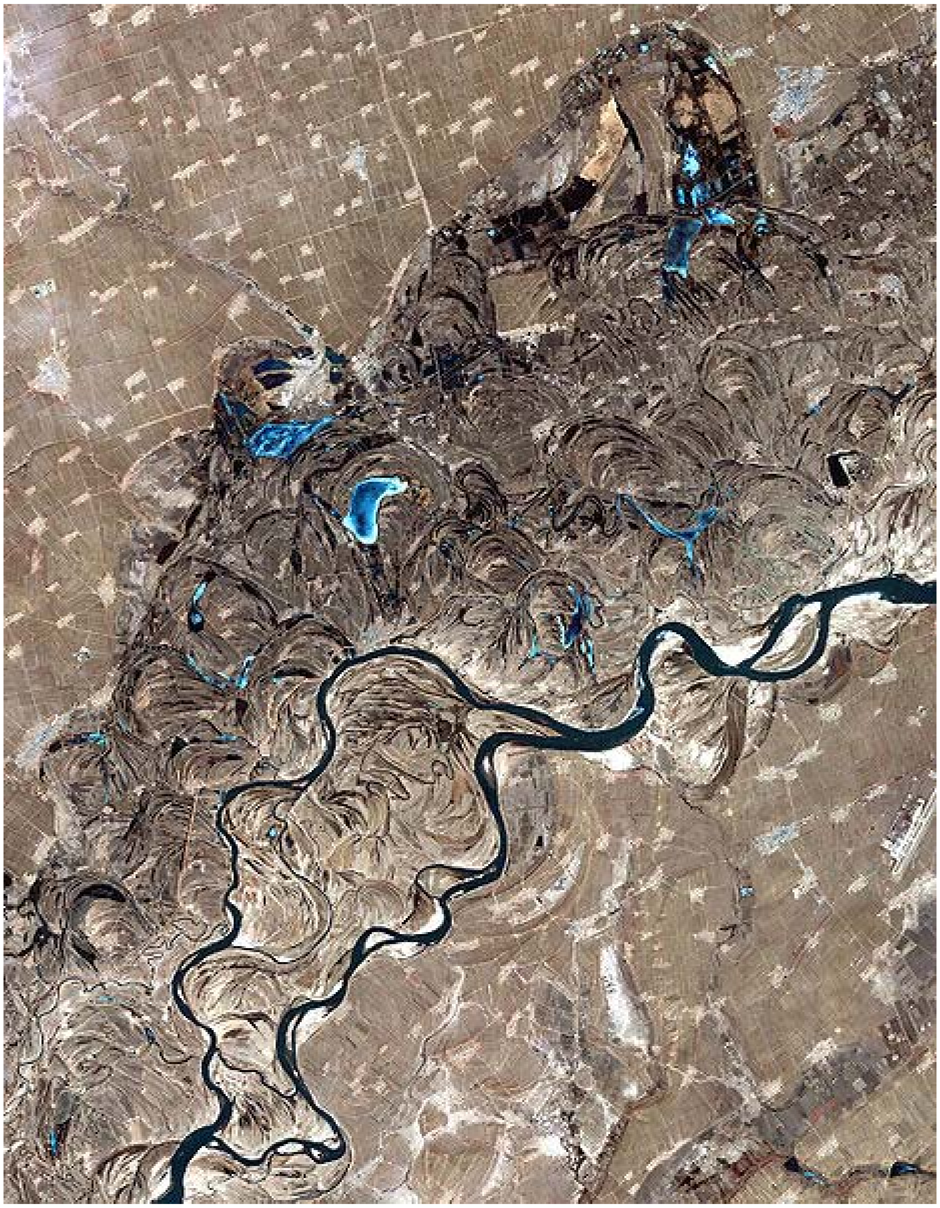
Oxbow lakes

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 is 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.

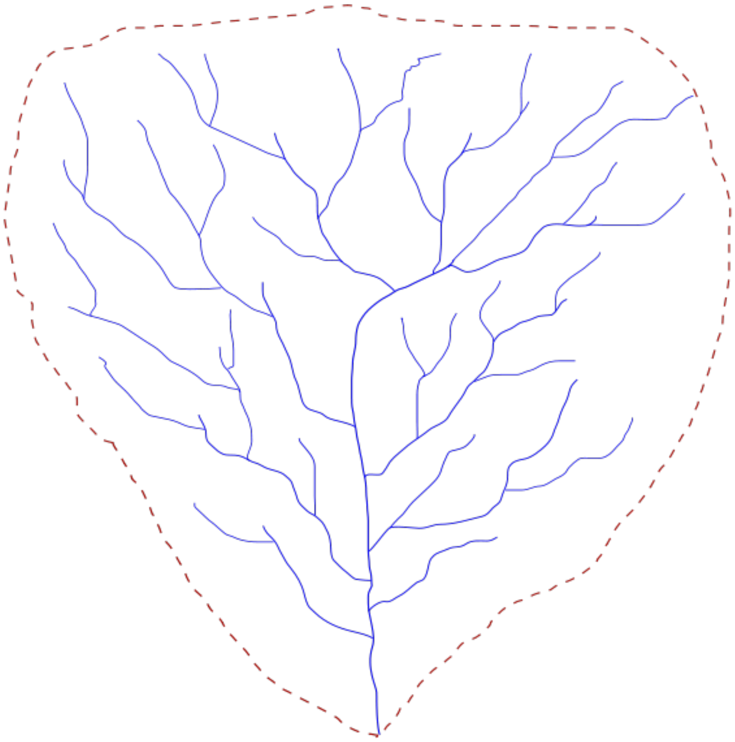
Sinuosity indices are calculated from the map or from an aerial photograph measured over a distance called the reach, which should be at least 20 times the average fullbank channel width. The length of the stream is measured by channel, or thalweg, length over the reach, while the bottom value of the 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 13

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.

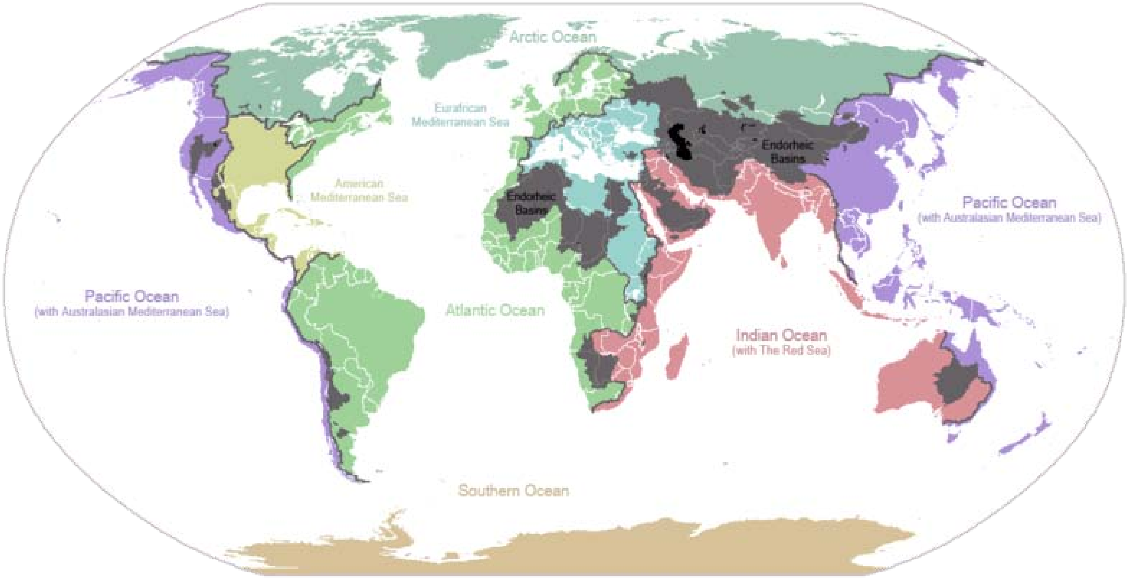
Other terms that are used to describe a drainage basin are **catchment**, **catchment area**, **catchment basin**, **drainage area**, **river basin**, **water basin** and **watershed**. In the technical sense, a watershed refers to a divide that separates one drainage area from another drainage area. 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 14

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.* - Gooseberies and Currants
- *Rosa pisocarpa* - Swamp Rose or Cluster Rose
- *Symphoricarpos albus* - Snowberry
- *Spirea 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
- *Leptospernum 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.

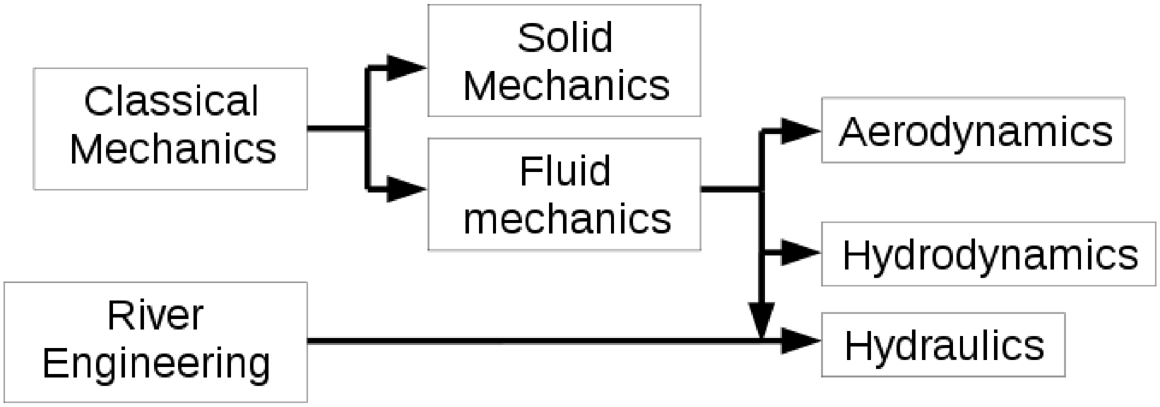
The Natural Sequence Farming technique involves placing obstacles in the water's pathway to lessen the energy of a flood, and help the water to deposit soil and seep into the flood zone. Another technique is to encourage fast growing plants such as "weeds" to grow, as these can quickly stabilize the 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 15

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 *ὑδραυλικός* (*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 16

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 $Re_p *$.

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

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

Particle Reynolds Number

In general, a particle Reynolds Number has the form:

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

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

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

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

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

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

$\kappa = 0.407$.

The particle Reynolds number is therefore given by:

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

Bed shear stress

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

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

which solves the right-hand side of the equation

$\tau_b * = \tau_c *$.

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

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

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

Depth-slope product

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

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

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

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

Shear velocity, velocity, and friction factor

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

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

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

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

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

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

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

Unsteady flow

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

Solution

Set-up

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

$$\tau_b{}^* = \tau_c{}^* .$$

In this equation,

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

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

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

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

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

Solution

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

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

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

Moving and re-combining the terms, we obtain:

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

where R is the submerged specific gravity of the sediment.

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

$$\tau_c * = 0.06.$$

Later researchers have shown that this value is closer to

$$\tau_c * = 0.03$$

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

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

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 downtream in the form of wash load.

Rouse number

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

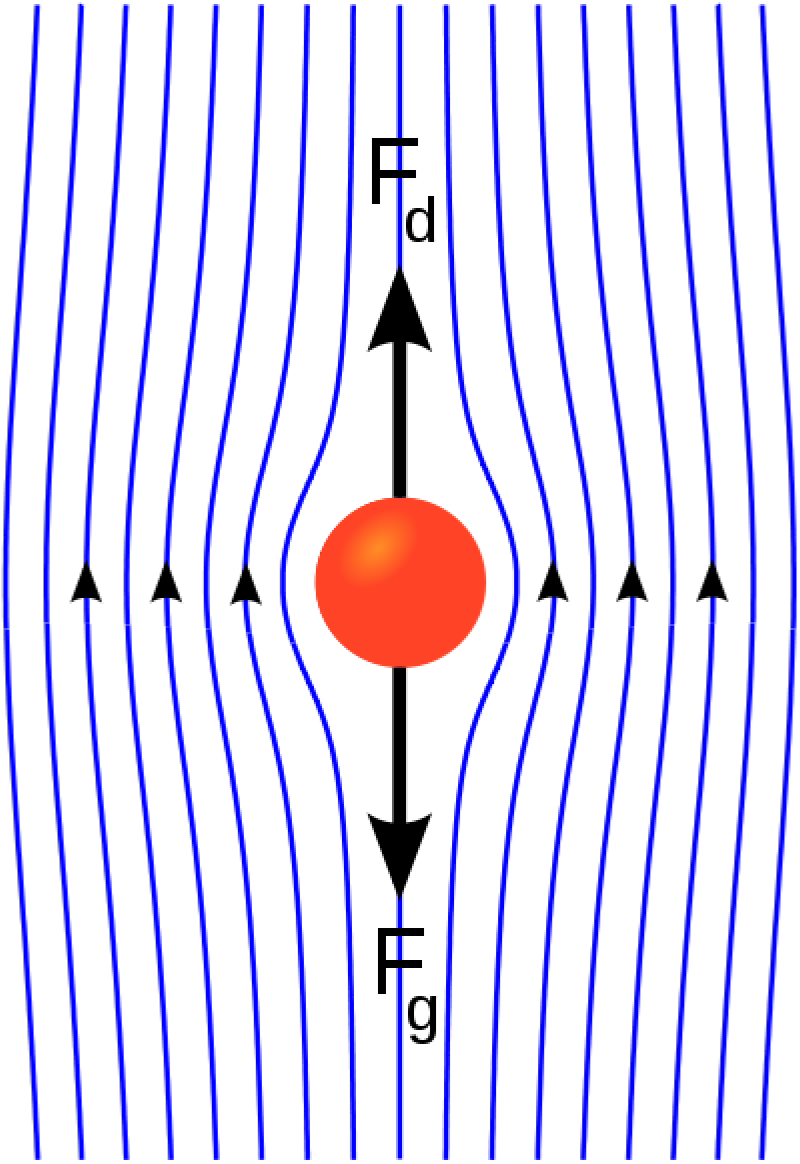
$$P = \frac{w_s}{\kappa u_*}$$

Here, the Rouse number is given by P. The term in the numerator is the (downwards) sediment the sendiment settling velocity w_s, which is discussed below. The upwards velocity on the grain is given as a product of the von Kármán constant, $\kappa = 0.4$, 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 x 10^{-6} m^2/s for water at 20°C.

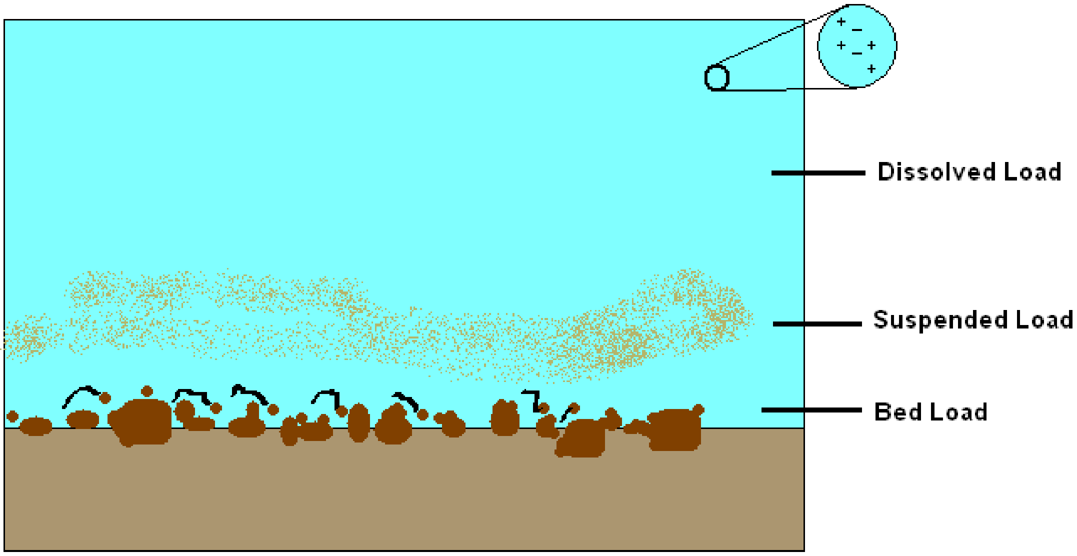
C_1 and C_2 are constants related to the shape and smoothness of the grains.

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

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

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

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

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

Their formula reads:

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

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

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

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

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

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

Wilcock and Crowe

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

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

The "hiding function" takes into account the fact that, while small grains are inheriently 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 $\varphi < 1.35$:

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

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:

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

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.