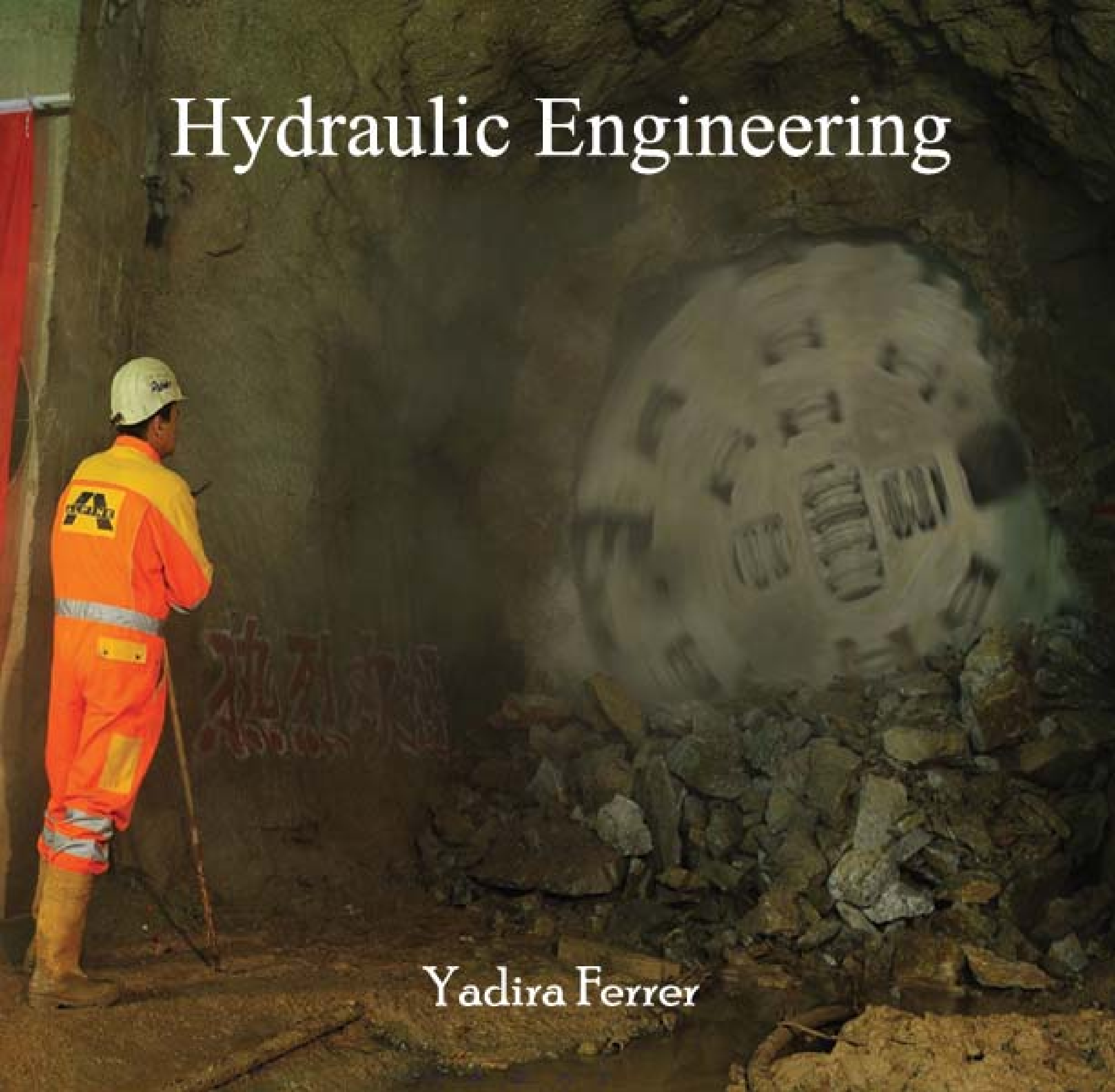

Hydraulic Engineering

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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.

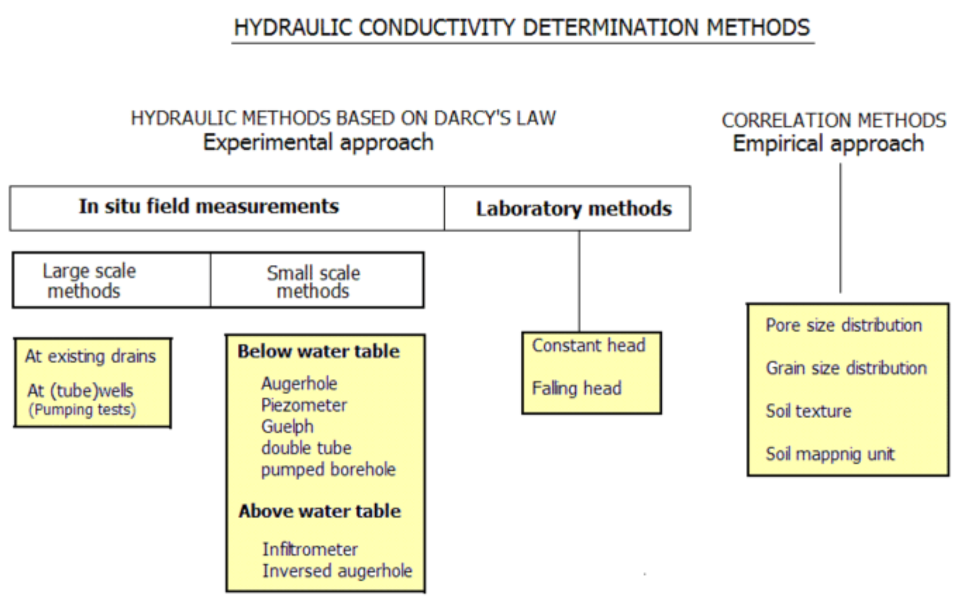
The modern hydraulic engineer uses the same kinds of computer-aided design (CAD) tools as many of the other engineering disciplines while also making use of technologies like computational fluid dynamics to perform the calculations to accurately predict flow characteristics, GPS mapping to assist in 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.

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

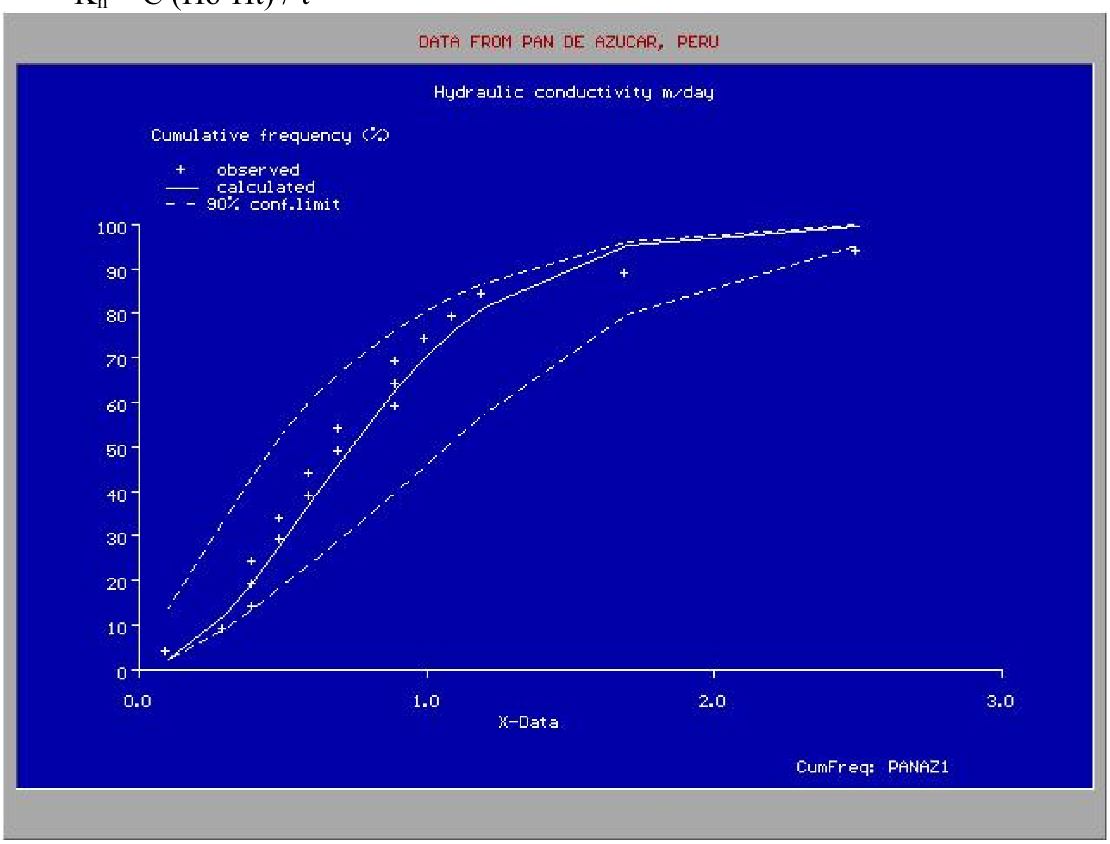
In-situ (field) methods

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

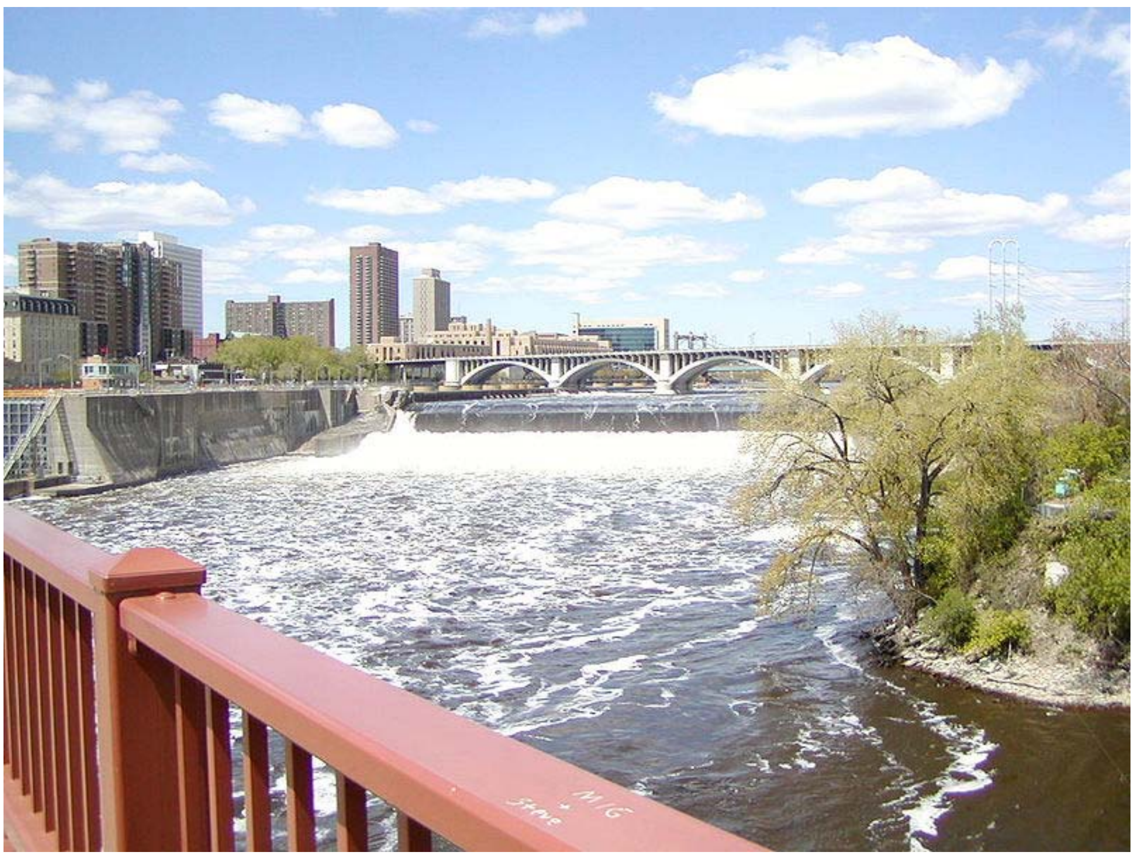
Table of saturated hydraulic conductivity (*K*) values found in nature

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.

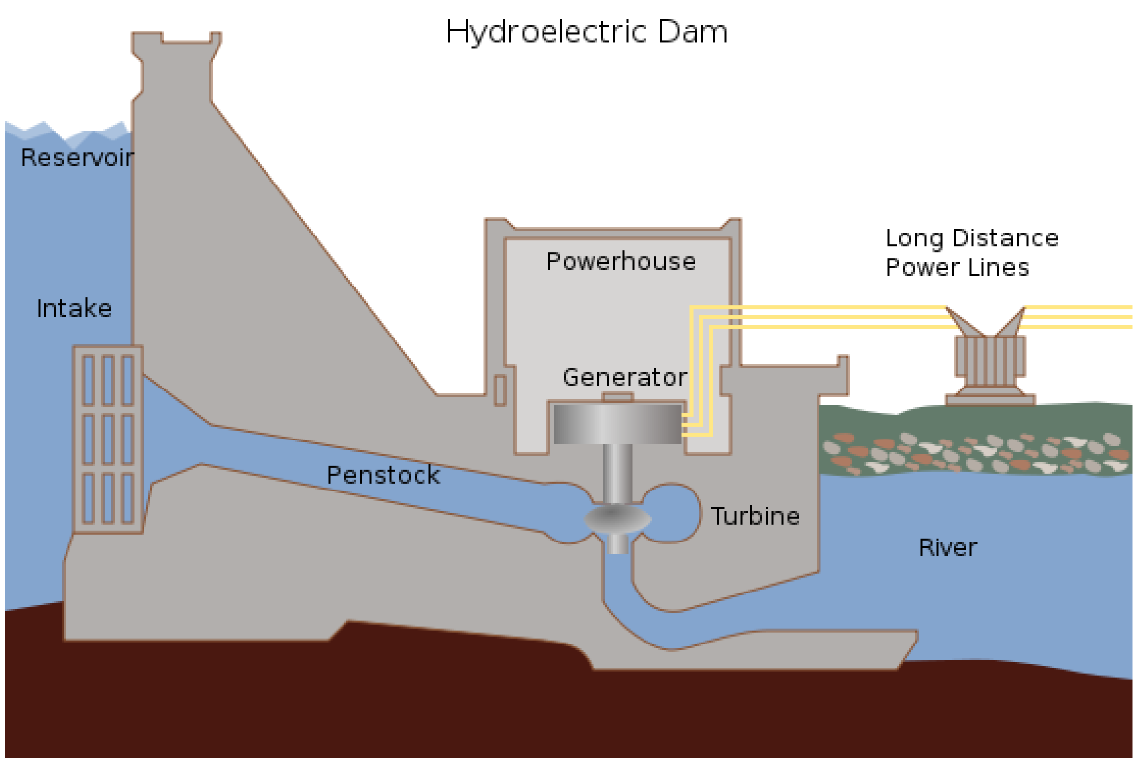
Compressed air hydro

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

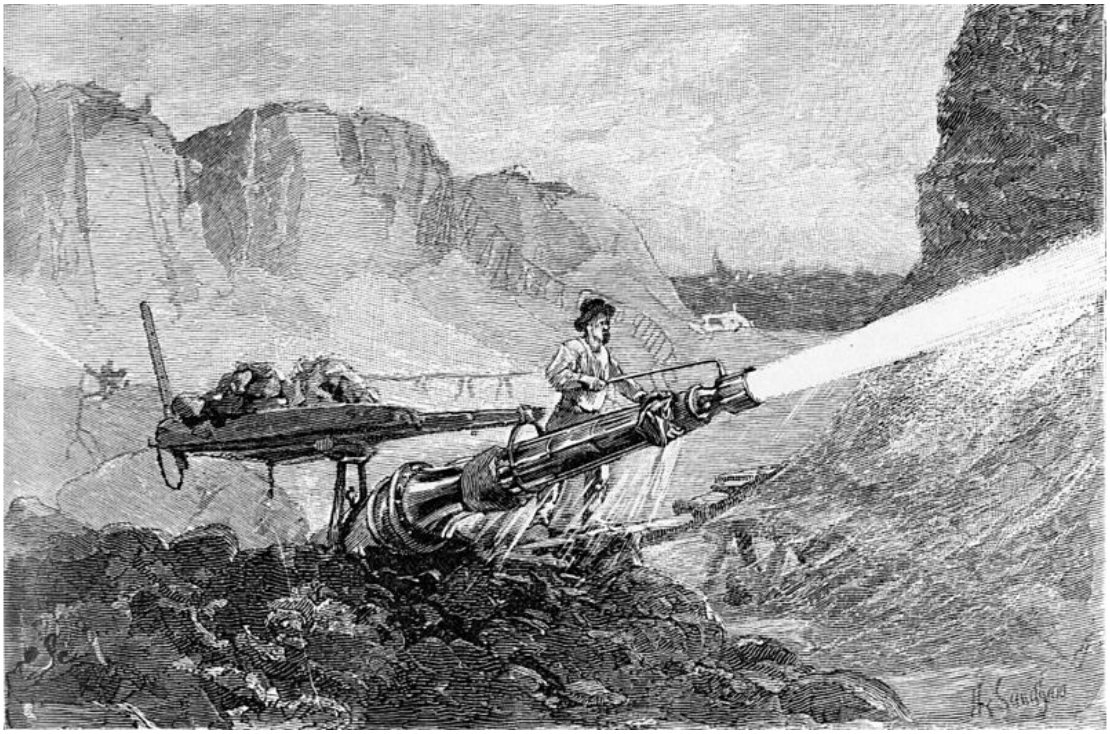
Hydraulicking had its precursor in the millennia-old practice of ground sluicing, also known as "hushing", in which surface streams of water were diverted so as to erode gold-bearing gravels. The Romans used ground sluicing to remove overburden and then gold-bearing debris in Las Médulas of Spain, and 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.

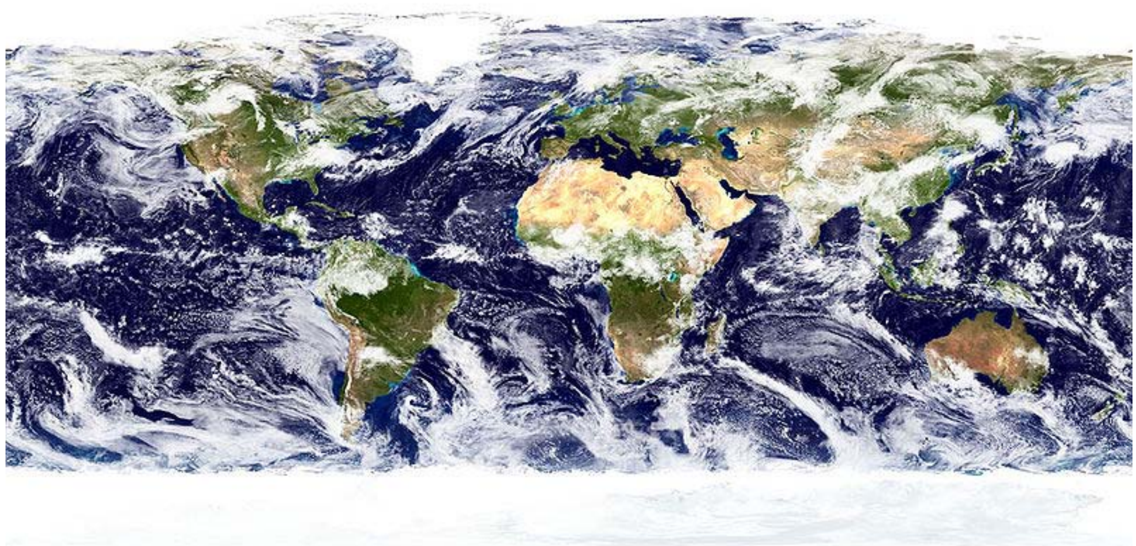
In addition to its use in true mining, hydraulic mining can be used as an excavation technique, principally to demolish hills. For example, the Denny Regrade in Seattle was largely accomplished by hydraulic mining.

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

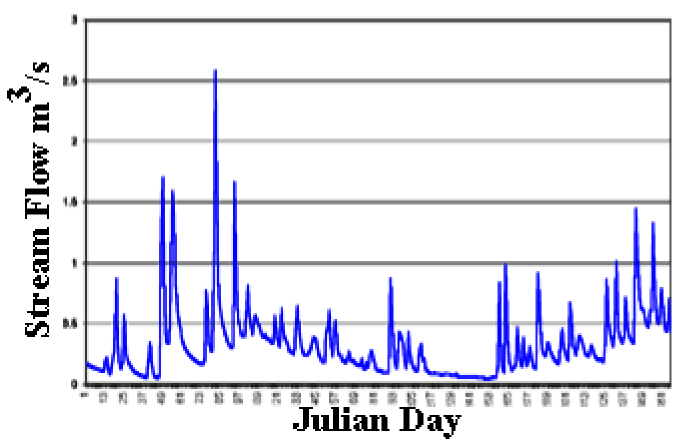
Water movement is a significant means by which other material, such as soil or pollutants, are transported from place to place. Initial input to receiving waters may arise from a point source discharge or a line source or area source, such as surface runoff. Since the 1960s rather complex mathematical 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)

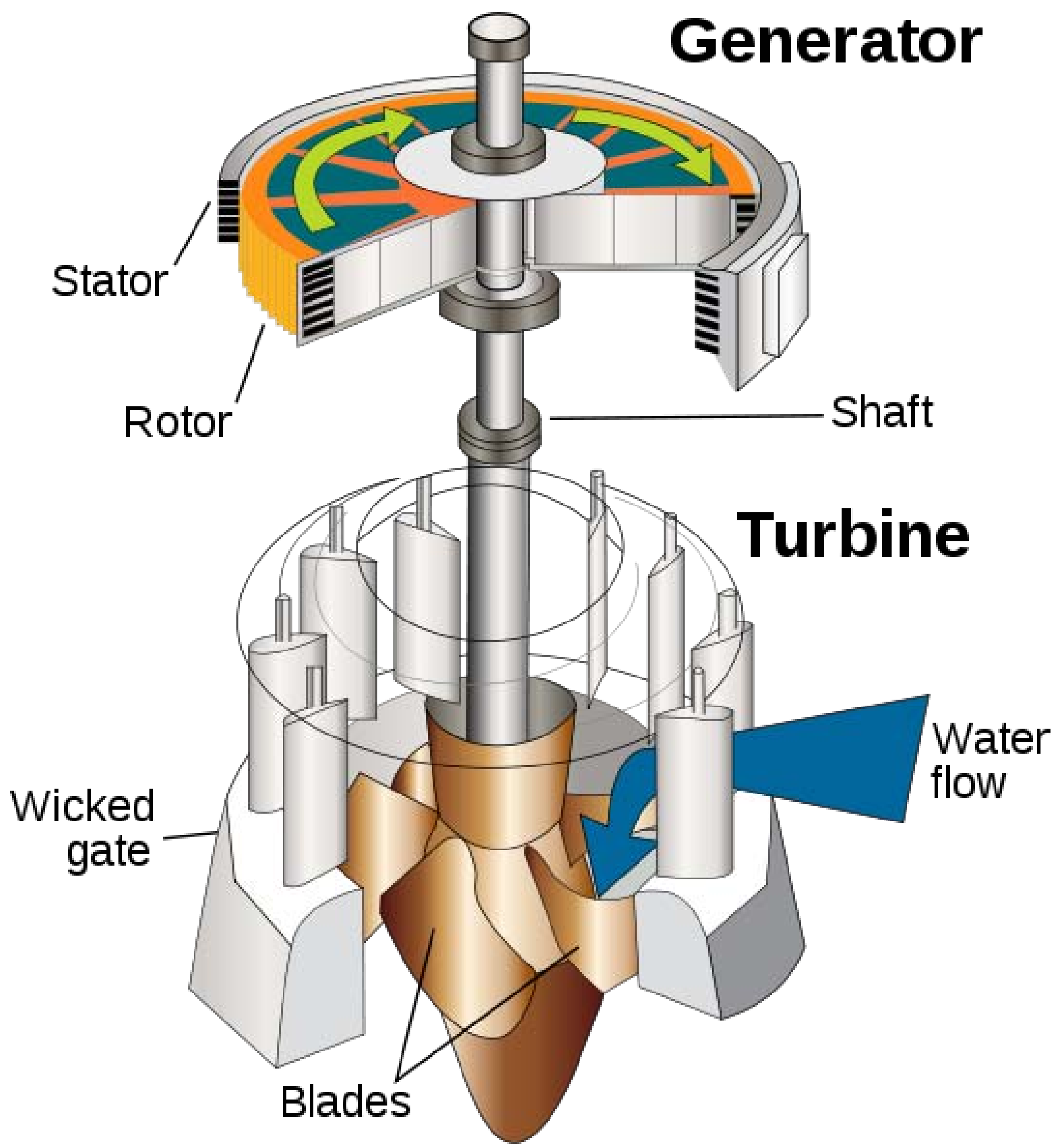
Subsurface hydrology hydrograph

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.

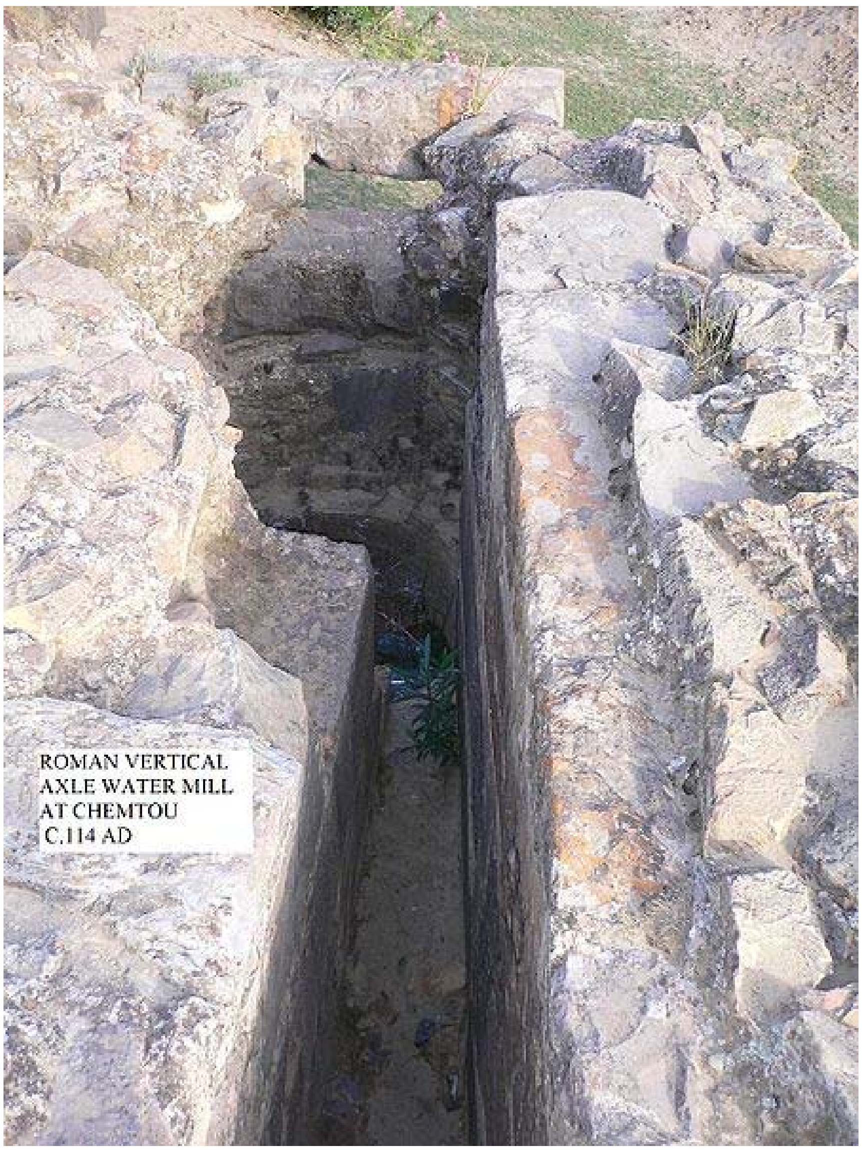
History

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.

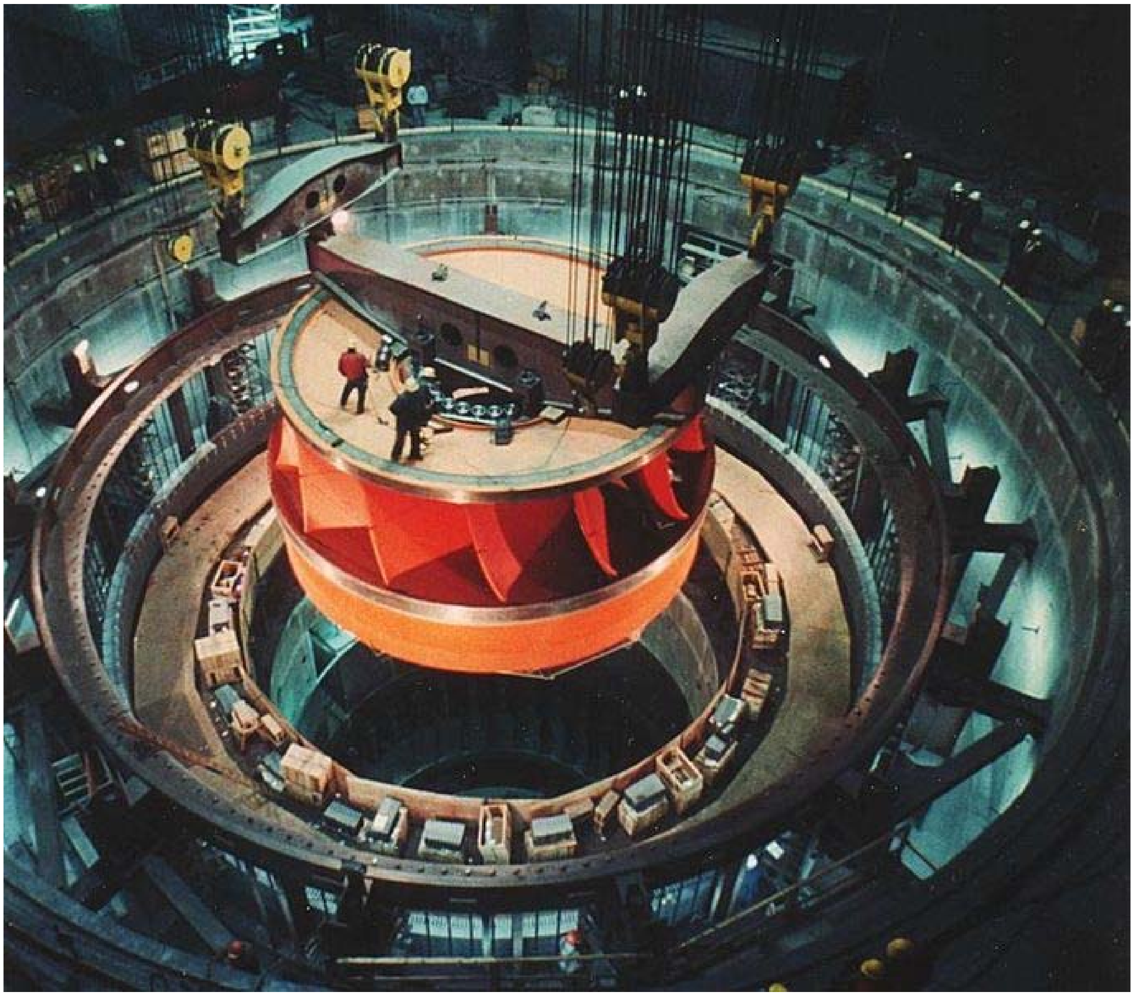
Swirl

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

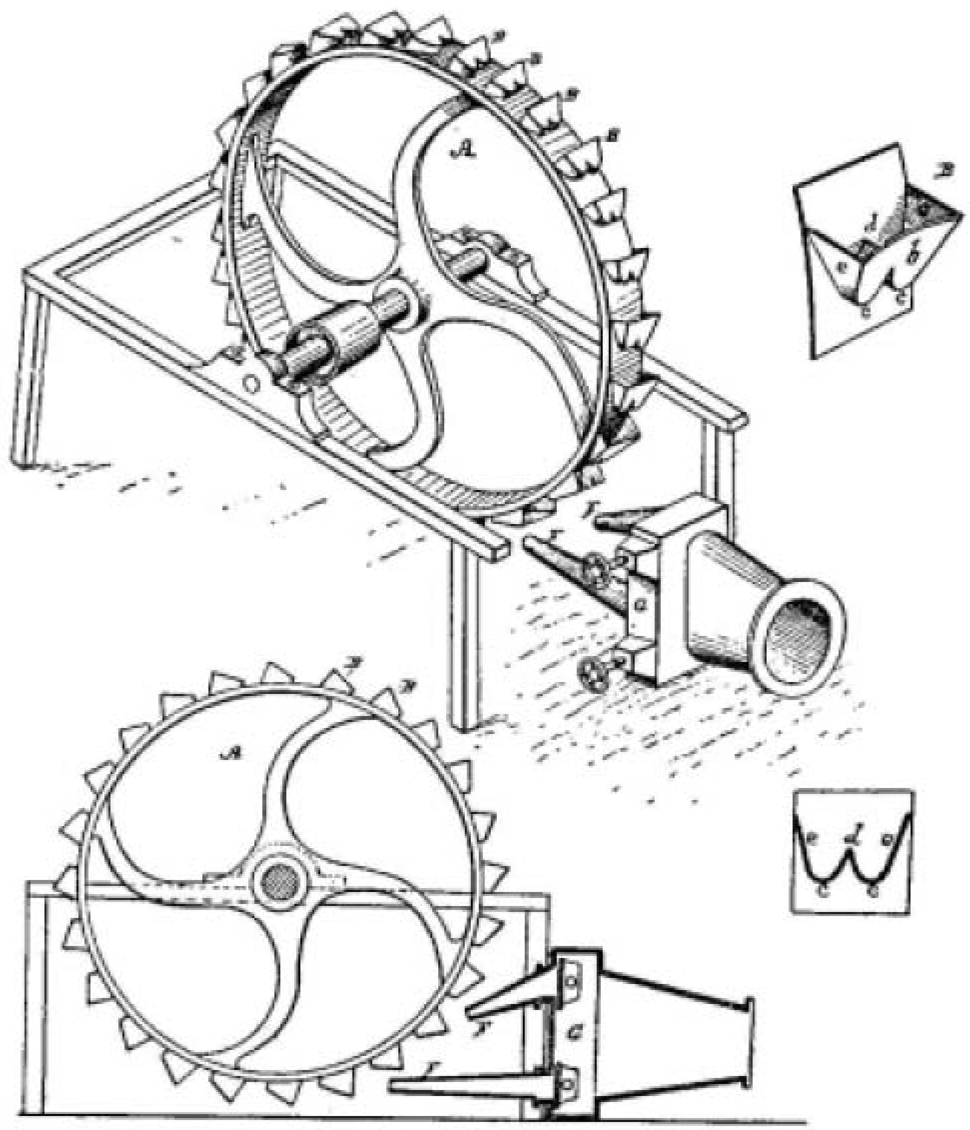


Figure from Pelton's original patent (October 1880)

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/m^3)
- g = acceleration of gravity (9.81 m/s^2)
- 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 (m^3/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

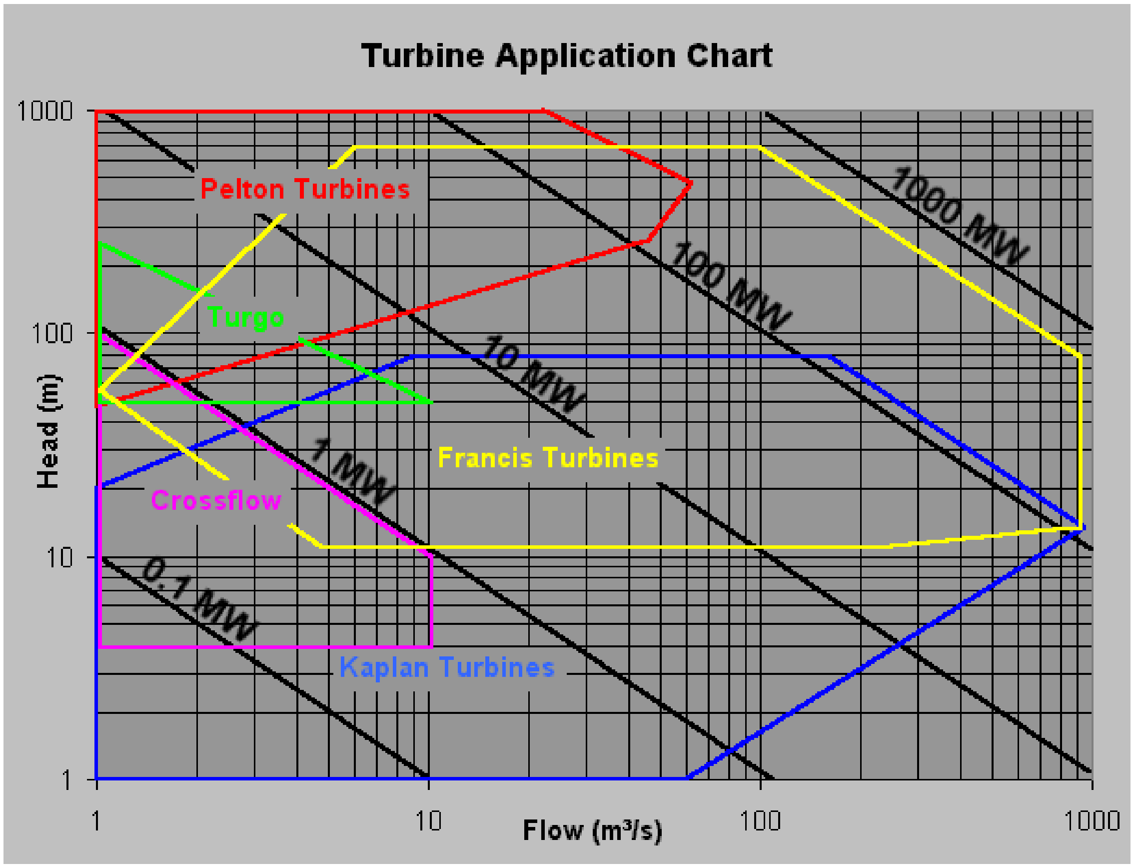
Reaction turbines:

- 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 Mohenjo-daro 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.

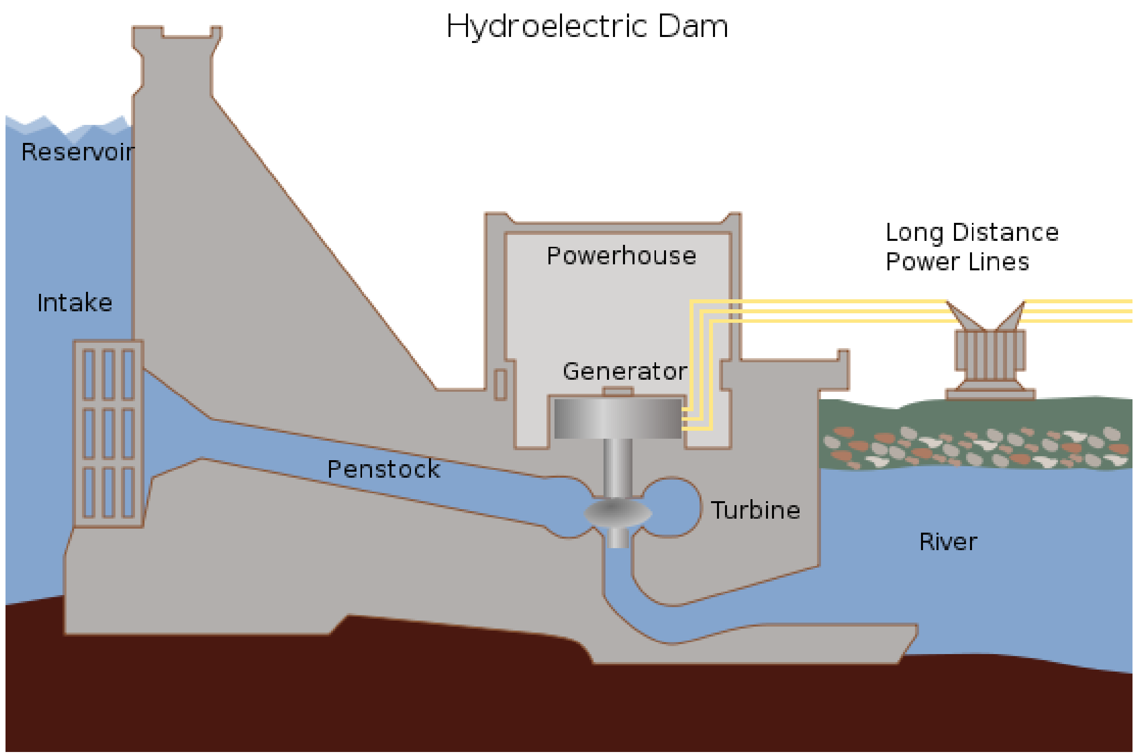
Uses

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

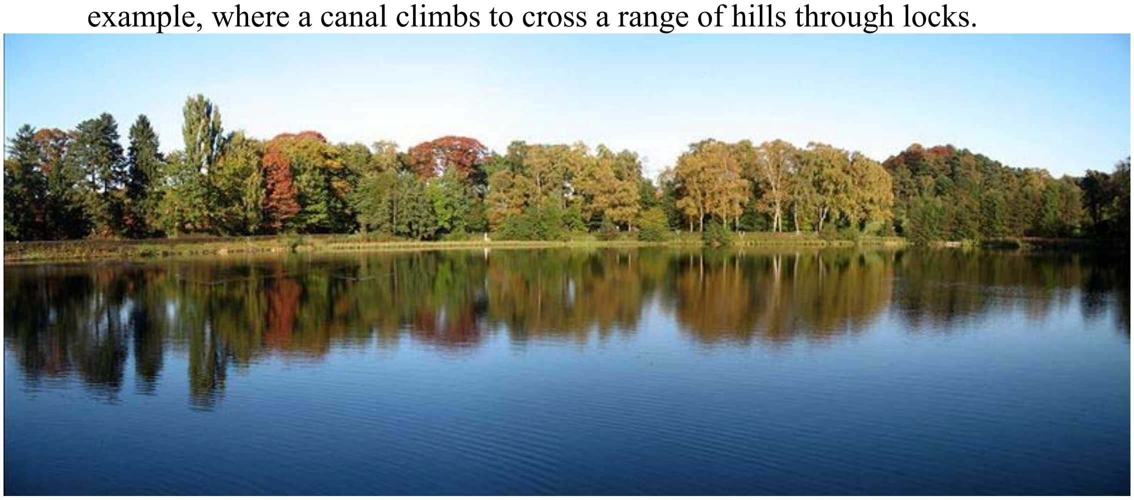
Reservoirs can be used in a number of ways to control how water flows through downstream waterways.

> **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

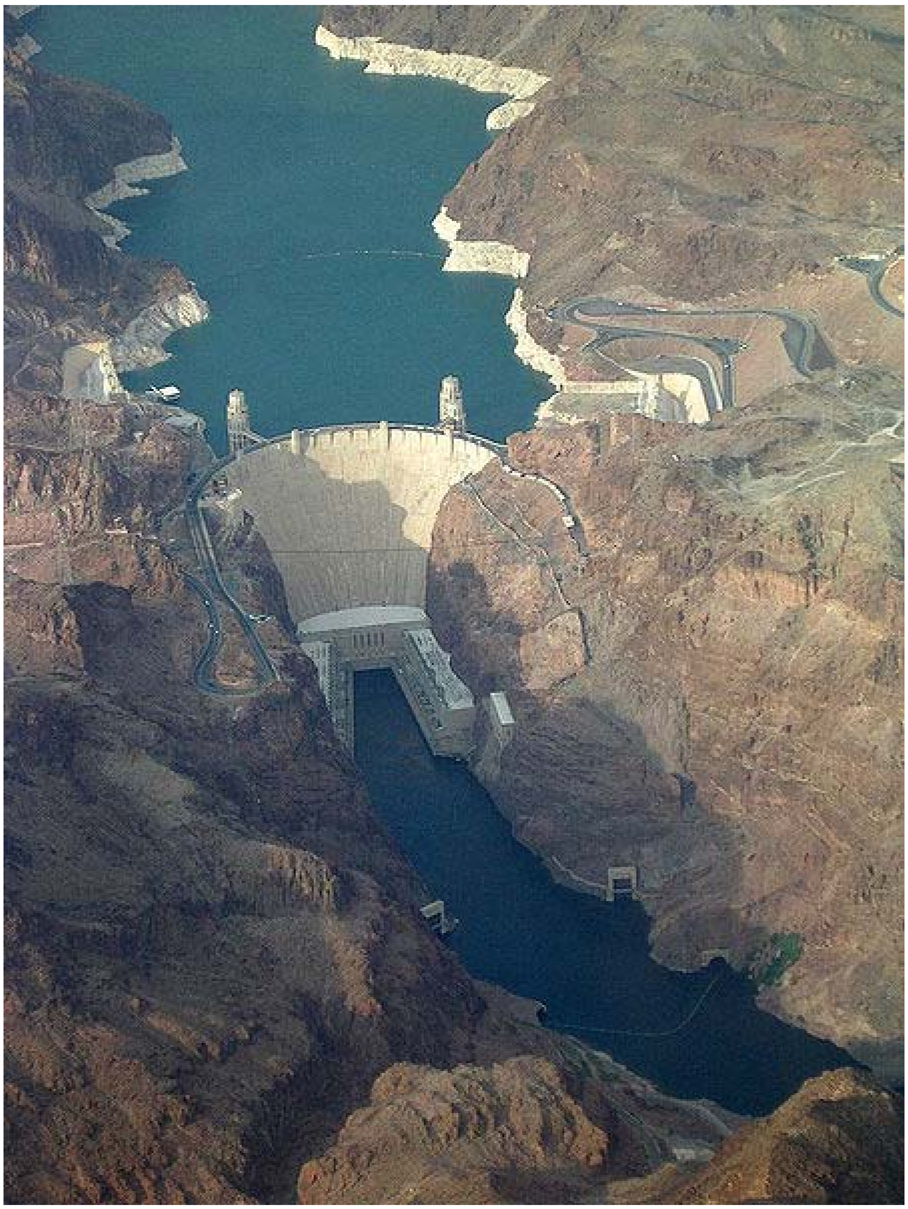
Large reservoirs have been indicated as contributing to earthquakes, due to changes in loading and/or the height of the water table.

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

Dam



Hoover Dam, a concrete arch-gravity dam in Black Canyon of the Colorado River. Lake Mead in the background is impounded by the dam.

Glen Canyon Dam

A **dam** is a barrier that impounds water or underground streams. Dams generally serve the primary purpose of retaining water, while other structures such as floodgates or levees (also known as dikes) are used to manage or prevent water flow into specific land regions. Hydropower and pumped-storage hydroelectricity are often used in conjunction with dams to generate electricity. A dam can also be used to collect water or for storage of water which can be evenly distributed between locations.

History

The sizable Roman Harbaqa Dam in Syria is 21 m high and 365 m long.

The Roman dam at Cornalvo in Spain has been in use for almost two millennia.

Grand Anicut dam on river Kaveri in Tamil Nadu, South India (19th century on 1st-2nd century foundation)

The word *dam* can be traced back to Middle English, and before that, from Middle Dutch, as seen in the names of many old cities.Early dam building took place in Mesopotamia and the Middle East. Dams were used to control the water level, for Mesopotamia's weather affected the Tigris and Euphrates rivers, and could be quite unpredictable.

The earliest known dam is the Jawa Dam in Jordan, 100 km northeast of the capital Amman. This gravity dam featured a 4.5 m high and 1 m wide stone wall, supported by a 50 m wide earth rampart. The structure is dated to 3000 BC. The Ancient Egyptian Saddel-Kafara Dam at Wadi Al-Garawi, located about 25 kilometers south of Cairo, was 102 m long at its base and 87 m wide. The structure was built around 2800 or 2600 B.C. as a diversion dam for flood control, but was destroyed by heavy rain during construction or shortly afterwards. By the mid-late third century BC, an intricate water-management system within Dholavira. in modern day India, was built. The system included 16 reservoirs, dams and various channels for collecting water and storing it.

Roman dam construction was characterized by "the Romans' ability to plan and organize engineering construction on a grand scale". Roman planners introduced the then novel concept of large reservoir dams which could secure a permanent water supply for urban settlements also over the dry season. Their pioneering use of water-proof hydraulic mortar and particularly Roman concrete allowed for much larger dam structures than previously built, such as the Lake Homs Dam, possibly the largest water barrier to date, and the Harbaqa Dam, both in Roman Syria. The highest Roman dam was the Subiaco Dam near Rome; its record height of 50 m remained unsurpassed until its accidental destruction in 1305.

Roman engineers made routine use of ancient standard designs like embankment dams and masonry gravity dams. Apart from that, they displayed a high degree of inventiveness, introducing most of the other basic dam designs which had been unknown until then. These include arch-gravity dams, arch dams, buttress dams and multiple arch buttress dams, all of which were known and employed by the 2nd century AD. Roman workforces also were the first to build dam bridges, such as the Bridge of Valerian in Iran.

Eflatun Pınar is a Hittite dam and spring temple near Konya, Turkey. It's thought to the time of the Hittite empire between the 15th and 13 century BC.

The Kallanai is a massive dam of unhewn stone, over 300 meters long, 4.5 meters high and 20 meters (60 ft) wide, across the main stream of the Kaveri river in Tamil Nadu, South India. The basic structure dates to the 1st century AD. and is considered one of the oldest water-diversion or water-regulator structures in the world, which is still in use. The purpose of the dam was to divert the waters of the Kaveri across the fertile Delta region for irrigation via canals.It is considered to be the oldest dam still in use.

Du Jiang Yan is the oldest surviving irrigation system in China that included a dam that directed waterflow. It was finished in 251 B.C. A large earthen dam, made by the Prime Minister of Chu (state), Sunshu Ao, flooded a valley in modern-day northern Anhui province that created an enormous irrigation reservoir (62 miles in circumference), a reservoir that is still present today.

In Iran, bridge dams such as the Band-e Kaisar were used to provide hydropower through water wheels, which often powered water-raising mechanisms. One of the first was the Roman-built dam bridge in Dezful, which could raise 50 cubits of water for the water supply to all houses in the town. Also diversion dams were known. Milling dams were introduced which the Muslim engineers called the *Pul-i-Bulaiti*. The first was built at

Shustar on the River Karun, Iran, and many of these were later built in other parts of the Islamic world. Water was conducted from the back of the dam through a large pipe to drive a water wheel and watermill. In the 10th century, Al-Muqaddasi described several dams in Persia. He reported that one in Ahwaz was more than 3,000 feet long, and that and it had many water-wheels raising the water into aqueducts through which it flowed into reservoirs of the city. Another one, the *Band-i-Amir* dam, provided irrigation for 300 villages.

In the Netherlands, a low-lying country, *dams* were often applied to block rivers in order to regulate the water level and to prevent the sea from entering the marsh lands. Such dams often marked the beginning of a town or city because it was easy to cross the river at such a place, and often gave rise to the respective place's names in Dutch. For instance the Dutch capital Amsterdam (old name Amstelredam) started with a *dam* through the river Amstel in the late 12th century, and Rotterdam started with a *dam* through the river Rotte, a minor tributary of the Nieuwe Maas. The central square of Amsterdam, covering the original place of the 800 year old dam, still carries the name *Dam Square* or simply *the Dam*.

The age of hydropower and large dams emerged following the development of the turbine. French engineer Benoît Fourneyron perfected the first water turbine in 1832. The era of mega-dam building was initiated after Hoover Dam was completed on the Colorado River in 1936. By 1997, there were an estimated 800,000 dams worldwide, some 40,000 of them over fifteen meters high.

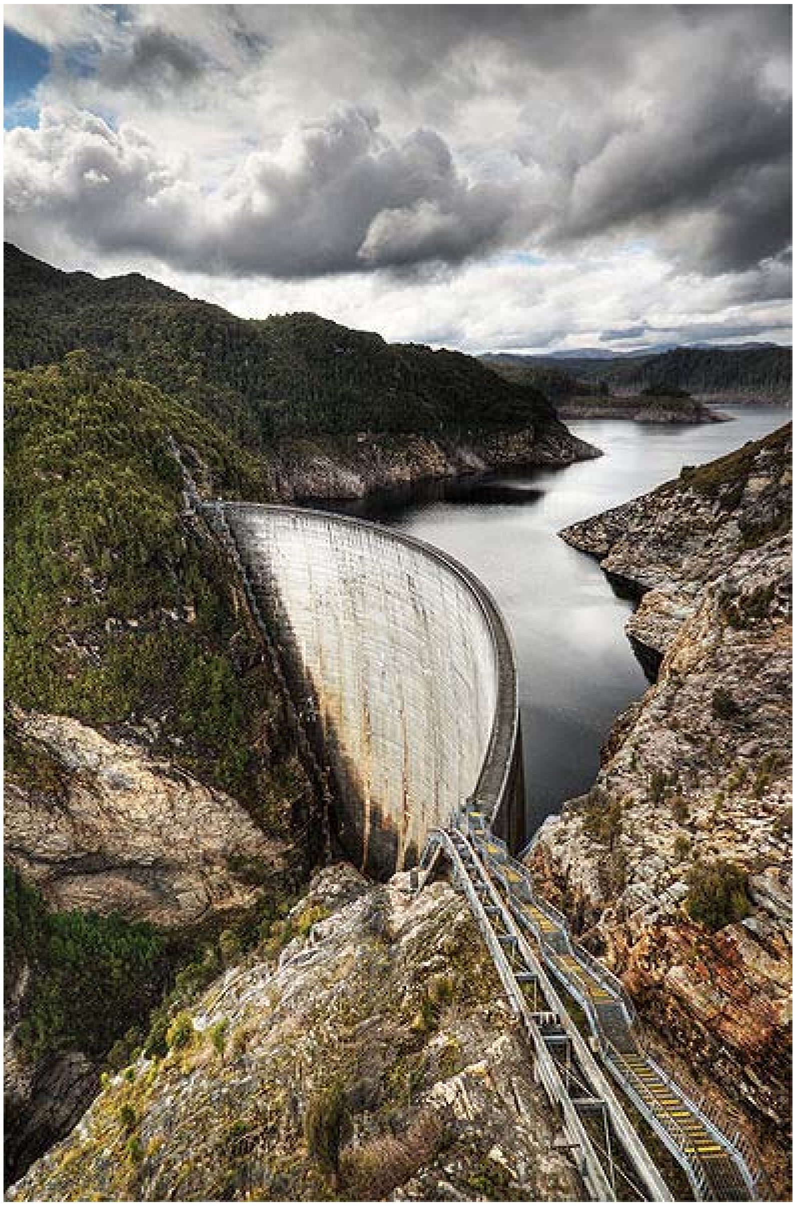
Types of dams

Dams can be formed by human agency, natural causes, or even by the intervention of wildlife such as beavers. Man-made dams are typically classified according to their size (height), intended purpose or structure.

By structure

Based on structure and material used, dams are classified as timber dams, arch-gravity dams, embankment dams or masonry dams, with several subtypes.

Arch dams



Gordon Dam, Tasmania is an arch dam.

In the arch dam, stability is obtained by a combination of arch and gravity action. If the upstream face is vertical the entire weight of the dam must be carried to the foundation by gravity, while the distribution of the normal hydrostatic pressure between vertical cantilever and arch action will depend upon the stiffness of the dam in a vertical and horizontal direction. When the upstream face is sloped the distribution is more complicated. The normal component of the weight of the arch ring may be taken by the arch action, while the normal hydrostatic pressure will be distributed as described above. For this type of dam, firm reliable supports at the abutments (either buttress or canyon side wall) are more important. The most desirable place for an arch dam is a narrow canyon with steep side walls composed of sound rock. The safety of an arch dam is dependent on the strength of the side wall abutments, hence not only should the arch be well seated on the side walls but also the character of the rock should be carefully inspected.

Daniel-Johnson Dam, Quebec, is a multiple-arch buttress dam.

Two types of single-arch dams are in use, namely the constant-angle and the constant-radius dam. The constant-radius type employs the same face radius at all elevations of the dam, which means that as the channel grows narrower towards the bottom of the dam the central angle subtended by the face of the dam becomes smaller. Jones Falls Dam, in Canada, is a constant radius dam. In a constant-angle dam, also known as a variable radius dam, this subtended angle is kept a constant and the variation in distance between the abutments at various levels are taken care of by varying the radii. Constant-radius dams are much less common than constant-angle dams. Parker Dam is a constant-angle arch dam.

A similar type is the double-curvature or thin-shell dam. Wildhorse Dam near Mountain City, Nevada in the United States is an example of the type. This method of construction minimizes the amount of concrete necessary for construction but transmits large loads to the foundation and abutments. The appearance is similar to a single-arch dam but with a distinct vertical curvature to it as well lending it the vague appearance of a concave lens as viewed from downstream.

The multiple-arch dam consists of a number of single-arch dams with concrete buttresses as the supporting abutments, as for example the Daniel-Johnson Dam, Québec, Canada. The multiple-arch dam does not require as many buttresses as the hollow gravity type, but requires good rock foundation because the buttress loads are heavy.

Gravity dams

The Grand Coulee Dam is an example of a solid gravity dam.

In a gravity dam, stability is secured by making it of such a size and shape that it will resist overturning, sliding and crushing at the toe. The dam will not overturn provided that the moment around the turning point, caused by the water pressure, is smaller than the moment caused by the weight of the dam. This is the case if the resultant force of water pressure and weight falls within the base of the dam. However, in order to prevent tensile stress at the upstream face and excessive compressive stress at the downstream face, the dam cross section is usually designed so that the resultant falls within the middle at all elevations of the cross section (the core). For this type of dam, impervious foundations with high *bearing* strength are essential.

When situated on a suitable site, gravity dams can prove to be a better alternative to other types of dams. When built on a carefully studied foundation, the gravity dam probably represents the best developed example of dam building. Since the fear of flood is a strong motivator in many regions, gravity dams are being built in some instances where an arch dam would have been more economical.

Gravity dams are classified as "solid" or "hollow" and are generally made of either concrete or masonry. This is called "Zoning". The core of the dam is zoned depending on the availability of locally available materials, foundation conditions and the material attributes. The solid form is the more widely used of the two, though the hollow dam is frequently more economical to construct. Gravity dams can also be classified as "overflow" (spillway) and "non-overflow." Grand Coulee Dam is a solid gravity dam and Itaipu Dam is a hollow gravity dam.

Arch-gravity dams

The Hoover Dam is an example of an arch-gravity dam.

A gravity dam can be combined with an arch dam, an arch-gravity dam, for areas with massive amounts of water flow but less material available for a purely gravity dam.

Barrages

The Prakasham barrage is an example of a barrage.

A barrage dam is a special kind of dam which consists of a line of large gates that can be opened or closed to control the amount of water passing the dam. The gates are set between flanking piers which are responsible for supporting the water load. They are often used to control and stabilize water flow for irrigation systems.

Barrages that are built at the mouth of rivers or lagoons to prevent tidal incursions or utilize the tidal flow for tidal power are known as tidal barrages.

Embankment dams

Embankment dams are made from compacted earth, and have two main types, rock-fill and earth-fill dams. Embankment dams rely on their weight to hold back the force of water, like the gravity dams made from concrete.

Rock-fill dams

Rock-fill dams are embankments of compacted free-draining granular earth with an impervious zone. The earth utilized often contains a large percentage of large particles hence the term *rock-fill*. The impervious zone may be on the upstream face and made of masonry, concrete, plastic membrane, steel sheet piles, timber or other material. The impervious zone may also be within the embankment in which case it is referred to as a *core*. In the instances where clay is utilized as the impervious material the dam is referred to as a *composite* dam. To prevent internal erosion of clay into the rock fill due to seepage forces, the core is separated using a filter. Filters are specifically graded soil designed to prevent the migration of fine grain soil particles. When suitable material is at hand, transportation is minimized leading to cost savings during construction. Rock-fill dams are resistant to damage from earthquakes. However, inadequate quality control during construction can lead to poor compaction and sand in the embankment which can lead to liquefaction of the rock-fill during an earthquake. Liquefaction potential can be reduced by keeping susceptible material from being saturated, and by providing adequate compaction during construction. An example of a rock-fill dam is New Melones Dam in California.

Earth-fill dams

The Atatürk Dam in Turkey is an embankment dam.

Earth-fill dams, also called earthen, rolled-earth or simply earth dams, are constructed as a simple embankment of well compacted earth. A *homogeneous* rolled-earth dam is entirely constructed of one type of material but may contain a drain layer to collect *seep* water. A *zoned-earth* dam has distinct parts or *zones* of dissimilar material, typically a locally plentiful *shell* with a watertight clay core. Modern zoned-earth embankments employ filter and drain zones to collect and remove seep water and preserve the integrity of the downstream shell zone. An outdated method of zoned earth dam construction utilized a hydraulic fill to produce a watertight core. *Rolled-earth* dams may also employ a watertight facing or core in the manner of a rock-fill dam. An interesting type of temporary earth dam occasionally used in high latitudes is the *frozen-core* dam, in which a coolant is circulated through pipes inside the dam to maintain a watertight region of permafrost within it.

Tarbela Dam is a large dam on the Indus River in Pakistan. It is located about 50 km (31 mi) northwest of Islamabad, and a height of 485 ft (148 m) above the river bed and a reservoir size of 95 sq mi (250 km2) makes it the largest earth filled dam in the world. The principal element of the project is an embankment 9,000 feet (2743 meters) long with a maximum height of 465 feet (143 meters). The total volume of earth and rock used for the project is approximately 200 million cubic yards (152.8 million cu. Meters) which makes it the largest man made structure in the world , except for the Great Chinese Wall which consumed somewhat more material.

Because earthen dams can be constructed from materials found on-site or nearby, they can be very cost-effective in regions where the cost of producing or bringing in concrete would be prohibitive.

Asphalt-concrete core

A third type of embankment dam is built with asphalt concrete core. The majority of such dams are built with rock and/or gravel as the main fill material. Almost 100 dams of this design have now been built worldwide since the first such dam was completed in 1962. All asphalt-concrete core dams built so far have an excellent performance record. The type of asphalt used is a viscoelastic-plastic material that can adjust to the movements and deformations imposed on the embankment as a whole, and to settlements in the foundation. The flexible properties of the asphalt make such dams especially suited in earthquake regions.

By size

International standards (including International Commission on Large Dams, **ICOLD**) define *large dams* as higher than 15 meters and *major dams* as over 150 meters in height. The *Report of the World Commission on Dams* also includes in the *large* category, dams, such as Barrages, which are between 5 and 15 meters high with a reservoir capacity of more than 3 million cubic meters.

The tallest dam in the world is the 300-meter-high Nurek Dam in Tajikistan.

By use

Saddle dam

A saddle dam is an auxiliary dam constructed to confine the reservoir created by a primary dam either to permit a higher water elevation and storage or to limit the extent of a reservoir for increased efficiency. An auxiliary dam is constructed in a low spot or *saddle* through which the reservoir would otherwise escape. On occasion, a reservoir is contained by a similar structure called a dike to prevent inundation of nearby land. Dikes are commonly used for *reclamation* of arable land from a shallow lake. This is similar to a levee, which is a wall or embankment built along a river or stream to protect adjacent land from flooding.

Weir

A weir (also sometimes called an *overflow dam*) is a type of small overflow dam that are often used within a river channel to create an impoundment lake for water abstraction purposes and which can also be used for flow measurement.

Check dam

A check dam is a small dam designed to reduce flow velocity and control soil erosion. Conversely, a *wing dam* is a structure that only partly restricts a waterway, creating a faster channel that resists the accumulation of sediment.

Dry dam

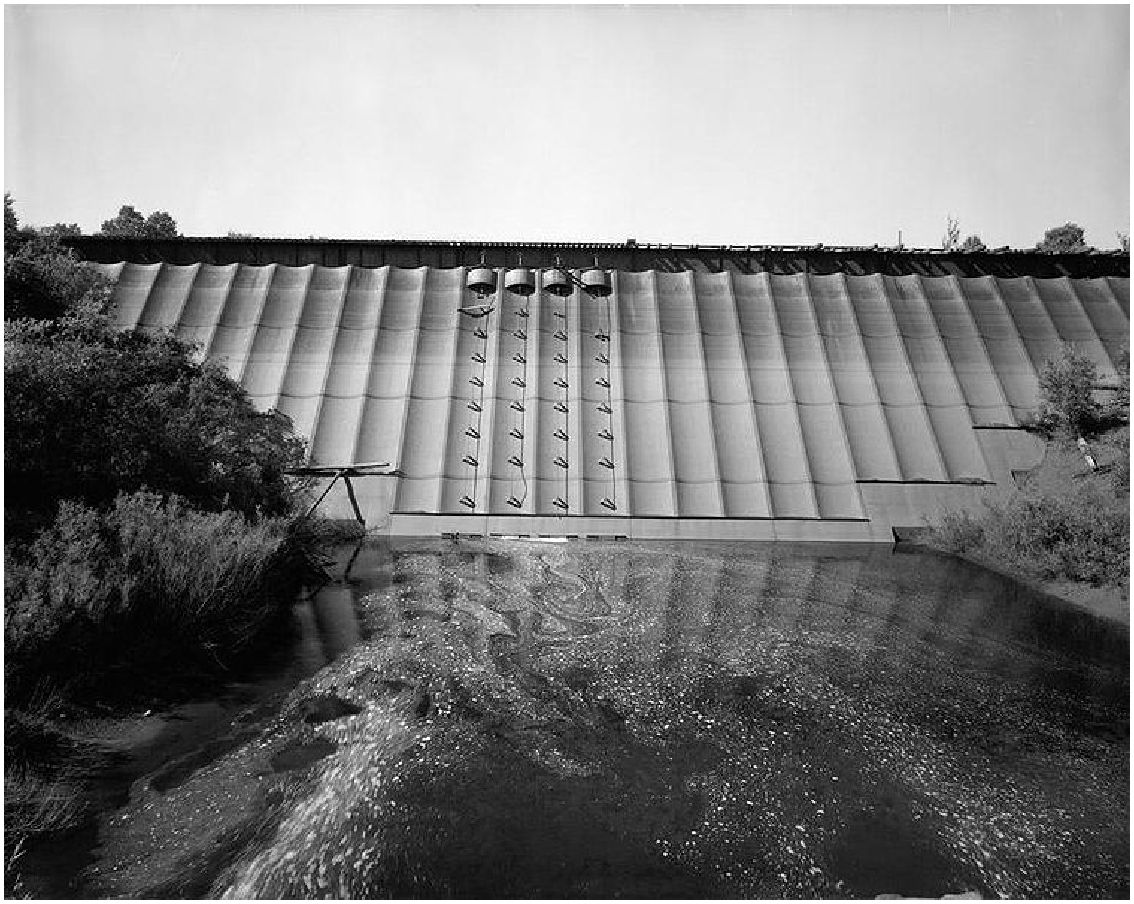
A dry dam is a dam designed to control flooding. It normally holds back no water and allows the channel to flow freely, except during periods of intense flow that would otherwise cause flooding downstream.

Diversionary dam

A diversionary dam is a structure designed to divert all or a portion of the flow of a river from its natural course.

By material

Steel dams



Red Ridge steel dam, b. 1905, Michigan.

A steel dam is a type of dam briefly experimented with in around the turn of the 19th-20th Century which uses steel plating (at an angle) and load bearing beams as the structure. Intended as permanent structures, steel dams were an (arguably failed) experiment to determine if a construction technique could be devised that was cheaper than masonry, concrete or earthworks, but sturdier than timber crib dams.

Timber dams

A timber crib dam in Michigan, photographed in 1978.

Timber dams were widely used in the early part of the industrial revolution and in frontier areas due to ease and speed of construction. Rarely built in modern times by humans because of relatively short lifespan and limited height to which they can be built, timber dams must be kept constantly wet in order to maintain their water retention properties and limit deterioration by rot, similar to a barrel. The locations where timber dams are most economical to build are those where timber is plentiful, cement is costly or difficult to transport, and either a low head diversion dam is required or longevity is not an issue. Timber dams were once numerous, especially in the North American west, but most have failed, been hidden under earth embankments or been replaced with entirely new structures. Two common variations of timber dams were the *crib* and the *plank*.

Timber crib dams were erected of heavy timbers or dressed logs in the manner of a log house and the interior filled with earth or rubble. The heavy crib structure supported the dam's face and the weight of the water. Splash dams were timber crib dams used to help float logs downstream in the late 19th and early 20th centuries.

Timber plank dams were more elegant structures that employed a variety of construction methods utilizing heavy timbers to support a water retaining arrangement of planks.

Very few timber dams are still in use. Timber, in the form of sticks, branches and withes, is the basic material used by beavers, often with the addition of mud or stones.

Other types

Cofferdams

A cofferdam during the construction of locks at the Montgomery Point Lock and Dam.

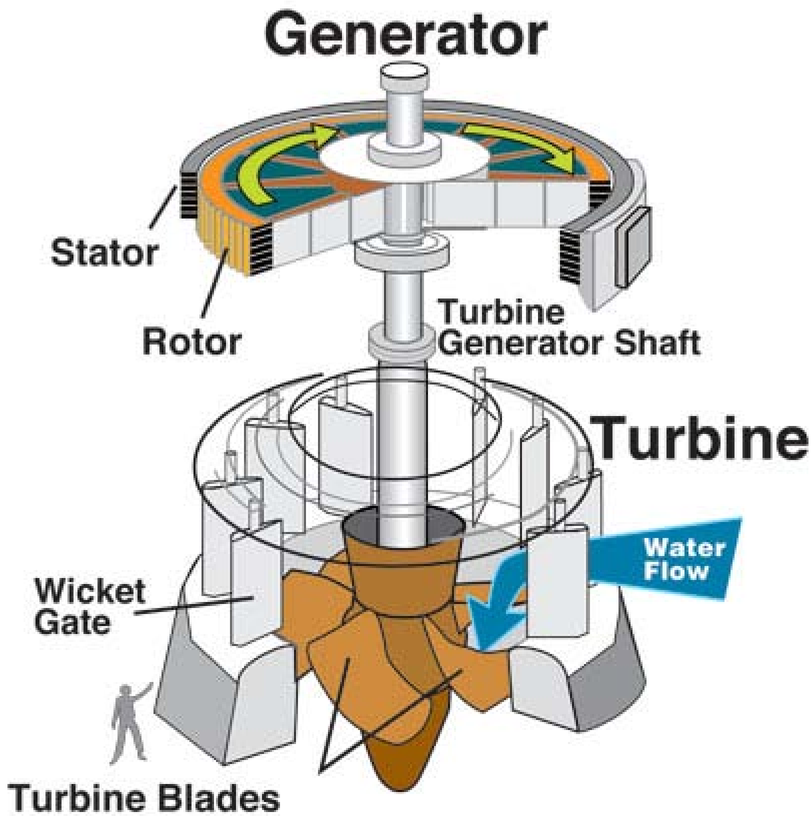
A cofferdam is a (usually temporary) barrier constructed to exclude water from an area that is normally submerged. Made commonly of wood, concrete or steel sheet piling, cofferdams are used to allow construction on the foundation of permanent dams, bridges, and similar structures. When the project is completed, the cofferdam may be demolished or removed. Common uses for cofferdams include construction and repair of off shore oil platforms. In such cases the cofferdam is fabricated from sheet steel and welded into place under water. Air is pumped into the space, displacing the water allowing a dry work environment below the surface. Upon completion the cofferdam is usually deconstructed unless the area requires continuous maintenance.

Beaver dams

Beavers create dams primarily out of mud and sticks to flood a particular habitable area. By flooding a parcel of land, beavers can navigate below or near the surface and remain relatively well hidden or protected from predators. The flooded region also allows beavers access to food, especially during the winter.

Construction elements

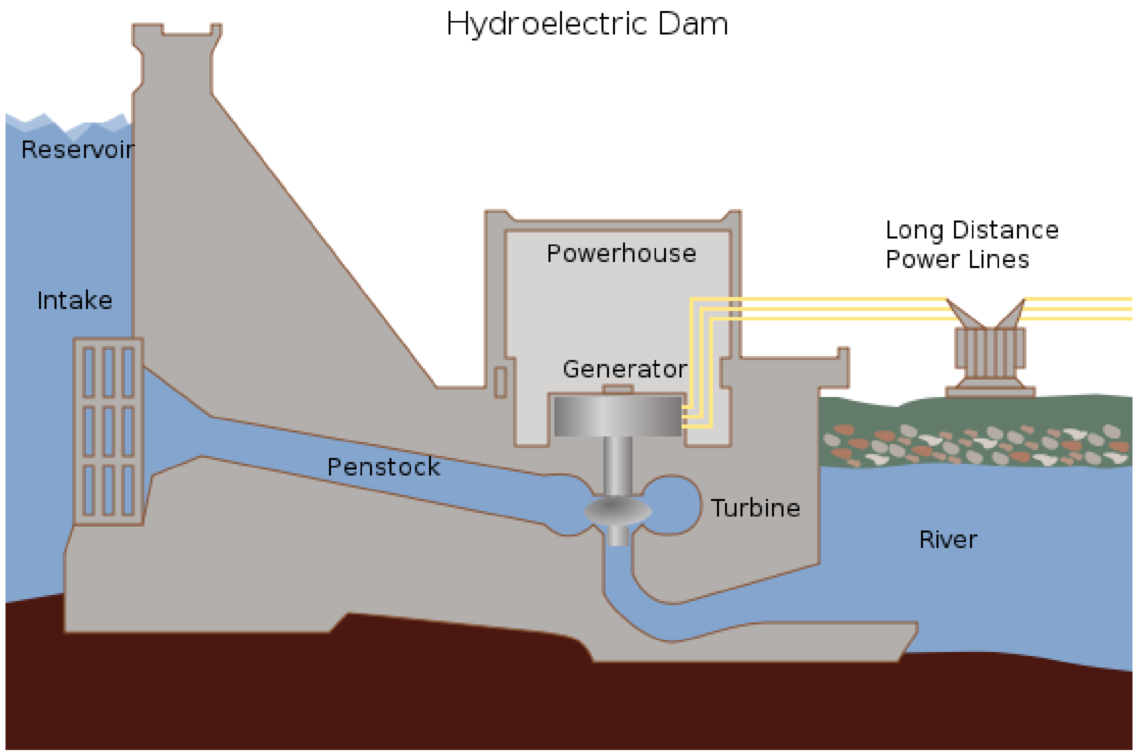
Power generation plant



Hydraulic turbine and electrical generator.

As of 2005, hydroelectric power, mostly from dams, supplies some 19% of the world's electricity, and over 63% of renewable energy. Much of this is generated by large dams, although China uses small scale hydro generation on a wide scale and is responsible for about 50% of world use of this type of power.

Most hydroelectric power comes from the potential energy of dammed water driving a water turbine and generator; to boost the power generation capabilities of a dam, the water may be run through a large pipe called a penstock before the turbine. A variant on this simple model uses pumped storage hydroelectricity to produce electricity to match periods of high and low demand, by moving water between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine.



Hydroelectric dam in cross section.

Spillways

Spillway on Llyn Brianne dam, Wales soon after first fill.

A *spillway* is a section of a dam designed to pass water from the upstream side of a dam to the downstream side. Many spillways have floodgates designed to control the flow through the spillway. Types of spillway include: A *service spillway* or *primary spillway* passes normal flow. An *auxiliary spillway* releases flow in excess of the capacity of the service spillway. An *emergency spillway* is designed for extreme conditions, such as a serious malfunction of the service spillway. A *fuse plug spillway* is a low embankment designed to be over topped and washed away in the event of a large flood. Fusegate elements are independent free-standing block set side by side on the spillway which work without any remote control. They allow to increase the normal pool of the dam without compromising the security of the dam because they are designed to be gradually evacuated for exceptional events. They work as fixed weir most of the time allowing overspilling for the common floods.

The spillway can be gradually eroded by water flow, including cavitation or turbulence of the water flowing over the spillway, leading to its failure. It was the inadequate design of the spillway which led to the 1889 over-topping of the South Fork Dam in Johnstown, Pennsylvania, resulting in the infamous Johnstown Flood (the "great flood of 1889").

Erosion rates are often monitored, and the risk is ordinarily minimized, by shaping the downstream face of the spillway into a curve that minimizes turbulent flow, such as an ogee curve.

Dam creation

Common purposes

Function	Example
Power generation	Hydroelectric power is a major source of electricity in the world. Many countries that have rivers with adequate water flow, that can be dammed for power generation purposes. For example, the Itaipu on the Paraná River in South America generates 14 GW and supplied 93% of the energy consumed by Paraguay and 20% of that consumed by Brazil as of 2005.
Water supply	Many urban areas of the world are supplied with water abstracted from rivers pent up behind low dams or weirs. Examples include London - with water from the River Thames and Chester with water taken from the River Dee. Other major sources include deep upland reservoirs contained by high dams across deep valleys such as the Claerwen series of dams and reservoirs.
Stabilize water flow / irrigation	Dams are often used to control and stabilize water *flow*, often for agricultural purposes and irrigation. Others such as the Berg Strait dam can help to stabilize or restore the water *levels* of inland lakes and seas, in this case the Aral Sea.
Flood prevention	Dams such as the Blackwater dam of Webster, New Hampshire and the Delta Works are created with flood control in mind.
Land reclamation	Dams (often called dykes or levees in this context) are used to prevent ingress of water to an area that would otherwise be submerged, allowing its reclamation for human use.
Water diversion	A typically small dam used to divert water for irrigation, power generation, or other uses, with usually no other function. Occasionally, they are used to divert water to another drainage or reservoir to increase flow there and improve water use in that particular area. See: diversion dam.

Navigation	Dams create deep reservoirs and can also vary the flow of water downstream. This can in return affect upstream and downstream navigation by altering the river's depth. Deeper water increases or creates freedom of movement for water vessels. Large dams can serve this purpose but most often weirs and locks are used.
Recreation and aquatic beauty	Dams built for any of the above purposes may find themselves displaced by time of their original uses. Nevertheless the local community may have come to enjoy the reservoir for recreational and aesthetic reasons. Often the reservoir will be placid and surrounded by greenery, and convey to visitors a natural sense of rest and relaxation.

Location

The discharge of Takato Dam

One of the best places for building a dam is a narrow part of a deep river valley; the valley sides can then act as natural walls. The primary function of the dam's structure is to fill the gap in the natural reservoir line left by the stream channel. The sites are usually those where the gap becomes a minimum for the required storage capacity. The most economical arrangement is often a composite structure such as a masonry dam flanked by earth embankments. The current use of the land to be flooded should be dispensable.

Significant other engineering and engineering geology considerations when building a dam include:

- permeability of the surrounding rock or soil
- earthquake faults
- landslides and slope stability
- water table
- peak flood flows
- reservoir silting
- environmental impacts on river fisheries, forests and wildlife
- impacts on human habitations
- compensation for land being flooded as well as population resettlement
- removal of toxic materials and buildings from the proposed reservoir area

Impact assessment

Impact is assessed in several ways: the benefits to human society arising from the dam (agriculture, water, damage prevention and power), harm or benefits to nature and wildlife (especially fish and rare species), impact on the geology of an area - whether the change to water flow and levels will increase or decrease stability, and the disruption to human lives (relocation, loss of archeological or cultural matters underwater).

Environmental impact

Wood and garbage accumulated because of a dam

Reservoirs held behind dams affect many ecological aspects of a river. Rivers topography and dynamics depend on a wide range of flows whilst rivers below dams often experience long periods of very stable flow conditions or saw tooth flow patterns caused by releases followed by no releases. Water releases from a reservoir including that exiting a turbine usually contains very little suspended sediment, and this in turn can lead to scouring of river beds and loss of riverbanks; for example, the daily cyclic flow variation caused by the Glen Canyon Dam was a contributor to sand bar erosion.

Older dams often lack a fish ladder, which keeps many fish from moving up stream to their natural breeding grounds, causing failure of breeding cycles or blocking of migration paths. Even the presence of a fish ladder does not always prevent a reduction in fish reaching the spawning grounds upstream. In some areas, young fish ("smolt") are transported downstream by barge during parts of the year. Turbine and power-plant designs that have a lower impact upon aquatic life are an active area of research.

A large dam can cause the loss of entire ecospheres, including endangered and undiscovered species in the area, and the replacement of the original environment by a new inland lake.

Large reservoirs formed behind dams have been indicated in the contribution of seismic activity, due to changes in water load and/or the height of the water table.

Human social impact

The impact on human society is also significant. For example, the Three Gorges Dam on the Yangtze River in China is more than five times the size of the Hoover Dam (U.S.), and will create a reservoir 600 km long to be used for hydro-power generation. Its construction required the loss of over a million people's homes and their mass relocation, the loss of many valuable archaeological and cultural sites, as well as significant ecological change. It is estimated that to date, 40-80 million people worldwide have been physically displaced from their homes as a result of dam construction.

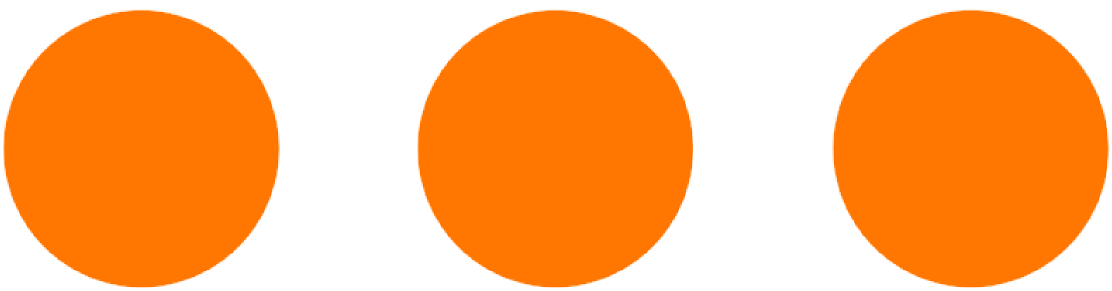
Economics

Construction of a hydroelectric plant requires a long lead-time for site studies, hydrological studies, and environmental impact assessment, and are large scale projects by comparison to traditional power generation based upon fossil fuels. The number of sites that can be economically developed for hydroelectric production is limited; new sites tend to be far from population centers and usually require extensive power transmission lines. Hydroelectric generation can be vulnerable to major changes in the climate, including variation of rainfall, ground and surface water levels, and glacial melt, causing additional expenditure for the extra capacity to ensure sufficient power is available in low water years.

Once completed, if it is well designed and maintained, a hydroelectric power source is usually comparatively cheap and reliable. It has no fuel and low escape risk, and as an alternative energy source it is cheaper than both nuclear and wind power. It is more easily regulated to store water as needed and generate high power levels on demand compared to wind power, although dams have life expectancies while renewable energies do not.

Dam failure

The reservoir emptying through the failed Teton Dam.



International special sign for works and installations containing dangerous forces

Dam failures are generally catastrophic if the structure is breached or significantly damaged. Routine deformation monitoring of seepage from drains in and around larger dams is necessary to anticipate any problems and permit remedial action to be taken before structural failure occurs. Most dams incorporate mechanisms to permit the reservoir to be lowered or even drained in the event of such problems. Another solution can be rock grouting - pressure pumping portland cement slurry into weak fractured rock.

During an armed conflict, a dam is to be considered as an "installation containing dangerous forces" due to the massive impact of a possible destruction on the civilian population and the environment. As such, it is protected by the rules of International Humanitarian Law (IHL) and shall not be made the object of attack if that may cause severe losses among the civilian population. To facilitate the identification, a protective sign consisting of three bright orange circles placed on the same axis is defined by the rules of IHL.

The main causes of dam failure include spillway design error (South Fork Dam), geological instability caused by changes to water levels during filling or poor surveying (Vajont Dam, Malpasset, Testalinden Creek Dam), poor maintenance, especially of outlet pipes (Lawn Lake Dam, Val di Stava Dam collapse), extreme rainfall (Shakidor Dam), and human, computer or design error (Buffalo Creek Flood, Dale Dike Reservoir, Taum Sauk pumped storage plant).

A notable case of deliberate dam failure (prior to the above ruling) was the Royal Air Force 'Dambusters' raid on Germany in World War II (codenamed *"Operation Chastise"*), in which three German dams were selected to be breached in order to have an impact on German infrastructure and manufacturing and power capabilities deriving from the Ruhr and Eder rivers. This raid later became the basis for several films.

Since 2007, the Dutch IJkdijk foundation is developing, with an open innovation model and early warning system for levee/dike failures. As a part of the development effort, full scale dikes are destroyed in the IJkdijk fieldlab. The destruction process is monitored by sensor networks from an international group of companies and scientific institutions.

Chapter 11

Breakwater (Structure)

Breakwaters create safer harbours, but can also trap sediment moving along the coast. Alamitos Bay, CA entrance channel.

Breakwaters are structures constructed on coasts as part of coastal defence or to protect an anchorage from the effects of weather and longshore drift.

Purposes of breakwaters

Offshore breakwaters, also called bulkheads, reduce the intensity of wave action in inshore waters and thereby reduce coastal erosion. They are constructed some distance away from the coast or built with one end linked to the coast. The breakwaters may be small structures, placed one to three hundred feet offshore in relatively shallow water, designed to protect a gently sloping beach. Breakwaters may be either fixed or floating: the choice depends on normal water depth and tidal range. They are made of large pieces of concrete and are spaced about 50m from each other. Breakwater construction is usually parallel or perpendicular to the coast to maintain tranquility condition in the port. Most of Breakwater construction depends upon wave approach and considering some other environmental parameters

When oncoming waves hit these breakwaters, their erosive power is concentrated on these structures some distance away from the coast. In this way, there is an area of slack water behind the breakwaters. Deposition occurring in these waters and beaches can be built up or extended in these waters. However, nearby unprotected sections of the beaches do not receive fresh supplies of sediments and may gradually shrink due to erosion, namely longshore drift.

Breakwaters are subject to damage, and overtopping by big storms can lead to problems of drainage of water that gets behind them. The wall also serves to encourage erosion of beach deposits from the foot of the wall and can increase longshore sediment transport.

3 of the 4 breakwaters forming Portland Harbour

The eight offshore breakwaters at Elmer, UK

Protection of anchorages

An anchorage is only safe when ships anchored there are protected from the force of high winds and powerful waves by some large underwater barrier which they can shelter behind. Natural harbours are formed by natural barriers such as headlands or reefs. Mobile harbours, such as the D-Day Mulberry harbours were floated into position and acted as breakwaters. Some natural harbours, such as those in Plymouth Sound, Portland Harbour and Cherbourg, have been enhanced or extended by breakwaters made of rock.

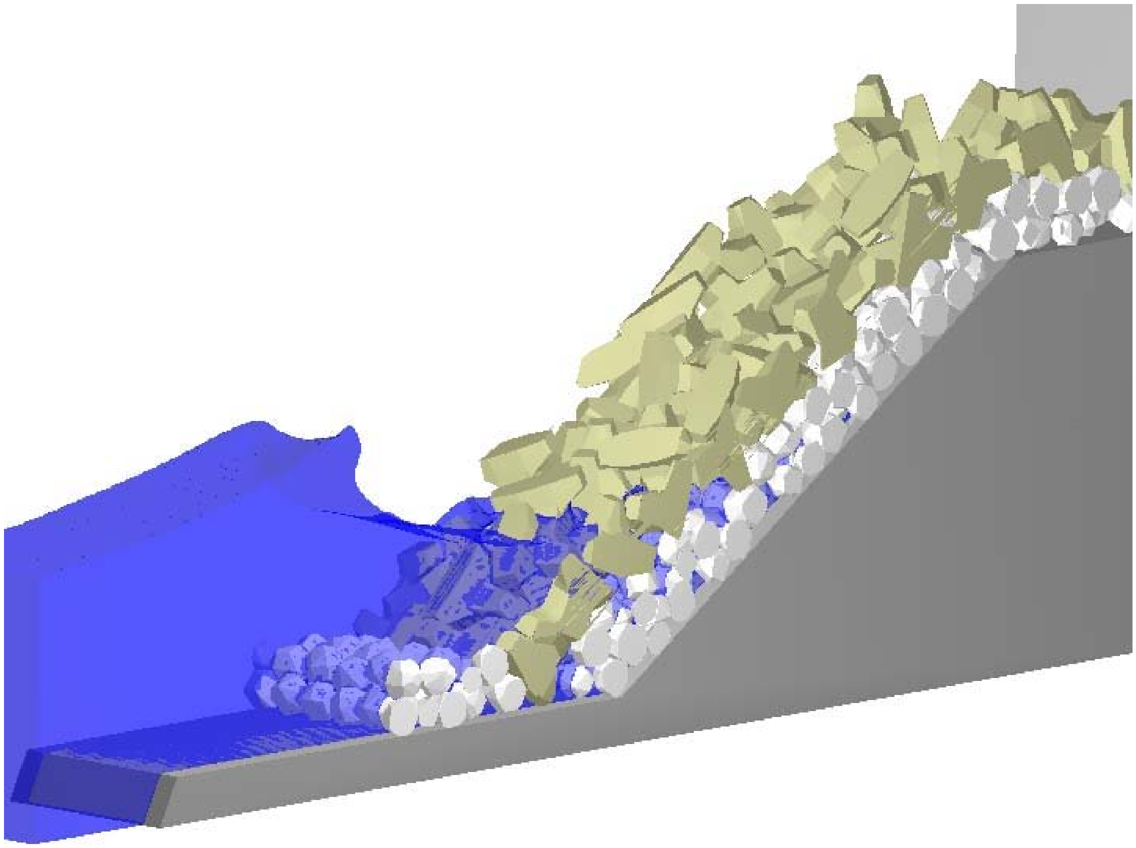
Types of breakwater structures

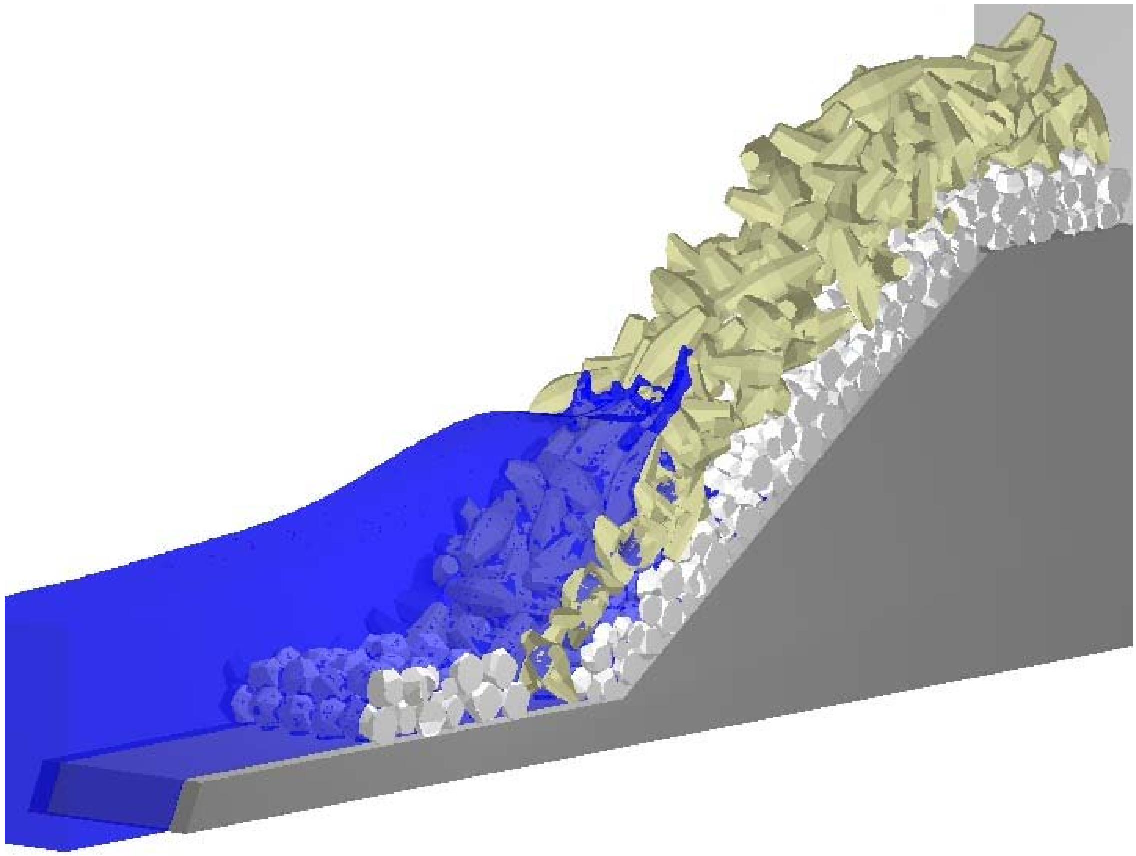
A breakwater is constructed some distance away from the coast or built with one end linked to the coast. Breakwaters may be either fixed or floating: the choice depends on normal water depth and tidal range. A breakwater structure is designed to absorb the energy of the waves that hit it. This is done either by using mass (e.g. with caissons) or by using a revetment slope (e.g. with rock or concrete armour units).

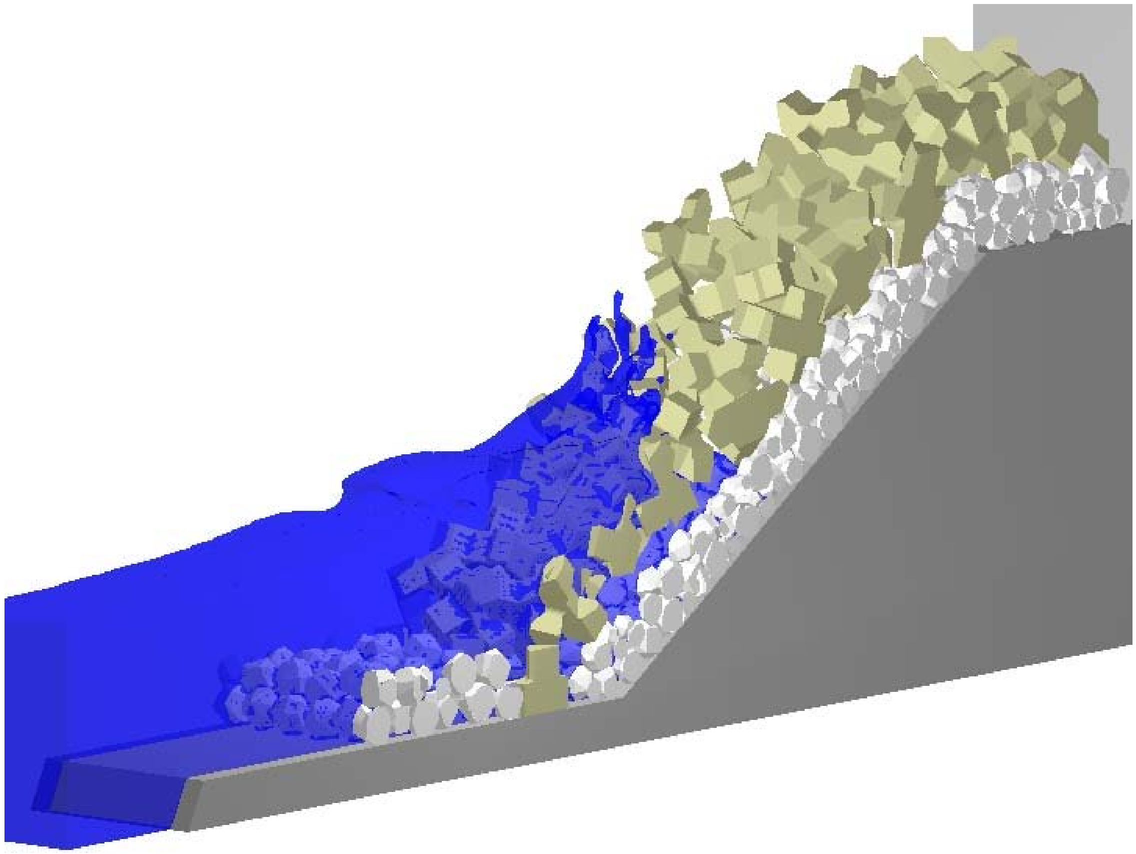
Caisson breakwaters typically have vertical sides and are usually used where it is desirable to berth one or more vessels on the inner face of the breakwater. They use the mass of the caisson and the fill within it to resist the overturning forces applied by waves hitting them. They are relatively expensive to construct in shallow water, but in deeper sites they can offer a significant saving over revetment breakwaters.

Rubble mound breakwaters use the voids in the structure to dissipate the wave energy. Rock or concrete armour units on the outside of the structure absorb most of the energy, while gravels or sands are used to prevent the wave energy continuing through the breakwater core. The slopes of the revetment are typically between 1:1 and 1:2, depending upon the materials used. In shallow water revetment breakwaters are usually relatively cheap, but as water depth increases, the material requirements, and hence costs, increase significantly.

Advanced Numerical Study







3D Numerical Simulation - MEDUS 2009

The Maritime Engineering Division University Salerno (MEDUS) developed a new procedure to study, with a more detailed and innovative approach, the interactions between maritime breakwaters (submerged or emerged) and the waves, by an integrated use of CAD and CFD software.

In the numerical simulations the filtration motion of the fluid within the interstices, which normally exist in a breakwater, is estimated by integrating the RANS equations, coupled with a RNG turbulence model, inside the voids, not using a classical equations for porous media.

The breakwaters were modelled, as it happens in the full size construction or in physical laboratory test, by overlapping three-dimensional elements and the numerical grid was thickened in such a way to have some computational nodes along the flow paths among the breakwater's blocks (AccropodeTM, Core-locTM, Xbloc, IAS (Integrated Armor System).

Chapter 12

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.

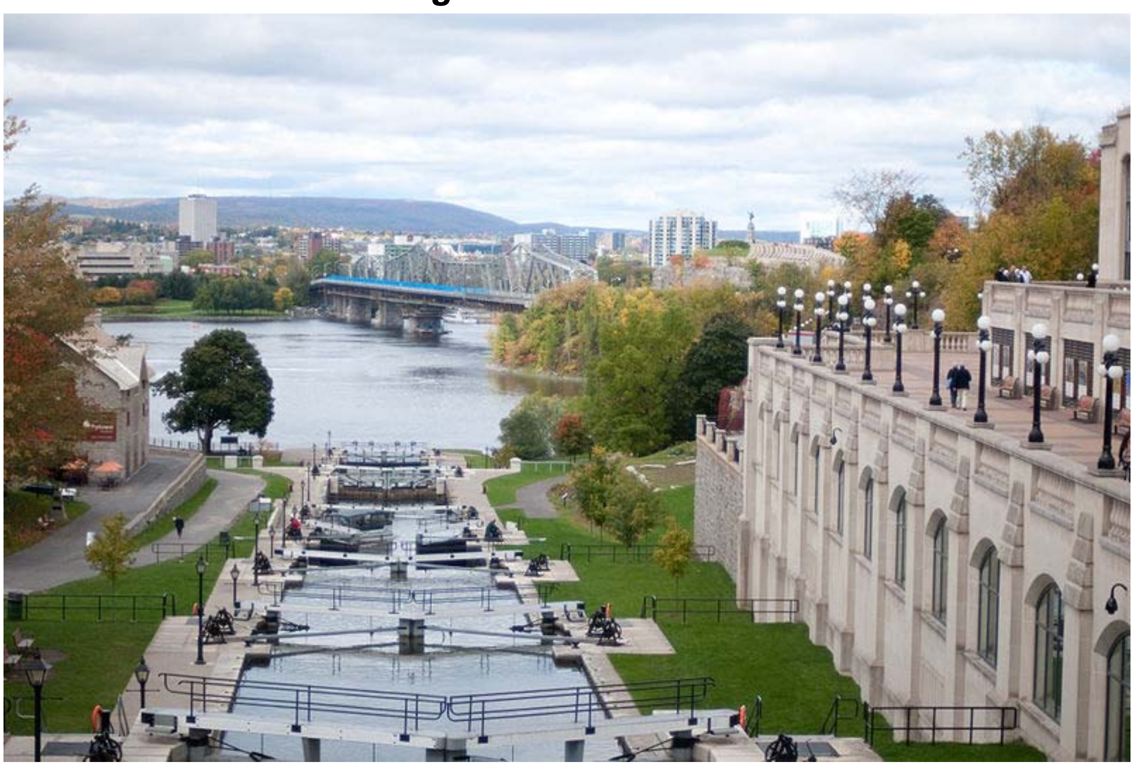
Pound locks were used in ancient China during the Song Dynasty (960–1279 AD), having been pioneered by the government official and engineer Qiao Weiyo in 984. They replaced earlier double slipways that had caused trouble and are mentioned by the Chinese polymath Shen Kuo (1031–1095) in his book *Dream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

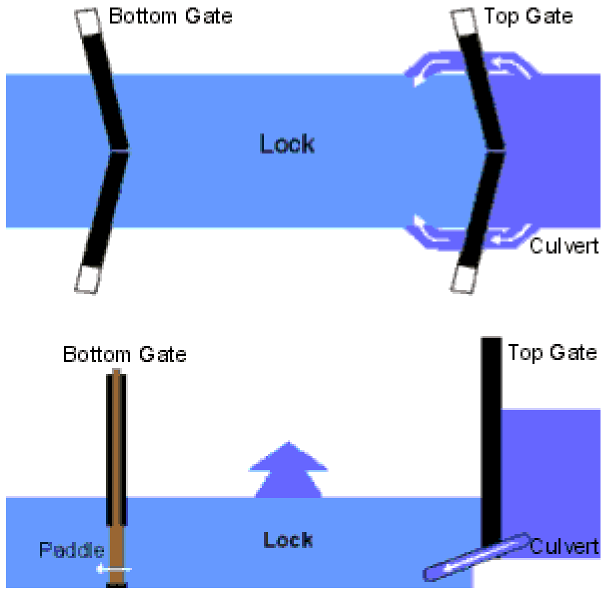
- Where a longer cut bypasses a circuitous stretch of river, the upstream end of the cut will often be protected by a *flood lock*.
- The longer the cut, the greater the difference in river level between start and end of the cut, so that a very long cut will need additional locks along its length. At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

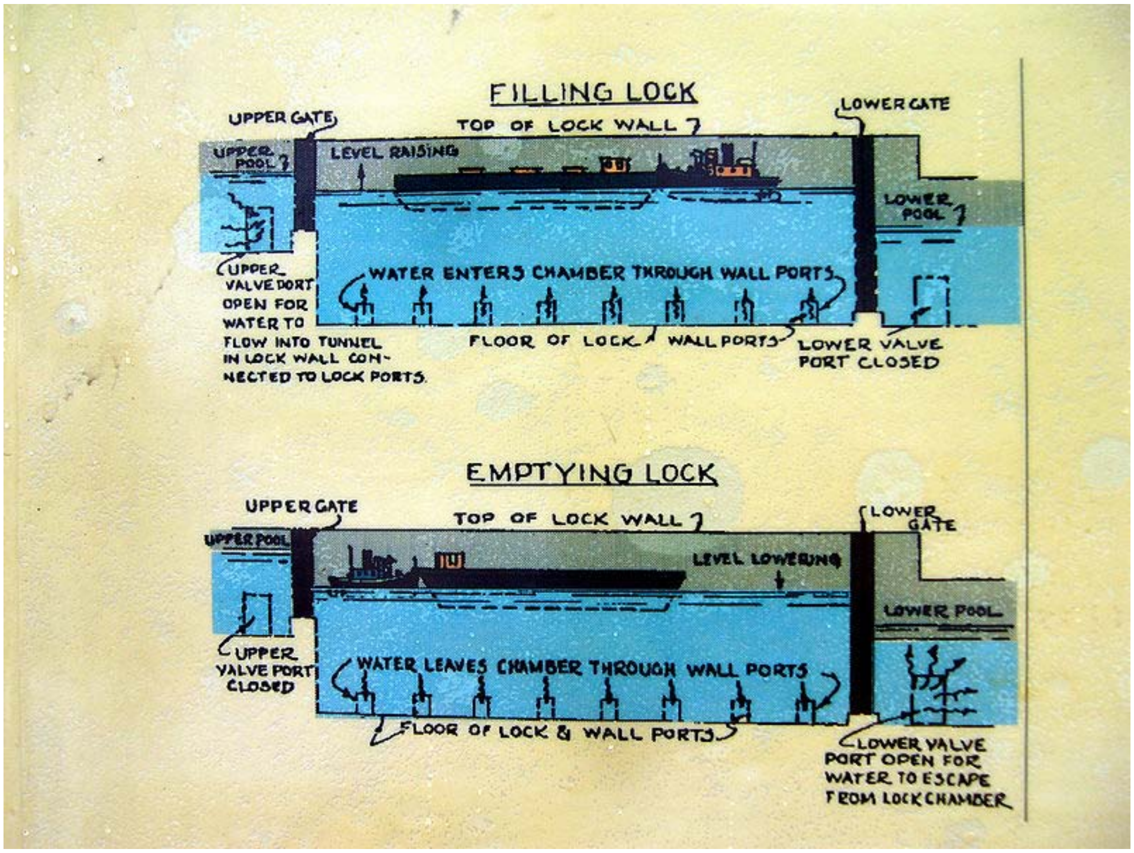
The principle of operating a lock is simple. For instance, if a boat travelling downstream finds the lock already full of water:

- 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

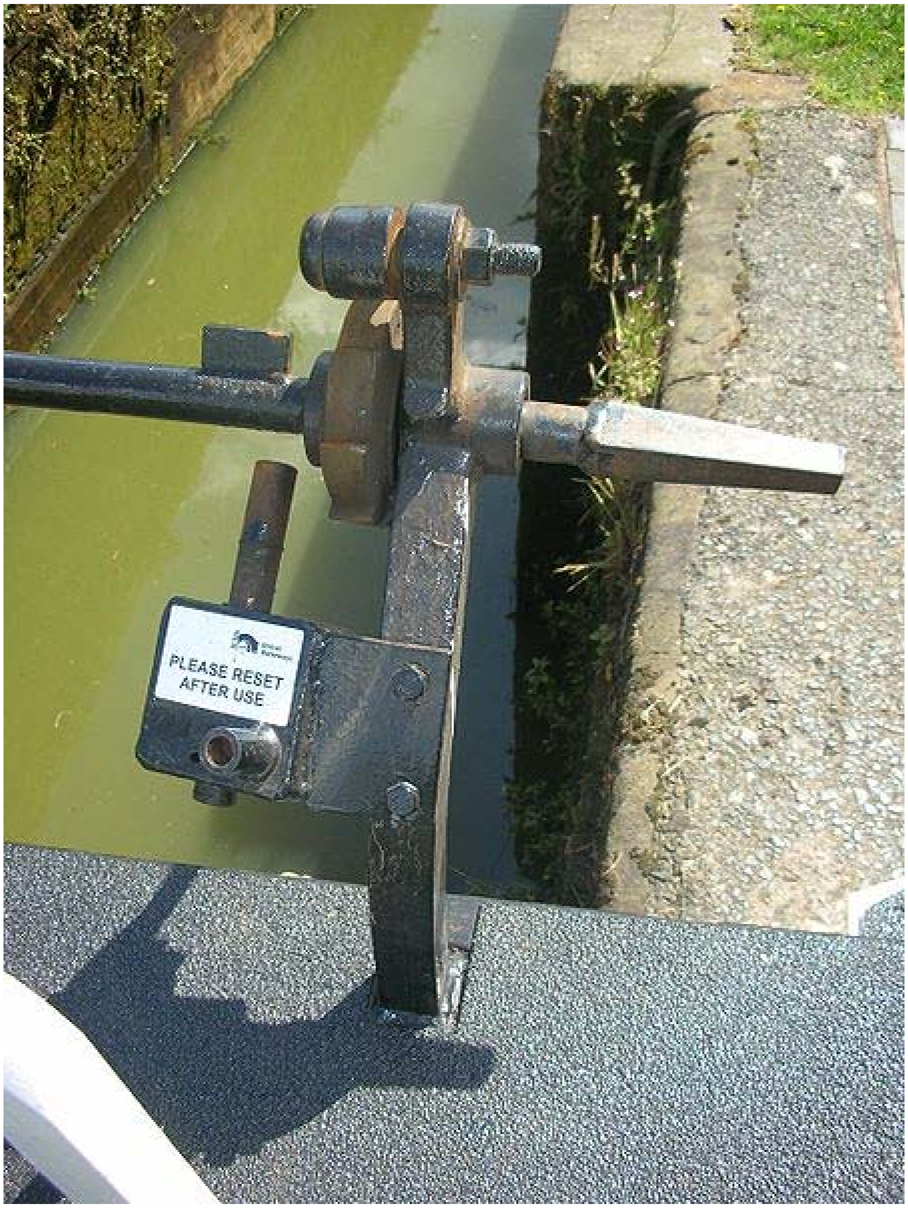
The main feature of a lock. It is a watertight (masonry, brick, steel or concrete) enclosure which can be sealed off from the pounds at either end by means of *gates*. The chamber may be the same size (plus a little manoeuvring room) as the largest vessel for which the waterway was designed; sometimes 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* (see below) onto the end of the axle and turns the windlass perhaps a dozen times. This rotates the pinion and lifts the paddle. A pawl engages with the rack to prevent the paddle from dropping inadvertently while being raised, and to keep it raised when the windlass is removed, so that the operator can attend to other paddles. Nowadays it is considered discourteous and wasteful of water to leave a paddle open after a boat has left the lock, but in commercial days it was normal practice. To lower a paddle the pawl must be disengaged and the paddle wound down with the windlass. Dropping paddles by knocking the pawl off can cause damage to the mechanism – the paddle gear is typically made of cast iron and can shatter or crack when dropped from a height. In areas where water-wastage due to vandalism is a problem, (for example the Birmingham Canal Navigations), paddle mechanisms are commonly fitted with vandal-proof locks (nowadays rebranded *water conservation devices*) which require the boater to employ a key before the paddle can be lifted. The keys are officially known as "water conservation keys", but boaters usually refer to them as *T-keys*, from their shape, *handcuff key* because the original locks, fitted on the Leeds and Liverpool Canal, resembled handcuffs, *Leeds and Liverpool Keys* after that canal, or simply *Anti-Vandal Keys*.

Hydraulic paddle gear

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

Windlass ("lock key")

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

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

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

"Turning" a lock

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

"Lock Mooring"

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

Variations

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

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

- Single gates on narrow canals (locks approx. 7 feet / 2.1 m wide)
    - On most English narrow canals, the upper end of the chamber is closed by a single gate the full width of the lock. This was cheaper to construct and is quicker to operate with a small crew, as only one gate needs to be opened.
    - Some narrow locks (e.g. on Birmingham Canal Navigations) go even further. They have single gates at the lower end also. This speeds up passage, even though single lower gates are heavy (heavier than a single upper gate, because the lower gate is taller) and the lock has to be longer (a lower gate opens INTO the lock, it has to pass the bow or stern of an enclosed boat, and a single gate has a wider arc than two half-gates).
    - A few narrow locks imitate wide locks in having paired gates at both ends (e.g. Bosley, on the Macclesfield Canal)

- Steel Gates. Steel gates and/or balance beams are frequently used nowadays, although all-wooden versions are still fitted where appropriate.
    - Swinging gates: Even very large steel-gated locks still can use essentially the same swinging gate design as small 250-year-old locks on the English

canals. On English canals, steel gates usually have wooden mitre posts as this gives a better seal.
    - Sliding gates: Some low-head locks use sliding steel gates.
    - Guillotine gates: Some locks have vertically moving steel gates — these are quite common on river navigations in East Anglia. Sometimes just one of the pairs of swinging gates is replaced by a guillotine: for instance at Salterhebble Locks, where space to swing the balance beams of bottom gates of the lowest lock was restricted by bridge widening. On the River Nene most locks have this arrangement as in time of flood the top mitre gates are chained open and the bottom guillotines lifted so that the lock chamber acts as an overflow sluice. Guillotine gates are also used on the downstream side of larger locks such as the 23m Bollène lock on the River Rhône, the aperture being large enough for a boat to travel under it.
    - Vertically-rotating gates: Gates which, when open, lie flat on the canal bed and which close by lifting (London Flood Barrier).
    - Rotating-sector gates. Some of these work very like traditional swinging gates, but with each gate in the form of a sector of a cylinder. They close by rotating out from the lock wall and meeting in the centre of the chamber. Water is let in or out by opening the gates slightly: there are no paddles or other lock gear. The lock at Limehouse Basin, which gives access to the River Thames, is an example. A dramatically-large one can be seen at the Rotterdam flood defences (huge flood gates). There is a different type at the sea lock on the Ribble Link: this is a rising sector gate, which has a horizontal axis: the gate drops to the bed of the river to allow boats to pass.

- Alternate paddle gear
    - Some manually-operated paddles do not require a detachable handle (windlass) because they have their handles ready-attached.
    - On the Leeds and Liverpool Canal there is a variety of different lock gear. Some paddles are raised by turning what is in effect a large horizontal wing nut (butterfly nut) lifting a screw-threaded bar attached to the top of the paddle. Others are operated by lifting a long wooden lever, which operates a wooden plate which seals the culvert. These are known locally as "jack cloughs". Bottom gate paddles are sometimes operated by a horizontal ratchet which also slides a wooden plate sideways, rather than the more common vertical lift. Many of these idiosyncratic paddles have been "modernised" and they are becoming rare.
    - On the Calder and Hebble Navigation, some paddle gear is operated by repeatedly inserting a *Calder and Hebble Handspike* (length of 4" by 2" hardwood) into a ground-level slotted wheel and pushing down on the handspike to rotate the wheel on its horizontal axis.
    - On some parts of the Montgomery Canal bottom paddles are used in place of side paddles. Rather than passing into the lock through a culvert around the side of the lock gate, the water flows through a culvert in the bottom of the canal. The paddle slides horizontally over the culvert.

- Lock keepers. Some locks are operated (or at least supervised) by professional lock keepers. This is particularly true on commercial waterways, or where locks are large or have complicated features that the average leisure boater may not be able to operate successfully. For instance, although the Thames above Teddington (England) is almost entirely a leisure waterway, the locks are usually staffed. Only recently have boaters been allowed limited access to the hydraulic gear to operate the locks when the keeper is not present.

- Powered operation. On large modern canals, especially very large ones such as ship canals, the gates and paddles are too large to be hand operated, and are operated by hydraulic or electrical equipment. Even on smaller canals, some gates and paddles are electrically operated, particularly if the lock is regularly staffed by professional lock keepers. On the River Thames below Oxford all the locks are staffed and powered. Powered locks are usually still filled by gravity, though some very large locks use pumps to speed things up.

- Fish Ladders. The construction of weirs on rivers obstructs the passage of both fish and ships. Some fish such as trout and salmon go upstream to spawn. Measures such as a fish ladder are often taken to counteract this.

- Weigh lock. A weigh lock is a specialized canal lock designed to determine the weight of barges in order to assess toll payments based upon the weight and value of the cargo carried.

Special cases

Lock flights

Flight of locks, Bratch, Staffordshire and Worcestershire Canal

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

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

"Flight" is not synonymous with "Staircase" (see below). 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

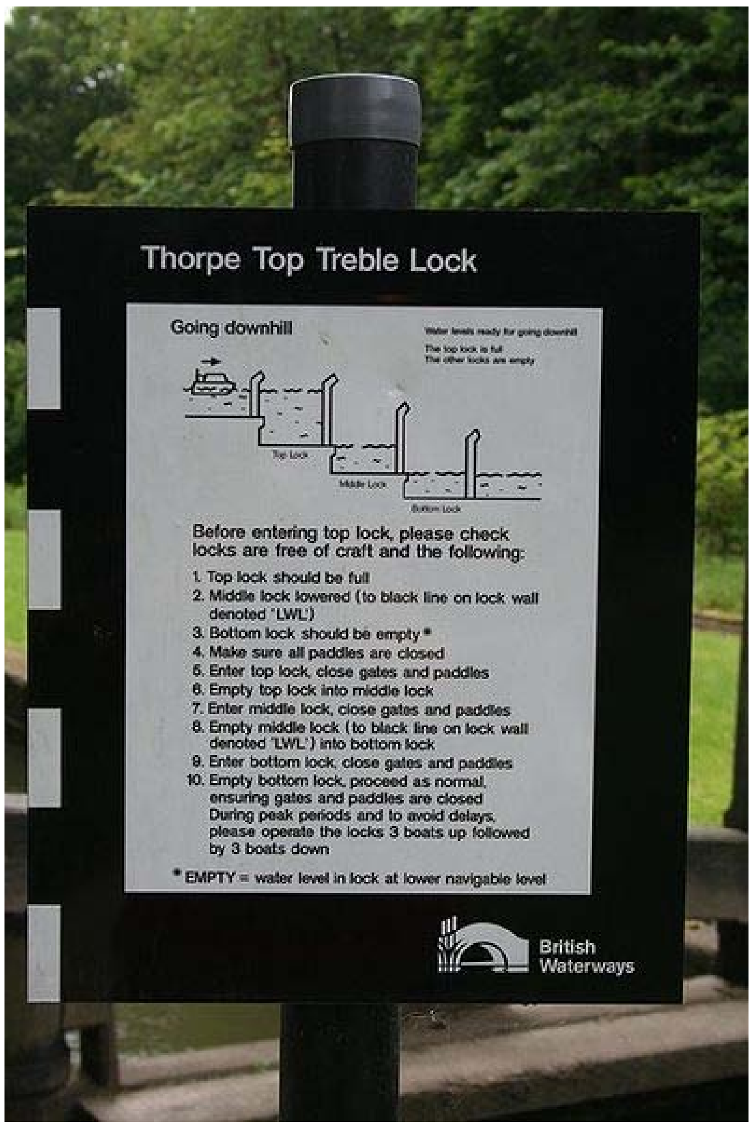
Staircase of five locks, dating from 1774, at Bingley, England

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.



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

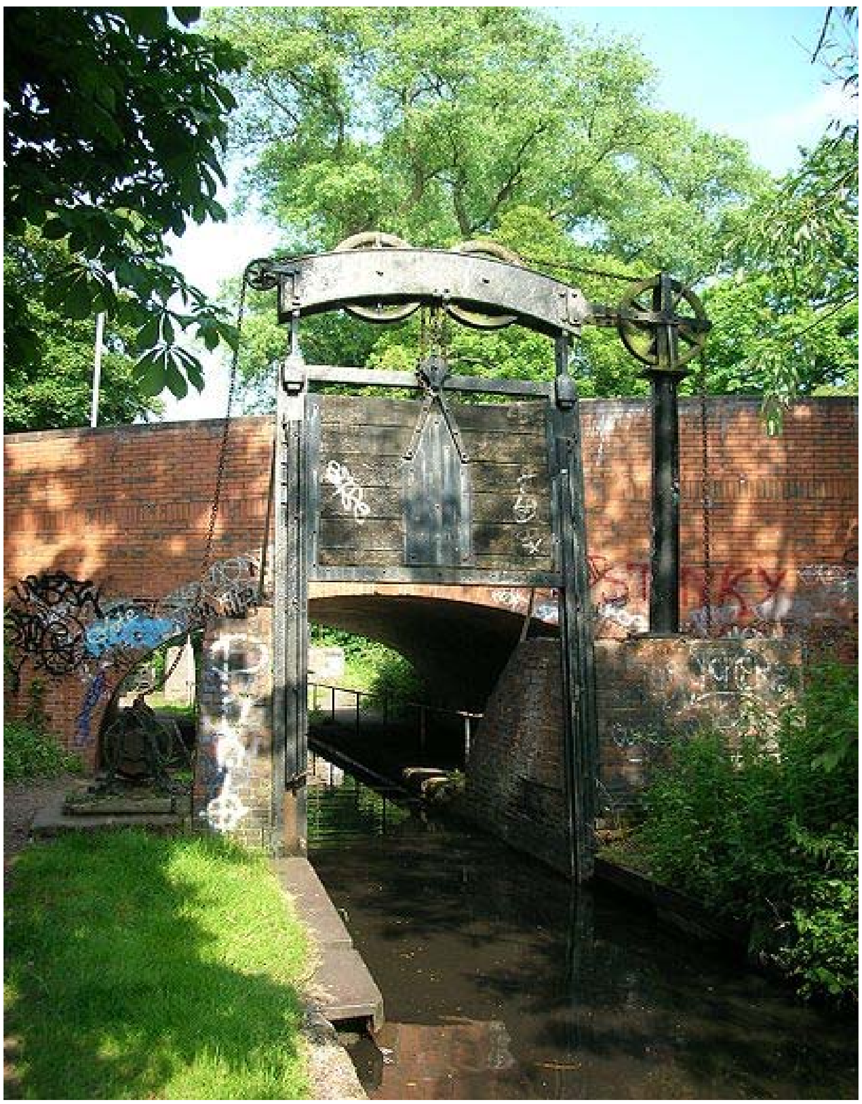
Locks can be built in parallel (i.e. side by side). This can be called *doubling, pairing, or twinning*. There are several examples (in this case called "double locks") on the Trent and Mersey Canal north of Harecastle Tunnel. Doubling gives advantages in speed: avoiding hold-ups at busy times; or increasing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

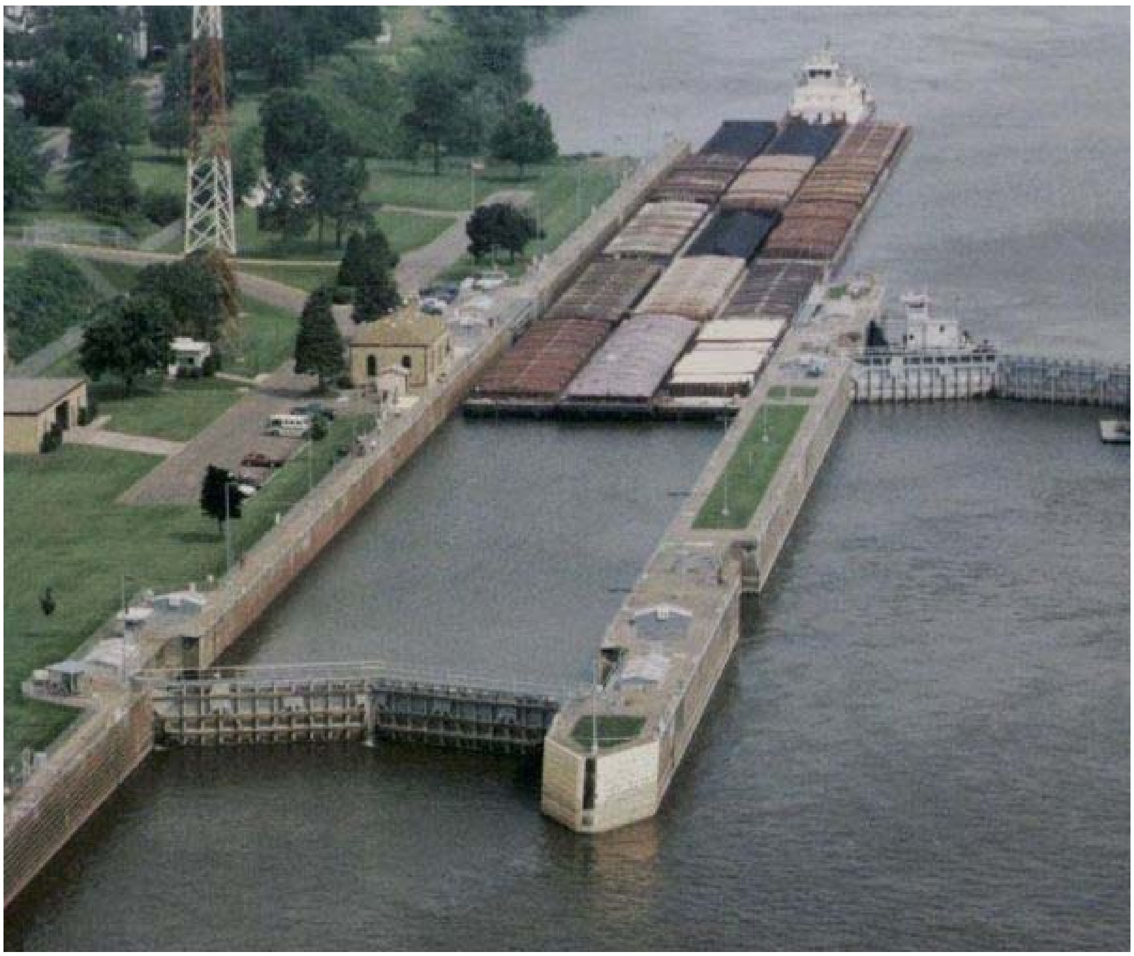
Loosely, any lock connecting tidal with non-tidal water. This includes a lock between a tidal river and the non-tidal reaches; or between a tidal river and a canal; or a sea lock. However, the term usually refers specifically to a lock whose method of operation is affected by the *state* of the tide.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

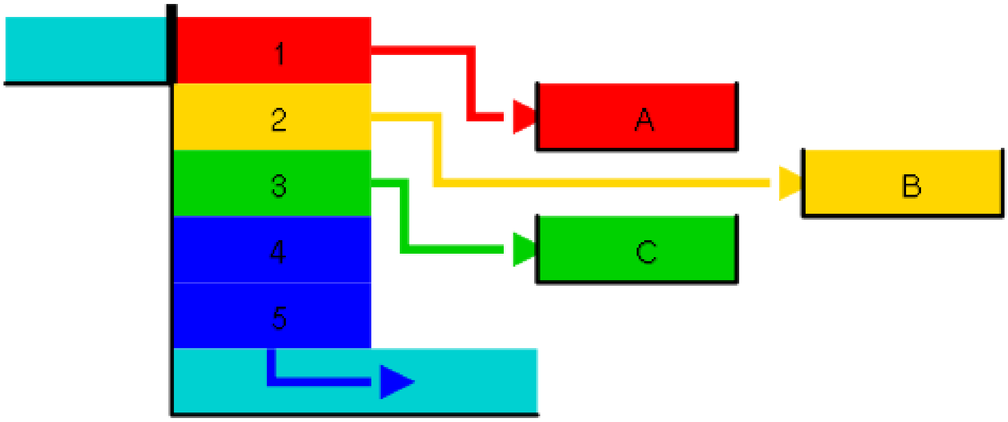


Diagram of water saving basins (descending)

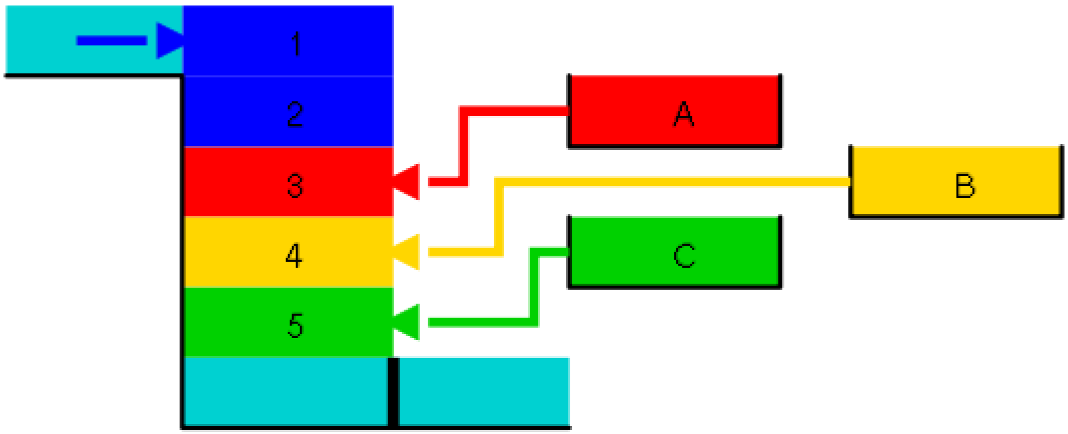


Diagram of water saving basins (ascending)

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.

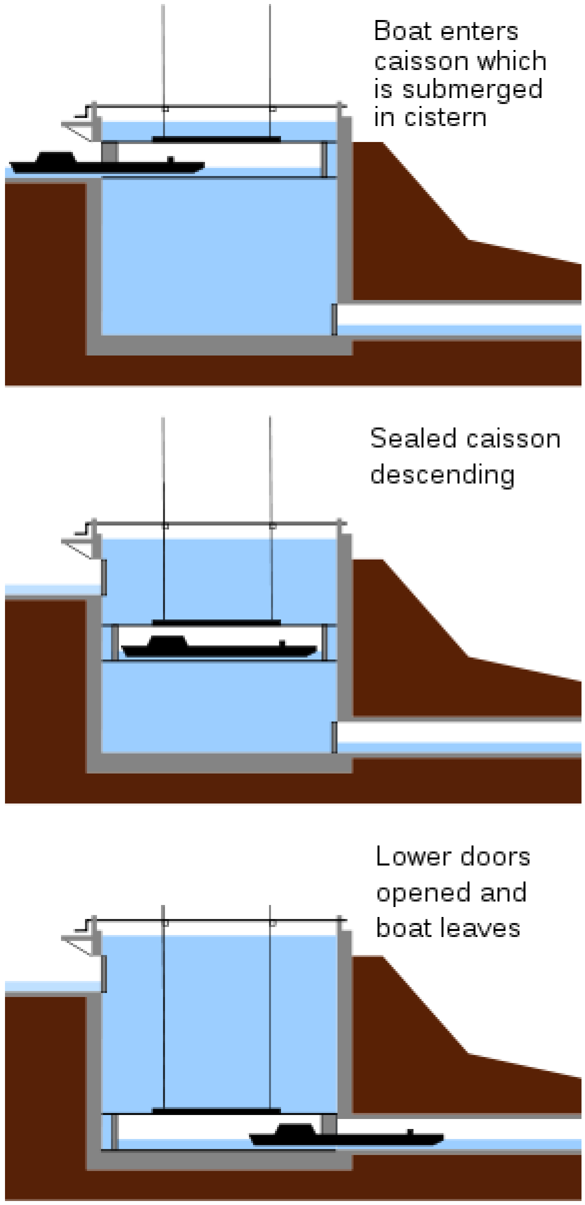
The Victorian Anderton Boat Lift, the world's first vertical boat lift, linking the Trent and Mersey Canal and the River Weaver in Cheshire, has recently been restored. The world's highest boat lift of Strépy-Thieu in Belgium raises or lowers 1,350 tonnes boats by 73.15 metres.

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