Hydraulic structures

Module 2: Hydraulic structures. In this module the topics cover sediment transport phenomena and watershed sediments budget, erosion and erosion control structures and its design, basics of sediment in natural watercourses and design of sediment control structures, like weirs, check dams, debris dams and side walls. Finally, structures for flood control, like reservoirs, levees, bypass canals and urban storm water drainage structures are discussed. Principle features of these structures, basic design and design criteria are presented

14. Hydraulic structures

In this lesson hydraulic engineering and structures are discussed on a basic informative level. The students will get familiar with types of structures and the basic principles of design.

14.1 Introduction

Hydraulic engineering is a sub-discipline of civil engineering concerned with the flow and conveyance of fluids, principally water. This area of engineering is intimately related to the design of dams, channels, canals, levees, elevators, and to environmental engineering.

Common topics of design for hydraulic engineers includes *hydraulic structures*, including dams and levees, water distribution networks, water collection networks, storm water management, sediment transport, and various other topics.

14.2 Design of hydraulic structures

Hydraulic design involves the application of flow theory to the design of various water containment and control structures. The designer should ensure that the structure and the systems will function effectively and economically under all foreseeable service conditions. Hydraulic structures must be capable of withstanding flow conditions and forces caused by both static and flowing water loading. They must be so designed as to last over their design life span and be resistant to deterioration, aging, and extemporaneous forces due to weather extremes and earthquakes.

In designing a hydraulic structure, the designer chooses from many options available, and from past experience, that particular design believed to be the most cost-effective, functional, and safe.

Examples of waterworks and systems comprising many detailed hydraulic structural components are the following: raw water storage reservoirs, dams, hydroelectric power plants, pumping stations, intake structures and diversion weirs, tunnels, canals and pipelines, water treatment and sewerage disposal works, flocculation tanks, clarifiers, control and measuring structures, storm-water draining and confining structures, clear water (municipal) reservoirs, water towers, surge tanks, spiral casings, draft tubes, manifolds, energy dissipating devices, spillways, and stilling basins.

In addition to the above listing of structures, which are concerned mainly with water supply and distribution, there are also the following categories of water-related structures and water-control operations not further discussed in this article. These are also dealt with by hydraulic design engineers, with the aid of hydraulic theory and its application, hydraulic engineering:

- harbors, docks, piers, seawalls, breakwaters, coastal and beach protection, locks and canals
- ocean pipelines for effluents, gas or petroleum products, moorings, and anchorages
- deep ocean construction, floating, guyed, or free-standing platforms such as used for oil rigs
- undersea tunnels, manmade islands in oceans and estuaries, coastal engineering, lighthouses
- bridges and piers for road and rail, river training works, offshore airport runways, caissons
- hydraulic-fill dams, slurry and tailings dams, hydraulic dumping, hydraulic mining (monitoring)
- underwater excavation, dredging, deep-drilling, hydrofracturing, tremie-concrete foundations

14.3 Concepts and principles for sustainable hydraulic structures

The following considerations apply to the design of sustainable hydraulic structures: *sustainability, stochastic design, modeling difficulties,* and *structural integrity.*

- *Sustainability.* The concept of sustainability of a water resource development includes the design of structures, which with proper maintenance should last indefinitely or which if destroyed cause only a manageable disruption of living conditions.
- *Stochastic Design.* Design procedures should provide for any uncertainty in the variables, which enters from input uncertainties to design criteria. For hydraulic structures design in the water resources context, one has the following main sequence of criteria to satisfy, individually and collectively.
- *Hydrology:* data must be adequate, well understood, and the information stochastically modelled.
- *Hydraulics:* Methodology must be sound, adequate to deal with the spatial and temporal variables.
- *Hydraulic structures:* Components must be designed to resist all loads, be permanent, maintainable, and cost effective.
- *Environment: S*ystems must comply with the social order, be economical, and natural environment friendly, in perpetuity.

15. Watershed sediment budget

This chapter briefly presents methods for estimating sediment production and yield in a catchment (watershed) as a result of erosion. At the end of this lesson, the students will be able to estimate the sediment yield from a catchment.

15.1 Erosion

Erosion is displacement of solids (sediment, soil, rock and other particles) usually by the agents of currents such as, wind, water, or ice by downward or down-slope movement in response to gravity or by living organisms (in the case of bioerosion). There are two different types of erosion "mechanical erosion" and "chemical erosion" Each of these has a different effect on the environment. Mechanical erosion would include water, wind, sun, ice, natural disasters such as earthquakes and shoreline erosion. Chemical erosion would be acid rain, over use of fertilizer, human land use, deforestization and overgrazing.

Erosion is an intrinsic natural process but in many places it is increased by human land use. Poor land use practices include deforestation, overgrazing, unmanaged construction activity and road or trail building. Land that is used for the production of agricultural crops generally experiences a significant greater rate of erosion than that of land under natural vegetation.

15.2 Natural factors

The processes of rock cracking, mass movement, erosion, transportation, and deposition modify natural slopes. Due to weathering, rock is broken up into small fragments or particles. Being triggered by exogenous agents of rainfall and earthquakes, etc., the slope may partly or wholly collapse through the action of gravity, a process known as mass movement. Thus, earth slopes are formed. With the effects of water and wind, etc., soil is detached, moved, and deposited repeatedly on such an earth slope. This soil erosion may be grouped into natural and anthropogenic erosion. Types of erosion differ greatly in their morphology and state of occurrence, and are obviously determined by a variety of factors, including causative and incentive factors.

Soil erosion is predicted through an erosion model using available data on rainfall, hydrologic properties, soil properties, topography (slope steepness, slope length, etc.), and crop management and erosion-control practice for the area of interest.

15.3 Sediment yield

15.3.1 Erosion prediction

Soil erosion prediction models play an important role both in meeting practical needs of soil conservation goals and in advancing the scientific understanding of soil erosion processes. They are used to help land managers choose practices to reduce erosion rates. Erosion models are also used for engineering purposes, such as predicting rates of sediment loading to rivers, estuaries and reservoirs. Erosion models and their results are used as a basis for regulating conservation programs. Models are used wherever the costs or time involved in making soil erosion measurements are prohibitive.

In selecting or designing an erosion model, a decision must be made as to whether the model is to be used for on-site concerns, off-site concerns, or both. Conservationists refer to this process as soil loss, referring to the net loss of soil over only the portion of the field that experiences net loss over the long-term (excluding deposition areas). Off-site concerns, on the other hand, are associated with the sediment that leaves the field, which we term here sediment yield. Sediment originated in rainfall erosion flows downstream in a body of turbid water. The flow of turbid water changes the appearance of the river, and results in a loss of its amenity value.

Erosion models fall into two broad categories: material and mathematical (also know as "formal"). Material models are physical representations of the system being modeled, and may be either iconic or analog. Iconic models are physical models that are composed of the same types of materials as the system that is being modeled, but simpler in form.

15.3.2 Universal Soil Loss Equation (USLE)

The USLE was developed by applying statistical multivariate regression techniques to the large data bases collected by the USDA Agricultural Research Service.

The erosion risk (A=annual soil loss) is calculated from a number of factors that have been measured for all climates, soil types, topography and kinds of land. This technique helps to predict erosion. It also identifies erosion-sensitive areas. The factors are combined in a number of formulae of the Universal Soil Loss Equation, which returns a single number, the tolerance factor, equivalent to predicted erosion in ton/ha:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \qquad (15.1)$$

where:

- *A* Average annual soil loss: the predicted erosion or tolerance factor in ton/ha, calculated from all others.
- *R* Rainfall erosivity factor: a factor dependent on climate and likelihood of extreme events.
- *K* Soil erodibility factor: an estimate made from soil properties as catalogued in the literature. It depends on the particle sizes and proportions of sand, silt and clay, organic matter, granularity and profile permeability to water.
- *L* Slope length factor: the slope length is the length of the field in a down-slope direction. The larger slope length, the more water accumulates at the bottom of the field, increasing erosion. It also depends on the land's slope.
- *S* Slope steepness factor: calculated from the slope of the land in (%).
- *C* Cover management factor: depends on crop growth rate in relation to the erosivity variation in the climate.
- *P* Supporting practice factor: reflects the use of contours, strip cropping and terracing.

15.3.3 Other equations for sediment yield estimation

The sediment yield from individual river catchments varies from as little as 1 t/km^2/year to as much as 50 000 t/km^2/year.

The USLE is not suited for the estimation of sediment yield from large catchments. *Garde* and *Kothyari* analyzed data from Indian catchments of small to large sizes, and proposed the following equation for sediment yield:

$$V_s = 0{,}02\,p^{0,60} F_e^{1,7}\,\overline{S}^{0,25} D_d^{0,10} \left(\frac{P_{\max}}{p}\right)^{0,19} \qquad (15.2)$$

Here V_s is the annual sediment yield expressed in centimeters of absolute volume, $\overline{S}$ is the average slope of the catchment, p is the average annual precipitation expressed in centimeters and D_d is the drainage density expressed in km^{-1}. F_e is the erosion factor, defined as:

$$F_e = \frac{1}{a}(0{,}80a_A + 0{,}60a_G + 0{,}30a_F + 0{,}10a_W) \qquad (15.3)$$

in which a is the total catchment area out of which a_A = arable area, a_G = grass land area.a_F = forest area and a_W = waste land area.
The range of data used in developing the equation above is as given below:

a = 347 km^2 to 132 090 km^2
F_e = 0.28 to 0.79
D_d = 0.04 to 0.31 km^{-1}
Fe = 0.005 to 0.045
p = 38.6 cm to 455.6 cm.

The areas required for calculation of F_e may be obtained from the soil cover map or land-use map of the catchment. A map giving the drainage network in the catchment will have to be used to determine D_d.
The significant features of Eq. (15.2) are that it takes into account practically all the factors which affect sediment yield and that it is derived using field data covering a wide range of pertinent variables. As such, the equation is recommended for use in preliminary estimates of sedimentation rates in reservoirs.

15.3.4 Process-based erosion models

Process-based erosion models (also termed physically-based) attempt to address soil erosion on a relatively fundamental level using mass balance differential equations for describing sediment continuity on a land surface. The fundamental equation for mass balance of sediment in one dimension on a hillslope profile is given as:

$$d(cq)/dx + d(ch)/dt + S = 0 \qquad (15.4)$$

where c (kg/m^3) is sediment concentration, q (m^2/s) is unit discharge of runoff, h (m) is depth of flow, x (m) is distance in the direction of flow, t (s) is time, and S (kg/m^{2}s) is the source/sink term for sediment generation. Equation (15.4) is exact. It is the starting point for development of physically-based models. The differences in various erosion models are primarily: a) whether the partial differential with respect to time is included, and b) differing representations of the source/sink term, S. If the partial differential term with respect to time is dropped, then the equation is solved for the steady-state, whereas the representation of the full partial equation represents a fully dynamic model.
The disadvantage of the process-based model is complexity. Data requirements are greater, and with every new data element come the opportunity to introduce uncertainty. Model structure interactions are also large.

16. Erosion control and protection

In this chapter the approaches for erosion prevention and control are described, as well as basics of erosion control

16.1 Erosion control measures

Erosion control is the practice of preventing or controlling erosion in agriculture, forestry, land development and construction. This usually involves the creation of some sort of physical barrier, such as vegetation or rock, to absorb some of the energy of the wind or water that is causing the erosion.

Examples of some erosion control methods include:

- *Conservation tillage***.** No-till farming is considered a kind of conservation tillage system and is sometimes called *zero tillage*. It is a way of growing crops from year to year without disturbing the soil through tillage.
- *Contour ploughing* or *contour farming* is the farming practice of plowing across a slope following its contours. The rows formed have the effect of slowing water run-off during rainstorms so that the soil is not washed away and allows the water to percolate into the soil. In contour plowing, the ruts made by the plow run perpendicular rather than parallel to slopes, generally resulting in furrows that curve around the land and are level

Figure 16.1 Terraces, conservation tillage, and conservation buffers

- *Cover crops* is any annual, biennial, or perennial plant grown as a monoculture or polyculture, to improve any number of conditions associated with sustainable agriculture
- *Gabions* are wire mash cages, cylinders, or boxes filled with earth or sand that are used among others, for erosion control dams or foundation building, to stabilize shore against erosion, or retaining walls, temporary floodwalls, to filter silt from runoff, and for small or temporary dams. They may be used to direct the force of a flow of flood water around a vulnerable structure.
- *Hydroseeding* (or hydraulic mulch seeding, hydro-mulching) is a planting process which utilizes a slurry of seed and mulch.
- *Mulching* is a protective cover placed over the soil, primarily to modify the effects of the local climate and reduce erosion and soil loss. A wide variety of natural and synthetic materials are used.
- *Polyacrylamide* is a soil conditioner on farmland and construction sites for erosion control

- *Reforestation* is the restocking of existing forests and woodlands which have been depleted, with native tree stock. The term reforestation can also refer to *afforestation*, the process of restoring and recreating areas of woodlands or forest that once existed but were deforested or otherwise removed or destroyed at some point in the past. The resulting forest can provide both ecosystem and resource benefits and has the potential to become a major carbon sink. Reforestation can occur naturally if the area is left largely undisturbed. Native forests are often resilient and may re-establish themselves quickly. Conceptually, it involves taking no active role in reforesting a deforested area, but rather just letting nature take its course.
- *A riparian zone* is the interface between land and a flowing surface water body. Plant communities along the river margins are called riparian vegetation, characterized by hydrophilic plants. Riparian zones are significant in ecology, environmental management, and civil engineering due to their role in soil conservation, their biodiversity, and the influence they have on aquatic ecosystems. Riparian zones occur in many forms including grassland, woodland, wetland or even non-vegetative. In some regions the terms *riparian woodland, riparian forest, riparian buffer zone* or *riparian strip* are used to characterize a riparian zone. Riparian zones may be natural or engineered for soil stabilization or restoration. These zones are important natural biofilters, protecting aquatic environments from excessive sedimentation, polluted surface runoff and erosion. They supply shelter and food for many aquatic animals and shade that is an important part of stream temperature regulation. When riparian zones are damaged, biological restoration can take place, usually by human intervention in erosion control and revegetation
- *Riprap* (also known as *rip rap, rubble, revetment, shot rock* or *rock armour*) is rock or other material used to armor shorelines against water erosion. Riprap reduces water erosion by resisting the hydraulic attack and dissipating the energy of flowing water or waves. The shape of rock is important. Coarse, angular rock, usually made by crushing or blasting, is more effective at ground reinforcement than round river rock. The velocity of water flow is generally the determining factor for size of stone. Riprap is often used in conjunction with a geotextile or in gabion baskets.
- *Strip farming* is a method of farming used when a slope is too steep or too long, or when other types of farming may not prevent soil erosion. It helps to stop soil erosion by creating natural dams for water, helping to preserve the strength of the soil. The term strip farming also refers to a method of dry farming.
- *Terracing*. In agriculture and forestry management, a *terrace* is a leveled section of a hilly cultivated area, designed as a method of soil conservation to slow or prevent the rapid surface runoff of irrigation or rainwater. Often such land is formed into multiple terraces, giving a stepped appearance. The human landscapes of rice cultivation in terraces that follow the natural contours of the escarpments like contour plowing.
- *Wattle* - mat of woven (willow) sticks and weeds; used in wall and dike construction, but also for afforestation on steep slopes..
- *Windbreaks* or *shelterbelts* are plantations usually made up of one or more rows of trees or shrubs planted in such a manner as to provide shelter from the wind and to protect soil from erosion. They are commonly planted around the edges of fields on farms.

16.2 Erosion control structures

16.2.1 Check dams

A *check dam* is a small barrier constructed of concrete, masonry, rock, gravel bags, sandbags, fiber rolls, or reusable products, placed across a constructed swale or drainage ditch. Check dams reduce the effective slope of the channel, thereby reducing the velocity of flowing water, allowing sediment to settle and reducing erosion.

Check dams reduce the effective slope and create small pools in swales and ditches. Reduced slopes reduce the velocity of stormwater flows, thus reducing erosion and promoting sedimentation. Use of check dams for sedimentation will likely result in temporary net removal of sediment because of the small detention time. Using a series of check dams will generally increase their effectiveness. A sediment trap may be placed immediately upstream of the check dam to increase sediment removal efficiency.

Check dams work by decreasing the effective slope in ditches and swales. An important consequence of the reduced slope is a reduction in capacity of the ditch or swale.

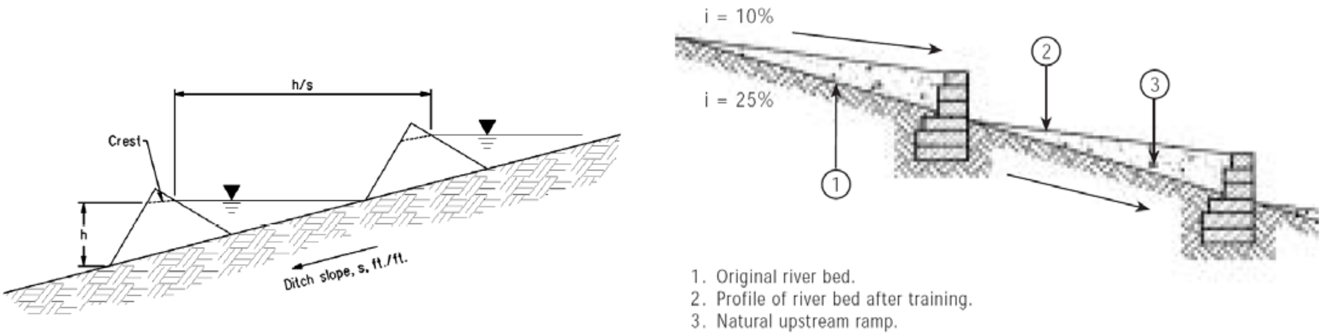

Figure 16.2 Earthfill check dams (a) and gabion check dams (b)

16.2.2 Debris flow and torrent control structures

Debris flow is defined as a type of mass movement that involves water-charged, predominantly coarse-grained inorganic and organic material flowing rapidly down a steep confined, pre-existing channel.It occurs in cases of heavy torrential rainfalls in erosion prone areas with steep slopes. This occurs often during simmer flash floods.
The primary function of debris flow control structures is to constrain or contain the coarse-grained portion of the debris flow.

Deposition of a channelized debris flow is the result of a number of conditions that can work singly or together. These include: decrease in channel gradient, loss of confinement of the debris and any impediments to flow, either natural or artificial. All lead to a separation of water from the flowing debris mass, which in turn changes the rheological characteristics of the mass, thus decreasing velocity and ultimately deposition.
The mass of the debris (t/m^3 or kg/m^3) may be determined with te following relation:

$$Y_o=Y_n/(1-n) \tag{16.1}$$

where Y_o is volume weight of the sediments (t/m^3 or kg/m^3), Y_n specific weight (kg/m^3 or $t/m^{3)}$; and n is porosity (40-70 %)

In general, debris flow control structures can be divided into two basic types: open and closed. Open control structures are designed primarily to *constrain* the flow of a channelized debris flow; closed control structures are designed primarily to *contain* a channelized debris flow.

Open debris flow control structures include:

- *Unconfined deposition areas*- referred to as “debris flow deposition works”, are areas on the debris fan that are designed and prepared to receive a portion or all of the debris from a channelized debris flow.
- *Impediments to Flow (Baffles)* - Impediments to flow, or baffles, are used primarily to slow down a debris flow and thereby encourage it to deposit. In some instances they are used to deflect the flow. Impediments can be either natural or artificial. When trees are used, they have been referred to as “debris flow dispersing forest zones”. Artificial impediments can be constructed of earth berms, timber, or steel, and function in much the same way as snow avalanche retarding structures. They can be placed as single units, in lines or staggered. Although they can be used by themselves, they are more commonly used in concert with other forms of control
- *Check Dams* Check dams, usually constructed in series in the transportation zone of a channelized debris flow, are used to reduce steep channel gradients locally and to minimize scour along the bottom and sides of the stream. They can, however, also be constructed on the debris fan (Figure

16.3), usually near the apex. This can artificially lower the gradient of the upper portion of the fan or help maintain flow within a particular channel.

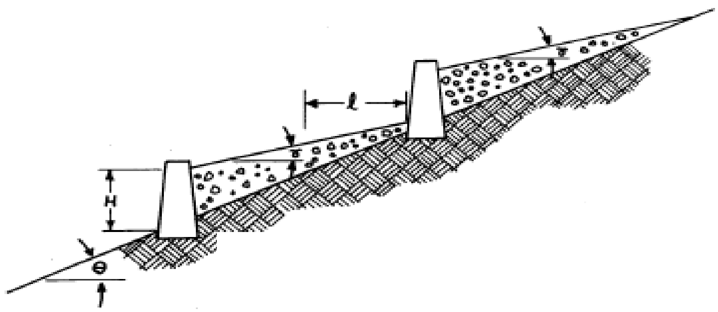

Figure 16.3 Spacing of check dams for debris and torrent control

Design considerations for check dams include the likely flow path immediately upstream of the structure, and the maximum discharge of the channelized debris flow past the location of the structure. Check dams, similar to gravity-retaining structures, are usually designed to withstand dynamic and point impact forces, sliding, overturning, uplift pressures, and foundation and abutment loadings. The spacing L between the check dams for torrent control should be:

$$L \geq 2l > \frac{H}{\tan\theta - \tan\gamma} \tag{16.2}$$

where θ is original channel gradient, H is height of the check dam, γ is angle of deposition of material behind check dam, and l is length of potential downhill scour.

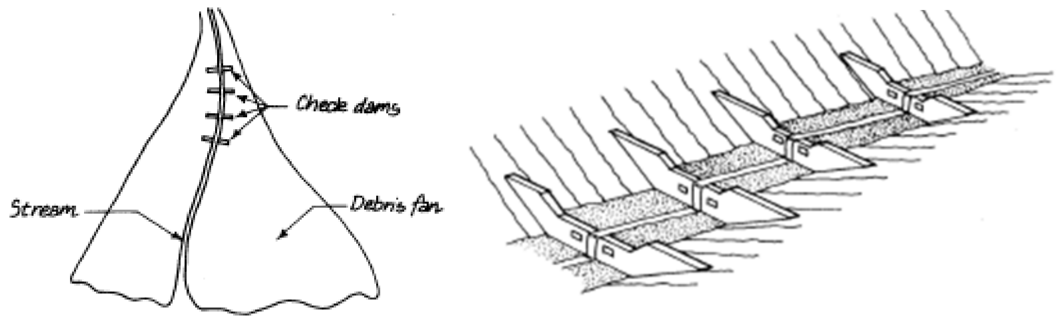

Figure 16.4 Disposition of check dams in a torrential valley

Check dams are commonly less than 5 m in height, but can extend up to 15 m. They can be constructed as timber and steel rock-filled cribs, and as stone masonry and gabion structures, but are now more commonly constructed of concrete and reinforced concrete.
The weir portion of the check dam must be designed to pass both flood water discharges and channellized debris flow discharges, the latter being potentially much larger.
Drainage holes or galleries are incorporated into the check dam to allow passage of normal stream flows during construction, and to allow drainage of water from the entrapped material afterwards.

Lateral Walls (Berms)
Lateral walls or berms, also referred to as "guiding walls" and "training walls", are constructed parallel to the desired path of the debris flow. They are used to constrain the lateral movement of a debris flow, encourage the debris to travel in a straight path, and thereby protect an area of or a structure on the debris fan. They can be constructed of earth berms, concrete, or composite structures. Forest belts, left or grown on both sides of the flow path, can perform a similar function. The main design consideration for lateral berms or barriers is the maximum discharge and flow depth of the debris flow at the location of the structure. The structure walls or berms, should be designed with a freeboard above the estimated flow

depth. These structures must be designed for both stability and flow hydraulics, and some form of erosion protection or armouring must be included in the design to minimize erosion and the addition of material from the structure to the debris flow mass. Erosion protection from coarse-grained debris can be in the form of rip-rap, dimension stone, concrete, or fibre reinforced shotcrete.

Deflection Walls (Berms)
Deflection walls or berms are referred to as "deflection dams" and "debris flow direction controlling works". They are similar to lateral berms in that they are usually built immediately downslope from the apex of the debris fan, and parallel to the desired path of the debris flow whose lateral movement they are used to constrain. They differ from lateral walls or berms in that they deflect the flow path and prevent it from going straight. They can be used to protect a structure, deflect the flow to another area of the fan, or increase the length of the flow path, thereby decreasing the overall gradient and encouraging deposition.

Terminal Walls, Berms, or Barriers
Terminal walls, berms, or barriers are constructed across the path of a debris flow to encourage deposition by presenting a physical obstruction to flow. They do this by increasing the length of the flow path. They are built with a finite length so that normal water flows and fine-grained sediment and water from the debris flow can find their way around either end of the berm. Once a debris flow has been deposited upstream of a terminal structure, the coarse-grained debris must be removed from the area.

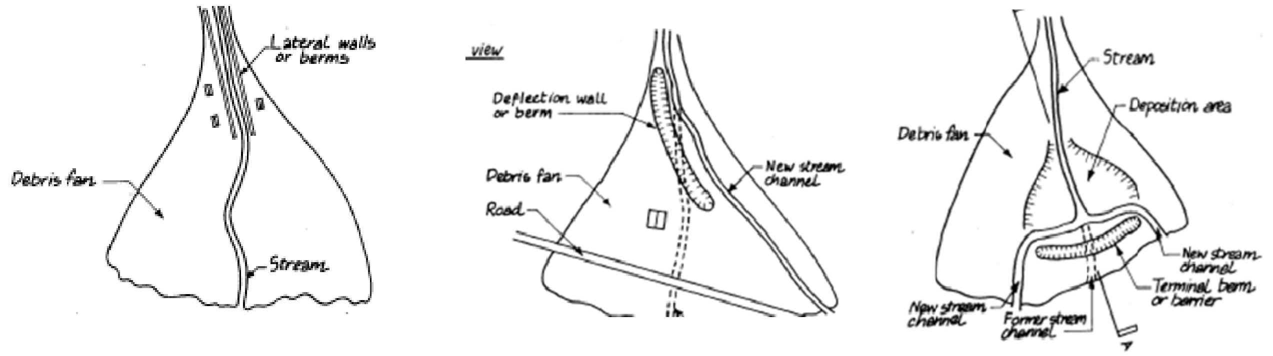

Figure 16.5 Lateral walls, deflection walls and terminal walls

Closed debris and torrent control structures

Debris racks, Grizzlies, other Debris-straining structures
These structures are used to separate the coarse-grained debris from the fine-grained debris and water of the debris flow, thus encouraging the coarse-grained portion to be deposited. These sorts of structures are referred to as "slit dams","separating dykes", debris fences" or "drainage screens". These are screens and mashes, either in a plane perpendicular to the flow, or three-dimensional structures made of various materials allowing the water and fine sediment flow, but preventing coarse sediment and debris flow. The 3-D structure allows that less material is used with the same effect as gravitational barriers. Various types of these structures are invented and used around the world. In Macedonia several torrents are controlled with a *Herheulidze* type of torrent mash – three dimensional reinforced concrete poles and beams interlocked under a specified angle.

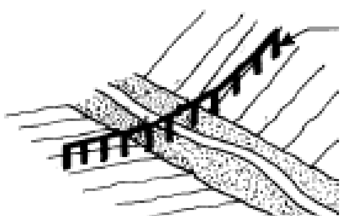

Figure 16.6 Debris rack

Debris barriers

Debris barriers and storage basins, with some form of debris-straining structure incorporated into the barrier. This system of debris flow control is similar to that achieved by a terminal berm or barrier, in that both are located across the debris flow path and designed to encourage deposition. Unlike terminal berms or barriers, however, debris barriers are designed as a closed barrier, or dam, so that all the coarse-grained debris is contained within the storage basin located upslope of the barrier. The debris-straining structure must be designed so that during normal conditions, stream water and bedload can travel through the structure and, after a debris flow, the water that was in the flow and some of the fine-grained sediment can escape.

17. Sediment transport

Upon completion of this lesson, the students will be able to calculate the various sediment transportation processes in watercourses.

17.1 Introduction

Sediment is any particulate matter that can be transported by fluid flow and which eventually is deposited as a layer of solid particles on the bed or bottom of a body of water or other liquid. *Sedimentation* is the deposition by settling of a suspended material.
River sediment is mainly formed by the physical and chemical disintegration of rocks in the catchment as the result of surface rainfall erosion. Catchment surfaces supply the rivers with sediment.
In a river, depending on the energy of the water movement, the bed sediment will be rolling, or sliding in continuous contact with the bed or will be moving along the bed by jumps (saltation), or will be going into suspension. Usually, the transport of particles by rolling, sliding and saltation is called bed-load transport, while the suspended particles are transport as suspended load transport. A sharp distinction between these two modes of transport is not possible. The equilibrium of a particle on the bed of a river is disturbed if the resultant effect of the disturbing forces (drag force, lift force, viscous force on the particle surface) becomes greater than the stabilizing forces as gravity and cohesion.
The different modes of the transport of (non-cohesive) sediments as bed load and as suspended load will be presented. The formulae for the calculations of the transport of the total load will be exposed, as well as their domain of application.

17.2 Water-sediment mixture

The flow of water over a mobile bed has the ability to entrain the sediments (solid particles); a water-sediment mixture displaces itself in the water-course. The movement of sediments - erosion*, transport, deposition* - modifies the flow, but also the channel bed, its elevation, slope and roughness. The interaction between water and sediments makes the problem a coupled one. When the bed is a *mobile* one, the hydraulics must concern itself with both the flow of the liquid phase, namely the mixture, and the movement of the solid phase, namely the sediments in the mixture.
A characterization of the liquid and the solid phase of a water-sediment mixture is a difficult task. *Liquid* phase is rather well described by: its density, ρ , its viscosity, μ , the average velocity of the flow, U , and the friction velocity, $u*$. *Solid* phase is more difficult to characterize; considered should be: the size of the solid particles, given by its granulometric curve, which includes different types of diameters such as d_{50} , d_{90} , d_{35} , etc., the form of these particles, the density of the particles, ρ_s , together, these parameters can be defined by the settling velocity of the particles, v_{ss} , and possibly, the cohesion between the particles.

17.3 Modes of transport

The transport of sediments by flow of water is the entire solid transport which passes through a cross section of a watercourse. Traditionally (but a bit artificially) the transport of sediments is classified in different modes of transport which correspond to different physical mechanisms.
In a watercourse the sediments, namely the solid phase, are transported as:

- *bed load*, q_{sb} volumetric solid discharge per unit width [m^3/sm] when the particles stay in close contact with the bed and displace themselves by gliding, rolling or (shortly) jumping ; this type of transport concerns the larger particles ;
- *suspended load*, q_{ss} when the particles stay occasionally in contact with the bed and displace themselves by making more or less large jumps remaining surrounded by water; this type of transport concerns the smaller particles;
- bed load + suspended load, being the (total) *bed-material load*, $q_s = q_{sb} + q_{ss}$, when the particles stay more or less in continuous contact with the bed;
- *wash load*, q_{sw} when the particles are almost never in contact with the bed and are washed through the cross section by the flow ; this type of transport concerns the finest particles.

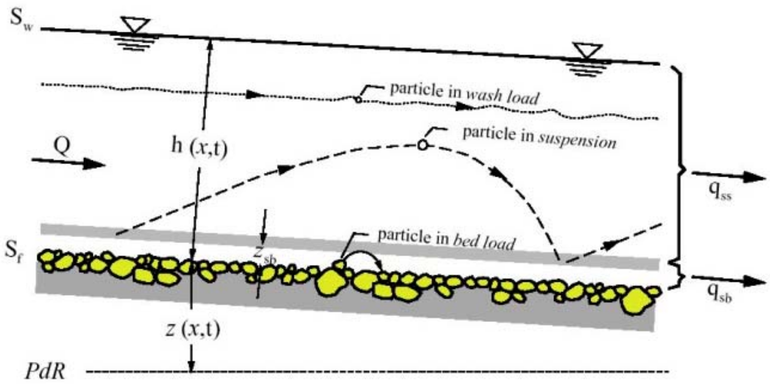

Figure 17.1. Modes of transport

The transport of sediments, namely the erosion of the bed, commences upon attainment of a certain critical value, which can be parameterized, for example, by the critical shear stress τ_{ocr}.
It will be useful to give limiting values for the separation of the different modes of transport. Given are purely indicative values using the ratio of the shear velocity of the flow u_*, and the settling velocity of the particles, v_{ss}:

beginning of bed-load transport	$u_* / v_{ss} > 0{,}10$	*(17.1)*
beginning of suspended load transport	$u_* / v_{ss} > 0{,}40$	*(17.2)*

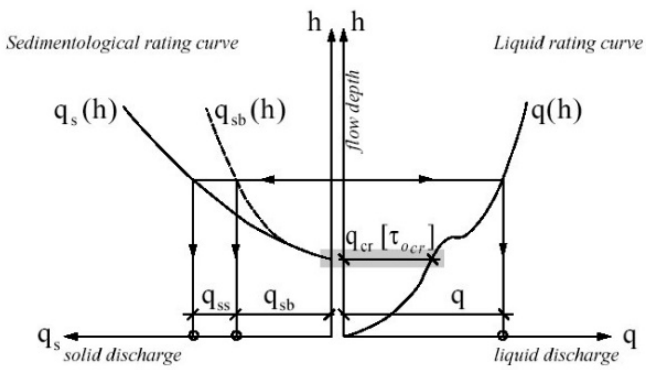

Figure 17.2 Rating curves for liquid discharge and solid discharge.

The different modes of transport of sediments, quantified in form of solid discharge, q_{sb}, q_{ss} and q_s, should be related to the liquid discharge, q. It gives the relation of the "sedimentological" rating curve, Figure 17.2, for a given cross section of the channel. This curve together with the "liquid" rating curve give a rather complete hydraulic description for a given cross section of a channel having a mobile bed.

17.4 Settling velocity

For a fluid to begin transporting sediment, the bed shear stress exerted by the fluid must exceed the critical shear stress of the bed. Once this critical stress is exceeded, the way in which the sediment is transported depends on the characteristics of the sediment and the fluid. If a fluid, such as water, is flowing, it can carry suspended particles. The *settling velocity* is the minimum velocity a flow must have in order to transport, rather than deposit, sediments, and (for a dilute suspension) is given by *Stokes*' Law:

$$w = \frac{2(\rho_p - \rho_f)gr^2}{9\mu} \tag{17.3}$$

where w is the settling velocity, ρ is density (the subscripts p and f indicate particle and fluid respectively), g is the acceleration due to gravity, r is the radius of the particle and μ is the dynamic viscosity of the fluid. This equation is only valid for particle *Reynold's* numbers <1.

If the flow velocity is greater than the settling velocity, sediment will be transported downstream as *suspended load*. As there will always be a range of different particle sizes in the flow, some will have sufficiently large diameters that they settle on the river or stream bed, but still move downstream. This is known as *bed load* and the particles are transported via such mechanisms as *saltation* (jumping up into the flow, being transported a short distance then settling again), rolling and sliding. Saltation marks are often preserved in solid rocks and can be used to estimate the flow rate of the rivers that originally deposited the sediments.

17.5 Bed-load transport

Transport as bed-load is the mode of transport of sediments (see Figure 17.1) where the moving solid particles stay very close to the bed, $0 < z < z_{sb}$, which they may leave only temporarily. The displacement of the particles is intermittent; the turbulence plays an important role.

Considered will be the case where the bed of a channel is plane but mobile, composed of particles of uniform size and being non-cohesive. These particles displace themselves under the action of a uniform and steady flow. The forces, which enter into the description of the uniform and steady motion of a single particle, isolated and without cohesion, are :

the hydrodynamic force : $F_H \propto (u_* d / \nu)\rho d^2 u_*^2$ *(17.4)*

the submerged weight of the particle : $W_D \propto g(\rho_s - \rho)d^3$ *(17.5)*

where u_* is the friction velocity, considered as being proportional to the velocity of the particle.
The components of this two-phase flow are:

- the *fluid*, by its density ρ, and its viscosity ν ;
- the *solid material*, by its density, ρ_s, and a characteristic diameter, d;
- the *flow*, by its flow depth, h or R_h , the slope, S_f , and the gravity, g ; thus by the friction velocity,

  $u_* = \sqrt{\gamma R_h S_f}$, which characterizes the turbulence.

In all, there are thus 7 parameters.
A dimensionless analysis shows that the arguments which quantify the two-phase flow, such as the bed-load transport, can now be expressed by 4 dimensionless quantities, namely :

- *Reynolds* number of the particle:

$$R_{e*} = (u_* d / \upsilon) \tag{17.6}$$

- dimensionless shear stress:

$$\tau_* = \frac{\rho u_*^2}{(\gamma_s - \gamma)d} = \frac{\tau_o}{(\gamma_s - \gamma)d} = \frac{\gamma R_h S_f}{(\gamma_s - \gamma)d} \tag{17.7}$$

- densimetric *Froude* number of particle:

$$Fr_{*D} = \frac{u_*}{\sqrt{(s_s - 1)gd}} = \sqrt{\tau_*} \tag{17.8}$$

- relative depth: h/d or R_h/d

- relative density:

$$s_s = \rho_s/\rho \tag{17.9}$$

In addition, a dimensionless particle diameter can be obtained or:

$$d_* = d\left[(s_s - 1)(g/v^2)\right]^{1/3} \tag{17.10}$$

A relation was proposed by *Shields*, such as

$$\tau_* = f(Re_*) \quad \text{or} \quad \tau_* = f(d_*) \tag{17.11}$$

for the study of the beginning of erosion, expressed by the dimensionless shear stress, τ_{*cr} . Thus, a relation of the form:

$$\tau_{*cr} = f(Re_*) \tag{17.12}$$

gives a delimitation of the zone of "motion" from the zone of "no motion" of the particles; this was developed experimentally from laboratory data. The function of *Shields*, Eq. (17.12), given in graphical form in Figure 17.3, is generally agreed upon as being useful if the granulometry is uniform or almost so.

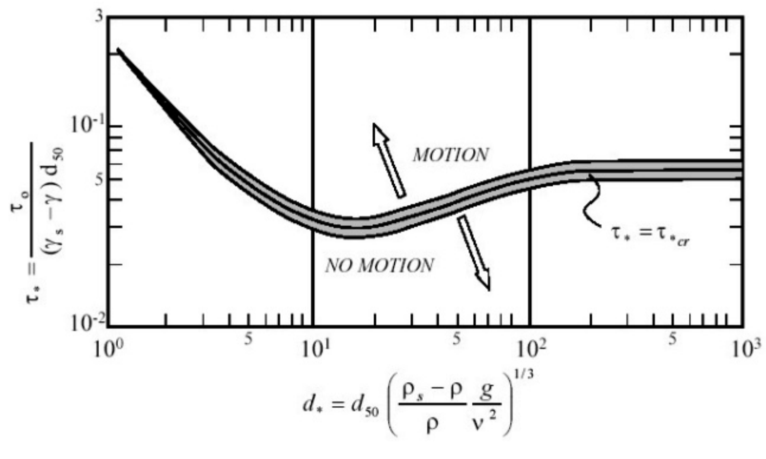

Figure 17.3 Dimensionless shear stress, τ = f (d*), after Shields-Yalin.*

The transport of sediments can be expressed as a function of these 4 dimensionless quantities, namely:

$$\Phi = f(d_*, \tau_*, R_h/d, \rho_s/\rho) \tag{17.13}$$

An expression for a dimensionless *intensity of the solid discharge* as the bed load may be:

$$\Phi = \frac{q_{sb}}{\sqrt{(s_s - 1) g d^3)}} \tag{17.14}$$

with q_{sb} [m^2/s] as the volumic solid discharge per unit width.
Since the terms, R_h/d and ρ_s/ρ, are included in the term, τ_*, and taking $\tau_* = f(Re_*)$ one can formulate now a rather simple relationship:

$$\Phi = f(\tau_*) \quad \text{or} \quad \frac{q_{sb}}{\sqrt{(s_s - 1) g d^3}} = f\left(\frac{\tau_o}{(\gamma_s - \gamma) d}\right) \tag{17.15a}$$

which is often written as:

$$\Phi = f(\psi) \tag{17.15b}$$

where $\tau_* \equiv \Psi^{1}$, and Ψ is called the dimensionless *intensity of shear stress*, applied upon the solid particles.

17.5.1 Bed-load relations

The formulae for a determination of the solid discharge as bed load give only reasonably satisfying results within a domain of the parameters for which the chosen formula has been established. Consequently, the application and use of such formulae has to be done with great care. Here will be given a selection of some of the many available formulae; their most characteristic hydraulic aspects will be pointed out.

Meyer-Peter et al.:

$$0{,}25 \rho^{1/3} \frac{(g'_{sb})^{2/3}}{(\gamma_s - \gamma) d} = \frac{\gamma R_{hb} \xi_M S_e}{(\gamma_s - \gamma) d} - 0{,}047 \tag{17.16}$$

where $g_{sb}' = g_{sb}(\gamma_s - \gamma)/\gamma_s$ is the solid discharge in weight under water and $g_{sb}/\gamma_s = q_{sb}$; R_{hb} is the hydraulic radius of the bed. For a non-uniform granulometry, the mean diameter, $d = d_{50}$, is taken as the equivalent diameter.

Einstein (1950):

$$p_e = 1 - \frac{1}{\sqrt{\pi}} \int_{-B_* \psi_* - 1/\eta_0}^{+B_* \psi_* - 1/\eta_0} e^{-\xi^2} d\xi = \frac{A_* \Phi_*}{1 + A_* \Phi_*} \tag{17.17}$$

namely a functional relation, see Eq. (17.15b), such as :

$$\Phi_* = f(\psi_*) \tag{17.18a}$$

The (universal) constants have now to be determined experimentally both for uniform and non-uniform granulometries; they are given by *Graf* as being:

$$A_* = 43{,}6 \qquad B_* = 0{,}143 \qquad \eta_o = 0{,}5 \tag{17.18b}$$

The relation, Eq. (17.17), is plotted in Figure 17.4, together with the data of Meyer-Peter et al. and Gilbert. The graphical representation facilitates the use of the above relation, Eq. (17.17). Since a non-uniform granulometry can be broken down into its fractions, i_{sb}/i_b , this relation is rather flexible. For a quasi-uniform granulometry, an equivalent diameter of $d = d_{35}$ can be taken.

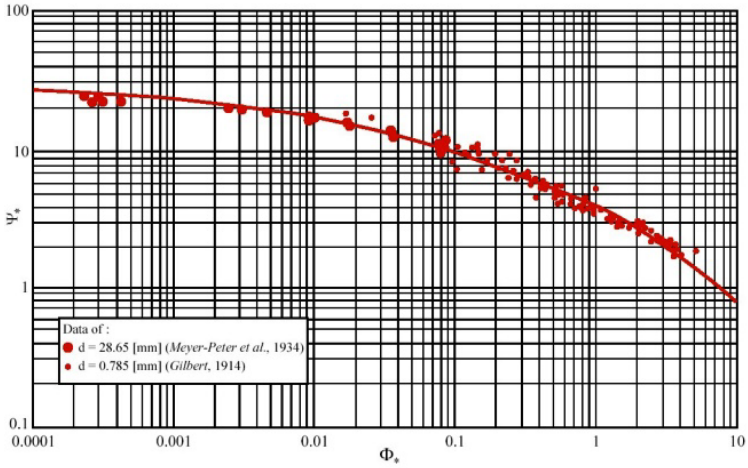

Figure 17.4 Equation of bed-load, Φ = f (Ψ*)*

The equation of Einstein, Eq. (17.17) and Figure 17.4, is well suited to uniform and non-uniform granulates over a large range of diameters, d > 0.7 [mm], and of bed slopes. It is used world-wide with great success.

17.6 Suspended-load transport

Transport of sediments in suspension is the mode of transport where the solid particles displace themselves by making large jumps, but remain in contact with the bed load and also with the bed. The zone of suspension is delimited by: $z_{sb} < z < h$.
Transport as suspended load could be considered as an advanced stage of transport as bed load; however the analytical methods do not allow a description of these two modes of transport with a single relationship.
The volumetric solid discharge in suspension per unit width, in a region delimited by $z_{sb} < z < h$, is obtained by :

$$q_{ss} = \int_{z_{sb}}^{h} c_s u \cdot dz \qquad (17.19)$$

where c_s (z) is the local concentration, Eq. (30), and $u(z)$ is the local velocity. However, this relation is valid for a single particle size, d or v_{ss} .
There exist different methods for the calculation of the suspended-load transport, but only the one of Einstein (1950) will be presented, being the most popular one.

$$q_{ss} = 11{,}6 c_{sa} u_*' z_{sb} \left| 2{,}303 \log\left(30{,}2 \frac{h}{\Delta} \right) I_1 + I_2 \right| \qquad (17.20)$$

where Δ is a correction term, given by Einstein (1950, p.8) and u_*' is the friction velocity due to the granulate, and q_{ss} is the volumic solid discharge per unit width of the suspended load.

17.7 Total-load transport

Total-load transport of sediments or better called *total bed-material load transport* is made up of transport as bed load and as suspended load or :

$$q_s=q_{sb}+q_{ss}+q_{sw} \qquad (17.21)$$

The total-load transport may be calculated according to:

$$C_s=\frac{q_s}{q}=G_{gr}\frac{d}{h_m}(\frac{U}{u_*})^{n_w} \qquad (17.22)$$

where Cs is the volumetric average concentration in a section and $h_m=A/B$ is the average flow depth. The coefficients in the above relations were determined by regression analysis, using close to 1000 experiments in the laboratory and close to 250 experiments in the field, with sediments having a uniform and a non-uniform granulometry, $0.04 < d_{50}$ [mm] < 4.0 and for flow at $Fr < 0.8$ (see Table 17.1). The resulting values of these coefficients are the following:
Above, the dimensionless particle diameter, d^*, is used. For a non-uniform granulometry, one takes $d = d_{35}$ as the equivalent diameter.
Different formulae for the determination of the solid transport have been presented. However, none of these relations can pretend to translate the complexity of the transport of sediments.

coefficient	$d_0 > 60$ and $d > 2.5$ [mm]	$1.0 < d_* \leq 60$	$d_* < 1$ $d < 0.04$ [mm]
n_W	0.0	$(1-0{,}56\log d_*)$	1.0
m_W	1.50	$(9{,}66/d_*)+1{,}34$	
A_W	0.17	$0{,}23/\sqrt{d_*}+0{,}14$	
C_W	0.025	$\log C_w = 2{,}86\log d_* - (\log d_*)^2 - 3{,}53$	

Table 17.1 Coefficients for suspended load calculation

17.8 Wash load

The wash load, q_{sw}, contains all these particles which are never in contact with the bed and displace themselves by being carried (washed) through the channel by the flow (see Figure 17.1). This mode of the transport of sediments is limited to the very finest particles which are rare in the granulometry of the bed material. The distribution of these particles is rather uniform over the entire flow depth.
Einstein has proposed that the granulometry of the wash load is the fraction of granulometry of the bed which is smaller than 10 %. It was also proposed that the wash load is composed of the fine particles having a diameter of $d < 0.06$ [mm].
Since there exists no physical relationship to the flow, it has been difficult to advance an analytical method for the determination of the wash load. The wash load depends more on the hydrological, geomorphological and meteorological conditions within the drainage basin, namely on the overland surface erosion and less on the erosion in the stream bed.
Thus it is to be remarked, that at the present no methods exist for the prediction of the wash load. In order to obtain quantitative information on the wash load, measurements in the field must be performed. One measures thus the total suspended load, $q_{ss} + q_{sw}$. Subsequently is calculated the suspended load, q_{ss} , and consequently the suspended wash load, q_{sw}, can be obtained.

18. Flood control measures and structures

Measures for flood protection and mitigation are presented in this lesson. Besides non-structural measures, basic types of flood protection structures are presented, with

18.1 Flood control measures

While it is not possible to entirely prevent loss of life or damage to property in flood-prone situations, the severity thereof could be mitigated by means of well-planned and expertly executed flood control works. The basic approach will be dealt with in the following section.

The aim of flood control works is to protect and reduce the severity of the impact of floods on community development as well as the environment. Protection works can range from erosion- and runoff-control dikes, river banks built-up by levees, runoff detention basins, channel improvement by dredging, canal lining, groins and flood absorption dams.

From analysis of the history of the floods, measures to prevent and reduce damage produced by floods can be classified in two large groups:

- *Structural actions*. These are measures to interfere in the phenomena of flood formation and routing:
  - Soil conservation and correction in the drainage basins.
  - Dams. Flood control and regulating reservoirs.
  - Hydraulic works in rivers (levees and dikes, diversions, channel improvements, etc.).
- *Non-structural actions*. These are measures to mitigate or reduce the damage produced by floods:
  - Risk maps.
  - Flood plains: Zoning. Land-use patterns.
  - System of insurances.
  - General legal regulation. Building regulations.
- Other types of *non-structural* measures:
  - Flood forecasting and flood warning systems.
  - Emergency Action Plans.

The planning of flood hazard reduction measures should be carried out for the whole of the basin, with analysis of each of the potential measures and their inter-relations, as well as their downstream effects on flood routing.

18.2 Flood protection structures

As mentioned above, Flood protection structures interfere in the phenomena of flood formation and routing, and may address soil conservation and correction in the drainage basins, dams for flood control and regulating reservoirs, and finally hydraulic works in rivers (levees and dikes, diversions, channel improvements, etc.).

Design flood is the flood (return period) used in the design of a hydraulic structure, for example for sizing the spillway of a dam and for determining the flood storage or the flood discharge.

18.3 Dams and reservoirs

Dams and reservoirs can be classified into four categories according to their purpose in flood mitigation:

- Reservoirs with a single purpose of regulation (water supply, irrigation or hydropower), in which the incidence of flood mitigation is usually small.
- Multipurpose reservoirs whose principal purpose is water storage, but in which flood mitigation is also an important objective.
- Multipurpose reservoirs with a principal objective of flood mitigation, combined with other objectives of water regulation.
- Reservoirs with a single purpose of flood mitigation and reduction of downstream damage. These are known as flood mitigation dams.

The hydrologic criteria for the design of flood mitigation dams are based on two design floods:

- An "Inflow Design Flood" or "Safety Check Flood" to assure the hydrologic dam safety.
- The protection design flood, which is the flood that the dam is capable of routing without producing damage downstream.

In general, and without specific analysis in each case, the protection design floods recommended are:

- In rural areas, return periods of between 20 and 50 years.
- In urban areas, return periods of between 50 and 200 years. In cases of protection of important cities, and if economic, social and environments aspects are favourable, return periods of 500 or even 1000 years may be considered.

In the real cases studied by ICOLD the design flood protection varied between return periods of 35 and 200 years, with a few exceptional situations in which important settlement of a flood plain required values as high as 500 or 1000 years.

18.3.1 Design features and details of flood control dams

Flood control dams are constructed across flood-ways to temporarily impound and retard the flow and thus reduce the peak of the flood downstream. The main features of flood control dams are discussed below:

- *Spillways.* The ideal flood control dam would consist of an embankment with a low and fairly narrow spillway section, to ensure a large surcharge level increase, and consequently greater flood absorption potential, during a flood.
- *Crest Gates.* These, when fitted to a flood control dam, act as flood control devices, permitting a greater degree of maneuverability and flexibility of operation. They do permit various constant-pool flood-routing options, i.e. involving either no flood absorption at all, or maximum flood absorption by means of pre-releases.
- *Gated Outlets.* An important criterion in any impounding structure is having adequate bottom-gate release capacity, to permit drawing down the reservoir in the face of an impending flood, or any threatening unsafe condition, that may otherwise lead to an eventual over-topping or dam-break.

18.3.2 Operation principles of flood control dams

The principles of proper operation are dealt with by category, below:

- Flood absorption, or reduction of the flood peak by temporary retention is effected naturally by an uncontrolled spillway. The storage equation states that the *rate of increase in storage is equal to inflow minus outflow*. The percentage of discharge peak reduction is known as the flood absorption value, and this is dependent on the reservoir's area-capacity versus height characteristics, as well as the properties of the flood hydrograph (*peak flow, flood volume, time of rise and time of decline*).
- *Pre-release* is making a storage volume temporarily available below crest level, in anticipation of floodwater that will eventually occupy this space again.

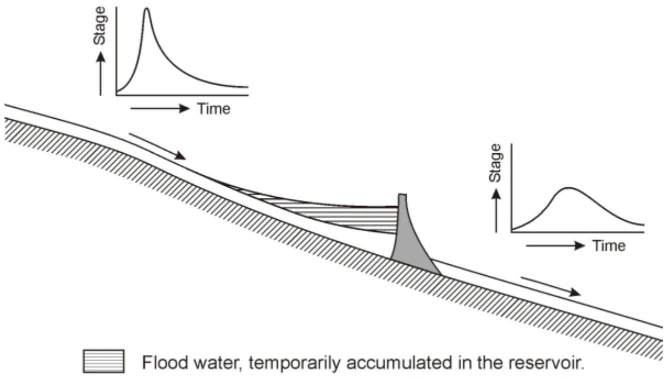

Figure 18.2 Flood peak flow attenuation by a reservoir

A flood control dam needs to be equipped with fail-safe devices in the event of an uncontrollable flooding situation arising.
Any human interference with the natural flow regime of a watercourse, such as a stream or river, could engender an opposite effect from what is aimed for. Instead of reducing flood severity, under certain circumstances the flood intensity may actually be increased. A number of these aspects are discussed below.
Dam-break Generated Flood Waves. When designing a flood protection dam, the designer must bear in mind that the consequences of its failure during a flood may be worse than had it not been there at all. According to the laws of most countries, all dams must be subjected to a dam-failure analysis.

18.4 Flood plain detention

Of all flood control measures, the most effective and direct one is where the impending flood is confined close to its origin, i.e. high up in the drainage area, where the main dams for water storage and power generation purposes are generally situated.
Detention basins on flood plains may also be utilized. These basins are normally kept empty, but are effective in stemming flash floods. Possible side effects of increasing precipitation interception, hence producing more eventual run-off elsewhere, have to be allowed for, but is a small premium to pay for effectively reducing the flood peaks.

18.5 River confinement techniques

A number of structural measures to contain and limit the extent of inundation along natural water courses are discussed next, with reference to other themes.
Levees In many countries, the practice of building-up river banks to prevent over-flooding of adjacent populated or farming areas is well established; and in some instances rivers can be made to flow several meters above the thus protected surrounding countryside. However, during extreme floods, these levees may be over-topped or breached, with serious consequences. Usually the levees are set a certain distance back from the proper riverbanks to create a flood plain, and over-bank channels of ample proportions.

Diversion Channels, Cut-offs
Meandering rivers have been straightened through cut-offs to shorten them, increase their slope and improve their carrying capacity. This will, however, serve no purpose where the meanders cross the entire floodplain, as they anyhow become short-circuited during over-bank floods. Diversion channels can be provided for waterways and navigational canals, short-circuiting large river bends. Braided rivers are often improved by deepening certain channels.

Canalization, Channel Improvement

Where a natural river channel is overgrown with dense vegetation and interrupted sand-bank deposits, it serves a good purpose where the river-banks are smoothened, vegetation removed, and the channel sides brought to an even grade on both sides. The hydraulic roughness is thus decreased, and the cross-section and conveyance increased. A degree of bank protection against bend erosion, as well as dredging on the inside of bends is necessary for maintaining adequate carrying capacity.

A *flood bypass*
It is a region of land or a large man-made structure that is designed to convey excess flood waters from a river or stream in order to reduce the risk of flooding on the natural river or stream near a key point of interest, such as a city. Flood bypasses, sometimes called *floodways*, often have man-made diversion works, such as diversion weirs and spillways, at their head or point of origin. The main body of a flood bypass is often a natural flood plain. Many flood bypasses are designed to carry enough water such that combined flows down the original river or stream and flood bypass will not exceed the expected maximum flood flow of the river or stream. Flood bypasses are typically used only during major floods and act in a similar nature to a detention basin. Since the area of a flood bypass is significantly larger than the cross-sectional area of the original river or stream channel from which water is diverted, the velocity of water in a flood bypass will be significantly lower than the velocity of the flood water in the original system. These low velocities often cause increased sediment deposition in the flood bypass, thus it is important to incorporate a maintenance program for the entire flood bypass system when it is not being actively used during a flood operation.

19. Storm water drainage design

This chapter provides basic techniques and criteria for the design of storm water runoff and drainage facilities and procedures to determine the required storage volume for detention and retention basins. This section provides an overview of hydrologic methods and procedures commonly used in urban drainage design.

Municipal sewer systems handle both sanitary wastewater and stormwater. Sanitary wastewater is generally introduced through house inlets into sanitary sewers. Stormwater is generally introduced through stormwater inlets and street inlets into storm sewers. Both are basically conveyed by gravity. Pressure pipes are sometimes used.

The basic function of municipal sewer systems is to convey wastewater to a treatment plant and stormwater to public water bodies. In other words, sewer systems improve the living environment and protect cities and streets from inundation.
It is important to make accurate calculations of flow rate, flow velocity and gradient in order to make rational and efficient sewer systems. In most large cities where sewer systems were constructed many years ago, rehabilitation of deteriorated sewers is an urgent and important task. In some countries, utilization of heat in wastewater or sewer optical fiber networks has been introduced.

There are two types of collecting systems, *combined* and *separate*. Combined systems carry away both stormwater and sanitary wastewater in one sewer system. Separate systems take care of sanitary wastewater and stormwater in two different systems. Combined systems are often used because the construction costs are less than that of separate system. Their disadvantage is that stormwater mixed with sanitary wastewater is allowed to flow directly into rivers or the sea in wet weather. In separate systems, stormwater is normally not allowed to mix with wastewater, but it carries pollutants from road surfaces into rivers and seas. The construction is more complex and obviously more expensive, since two different systems are constructed.
In combined sewer overflow (CSO) control, the volume of wastewater going to the treatment plant in wet weather is increased by enlarging the capacity of the interceptor. Moreover, a CSO storage tank is installed to prevent the polluted first flush from flowing into the receiving water in the early stages of a rainstorm. CSO storage facilities are installed at outfalls, pumping stations and treatment plants.

Rainfall, along with watershed characteristics, determines the flood flows upon which storm drainage design is based. The following sections describe three representations of rainfall which can be used to derive flood flows: constant rainfall intensity, dynamic rainfall, and synthetic rainfall events.
Although rainfall intensity varies during precipitation events, many of the procedures used to derive peak flow are based on assumed constant rainfall intensity. Intensity is defined as the rate of rainfall and is typically given in units of millimetres per hour.

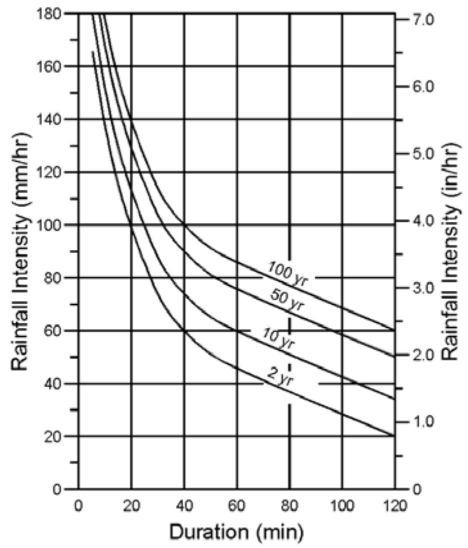

Figure 19.1 Intensity-Duration-Frequency curves (IDF curve)

Intensity-Duration-Frequency curves (IDF curves) have been developed for many regions through frequency analysis of rainfall events. The IDF curve provides a summary of a site's rainfall characteristics by relating storm duration and exceedence probability (frequency) to rainfall intensity (assumed constant over the duration). Figure 19.1 illustrates an example IDF curve.

Dynamic Rainfall (Hyetograph). In any given storm, the instantaneous intensity is the slope of the mass rainfall curve at a particular time. The mass rainfall curve (Figure 19.2) is simply the cumulative precipitation which has fallen up to a specific time. For hydrologic analysis, it is desirable to divide the storm into convenient time increments and to determine the average intensity over each of the selected periods.

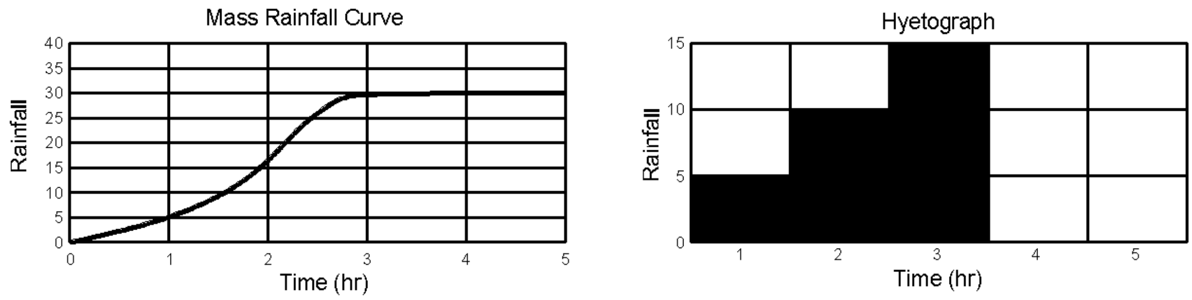

Figure 19.2 Example mass rainfall curve and corresponding hyetograph

19.1 Detention and retention facilities

Land development activities, including the construction of roads, convert natural pervious areas to impervious and otherwise altered surfaces. These activities cause an increased volume of runoff because infiltration is reduced, the surface is usually smoother thereby allowing more rapid drainage, and depression storage is usually reduced. In addition, natural drainage systems are often replaced by lined channels, storm drains, and curb-and-gutter systems. These man-made systems produce an increase in runoff volume and peak discharge, as well as a reduction in the time to peak of the runoff hydrograph. This concept is illustrated by the hydrograph in Figure 19.3.

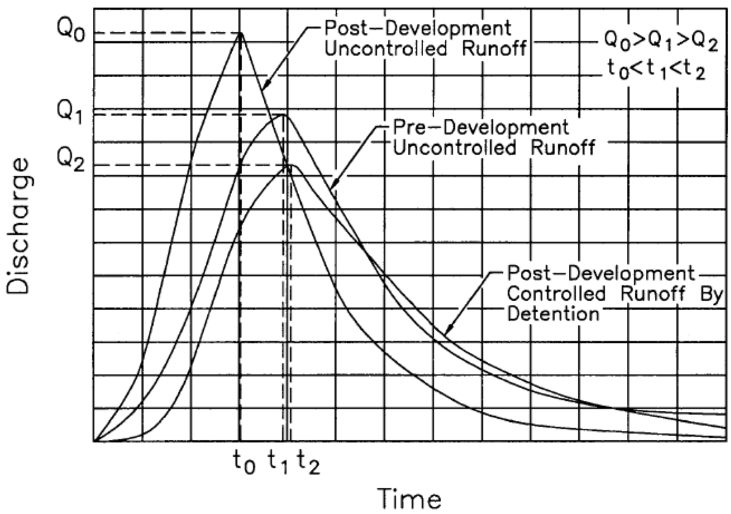

Figure 19.3 Change of flood peak discharge with time

The temporary storage or detention/retention of excess storm water runoff as a means of controlling the quantity and quality of storm water releases is a fundamental principle in storm water management and a necessary element of a growing number of highway storm drainage systems. Previous concepts which called for the rapid removal of storm water runoff from developed areas, usually by downstream channelization, are now being combined with methods for storing storm water runoff to prevent overloading of existing downstream drainage systems. The storage of storm water can reduce the frequency and extent of downstream flooding, soil erosion, sedimentation, and water pollution. Detention /retention facilities also have been used to reduce the costs of large storm drainage systems by reducing the required size for downstream storm drain conveyance systems. The use of detention/retention facilities can reduce the peak discharge from a given watershed, as shown in Figure 19.3. The reduced post-development runoff hydrograph is typically designed so that the peak flow is equal to or less than the pre-developed runoff peak flow rate. Additionally, the volume of the post-development hydrograph is the same as the volume of the reduced post-development runoff hydrograph.

Stormwater quantity control facilities can be classified by function as either detention or retention facilities. The primary function of detention is to store and gradually release or attenuate stormwater runoff by way of a control structure or other release mechanism. True retention facilities provide for storage of stormwater runoff, and release via evaporation and infiltration only. Retention facilities which provide for slow release of storm water over an extended period of several days or more are referred to as extended detention facilities.

Detention facilities

The detention concept is most often employed in municipal stormwater management plans to limit the peak outflow rate to that which existed from the same watershed before development for a specific range of flood frequencies. Detention storage may be provided at one or more locations and may be both above ground or below ground.These locations may exist as impoundments, collection and conveyance facilities, underground tanks, and on-site facilities such as parking lots, pavements, and basins. The facility may have a permanent pool, known as a wet pond. Wet ponds are typically used where pollutant control is important. Detention ponds are the most common type of storage facility used for controlling stormwater runoff peak discharges. The majority of these are dry ponds which release all the runoff temporarily detained during a storm.

Detention facilities should be provided only where they are shown to be beneficial by hydrologic, hydraulic, and cost analysis. The following are design guidance and criteria for detention storage:

- Design rainfall frequency, intensity, and duration must be consistent with standards and local requirements.
- The facility's outlet structure must limit the maximum outflow to allowable release rates. The maximum release rate may be a function of existing or developed runoff rates, downstream channel capacity and, potential flooding conditions.
- The size, shape, and depth of a detention facility must provide sufficient volume to satisfy the projects' storage requirements. This is best determined by routing the inflow hydrograph through the facility.
- An auxiliary outlet must be provided to allow overflow which may result from excessive inflow or clogging of the main outlet. This outlet should be positioned such that overflows will follow a predetermined route. Preferably, such outflows should discharge into open channels, swales, or other approved storage or conveyance features.
- The system must be designed to release excess stormwater expeditiously to ensure that the entire storage volume is available for subsequent storms and to minimize hazards. A dry pond, which is a facility with no permanent pool, may need a paved low Flow channel to ensure complete removal of water and to aid in nuisance control.
- Access must be provided for maintenance.
- If the facility will be an "attractive nuisance" or is not considered to be reasonably safe, it may have to be fenced and/or signed.

Retention Facilities

Retention facilities as defined here include extended detention facilities, infiltration basins, and swales. In addition to stormwater storage, retention may be used for water supply, recreation, pollutant removal, aesthetics, and/or groundwater recharge. Infiltration facilities provide significant water quality benefits, and although groundwater recharge is not a primary goal of highway stormwater management, the use of infiltration basins and/or swales can provide this secondary benefit.

Retention facilities are typically designed to provide the dual functions of stormwater quantity and quality control. These facilities may be provided at one or more locations and may be both above ground and below ground. These locations may exist as impoundments, collection parking lots and roadways using pervious pavements.

Design criteria for retention facilities are the same as those for detention facilities except that it may not be necessary to remove all runoff after each storm. However the following additional criteria should be applied:

Wet Pond Facilities

- Wet pond facilities must provide sufficient depth and volume below the normal pool level for any desired multiple use activity.
- Shoreline protection should be provided where erosion from wave action is expected.
- The design should include a provision for lowering the pool elevation or draining the basin for cleaning purposes, shoreline maintenance, and emergency operations.

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Infiltration Facilities

- A pervious bottom is necessary to ensure sufficient infiltration capability to drain the basin in a reasonable amount of time so that it will have the capacity needed for another event.
- Because of the potential delay in draining the facility between events, it may be necessary to increase the emergency spillway capacity and/or the volume of impoundment.
- Detailed engineering geological studies are necessary to ensure that the infiltration facility will function as planned.
- Particulates from the inflow should be removed so that they do not settle and preclude infiltration.

19.2 Storm Sewers

When diversions, surface drains, and channels cannot adequately handle the volume or velocity of runoff, storm sewers may be necessary. These systems can be designed to convey large volumes of runoff at relatively high velocities.

Because storm sewers are underground and enclosed, most concerns related to erosion from water flow are reduced. However, the flow of sediment into the sewer system must be controlled to allow the system to operate at full capacity. Catch basins provide a sump that allows sediment and debris to settle out before storm water flows into the drain pipe, but they should only be employed where regular maintenance will be provided to clean out the sump and control mosquito breeding. Drop inlets do not have a sump and allow storm water to flow directly into the pipe. Traps or filters located at the inlet will reduce the amount of sediment that enters the underground system, but these must also be regularly cleaned out to maintain the full capacity of the system. Sediment can be controlled at a surface outlet point of an underground system by providing detention areas that will allow it to settle out before runoff is again released.

Because of the relatively high volume and velocity of runoff in a storm sewer, proper controls are necessary at an outlet to minimize erosion. If an existing storm sewer of sufficient capacity is reasonably close, the new system can be tied into it. If such an existing system is not available, an on-site surface outlet, such as a detention basin, may be required. This basin should be large enough to handle the volume of flow, and it should be stabilized sufficiently to resist eroding. The rate of release from the sewer should also be controlled or dissipated to reduce erosion potential.

References

1. International Association of Hydrological Sciences (IAHS). Rodier, J.A., Roche, M. (1984). "World catalogue of Maximum Observed Floods". IAHS Publication no.143
2. L. Berga, (2004), DAMS AND FLOODS, in *Water Storage, Transportation and Distribution* , [Ed. Yutaka Takahasi], in *Encyclopedia of Life Support Systems (EOLSS),* Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford ,UK.
3. Martinez Alfaro Pedro Emilio, (2004), GROUNDWATER, in *GroundWater*, [Eds. Luis Silveira, Stefan Wohnlich, and Eduardo J. Usunoff], in *Encyclopedia of Life Support Systems (EOLSS),* Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford ,UK.
4. J.M. Jordaan, (2004), DESIGN OF SUSTAINABLE HYDRAULIC STRUCTURES , in *Hydraulic Structures, Equipment and Water Data Acquisition Systems*, [Eds. Jan Malan Jordaan, and Alexander Bell], in *Encyclopedia of Life Support Systems (EOLSS),* Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford ,UK.
5. VanDine, D. F. 1996. Debris flow control structures for forest engineering. Res. Br., B.C. Min.For., Victoria, B.C., Work. Pap. 08/1996
6. EM 1110-2-1619 U.S. Army Corps of Engineers CECW-EH-Y Washington, DC 20314-1000 Manual No. 1110-2-1619 1 August 1996 Engineering and Design RISK-BASED ANALYSIS FOR FLOOD DAMAGE REDUCTION STUDIES.
7. Bonacci, Ognjen, 2003. Ekohidrologija vodnih resursa i otvorenih vodotoka. (In Croatian) ISBN 953-6116-27-8. Split ; Zagreb : Građevinsko-arhitektonski fakultet ; Institut građevinarstva Hrvatske , 2003
8. Popovska, Cvetanka, 2003. Fluid mechanics. (In Macedonian). Gradezen Fakultet, Skopje, 2003