WATER RESOURCES AND THE ENVIRONMENT

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Contents

Summary

Apart from air, water is humankind's most important natural resource, and the "hydrological cycle" refers to the circulation of water throughout the Earth. Water falls to Earth's surface where it is dispersed as run-off, infiltration/percolation, or evapotranspiration, in amounts that vary with climatic regime. Water is stored in reservoirs, but not all water in storage is available for use; unavailable water is referred to as "dead storage." Storage capacity is reduced by sedimentation, Bank stability is important in this context, as landslides that flow into a reservoir reduce its capacity. The location of a reservoir has to take into account precipitation, the run-off of the catchment area, topography, and geological conditions, which determine the amount of leakage that is likely to take place. The smaller the surface area in relation to the reservoir volume, the better for limiting evaporation loss. The location of a reservoir depends upon the location of the dam. The geological conditions influence the type of dam chosen.

The source of most groundwater is the precipitation that remains after run-off and evapotranspiration, which can infiltrate the ground and percolate under gravity to the water table: the upper surface of the zone, below which the ground is saturated. The amount of water available, the "specific yield," is more important than the amount of water in storage. Not all groundwater is available, some being retained by capillary or suction forces.

A rock or soil formation that yields water readily is referred to as an “aquifer.” Aquifers are either open to the surface or confined by an overlying less permeable geological formation. Under what are known as “artesian conditions,” the water in an aquifer is under sufficient pressure to bring it to the surface in a borehole sunk into the aquifer. Wells are sunk into aquifers to obtain water, but the amount of water removed ideally should take into account the rate of groundwater recharge. If this is exceeded the level of the water table declines, which can give rise to a number of problems. Aquifers can be recharged artificially.

Water quality, and particularly its chemical and biological content, is important, especially for domestic purposes. Quality is affected by the soil and rock formations through which groundwater flows. Usually the ground conditions act as a filter. Unfortunately groundwater may become polluted by contaminants entering the groundwater system, or at the coast by saline intrusion. Irrigation is used to enhance crop yields, particularly in regions with deficient rainfall. However, its improper use can lead to soil spoilation through salinization.

1. The Hydrological Cycle

The hydrological cycle involves the movement of water in all its forms over, on, and through the Earth. The cycle can be visualized as starting with the evaporation of water from the oceans, and the subsequent transport of the resultant water vapor by winds and moving air masses. Some water vapor condenses over land and falls back to the surface of the Earth as precipitation. To complete the cycle this precipitation then must make its way back to the oceans via streams, rivers, or underground flow, although some precipitation may be evapotranspired and describe several subcycles before completing its journey. Groundwater forms an integral part of the hydrological cycle. Although groundwater represents only 0.5% of the total water resources of Earth, and not all this is available for exploitation, about 98% of the usable fresh water is stored underground.

Run-off is made up of two basic components, surface water run-off and groundwater discharge. The former is usually the more important, and is responsible for the major variations in river flow. Run-off generally increases in magnitude as the time from the beginning of precipitation increases.

“Infiltration” refers to the process whereby water penetrates the ground surface and starts moving down through the zone of aeration. The subsequent gravitational movement of the water down to the zone of saturation is termed “percolation,” although there is no clearly defined point where infiltration becomes percolation. Whether infiltration or run-off is the dominant process at a particular time depends upon several factors, such as the intensity of the rainfall and the porosity and permeability of the surface. For example, if the rainfall intensity is much greater than the infiltration capacity of the soil, then run-off is high.

If lower strata are less permeable than the surface layer, the infiltration capacity is reduced so that some of the water that has penetrated the surface moves parallel to the water table and is called “interflow.” The water that becomes interflow will probably be discharged to a river channel at some point, and forms part of the baseflow of the river.

The remaining water may continue down through the zone of aeration until it reaches the water table and becomes groundwater recharge.

2. Reservoirs

Although most reservoirs are multipurpose, their principal function is to stabilize the flow of water in order to satisfy a varying demand from consumers or to regulate water supplied to a river course. As a consequence, the most important physical characteristic of a reservoir is its storage capacity. Probably the most important aspect of storage in reservoir design is the relationship between capacity and yield. The yield is the quantity of water that a reservoir can supply at any given time. The maximum possible yield equals the mean inflow less evaporation and seepage loss. In any consideration of yield the maximum quantity of water that can be supplied during a critical dry period (that is, during the lowest natural flow on record) is of prime importance, and is defined as the “safe yield.”

The maximum elevation to which the water in a reservoir basin will rise during ordinary operating conditions is referred to as the “top water” or “normal pool” level. For most reservoirs the top of the spillway fixes this. Conversely, minimum pool level is the lowest elevation to which the water is drawn under normal conditions, this being determined by the lowest outlet. Between these two levels the storage volume is termed the “useful storage,” while, the water below the minimum pool level, because it cannot be drawn upon, is the “dead storage.”

In any adjustment of a river regime to the new conditions imposed by a reservoir, problems may emerge both up- and downstream. Deposition around the head of a reservoir may cause serious aggradation upstream, resulting in a reduced capacity of the stream channels to contain flow. Hence, flooding becomes more frequent and the water table rises. Removal of sediment from the outflow of a reservoir can lead to erosion in the river regime downstream of the dam, with consequent acceleration of headward erosion in tributaries and lowering of the water table.

In an investigation of a potential reservoir site, consideration must be given to the amount of rainfall, run-off, infiltration, and evapotranspiration that occurs in the catchment area. The climatic, topographical, and geological conditions are therefore important, as is the type of vegetative cover. Accordingly, the two essential types of basic data needed for reservoir design studies are adequate topographical maps and hydrological records. Indeed, the location of a large, impounding direct supply reservoir is very much influenced by topography, since this governs its storage capacity. Initial estimates of storage capacity can be made from topographic maps or aerial photographs, with more accurate information being obtained, where necessary, from subsequent surveying. Catchment areas and drainage densities can also be determined from maps and aerial photography.

Records of stream flow are required for determining the amount of water available for conservation purposes. Such records contain flood peaks and volumes, which are used to determine the amount of storage needed to control floods, and to design spillways and other outlets. Records of rainfall are used to supplement stream flow records, or as a basis for computing stream flow where there are no flow records obtainable. Losses due to seepage and evaporation must also be taken into account.

The most attractive site for a large impounding reservoir is a valley constricted by a gorge at its outfall, with steep banks upstream so that a small dam can impound a large volume of water with a minimum extent of water spread. However two other factors have to be taken into consideration, namely the water tightness of the basin, and bank stability. The question whether or not significant water loss will take place is chiefly determined by the groundwater conditions, more specifically by the hydraulic gradient. Consequently, once the groundwater conditions have been investigated an assessment can be made of water tightness and possible groundwater control measures. Seepage is a more discreet flow than leakage, which spreads out over a larger area, but may be no less in total amount.

Apart from the conditions in the immediate vicinity of a dam, the two factors that determine the retention of water in reservoir basins are the piezometric conditions in, and the natural permeability of, the floor and flanks of the basin. If the groundwater divide and piezometric level are at a higher elevation than the proposed top water level, then no significant water loss occurs. Seepage can take place through a separating ridge into an adjoining valley where the groundwater divide, but not the piezometric level, is above the top water level of a reservoir. The flow rate of the seepage is determined by the *in situ* permeability. When both the groundwater divide and piezometric level are at an elevation lower than the water level but higher than the reservoir floor, then the increase in groundwater head is low and the flow from the reservoir may be initiated under conditions of low piezometric pressure in the reservoir flanks. A depressed water table does not necessarily mean that reservoir construction is out of the question, but groundwater recharge will take place on filling, which will give rise to a changed hydrogeological environment as the water table rises. In such instances the impermeability of the reservoir floor is important. When impermeable beds are more or less saturated, particularly when they have no outlet, seepage is appreciably decreased. At the same time the accumulation of silt on the floor of the reservoir tends to reduce seepage. If, however, any permeable beds present contain large pore spaces or discontinuities and they drain from the reservoir, then seepage continues.

Although a highly leaky reservoir may be acceptable in an area where run-off is evenly distributed throughout the year, a reservoir basin with the same rate of water loss may be of little value in an area where run-off is seasonally deficient. Leakage from a reservoir downstream of the dam site can take the form of sudden increases in stream flow, with boils in the river and the appearance of springs on the valley sides. It may be associated with major defects in the geological structure. Serious leakage has taken place at reservoirs via cavern conditions in limestone, and sites are best abandoned where large and numerous solution cavities extend to considerable depths. Where the problem is not so severe, solution cavities can be cleaned and grouted. Sinkholes and caverns can develop in thick beds of gypsum more rapidly than they can in limestone. Buried channels may be filled with coarse, granular stream deposits or deposits of glacial origin, and if they occur near the perimeter of a reservoir they almost invariably pose leakage problems. A thin layer of relatively impermeable superficial deposits does not necessarily provide an adequate seal against seepage. Where artesian conditions exist, springs may break through the thinner parts of the superficial cover. If the water table below the deposits is depressed, there is a risk that the weight of water in the reservoir may puncture the cover. Finally, there is a possibility that the superficial material may be ruptured or partially removed to expose the underlying rocks on filling a reservoir. Leakage along faults generally is not a serious problem as far as reservoirs are concerned, since the length of the flow path is usually too long. However, fault zones occupied by permeable fault breccia running beneath the dam must be given special consideration. Open discontinuities also represent pathways for water leakage.

Some soils or rocks that are brought within the zone of saturation by the rising water table may become unstable and fail. This can lead to slumping and sliding on the flanks of a reservoir. Landslides that occur after a reservoir is filled reduce its capacity. Also ancient landslipped areas that occur on the rims of a reservoir can be reactivated, as well as presenting a potential leakage problem.

Sedimentation in a reservoir may lead to one or more of its major functions being seriously curtailed, or even to it becoming inoperative. In a small reservoir, sedimentation may seriously affect the available carry-over water supply, and ultimately necessitate abandonment. The size of a drainage basin is the most important consideration as far as sediment yield is concerned, the rock types, drainage density, and gradient of slope also being important. The sediment yield also is influenced by the amount and seasonal distribution of precipitation and the vegetative cover. In those areas where streams carry heavy sediment loads, the rates of sedimentation must be estimated accurately in order that the useful life of any proposed reservoir may be determined.

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Biographical Sketch

Fred Bell graduated with a B.Sc. and M.Sc. from the University of Durham and received his Ph.D. from the University of Sheffield, UK in 1974. More recently, he received a D.Sc. from the University of Natal. He is a fellow of the Royal Society of South Africa, a fellow of the Institution of Civil Engineers and the Institution of Mining and Metallurgy, and a fellow of the Geological Society, being both a chartered engineer and a chartered geologist. He is the recipient of several awards.

Professor Bell is now a Visiting Research Associate at the British Geological Survey. Previously, he was Professor and Head of the Department of Geology and Applied Geology, University of Natal, Durban, South Africa, during which time he also was a Distinguished Visiting Professor, Department of Geological Engineering, University of Missouri-Rolla, USA.

Professor Bell's research subjects have included ground stability, subsidence, ground treatment, engineering behavior of soils (clays, expansive clays, saprolites, tills, laminated clays, dispersive and collapsible soils, sands), engineering behavior of rocks (sandstones, carbonates, evaporites, shales, basalts, dolerites, granites), cement, lime and PFA stabilization of clay soils, acid mine drainage, mining impacts, landfills, derelict and contaminated ground, rock durability in relation to tunneling, slope stability, aggregates, building stone, and geohazards.

In his professional activity Professor Bell has been involved in a variety of work in the UK, southern Africa, and Malaysia concerning site investigations; foundations; settlement problems on clays, fills and sands; old mine workings and subsidence; longwall mining and subsidence; ground treatment; groundwater resource assessment; slope stability; use of mudrocks for brickmaking; assessment of various rock types for aggregates; contaminated ground; acid mine drainage; landfills, and dam sites.

Professor Bell is the author/editor of 17 books, several reprinted, one in its fourth edition, one translated into French, two into Italian and yet another into Malay, and an Indian edition (in English). He is also author of over 200 papers on geotechnical subjects. He has served on the editorial boards of five international journals and has been a series editor for three publishers.