WATER RESOURCES AND THE ENVIRONMENT

Fred G. Bell
British Geological Survey, Blyth, Nottinghamshire, United Kingdom

Keywords: hydrological cycle, dispersal of precipitation, reservoirs, dams and dam sites, geological conditions, groundwater, aquifers, wells, safe yield, conjunctive use, water quality, irrigation

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.

3. Dam Sites

The type and size of dam constructed depend upon the need for and the amount of water available, the topography and geology of the site, and the construction materials that are readily obtainable. Dams can be divided into two major categories according to the type of material with which they are constructed, namely concrete dams and earth dams. Concrete dams can be subdivided into gravity, arch, and buttress dams (Figure 1, 2 and 3). Earth dams (Figure 4) comprise rolled-fill and rockfill embankments. In dam construction the prime concern is safety (this coming before cost), that is, the foundations and abutments must be adequate for the type of dam selected. Some sites that are geologically unsuitable for a specific type of dam design may support one of composite design.

Figure 1. Nagle Dam, Valley of a Thousand Hills, Natal, South Africa (a concrete gravity dam). Note the second dam on the far left. This controls the flow into the reservoir and acts as a silt trap. Excess flow and silt can be removed through a sluice to the right of this dam, the water and silt flowing through a cutting into the river below Nagle Dam.

Percolation of water through the foundations of concrete dams, even when the rock masses concerned are of good quality and of minimum permeability, is always a decisive factor in the safety and performance of dams. Such percolation can remove filler material that may be occupying joints, which in turn can lead to differential settlement of the foundations. It also may open joints, which decreases the strength of the rock mass. In highly permeable rock masses excessive seepage beneath a dam may damage the foundation. Reducing the hydraulic gradient beneath the dam by incorporating a cutoff into the design can lower seepage rates. Uplift pressure acts against the base of a dam, and is caused by water seeping beneath it which is under hydrostatic head from the reservoir. It can be reduced by allowing water to be conducted downstream by drains incorporated into the foundation and base of the dam.

Of the various natural factors that directly influence the design of dams, none are more important than geological ones. Not only do they control the character of the foundation, but they also govern the materials available for construction. The major points to be addressed include the depth at which adequate foundations exist, the strengths of the rocks involved, the likelihood of water loss, and any special features having a bearing on excavation.

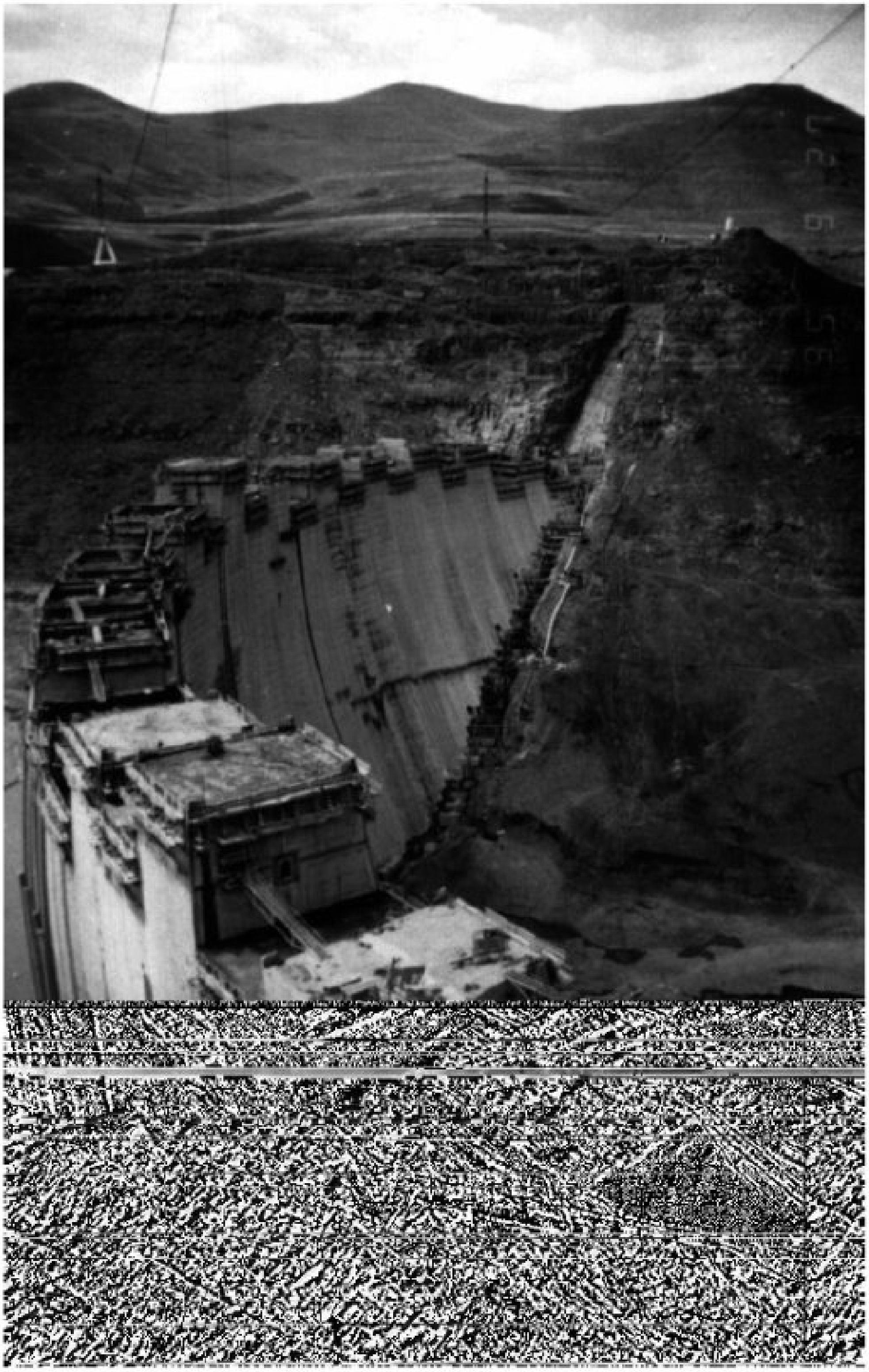

Figure 2. Katse Dam nearing completion, Lesotho (a double arch dam)

Figure 3. Errochty Dam, Scotland (a buttress dam)

Figure 4. Hardap Dam, Namibia (an embankment dam)

The character of the foundations upon which dams are built and their reaction to the new conditions of stress and strain, of hydrostatic pressure, and of exposure to weathering must be ascertained so that the proper factors of safety may be adopted to ensure against subsequent failure. Excluding the weaker types of compaction shales, mudstones, pyroclasts, and certain very friable types of sandstone, there are few foundation materials deserving the name "rock" that are incapable of resisting the bearing loads even of high dams.

In their unaltered state plutonic rocks are essentially sound and durable, with adequate strength for any engineering requirement. In some instances, however, intrusives may be highly altered by weathering or hydrothermal attack. Thick, massive basalts make satisfactory dam sites, but many basalts of comparatively young geological age are highly permeable, transmitting water via their open joints, pipes, cavities, tunnels, and contact zones. Foundation problems in young volcanic sequences are twofold: first, weak beds of ash and tuff may occur between the basalt flows giving rise to problems of differential settlement or sliding, and second, weathering during periods of volcanic inactivity may have produced fossil soils—these being of much lower strength. Pyroclastics usually give rise to extremely variable foundation conditions, because of wide variations in strength, durability, and permeability. Ashes are invariably weak and often highly permeable; they may also undergo hydrocompaction on wetting.

Freshly metamorphosed rocks may be very strong and so afford excellent dam sites. Marble has the same advantages and disadvantages as other carbonate rocks. Cleavage and schistosity in regional metamorphic rocks may adversely affect their strength and make them more susceptible to decay. For instance, certain schists and phyllites are so poor as to be wholly undesirable in foundations and abutments.

Joints and shear zones may be responsible for unsound rock encountered at dam sites on plutonic and metamorphic rocks. Unless they are sealed they may permit leakage through foundations and abutments. Slight opening of joints on excavation leads to imperceptible rotations and sliding of rock blocks, large enough to appreciably reduce the strength and stiffness of the rock mass. Sheet or flat-lying joints tend to be approximately parallel to the topographic surface, and introduce a dangerous element of weakness into valley slopes.

Sandstones have a wide range of strength depending largely upon the amount and type of cement-matrix material occupying the voids. With the exception of shaly sandstone, sandstone is not subject to rapid surface deterioration on exposure. As a foundation rock, even poorly cemented sandstone is not susceptible to plastic deformation. However, friable sandstones introduce problems of scour within the foundation. Moreover, sandstones are highly vulnerable to the scouring and plucking action of the overflow from dams, and have to be adequately protected by suitable hydraulic structures. Sandstones frequently are interbedded with beds of shale that may constitute potential sliding surfaces.

Limestone dam sites vary widely in their suitability. Thick-bedded horizontally lying limestones relatively free from solution cavities afford excellent dam sites. On the other hand, thin-bedded, highly folded, or cavernous limestones are likely to present serious foundation or abutment problems involving bearing capacity, water tightness, or both. If the rock mass is thin-bedded, a possibility of sliding may exist. Similarly, beds separated by layers of clay or shale, especially those inclined downstream, may under certain conditions, serve as sliding planes and give rise to failure. Some solution features will always be present in limestone. The size, form, abundance, and downward extent of these features depend upon the geological structure and the presence of interbedded impervious layers. Individual cavities may be open, they may be partially or completely filled with clay, silt, sand, or gravel mixtures, or they may be waterfilled conduits. Solution cavities present numerous problems in the construction of large dams, among which bearing capacity and water tightness are paramount.

Well-cemented shales, under structurally sound conditions, present few dam site problems, though their strength limitations and elastic properties may be factors of importance in the design of concrete dams of appreciable height. However they have lower moduli of elasticity and lower shear strength values than concrete, and therefore are unsatisfactory foundation materials for arch dams. Besides, if the lamination is horizontal and well developed, then the foundations may offer little shear resistance to the horizontal forces exerted by a dam. A structure keying the dam into such a foundation is then required. Severe settlements may take place in low-grade compaction shales. Thus, such sites are generally developed with earth dams, but associated concrete structures such as spillways will involve these problems. The stability of slopes in cuts is one of the major problems in shale both during and after construction.

Earth dams are usually constructed on clay soils, as they lack the load-bearing properties necessary to support concrete dams. Beneath valley floors, clays are frequently contorted, fractured, and softened because of valley creep, so that the load of an earth dam may have to spread over wider areas than is the case with shales and mudstones. Rigid ancillary structures necessitate spread footings or raft foundations. Slope stability problems also arise, with rotational slides a hazard.

Glacial deposits may be notoriously variable in composition, both laterally and vertically. As a result, dam sites in glaciated areas are often among the most difficult to appraise on the basis of surface evidence. A primary consideration in glacial terrains is the discovery of sites where rock foundations are available for spillway, outlet, and powerhouse structures. Generally, earth dams are constructed in areas of glacial deposits.

The major problems associated with foundations on alluvial deposits generally result from the fact that the deposits are poorly consolidated. Silts and clays are subject to plastic deformation or shear failure under relatively light loads, and undergo consolidation for long periods of time when subjected to appreciable loads. Many large earth dams have been built upon such materials, but this demands a thorough exploration and testing program in order to design safe structures. The slopes of an embankment dam may be flattened in order to mobilize greater foundation shear strength, or berms may be introduced. Where soft alluvial clays are not more than 2.3 m thick they should consolidate during construction if covered with a drainage blanket, especially if resting on sand and gravel. With thicker deposits it may be necessary to incorporate vertical sand drains within the clays. However, coarser sands and gravels undergo comparatively little consolidation under load and therefore afford excellent foundations for earth dams. Their primary problems result from their permeability. Alluvial sands and gravels form natural drainage blankets under the higher parts of an earth or rockfill dam, so that seepage through them beneath the dam must be cut off.

Landslides are a common feature of valleys in mountainous areas, and large slips often cause the narrowing of a valley, which therefore looks topographically suitable for a dam. Unless landslides are shallow-seated and can be removed or effectively drained, it is prudent to avoid landslipped areas in dam location, because their unstable nature may result in movement during construction or subsequently on inundation by reservoir water.

Fault zones may be occupied by shattered or crushed material, and so represent zones of weakness that may give rise to landsliding upon excavation for a dam. Movement along faults in active seismic regions occurs not only in association with large and infrequent earthquakes but also in association with small shocks and continuous slippage known as "fault creep." Zoned embankment dams can be built with safety at sites with active faults.

Wherever possible, construction materials for an earth dam should be obtained from within the future reservoir basin. Embankment soils need to develop high shear strength, low permeability and low water absorption, and undergo minimal settlement. This is achieved by compaction. In some cases only one type of soil is easily obtainable for an earth dam. If this is impervious, the design will consist of a homogeneous embankment, which incorporates a small amount of permeable material, in the form of filter drains, to control internal seepage. On the other hand, where sand and gravel are in plentiful supply a very thin clay core may he built into a dam if enough impervious soil is available; otherwise an impervious membrane may be constructed of concrete or interlocking steel-sheet piles. However, since concrete can withstand very little settlement such core walls must be located on sound foundations. Sites that provide a variety of soils lend themselves to the construction of zoned dams. The finer, more impervious materials are used to construct the core, while the coarser materials provide strength and drainage in the upstream and downstream zones.

-
-
-

Bibliography

Brown R.H., Konoplyantsev A.A., Ineson J., and Kovalevsky V.S. (eds.) (1972). *Groundwater Studies: An International Guide for Research and Practice*, Paris: UNESCO Studies and Reports in Hydrology 7.

Campbell M.D. and Lehr J.H. (1973). *Water Well Technology*, New York: McGraw Hill.

Chow V.T. (ed.) (1986). *Handbook of Applied Hydrology*, New York: McGraw-Hill.

Cripps J.C., Bell F.G., and Culshaw M.G. (1986). *Groundwater in Engineering Geology*, London: Geological Society Engineering Geology Special Publication No. 3.

EEC. (1980). *Directive Relating to the Quality of Water intended for Human Consumption (80/778/EEC)*, Brussels: Commission of the European Community.

Freeze R.A. and Cherry J.A. (1979). *Groundwater*, Englewood Cliffs, NJ: Prentice Hall.

Gower A.M. (ed.) (1980). *Water Quality in Catchment Ecosystems*, Chichester, UK: Wiley.

Hamill L. and Bell F.G. (1986). *Groundwater Resource Development*, London: Butterworths.

Hansen V.E., Israelsen O.W., and Stringham G.E. (1980). *Irrigation Principles and Practice* (Fourth Edition). New York: Wiley.

Helweg O.J. (1985). *Water Resources, Planning, and Management*, New York: Wiley.

Hem J.D. (1985). *Study and Interpretation of the Chemical Characteristics of Natural Water*, Washington, D.C.: United States Geological Survey, Water Supply Paper 2254.

Linsley R.K. and Franzini J.B. (1972). *Water Resources Engineering*, New York: McGraw-Hill.

Sawyer C.N. and McCarty P.L. (1967). *Chemistry for Sanitary Engineers* (Second Edition). New York: McGraw Hill.

Sherard J.L., Woodward R.L., Gizienski S.F., and Clevenger W.A. (1967). *Earth and Earth Dams*, New York: Wiley.

Skeat W.D. (ed.) (1969). *Manual of British Water Engineering Practice: Volume 2*, London: Institution of Water Engineers.

Todd D.K. (1980). *Groundwater Hydrology* (Second Edition). New York: Wiley.

Walters R.C.S. (1962). *Dam Geology*, London: Butterworths

Wilson E.M. (1983). *Engineering Hydrology* (Third Edition). London: Macmillan.

WHO. (1993). *Guidelines for Drinking Water Quality*, Geneva: World Health Organization.

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.