ORIGIN, DISTRIBUTION, FORMATION, AND EFFECTS

Tóth J.
University of Alberta, Edmonton, Canada

Keywords: groundwater, hydrogeology, geohydrology, hydrologic cycle, water balance, reference volume, reference time-interval, hydraulic conductivity, hydrostratigraphy, Darcy's law, hydraulic head, flow system, manifestations of groundwater flow

Contents

Summary

This article presents a concise overview of the fundamental aspects of groundwater studies. It provides basic definitions used in these studies and surveys the controlling

factors behind the provenance of groundwater, its modes of occurrence, hydraulics and regional flow patterns, and its environmental effects. Groundwater is envisaged here in its three, virtually independent, component entities: as a human commodity, as the subsurface segment of the hydrologic cycle, and as a geological agent.

In Section 1, an attempt is made to provide the basic information needed to understand and appreciate all three of the above aspects. Clarification is also provided regarding the (sometimes ambiguously-used) terms for, and mutual relations between, the various disciplines dealing with groundwater. Etymologically-based explanations are given for the terms hydrogeology, geology, hydrology, groundwater hydrology, and geohydrology.

In Section 2, the hydrologic cycle is reviewed, with the emphasis on groundwater as its subsurface component. The systems structure of the mass-movement of water in general, and of groundwater in particular, is revealed as an indispensable concept for the correct formulation of hydrologic budgets. The need to write the hydrologic equation for bounded reference volumes in space, and using specified reference intervals of time, is explained.

Section 3 discusses the basic parameters needed to describe the storage, flow characteristics, and the different types of subsurface water, such as porosity, permeability, hydraulic conductivity, compressibility, and aquifer types. In connection with Darcy's law, the nature of hydraulic head as a measure of energy is stressed, and the hydraulic gradient is presented as a measure of the fluid-driving force. The various qualifying adjectives applied to groundwater in different capacities, or from different viewpoints, are tabulated. Regional patterns of groundwater flow impelled by various force types, such as gravity, buoyancy, sediment compaction, dilatation of the rock upon erosional unloading, and tectonic compression, are presented in conclusion.

Section 4 presents groundwater as a geological agent, as well as considering the causes and principal controlling factors of this agency. Gravity-driven systems of groundwater flow are used by way of example, because of their tractability relative to flow due to other types of impelling forces. The main processes of interaction between groundwater and its environment are reviewed in three categories: chemical, physical, and kinetic or transport processes. The resulting effects and manifestations are grouped as follows: hydraulics and hydrology; chemistry and mineralogy; vegetation; soil and rock mechanics; geomorphology; and transport and accumulation.

1. Introduction

1.1. Definition, Sources, and Aspects of Groundwater

Groundwater is water beneath the surface of the Earth. It occupies pores, fissures, channels, and other types of void spaces in the rock framework that are not filled with other materials such as solid mineral matter, liquid hydrocarbons, or various gases including air. The depth of the realm of groundwater is determined by that of the open spaces in the crust, and may reach tens of kilometers. Common synonyms of the term *groundwater* include *subsurface water* and *formation water* in English, and their equivalents in several other languages.

The two principal sources of groundwater are infiltrated meteoric precipitation and water embedded in the accumulating sediments of seas and oceans, commonly referred to as *connate water*. The relative proportions of water derived from these two sources in the subsurface water body at any given time are difficult to estimate, and probably depend on the geological time span for which these calculations are made. There is strong evidence that connate waters are diluted, or even flushed, over long timespans by terrestrially infiltrated meteoric waters. A third, and presumably insignificant, portion of groundwater is thought to result directly from magmatic processes, and is called *juvenile water*. In addition, diagenesis of some minerals (for example, transformation of smectite to illite) may release water from crystal lattices into rock-void space. However, since diagenetic water must have come initially from one of the previously mentioned waters, this cannot be considered a true "original source."

Because of its utilitarian value, its migration underground from areas of infiltration to sites of discharge, and the consequences of its many-faceted interactions with its natural environment, groundwater can be considered to have three different aspects worthy of study: as a human commodity, as the subsurface element of the hydrologic cycle, and as a geological agent. As a human commodity it may be compared to an economic mineral: it must be sought, exploited, and possibly even improved. However, it is also a renewable resource that requires planned development, responsible management, and careful protection if it is to satisfy the needs of human societies on a sustainable basis. As the subsurface segment of the hydrologic cycle, groundwater flow transports infiltrating meteoric water underground to areas where it resurfaces. Here it is evaporated and thus enters the atmospheric moisture body, to be utilized by plants in their biological processes or to be discharged into various standing, flowing, or frozen bodies of surface water. However, groundwater is also a geological agent due to its ability to mobilize, transport, and deposit mineral matter, microorganisms, and heat in the subsurface mass. Indeed, groundwater flow is the only ubiquitous transport mechanism operating beneath the surface of the Earth. The effects of the interactions of groundwater with its environment are manifested in a great variety of natural processes and phenomena, both above and below the land surface.

1.2. The Sciences Dealing with Groundwater

Owing to the diversity and importance of the natural processes and practical problems involved with studying groundwater, a wide range of scientific skills and technical approaches are needed to deal with the various theoretical and practical questions it raises. The names of several of these disciplines have not been universally standardized, and inconsistencies in their usage are common. In an attempt to minimize this problem, an internally consistent set of names of groundwater-related sciences is proposed here. The proposed terms are advanced on the basis of their etymological meaning and grammatical structure.

The central—or "umbrella"—discipline of groundwater studies is *hydrogeology*. This term means "geology of water" or "water geology" ("hydro-," a Greek combining form for "water," modifies the noun "geology" here). Hydrogeology may be defined as "the science of those processes and phenomena resulting from the interactions between groundwater and the rock framework," or for short, "the study of interactions between groundwater and the rock framework." The processes and phenomena involved may be physical, chemical, geological, and biological. They may occur on, near, or deep below the land surface. They occur over varying timescales (days, seasons, years, decades, centuries, and entire geological periods). They involve transport of mass and energy, chemical reactions, and changes in heat and pore pressure. In scope, hydrogeology is both an earth science and an engineering discipline. It encompasses the occurrence, migration, and chemistry of groundwater, as well as its manifestations and applications for human purposes.

To cover this broad scope hydrogeology draws upon certain areas of several other sciences, both basic and applied, including mathematics, physics, chemistry, geology, hydrology, soil- and rock-mechanics, pedology, botany, and so on. The relation of hydrogeology to other sciences that deal with groundwater may be characterized briefly as follows.

- *Geology* is the science of rocks, providing information on the receptacle of groundwater.
- *Hydrology* deals with water, which is also the object of hydrogeology. It studies the processes and volumes involved in the movement of, and the exchange of, water masses within and between the atmosphere, hydrosphere, and lithosphere.
- *Groundwater hydrology* deals with the underground water-masses. The causes and effects of rock–water interactions are sideline issues for groundwater hydrology, unlike for hydrogeology.
- *Geohydrology* is a word in which "geo-" (Earth-) is the modifier of the noun "hydrology" (water science), and therefore means "hydrology of the Earth." Thus, the term is regarded here as the science dealing with the volumes of water masses on a global scale.

2. The Hydrologic Cycle

2.1. Concept and Characteristics

The *hydrologic cycle* may be defined as a system of continuous exchange of water masses between the three global environments, namely the atmosphere, hydrosphere, and lithosphere. It is the central concept of hydrology and is based on the empirical observation that no permanent depletion or accretion of water occurs in any of the three "spheres." In the present context, the atmosphere is considered to be the space above the Earth's surface occupied by air; the hydrosphere comprises all bodies of liquid and solid water on the surface of the Earth; and the lithosphere is the upper part of the Earth's crust, the void spaces and crystal lattices within which are filled with free or chemically-bonded water.

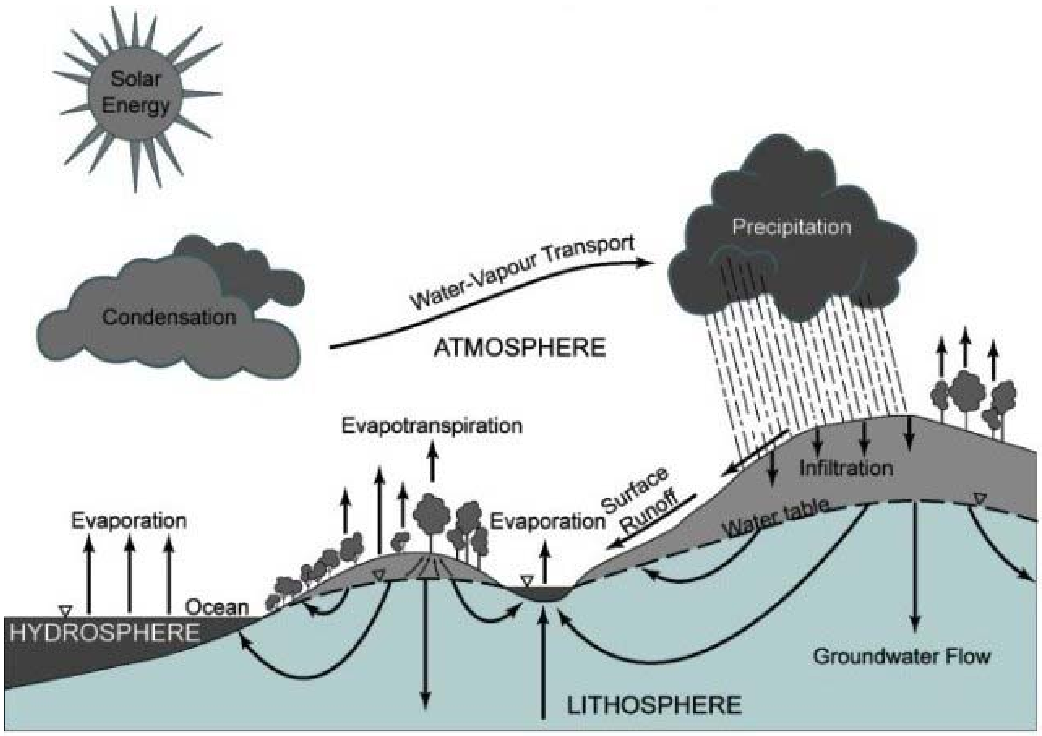

Figure 1. Conceptual illustration of the hydrologic cycle (modified from Manning, 1992, Figure 1.1)

The movement of water in the hydrologic cycle is conceptualized as the circular transfer of water masses between the three spheres, following a path of monotonically decreasing energy (Figure 1). The starting point of the cycle can be identified as the surfaces of land, vegetation, and open water bodies where the Sun's direct radiation and environmental heating raises the energy level of the water particles to a maximum, causing evaporation and vegetal transpiration. From here on, the water particles seek a state and position of minimum energy through a continuous series of varying processes and forms of energy loss, such as condensation, precipitation, and flow above and below the land surface. They return ultimately to their initial state of relative minimum energy, to be re-launched on their cycle by energy input from the Sun. Based on this scenario, combined with the observation that there are no sources or sinks that alter the total mass of globally-circulating water, the *global hydrologic cycle* may be said to have three fundamental properties: it is *closed*, *conservative*, and *energy driven*.

2.2. Component Processes and Systems Structure

These general processes of water circulation can be broken down into a number of specific processes, all of which can occur on local, regional, or global scales. Through each of these processes, or elements, of the hydrologic cycle the energy level of the water particles drops due to a loss of heat, altitude, pressure, or some combination thereof.

The initial step in the cycle is *evaporation* and *vegetal transpiration* (together also termed *evapotranspiration*), in which the energy level of the water molecules is raised from the local minimum to a maximum by the Sun's heat and light energy. This energy is converted to the potential of the water particles by lifting them from open water bodies, snow and ice, moist soils, and the leaves of plants into the atmosphere. By losing some portion of this energy through *condensation* and *precipitation*, the water will subsequently fall back onto the lithosphere or hydrosphere in the form of rain, snow, sleet, dew, frost, and so on. Upon reaching the surface, that part of the precipitation that has not already evaporated will remain temporarily on the surface, infiltrate into the ground, or flow overland. *Interception* and *surface detention* are those elements of the hydrologic cycle by which water is retained temporarily above ground level by plant leaves, buildings, paved or metalled surfaces (interception), or depressions in the land surface (surface detention). By means of *infiltration*, an element of the precipitation either will be added to the soil moisture or will reach the water table. Through *overland flow* and *interflow* the third element of precipitated water moves over the land surface as sheet flow or in rivulets, and in the unsaturated zone above the water table, towards areas of lower energy levels, either to reach bodies of surface water or to be evaporated *en route*. Those portions of the circulating water reaching the water table and streams will participate in the *runoff* components of the cycle. The main types of runoff are the *surface runoff* or *stream flow*, and *subsurface runoff* or *groundwater flow*. Consequently, runoff = surface runoff + groundwater flow.

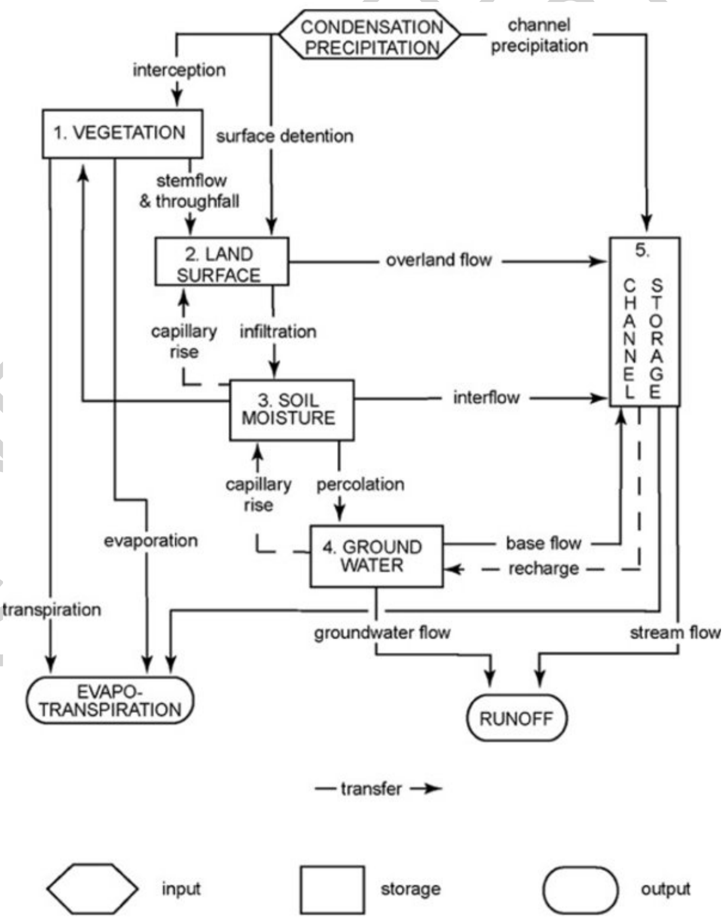

Figure 2. System structure of the hydrologic cycle, on local and regional scales: open system (modified from Ward, 1975, Figure 1.5)

The hydrologic cycle may be considered as a physical, sequential, dynamic system, comprising seven *subsystems*. According to this view, a *system* is an assemblage of parts united by some kind of regular interaction. A *physical system* is a system in the real world; a *sequential system* consists of an input, throughput, and output of some working medium (for example, matter); and a *dynamic system* is a physical system which receives certain quantitative inputs and accordingly acts concertedly under given constraints to produce certain quantitative outputs (Figure 3).

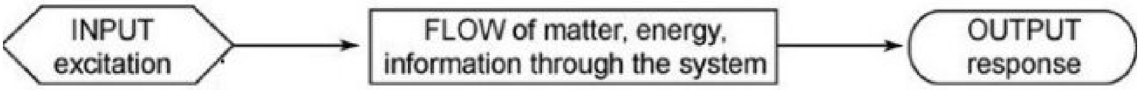

Figure 3. Diagrammatic representation of a sequential system (after Ward, 1975, Figure 1.4)

The seven subsystems of the hydrologic cycle (Figure 4), each having its own "input → throughput → output" sequence, are

- vegetation
- land surface
- soil moisture
- groundwater
- channel storage
- ocean basins, and
- atmosphere

These subsystems are linked by the different components of the hydrologic cycle mentioned above.

Attributing a systems structure to the hydrologic cycle has some distinct advantages. It provides a unifying framework which facilitates an overview of a complex group of processes and phenomena.

It demands a rigorous formulation of concepts, and full consideration of the mutual interactions between the various subsystems, comparable in some ways to the advantages offered by computer programs as opposed to unconstrained quantitative descriptions. It also enables and simplifies mathematical simulations, resulting in real-life models.

Figures 2 and 4 present systems diagrams of the hydrologic cycle, on a local or regional scale and on the global scale respectively. Although the subsystems and the component processes are the same on both scales, one fundamental difference exists.

On a spatially delimited (local or regional) scale the hydrologic cycle is an *open system*: water can move both into and out of it across its geographical boundaries, and thus the total amount of water within those boundaries can vary. On the global scale, however, the cycle is closed. Water is neither gained nor lost by the system, and its total volume therefore remains constant.

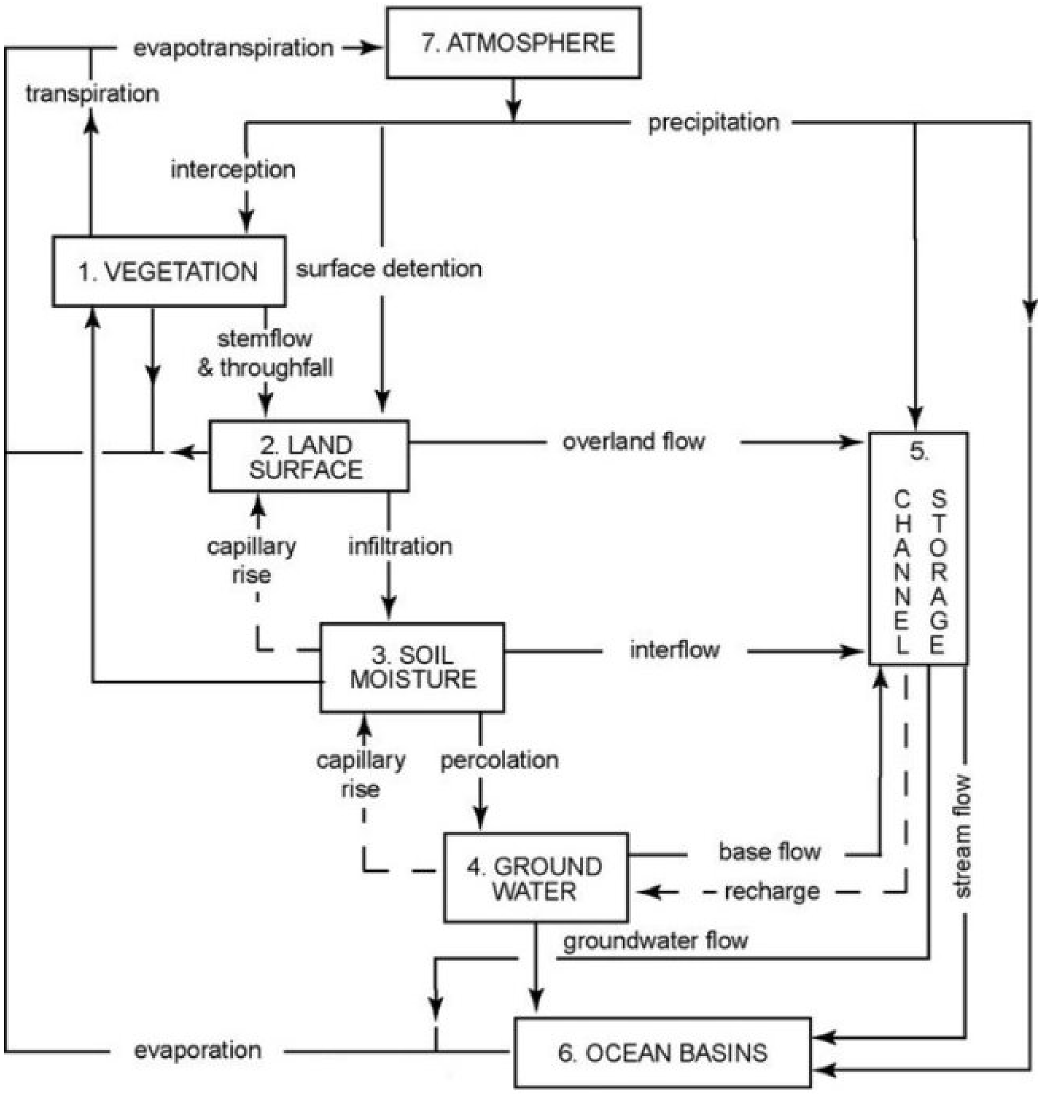

Figure 4. System structure of the hydrologic cycle, global scale: closed system (modified from Ward, 1975, Figure 1.6)

-
-
-

Bibliography

Bethke C.M. (1989). Modeling subsurface flow in sedimentary basins. *Geologische Rundschau* **78**(1), 129–154. [A thorough review of theoretical patterns of groundwater flow induced by the most common driving forces occurring in sedimentary basins.]

Butler S.S. (1957). *Principles of Hydrology*. 367 pp. Englewood Cliffs, NJ: McGraw-Hill. [A general text on hydrology with much quantitative data on the hydrologic cycle.]

Engelen G.B. and Kloosterman F.H. (1996). *Hydrological Systems Analysis: Methods and Applications*. 152 pp. Dordrecht, the Netherlands; Boston; London: Kluwer. [Presents detailed characterizations and interpretations of groundwater conditions in, and as affected by, natural systems of groundwater flow, based on field observations and modeling in the Netherlands, Poland, and Indonesia.]

Fetter C.W. (1994). *Applied Hydrogeology*, 3rd edition. 691 pp. Toronto: Maxwell Macmillan Canada. [Presents the theoretical background and numerous case studies of groundwater conditions in different rock types and geological environments.]

Freeze R.A. and Cherry J.A. (1979). *Groundwater*. 604 pp. Englewood Cliffs, NJ: Prentice-Hall. [Contains concise characterizations of groundwater conditions in different rock types and geological environments.]

Hubbert M.K. (1940). The theory of ground-water motion. *Journal of Geology* **48**(8), 785–944. [The first rigorous and complete theoretical analysis of the fundamentals of regional groundwater flow.]

Ingebritsen S.E. and Sanford W.E. (1998). *Groundwater in Geological Processes*. 341 pp. Cambridge, UK; New York: Cambridge University Press. [An in-depth presentation of the methods and results of numerical analyses of various geological processes and effects of deep-basinal groundwater flow driven by different types of impelling forces.]

Kruseman G.P. and de Ridder N.A. (1990). *Analysis and Evaluation of Pumping Test Data*. 377 pp. Publication 47, International Institute for Land Reclamation and Improvement. Wageningen, the Netherlands: International Institute for Land Reclamation and Improvement. [Presents and exemplifies the theories and practice of pumping tests with regard to a great variety of different aquifer types.]

Manning J.C. (1992). *Applied Principles of Hydrogeology*. 276 pp. Upper Saddle River, NJ: Prentice Hall.

McPherson B.J.O.L. and Garven G. (1999). Hydrodynamics, and overpressure mechanisms in the Sacramento Basin, California. *American Journal of Science*, **299** (June), 429–466. [Presents numerical experiments to determine the probable mechanism(s) generating observed overpressures in a deep sedimentary basin.]

Schumacher D. and Abrams M.A. eds. (1996). *Hydrocarbon Migration and its Near-Surface Expression*. 446 pp. AAPG Memoir 66. Tulsa, OK: American Association of Petroleum Geologists. [Presents the theories of the origin of near-surface expressions of petroleum migration, along with techniques of detection and analysis, and case histories of utilization, in 33 separately authored topical chapters.]

Tóth J. (1999). Groundwater as a geological agent: An overview of the causes, processes and manifestations. *Hydrogeology Journal* **7**(1), 1–14. [An overview of the genesis and types of natural phenomena induced by gravity-driven groundwater flow-systems.]

Tóth J. ed. (1999). Groundwater as a geological agent. 150 pp. *Hydrogeology Journal Theme Issue* **7**(1) [Contains nine topical papers and a general overview of the various types and nature of various effects of gravity-driven, relatively shallow, regional groundwater flow.]

Tóth J. and Almási I. (2001). Interpretation of observed fluid potential patterns in a deep sedimentary basin under tectonic compression: Hungarian Great Plain, Pannonian Basin. *Geofluids* **1**, 11–36. [Presents a comprehensive picture of the occurrence and flow of groundwater inferred from over 16 000 pore-pressure data in an extensive (± 40 000 km^2) and deep (> 4 km) basin of semi/fully-consolidated clastic sediments under the influence of gravity drive and tectonic compression.]

Ward R.C. (1975). *Principles of Hydrology*. 356 pp. London: McGraw-Hill. [A general text of hydrology, with an emphasis on the position and system nature of groundwater within the hydrologic cycle.]

Biographical Sketch

József Tóth, Professor Emeritus at the University of Alberta, studied exploration geophysics at the School of Mining and Geodesy of Sopron in his native Hungary. He fled that country from the invading troops of the Soviet Union in 1956, resumed his studies, and obtained a Ph.D. in hydrogeology in 1965 at the State University of Utrecht, the Netherlands. He moved to Canada in 1960 and worked at the Alberta Research Council for twenty years, the last twelve of them as Head of the Groundwater Department. He formulated, directed, and administered the scientific and technical activities of the Department, including a ten-year-long hydrogeological mapping program covering the entire Province of Alberta (660 000 km^2). He became the Council’s first Research Fellow in 1980. That year he joined the Department of Geology (Department of Earth and Atmospheric Sciences since 1995), University of Alberta. He worked and lectured in over fifteen different countries, and was the Hydrogeologist Member on the Technical Advisory Committee of Canada’s Nuclear Fuel Waste Management Program for eleven years.

Tóth’s research interests center on the theoretical and applied aspects, and natural manifestations, of regional groundwater flow, as reflected by over 80 publications that he has authored or co-authored. He was the first recipient of the O.E. Meinzer Award of the Geological Society of America for “Distinguished Contribution to Hydrogeology” in 1965; thirty-four years later he received the International Association of Hydrogeologists’ “President’s Award 1999,” which is “…presented annually to a senior hydrogeologist who has made outstanding contributions to the advancement of hydrogeology.” Several of his concepts and ideas concerning basinal groundwater flow are applied to problems involving water resources, soil salinization, slope stability, strata-bound ore genesis, lakes and wetlands, radioactive waste disposal, and petroleum migration and exploration. His current research is focused on groundwater flow and its effects in the Pannonian Basin, Hungary.