GROUNDWATER: PLANNING AND PROTECTION

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Summary

Groundwater is a resource, providing water supplies for drinking, industry, and agriculture, as well as sustaining many surface waters and wetlands, and their ecology. Indeed, the various types of water are closely connected in the hydrologic cycle, which describes the movement of waters above, on, and below the earth's surface. Protecting the quantity of groundwater and its correct contemporary exploitation require a detailed knowledge of aquifers as detailed in Section 3.

Contamination problems are increasing, primarily because of the large and growing number of toxic compounds used in industry and agriculture. Once an aquifer is contaminated it may be unusable for years. Restoration requires great efforts; polluted groundwater is very difficult and expensive to clean up. The best thing to do is to adopt pollution prevention by contamination control measures and—at regional scale—vulnerability and risk mapping.

1. The Importance of Groundwater

The importance of groundwater as a source of fresh water is worthy of note—in Europe and the United States, more than 50% of the water supply is obtained from groundwater. This percentage increases dramatically in rural environments—more than 99% of rural

US citizens use groundwater. Even in Canada—land of lakes, rivers, and glaciers—groundwater is the sole source of water for about a quarter of Canadians, and two-thirds of them live in rural areas.

In recent years, a number of events affecting groundwater quality and quantity have contributed to bring to public attention the importance and vulnerability of the resource. In 1993, for example, the US Environmental Protection Agency (USEPA) identified more than 200 chemical compounds in groundwater—some of these extremely hazardous for human health.

Groundwater protection is a priority environmental concern in many countries. The correct way forward is to prevent contamination by protecting groundwaters and to avoid unacceptable drawdowns of the water table by planning groundwater exploitations.

2. Basic Concepts in Hydrogeology

Water underground is known as subsurface water**;** it fills void spaces in the rocks in different quantities and with different characteristics. The term “groundwater” indicates the part of subsurface water that completely saturates these spaces.

In unconsolidated deposits (e.g., clay, sand, gravel) consisting of particles of rocks or minerals ranging in size from fractions of millimeters to several meters, the void spaces between particles are called pores. In consolidated rocks—which consist of mineral particles of different sizes that have been welded by natural reactions into a solid mass (e.g., granite or limestone)—the void spaces may be caused by fractures caused by decompression, cooling, deformations in the rock, and so on; or dissolution phenomena, as in limestone (see *Groundwater Studies in Consolidated Rocks*), bedding planes, and so on.

Finally, in some rocks (tuff, sandstone), spaces include both pores and fractures (semiconsolidated rocks). A rock with internal void spaces, regardless of their origin, is defined as porous, or otherwise compact.

Almost all subsurface waters originate from infiltration from precipitation or surface water (rivers, lakes, and so on). Some groundwater found in sedimentary rocks may, however, be the same water that was present when the sediments accumulated (connate water). In the midwestern United States, for example, groundwater with high chloride content is in part water from the sea that covered the area millions of years ago. In other situations groundwater is given off during volcanic eruptions or during the cooling of magma (juvenile water). Connate or juvenile waters are clearly poorer in quantity than water of external origin.

In the hydrosphere the volume of subsurface water is considerable (Table 1).

Types of water	**Volume (km$^3 \times 10^3$)**

Oceans	1 350 000
Ice caps and glaciers	26 000
Subsurface water	7150
Water on land surface	225
Atmosphere (water vapor)	13

Note: these data are approximations.

Table 1. Distribution of the various types of water in the hydrosphere.

These various kinds of water are closely connected in the hydrological cycle (Figure 1), which describes the constant movement of waters above, on, and below the earth's surface.

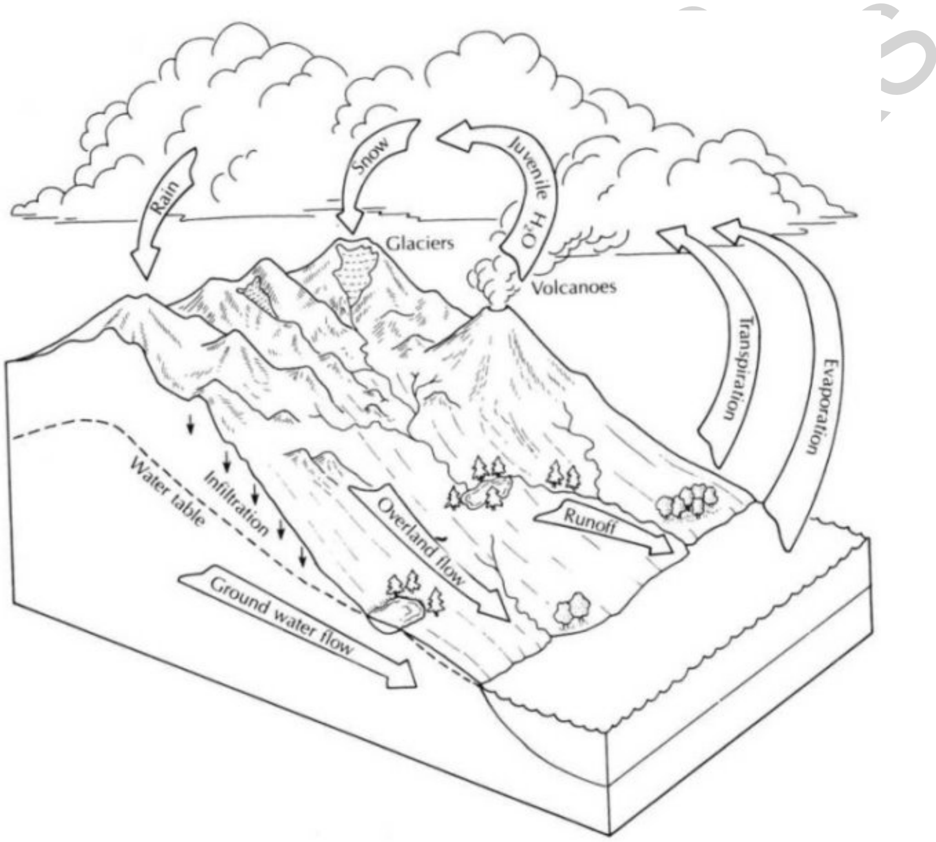

Figure 1. The hydrological cycle

In the cycle, solar radiation is the source of constant energy—water evaporates from vegetation, from exposed moist surfaces (including the land surface), and from the ocean. This mixture—and transpiration by plants—forms clouds that return the water to the land surface or ocean in the form of precipitation. On the land surface the presence of porous rocks allows a fraction of these waters to penetrate underground—infiltration rates vary depending on the rock present, the land use and the humidity it contains, the intensity and duration of precipitation, and so on—while the rest activates an overland runoff that feeds the rivers, finally ending in the sea. Water from infiltration moves as groundwater flow through the rocks until it discharges as a spring or as seepage into a lake, river, or ocean. Thus evaporation perpetuates the cycle.

It is a consolidated opinion that the total quantity of water employed in the hydrological cycle has remained practically constant, at least in recent geological times; the limited addition of new water (juvenile waters) is in fact balanced by subduction of water in the ocean sediments.

The land surface redistributes the waters from precipitation in two circuits—one superficial and the other underground. One of the principal differences between these is the low velocity of water in the latter—in sandy soil, for example, the waters in saturated zones move with horizontal velocity of a few decimeters per day. The consequences are:

- the slow filtration encourages self-cleaning processes;
- as the rocks slowly return the water absorbed, they fulfill an important function of storing and thus guaranteeing the discharge from streams even in dry spells; and
- the prolonged contact between water and rock allows the water to acquire a physical and chemical setting, sometimes of a very particular nature (mineral water).

Water that has infiltrated the rock (subsurface water) occurs in two different zones. In the first, immediately below the land surface, the pores contain both air and water: this is the unsaturated zone or zone of aeration. This zone is almost always above another where all the interconnected pores are completely saturated with water (saturated zone). The upper surface of the zone of saturation is called the water table.

Recharge of the saturated zone occurs by percolation of water from the land surface through the unsaturated zone; here three zones can be distinguished with a degree of saturation that increases with depth:

- the soil zone—near the land surface—that discharges water into the atmosphere by evaporation and transpiration; it is 1–2 m in thickness and supports plant growth;
- the intermediate zone; and
- the capillary zone extends immediately above the zone of saturation to the limit of the capillary rise of water—water rises against the force of gravity in small-diameter pores as a result of the attraction between water and rocks.

Not all the water present in the rock can be utilized. The forces of molecular attraction—adhesion and cohesion—join the water particles in the unsaturated zone and part of the water in the saturated zone to the surface of the pores. These forces are present in thicknesses of around a micron; elsewhere the force of gravity prevails. The amount of water is much greater in rocks with small interstices—it increases for small grains, with a variety of size of grains, and also in relation to the extent of the fracture networks. In rocks with very small pores (e.g., clay, silt, fine sand) the water present is generally not available for human use. Thus, only part of the water in saturated zones—

defined as groundwater—constitutes the groundwater flow, feeds springs, and this is the only quantity of subsurface water that man can exploit (e.g., through wells).

It is less that a rock contains water than that the rock is permeable (i.e., it can transmit a liquid). Permeability is expressed numerically by hydraulic conductivity, which can be measured in the laboratory or *in situ*—by pumping or tracer tests, and so on. As regards permeability, rocks can be divided into:

- *Aquifer*. Rock that enables groundwater flow—including a saturated zone—and yields significant quantities of water.
- *Aquitard*. A saturated bed of rock that yields negligible quantities of water for wells, drains, and springs, but through which water leakage is possible.
- *Aquiclude*. A saturated bed of rock in which the yields of water and leakage are negligible.

An aquifer serves as a transmission conduit and transports water from recharge areas to surface bodies of water, springs, wells, and other water-collecting devices; it also serves as a storage reservoir and provides reserve water for use during periods when withdrawals exceed recharge.

The presence or otherwise of aquitards or aquicludes creates different aquifers (Figure 2).

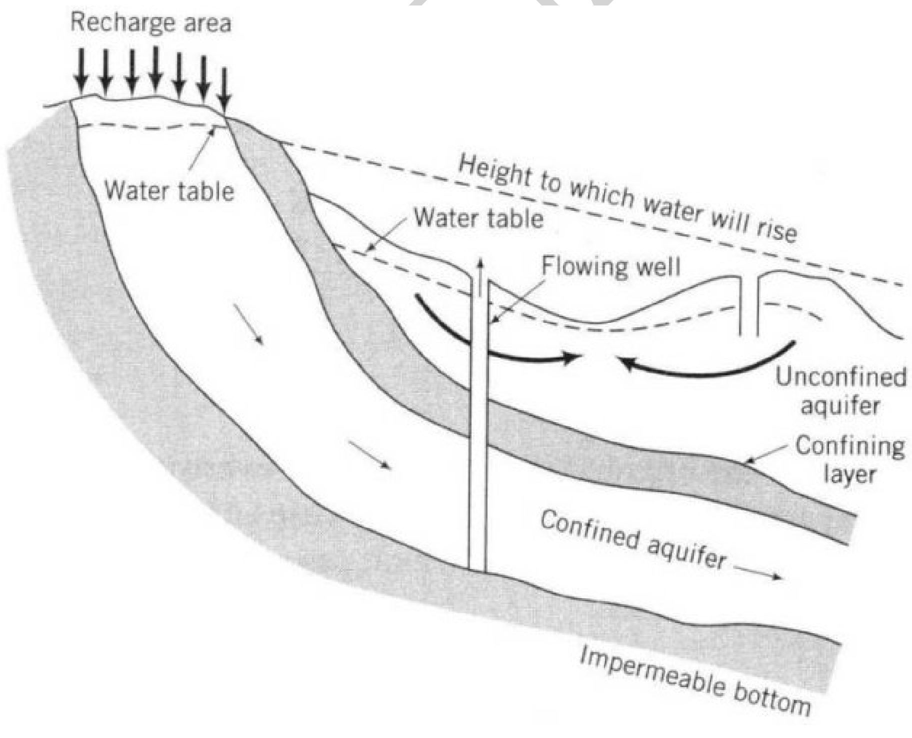

Figure 2. Schematic cross-section illustrating the difference between a confined and an unconfined aquifer

In an unconfined aquifer the upper surface of the zone of saturation (water table) is in contact with the air contained in the pores in the rock—and is thus at atmospheric pressure—and the water table is at the same depth as the water level in unused wells.

An artesian aquifer is one in which groundwater is confined under pressure by overlying aquitards or aquicludes, and water levels in wells rise above the top of the aquifer—in some cases the water may rise above ground surface (flowing wells).

The imaginary surface to which water rises in wells is called the piezometric surface, and its oscillations correspond to changes in the pressure of the water. Furthermore, an artesian aquifer can be classed as leaky or nonleaky if it is confined by aquitards or aquicludes.

In the first case groundwater flow is possible from and to the aquifer; in the presence of an aquiclude such flow is negligible. Finally, an artesian aquifer may become an unconfined aquifer if the piezometric surface declines below the top of the aquifer.

The law governing the movement of subterranean waters is, in most cases, that defined by Henry Darcy (1856):

$$Q = K\,A\,i \qquad (1)$$

where Q is the discharge [$l^3\ t^{-1}$], K is the hydraulic conductivity of the aquifer [$l\ t^{-1}$], A the area traversed by flow [l^2] and i (dimensionless) is the hydraulic gradient (or the slope of the water table).

The true velocity (v) of groundwater can be obtained from this law:

$$\mathrm{v = K\ i/n} \qquad (2)$$

n (dimensionless) considers the spaces actually available at groundwater flow in that it also considers the thickness of water bound to the surface of the pores.

When the water table intersects the land surface, a spring is formed. These are more frequent in mountainous areas and their origin may be linked to a variety of different, complex geological situations—they are often found on slopes where an aquifer is limited, either at its base or laterally, by less permeable rock (Figure 3).

Groundwater tends to maintain a physical and chemical balance with aquifers.

The temperatures of subterranean waters is worthy of note. In fact, because of the thermic inertia of the rocks, the seasonal fluctuations of the heat of the sun are attenuated in the subsoil, and in shallow groundwater (at 10 m or more below the land surface), the temperature is roughly the same as the average annual air temperature.

At greater depths the temperature of groundwater increases according to the geothermal gradient (about 30 °C km^{-1}).

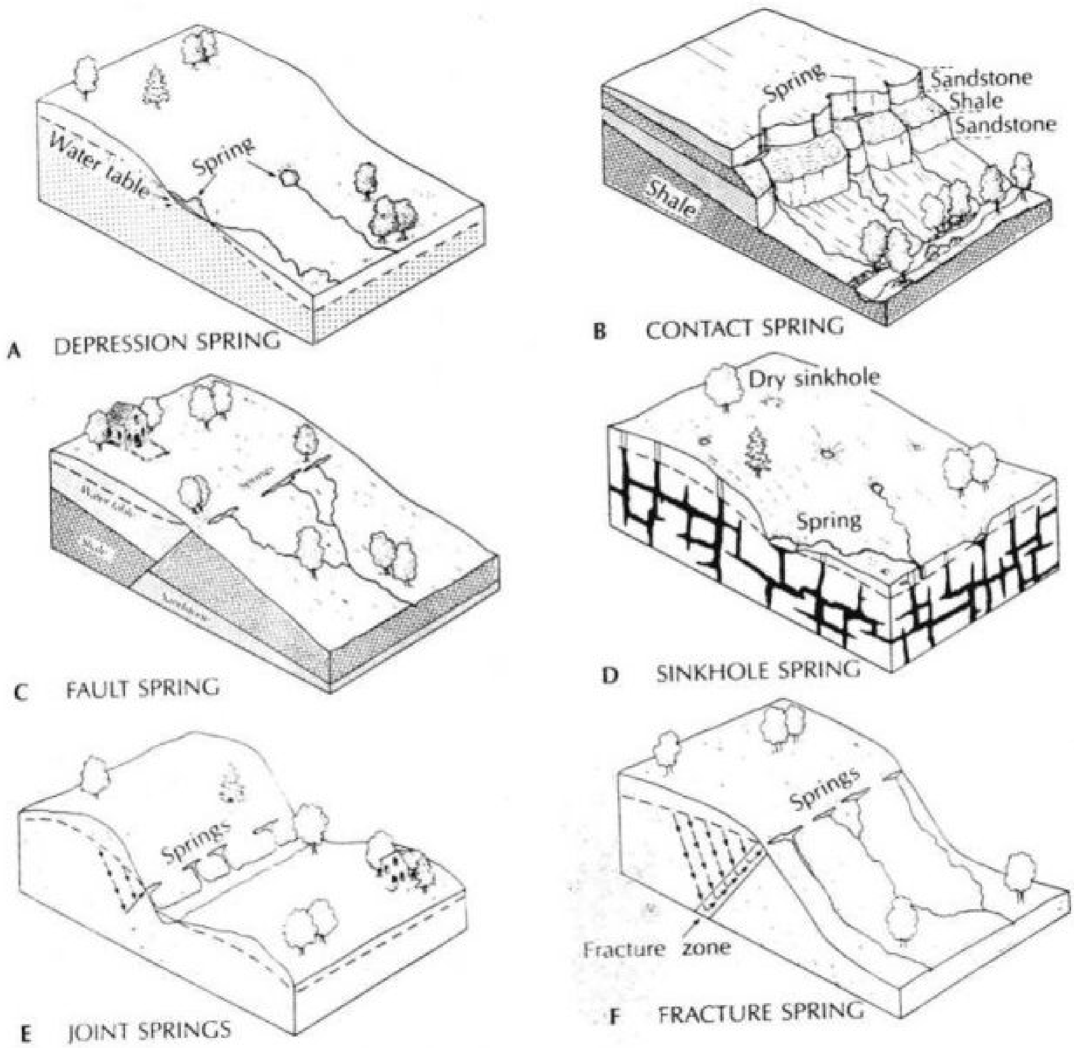

Figure 3. Types of spring

The chemical composition of groundwater depends equally on the nature of the aquifers—above all on solubility—but is influenced by other factors, such as contact time between water and rock, water temperature, the presence of gases, and so on.

In all groundwater the most important ions are:

Cations	Ca^{++}	Mg^{++}	Na^{+}	K^{+}
Anions	HCO_3^{-}	SO_4^{--}	Cl^{-}	

Quantities are expressed in mg l^{-1} (milligrams per liter), ppm (parts per million), or meq l^{-1}(milli-equivalents per liter). Another commonly used parameter in the evaluation of water quality is TDS (total dissolved solids in mg l^{-1}), which is a measure of the total amount of mineral dissolved in water.

3. Hydrogeological Studies

The withdrawal of groundwaters for various uses—drinking, irrigation, and so on—can be carried out directly at the source or below the surface by means of wells or other water-collecting devices—tunnels, drains, and so on.

Correct use of groundwaters necessitates detailed knowledge of the aquifers to be utilized, regarding:

- lithology and properties of the rocks (e.g., porosity, grain-size distribution);
- presence or otherwise of aquitards or aquicludes, their position in relation to the aquifer, and links with nearby aquifers;
- permeability, storativity, and so on of the aquifer;
- groundwater flow;
- evaluation of natural recharge of the aquifers (see *Groundwater Budget*);
- interactions with surface water, and where applicable, the sea; and
- physical and chemical characteristics of the groundwater and its possible contamination.

It is not always easy to obtain such information, especially since in some cases, costly *in situ* investigations are required. Study methods are determined by the lithology of the aquifer—consolidated or unconsolidated rocks—and the morphology of the area.

Thus, in a mountainous area where the rocks are outcropping, field observations are of primary importance; while in plain areas measures *in situ* (e.g., measurements of groundwater levels, chemical analysis) or drill log interpretations are necessary.

Apart from the geological environment, some studies are routine, such as geoelectrical or geoseismic investigations to analyze the response of rock to artificial external impulses—electrical current or seismic waves. Chemical analysis of the water is also common.

Research techniques make use of artificial tracers—saline, colorant, radioactive—or natural tracers—stable isotopes, such as deuterium and oxygen-18; or radioactive isotopes, such as tritium and carbonium-14.

These are substances that enable the researcher to follow the movements of groundwater, or to define its velocity, or evaluate the time since infiltration in the subsoil.

The use of remote sensing is of interest: from a normal aerial photo, color or monochrome, using stereoscopic vision to provide a 3-D view of the land surface, to airplane or satellite sensors to analyze radiation of different wavelengths emitted by the earth's surface.

The 9–11 micron band is used to highlight the superficial temperature of an area and thus to point out fractures, or in the sea, the presence of continental springs.

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Bibliography

Aller L., Bennet T., Leher J.H., Petty R.J., and Hackett G. (1987). *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeological Settings, EPA 600/2-87-035*, 622 pp. Washington, D.C.: US Environmental Protection Agency. [This paper explains the DRASTIC methodology, designed for producing groundwater pollution potential maps by a standardized non-subjective method. The seven principal factors, which by their initials produce the acronym DRASTIC, are described in detail on the basis of the peculiar hydrogeological settings.]

Custodio E. and Llamas M.R. (1983). *Hidrologìa Subterrànea, Second Edition*, Vols 1–2, 2359 pp. Barcelona, Spain: Omega.[These two volumes constitute a comprehensive book which collates the experiences of well-known hydrogeologists, at the Masters Course in Groundwater Hydrology (CIHS-Technical University of Catalonia, Spain). The main topics of the basic hydrogeology are described in detail in 24 chapters, which include exercises and case studies.]

Domenico P.A. and Schwartz F.W. (1998). *Physical and Chemical Hydrogeology, Second Edition*, 535 pp. New York: John Wiley. [Concentrating on the practice of hydrogeology, this book ,after presenting preliminary information on the hydrologic cycle and the porosity and permeability of porous material, deals with fluid, energy, and mass transport in porous media.]

Fetter C.W. (2001). *Applied Hydrogeology, Fourth Edition*, 598 pp. Upper Saddle River, NJ: Prentice-Hall.[An introductory textbook suitable for advanced undergraduate or the start of graduate level courses, offering a complete treatment of the elements of physical hydrology and the basic concepts of chemical and contaminant hydrogeology.]

Hem J.D. (1985). *Study and Interpretation of the Chemical Characteristics of Natural Water, US Geological Survey (USGS) Water-Supply Paper 2254*, 263 pp. Alexandria Va., USGS. [This book introduces the topics of low-temperature aqueous geochemistry and of applied and theoretical water chemistry, and is an aid to hydrologists and hydrogeologists who may need to evaluate water quality and incorporate water chemistry into their investigations of water resources.]

Lerner D.N., Issar A.S., and Simmers I. (1990). *Groundwater Recharge. A Guide to Understanding and Estimating Natural Recharge*, 345 pp. Heise, Hannover, Germany: IAH/AIH. [This manual of practice especially refers to the arid and semi-arid zones of the world, these being the areas where the need for reliable estimates of groundwater recharge are greatest. Considerations on estimation of natural and human-induced groundwater recharge are also included.]

Struckmeier W.F. and Margat J. (1995). *Hydrogeological Maps. A Guide and a Standard Legend*, 177 pp. Heise, Hannover, Germany: International Association of Hydrogeologists (AIH/IAH). [This book contains a methodological guide on the preparation of hydrogeological maps and, in the second part, an international standard legend with a catalogue of colours, signs and symbols explained in English, French and German.]

Todd D.K. (1980). *Ground Water Hydrology*, 535 pp. New York: John Wiley. [This basic book treats fundamental principles, methods, and problems of the Groundwater Hydrology.]

US Environmental Protection Agency (USEPA). (1990, updated 1999). *Citizen's Guide to Ground-Water Protection*, *EPA/440/6-90*-004, 34 pp. Washington, D.C.: USEPA. [This document includes the basic information about groundwater, the major sources of groundwater contamination, and how to protect groundwater quality. The 1999 version of the Guide contains a new Appendix that describes the new Source Water Assessment Programme and how to obtain contact information for state agencies and EPA regional offices.]

Biographical Sketches

Alfonso Corniello is a full Professor of Hydrogeology at the Engineering Faculty of Naples, Italy, where he has been a teacher of Applied Geology for many years. He is head of local research units for the *Gruppo Nazionale per la Difesa dalle Catastrofi Idrogeologiche* of the Italian National Research Council (CNR–GNDCI). He has been a member of the Council of the National Group of Applied Geology, and at the present time, he is councillor of the Italian Division of the International Association of Hydrogeologists (AIH/IAH). He is the author of many studies relating to a) groundwater-resources evaluation and groundwater-flow studies in different geological settings; b) hydrogeochemistry and origin of mineral waters; and c) aquifer vulnerability and risk assessment and mapping.

Roberto de Riso is a full Professor of Applied Geology at the Faculty of Engineering, Federico II University of Naples, Italy. He is former Head of the Institute of Applied Geology, now a section of the Department of Geotechnical Engineering, and head of local research units for the ltalian Ministry of University and Research (MURST). He is a member of the International Association of Engineering Geology and Environment (IAEGE), the International Association of Hydrogeology (AIH/IAH), the Italian Geological Society (SGI), and the Italian Geotechnical Association (AGI), and a member of the Scientific Committee of IAEGE—Italian Chapter. He is co-author of a textbook and of several papers regarding the following topics (mainly related to southern Italy case studies): hydrogeology, mass movements, geothematic mapping, and the engineering-geological characterization of rocks.

Daniela Ducci is a research hydrogeologist and Professor of Applied Geology in the Faculty of Engineering, Federico II University of Naples, Italy. She received the Diploma in Geology from the Faculty of Science of Naples in 1982, and in 1983 she obtained her Postgraduate Diploma in Groundwater Hydrology (CIHS) from the Technical University of Catalonia, Spain (UPC–Barcelona–ES). She joined the Department of Applied Geology in 1986, after studying groundwater modeling for one year at the Technical University of Catalonia, as a fellowship recipient. Her research focuses on resources evaluation in karstic environments, hydrogeologic mapping, hydrogeochemistry and aquifer contamination, and groundwater-pollution vulnerability and risk assessment. In the last few years her research interests have concentrated especially around the use of the GIS in groundwater-protection assessment.