GROUNDWATER DEVELOPMENT

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Summary

Groundwater development is designed to satisfy a certain demand for water or to assess the groundwater resources of a watershed. Therefore it comprises the following highly interrelated phases:

- Surveying;
- Construction of abstraction systems;
- Design, construction, operation and optimization of monitoring networks, and
- Mathematical modeling.

This Topic Level contribution describes these phases focusing special attention on the different kinds of aquifers (inter-granular, karst and fissured).

1. Introduction

Groundwater development is designed to satisfy a certain demand of water or to assess the groundwater resources of a watershed. Therefore it comprises the following highly interrelated phases:

- Surveying;
- Construction of abstraction systems;
- Design, construction, operation and optimization of monitoring networks, and
- Mathematical modeling.

Surveying is the initial stage of any groundwater exploitation system and primarily deals with the identification of the perspective zones. Broad use is made at this stage of geological, geomorphological, geophysical and special hydrological methods. Exploration boreholes are drilled and pumping and permeability tests are developed in order to obtain numeric indices of groundwater potential. Chemical analysis of water and, sometimes, of rocks and sediments is also performed in order to clarify the process governing water composition and quality.

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Construction of abstraction systems where aquifer potential and water quality allows exploitation is usually the second stage. Wells, trenches and springs are then adequately built or adapted. Wells are built with the diameter, depth, casing and filters derived from the results of the surveying phase. Wells and trenches are tested again to define efficiency. In some cases protection perimeters could be required, and computations are performed for their proper design. A maintenance program for the abstraction system is identified at this stage.

Design, construction, operation and optimization of monitoring networks is the final stage of a groundwater development program but it does not necessarily or exclusively have to follow the preceding phase. In effect, when regional studies are performed or when controls of groundwater regime and quality are required, groundwater monitoring networks are designed, constructed and operated to prevent pollution, groundwater level depletion, undesirable side effects of groundwater exploitation or to control the effectiveness of mitigation or rehabilitation measures.

Mathematical modeling is required to manage groundwater resources. Therefore the construction of a mathematical model is commonly a phase of groundwater development linked with the design, operation and optimization of the monitoring network. This stage is not always necessary, although it can be used in other stages, in order to save time and money, such as in surveying, or in the reorientation of surveying, in well data processing, in geochemical hydrodynamics assessments, etc.

2. Surveying

2.1. Factors Controlling Groundwater Occurrence

Groundwater occurrence depends upon the interrelation of several groups of factors. They control how groundwaters are formed, move, gain their chemical composition, and vary in amount and availability. These factors are of different nature and involve geodynamics, morphodynamics, climate, hydrodynamics, geochemistry and thermodynamics.

2.2. Productivity Indices

The above-mentioned geodynamic, morphodynamic, hydrodynamic, geochemical and thermodynamic factors provides the basis for identifying the productivity of aquifers in any region of the world. These are the most important but not unique sources of information. They should be complemented with historical, social and economic data before any prospecting should be developed.
Selection of adequate indices is always linked with the type of aquifer, the goals of the development and the financial availability.

As far as it concerns to the type of aquifer, it is necessary, first of all, to know about the geologic structure of the territory and the morphological expression of the potential productive rocks in the landscape. After it, the conditions for groundwater occurrence could be primarily inferred.

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Indices are collected following particular techniques of documentation and inspection in the field and in libraries and archives. Inhabitants of the territory under consideration are always an important source of qualitative information as well as local place names which can be excellent indices of geologic, geomorphologic and hydrologic features.

Therefore, the key elements that could be considered as direct or indirect indices of groundwater productivity are:

- Geologic
- Geomorphologic
- Climatic
- Hydrologic
- Historic

There are also indices for groundwater quality, like:

- Socio-economic level of development
- Main economic activities
- Medical history of the community

2.2.1 Geologic Indices

Several geologic indices are useful for a diagnosis of productivity. They should be taken into account during development planning. The most important are:

- Lithology
- Tectonic structure
- Stratigraphy

2.2.2 Geomorphologic Indices

The type of landscape is of fundamental importance in assessment of the costs of groundwater exploration and development.

The relation landscape-lithology-geologic structure defines the occurrence, extension and productivity of aquifers.

2.2.3 Climatic Indices

Precipitation is the main source for groundwater replenishment. Climatic factors are of outstanding importance in assessment of whether a continuous source of groundwater recharge is available in a reasonable time span. In turn this defines whether or not groundwater could be exploited within the natural cycle of groundwater replenishment, avoiding resource depletion.

Groundwater prospecting and development vary according to the climatic peculiarities of each territory. In terms of precipitation, the most important source for groundwater replenishment, the following types should be considered:

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- Extremes:
  - Arid or semi-arid
  - Polar, subpolar and tundra
- Tropical:
  - Permanent humid
  - Seasonally humid
- Temperate

2.2.4. Hydrodynamic Indices

Several hydrogeologic processes and factors describing overall mass transport have already been mentioned. The way that they are expressed in the landscape suggests the potential groundwater productivity of a region. Three of them can be specially mentioned:

- Springs
- Permanent rivers and lakes
- Water-filled caves in karst regions

Other indices of reliable importance are:

- Lineaments of phreatophytes in metamorphic or igneous rocks, commonly linked with water bearing fractures;
- Interior wetlands, mainly linked with high groundwater levels;
- Existence of dug wells.

Indirect hydrodynamic and hydraulic information can be gathered from topographic maps or aerial photographs. Cemeteries indicate that high groundwater levels do not reach ground surface or at least are deeper than two meters. Rural footpaths use to follow the dry zones along watershed divides and, in turn, can help in the determination of productive zones. The frequency and duration of floods in surface streams, particularly those occurring during the dry season, are an index of the self-regulation capability of the aquifer.

2.2.5. Geochemical Indices

When properly related to spring or well yield, geochemical indices are also hydrodynamic indices in the sense that they offer valuable information regarding the processes governing the acquisition of the physical, chemical and bacteriological composition of waters. In this way, they define water quality and, hence, the possible use of water and, eventually, the treatment it has to receive to fulfill the requirements for sustainable exploitation. Therefore, knowledge of the processes governing water quality composition is very relevant.

This process is strongly influenced by several factors acting from the recharge zone to the discharge zone along the flow paths. No matter whether the discharge zone is natural, like a spring, or man-made, like a well, the importance is the same. Among the factors controlling water quality, the following are especially important:

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- The physical, chemical and bacteriological composition of atmospheric precipitation and, in particular of the recharge fraction.
- The losses by evaporation and evapotranspiration that take place in shallow aquifers or that are produced on infiltration waters during its transit through the unsaturated zone.
- The acidity and degree of unsaturation of recharge waters and of groundwaters, with respect to the basic minerals of the aquifer rocks.
- The availability of soluble rocks and their solubility.
- The solution rate of these rocks and the water-rock contact time.
- The extent and intensity where pure hydrological processes like dilution by fresh recharge waters or mixing of ground and surface waters exert their action.
- The man-made processes affecting the natural composition of waters.

The most important geochemical indices are the following:

- Temperature, pH and Specific Electric Conductivity
- Dissolved solids
- Dominant chemical character
- Dissolved Oxygen and REDOX potential
- Isotopic composition
- Age of waters

Temperature is a good index of movement conditions of groundwater. It depends on the initial temperature of precipitation, on the temperature in the different circulation scenarios and on the chemical reactions that take place in the aquifer and that can add or reduce heat. It is important to note that in temperate climates, unconfined aquifers show remarkable fluctuations of temperature within the year, while in confined or semi confined aquifers, those variations are of negligible importance. In many cases, temperature measurements in springs could help in the identification of when diffuse or concentrated flow conditions prevail within the aquifer or after a remarkable hydrological event.

pH could contribute to define the relative concentration of solutions with respect to the prevailing minerals, the presence of mixed waters and, in conjunction with other indices contribute to define the concentration of gases like CO_2, O_2, H_2S, NH_3 and the presence of algae or bacteria.

The **Specific Electric Conductivity (SPC)** is the best indicator of salt concentration in waters. SPC depends directly on the load and mobility of ions and of their concentrations. Measurements of SPC and yield are successfully employed to define the chemical yield or the expected concentrations in several stations along the same flow line.

Total Dissolved Solids (TDS) are directly related to SPC. For several prevalent chemical types empirical relations between them could be established. It is important to note that the solutes present in groundwaters are a direct consequence of the composition of precipitation waters, the mineralogical compositions of the aquifer rocks, and of the chemical variations derived from hydrologic or geologic processes like

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evaporation, weathering or pollution. Indirect indices of water mineralization are, for example, travertine or tufa deposits at the discharge of springs. In fluvial beds, the presence of these deposits almost suggests the presence of waters of different chemical composition and re-precipitation by mixing waters. Weathering crusts of duricrust or caliche type indicate natural recharge deficits associated with evaporation of transit waters.

The **Prevalent Chemical Character (PCC)** indicates the relative abundance of the different anions and cations present in water, and allows categorization according to their type and origin. There are several classifications for this purpose but they will not be mentioned here. The most important remark is that the ions that are usually more abundant in any kind of groundwater are the following:

Bicarbonate	HCO3 -
Sulphate	SO4 + -
Chloride	Cl-
Calcium	Ca ++
Magnesium	Mg++
Sodium	Na+
Potasium	K+

Concentrations of these major constituents are usually expressed in milligrams per liter (mg/l) or milliequivalents per liter (mEq/l). Commonly, the type of water is defined after the higher concentrations of cations and anions, in such a way that the usual denominations are “calcium bicarbonate waters”, “sodium chloride waters”, and so on.

The relations among these ions offer many indications of the groundwater regime, the geological composition of the terrain along which circulation takes place, sources and losses, pollution sources and the transit time of waters.

Therefore the composition of travertine or tufa deposits is a field index to characterize the PCC of the discharging groundwaters. The teeth health and the complexion of the inhabitants of a certain place is also an index of the relative importance of calcium and fluorine in drinking water. Renal diseases are also indications of a high concentration of iron in waters; keratosis always indicates high levels of arsenic; corroded pipelines indicates aggresiveness of waters, and so on.

Dissolved oxygen (OD) in groundwaters is an important index of contamination. Potentially, the presence of residual sewers reduces the normal value of non-polluted waters that is usually of the order of the 8.25 mg/l of OD. REDOX potential can help to establish the degree of oxidation of the waters when the OD is below the detection limit.

The **isotopic composition and the relative age** of waters are very important indices. Their determination, however, requires specific and expensive analysis mainly because, to be reliable, they require at least an annual set of data on chemical and isotopic composition of groundwater and amount and isotopic composition of precipitation. There are no doubts about their value, however, in identification of an important group of hydrological processes. Examples of these are the time and spatial distribution of

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evaporation and natural recharge, the transit or turnover time of waters, the renovation rate of groundwaters and the process of horizontal and vertical mixing of the different aquifer horizons. Isotopic composition is also important in determining the sources of contaminants and the safe yield of aquifers.

The **environmental isotopes** commonly used in hydrogeology are of two kinds: stable and radioactive. The first comprise deuterium (^{2}H), the isotopes of carbon (^{12}C, ^{13}C) and of oxygen (^{18}O, ^{17}O, ^{16}O). The second, i.e. radioactive, group includes tritium (^{3}H) and carbon–14 (^{14}C) which generate β particles during the process of radioactive disintegration with half-lives, respectively, of 12.26, 5 and 30 years.

2.3. Geologic and Geomorphologic Exploration

2.3.1. Types of Aquifers

The different action, in space and time, of the processes and factors described above control the development of groundwater in the Earth's crust. This differentiated action allows the distinction among different types of aquifers according to:

- The geologic structure.
- The geomorphologic features.
- The hydraulic properties.

Thus an aquifer is a flow system where the main fluid is water.

From the geological point of view it can be defined as a tectonic unit absorbing, storing and transmitting and discharging water. Therefore, according to geology, the following types of aquifers could be distinguished:

- Karst
- Fissured
- Inter-granular or detritic

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Bibliography

Agterberg F.P (1974). *Geomathematics*. Elsevier, 595 pp [This book provides comprehensive information on geomathematic techniques]

Bear, J.D., D. Zaslavsky , S. lrmay (1968).*Physical Principles of Water Percolation and Seepage.* Unesco, Ariz Zone Research, XXIX, Paris, 465 pp [A classical book on the physical and mathematical fundamentals of groundwater hydraulics]

Bear, J., Ch-Fu Tsang, G. de Marsily (1993).*Flow and contaminant transport in fractured rock.* Academic Press, California, 560 pp [A complete book on the theoretical basis of mathematical modeling of flow and transport in fissured rocks]

Barenblatt, G.I.; Iu. Zheltov and I.N. Kochina (1960).Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks. *J. Appl. Math. Mech*., 24 pp 1286-1303. [A classical paper with the fundamentals of double-porosity models for fractured rocks]

Bogardi, J., H-T. Nachtenebel (1994). *Multicriteria Decision Analysis in Water Resources Management.* Unesco, Paris, 467 pp [This book provides the theoretical basis for the adequate formulation of decision-making on groundwater resources, with a special reference to uncertainty]

Boulton, N.S., T.D. Streltsova (1977). Unsteady flow to a pumped well in a fissured water-bearing formation. *J. Hydrol.* 35 pp 257-269 [An elegant mathematical demonstration of the application of double-porosity models to a special case of flow to a well in a fractured rock aquifer]

Brower, G.K. (1983). Reduction of a Groundwater Level Network. Intematl. Symp. MIIGS, The Netherlands, Unesco, TNO pp 101 – 117 [This article provides information on the principles for reduction of network components based on the information theory principles]

Delhomme, JP (1978). Kriging in the Hydrosciences. *Adv. in Water Resourc.* 1(5) pp 251-261 [A very complete paper describing the principles and applications of kriging techniques]

DeWiest, R.J.M (1971). *Geohydrology*. Edic. Revolucionaria, La Habana, 366 pp [This book is a comprehensive outline of groundwater hydrology]

Mardia, K-V, J.T Kent, Bibby J.M. (1979). *Multivariate Analysis*. Academic Press, 521 pp [This book provides instruction on the mathematical fundamentals and applications of multivariate analysis]

Mejerink, A. M. J., H.A.M. de Brouwer, C.M. Mannaerts, C.R. Valenzuela (1994). *Introduction to the use of Geographical Information Systems for Practical Hydrology*. ITC-Unesco, Publ. No. 23, The Netherlands, 243 pp. [A comprehensive textbook for design and use of GIS in water resources research and management]

Molerio León, L.F., A. Menéndez Gómez, E. Flores Valdés, M.G .Guerra Oliva, C. Bustamante Allen (1996). Aguas Subterráneas en las Zonas de Montaña de Cuba. *Voluntad Hidráulica* (86)-pp 23-33 [An article dealing with groundwater management in karstic mountains of the Humid Tropics]

Molerio León, LF, M Guerra, E Rocamora, E Flores, M Núñez (1997).Prospección Hidrogeológica en Rocas de Baja Permeabilidad en Cuba. Resultados de la Aplicación de Técnicas Geomatemáticas y Geometría del Fractal. in/J.G. Yelamos & F. Villarroya (Eds). *Hydrogeology of Hard Rocks. Some Experiences from Iberian Peninsula and Bohemian Massif*, Madrid, pp 79-87. [This paper deals with the application of geomathematical techniques in groundwater development in hard rock aquifers]

Nawalany, M (1983).Application of the Observer Theory Optimization of Groundwater Monitoring Network. Internatl. Symp. MllGS, The Netherlands, Unesco, TNO pp73-85 [This paper describes Luenberger's thoeretical approach for the simulation of an observer in the optimization of groundwater monitoring networks]

Peck A., S. Gorelick, G. de Marsily, S. Foster, V. Kovalevsky (1988). *Consequences of Spatial Variability in Aquifer Properties and Data Limitations for Groundwater Modeling Practice* IAHS Publ. 175, Oxfordshire 272 pp [A detailed analysis of sources of error in mathematical modeling of groundwater]

Pérez Franco, D. (1982). *Hidráulica subterránea*. Edit. Científico-Técnica, La Habana, 424: [A comprehensive textbook emphasizing the non-linear approach to groundwater hydraulics]

Repsold, H. (1989). Well logging in groundwater development. Internatl. Ass. Hydrogeol. R. van Acken, Germany, 139 pp [A complete outline of the modern geophysical techniques of well logging in groundwater development]

UNESCO – EOLSS SAMPLE CHAPTERS

USACE (1999).*Groundwatr Hydrology*. Dept. Army, U.S. Army Corps of Engineers. EM 1110-2-1421. [A complete handbook of best practice in hydrogeological research]

USDI (1977). *Groundwater Manual. A Water Resources Technical Publication*. U.S. Dep. Interior, Washington, 480 pp [A complete handbook covering all phases of groundwater prospecting]

Biographical Sketch

Leslie F. Molerio León gained his Bachelor in Geology and Hydrogeology (1980) at the Institute of Oil and Mines, Cuba. He later earned Post-Graduate Diplomas in Karst Geomorphology (1981); an IAEA sponsored Diploma in Isotope Hydrology (1991), Vienna, Austria; Groundwater Mathematical Models (1991), Politechnical Higher Institute, Habana, CUBA; Automatic Control Techniques (1997), University of Huelva, Spain; and a British Geological Survey sponsored Diploma in Environmental Impact of Mining (2000), Havana, Cuba

He has been in the field of karst research since 1962 and in hydrogeology and engineering geology since 1969. He was Deputy Director at the National Institute (Ministry) of Water Resources of Cuba and Head of the National Bureau of Hydrogeology. Since 1998 he has been based at the Ministry of Science, Technology and Environment, as Senior Hydrogeologist and Head of the Group of Terrestrial Waters. He is also a consultant for CESIGMA, S.A., a Cuban-Spanish Environmental Consultancy. Much of his work in the field of applied hydrogeological research has been done in karst and hard-rock aquifers. He has done applied hydrogeological investigations in Angola, Austria, Bulgaria, Cuba, Ecuador, Jamaica, Czechoslovakia, Grenada, Mexico, Nicaragua, Dominican Republic and Venezuela. As a Consultant or Expert of several international agencies he has been member of several working groups in Argentina, Cambodia, Colombia, Cuba, Haiti, Mexico, Nicaragua, Dominican Republic and Venezuela. He has give lectures at several universities in Argentina, Bulgaria, Cuba and Mexico and has integrated several working groups as an Expert for UNESCO, UNICEF, WMO, CYTED, UIS, IAEA and FAO.

His honours, memberships and publication record includes:

- First Vice-President, Cuban Speleological Society.
- Board member (elected 2002) of ALHSUD, the Latin American Association of Groundwater Hydrology for Development.
- Ex-Associate Editor of the Hydrogeology Journal, Official Journal of the International Association of Hydrogeologists.
- Over 60 technical papers have been presented at international conferences, congresses and symposia on water resources development, held in different countries like Argentina, Austria, Bulgaria, Brazil, Cuba, Dominican Republic, Mexico, Russia and Spain.

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