SURVEY METHODS

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Contents

1. Introduction
2. Surveying Guidelines
2.1. Geology
2.1.1. Lithology
2.1.2. Tectonic structure
2.1.3. Stratigraphy and rock age
2.2. Geomorphology
2.3. Climate
2.3.1. Extreme climates
2.3.2. Tropical climates
2.3.3. Temperate climates
2.4. Hydrodynamics
2.5. Geochemistry
3. Geologic and Geomorphologic Exploration
3.1. Types of aquifers
3.1.1. Karst aquifers
3.1.2. Hard rocks aquifers
3.1.3. Intergranular aquifers
3.2. Landscapes
3.2.1. Mountains
3.2.2. Plains and Flatlands
3.3. Hydrodynamic types of aquifers
4. Geophysical Methods
5. Tracer Hydrology
5.1. Types of tracers
5.1.1. Suspended solids
5.1.2. Soluble chemicals
5.1.3. Dyes
5.1.4. Environmental isotopes
6. Geochemical Exploration
7. Pumping Tests
7.1. Planning
7.2. Well hydraulics
7.2.1. Steady state equations
7.2.2. Unsteady, transient, conditions
7.2.3. Recovery tests
7.3. Leaky aquifers

7.3.1. Time–drawdown under unsteady conditions
7.3.2. Steady state drawdown
7.3.4. Delayed yield solutions
7.3.5. Double porosity models
7.3.6. Solutions for turbulent, non-linear flows
Acknowledgements
Glossary
Bibliography
Biographical Sketch

Summary

This article describes the most important survey methods for groundwater development. Article emphasizes the role of geological, geomorphologic, geochemical and geophysical methods, devoting special attention to tracer hydrology.

1. Introduction

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. Survey methods comprise a group of geologic, geomorphologic, geophysical, geochemical and hydraulic methods. While these methods are general in nature they must be adjusted depending of the kind of aquifer e.g. intergranular, fissured or karstic, and also the landscape where groundwater occurs.

2. Surveying Guidelines

The following elements that should be considered:

- 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

2.1. Geology

The most important are:

- Lithology

- Tectonic structure
- Stratigraphy

2.1.1. Lithology

According to lithology, three main types of aquifers could be distinguished:

- In carbonate rocks (Karst aquifers)
- In igneous and metamorphic rocks (Fissured -non-karstic- aquifers)
- In granular rocks (Intergranular aquifers)

Carbonate rocks are sedimentary rocks mainly composed of carbonate minerals forming three main types: aragonite, calcite and dolomite.

Of all carbonate rocks, of which there are more than 600 types, limestone and dolomites are the most common. Carbonate rocks are genetically divided into two groups: allochthonous and autochthonous, differentiated after the carbon content and the fractions of quartz or shales present. The most important post-sedimentary alterations in carbonate rocks is karstification. Karst is a good indicator of productivity, particularly in the humid tropics

In some **igneous and metamorphic rocks,** like granites and diorites (igneous – intrusive), pegmatites and porfides (igneous – filonian) and magmatic like gneisses and some shales, fissured-non-karstic- aquifers are developed. In terms of productivity, the rock type is not as important as the joint pattern, because these rocks are only productive along joints. Nevertheless it should be remembered that these are low-permeability rocks, and productivity is always very low. Basalts are commonly included in such aquifers but they often form very important aquifers.

Granular rocks are also sedimentary rocks but they are commonly differentiated, for hydrogeological purposes as unconsolidated, like sands, pebbles and gravels, and consolidated, like sandstones. The degree of consolidation determines important hydraulic properties like storage, specific yield and permeability.

Therefore, **unconsolidated granular rocks** usually form important aquifers and their existence, when linked with surface streams and rivers, is almost an indicator of groundwater. On the other hand, **consolidated granular rocks** are also productive but, in this case, fracturing is a factor to be added to grain size when considering the potential productivity of these rocks.

Some volcanic rocks, like certain tuffs, are usually included within these aquifers, while others like lava and basalt are frequently included in the hard rocks aquifers.

2.1.2. Tectonic structure

For the most karstic carbonate rocks, igneous, metamorphic and several consolidated granular rocks, the tectonic structure, in terms of the fracturing pattern is the most important factor in defining their potential productivity for groundwater development.

In karstic carbonate rocks, fracturing defines the preferential directions for groundwater flow. Those preferential directions are blocks or sectors of high transmissivity, and in consequence, of high yield among others of low transmissivity or negligible transmissivity whose productivity is almost null.

The problem is more complex in the case of the hard rock aquifers where, definitely, groundwater flow only occurs in fractures. It could seem that groundwater development would be easy but, on the contrary, it can be very difficult because not all fractures are capable of storing and transmitting water. Groundwater development in low permeability aquifers is particularly complicated by the following facts:

- Not all fractures of the same tectonic episode or the same genetic type are productive.
- Not all fractures of the same family (orientation and dip) are productive.

A rigorous analysis of fracturing and of the physical connection among different joints therefore has to be carried out in order to increase success and reduce costs.

2.1.3. Stratigraphy and rock age

For hydrogeological purposes, unless common features in rocks of the same age, as in several geologic formations, can be recognized, the position of certain groups of rocks in the stratigraphic scale is not so important. Age is most important as an indicator of the kind of processes, such as diagenesis, volcanism, flooding and fracturing, that might have increased or decreased the water bearing spaces of the rocks and their pores, fractures and caves.

2.2. Geomorphology

The type of landscape is of fundamental importance in the assessment of the costs of groundwater exploration and development. The relation *landscape-lithology-geologic structure* defines the occurrence, extension and productivity of aquifers.

From a hydrogeological point of view, landscape could be typified according to Table 1.

	Relief types	**Hydrogeologic index**
Mountains	1. According to their geologic structure	1. Homogeneous lithology 2. Heterogeneous lithology 3. Folded and faulted in simple systems 4. Folded and faulted in complex structures
	2. According to the degree of dissection of the relief	1. Alternation of erosion surfaces 2. a - High or b - low dissection degree a - horizontal, or b - vertical (or both)
	3. According to the development of the fluvial net and their hydrological activity	1. Forming suspended valleys 2. Drainage a - endorheic or b - exorheic 3. Drainage a - permanent, b - seasonal or c - episodic
	4. According to their altitude	1. High mountain

	and geometric classification	2. Low mountains and stockings 3. hills or isolated hills 4. Forming chains or plateaus
Plains	1. According to their genetic type or their current position in the geomorphic system	1. Coastal or deltaic 2. Marshy or lacustrine 3. Fluvial 4. Inland plains
	2. According to their geologic structure	1. Sedimentary basins 2. Eroded anteclises and sineclises 3. Subsidence or uplifting areas 4. Lithology a - homogeneous or b - heterogeneous with lateral or vertical facial changes
	3. According to the degree of dissection of the relief	1. Alternations of erosion surfaces 2. a) High or b) low degree of horizontal, vertical dissection (or both)
	4. According to the development of the fluvial net	1. Forming suspended valleys 2. Drainage a: endorheic b:exorheic 3. Drainage a: permanent, b: seasonal, c: episodic
	5. According to their altitude and geometric classification	1. High mountain 2. Low mountains 3. Hills or isolated hills 4. Forming chains or plateaus

Table 1. Landscape types in relation to hydrogeology.

The geomorphologic features mentioned in Table 1 can be combined as shown in Table 2, in order to assess the feasibility of groundwater development.

Morphological feature	High productivity	Medium productivity	Low productivity	Undefined or negligible productivity
A.1.1	X			
A.1.2		X		
A.1.3		X	X	
A.1.4			X	X
A.2.1			X	
A.2.2 a.a	X			
A.2.2.a.b		X	X	
A.2.2.b.a	X	X		
A.2.2.b.b		X	X	
A.3.1			X	X
A.3.2.a		X		
A.3.2.b	X	X		
A.3.3.a	X			
A.3.3.b	X	X		
A.3.3.c			X	X
A.4.1				X
A.4.2		X	X	
A.4.3			X	
A.4.4	X	X		
B.1.1	X	X		

B.1.2		X		
B.1.3	X	X		
B.1.4		X	X	
B.2.1	X	X		
B.2.2		X	X	
B.2.3		X	X	
B.2.4.a	X	X		
B.2.4.b			X	X
B.3.1			X	
B.4.1			X	
B.4.2.a	X	X		
B.4.2.b		X	X	
B.4.3.a	X			
B.4.3.b		X		
B.4.3.c			X	X
B.5.1a	X	X		
B.5.1b		X	X	
B.5.1.c			X	X
B.5.2				X

Table 2. Aquifer productivity matrix of geomorphologic features

2.3. Climate

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

Groundwater prospecting and development differs according to the climate peculiarities of each territory. The following types of precipitation—the most important source for groundwater replenishment—should be considered:

- Extreme:
    - Arid or semiarid
    - Polar, subpolar and tundra
- Tropical:
    - Permanent humid
    - Seasonally humid
- Temperate

2.3.1. Extreme climates

About 20% of the land on Earth is desert and another 20% is semiarid. Such areas are extensive in northern Africa, the Middle East and Australia, and similar, but less extensive zones are also found in the southern part of North America, southern Africa and South America.

In these regions precipitation is very low and generally does not exceed 200 mm yearly; natural recharge is practically negligible and evaporation rates are very high. These facts are of extreme importance for groundwater development.

One of the most important factors is the replenishment rate of groundwater, which is usually very low. In the Sahara this rate is estimated to be around 100 000 years, in terms of turnover time of groundwater, i.e. the time span between recharge and discharge.

Most of the aquifers developed in these regions are very deep and groundwater infiltrated in past geologic times. In modern geologic times, the hydrologic cycle of deserts shows particular features which in turn define the type of works that has to be built for groundwater development. Condensation, for example, is very important as a consequence of the daily difference in temperature and relative humidity, so water can be collected in shallow horizontal galleries, named *kanats*. These were constructed from immemorial times to facilitate collection of condensation water.

In **permanent frozen zones** (polar, subpolar and tundra) groundwater development is also very complex and expensive because of the lack of clear indices for aquifer development. Commonly prospecting involves searching for groundwater associated with non-permanently frozen lakes, the location of hydro-lacolites, clear indices of permafrost, and the presence of trees with deep roots like poplars.

2.3.2. Tropical climates

In **tropical climates,** precipitation, expressed as rainfall, is not a limiting factor for groundwater recharge. It is so abundant that a steady replenishment of groundwater is guaranteed. These regions receive almost 50% of the world distribution of atmospheric moisture; geologic and geomorphologic factors therefore become more important. It has to be stressed, however, that while rainfall is abundant and well distributed through the year, evaporation and evapotranspiration are also very important in the hydrologic balance.

As a rule, well and spring productivity should be assessed during the dry (or dryer) season in order to approach more unfavorable conditions of recharge and discharge. Most tropical regions are prone to extreme events of precipitation like hurricanes and heavy rains. High intensity rainstorms, depending on the recharge capabilities of the aquifer, can constitute intensive instantaneous natural recharge. This characteristic must be carefully accounted for in groundwater development in these regions because, depending on the geologic type of aquifer, the response to instantaneous recharge is differently expressed.

2.3.3. Temperate climates

Temperate climates are common in continental areas. The seasonal distribution of precipitation is clearly linked to the annual distribution of insolation and radiation. Rain and snow, with a clear distribution within the year, are the main agents of natural recharge to aquifers. Therefore, the seasonal components of precipitation, evaporation, runoff and infiltration, can be more readily distinguished in continental temperate regions than in tropical climates.

2.4. Hydrodynamics

Indications of groundwater occurrence are:

- 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;
- Internal wetlands, mainly linked with high groundwater levels;
- Existence of dug wells.

Indirect hydrodynamic and hydraulic information can be gathered from topographic maps and aerial photographs.

Cemeteries indicate that high groundwater levels do not reach the ground surface, or at least are deeper than two meters. Rural footpaths traditionally 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.

In the case of **springs**, additional information should be gathered on:

- Genetic type of spring.
- Seasonal and annual flow variability.
- Relation with other springs, wells or rivers.
- Shape and dimension of the drainage basin, lithologic composition and geomorphology.
- Transit time of groundwater and self regulation capability of the system.
- Shape, yields and duration of floods.

These data allow hydrograph separation and, hence, identification of spring base flow (somewhat equivalent to its safe yield and exploitation resources), the distribution of the most productive zones within the aquifer, and the quality of groundwaters.

Permanent lakes and rivers are clear evidence of the existence of groundwater sources feeding them. Observations of their regime provide the same information as mentioned in the case of springs.

In karstic regions, **freshwater filled caves** are also evidence of aquifer productivity. However, it is necessary to define whether they belong to an epikarst developed in the unsaturated zone or to the saturated zone of the aquifer. When epikarstic or hypodermic flows fill caves, it must be clarified if it is a single, local phenomenon or whether it is a seasonal or episodic event related to heavy rains, surface runoff or local perched aquifers. In cases not associated with the aquifer system, exploitation should only be recommended after a special research effort.

Nevertheless, when these caves are associated with local groundwater levels, they can be pumped directly without drilling wells. In the particular case of **cenotes** or **casimbas**, special care has to be accounted for water quality.

However, in the case of caves, the following information has to be obtained:

- Genetic type,
- Hydrological position with respect to the local, intermediate or regional flow system,
- Input-output yields,
- Chemical composition of waters,
- Water level and yield variations, and
- Hydraulic relation with springs, wells, rivers or lakes.

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Biographical Sketch

Leslie F. Molerio Leon is based at the Group of Terrestrial Waters, Institute of Geophysics, Cuba.

EDUCATION:

- British Geological Survey sponsored Postgraduate Diploma in Environmental Impact of Mining (2000), Habana, CUBA.
- Postgraduate Diploma in Automatic Control Techniques (1997), University of Huelva, SPAIN.
- Postgraduate Diploma in Groundwater Mathematical Models (1991), Politechnical Higher Institute, Habana, CUBA
- IAEA sponsored Postgraduate Diploma in Isotope Hydrology (1991), Vienna, AUSTRIA.
- Postgraduate Diploma in Karst Geomorphology (1971).
- Bachelor in Geology and Hydrogeology (1980) Institute of Oil and Mines, CUBA.

WORK EXPERIENCE

L.F. Molerio Leon has worked 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, Czekoslovakia, 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 given 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.

HONOURS, MEMBERSHIPS and PUBLICATIONS

- First Vice-President, Cuban Speleological Society.
- Board member (elected in 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 presented attending international conferences, congresses and symposia on water resources development, held in different countries, Duch as Argentina, Austria, Bulgaria, Brazil, Cuba, Dominican Republic, Mexico, Russia and Spain.