INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

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Delineating environmental groundwater vulnerability and protection zones mapping in fractured rock masses

HELEN MEERKHAN

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Instituto Superior de Engenharia do Porto

DEPARTAMENTO DE ENGENHARIA GEOTÉCNICA

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To my country Syria…

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Keywords

Hard-rock hydrogeology, GIS mapping, Vulnerability assessment, Hydrogeological conceptual model.

Abstract

Hard-rock watersheds commonly exhibit complex geological bedrock and morphological features. Hydromineral resources have relevant economic value for the thermal spas industry. The present study aims to develop a groundwater vulnerability approach in Caldas da Cavaca hydromineral system (Aguiar da Beira, Central Portugal) which has a thermal tradition that dates back to the late 19th century, and contribute to a better understanding of the hydrogeological conceptual site model. In this work different layers were overlaid, generating several thematic maps to arrive at an integrated framework of several key-sectors in Caldas da Cavaca site. Thus, to accomplish a comprehensive analysis and conceptualization of the site, a multi-technical approach was used, such as, field and laboratory techniques, where several data was collected, like geotectonics, hydrology and hydrogeology, hydrogeomorphology, hydrogeophysical and hydrogeomechanical zoning aiming the application of the so-called DISCO method. All these techniques were successfully performed and a groundwater vulnerability to contamination assessment, based on GOD-S, DRASTIC-Fm, SINTACS, SI and DISCO indexes methodology, was delineated. Geographical Information Systems (GIS) technology was on the basis to organise and integrate the geodatabases and to produce all the thematic maps. This multi-technical approach highlights the importance of groundwater vulnerability to contamination mapping as a tool to support hydrogeological conceptualisation, contributing to better decision-making of water resources management and sustainability.

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Palavras-chave

Hidrogeologia de rochas fracturadas, Cartografia SIG, Vulnerabilidade à contaminação, Modelo hidrogeológico conceptual.

Resumo Alargado

As bacias hidrogeológicas em rochas fracturadas apresentam normalmente características geológicas e morfotectónicas complexas, constituindo uma fonte valiosa de recursos hídricos a nível regional, quer para fins domésticos, industriais e agrícolas, quer para abastecimento público. Os recursos hidrominerais têm um importante valor económico para a indústria do termalismo. Esta dissertação tem como principal objectivo desenvolver uma avaliação da vulnerabilidade à contaminação do sistema hidromineral das Termas das Caldas da Cavaca (Aguiar da Beira, Portugal Central), as quais apresentam uma tradição termal que remonta aos finais do Século XIX, e contribuir para uma melhor compreensão do modelo conceptual hidrogeológico local. A área das Caldas da Cavaca é constituída por rochas graníticas, por vezes intersectadas por filões doleríticos. Neste trabalho procedeu-se a uma avaliação integradora e multidisciplinar, na qual foram cruzados diversos níveis de informação, incluindo dados de campo e de gabinete, tais como a geotectónica, hidrologia e hidrogeologia, hidrogeomorfologia, hidrogeofísica e hidrogeomecânica, conduzindo à geração de diversos mapas temáticos da área das Termas das Caldas da Cavaca. Para tal, foi retomado todo o conhecimento prévio sobre a cartografia, a hidroclimatologia, a geologia, a morfotectónica, a hidrologia e as investigações hidrogeotécnicas "in situ" da área. Foram compiladas e avaliadas as características hidrogeológicas, hidrogeotécnicas e hidrogeomecânicas de três taludes rochosos, talude da Lagoa, talude dos Amores e talude da Cancela, as quais foram agrupadas, sintetizadas permitiram definir zonas hidrogeomecânicas com base na presença de água (características de drenagem, hidrogeologia e hidrogeotecnia) tendo em vista, especialmente, a aplicação do método de vulnerabilidade designado DISCO. Todas estas técnicas foram aplicadas com sucesso e foi feita uma avaliação da vulnerabilidade à contaminação das águas subterrâneas com base em diversos sistemas paramétricos de referência internacional, alguns deles adaptados e revistos (nomeadamente, GOD-S, DRASTIC-Fm, SINTACS, SI e DISCO). O método DISCO, em conjunto com a avaliação obtida pelos restantes métodos, permitiu, ainda, confirmar, com maior rigor, as áreas de protecção das captações de água mineral das Termas das Caldas da Cavaca. Os Sistemas de Informação Geográfica (SIG) constituíram a base para organizar e integrar todas as bases de dados e ainda para a produção de todos os mapas temáticos. Esta abordagem multitécnica permitiu destacar a importância da cartografia da vulnerabilidade à contaminação das águas subterrâneas como uma ferramenta para apoiar a conceptualização hidrogeológica, contribuindo assim para tomadas de decisão mais adequadas na gestão dos recursos hidrominerais e na avaliação da sua sustentabilidade.

Table of Contents

List of Figures

List of Tables

List of Formulas

1. Introduction

1.1. Introduction

Groundwater is an important and valuable renewable resource for human and economic development. It constitutes a main part of the Earth's water circulation system known as Hydrologic Cycle (or Water Cycle) and is significant mainly in permeable geologic formations known as Aquifers (e.g., Fetter, 2001; Fitts, 2013; Bengtsson et al., 2014). The concept of groundwater begins with an overview of groundwater's role in the hydrologic cycle and in water supply, and introduces physical principles: properties of subsurface materials, groundwater flow, groundwater protection in fractured media, groundwater vulnerability and protection zones, and flow modeling techniques (e.g., Fitts, 2013; Singhal & Gupta, 2010).

More than 50% half of the Earth's land surface is covered with hard rocks (igneous, metamorphic and strongly cemented sedimentary rocks and carbonate rocks) of low permeability. These rocks may gain moderate to good permeability on account of fracturing and hence are broadly grouped under the term fractured or fissured rocks, in the context of hydrogeology (e.g., Singhal & Gupta, 2010) (Fig. 1).

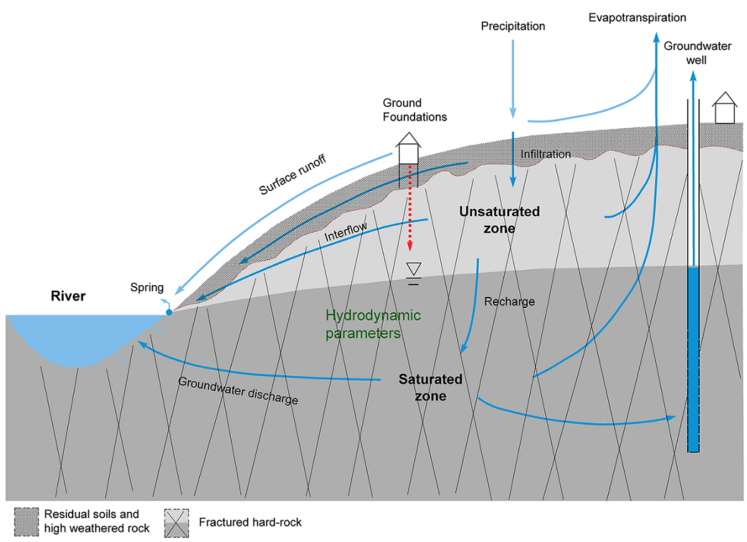


Figure 1. Schematic diagram of the hydrological cycle in a hard rock fissured framework (Fitts, 2013;adapted from Chaminé et al., 2013).

Rock fractures form in response to stress, which origin can be lithostatic, high fluid pressure, tectonic forces, or thermal loading. Fractures are very important in engineering, geotechnical, and hydrogeological practice, since they can act as hydraulic vehicles, providing conduits for fluid flow or barriers that prevent flow across them and also can control the transport of chemical contaminants into and through the subsurface (CFCFF, 1996; Singhal & Gupta, 2010; Gustafson, 2012), (Fig. 2). This way, there is a need to establish relationships between the geological origin of fractures, flow, and transport properties.

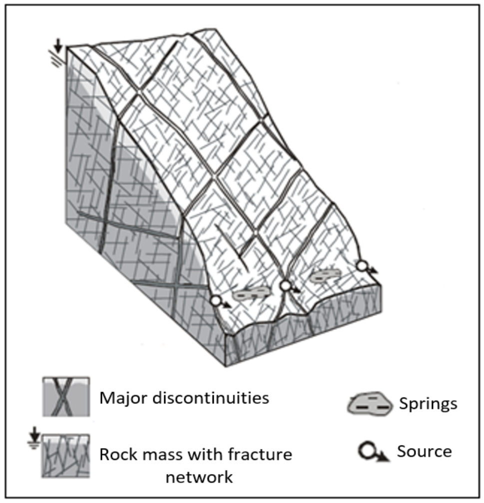


Figure 2. Conceptual diagram of a fractured rock mass aquifer (adapted from Pochon & Zwahlen, 2003).

Most of the groundwater flows slowly and is usually hidden from view, but it sometimes leaves evidence in a cave, geyser, or large spring (Fitts, 2002). Water circulation in hard rocks occurs through a system of "vacuums" that is quite different from that of soils. In most rock masses, water circulation occurs through the many primary discontinuities (stratification, schistosity, karstic cavities) and/or secondary discontinuities (fractures, faults and shear zones). Therefore, it is extremely important to understand and describe the structure of the rock-mass and quantify the pattern and nature of its discontinuities (e.g., Scesi & Gattinoni, 2009; Singhal & Gupta, 2010).

To describe the hydraulic properties of hard rocks is necessary to analyze the geometry of the channels through which the groundwater flows. Generally, the flow of groundwater is according to the laws of physics and thermodynamics and the groundwater is conducted through the fractures in the rock, for that the flow will be governed by their geometry (e.g., Fetter, 2001; Gustafson, 2012).

The groundwater flow in fractured rocks is complex and difficult to analyze for two reasons: i) flow occurs along discrete fractures, which the distribution and properties are mostly unknown; ii) flow in some larger fractures is turbulent, so Darcy's law should not be applied to these (e.g. Fitts, 2013). Groundwater flows through a rock mass along paths that vary with that of the piezometric gradient, this occurs in isotropic and homogeneous aquifer. When media presents a high hydraulic conductivity in a certain direction, the flow is highly conditioned by this anisotropy and tends to occur as to favor the mass transfer in that direction. Similar effects occur in the presence of impermeable layers that, preventing the flow along the direction orthogonal to their surface, determine the flow orientation that encounter with the above mentioned impermeable layer (Fig. 3) (e.g., Scesi & Gattinoni, 2009; Singhal & Gupta, 2010; Gustafson, 2012).

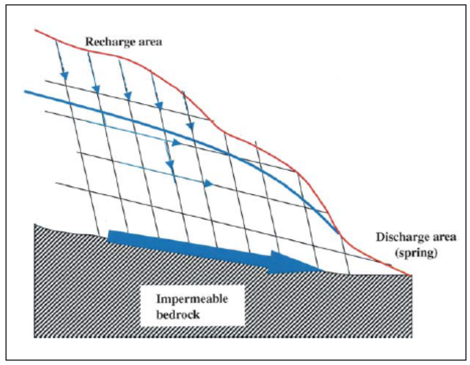


Figure 3. Diagram of the flow condition typical of a rock slope with an impermeable bedrock with indication of the water flow direction within the discontinuity network (Scesi & Gattinoni, 2009).

Groundwater flow through various rock types may be either laminar or turbulent depending on the permeability and the hydraulic gradient of rocks (Fig. 4). In laminar flow, the velocity of flow is proportional to the first power of the hydraulic gradient, and the flow lines are parallel. However, turbulent flow is characterized by high velocities and the formation of eddies along the track (Singhal & Gupta, 2010).

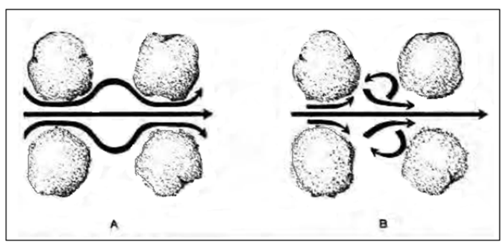


Figure 4. Flow paths of molecules of water. A: in laminar flow; B: in turbulent flow (Fetter, 2001).

Flow in fractured aquifers is difficult to analyze for various reasons: i) the most important is the flow occurs along separate fractures, therefore the distribution and properties of which are mostly indistinct, and it is not possible to draw a map of the location and orientation of the fractures which contain water in the subsurface, or to know their width and length; ii) because the flow in some wider fractures is turbulent instead of laminar, being not possible to apply Darcy's law to these fractures (e.g., Singhal & Gupta, 2010; Fitts, 2013).

Generally, the groundwater protection is considered a general issue worldwide, and it aims mainly to preserving the quality and the quantity of groundwater, also preventing chemical spills which can cause a real risk for groundwater quality (e.g., Granlund et al., 1993; Zaporozec, 2004; Witkowski et al., 2007). The necessity for protecting aquifers increases after the detection of increasing demands on groundwater resources, and deteriorating its quality caused by the different pollution sources: industry, urban runoff, sanitary landfill and agriculture (Fig. 5).

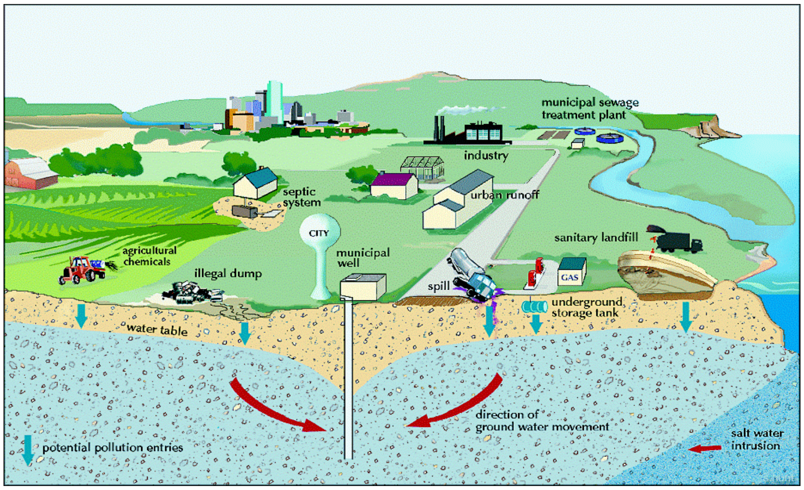


Figure 5. Schematic overview of the main sources of groundwater contamination (Zaporozec, 2004).

Groundwater protection for human activities with appropriate quality, makes necessary to determine source protection zones for watersheds in urban areas to protect them from risks of the contamination due to various human activities that exist in their environment. First of all, the use of vulnerability studies is considered as a standard to create a priority order in regional application of source protection zones. The concept of groundwater vulnerability is a measure of how easy or hard it is for contamination load at the land surface to affect groundwater. Vulnerability assessments is aim to provide a decision based on the best available data and good scientific study. It leads to direct groundwater protection efforts such that the most environmental and public health benefits are achieved at least cost (Harter & Walker, 2001; Harter, 2003).

Groundwater vulnerability assessment is not a characteristic that can be directly measured in the field. It is an idea based on produce a map that characterize between the areas of greater groundwater vulnerability from areas of lesser groundwater vulnerability (e.g., Gogu & Dassargues, 2000).

To mapping groundwater vulnerability is often used Geographic Information Systems (GIS) technologies. It is a digital form of map and a powerful tool for analyzing, processing and combining spatial data sets. It can be considered as an excellent computer-coded map which allows storage, selective choice, display and output of spatial data. It offers a graphic image of the site of pollution sources in relation to other data elements (e.g., Zaporozec, 2004; Singhal & Gupta, 2010). GIS has become a useful tool for creating vulnerability maps and for simple testing of methods of display, also offering good possibilities in order to provide vulnerability assessment results on maps (e.g., CAGWV & NRC, 1993; Teixeira et al., 2013; Barroso et al., 2015; Chaminé et al., 2013, 2014, 2015; Chaminé, 2015).

The concept of groundwater vulnerability mapping is growing based on hydrogeological properties and assumes that the physical medium which consist of soil, rock and groundwater, may provide self-purification or natural attenuation. From the vulnerability map which is usually done using a GIS system, the groundwater protection zones are defined precisely. The groundwater vulnerability is an important object all over the world arising from the decline the water table of groundwater and increasing pollution which represent a real risk to the environment. To identify this risk, research has been carried out to evaluate the groundwater vulnerability by using several methods. Some common overlay and index methods are DRASTIC, DRASTIC-Fm, SEEPAGE, SINTACS, GOD, GOD-S, EPIK and DISCO; nevertheless, DRASTIC method is the most popular worldwide for groundwater vulnerability assessment (e.g., Gogu & Dassargues, 2000; Shirazi et al., 2012), (Fig. 6).

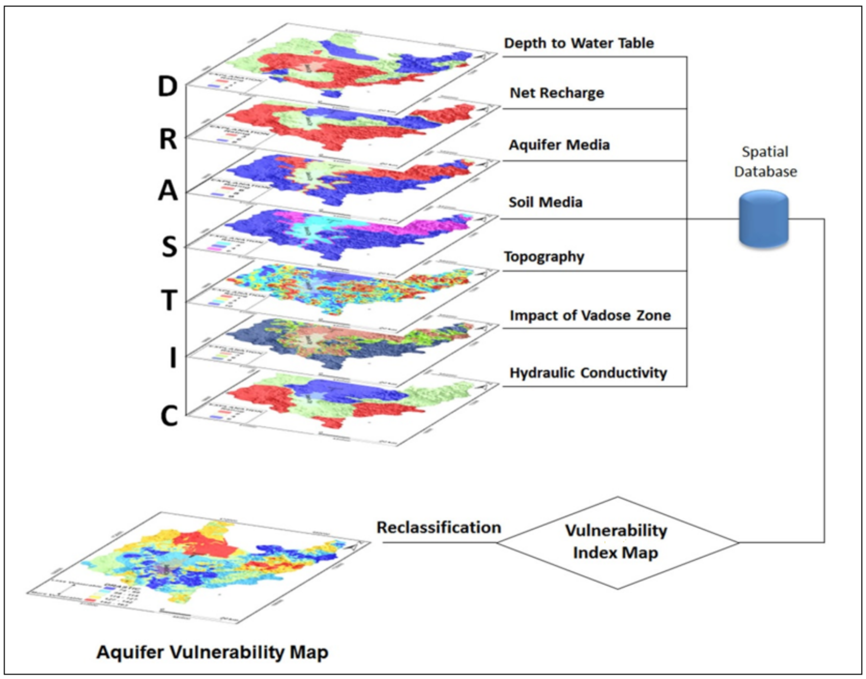


Figure 6. Illustration of the methodology flowchart for DRASTIC method (Alwathaf & El Mansouri, 2011).

It is very problematic to delineate protection zones for aquifers according to a uniform method, because the fractured media have differences of geological and hydrogeological conditions. Thus, the first step of this approach is to study and assess the main information of the specific watershed facility (spring or well) and of the aquifer. The information such as discharge, physico-chemical parameters, turbidity and biology permit to evaluate the vulnerability of the watershed facility (Pochon & Zwahlen, 2003). In case of a low vulnerability of the spring, it is possible to apply a fixed radius approach ("distance method"). If the aquifer is evaluated as a little heterogeneous, it is possible to use the calculated radius method depending on tracer test results ("isochrone method") for delineation of protection zones. If the heterogeneity is high, a groundwater vulnerability mapping method is applied ("DISCO method"), according to evaluating discontinuities, protective cover and runoff parameters (Fig. 7) (Pochon et al., 2008).

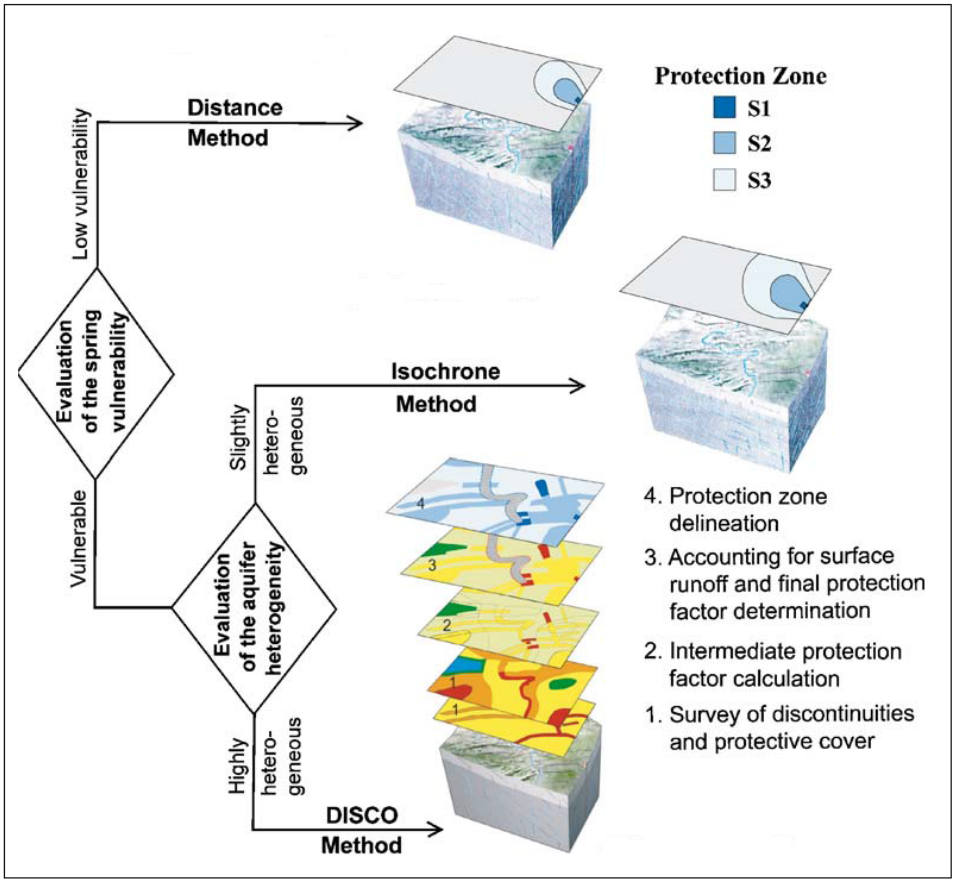


Figure 7. Decision process allowing the selection of one of three specific methods to delineate groundwater protection zones in fractured media (Pochon et al., 2008).

The concept of fractured media, aquifer vulnerability is really important and it aims to help designer to protect aquifers as an economic and human resource. The concept of aquifer vulnerability combines the hydraulic inaccessibility of the saturated zone to the penetration of pollutants, with the attenuation capacity of the strata overlying the saturated zone as a result of physico-chemical retention or reaction of pollutants (Witkowski et al., 2007).

Groundwater supply protection zones should be delineated to provide special cautious against pollution, regarding water specified for sensitive human uses. Consideration must also be given to sources developed for other potentially sensitive purposes. The delineation of groundwater capture and flow-time zones, with the mapping of aquifer pollution vulnerability, is an essential component of groundwater protection (Foster et al., 2002).

1.2. The purpose

The main aim of this dissertation is to characterize fractured aquifers, on a GIS-based vulnerability mapping, with a multi-technique approach involving geotectonics, hydrogeology, hydrogeomorphology, hydrogeophysics and hydrogeotechnics to attain a groundwater protection. To achieve this goal, groundwater vulnerability indexes were applied on Caldas da Cavaca site (Aguiar da Beira, Central Portugal). Due to the great diversity of geological and hydrogeological conditions in these fractured media, it is not possible to delineate protection zones for such aquifers according to only one method, so several methods were applied: GOD-S (e.g., Foster et al., 2002), DRASTIC-Fm (e.g., Aller et al., 1987; Denny et al., 2007), SINTACS (e.g., Civita & De Maio, 2000; Civita, 2010), SI (e.g., Ribeiro, 2000; Stigter et al., 2006) and DISCO (Pochon & Zwahlen, 2003; Pochon et al., 2008), and confronted with land use, hydrological and well data of the study site. This study was focused in the application of the DISCO methodology on the well and spring areas.

The role of this multidisciplinary methodology to improve the hydrogeological conceptual model for fractured aquifers focused on vulnerability issues, as well as the hydromineral resources will also be analyzed.

2. Groundwater protection in fractured media: a review

2.1. Introduction

Groundwater, is the expression used for water existing under the earth's surface, is an important constituent of hydrological cycle and is the major source of water supply in several sections. Groundwater flows in the subsurface at velocities that typically range from a few centimeters to several meters per year. The geologic aquifer making the prediction and characterization of flow and transport through fractured hard rock mass is complex as the geometry of the flow and path in these rocks is often very heterogeneous according to the fracture properties. In fractured rocks, the groundwater movement takes place along discontinuities, i.e. fractures, joints and shear zones (e.g., Ahmed et al., 2008; Singhal & Gupta, 2010).

Groundwater seeps slowly through the small voids and fractures in the rock that constitutes the Earth's crust. Its occurrence in a geological system is mainly controlled by the lithology (permeability and porosity) and structure (fractures, faults, joints). Groundwater reservoirs are generally called aquifers. Fractured aquifers represent an essential groundwater resource for large parts of the earth (Hardisty & Özdemiroğlu, 2005).

Although groundwater is usually hidden under the earth's surface, it is vulnerable. It can be polluted by a lot of human activities. Perhaps the biggest concern with underground contamination is that we can't see it when it is happening, and we do not know where it is going until it gets there. For that protection of groundwater resources is one of the main drivers of remedial activity, which is mainly aims to protect the drinking water against contaminants (e.g., Ahmed et al., 2008). To determine this susceptibility, research has been carried out to evaluate the groundwater vulnerability by using several methods, namely DRASTIC, SEEPAGE, SINTACS, GOD, DISCO, EPIK.

2.2. The distribution of earth's water

The water is the most common component to be found in the natural environment and it is the source of all living organisms on Earth. Earth includes 70% of water but it is hard to understand the total quality of water when we only see a small part of it. The main sources of water include: rainwater, surface water (lakes and streams), and groundwater. However, the distribution of water on Earth is not uniform (many sites have a lot of it while others have very little). Water exists on Earth in three forms, solid (ice), liquid or gas (vapor). However, the total amount of the earth's water does not change, because of glaciers, rivers and groundwater flow (e.g., Custodio & Llamas, 2001; Fetter, 2001; Younger, 2007).

Earth's total water is about (1386 x 10^6 km^3), being 96 % salt water. From the total freshwater, about 68 % is confined in ice caps and glaciers; 30 % of freshwater is in the land. Fresh surface-water sources, such as rivers and lakes, only represent around (84 x 10^5 km^3) (Fig. 8) (Shiklomanov, 1998).

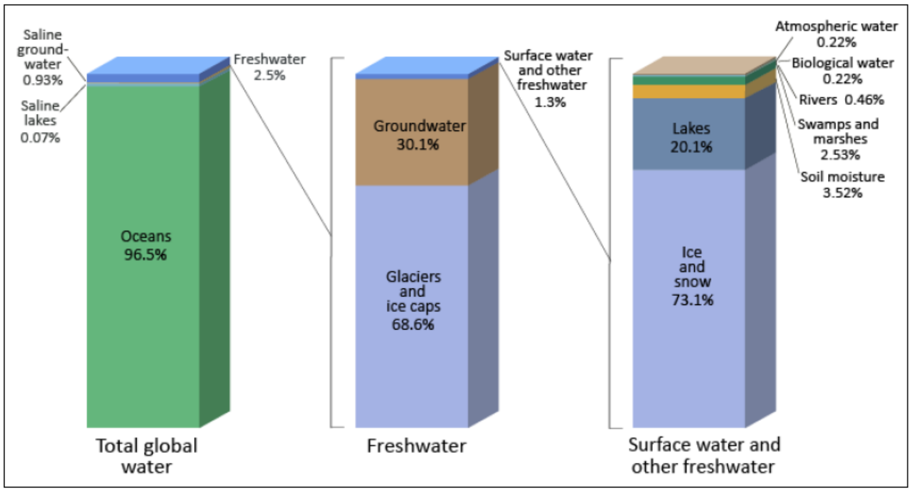


Figure 8. Distribution of Earth's water (Shiklomanov, 1998).

2.3. The hydrological cycle

The hydrological cycle (or water cycle) is essentially as a result of the general principle of the conservation of water in its three phases (solid, liquid, and gas) on the land (Oliver & Oliver, 1995; Bengtsson et al., 2014). It is defined as a concept to describe the storage and circulation of water between the biosphere, atmosphere, hydrosphere, and the lithosphere, through the atmosphere, oceans, streams, rivers, lakes, soils, glaciers, ice, and groundwater aquifers (Fig. 9). Circulation of water between these storage parts is caused by such processes as evaporation, condensation, precipitation, infiltration, sublimation, transpiration, runoff, and groundwater flow, which are called the water cycle components (e.g., Fetter, 2001; Marsalek et al., 2006; Younger, 2007; Bengtsson et al., 2014).

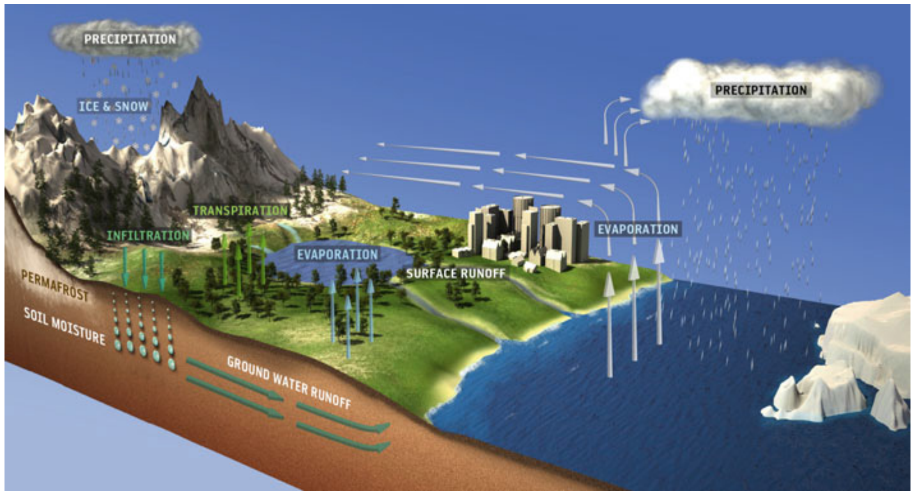


Figure 9. The hydrologic cycle (Bengtsson et al., 2014).

The total amount of water does not change on the ground and within its atmosphere because precipitation and rivers should constitute a movement that removes the water in a never-ending cycle. Thus, it is possible to define the hydrological cycle as the circulation and storage of Earth's water as it circulates from the land to the atmosphere and back again to the land (FWR, 2005).

The hydrological cycle is a model used by water engineers and scientists across our planet to describe the different stages water goes through during its journey from the oceans to the atmosphere, onto the land and back to the oceans. There is no definite start- or end-point of the cycle but it is best to describe the start of the cycle from the oceans as they represent a great reservoir of water. Water evaporates from the ocean surface then it goes to the atmosphere where in vapor form it subjects circulation according to the distribution of temperature and wind velocity (e.g., Singhal & Gupta, 2001; Bengtsson et al., 2014).

The hydrological cycle includes the following components (e.g., Fetter, 2001; Marsalek et al.,2006; Brassington, 2007, Bengtsson et al., 2014):

i. Evaporation from the oceans and lakes and transpiration: it is the turn process of the water from a liquid to vapor. This process requires large amounts of energy; therefore the sun provides great heat to evaporate water from the Earth's surface, lakes, rivers and oceans. Plants and trees also lose water to the air through the pores of plants this process called transpiration;

ii. Transport of water vapor by atmospheric circulation**:** the movement of water occurs through the atmosphere in several forms the most important is from the oceans to land

and the Earth's moisture transport as clouds (cloud droplet formation and cloud dynamics);

iii. Condensation over land and oceans: it is the turn process of water vapor in the air to the liquid water, when the atmosphere is cooled to a temperature that causes condensation. This process is important to the water cycle because it is primary for the formation of clouds;

iv. Precipitation over land and oceans: precipitation is water emission from clouds in several forms, rain, freezing rain, sleet, or snow. It is the basic connection in the water cycle that supplies the ground with water;

v. Infiltration: where rain, or melting snow, falls on the ground, the water starts to seep into the soil under gravity and capillary forces; this process is called infiltration. The speed of infiltration depend on the type of soil and the amount of water;

vi. Runoff: water that doesn't seep into the soil, it may be flows on the surface as runoff and the rainfall that arrives to the surface of the Earth. Runoff may be achieved from melted snow not just from liquid water. Also it includes water flowing in streams, rivers and lakes. Much of rainfall evaporates before arriving to the ocean or an aquifer for that not all rainfall water reaches to the sea as runoff;

vii. Groundwater flow: water that seeps through the soil to access to the water table becomes groundwater. Groundwater considered as an important source of drinking water in the world, because it has the essential importance of providing rivers and streams with water during dry periods. The volume of water percolating into the aquifers determines the groundwater resources; also flow rates will differ from place to another depending on the amount of water. Small groundwater flow rates can transfer large amounts of pollution over long periods of time.

2.4. Classification of subsurface water

The subsurface water is the water which occurs below the ground surface. It is possible to divide the subsurface water into two main categories depending on its depth of occurrence and the extent to which it saturates the soil: aeration zone (vadose zone or unsaturation zone) and the saturation zone (phreatic or groundwater zone) (Fig.10). The border line between these two zones is called the water table, which is defined as the surface on which the pore water pressure equals atmospheric pressure. The water table is labeled with the symbol ∇ (Younger, 2007; Fitts, 2013).

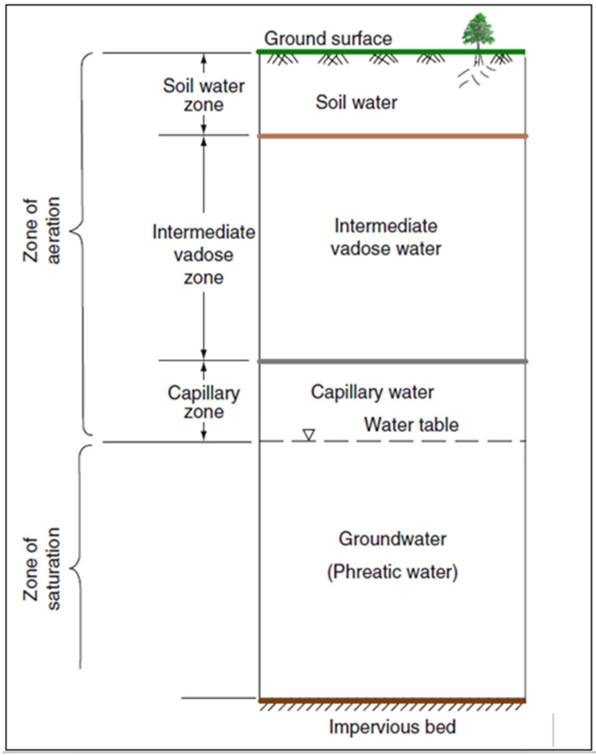


Figure 10. Classification of subsurface water (Singhal & Gupta, 2010).

The aeration zone is the zone above the water table where the space is partly filled with water and air, and the water pressure is less than atmospheric. The saturated zone is the zone below the water table where the space is totally filled with water, and the water pressures are greater than atmospheric (Fetter, 2001; Fitts, 2013). The aeration zone is divided into three zones from top to bottom:

i. soil water zone: very important to agriculture because it provides the water for plant. The water is lost from the soil-water zone by transpiration, evaporation and percolation;
ii. intermediate vadose zone: cannot keep all the amount of water because most of water in this zone moves down, and some of it is still in this zone but cannot be restored only by applying a void to soil. The thickness of this zone may be thin or zero when water-table is close to the ground surface.
iii. capillary zone or capillary fringe: its thickness varies depending on the pore sizes in the medium and may disappear where rough grained sediments are present.

2.5. The properties of water

2.5.1. Physical properties

The physical properties of water are very important for groundwater investigations because the distribution of material properties of water is basic to understand groundwater mobility. Also, the distribution and the geometry of pores are necessary to know the facility of groundwater to move through the material and the structure of rock. The water has several properties that make it a very unique substance (Table. 1).

Table 1. Typical physical properties of fresh water (Fitts, 2013).

Properties	Symbol	Dimensions	Value
Mass density	ρ_w	M/L^3	$1.0\ g/cm^3$ 1000 kg/m^3
Weight density	$\rho_w g$	F/L^3	9810 N/m^3
Compressibility	β	L^2/F	$4.5 \times 10^{-10}\ m^2/N$
Dynamic viscosity	μ	FT/L^2	1.4×10^{-3} N·sec/m^2
L = length, M = mass, T = time, F = ML/T^2 = force.			

The density of water is defined as its mass per unit volume (mass density ρ_w). In some cases, density is also defined as its weight per unit volume (weight density $\rho_w g$). This property of water varies slightly with a number of conditions, such as the concentrations of dissolved minerals, pressure, and temperature. The high temperature leads to reduce the density but the high pressure leads to increase the density. The density can be calculated by using formula [1] which ρ is the density of the water, m is the mass, and v is the volume (Spellman, 2008):

$$\rho = m/v \qquad [1]$$

The compressibility of water is the volume change of a material when pressure is applied. As water pressure P rises an amount dP at a constant temperature, the density of water increases $d\rho_w$ from its original density ρ_w, which β is the coefficient of water compressibility, defined by formula [2] (Bear & Cheng, 2010):

$$\beta = d\rho_w/\rho_w * \ dP \qquad [2]$$

The viscosity is a measure of the internal resistance to flow or shear, and is a measure of the frictional properties of the fluid. The viscosity is a function of temperature and pressure and changes according to the temperature and pressure. Viscosity is expressed in two ways: dynamic viscosity and kinematic viscosity (Viswanath et al., 2007). The resisting force F can be calculated by using formula [3], which F is proportional to the area of the film between the plates A, a dynamic viscosity μ, the velocity of the plates relative to each other dv, and inversely proportional to the thickness of the fluid separating the two plates dz:

$$F = A * \mu * dv/dz \qquad [3]$$

2.5.2. Chemical properties

The chemical properties of water are very important, because water has a number of unique chemical properties that make it necessary for life. Hydrogen atoms are associated with one side of the oxygen atom to form a water molecule having a positive charge on this side and a negative charge on the other side, where the oxygen atom exist. For that the water is a polar molecule because the distribution of electrical charge associated with protons and electrons is different. The polarity of the water molecule leads to electrostatic attraction to other polar molecules and to charged molecules. The hydrogen ends of a water molecule are attracted to the oxygen ends of other water molecules, forming bonds called hydrogen bonds.

The normal formula of water is H_2O but there are isotopes of water which have the same atomic number but different atomic weights due to difference numbers of neutrons in the nucleus. Thus, many types of water molecules occur, the most significant being ${H_2}^{16}O$ light, the most common water molecule, $HD^{16}O$ and ${H_2}^{18}O$ heavy, rare water molecules (Mazor, 2003).

Natural waters are not always pure because they contain small amounts of dissolved gases, solids and dissolved salts, separated into cations, positively charged ions like sodium (Na^{+}), calcium (Ca^{+2}), magnesium (Mg^{+2}), and potassium (K^{+}), and anions, negatively charged ions like chloride (Cl^{-}), bicarbonate (${HCO_3}^{-}$), and sulfate (${SO_4}^{-2}$). The composition of groundwater varies as a result of interaction with geological formations. The concept of hydrochemical facies is used to find out the bodies of groundwater, in an aquifer, that suffers from difference in their chemical composition. The facies are a function of the lithology, solution kinetics, and flow model of the aquifer. Hydrochemical facies can be categorized according to the dominant ions in the facies by a trilinear diagram, the Piper Diagram (Fig. 11), (e.g., Fetter, 2001; Mazor, 2003; Appelo & Postma, 2005).

There is another type of diagram for chemical analysis called Stiff Diagram (Fig. 12). Stiff diagrams are helpful in making a visual comparison between groundwater which comes from different sources. The larger zone of the polygonal shape refers to the greater concentrations of ions (e.g., Fetter, 2001).

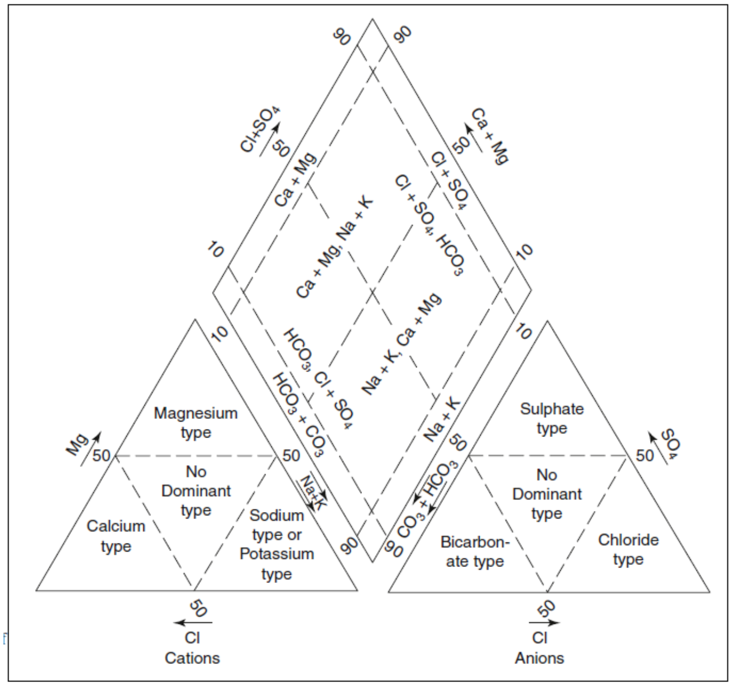


Figure 11. Exemplification of the Piper diagram showing hydrogeochemical classification for groundwater (Fetter, 2001).

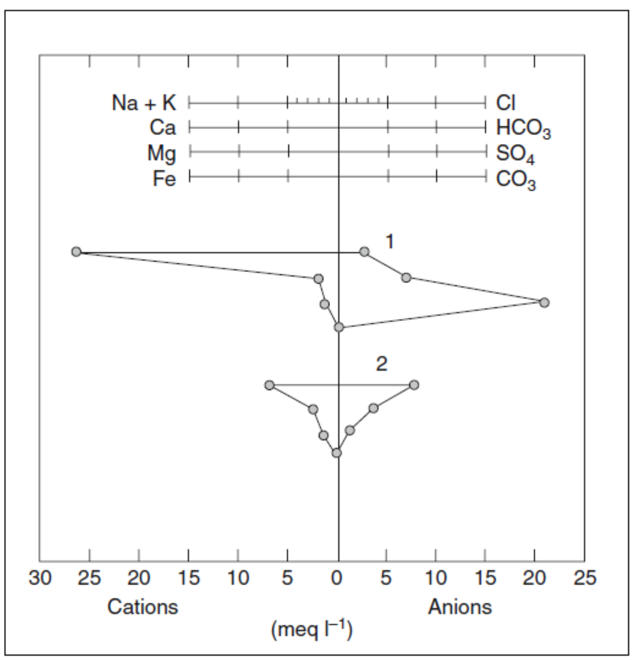


Figure 12. Illustration of a Stiff diagram (Fetter, 2001).

2.6. Hydrogeological classification of geological formations

The existence and movement of groundwater through geological formations depends on the hydrogeological properties of the sub-surface formations. These formations differ in their lithology, texture and structure which affect their hydrogeological properties. Geological formations are categorized into three types depending on their relative permeability (e.g., Sterrett, 2007; Bear & Cheng, 2010; Singhal & Gupta, 2010), (Fig. 13):

- Aquifer – a body of saturated rock that stores and transmits great quantities of groundwater and allows water to move through it under normal field conditions;
- Aquitard – a formation that has a low permeability but not enough to make it a source of water supply, however, it permits transmission of the groundwater slowly from one aquifer to another due to vertical leakage;
- Aquiclude – a confining formation which is impermeable or has some permeability but the value is very low.

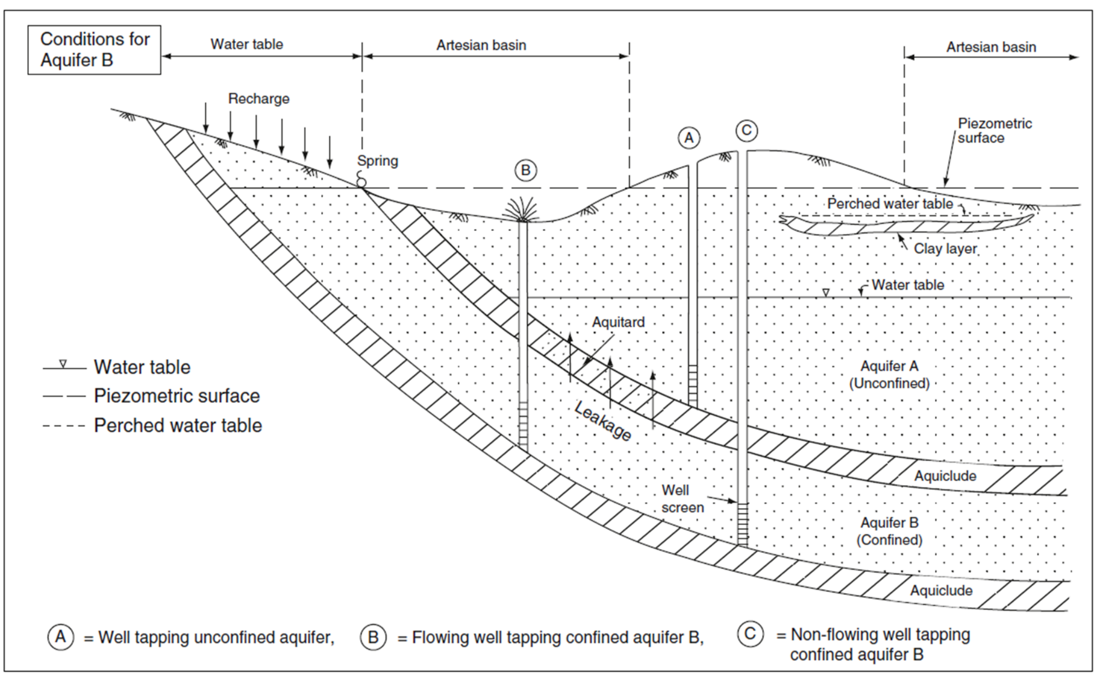


Figure 13. Types of geological formations. (A) Well tapping unconfined aquifer. (B) Flowing well tapping confined aquifer B, (C) Non-flowing well tapping confined aquifer B (Singhal & Gupta, 2010).

2.6.1. Types of aquifers

The aquifers may occupy a specific space or may extend over distances of several hundred kilometers. There are many types of boundaries that can be categorized as permeable or impermeable. Fig. 14 shows examples for each type of aquifer boundary (Brassington, 2007).

- The boundary between the two aquifers faulted against each other may be permeable and permit flow across it (Fig. 14.a);
- The faulted boundary is impermeable (Fig. 14.b);
- The aquifer A lies unconformably over a sequence that includes two separate aquifers, B and C (Fig. 14.c);
- The aquifer overlies a non-aquifer (Fig. 14.d);
- An unconsolidated aquifer overlies a limestone aquifer that forms a cliff. Groundwater flow is possible between the two aquifers, because of the topographic differences, thus it is a high probability to be from aquifer B to aquifer A (Fig. 14.e);
- A gravel aquifer overlies low-permeability bedrock (Fig. 14.f).

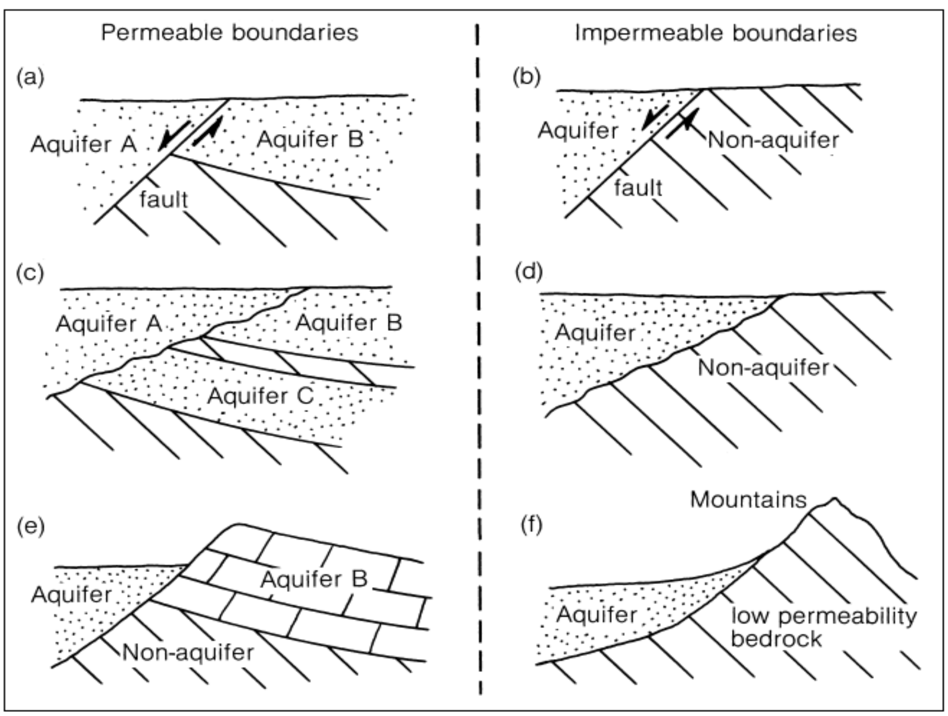


Figure 14. Types of aquifer boundary (Brassington, 2007).

Based on hydraulic characteristics of layers and the location of the piezometric surface, which is an imaginary surface to which the water will go up in wells tapping confined aquifer, it is possible to classify aquifers into the following types (Fig. 15) (Brassington, 2007; Sterrett, 2007; Bear & Cheng, 2010):

- confined aquifer: is bounded from above and below by a confining layer. Water in a confined aquifer occurs with a pressure higher than the atmospheric. The piezometric surface should be above the upper surface of the aquifer. In other words, the piezometric surface of a confined aquifer is above the impervious surface;
- unconfined (phreatic) aquifer: partially saturated with water, it is open to the surface without any intervening confining layer, but it is bounded from below by a confining layer;
- perched aquifer: is a special type of a phreatic aquifer separated from the main aquifer by clay lens or any other impermeable substance in the zone of aeration;
- leaky phreatic aquifer: is a phreatic aquifer that is underlain by an aquitard;
- leaky confined aquifer: is a confined aquifer, but one or both confining layers are aquitards, through which leakage might occur.

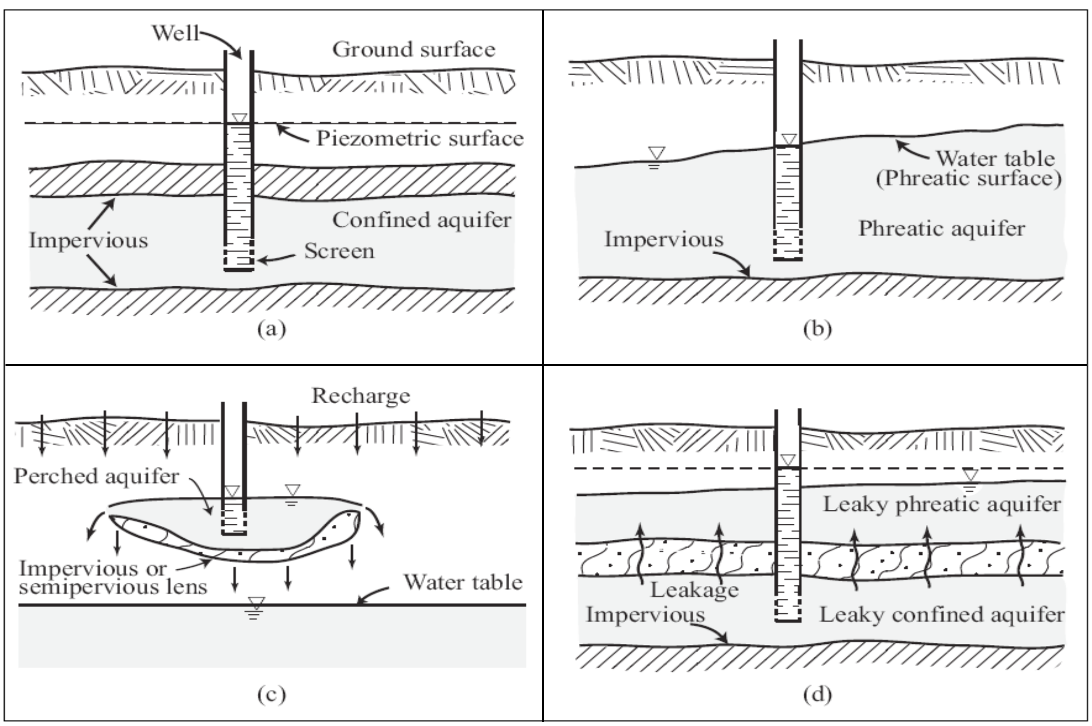


Figure 15. Types of aquifers: (a) Confined aquifer; (b) Phreatic aquifer; (c) Perched aquifer; (d) Leaky aquifer (Bear & Cheng, 2010).

Permeability is an important parameter for determining the hydrodynamic characteristics of aquifers. Based on permeability characteristics of layers, it is possible to classify the aquifer into the following types (e.g., Fetter, 2001; González de Vallejo & Ferrer, 2011):

- **Porous aquifers**

Porous aquifers have a porous structure which controls hydrodynamic properties of porous medium, its ability to store and transmit the water through pore spaces between grains and the primary porosity. Pore structure and permeability are important properties in determining the hydrodynamic properties of porous aquifer. The heterogeneous and geometry of rocks makes it hard to determine the permeability of such materials (Kim et al., 2011).

- **Fractured aquifers**

The occurrence and movement of groundwater in fractured aquifers is mainly controlled by fractures and other discontinuities. However, some big fractures may function as barriers to groundwater flow. There are several factors like stress distribution, fracture geometry and temperature, which control the groundwater flow through fractures. These properties can be used to evaluate the actual connections between fractures, which affect fluid flow (e.g., CFCFF, 1996; Singhal & Gupta, 2010). Also the velocity of groundwater flow is higher than in porous aquifer, yields are mostly low due to restricted groundwater volumes (e.g., Lewis et al., 2008) (Fig. 16). Table. 2 shows some comparison between porous and fractured aquifers.

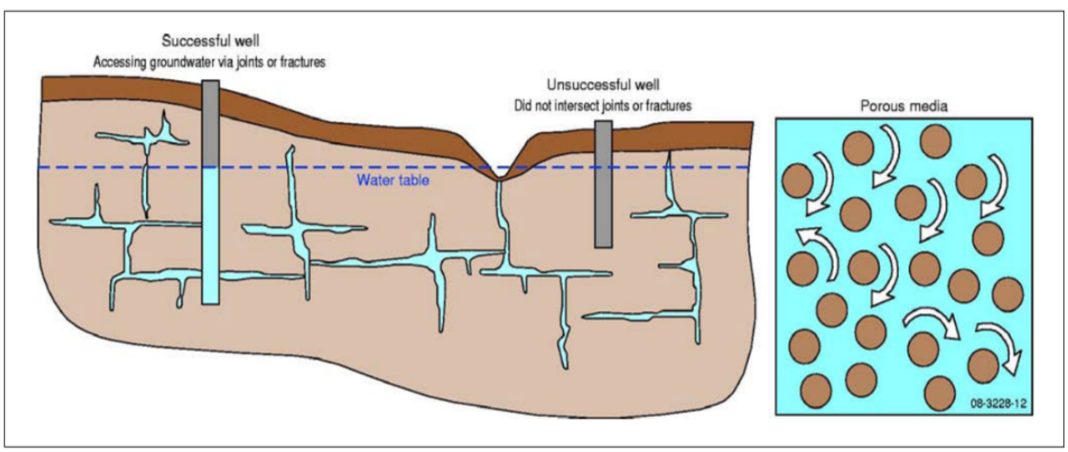


Figure 16. Comparison of groundwater systems in fractured aquifers (left) and porous media (right) (Lewis et al., 2008).

Table 2. Comparison between porous and fractured aquifers (adapted from Ahmed et al., 2008).

Properties	Porous aquifer	Fractured aquifer
Effective porosity	Mostly primary	Mostly secondary through joints, fractures, etc.
Isotropy	More isotropic	Mostly anisotropic
Homogeneity	More homogeneous	Less homogeneous
Flow	Laminar	Possibly rapid and turbulent
Flow predictions	Darcy's law usually applies	Darcy's law may not apply, applies cubic law applicable
Recharge	Dispersed	Primarily dispersed with some point recharge
Temporary head variation	Minimal variation	Moderate variation
Water quality variation	Minimal variation	Greater variation

Hydraulic conductivity of fractured rocks depends on the fracture properties, like connectivity, aperture spacing, stress and infilling. The connectivity of fractures is very important for groundwater flow which takes place in fractures and can move through connected fractures. The connectivity of fractures increases with increasing fracture density, fracture length and fractures intersection. So the groundwater flow will increase with increasing fractures connectivity (e.g., Fitts, 2013).

High permeability fracture networks in a rock can generate high conductivity vacuum for the flow of liquid through the aquifer, producing bigger flow rates thus, bigger permeability (e.g., Philip et al., 2005). Fractured aquifers have a double porosity (porous matrix and fractures) and their permeability decreases with increasing temperature which cause reduction in fracture aperture and similar reduction in permeability. Moreover, the fracture permeability also reduces by filling, cementation and weathering. The decrease in permeability with depth in fractured aquifers is usually returned to reduction in fracture aperture and fracture spacing due to increased stress. According to the porosity and permeability of the fractures and the matrix blocks, it is possible to classify the fractured aquifers into three types (Fig. 2.17). In a purely fractured medium, the porosity and permeability is a result of interconnected fractures while blocks are impervious; in double porosity medium, fractures and matrix blocks contribute to groundwater flow but fractures are the main contributors; when fractures are filled with weathered material, the fracture permeability is reduced and the medium is called as heterogeneous (Singhal & Gupta, 2010).

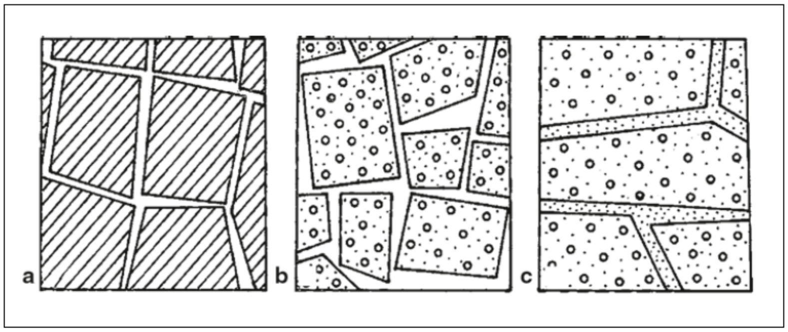


Figure 17. Schematic representation of (a) purely fractured medium, (b) double-porosity medium, and (c) heterogeneous medium (Singhal & Gupta, 2010).

The description of flow and transport through fractured aquifers are really hard as the geometry of the flow and way in these aquifers is very complex and heterogeneous according to the fracture properties. The connections between rock fractures and their spacing and aperture size constitute the extent of porosity and permeability of such fracture rocks. The fractures which are not filled with weathered materials constitute potential path for groundwater movement and their permeability is decreased when filled. These filling materials affect the movement of fluid from the fractures into the porous matrix (Ahmed et al., 2008).

Weathering processes in fractured aquifers are often the best source for groundwater supplies in fractured aquifers because it opens new fractures and extends the old fractures. Knowledge of groundwater flow and contaminant transport in weathered and fractured zones of rocks is necessary for determining the surface and subsurface waste sites and to evaluate the environmental effect of a contamination source (e.g., Sharp, 2014).

Most of the areas where arisen since a long time, thus exposed during long periods to the weathering processes, under humid climates. The outcropping rocks thus actually include many tens of meters thick surface weathered formation, where it has not been eroded. This surface layer corresponds to a type weathering profile. A typical weathering profile consists of several layers that have certain hydrodynamic characteristics (Fig. 18).

However, fractures may be filled by minerals, like quartz veins. The mineral fillings have important results for liquid flow because they may change the flow characteristics of the fractured aquifer. The mineral fillings may have different permeability than the host rock, and veins may remain fractures open and may serve as barriers to groundwater flow. The mineral fillings also offer information about the nature of the liquid flowing in the fractures and the physical and chemical surrounding conditions (CFCFF, 1996). Veins, whose weathering products are of low permeability, do not provide good hydrodynamic characteristics for fractures.

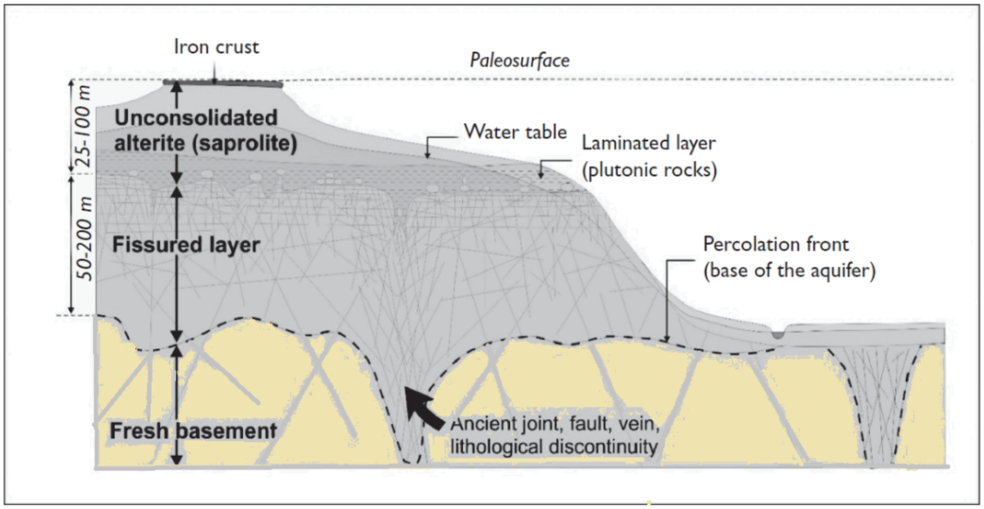


Figure 18. Stratiform conceptual model of the structure and the hydrogeological properties of hard rock aquifers (Sharp, 2014).

2.6.2. Properties of aquifers

Porosity (Φ) and Effective porosity Φ_e

The porosity Φ is the volume of pore spaces in rocks in relation to the total rock volume, and it can be calculated by using formula [4]:

$$\Phi = 100 * V_{porespace}/V_{total} \qquad [4]$$

Where:

Φ is the porosity (%)

$V_{porespace}$ is the volume of void space in a unit volume of earth material (L^3, cm^3 or m^3)

V_{total} is the unit volume of earth material, voids and solids (L^3, cm^3 or m^3)

It is possible to distinguish between two origins of the porosity. Primary porosity arises from pore space between grains and clastic sediments. Secondary porosity, which arises from tectonic stress or tectonic pressure as fractured rocks, or from dissolution caves as carbonate rocks (Kirsch, 2009). In general, the porosity in unconsolidated rocks decreases with increasing grain size but the porosity of solid rocks is lower than the porosity of unconsolidated, because a part of the pore space is filled with cement.

Actually, porosity is controlled by the grain size and shape, the degree of rating, the extent of cementation and fracturing. The porosity which has a good rating for materials is higher than the porosity which has a weak rating for materials, because small grains can fill the space between the larger grains which lead to reduce the porosity (Fig. 19), (Brassington, 2007). Some particles have good rounded shapes but many grains are very irregular. Sphere shaped grains have less porosity than grains of other shapes (Fetter, 2001).

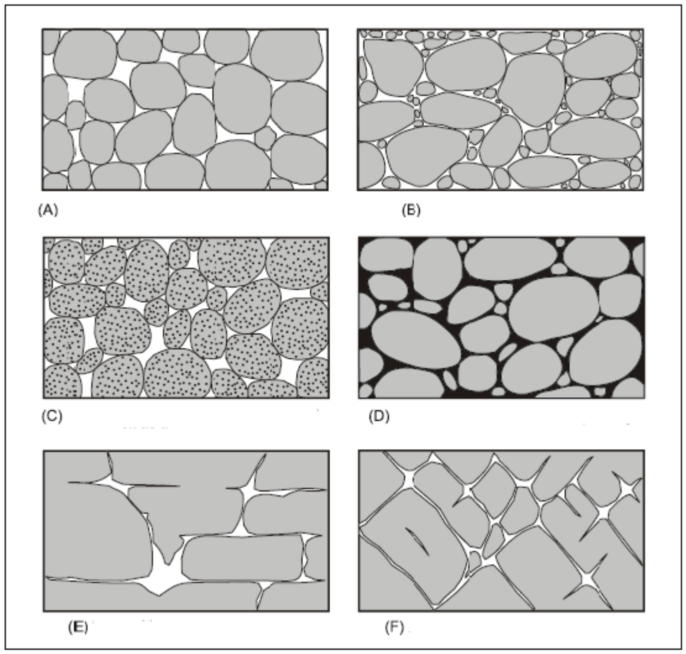


Figure 19. Porosity of typical aquifer materials. (a) Good rating sediments have a high porosity. (b) Poor rating sediments have a low porosity. (c) The grains are porous, so increasing the overall porosity of the formation. (d) The porosity is often reduced by the existence of cementing material. (e) Rock with porosity increased by solution. (f) Rock with porosity increased by fracturing (Brassington, 2007).

Effective porosity Φ_e is the part of total void spaces in a saturated porous material which water flow takes place, because not all the pore spaces allow the flow. The effective porosity can be calculated by using formula [5]:

$$\Phi_e = 100 * V_{\text{interconnected voids}} / V_{\text{total}} \qquad [5]$$

The fine grains which have weak rating for materials have low effective porosity as compared with coarse grains and good rating for materials, due to the greater retention of water on account of intergranular forces (Singhal & Gupta, 2010). The total porosity and effective porosity for unconsolidated sediments are almost similar. However, for consolidated rocks they can be quite different (Table. 3). The effective porosity of a porous medium is smaller than its porosity and it is more important for estimating the average velocity of groundwater and transport of contaminants.

Table 3. Effective porosity and porosity ranges for various rocks (Rowe, 2001).

Type of rock	Effective porosity Φ_e	Porosity Φ
Chalk	$5 * 10^{-4}$ to $2 * 10^{-2}$	$5 * 10^{-2}$ to $4 * 10^{-1}$
Limestone, dolomite	$1 * 10^{-3}$ to $5 * 10^{-2}$	0 to $4 * 10^{-1}$
Sandstone	$5 * 10^{-3}$ to $1 * 10^{-1}$	$5 * 10^{-2}$ to $1.5 * 10^{-1}$
Shale	$5 * 10^{-3}$ to $5 * 10^{-2}$	$1 * 10^{-2}$ to $1 * 10^{-1}$
Salt	$1 * 10^{-3}$	$5 * 10^{-3}$
Granite	$5 * 10^{-6}$	$1 * 10^{-3}$
Fractured crystalline rock	$5 * 10^{-7}$ to $1 * 10^{-4}$	0 to $1 * 10^{-1}$

Transmissivity (T)

Transmissivity is a measure of the rate of flow of water that can be moved through the base and top of the saturated thickness of the aquifer (vertically) under the prevailing field temperature and a unit hydraulic gradient (Fetter, 2001; Younger, 2006). The transmissivity is the result of the hydraulic conductivity and the saturated thickness of the aquifer [6]. Fig. 20 illustrates transmissivity.

$$T = b * K \qquad [6]$$

Where

T is transmissivity (L^2/T, m^2/d)
b is saturated thickness of the aquifer (L, m)
K is hydraulic conductivity (L/T, m/d)

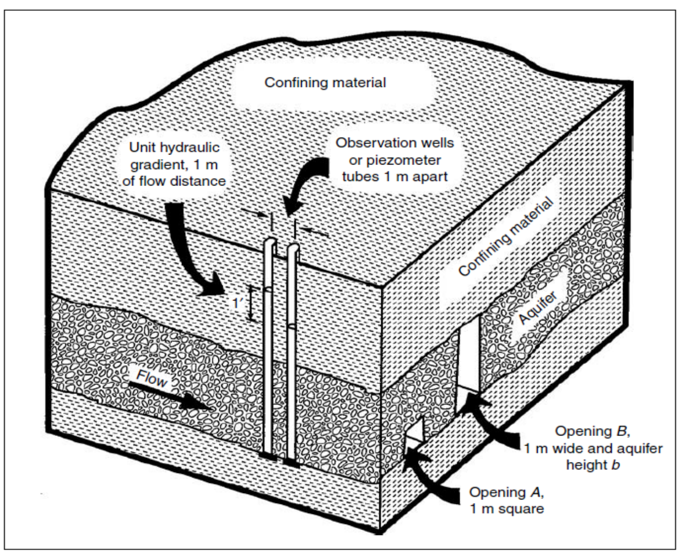


Figure 20. Diagram illustrating transmissivity (T) and coefficient of hydraulic conductivity (K). Flow of water through opening A will be equal to K and that through opening B equal to T (Delleur, 2007).

The total rate of flow (Q) in any zone (A) of the aquifer vertical to the flow direction under the prevailing gradient (I) given as [7].

$$Q = T * I * A \qquad [7]$$

Specific Storage (S_s)

Specific storage is the basic storage property of saturated materials. It defined as the amount of water extracted or stored from a unit volume of saturated formation due to compressibility of the mineral skeleton and the pore water per unit change in hydraulic head. When hydraulic head decreases, water is extracted from the volume because the pore space dilates and the solid matrix compresses. This kind of groundwater storage is defined as *Elastic Storage*, because the water and matrix are typically supposed to compress and dilate elastically (Scesi & Gattinoni, 2009). Specific storage has dimensions of L^{-1}. The value of specific storage is very small, generally 3048 x 10^{-5} m or less. The concept can be applied for each of aquifers and confining units and is shown on [8]:

$$S_s = \rho_w * g * (\alpha + n * \beta) \qquad [8]$$

Where

ρ_w is the density of the water (M/L^3, Kg/m^3)

g is the acceleration of gravity (L/T^2, m/s^2)

α is the compressibility of the aquifer skeleton (M/LT^2, m^2/N)

n is the porosity (L^3/L^3)

β is the compressibility of water (LT^2/M, m^2/N)

The specific storage is used in confined aquifer analysis and in unconfined aquifer the water extracted from storage is as a result of gravity drainage not to the compressibility of aquifer material or of water (Fetter, 2001).

Storage coefficient or Storativity (S)

Storage coefficient is the volume of water that a permeable unit will absorb or expel from storage per unit surface zone per unit increase or decrease in hydraulic head. It is a dimensionless quantity (Delleur, 2007).

In confined aquifers, the storativity is due to the pressure of the aquifer and expansion of the confined water when the pressure is decreased during pumping. The storativity of a confined aquifer is the product of the specific storage (S_S) and the aquifer thickness (b), [9]:

$$S = S_s * b \qquad [9]$$

Where

S_s is the specific storage

b is the saturated thickness of the aquifer (m)

In an unconfined unit, the level of saturation changes with changes in the amount of water in storage. As the water level drops, water drains from voids. This storage or release is as a result of the specific yield (S_Y) of the unit. For an unconfined unit, storativity is given as [10]:

$$S = S_y + S_s * b \qquad [10]$$

Where

S_y is the specific yield

S_s is the specific storage

b is the saturated thickness of the aquifer (m)

For most aquifers (unconfined or confined), the storage coefficient values are in the range of $5*10^{-6}$ to $5*10^{-3}$ (Younger, 2006). Generally, in unconfined aquifers this coefficient ranges from $5*10^{-2}$ to $3*10^{-1}$ and in confined aquifers from 10^{-6} to 10^{-3}. The storage coefficient has the same value as the specific yield in unconfined aquifers but not under confined conditions. There is a difference in the value of storage coefficients between confined and unconfined aquifers (Fig. 21). In an unconfined aquifer, unit decrease in head will result a volume of water equal to the specific yield by removing water from a unit volume of rock. In a confined aquifer, the unit decrease in head will produce a small drop of water and the aquifer will still saturated (Batu, 2006; Brassington, 2007).

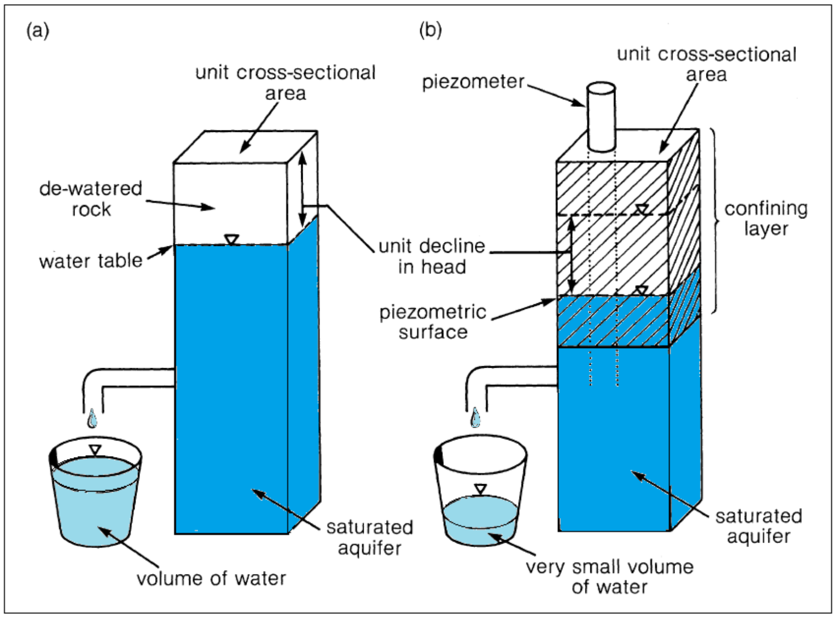


Figure 21. Diagrams illustrating storage coefficient for (a) unconfined aquifer and (b) confined aquifer (adapted from Brassington, 2007).

Specific yield (S_y)

The specific yield is the storage property of an unconfined aquifer and represents the ratio of the volume of unconfined aquifer releases from storage via gravity drainage, to the total volume of fully saturated aquifer. It is defined by equation [11]:

$$S_y = 100 * V_w/V \qquad [11]$$

Where

V_w is the volume of water which drains from a total volume V (L^3, cm^3 or m^3).

V is the unit volume of earth material, including both voids and solids (L^3, cm^3 or m^3).

The specific yield depends upon the shape and size of particle, distribution of voids, the duration of drainage and the pressure of the formation (Singhal & Gupta, 2010). While grain size decreases, total surface area will increase, leading to smaller specific yields for smaller grain sizes. The specific yields for coarse sands and fine gravels are the highest. The specific yields for clays are the lowest, because the clays have small particles and voids with large surface areas (Batu, 2006).

Actually, specific yield in unconfined aquifer is equal to effective porosity. Also the specific yield in unconfined aquifer is bigger than the storage coefficients in confined aquifer, thus more water can be drawn from storage in a particular zone of an unconfined aquifer than from the same zone of a confined aquifer (Fitts, 2013). Values of specific yield for various porous materials are given in Table. 4.

Table 4. Specific yields for various porous materials (Freeze & Cherry, 1979).

Formation	Specific Yield (%)	
	Range	Average
Clay	0 - 5	2
Sandy clay	3 - 12	7
Silt	3 - 19	18
Fine sand	10 - 28	21
Medium sand	15 - 32	26
Coarse sand	20 - 35	27
Gravelly sand	20 - 35	25
Fine gravel	21 - 35	25
Medium gravel	13 - 26	23
Coarse gravel	12 - 26	22

Permeability

Permeability is the most important property of aquifers; it describes how easily water is able to move through the rock mass. Permeability is depended on the connected void spaces and to the grain size of the rock. Actually, if rock is extremely porous, but each pore was isolated from the others, the rock will be impermeable and so make a bad aquifer. However, if void spaces are small, so the surface of water can hold the movement of water through the small spaces. For this reason clays are so impermeable, even though their high porosity but the small void spaces in clay impede the water movement. Thus sands make the best aquifers and clays make the worst. (Younger, 2006).

Unconsolidated sediments tend to be more permeable than consolidated sediments because the cement reduces the void spaces in the rock, which reduces the interconnection between pore spaces. Poorly sorted sediments are less permeable than well sorted sediments. Grain size affects permeability in a similar way to the way that it affects specific yield, which is related with permeability. This way, aquifers that have a high specific yield (big grain size) tend to be more permeable, and less permeable rocks usually have a lower specific yield (small grain size) (Fetter, 2001; Fitts, 2013).

Table. 5 shows the rock types according to their permeability. Primary permeability is a property of unconsolidated formations and weathered rocks. It also exists in most sedimentary rocks and igneous rocks which have a high porosity. Secondary permeability occurs as a result of fissuring or solution weathering.

Table 5. Rock types and prevailing permeability (Brassington, 2007).

Type of permeability	Sedimentary		Igneous and metamorphic	Volcanic	
	Unconsolidated	**Consolidated**		**Unconsolidated**	**Consolidated**
Primary	Gravely sand, clayey sand, sandy clay		Weathered granite and weathered gneiss	Weathered basalt	Volcanic ejecta, blocks, fragments of ash
Primary and Secondary		Breccia, conglomerate, sandstone, slate limestone, limestone, calcareous grit		Volcanic tuff, volcanic breccia, pumice	
Secondary		Limestone, dolomite, dolomitic limestone	Granite, gneiss, gabbro, quartzite, diorite, schist, mica-schist	Basalt, andesite, rhyolite	

Specific retention (S_r)

The specific retention is defined as the ratio of the volume of water held in pores against gravity forces via capillarity and molecules attraction to the total volume of the rock (Delleur, 2007). Specific retention depends on the grain size, shape and type of clay minerals. The specific retention increases with decreasing grain size (Singhal & Gupta, 2010). The specific retention given as [12]:

$$S_r = V_r/V \qquad [12]$$

Where

V_r is the volume of water retained in pores (L^3, cm^3 or m^3)

V is the unit volume of earth material, including both voids and solids (L^3, cm^3 or m^3)

The sum of specific yield and specific retention equals porosity as given in [13]:

$$\Phi = S_r + S_y \qquad [13]$$

2.7. Groundwater flow

Groundwater has several forms of energy: mechanical, thermal and chemical. As a result of the existence of this energy the groundwater moves and flows through rocks in fractured and porous media in a complex movement. The geometry and characteristics of pores and fractures varies from one rock to another, thus groundwater flow in rock must be different, where the flow of fluids and transport of solutes occur over a solid surfaces or boundaries. Different dissolved substances have different migration rates, depending on their physical and chemical properties and the properties of the aquifer materials (Douglas et al., 2005; Gustafson, 2012).

The flow of groundwater depends on the laws of thermodynamics and physics. Water always flows from zones with higher pressure towards zones with lower pressure. The water flows along its way, and loses some of its mechanical energy to internal viscous friction. This energy lost is very small and it adds a little heat to the surrounding medium. There are three mechanical energies effects on fluids. The first force is gravity, which attracts the fluids downward. The second force is external pressure above the saturation zone (atmospheric pressure with the weight of overlying water). The third force is molecular attraction, which the fluids stick to solid surfaces; also surface tension occurs in water when the water is subjected to air (Fetter, 2001).

2.7.1. Darcy's law and hydraulic conductivity

Darcy's law is the fundamental relationship that created to understand the motion of fluids in the Earth's crust (details in Bobeck, 2004). Henry Darcy prepared some experiments to study the factors that control the rate of water flow through vertical, homogeneous, saturated, sand filters. As a result of his experiments, identified empirical principles of groundwater flow, which are illustrated in equation [14] that is called Darcy's law (Bear, 2010):

$$Q = -K * \frac{dh}{dL} * \mathrm{A} \qquad [14]$$

Where

Q is discharge (flow rate) in the L direction [L^3/T]

K is the hydraulic conductivity, a property of the geologic medium [L/T]

A is the cross-sectional area of the column [L^2]

$\frac{dh}{dL}$ Represents the rate that head changes in the direction L and is known as the hydraulic gradient

It is necessary to put a minus sign in this equation because the head decreases in the direction of flow. If there is flow in the positive direction, Q is positive and $\frac{dh}{dL}$ is negative. Conversely, when flow is in the negative direction, Q is negative and $\frac{dh}{dL}$ is positive (Fitts, 2013). Q was proportional to the head difference Δh between the two manometers and inversely proportional to the distance between manometers L, Q is also proportional to the cross-sectional area of the column. Darcy's device included a sand-filled column with an inlet and an outlet. The experiment included two manometers each one measures the hydraulic head at two points (h1 and h2) within the column, where the sample is totally saturated, and a steady flow of water is obliged through at a discharge rate Q (Fig. 22).

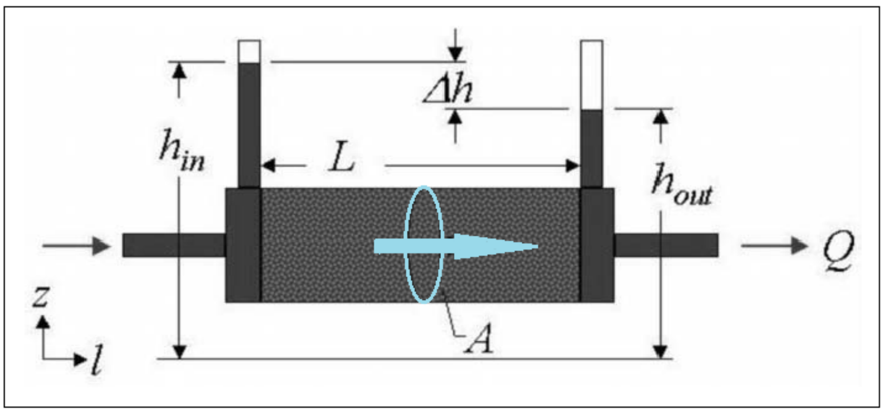


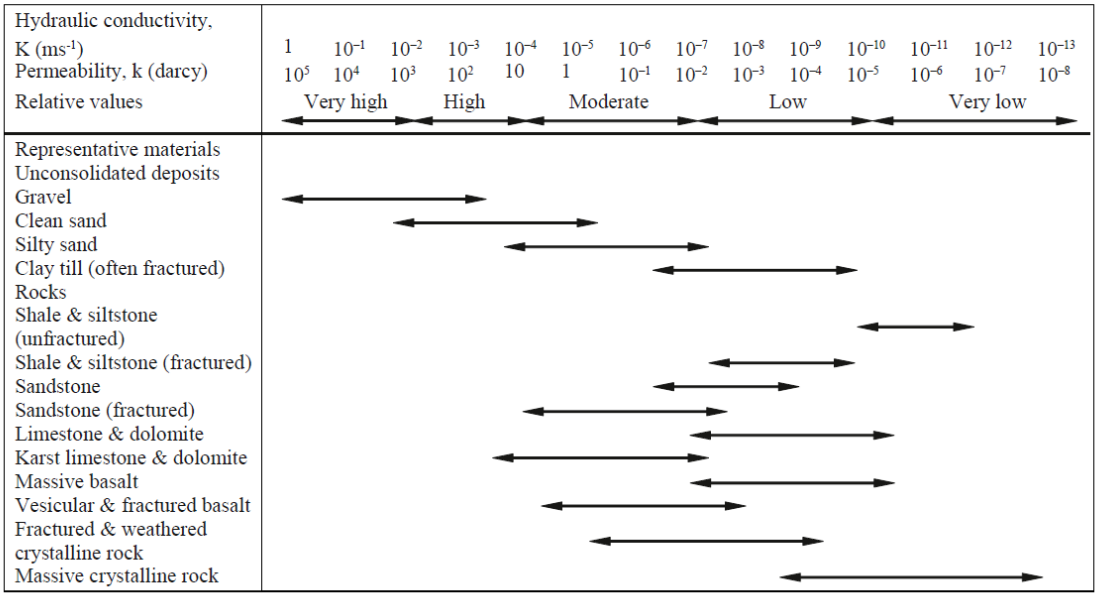
Figure 22. Schematic illustrating steady flow through a sand sample (Ahmed et al., 2008).

The hydraulic conductivity is the property of a water-bearing geologic material, is a measure of the capability of a formation to transmit the groundwater at a standard temperature and density. It depends on the characteristics of the rock and fluid (viscosity, density and the total dissolved solids concentration). Grain size properties are necessary where coarse grained and well sorted material will have high hydraulic conductivity but fine grained sediments will have low hydraulic conductivity. Also the compaction and cementation are necessary because the increase in degree of cementation will reduce the hydraulic conductivity. Hydraulic conductivity can be calculated by using formula [15]:

$$K = -Q * 1/A * dL/dh \qquad [15]$$

Table. 6 shows the range of hydraulic conductivity values for several types of rocks.

Table 6. Range of values of hydraulic conductivity for various types of rocks (Singhal & Gupta, 2010).



Darcy's velocity V assumes that flow of fluids take place through the whole cross section of the aquifer material without regard to solids and pores. An estimation of the groundwater flow velocity is important to understand the transport of chemicals in groundwater. The velocity of flow can be calculated by using formula [16] (Ahmed et al., 2008):

$$V = Q/A \qquad [16]$$

Here the flow is limited to the pore space only so the average interstitial velocity as given in [17] where Φ is the porosity:

$$V = Q/A * \Phi \qquad [17]$$

Groundwater flow through various types of rock depends on permeability and the prevailing hydraulic gradient of the medium. Thus the flow of groundwater may be laminar or turbulent. In laminar flow (viscous or streamline flow), the flow lines are parallel and the flow occurs at very low velocities where the velocity of flow proportional to the first force of the hydraulic gradient (Singhal & Gupta, 2010). Normally, water moves very slowly through the land and the laminar flow is dominant. In this type of flow, the water particles usually flow in ribbon like patterns through the pore openings, although water moving in the center of the pores moves faster than the water that exists close to the walls. There is no intermixing of individual water layers (Fig. 2.23) (Sterrett, 2007). The turbulent flow is distinguished by high velocities and the creation of eddies. Sometimes, turbulent flow takes place near wells and other points where big volumes of water must get together through tight openings. In turbulent flow, individual water particles intermix and follow irregular ways through the pores (Fetter, 2001).

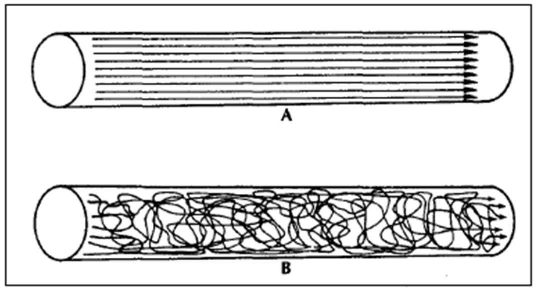


Figure 23. Schematic representation of laminar flow (A) and turbulent flow (B) (Sterrett, 2007).

It is possible to determine whether flow will be laminar or turbulent through the Reynolds number (R_e), which is a dimensionless number that is a ratio of inertial forces to viscous forces. For groundwater flow, the Reynolds number connects the dimension of the flow space and density, velocity, and viscosity of a moving liquid. For R_e < 2000 flow is laminar and for R_e ≥ 2000 turbulent flow is gradually arise, becoming completely turbulent at R_e = 10000 (Dreybrodt, 1988). The Reynolds number given as [18]:

$$R_e = v * d * \rho / \mu \qquad [18]$$

Where

ρ is the fluid density (M/L^3; kg/m^3)

v is its velocity(L/T; m/s)

µ is the dynamic viscosity of the fluid (M/T*L; kg/m*s)

d is a pore diameter or grain size (L; m)

2.7.2. Groundwater flow in fractured rocks

All consolidated and unconsolidated subsurface materials are fractured to some extent. The scales of fractures range from micro-cracks to crustal rift. Fracture zones may be areas of preferential flow but may act as barriers as well. When containing material that is more permeable than the host rock, fractures allow groundwater to flow (Neuman, 2005).

The flow in fractured aquifers is hard to analyze for various reasons, the most important is the flow occurs along a separate fractures, therefore the distribution and properties of which are mostly indistinct, and it is not possible to draw a map the location and orientation of the fractures which contain a water in the subsurface, or to know their width and length. Also because the flow in some larger fractures is turbulent instead of laminar, for that it is not possible to apply Darcy's law to these kind of flow (e.g., Fitts, 2013).

Fractured aquifers include fracture zones and porous media (double porosity). Fracture zones are distinguished by low porosity but great lateral continuity. But the porous matrix has greater porosity and shorter spatial continuity. Also fractures form the main way for groundwater flow and provide high conductivity conduits with fast hydraulic flows. On the other hand, blocks include most of the storage and serve as a source to fractures. For that fractured reservoirs is more important from that of the traditional reservoirs which composed only from inter-granular porosity and permeability (Altinors & Önder, 2008). Thus, the fluid is transferred between fractures and matrix, not between any two matrixes or blocks, and the connections between rock fractures and their width and length constitute the extent of porosity and permeability of such fracture rocks.

In comparing between the flow velocities in fracture and porous matrix, the flow velocities in the fracture are faster than the flow in porous rock matrix which makes the potential for mass and heat to be transferred through the rock relatively quickly (Kumar, 2012).

The fractures which are not filled with weathered materials constitute potential path for groundwater movement and their permeability is decreased when filled with weathered. These filling materials affect the flow of fluid from the fractures into the porous matrix (Ahmed et al., 2008).

2.8. Groundwater quality

Water quality is one of the fundamental aspects of all water resources and groundwater resources. It refers to the suitability of water for various types of uses, which differ in their criteria. The natural composition of groundwater expresses the original composition of the recharge water, the mineral composition of the underground zone and the climate; for this reason water quality depends on the lithology of aquifer, climatic conditions, sources of recharge and its residence time (Margat & Gun, 2013). Water quality is affected by changes in nutrients, pH, heavy metals, non-metallic pollutants, sedimentation, temperature, persistent organics and pesticides, biological factors, and many other contaminants which lead to deteriorate the quality of groundwater. Thus the quality of groundwater is evaluated through its chemical, physical and biological properties (Marsalek et al., 2006).

To ensure water is potable, it is necessary to monitor the water by chemical analysis, which should be done regularly to verify water quality, evaluate the effects of agriculture, industry and other human activities and estimate the consequences of contamination and pollution (WHO, 2011).

2.8.1. Water quality standards

Guidelines for reuse and drinking water quality are dependent on scientific research results. Therefore they develop guidance for making risk management decisions related to the preservation of the environment and the protection of public health. Water quality standards are legal issues developed by laws and regulations which are established by countries that provide guidelines to their national priorities and taking in account their technical, cultural, economic, social, and political properties. There are a lot of examples are shown in order to distinguish between standards and guidelines, and to show how countries have been adjusting with WHO guidelines to their conditions in order to develop national standards on drinking water quality, and for the use of treated sewage water for irrigation of crops (Hespanhol & Prost, 1993).

The Guidelines for Drinking-water Quality (WHO, 2011) offer a main base for derivation of standards for waters and development of drinking-water quality standards and guidelines, in addition for the development of legislations for protection of drinking-water sources, treatment and distribution of clean drinking-water. The approach followed in these guidelines is intended to lead to national standards and regulations that can be easily implemented and enforced and are protective of public health (WHO, 2011). Although the guidelines describe a quality of water which is consumable for lifetime, the establishment of these guidelines, including guideline values, should not be considered as implying that the quality of drinking-water may be deteriorated to the recommended limit. Drinking water standards as prescribed by Environmental Protection Agency (USEPA) and World Health Organization (WHO) are given in Table. 7. Table. 8 synthesizes the physical, chemical and biological parameters of groundwater.

Table 7. Comparison of upper limits of various constituents in drinking-water, between Environmental Protection Agency and World Health Organization (Singhal & Gupta, 2010).

Parameters	Environmental Protection Agency (USEPA)	World Health Organization (WHO) standards
pH	6.5 – 8.5	6.5 – 8.5
Total hardness, mg/l	---	500
Calcium, mg/l	---	75 - 200
Magnesium, mg/l	---	---
Chloride, mg/l	250	250
TDS mg/l	500	1000
Iron, mg/l	0.2	0.3
Fluoride, mg/l	4.0	1.5
Nitrate, mg/l	44	50
Sulfate, mg/l	250	400
Sodium, mg/l	---	200
Zinc, mg/l	5.0	5.0
Arsenic, mg/l	0.01	0.01
Copper, mg/l	---	0.1
Mercury, mg/l	0.002	0.001
Cadmium, mg/l	0.005	0.003
Turbidity (NTU)	5 - 10	10

Table 8. Physical, chemical and biological quality parameters of groundwater (Harter, 2003; Carr & Neary, 2008; Palaniappan et al., 2010; Olumuyiwa et al., 2012; WHO, 2011).

Quality properties	Parameters	Units	Origin and undesirable effects produced
Physical quality parameters	Color	OU_E/m3	1. The color in water is derived from the presences of colored substances such as humic, which originate from the decay of vegetation and dissolved roots and leaves. 2. Inorganic compounds such as iron and manganese also give water a red and blue color respectively by the influence of bacteria, which oxidize both of them to their ferric and manganic oxides respectively.
	Odor and Taste	TCU	Odor and taste found in water as a result of the presence of decomposed organic matter, algae, dissolved gases, and industrial waste.
	Turbidity	NTU	1. Caused by the presence of clay, silt, organic and inorganic matter, colloidal particles, and plankton and other microorganisms in the medium. 2. Turbidity of water has undesirable effects on the color. 3. Creates a suitable environment to the microbial proliferation and forms complexes of turbidity which are caused by humic substances and heavy metals.
	Temperature	ºC	1. High water temperatures promotes the growth of microorganisms and effects on metabolic rates in aquatic organisms, where the warmer water has less oxygen, which hinders the metabolic function. 2. High water temperature may increase problems related to taste, odor, color and corrosion. 3. Effects on the chlorination process and purification of water, where the sterilization of water takes longer when water is colder.
Chemical quality parameters	pH	Sörensen scale	1. pH standard was established to guarantee purification, treatment and disinfection with high quality. 2. Influences the taste and odor of a substance and also the amount of chemicals needed for suitable disinfection, and the ability of an analyst to detect contaminants. 3. A range of industrial activities, mining, and power plants in addition to acid rain can cause acidification of freshwater systems and release large quantities of nitrogen and sulfur oxides, which lead to pollute the groundwater.
	Total Dissolved Solids (TDS)	mg/l	1. Includes organic materials and inorganic salts (calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulphates). 2. Comes from sewage, effluent discharge, and urban runoff, and also from the rock when the water takes place in the pores or fractures. 3. Leads to increase concentration of certain constituents in the groundwater.
	Total Hardness (TH)	mg/l	1. Measure of the ability of water in forming lather with soap. 2. Calcium and magnesium are the main ions responsible for hardness, although iron and manganese may also contribute. 3. Groundwater is usually harder than surface water because of its high possibilities for dissolution, especially for rocks which contain gypsum, calcite and dolomite. 4. May have origin from sewage and runoff from soils especially limestone formations, building materials including calcium oxide and textile and paper substance containing magnesium.
	Chloride (Cl^{-1})	mg/l	1. Occurs in groundwater due to saline leaking, pumping brine in oil well operations, agricultural runoff, sewage flow, natural salt deposits and waste percolating. 2. May produce an undesirable taste in water even in low concentrations.
	Sulphate ($SO4^{-2}$)	mg/l	1. Occurs in groundwater due to dissolution of sulfur. 2. Its presence in drinking-water can cause undesirable taste, and great concentrations, which come from coal mine drainage, tanneries, textile factories, and domestic waste water, might cause a laxative effect in consumers.
	Fluoride	mg/l	1. May have origin from industrial and domestic discharges, and in groundwater sources with higher concentrations.

	(F^{-1})		2. In groundwater, fluoride concentrations change with the type of rock where the water takes place through but do not usually exceed 9-10 mg/l. 3. The fluoride is useful when exist in small concentration (0.8–1.0 mg/ l) in drinking water for calcification of dental enamel but it causes skeletal fluorosis if found in higher concentration.
	Iron (Fe^{+2})	mg/l	1. Occurs in water in its ferric and ferrous states, especially in full gaseous conditions. It also exists in mines waste, percolation of landfill, sewage, and industries discharges. 2. Its presence in drinking-water may cause problem when the iron exists in large concentrations; in drinking-water is usually less than 0.3 mg/l. 3. It provides bad color and taste and it also forms turbidity when exposed to air due to its conversion into ferric states. 4. Dissolved iron with time can also change into an insoluble mud which causes plugging of pipes, valves and water meters.
	Trace metals	µg/l	1. Trace metals, such as arsenic, zinc, copper, and selenium, are actually found in many different sources of water. 2. Some human activities like mining, industry, and agriculture can cause an increase in crowd of these trace metals outside of soils or waste products into fresh waters. 3. Even at extremely low concentrations, such additional materials can be toxic to aquatic organisms or can reduce reproduction and other functions.
	Nitrate ($NO3^{-1}$)	mg/l	1. May occur in surface water and groundwater as a result of agricultural activity, increasing use of artificial fertilizers, sewage and from oxidation of nitrogenous waste products in human and animal waste. 2. It is possible for surface water nitrate concentrations to change quickly because of surface runoff of fertilizer, uptake by plant plankton and de-nitrification by bacteria. 3. Groundwater may also have nitrate contamination as a result of percolating water from natural vegetation.
	Sodium (Na^{+})	mg/l	1. It is found in virtually all food and drinking-water. It concentration in potable water is typically less than 20 mg/l. 2. When sodium concentrations exceed 200 mg/l may give rise to unacceptable taste.
	Potassium (K^{+})	mg/l	1. An essential element in humans and is seldom, if ever, found in drinking water at levels that could be a concern for healthy humans. The recommended daily requirement is greater than 3000 mg. 2. Occurs widely in the environment, including all natural waters. It can also occur in drinking-water as a consequence of the use of potassium permanganate as an oxidant in water treatment.
Biological quality parameters	Actinomycetes Fungi Cyanobacteria Algae	----	1. Affect the validity of water and refer that the treatment of water are not suitable and they produce taste and odor in the water. 2. The highest risk that has effects on the groundwater quality is contamination by sewage, human and animal excreta which constitute the biological parameters of groundwater quality.

2.9. Groundwater contamination

The real meaning of contamination is defined for any addition of solute into the hydrological system as a result of Human's activity where the contamination exceeds levels that are considered to be undesirable (Freeze & Cherry, 1979; Chapman, 2007). There are an infinite number of sources of groundwater contamination that lead to decrease groundwater quality (Fig. 24), (Foster et al., 2002; Fetter, 2008).

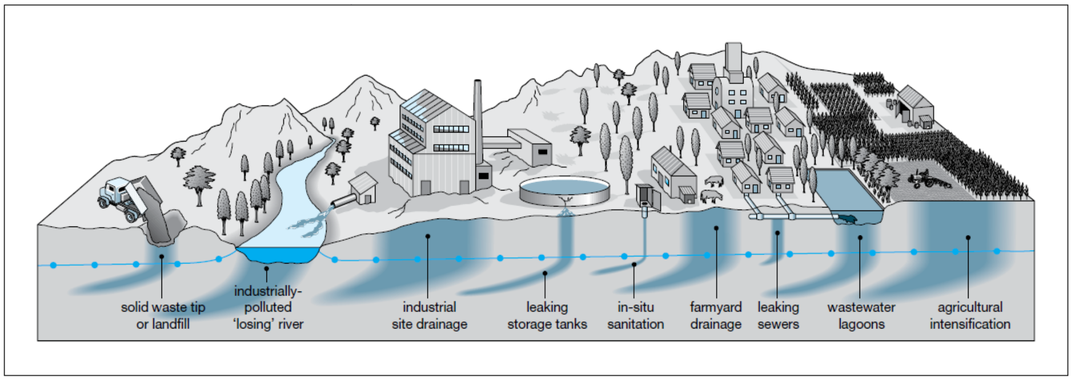


Figure 24. Common processes of groundwater pollution (Foster et al., 2002).

Groundwater contamination may have the following sources (e.g., Zaporozec, 2004; Fetter, 2008):

- Geogenic sources: usually due to this type of contamination increased concentration of toxic substances, fluoride, chromium, arsenic, iron and other heavy metals in groundwater;
- Anthropogenic sources: as a result of industrial activities, municipal waste and agricultural activities;
- Radioactive waste disposal: this include mining, milling and refining of uranium ore, fuel fabrication and fuel consumption in reactors, waste solidification and burial of solidified waste;
- Organic contaminants: the most common organic contaminants are the petroleum hydrocarbons which do not cause significant risk because of their lower aqueous solubility and toxicity. However, halogenated hydrocarbons are of greater concern due to their stability and toxicity (Kehew, 2001). Most of the organic compounds are mixed in water with limited dissolution between aqueous and organic phases. Such liquids are known as non-aqueous phase liquids (NAPLs). If the density of NAPL is less than that of water, the liquid is classified as a light non-aqueous phase liquid (LNAPL), like petroleum products (acetone, gasoline, kerosene and benzene). If the density of NAPL is greater than that of

water, it is classified as dense non-aqueous phase liquid (DNAPL), like phenol, coal tar and chloroform;

- Miscellaneous sources of groundwater contamination: like deforestation, over-irrigation, oil leaks and spills, road salts, sewage sludge, urban runoff, thermal power plants, deep well disposal of liquid waste, and sea-water intrusion.

Contamination sources may exist as point sources or diffuse sources (non-point) depending on the nature and source of the pollutant and on the nature of the groundwater system. At point sources, the contaminants are confined to a limited zone of well-defined dimensions, like sites for solid waste, leaking petrol station tanks, or injection wells. At diffuse sources, the contaminants extend over larger distances, like the pollutants in a river, a road, a leaking pipeline, and agricultural contamination (Zaporozec, 2004). However, it is very difficult to determine every single source of groundwater contamination and also very difficult to quickly restore the resource to be usefully utilized (Kresic & Mikszewski, 2013). The main sources of groundwater contamination and the character of sources are represented in Table. 9.

Contamination of the subsurface environment may occur through a variety of mechanisms: infiltration, recharge from surface water, direct migration, and inter-aquifer exchange. The first and second mechanisms affect directly on the surface aquifers, the third and fourth affect surface or deep aquifers (EPA, 1994).

The possibility of a contaminant to decrease groundwater quality is dependent upon its ability to move through the overlying soils to the bearing layers of groundwater and groundwater resource. Actually, groundwater contamination is discovered after a long time of occurrence. The reason for this delay in the detection of groundwater contamination is due to the slow movement of groundwater through aquifers (EPA, 1994). There are many factors that influence the movement of groundwater like the type of geological formation and its properties especially permeability, the infiltration, the rainfall, and the hydraulic gradient. The presence of geological fractures, faults, and channels also influence the movement of groundwater and contamination.

Generally, the pollutants move vertically downward towards the water table. Before reaching the water table and in the unsaturated zone (vadose zone), attenuation of contaminant will happen as some chemicals are adsorbed on clay minerals and organic material, some are decomposed through oxidation and bacterial activity and some are used by plants or released into the atmosphere. After reaching the water table, the dissolved pollutants will be transmitted with the groundwater in the direction of its hydraulic gradient by advection (Fig. 25) (Bear & Cheng, 2010).

There are two types of hydrodynamic: the longitudinal dispersion which takes place in the direction of flow, and the transverse dispersion which takes place normal to the direction of flow. The concentration of pollutants in groundwater decreases with the increasing distance of flow from the source, due to hydraulic dispersion and other attenuation effects. The spread of the solute in the direction of flow will be larger than in the vertical direction on the flow, generally the longitudinal dispersivity is more than the transverse dispersion (Singhal & Gupta, 2010).

Table 9. Major sources of groundwater contamination (Zaporozec, 2004).

Category	Source type	Usual character	Normal location
Natural sources	Inorganic substances	Not applicable	Not applicable
	Trace metals		
	Radionuclides		
	Organic compounds		
	Microorganisms		
Agriculture and forestry	Fertilizers	Diffuse	Surface
	Pesticides	Diffuse	Surface
	Animal waste	Diffuse/point	Surface/unsatured zone
	Animal feedlots	Point	Surface
	Irrigation return flow	Diffuse	Surface
	Stockpiles	Point	Surface
Urbanization	Solid waste sites	Point	Surface/unsatured zone
	On-site sanitation	Point	Surface/unsatured zone
	Wastewater, effluent	Point and line	Surface/unsatured zone
	Salvage and junk yards	Point	Surface/unsatured zone
	Leaking underground storage tanks	Point	Unsaturated zone
	Runoff, leaks, spills	Line and point	Surface
Mining/Industry	Mine tailings	Point	Surface/unsatured zone
	Mine water	Point and line	Various
	Solid waste	Point	Surface/unsatured zone
	Wastewater, effluent	Point and line	Surface/unsatured zone
	Injection wells	Point	Below water table
	Spills, leaks	Point	Surface
Water mismanagement	Well-field design	Point	Below water table
	Upcoming	Point	Below water table
	Seawater intrusion	Line	Below water table
	Faulty well construction	Point	Below water table
	Abandoned wells	Point	Below water table
	Irrigation practices	Diffuse	Surface
Miscellaneous	Airborne sources	Diffuse	Surface
	Surface water	Line	Below water table
	Transport sector	Point and line	Surface/unsaturated zone
	Natural disasters	Point and line	Surface/unsatured zone
	Cemeteries	Point	Unsatured zone

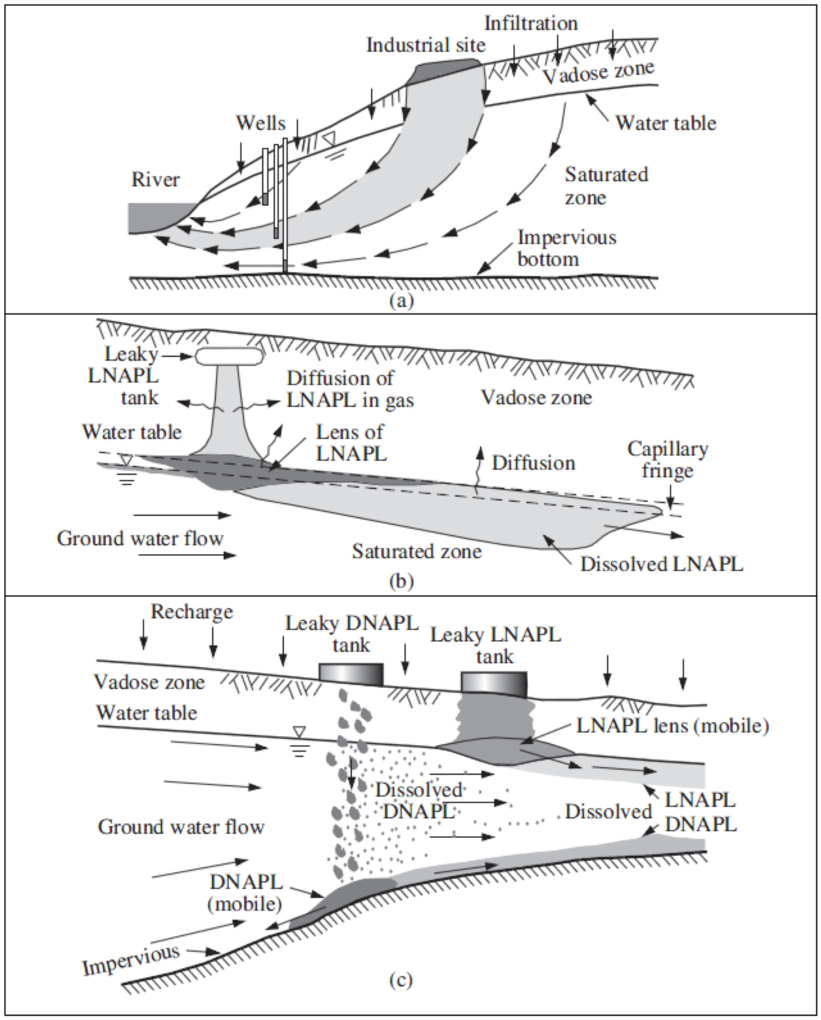


Figure 25. Typical cases of subsurface contamination (Bear & Cheng, 2010). (a) The migration of a contaminant that is leached from a landfill: the leachate travels through the vadose and then through the (saturated) aquifer, eventually draining to a river; (b) An LNAPL leaks from an underground storage tank and migrates through the vadose zone, eventually accumulating on an underlying water table; (c) Different routes through which a DNAPL and an LNAPL can contaminate an aquifer.

In fractured porous rocks, the main mechanisms of transport of solutes are by advection, hydrodynamic dispersion, radioactive or biological decay, adsorption, molecular diffusion, desorption and rock water interaction and retardation (Fetter, 2001). Most of the fractured rock aquifers have double porosity, so the mechanism of pollutants transport in fractured aquifer depends on the permeability and relative porosity of the matrix blocks and the fractures. If the rock matrix is impermeable and has negligible porosity, thus the advective transport through the fractures will be dominant. If the matrix is porous but has negligible permeability, the main mechanism in the matrix will be by molecular diffusion and transport through the rock matrix by advection will be generally intangible because of its low permeability. If the porous matrix has the same permeability as the fracture, in this case the transport of solute will take place in the same time in the fracture and matrix by advection, dispersion and diffusion depending on differences in the head and the concentration of the solutes in the fractures and the matrix (Germain & Frind, 1989, Singhal & Gupta, 2010).

The process of identifying the source of contamination accurately and following the migration of contaminants and its extent are usually complex operations. Therefore it is necessary to do comprehensive hydrogeological researches and determining the sufficient number and appropriate place of monitoring wells (Nemerow et al., 2009). Contamination influences the groundwater quality; therefore it is better to evaluate the effect of contamination on the groundwater quality as a part of water resource management. The evaluation should take into consideration the existing land-use zoning and potential development. It is necessary to rationalize water consumption, where the water of high quality, characterized by low salt content and good taste, should be used only for drinking, irrigation, and certain industries. Water with lower quality can be used for agricultural, industrial, livestock and domestic purposes except drinking and cooking (Mazor, 2004).

2.10. Groundwater vulnerability

The term ‘vulnerability of groundwater’ is derived from the assumption that the environment system may provide a certain degree of protection of groundwater against agriculture, industry and other human activities, especially with regard to contaminants which reach the subsurface environment, by ‘self-purification’ or ‘natural attenuation’. Thus the groundwater vulnerability is a measure of how easy or how difficult it is for contamination at the surface of the land to reach a producing aquifer It is not an absolute property, but a relative indication of where contamination is likely to occur (e.g., Foster et al., 2002; Schmoll et al., 2006).

Groundwater vulnerability is related to the source of contamination, pathway and receptor (water table, aquifer, or well). Where the contaminant "source" (e.g., gasoline) infiltrates into the ground and migrates downwards through the unsaturated zone along a "pathway" towards the water table. When the gasoline reaches the water table, it intersects with a "receptor". This is the groundwater vulnerability system (Fig. 26) (Jessica et al., 2009).

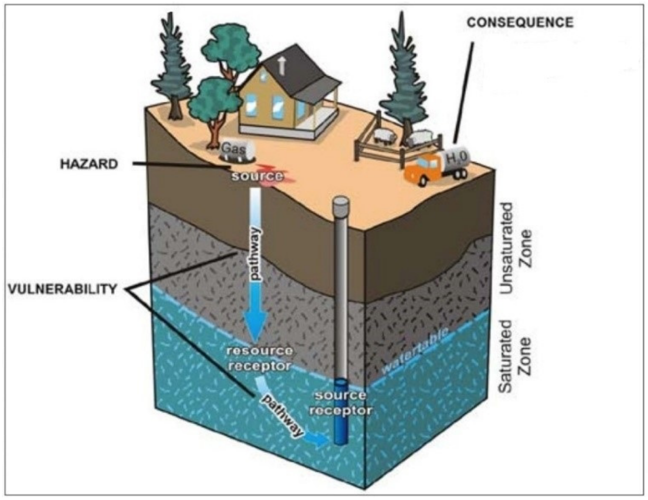


Figure 26. Source–pathway–receptor model for contaminants (NRC, 2005).

The potential for pollutants leak to groundwater which in its turn lead to groundwater vulnerability depends on different factors (CAGWV & NRC, 1993):

- The composition of soils and geologic materials in the unsaturated zone – this affects to a large extent on transitions and interactions between the rock and groundwater which lead to pollution. For example, organic matter and clay content together control the sorption potential where the clay content increases sorption and thus decreases the potential for pollution, because soils with low sorption potentials are more sensitive to groundwater contamination than soils with high sorption potentials (Huddleston, 1996);
- The leaching potential controls groundwater vulnerability, being the soil with high leaching potentials more sensitive to pollution than soils with low leaching potentials;
- The recharge rate – affects the rate and extent of transport of pollutants through the saturated zone;
- The vulnerability of a groundwater is dependent on the solubility and subsequent mobility of the pollutant as influenced by the specific mineralogy and associated geochemical conditions within the aquifer and pumped well;
- The depth to the water table – this has an important role because short flow paths decrease the potential for sorption and biodegradation, thus increasing the potential for pollutants to reach the groundwater. Conversely, longer flow paths from land surface to the water table can decrease the potential for pollution;
- Environmental factors, like temperature and water content, can greatly influence the degradation of contaminants by microbial transformations.

Vulnerability is a function of the ease movement of water and contaminants to the underlying groundwater, the attenuation capacity of the encountered materials and the travel time of the contaminants from the surface to the aquifer (BGS, 2007). These are identified by the properties of aquifer and soil and vary with hydrogeological system settings (Table. 10).

Table 10. Hydrogeological settings and their associated groundwater pollution vulnerability (Morris et al., 2003).

Hydrogeological setting and aquifer type		**Typical travel times to water table**	**Attenuation potential of aquifer**	**Pollution vulnerability**
Major alluvial and coastal	Unconfined	Weeks – months	Moderate	Moderate
plain sediments	Semiconfined	Years – decades	High	Low
Intermountain valley-fill	Unconfined	Months – years	Moderate	Moderate
volcanic systems	Semiconfined	Years – decades	Moderate	Moderate – Low
Glacial and minor alluvial deposits	Unconfined	Weeks – years	Moderate – low	High – moderate
Loess plateau	Unconfined	Weeks – months	Low – moderate	Moderate – high
Consolidated sedimentary	Porous sandstone	Weeks – years	Moderate	Moderate – high
Aquifers	Karstic limestone	Days – weeks	Low	Extreme
Coastal limestones	Unconfined	Days – weeks	Low – moderate	High – extreme
Extensive volcanic areas	Lava	Days – months	Low	High – extreme
	Ash/Lava sequences	Months – years	High	Low
Weathered basement	Unconfined	Days – weeks	Low	High – extreme
	Semiconfined	Weeks – years	moderate	Moderate

The vulnerability of an aquifer is defined as the sensitivity of groundwater to an imposed contaminant load, and the possibility of diffusion and filtration of pollutants from the surface of the land into natural water table reservoirs, under normal conditions (e.g., Vrba & Zaporozec, 1994), (Fig. 27).

The aquifer vulnerability concept generally includes two specific terms: "intrinsic vulnerability" defined as the natural sensitivity of receptors to pollution generated by human activities based on the properties of the environment (geological, hydrological and hydrogeological), independently of the nature of pollutants, and "specific vulnerability" that represents the groundwater vulnerability to contamination through the contamination properties and their relationship with the components of the environment.

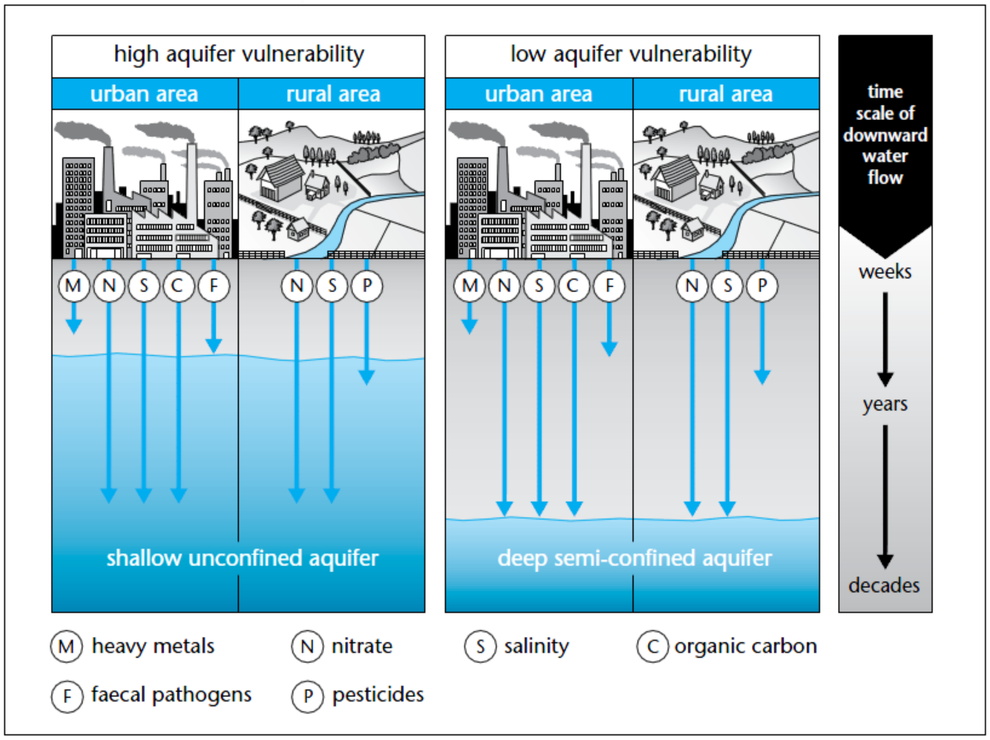


Figure 27. Significance of contrasting aquifer pollution vulnerability (Foster et al., 2002).

There are two main factors considered to determine aquifer pollution vulnerability: the inaccessibility of the saturated zone, in a hydraulic sense to the infiltration of contaminants and the attenuation capacity of the strata overlying the saturated zone due to physical and chemical retention or reaction of contaminants. These components of aquifer vulnerability interact with the components of subsurface contaminant loading which are the mobility and persistence of pollution and the mode of contaminant disposition in the subsurface especially, the magnitude of any hydraulic loading.

Commonly it is used the interaction between hazard from contaminant load and aquifer vulnerability to identify the risk of contaminants reaching the aquifer (Fig. 28) (Foster & Hirata, 1988).

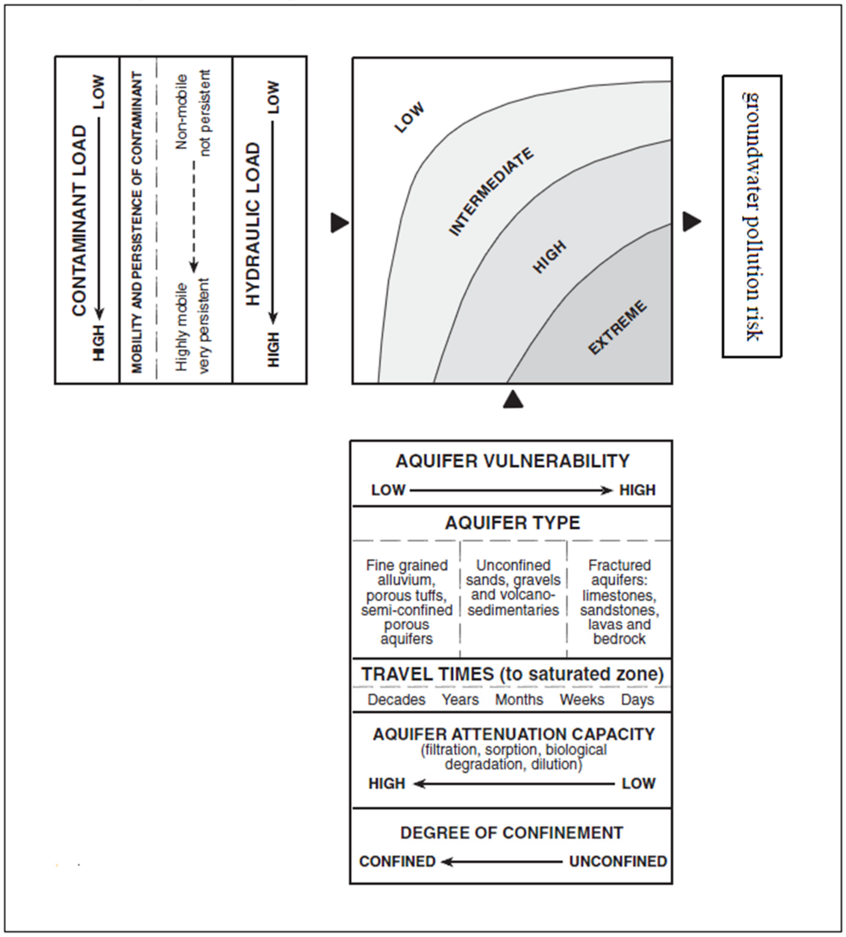


Figure 28. Conceptual scheme of groundwater pollution risk (Morris et al., 2002).

Groundwater vulnerability is an important issue all over the world arising from the decline the water table of groundwater and increasing pollution which represent a real risk to the environment. Therefore it is possible to determine protection zones from the vulnerability and to assess the groundwater vulnerability by using several methods. Some common overlay and index methods are DRASTIC, SEEPAGE, SINTACS, GOD, GOD-S, DISCO and EPIK (e.g., Gogu & Dassargues, 2000; Shirazi et al., 2012).

2.10.1. Fractured aquifer vulnerability

A vulnerability of groundwater is necessary to delineate groundwater protection zones around springs in fractured aquifer, because it takes into consideration the anisotropy of hydraulic conductivities, the heterogeneity of the aquifer and the variety of hydrogeological conditions which exist in fractured aquifers and provides suitable solutions for each type of them (Pochon et al., 2008).

Extreme vulnerabilities are associated with highly fractured aquifers with a shallow water table as they offer little chance for contaminant attenuation. In fractured aquifer where groundwater flow is easy and relatively rapid, contamination may become more widely dispersed (Morris et al., 2003). Generally, attenuation in the unsaturated zone occurs at much higher rates in the biologically active soil zone, due to its higher clay and organic contents, and large microbial populations. Attenuation is possible to take place in some fracture systems, especially when the soil can easily be bypassed or the soil may be absent (Robins, 1998). It is important to dismiss attenuation in unsaturated fracture systems because of the speed of groundwater transport from surface to water table. In some cases attenuation can occur in the soil and continue to dilated fractures under the soil. When the soil contains some organic carbon, this provides an active zone for ion exchange and sorption to occur in this soil (Witkowski et al., 2007).

Typical classes of vulnerability are shown in Table. 11 which extreme vulnerability describes highly fractured rocks with a shallow water table and low attenuation potential of aquifer.

Table 11. Classification of aquifer vulnerability (Robins et al., 2006).

Vulnerability class	Definition
Extreme	Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
High	Vulnerable to many pollutants except those highly absorbed and/or readily transformed
Low	Only vulnerable to the most persistent pollutants in the very long term
Negligible	Confining beds are present and prevent any significant vertical groundwater flow

The aquifers are classified on the basis of their permeability, into Major, Minor and Non-Aquifers:

- Major aquifers: are characterized by high permeability and fractures, therefore they are highly vulnerable to pollution, because the fractures increase vertical permeability which affect the rate of recharge and decrease the amount of pollution attenuation, also because the vulnerability is assessed on the basis of the vertical transport of pollutants to the water table, where the groundwater flow is predominantly through fracture (Robins, 1998).
- Minor aquifers: include potentially fractured rocks, which have a low permeability and other formations of low permeability including unconsolidated deposits, thus it is less susceptible to contamination in comparing with major aquifers (Fritch et al., 2000).
- Non-aquifers: are not considered to be at risk of pollution given their negligible permeability and potential for limiting the transport of pollutants from diffuse sources (Lake et al., 2003).

2.10.2. Groundwater vulnerability assessment

Vulnerability assessment of groundwater is not a property that can be directly measured in the field. It is a term based on the principle that some areas are more vulnerable to groundwater pollution than others. Groundwater vulnerability assessments aim to determine zones at a high risk of being contaminated, to estimate the risk of an aquifer to be contaminated from any sources (e.g., Vrba & Zaporozec, 1994; Gemitzi et al., 2005).

Groundwater vulnerability assessments are a tool to integrate the hydrogeological information into a form useable by decision and legislation makers, technical experts, planners and geoscientists. Moreover it permits to identify the prioritize zones for more investigation, surveillance and protection. In integrated water resource management, the vulnerability assessments are incorporated into a program of groundwater characterization and risk analysis, with serial approaches for hazard potential, risk and assessing vulnerability (Jessica et al., 2009).

In general, the assessment of vulnerability to groundwater pollution is based on the potential contaminant attenuation capacity from surface to the water table or to the aquifer and the travel time of contaminants percolating through the vadose zone from the ground surface to the water table. The greater travel time refers to more potential for pollutant attenuation, thus the lower vulnerability (Collin & Melloul, 2003).

The majority of the aquifer vulnerability assessment methods consider a homogeneous and isotropic aquifer. Moreover, vulnerability assessments are performed with respect to source of contaminants at the surface, transferring downwards through the unsaturated zone towards the water table or laterally through the saturated zone by several critical parameters: depth to water table, soil properties, recharge of the aquifer, hydraulic conductivity, topography, degree of confinement, and impact of the vadose zone (Schmoll et al., 2006).

It is possible to assess of groundwater supply pollution hazard by combining the supply protection perimeters on the aquifer vulnerability, then relating the zones and defined to summary maps derived from the inventory of potential subsurface contaminant load (Fig. 29).

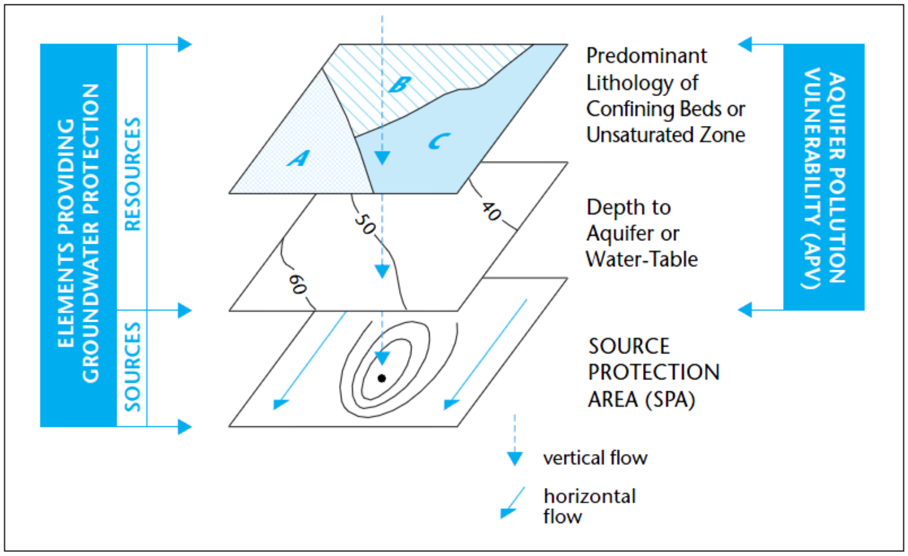


Figure 29. Components of groundwater pollution hazard assessment used for groundwater protection land surface zoning (Foster et al., 2002).

Therefore, three basic approaches can be distinguished in the assessment of groundwater vulnerability to contamination in relation to groundwater protection (Gogu & Dassargues, 2000):

i. Vulnerability assessment taking into account only the soil and unsaturated zone without the transport processes in the saturated zone. In this case, the assessment is limited to the relative probability that great concentrations of contaminants reach the saturated zone;
ii. Vulnerability assessment taking into account groundwater flow and contaminant transport processes within the saturated zone to some extent and it based on delineation of protection zones for groundwater supply systems;
iii. Vulnerability assessment taking into account the soil and unsaturated zones in addition to the aquifer.

2.10.3. Groundwater vulnerability maps

Vulnerability mapping is the suitable technique of assessing the geological and hydrogeological factors with potential groundwater for contamination in the specific area and displaying it on a map in a way that is easy and useful (Daly & Warren, 1998). Aquifer vulnerability maps aim to giving a first indication of the potential groundwater contamination risk to help planners, technicians and developers to make better judgments on new developments and giving priority for groundwater quality protection and monitoring (Robins, 1998). Thus vulnerability maps have becoming an important part of groundwater protection systems and a valuable tool in environmental management and groundwater pollution hazard assessment.

Vulnerability assessment and mapping were created by using a simple index and overlay system, which was combined with potentially polluting activity (Fig. 30). Based on subdividing the research zone into several hydrogeological units with different degree of vulnerability depending on several critical parameters: depth to water table, soil properties, hydraulic conductivity, thickness and composition of soil and vadose zone, etc. (Faybishenko et al., 2015).

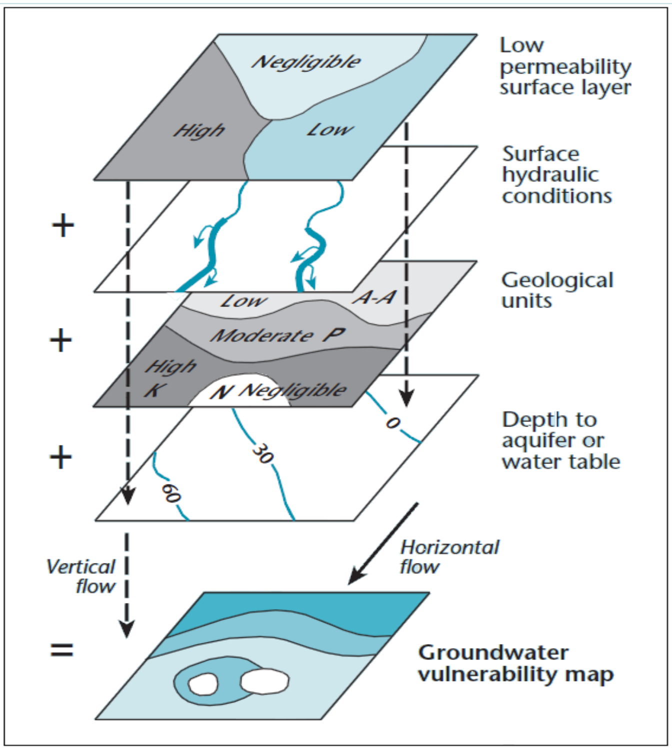


Figure 30. Combining factors to make a vulnerability map (Morris et al., 2003).

Essentially, there are two types of vulnerability maps (Witkowski et al., 2007):

i. **Intrinsic vulnerability maps** which are used to assess the intrinsic groundwater vulnerability to a public conservative pollutant;

ii. **Specific vulnerability maps** which have two main categories of maps:

- Single purpose maps: the vulnerability is assessed according to only one type of contaminant or group of contaminants but in similar characteristics;
- Multi-purpose maps: the vulnerability is assessed according to various groups of contaminants of different characteristics which have been determined in the mapped region.

Vulnerability maps can be created manually using background maps such as satellite imagery, road maps, property boundaries and topographic maps. It is necessary to involve municipalities' planning office to benefit from the main maps that previously created for other purposes (Edwards et al., 2007). Typically, vulnerability maps are created with Geographic Information System (GIS). It is a digital form of map and a powerful tool for analyzing, processing and combining spatial data sets. It can be considered as an excellent computer-coded map which allows storage, selective choice, display and output of spatial data (Singhal & Gupta, 2010). It offers a graphic image of the site of pollution sources in relation to other data elements. GIS technology has become as a useful tool for creating vulnerability maps and for simple testing of methods of display (CAGWV & NRC, 1993).
A number of hydrogeological conditions lead to some doubts for aquifer pollution vulnerability assessment and mapping (Foster et al., 2002):

- The occurrence of losing streams, because of doubts in evaluating the hydrological condition, in determining the quality of the waterway and in evaluating streambed attenuation capacity;
- Excessive aquifer exploitation for water supply uses, which lead to vary the depth of groundwater table and the degree of aquifer confinement;
- Over consolidated clays, where usually exist significant doubts about the magnitude of any preferential flow component.

2.11. Vulnerability methods

A diversity of methods has been created during the past years to assess and map groundwater vulnerability to contamination. These methods can be classified into three main categories (Harter, 2001):

- Index and overlay methods are the most suitable methods for groundwater vulnerability assessment and have been created because of the lack of monitoring information and due to the limitation to obtain more hydrogeological data. These methods depend on the quantitative or semi-quantitative compilation and interpretation of mapped data. Some common overlay and index methods are DRASTIC, SEEPAGE, SINTACS, GOD, DISCO, and EPIK;
- Process based computer simulations (modeling approaches);
- Statistical analysis.

2.11.1. GOD method

GOD method is an empirical system for the rapid assessment of aquifer pollution vulnerability, designed to map groundwater vulnerability in large areas with high vulnerability contrasts. The GOD method is based on the evaluation of three groundwater parameters (e.g., Foster et al., 2002):

G: Groundwater confinement, whether the aquifer is unconfined, confined, or semi-confined;

O: Overlying layers (vadose zone or confining beds), in terms of grade of consolidation and lithological character;

D: Depth to groundwater table or to groundwater strike in confined aquifers.

The GOD vulnerability index I_{GOD} which is used to assess and map the aquifer vulnerability is calculated by the following formula [19]:

$$I_{GOD} = I_G * I_O * I_D \qquad [19]$$

The range of values for each parameter in this formula is short and varying from 0 (minimum vulnerability) to 1 (maximum vulnerability). I_G is the groundwater occurrence which take values from 0 – 1, I_O is the overlying layers which take values ranging between 0.4 – 1.0 and I_D is the depth to groundwater table which take values ranging between 0.6 – 1.0 (Fig. 31). The final integrated aquifer vulnerability index is the product of component indices for these parameters.
Pascal (2008) considers that some limits should be considered when applying the GOD method:

- this method does not taking into account the soils in an agricultural sense. However, most of the processes causing pollutant attenuation in the unsaturated zone occur at much higher rates in the biologically active soil zone, due to its higher clay and organic contents, and large microbial populations;
- this approach are not always measurable; therefore it is necessary to choose empirical value sometimes. In this way, the result can represent at an approximate reality but typically, it does not interprets the real phenomenon;
- in urban regions the soil is often absent due to process of construction or the subsurface pollutant load is applied below its base in excavation work, thus the soil zone should be assumed not exist and the uncorrected hydrogeological vulnerability used.

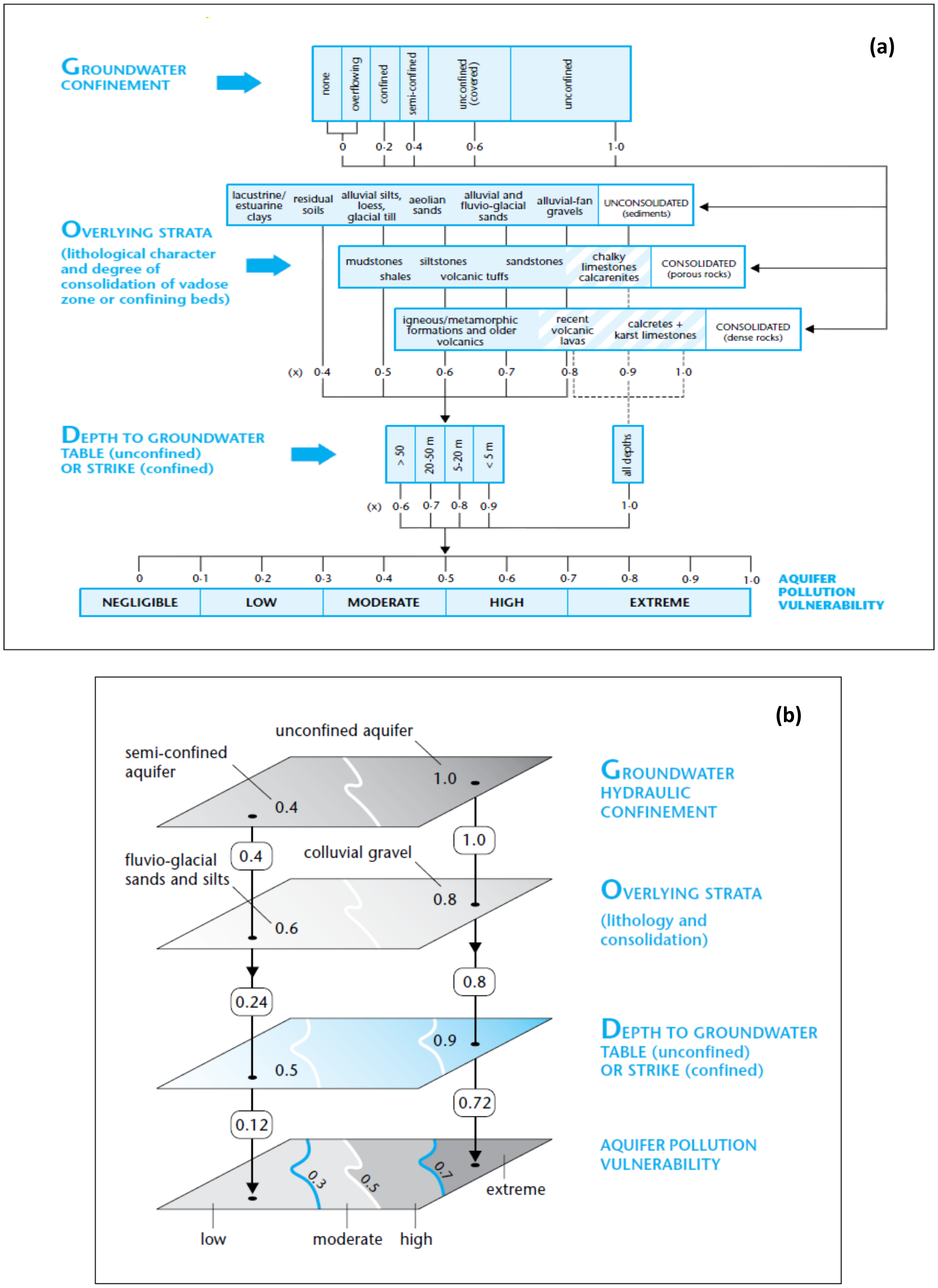


Figure 31. (a) GOD system for evaluation of aquifer pollution vulnerability; (b) Generation of aquifer pollution vulnerability map using the GOD system (Foster et al., 2002).

Because of the limits associated with the GOD method, this method has been developed to the GOD-S which includes a soil leaching susceptibility index, as an addition step able to reduce the overall ranking in some zones of high hydrogeological vulnerability. The GOD-S method involves assigning values of (S) according to the textural properties of the soil, which range from very fine (predominantly clayey) to very coarse (gravelly), in regions where this is more than 0.5 m thick (Fig. 32). Thus, the GOD-S vulnerability index is an evolution of GOD index, considering soil media properties (Foster et al., 2002).

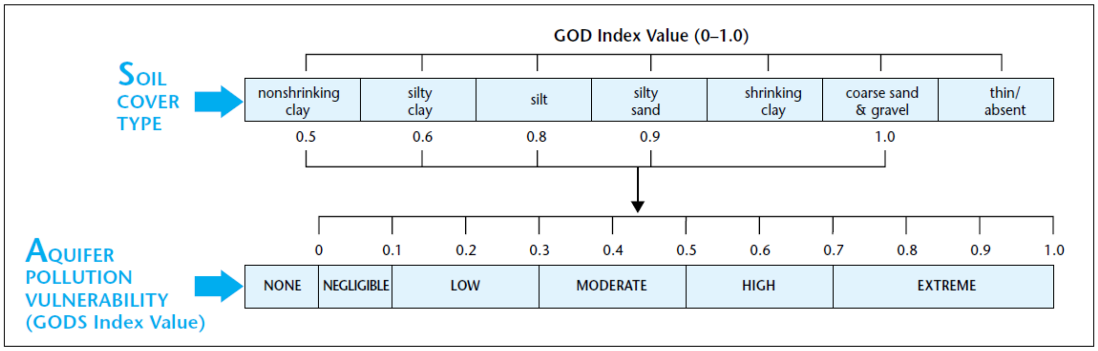


Figure 32. GOD-S system for evaluation of aquifer pollution vulnerability (Foster et al., 2002).

2.11.2. DRASTIC and DRASTIC-Fm methods

The DRASTIC method is a simple tool of assessing the susceptibility of certain regions to contaminants in regional scale (Aller et al., 1987). It determines groundwater vulnerability of aquifer depending on available data for a site, aquifer type, soil type, topography, water table and recharge using hydrogeological setting. However, it does not have any absolute value, but provides a value to assess relative vulnerability (Delleur, 2007). The DRASTIC method has the advantage of selecting the important variables and their relative importance depending on the existence of pollutants in groundwater in a given region. As well as, it is applicable in humid and arid to semi-arid climates. DRASTIC uses seven parameters to compute vulnerability index, which ensures the best presentation of hydrogeological settings (Fig. 33):

D: Depth to the water table

R: Recharge

A: Aquifer material

S: Soil type

T: Topography

I: Impact of the unsaturated zone

C: Hydraulic Conductivity

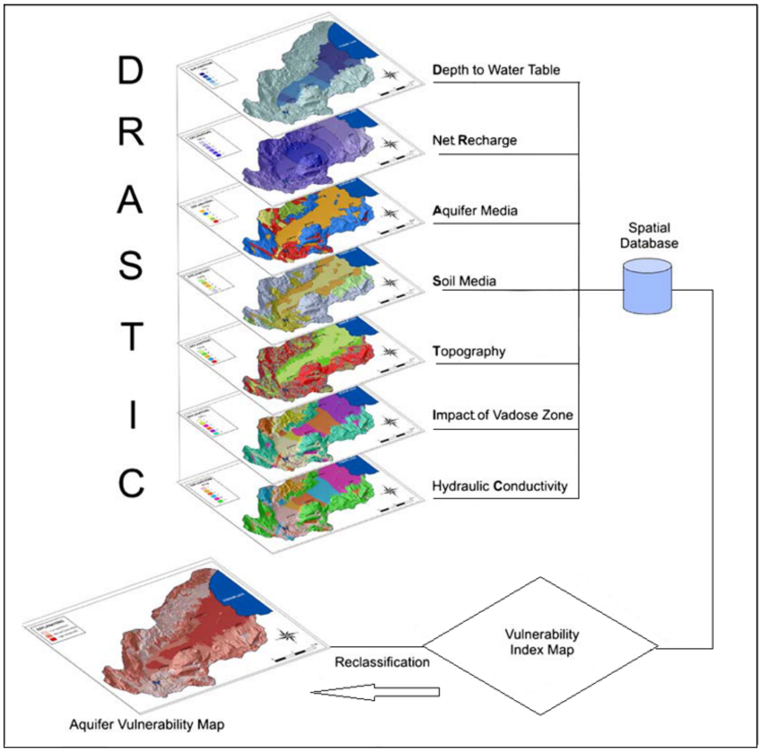


Figure 33. Schematic methodology of DRASTIC (Sener et al., 2009).

The DRASTIC vulnerability index is determined as a sum of seven rating indicators (D, R, A, S, T, I, C), being r_1 *to* r_7 the rating values and r_1 through r_7 the weight factors, computed by the formula [20] (Aller et al., 1987):

$$I_{DRASTIC} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \qquad [20]$$

The DRASTIC vulnerability index is important for the relative degree of groundwater vulnerability of an area. Where higher index value refers to the greater possibility of contamination to move through the unsaturated zone to the water table. Thus, refer to the high vulnerability in the area (Shirazi et al., 2012). In this index eight vulnerability classes are considered according to the degree of vulnerability, < 80, 80-100, 100-120, 120-140, 140-160, 160-180, 180-200 and > 200.

There are two weight categories for DRASTIC index, one for normal conditions and another for agricultural usage this one called pesticide DRASTIC (Table. 12). The weighting difference between the pesticide DRASTIC and the standard DRASTIC depending on the origins of the considered contaminants: in the normal one the contaminants are inorganic and in the second they are organic (Witkowski et al., 2007).

Different weighting factors for pesticides have typically less variability and more stability in the environment, and all parameters of DRASTIC are classified together as non-pesticides, except the impact of the vadose zone (I) and hydraulic conductivity (C) to the soil media (S) and topography (T) where the weighting is shifted away from them (Engel et al., 1996; Delleur, 2007).

Table 12. Weights of the factors in the DRASTIC pesticides and DRASTIC standard models (Aller et al., 1987).

Factor	Normal DRASTIC	Pesticide DRASTIC
Depth to the water table	5	5
Recharge	4	4
Aquifer material	3	3
Soil type	2	5
Topography	1	3
Impact of the unsaturated zone	5	4
Hydraulic Conductivity	3	2

Through this method it is also possible to develop the results in order to assess the risk of contamination which represent a real risk to the environment, thus it is necessary to do protection measures with the results of the vulnerability (Fig. 34) (Abdelmadjid & Omar, 2013).

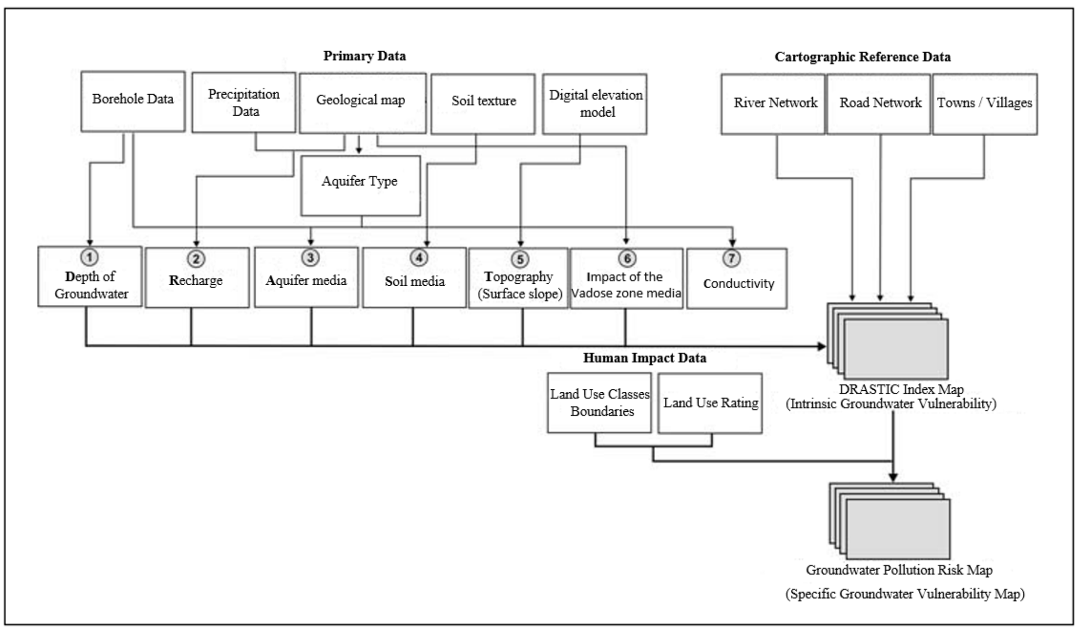


Figure 34. Schematic representation of the processes used to determine DRASTIC intrinsic vulnerability map and groundwater pollution risk map (Panagopoulos et al., 2005).

DRASTIC-Fm method is another approach (Denny et al., 2007). It is a modified version of DRASTIC and has been developed for fractured aquifers and includes an additional eighth parameter, the so-called fractured media, Fm.

The fractured media takes into account three basic properties that dictate the impact of a fracture network: orientation, length and fracture density (Denny et al., 2007; Singhal & Gupta, 2010; Shirazi et al., 2012; Teixeira et al., 2015):

- Fracture orientation: the orientation of faults and fractures are the basis of determining whether a fault or fracture acts as a hydraulic conduit or barrier to groundwater contamination;
- Fracture length: the length of a fracture determines whether it is a regional or discrete structure. Regional structures often include several fracture intersections, and this can increase to a large extent the hydraulic conductivity of a fault or fracture. By GIS the lengths of all fractures can be calculated and assigned DRASTIC-Fm ratings;
- Fracture density: fracture density may increase with proximity to known faults.

The vulnerability index is given by the formula [21] (Denny et al., 2007), where *r* and *w* has the same meaning of DRASTIC and the weight for Fm is 3. The same vulnerability classes of DRASTIC are assigned to this method.

$$D_rD_w + R_rR_w + A_rA_w + S_rS_W + T_rT_W + I_rI_w + C_rC_w + Fm_rFm_w \qquad [21]$$

2.11.3. SINTACS method

The SINTACS method is mainly derived from the DRASTIC method and has been created for vulnerability assessments and mapping in medium and large scale maps (e.g., Civita & De Maio, 2000; Civita, 2010). This method is much more effective in detailed studies and can offer good accurate and flexibility because it takes into account the effect of prevalent conditions, such as drainage and high anthropogenic modifications. It also has ability to distinguish degrees of vulnerability at regional scales even with exist different lithology, but it is much less effective at evaluating the vulnerability of carbonate aquifers because it has some limitations in applications to karstic aquifers and does not take into account the properties of karst (e.g., Civita & De Maio, 2004; Makonto, 2013).

The method uses seven parameters like the DRASTIC method, but is more flexible as to ratings and weights. The user encodes the input data as functions of local conditions in each zone, and has the ability of using different classifications according to the circumstances. Parameters are as the following (Civita & De Maio, 2000):

S: *Soggicenza* (depth to groundwater)

I: *Infiltrazione* (effective infiltration)

N: *Non saturo* (unsatured zone attenuation capacity)

T: *Tipologia della cobertura* (soil /overburden attenuation capacity)

A: *Acquifero* (satured zone characteristics)

C: *Conducibilità* (hydraulic conductivity)

S. *Superficie topografica* (topographic surface slope)

These parameters are sub-divided into ranges, representing different hydrological settings and are determined different rating in a scale of 1 in 10. The rating assigned to each of these parameters refers their relative importance within each parameter, in contributing to groundwater vulnerability (Kumar et al., 2013).

The SINTACS vulnerability index is determined as a sum of seven weighted indicators (ratings) and computed by the formula [22]. Six vulnerability classes are considered: 26-80 (very low), 80-105 (low), 105-140 (moderate), 140-186 (high), 186-210 (very high) and 210-260 (extremely high). Figures 35 and 36 show two schematic representations of SINTACS method.

$$I_{SINTACS} = \sum P_{(1,7)} * W_{(1,n)} \qquad [22]$$

Where:

$I_{SINTACS}$ is the SINTACS vulnerability index

The $P_{(1,7)}$ is the rating of each of the seven parameters used

The $W_{(1,n)}$ is the corresponding weight in each class, which can vary from 1 to n, and n is the number of weight classification arrays

Weights are a very useful tool used to adapt the pattern to different perceptions, where the set of weights is determined according to conditions that mainly contribute to the local vulnerability, which can increase the importance of some parameter and minimizing others (Gogu & Dassargues, 2000). This method provides six strings of multiplier weights that can be used in the same time in large regions, and also in different prevalent conditions, as in the case of areas that are modified by human activities and chemical process: normal, severe, seepage, karst, fissured and nitrates (Table. 13). To reflect the relative importance of these parameters, weights in the scale of 1 to 5 are determined to each of these parameters.

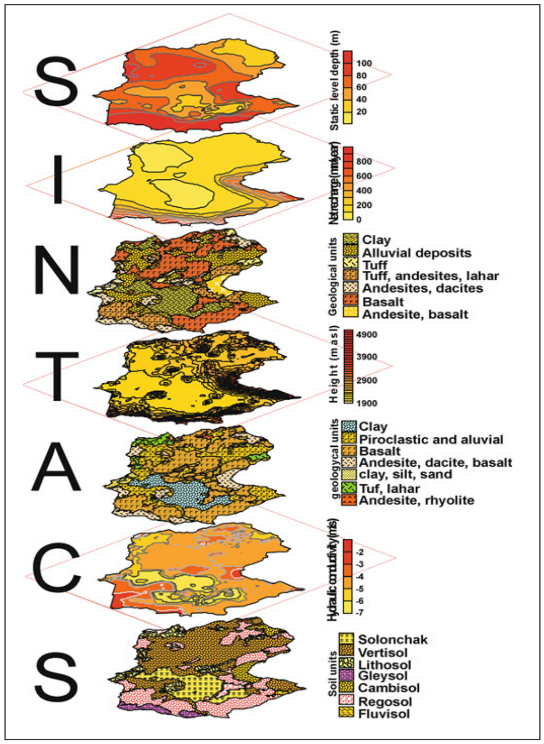


Figure 35. Schematic methodology of SINTACS (Leal et al., 2010).

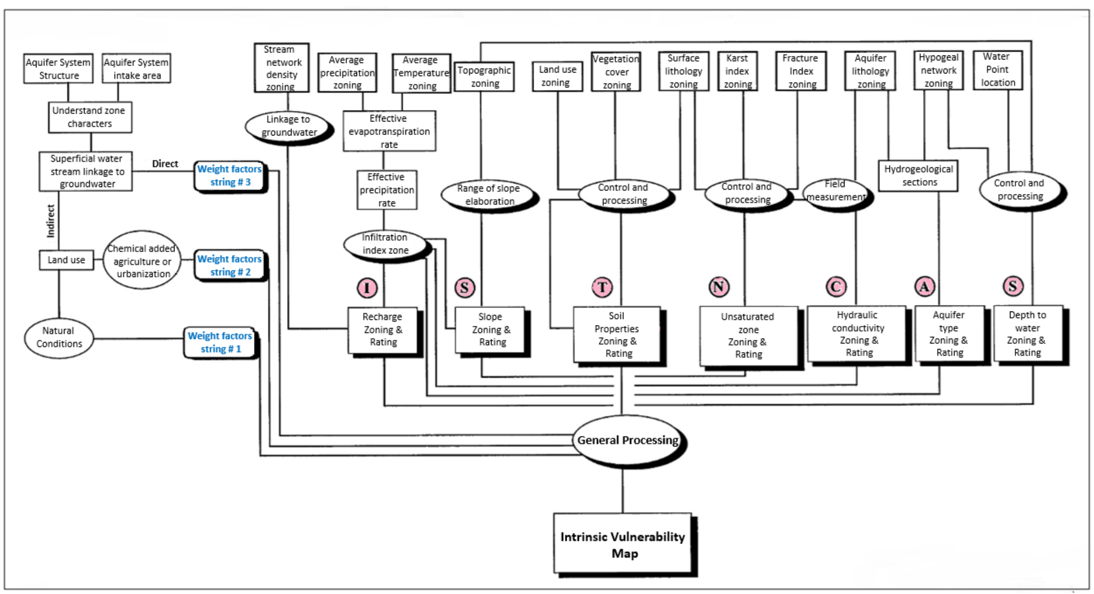


Figure 36. Schematic representation of the steps of SINTACS method (Gogu & Dassargues, 2000).

Table 13. SINTACS weights for different strings (Civita & De Maio, 2000).

Parameter	Normal	Seepage	Karst	Fissured	Nitrates
S	5	4	2	3	5
I	4	4	5	3	5
N	5	4	1	3	4
T	3	2	3	4	5
A	3	5	5	4	2
C	3	5	5	5	2
S	3	2	5	4	3

The most important differences between DRASTIC and SINTACS methods are the values of the ratings, the chosen of classes of weights, and the strategy used to determine them. Creating ranges and determining ratings and weights are the most accurate tasks (Civita, 1994).

2.11.4. SI method

SI method is an adaptation of the DRASTIC method and was created in order to evaluate aquifer vulnerability on a large to medium scale with respect to diffuse agricultural pollution in hydrogeological settings in the area study (Ribeiro, 2000; Frances et al., 2001). It is used to identify and protect the aquifer recharge areas (e.g., Stigter et al., 2006; Teixeira et al., 2015; Barroso et al., 2015). The SI method uses several parameters from DRASTIC method in addition to a new parameter, land use (LU):

D: Depth to the water table
R: Recharge
A: Aquifer material
T: Topography
LU: Land use

The main differences between SI and DRASTIC reside in the relative weights in all the common parameters. The weights of the SI parameters are presented in Table. 14.

Table 14. Weights for the SI parameters (Frances et al., 2001; Stigter et al., 2006).

Parameters	SI weights
D: Depth to the water table	0.186
R: Recharge	0.212
A: Aquifer material	0.259
T: Topography	0.121
LU: Land use	0.222

The SI vulnerability index is determined as a sum of the five rating indicators multiplied by the corresponding weight factors r_1 through r_5, and computed by formula [23]:

$$I_{SI} = D_r D_w + R_r R_w + A_r A_w + T_r T_w + LU_r LU_w \qquad [23]$$

Where higher index value refers to the greater possibility of contamination to move through the unsaturated zone to the water table (Table. 15).

Table 15. Evaluation criteria of degree of vulnerability for SI method (Stigter et al., 2006).

SI Vulnerability	Classes
Very high	80 - 90
High	70 - 80
Moderate to High	60 - 70
Moderate to Low	50 - 60
Low	40 - 50
Very low	30 - 40
Extremely low	< 30

2.11.5. DISCO method

DISCO method is created for the evaluation of intrinsic vulnerability in fractured aquifers and highly vulnerable springs especially in highly heterogeneous aquifers. It is a useful tool for delineating groundwater protection zones around springs taking into account the heterogeneity of the environment. This method is based on three parameters (Fig. 37), (Pochon & Zwahlen, 2003; Pochon et al., 2008):

- Hydrogeological properties of the fractured aquifer [discontinuities (DIS)];
- Properties and thickness of protective cover (CO);
- Runoff parameters which include flow phenomena of surface water before infiltration (slope runoff, permanent or temporary flow water).

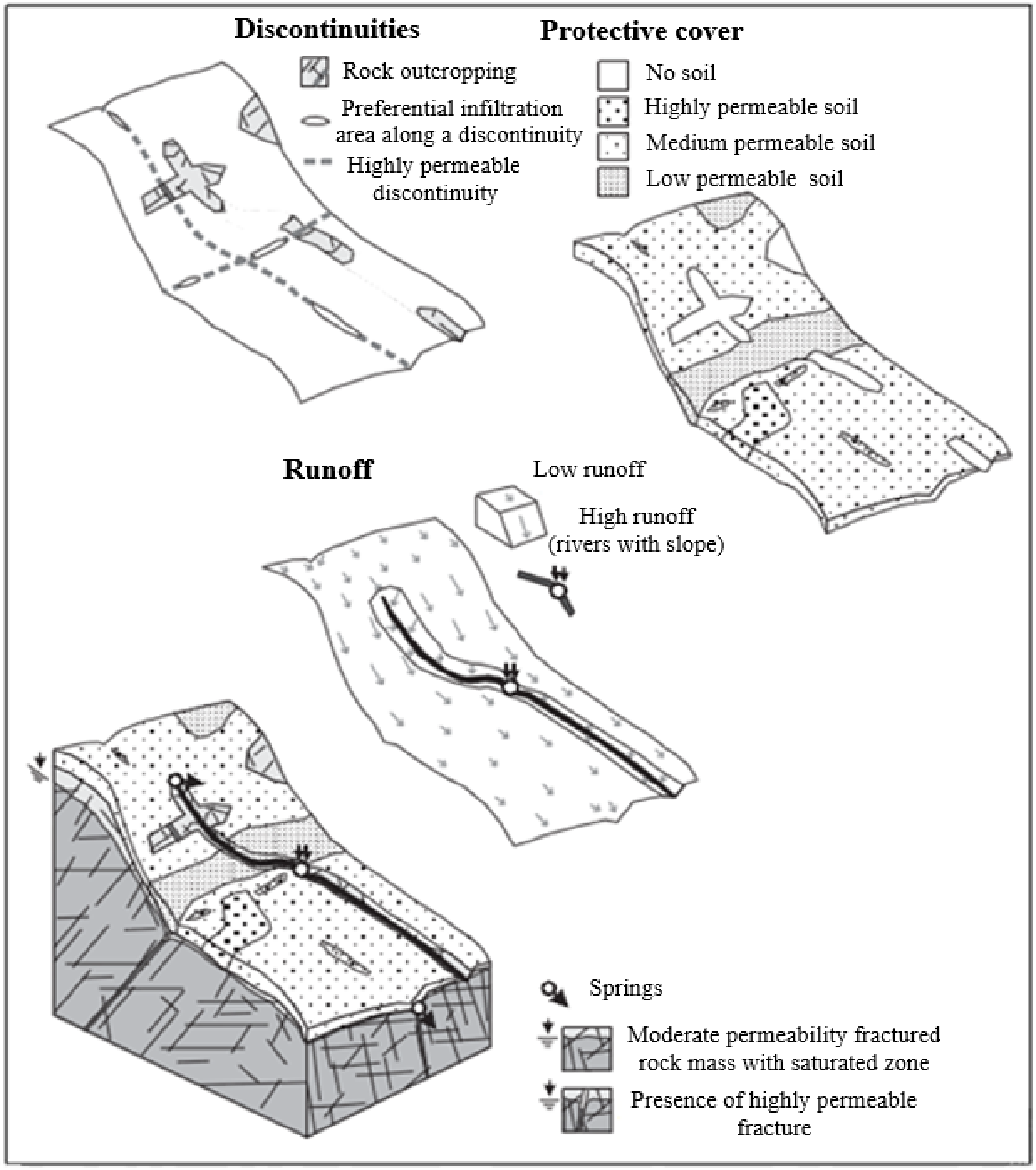


Figure 37. Representation of the three parameters considered in the DISCO method (adapted from

The evaluation of the combined effect of these three parameters is necessary to determine a natural protection factor at any point of the catchment. Thus, a protection factor map is estimated by combining all the parameter maps, after that it is possible to convert the protection factor map into protection zones (Pochon & Zwahlen, 2003). The application of the DISCO method includes four main steps:

Step 1: Assessment of the discontinuities (DIS) and protective cover (CO) parameters

This step includes the assessment and mapping of the parameters discontinuities and protective cover over the whole catchment region, and subdivided into zones which have uniform characteristics for each of the parameters. The discontinuities parameter symbolized by “D” takes into account the groundwater flow velocity within the fractured aquifer between an infiltration point in the water catchment region and the springs under consideration. The properties of different types of discontinuities can be measured on the one hand based on field observations (extension, opening, frequency, direction) and other share results from tracer tests. The map of discontinuities is performed across the catchment depending on the existing data (geological maps), field observations (geology, geomorphology), aerial photographs, and if necessary some geophysical profiles. The rating values of “D” range between 0 to 3 with increasing values corresponding to higher residence time and attenuation processes (Table. 16), (Pochon & Zwahlen, 2003; Pochon et al., 2008).

Table 16. Discontinuities parameter evaluation (Pochon et al., 2008).

Class	Rating	Evaluation criterion
D_0	0	Highly permeable discontinuities with preferential connection to the spring (maximum groundwater residence time of a few tens of hours) / no significant natural purification processes
D_1	1	Discontinuities with a relatively rapid connection to the spring (residence time of a few days) / limited purification processes
D_2	2	Discontinuities with a relatively slow connection to the spring (residence time of approx. ten days) / significant purification processes
D_3	3	Low permeability zone or discontinuities with a slow connection to the spring (residence time of several tens of days) / efficient purification processes

The protective cover parameter symbolized by “P” takes into account the protective effect related directly to the flow of water through the soil and geological formations overlying the fissured aquifer. The necessary data for the assessment of the parameter “P” may be evaluated using soil analysis, geomorphological mapping, hand drilling, and geophysics or infiltration tests (Pochon et al., 2008).

The rating values of “P” range from 0 to 4, with increasing the corresponding values on each of the higher protective cover thickness and lower permeability of the deposits. Where the ratings were defined based on field researches in many of the test sites (Tables. 17 and 18). Sometimes it is difficult to identify the thickness and lithology of these layers. However, civil engineering works (drilling, excavations) may give useful indications as well as the use of geophysics.

Table 17. Protective cover parameter evaluation taking into consideration pedological soil overlying the aquifer (Pochon et al., 2008).

Pedological soils						
Thickness (m)	High permeability soil (sand, pebbles)		Moderate permeability soil (silt, loam)		Low permeability soil (loam, clay)	
	Class	Rating	Class	Rating	Class	Rating
0.0 – 0.2	P_0	0	P_0	0	P_0	0
> 0.2 – 0.5	P_0	0	P_0	0	P_1	1
> 0.5 – 1.0	P_0	0	P_1	1	P_2	2
> 1.0	P_1	1	P_1	1	P_3	3

Table 18. Protective cover parameter evaluation taking into consideration geological formations other than pedological soils overlying the aquifer (Pochon et al., 2008).

Additional presence of low permeability formations (e.g. clay, loam, marl)								
Thickness (m)	Combined with P_0 soil		Combined with P_1 soil		Combined with P_2 soil		Combined with P_3 soil	
	Class	Rating	Class	Rating	Class	Rating	Class	Rating
< 1.0	P_1	1	P_2	2	P_3	3	P_3	3
1.0 – 2.0	P_2	2	P_3	3	P_3	3	P_4	4
> 2.0	P_3	3	P_3	3	P_4	4	P_4	4

Step 2: Determination of the intermediate protection factor (F_{int})

The intermediate protection factor is used to determine at any point if it is easy or not the contaminants seep into the ground and reach to the catchment. A very low protection factor corresponds to a very high vulnerability. The protection factor (F_{int}) can be computed by formula [24]:

$$F_{int} = 2 * D + P \qquad [24]$$

Step 3: Evaluation of the runoff parameter and determination of the final protection factor (F_{int})

The surface or subsurface runoff can create rapid contaminant flow over several tens or hundreds of meters especially when there are fractures. So, it is essential to take the fractured aquifers into consideration. The runoff parameter is only considered for regions where runoff may cause substantial pollutant movement toward vulnerable zones, unlike the discontinuities and protective cover parameters, which are mapped over the whole catchment region. The extent of local surface catchments is identified by evaluating the influence of runoff, i.e. slope gradient and soil permeability (Table. 19). Assessment of these factors needs field observation during important rainfall events. The final protection factor map is developed by modifying the intermediate protection factor map depending on the local surface catchments.

Table 19. Determination of the extension of surfaces to consider when taking into account the runoff parameter indicative values (Pochon & Zwahlen, 2003).

a) Runoff diffuse along the slopes (relatively uniform local watershed without channels or drainage system)	
Slope (%)	extension to assign to the local watershed
2 – 10	10 m upstream or around the surface considered vulnerable
10 – 25	20 m upstream the surface considered vulnerable
> 25	30 m upstream the surface considered vulnerable
In the presence of basins, channels, paths or drains collecting runoff, the extension of the local watershed to be considered must be extended accordingly. *The extension of the surfaces was set to consider on the basis of observations mainly on grazing areas. Generally runoff is often lower in forest areas, due to the presence of a soil more airy with a reduced thickness. In this case, taking into account local catchments of smaller extension (e.g., 10 m even if slopes are higher than 25%) can be allowed.*	
b) permanent watercourses or temporary infiltrations	
Extension to assign to the local watershed	Bed and banks of rivers, according to the local watershed slope criteria specified above for runoff.

Step 4: Protection zone delineation

In this step, the final protection factor "F" map is converted into protection zones "S". The delineation of protection zones is performed on the basis of an equivalence relation between the value of the final protection factor "F" and "S" zones; this relationship is shown in Table. 20.

Table 20. Conversion between the protection factor F and the groundwater protection zones (adapted from Pochon et al., 2008).

Protection factor F	**Vulnerability**	**S zones**
F very low (0, 1)	Very high	S_1
F low (2, 3, 4)	High	S_2
F moderate (5, 6, 7)	Moderate	S_3
F high (8, 9, 10)	Low to very low	Rest of the catchment area

In all cases, spring drains and draining trenches in addition to their immediate surroundings must be part of the S1 zone, with an isolating area of 10–30 m according to the gradient of the slope. As well as, a precautionary measure, no S3 zone must be defined at a distance of less than 100 m from the outer border of the S1 zone adjacent to the water supply, and no area corresponding to the rest of the catchment area should be determined closer than 200 m to this S1 zone boundary (Fig. 38).

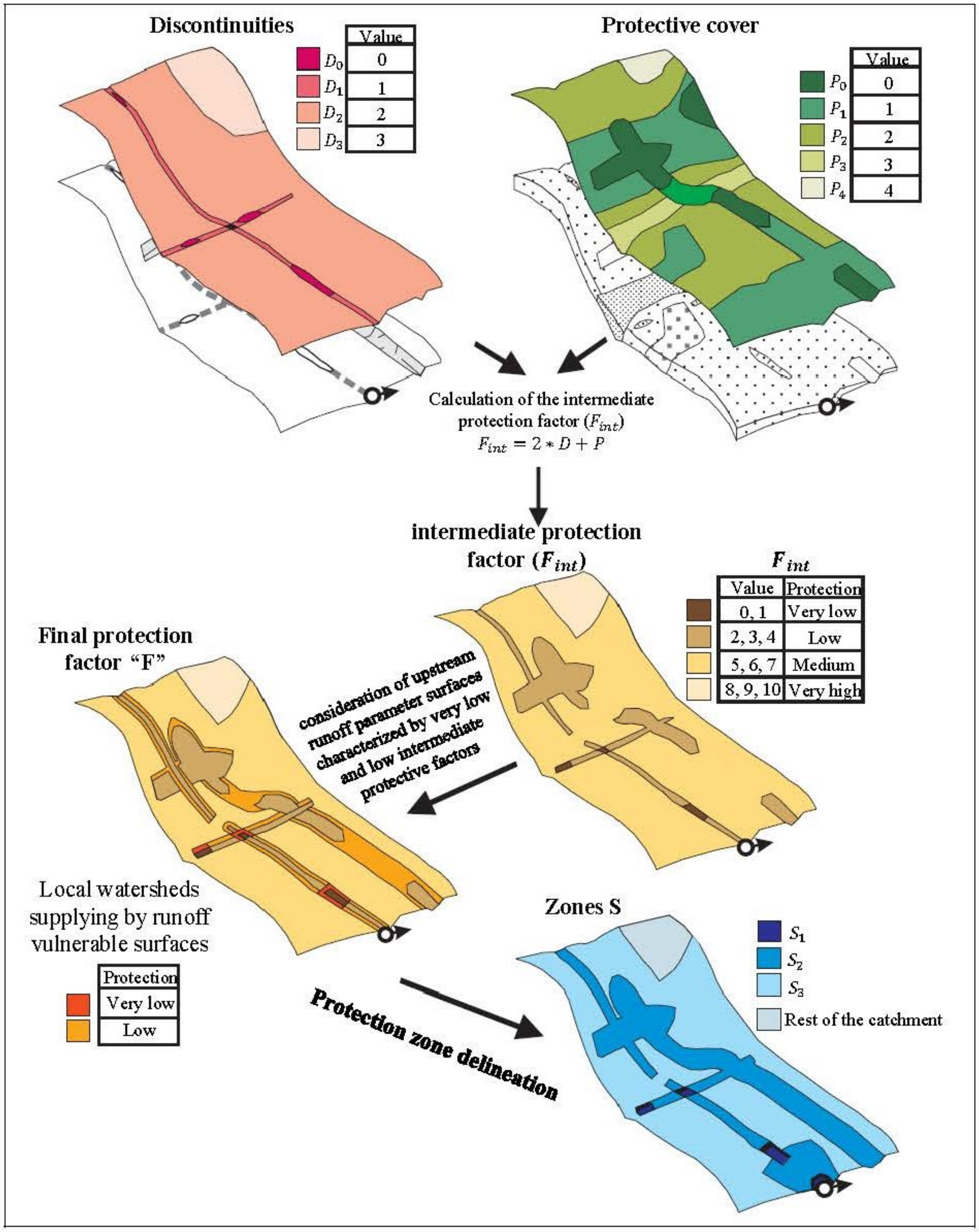


Figure 38. The delineation of protection zones (adapted from Pochon & Zwahlen, 2003).

3. Caldas da Cavaca site: a vulnerability assessment

3.1 Introduction

Groundwater in fractured aquifers is an important source for agriculture, domestic, industrial and public supply. Fractured aquifers represent an essential groundwater resource for large parts of the Earth, because of their high ability to store and transmit water through cracks, joints and fractures. Moreover, they can form the main way for groundwater flow and provide high conductivity conduits with fast hydraulic flows (Lewis et al., 2008). There are many factors controlling the flow paths and occurrence of groundwater, such as lithology, structure, topography, weathering grade, permeability, fracture extent, slope, drainage pattern, climate and land use (Jaiswal et al., 2003). All these factors can influence on the potential leakage of contaminants into groundwater which in its turn lead to groundwater vulnerability in varying degrees.

The term groundwater vulnerability was first mentioned in the 1970s (Albinet & Marget, 1970) and became more widely used in the 1980s (Aller et al., 1987; Foster & Hirata, 1988). Groundwater vulnerability is not a property that can be directly measured in the field. It is a concept which is based on the idea that some areas are more vulnerable to groundwater pollution than others (Vrba & Zaporozec, 1994). The concept of groundwater vulnerability to contamination represents the sensitivity of an aquifer to be adversely affected by an imposed contaminant load and the possibility of filtration of contaminants from the surface of the land (e.g., Vrba & Zaporozec, 1994; Foster et al., 2002). Extreme vulnerabilities are associated with highly fractured aquifers with a shallow water table as they offer little chance for contaminant attenuation, where the fractures increase vertical permeability which affect the rate of recharge and decrease the amount of pollution attenuation. Thus in fractured aquifer where groundwater flow is easy and relatively rapid, contamination may become more widely dispersed (Morris et al., 2003).

The assessment of groundwater vulnerability to contamination aims to determine zones at a high risk of being contaminated, to estimate the risk of an aquifer to be contaminated from any sources (Gemitzi et al., 2005). Groundwater vulnerability assessments usually result in a map of zones where the resource is vulnerable to contamination from surface activities (Vrba & Zaporozec, 1994). Vulnerability mapping is the suitable technique of assessing the geological and hydrogeological factors with potential groundwater for contamination in the specific area and displaying it on a map in a manner that is easy and useful (Daly & Warren, 1998).

This work demonstrates developing methodologies for evaluating aquifer vulnerability, delineating source protection zones in hard rock and assessment of fractured hydromineral systems for Caldas da Cavaca hydromineral system in Central Portugal, using hydrogeomorphology, GIS mapping techniques, remote sensing, vulnerability mapping in addition to the thematic maps like lithology and weathering grade, tectonic lineaments density, land cover, drainage network density, slope and rainfall. These maps were converted to GIS format after that are integrated using GIS software with the purpose of creating a vulnerability map aimed to delineate the leakage potential regions for the study area. Because the groundwater based mapping took advantage of the progress of geographical information systems (GIS) techniques, methods and analysis (Jha et al., 2007; Teixeira, 2011; Teixeira et al., 2015).

The use of GIS and remote sensing have been developed to assess aquifer vulnerability. For that the GIS and remote sensing tools are combined to different methods: GOD-S, DRASTIC-Fm, SINTACS and DISCO. The application of these methods displays the most vulnerable zone is the study area. Thus these maps can form a scientific basis for sustainable land use planning and groundwater management in the study area.

Finally, this study highlights the importance of the vulnerability mapping as a useful tool to creation of hydrological concepts, contributing to develop the guidelines of groundwater in different stages, like water resources planning and management, environmental sustainability and groundwater and surface water protection. Because it includes many types of information, as geology, geomorphology, hydrogeotechnics, surface hydrology and hydrogeology.

The organisation of the case study chapter is based on a general paper layout structure of an extended version from any international journal in the field of groundwater science. The present section follows the general layout of an original paper (extended version), which will be summarised, in near future, to a shorten version (typically, with 7.500/8.000 words; 7-8 figures and 1-3 tables; and supplementary material, as optional) to be submitted, in co-authorship, to an indexed international journal.

3.2 Regional framework: Caldas da Cavaca hydromineral system

The Caldas da Cavaca region is located in Central Portugal, in the municipality of Aguiar da Beira, Guarda district. It is sited between 40º44’N-40º47’N latitude and 7º34’W-7º35’W longitude. It is located in Beiras Variscan granitic belt – Dão complex granite (Boorder, 1965) in Central Iberian zone, near the western border of the Bragança-Vilariça-Manteigas major fault zone, with a general trend of NNE-SSW (Fig. 39) (Brum Ferreira, 1991; Ribeiro et al., 2007). The site relates to the regional morphotectonic unit of the Central Plateau, in the northern part of the large number of ridges, which are called ‘Cordilheira Central’ or Central Range (Brum Ferreira, 1980). The study area is predominantly constituted by granitic rocks that basically consist of coarse grained porphyritic granite, sometimes interrupted by quartz veins, pegmatite-aplite veins, dolerite dykes and alluvial deposits (Boorder, 1965; Teixeira et al., 2015). The mafic dykes are most susceptible over distances of less than 30 m and often highly weathering to fresh (Fig. 40).

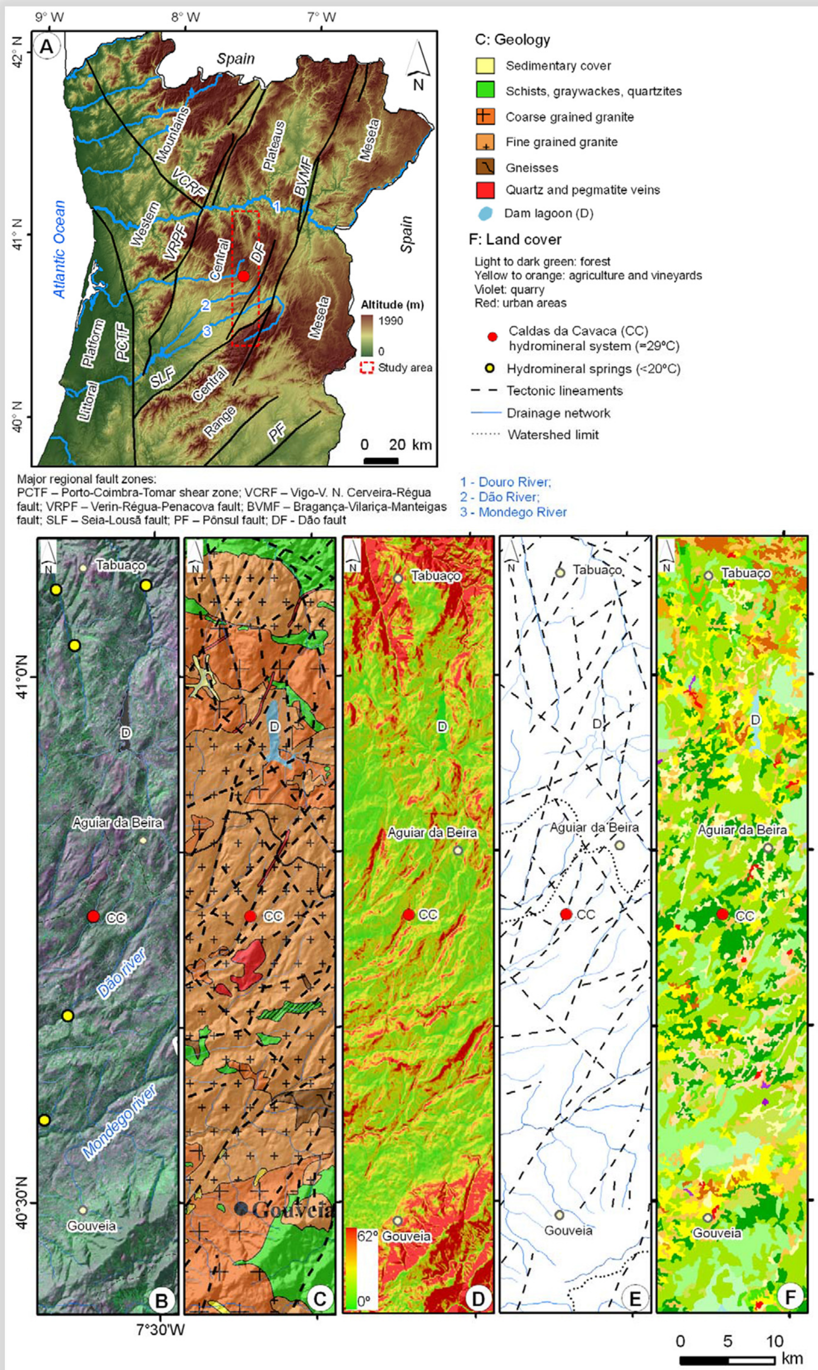


Figure 39. Regional framework of the study area (Caldas da Cavaca hydromineral system, Aguiar da Beira): A- Morphotectonic general features from Northern Portugal; B- Satellite image (compiled from Landsat 7 ETM+ data, 2000/01; all IR color, bands 7-4-5= RGB; adapted from Global Land Cover Facility) and main hydromineral springs; C- Shaded relief and regional geology; D- Slope; E- Drainage network and tectonic lineaments; F- Land cover (Brum Ferreira 1991; Carvalho 2006; CLC 2000). After Teixeira et al. (2010).

Figure 40. Views from Caldas da Cavaca area. Left: Granitic core stones, outcrops and weathered granite; Right: Dolerite dykes.

The drainage network in the study area (Caldas da Cavaca) is part of the Dão River watershed, which is a tributary of Mondego River. Locally, the main morphologic feature is the NNE-SSW Ribeira de Coja valley (bottom c. 521 m), with a lot of steep slopes and an altitude difference of about 170 m. The surrounding region is basically dominated by granitic rocks outcrops, some *Pinus pinaster* forest, and agriculture in small flattened areas. The slopes are mainly covered by bushes or scrub (Teixeira et al., 2010, 2015; Teixeira, 2011). Generally, the main regional tectonic structure is the NE-SW Dão fault zone and related fracture network systems, which control thermal water occurrences. All these structures have a significant impact in the regional drainage network, which was revealed by the rectangular pattern (Teixeira, 2011).

Caldas da Cavaca site is known as a region for the thermal spa tradition, which dates back to the late XIX century (Freire de Andrade, 1937, 1938a; Acciaiuoli, 1952/53). Lately, a completely rehabilitated thermal center has reopened, after many years of inactivity. In this site, many geological, geomorphological and hydrogeological studies were developed, as a result of the need to increase the supply from the old thermal spring and well (Freire de Andrade, 1935, 1938b) for therapeutic uses at the spa center, and to provide additional quantities of freshwater in the surrounding area for domestic use.

The hydromineral waters from Caldas da Cavaca have output temperatures around 29.8ºC and are characterized by some properties (Carvalho et al., 2005a; Espinha Marques, 2008a,b; Teixeira et al., 2010, 2015; Teixeira, 2011):

- Relatively high pH values (c. 8.3);
- TDS contents range between 262 - 272 mg/L;
- The existence of reduced sulphur species (HS, c. 0.9 mg/L);
- High silica contents about 55 mg/L which represents a significant percentage of total mineralization (ca. 21 %);

- Electrical conductivity (EC) measurements range between 353 - 427 μS cm^{-1} indicating the existence of medium mineralized waters;
- High fluoride concentrations up to 14 mg/L;
- HCO_3-Na hydrogeochemical facies.

The climate in Caldas da Cavaca is generally temperate (Köppen-Geiger Cfb climate, after McKnight & Hess, 2000 and Peel et al., 2007), which means a temperate humid climate, with a temperate summer. The mean annual temperature is 13ºC, ranging from 6.2ºC in January to 20.1ºC in July. The average annual precipitation is 1252.4 mm/year, being January the wettest month (mean rainfall reaching 189 mm) and July is the driest (16 mm). According to Thornthwait & Mather (1955) method, the annual water balance was calculated, with a field capacity of 150 mm (Table. 21). The region suffers from water deficit (dry period) from June to September, particularly in July and August, with a total deficit in the 4 months about 117.4 mm (Fig. 41) (Teixeira, 2011). The full field capacity is only achieved in November, and from December to May, a total water surplus about 743 mm is registered (Fig. 42). The estimated recharge is about 175 mm/year, which is equivalent to 14 % of the mean annual rainfall (Carvalho et al., 2005a; Teixeira, 2011).

Table 21. Monthly sequential water balance for the meteorological station of Aguiar da Beira (usable water capacity of 150 mm), (adapted from Teixeira, 2011).

Terms of Hydrological Balance	Oct	Nov	Dec	Jan	Feb	Mar	Abr	Mai	Jun	Jul	Aug	Sep	Total
P	112.6	149.4	178.8	189	155.2	136.9	101.2	88.7	50.9	16.1	18.2	55.4	1252.4
T	13.7	9.6	6.8	6.2	7.2	9.8	11.9	14.3	18.1	20.2	20.0	17.8	
Ji	4.5	2.7	1.6	1.4	1.7	2.7	3.7	4.8	6.9	8.1	8.0	6.7	52.9
N	11.2	10.0	9.4	9.7	10.6	12.0	13.3	14.4	15.0	14.7	13.7	12.5	146.5
EPT	56.8	30.2	18.3	16.6	20.1	38.5	53.8	77.4	107.8	126.8	116.6	87.8	750.8
P-EPT	55.8	119.2	160.5	172.4	135.1	98.4	47.4	11.3	-56.9	-110.7	-98.4	-32.4	501.6
L									-56.9	-167.6	-266.0	-289.4	-298.4
s_{so}	76.3	150.0	150.0	150.0	150.0	150.0	150.0	150.0	102.7	49.1	25.5	20.5	
Δs_{so}	55.8	73.7	0.0	0.0	0.0	0.0	0.0	0.0	-47.3	-53.6	-23.6	-4.9	0.0
ETR	56.8	30.2	18.3	16.6	20.1	38.5	53.8	77.4	98.2	69.7	41.8	60.3	581.8
DH	0.0								9.5	57.1	74.8	27.4	168.9
SH	0.0	45.6	16.0	172.4	135.1	98.4	47.4	11.3					670.6

P: Precipitation (mm). T: Temperature (ºC). Ji: Monthly heat index. N: Maximum hours of sunshine to latitude 40'N. ETP: Potential evapotranspiration (mm). L: Potential water loss. $\mathbf{s_{so}}$ Water storage in the soil (mm). $\mathbf{\Delta s_{so}}$Change in water storage in the soil (mm). ETR Actual evapotranspiration (mm). DH: Water shortages. SH: Water surplus.

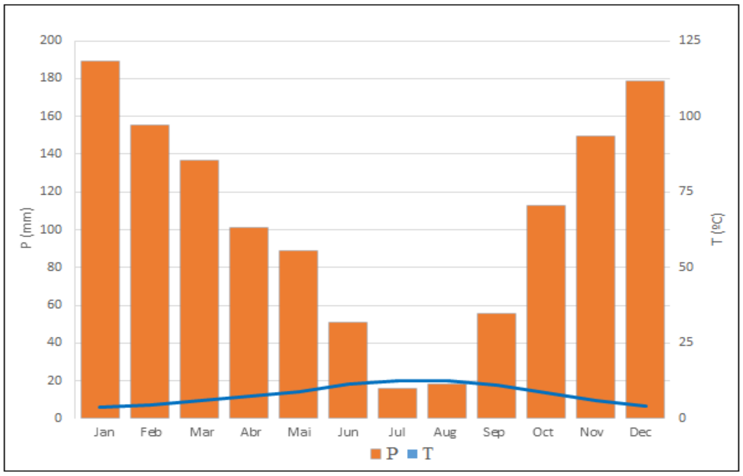


Figure 41. Thermo-pluviometric diagram concerning climatological station of Aguiar da Beira. (P) Precipitation; (T) Temperature (adapted from Teixeira, 2011).

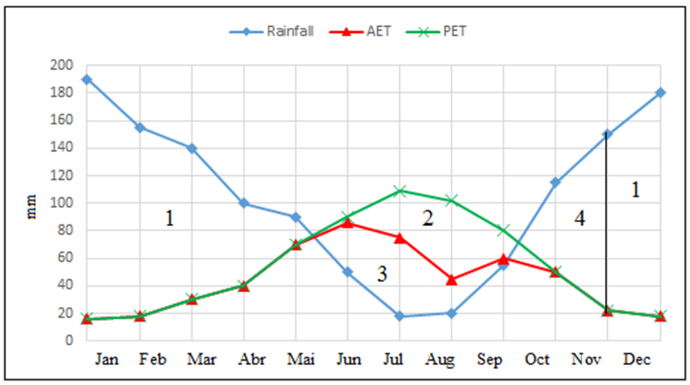


Figure 42. The annual water balance of Caldas da Cavaca area: 1- Water surplus; 2- Water deficit; 3- Soil moisture storage withdrawal; 4- Soil moisture storage increase; PET- Potential Evapotranspiration; AET- Actual Evapotranspiration. (adapted from Teixeira, 2011).

3.3 Materials and methods

In this study, data collection techniques and procedures mainly related to structural geology, engineering geosciences, applied geomorphology, and hydrogeology have been used (Dykes et al., 2005; Chaminé et al., 2013; Teixeira et al., 2013). In addition to the remote sensing and GIS mapping, which are the most important techniques, where the GIS procedure allowed the generation of many thematic maps like geology (i.e., lithology, structure, and weathering grade), drainage, land cover, slope, and rainfall, in order to achieve an integrated framework of the study area and the evaluation of groundwater vulnerability areas (Assaad et al., 2004).

Moreover, the topographic and geological maps, aerial orthophotos and LandSat ETM+ and SPOT5 images have been used to create many of thematic field maps to support all the study stages, regarding the basic geological description of rock masses, basic description of geography and basic hydrogeomorphology features. Besides, hydrogeological parameters like temperature, pH and electrical conductivity were measured during the field inventory using multiparametric portable equipment. Consequently, all the collected data can divide into two main groups (Fig. 43): i) basic cartographic description, which includes topography, remote sensing, morphotectonics, structural geology, land use and hydroclimatology, and ii) field and laboratory data, such as field hydrogeotechnics, hydrogeological inventory, hydrochemical, and isotopic analysis.

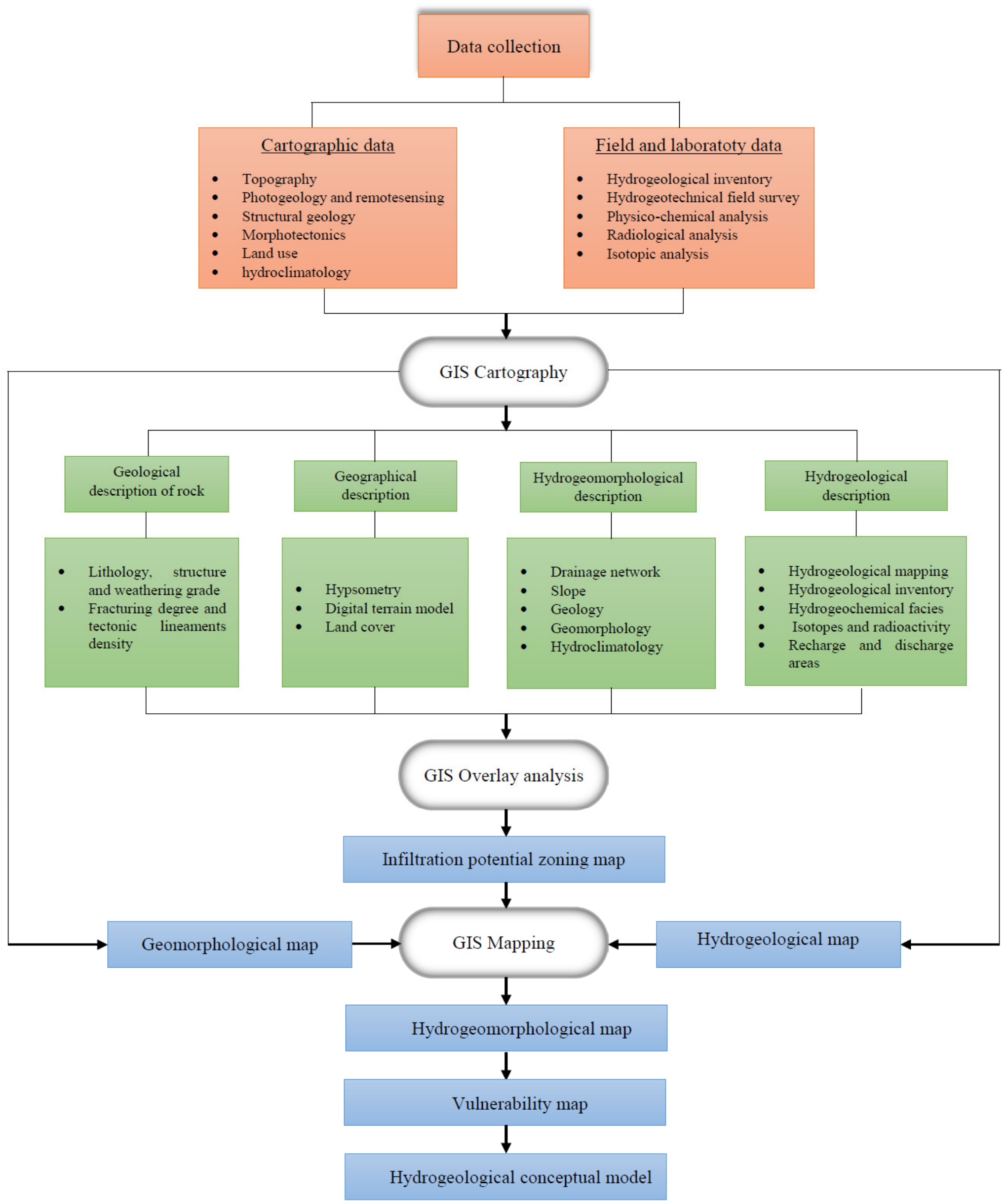


Figure 43. Conceptual flowchart representing the methodologies used in this study.

Cartographic, field and laboratory data were organized and assessed in a GIS environment, and a series of thematic maps were created. This mapping was the basis for the subsequent GIS overlay and analysis, precisely the infiltration potential zoning and the groundwater vulnerability mapping. These maps were grouped in four main groups: the geological description of rock masses, geographical description, hydrogeomorphological and hydrological features of the study site (e.g., Carvalho et al., 2005a; Cerqueira et al., 2006, Teixeira et al., 2010, 2015).

The infiltration potential is a key parameter in some vulnerability indexes. So, the identification of the explaining factors for the calculation of the infiltration potential zoning index is very important in the study. Where the relative weight and score for each factor was calculated using the Analytical Hierarchy Process (AHP) method (Kim et al., 2009), and the internal scores were basically evaluated from fieldwork data (Saaty, 2008). The assumed grid data structure consisted of a pixel of 1x1 m. The GIS analysis led to a map showing the spatial distribution of the infiltration potential index, ranging from 0 to 100, where the highest values represent a combination of suitable properties in most explaining factors.

GIS-based mapping was used to produce an interactive geodatabase, to evaluate the spatial distribution of the field and analytical data, in addition to create vulnerability maps. The assessment of groundwater vulnerability in this study was made using several methods, some of them adapted and revised from the bibliography: GOD-S (Foster & Hirata, 1988; Foster et al. 2002), DRASTIC-Fm (Aller et al., 1987; Denny et al., 2007; Teixeira et al, 2015), SINTACS (Civita & De Maio, 2000; Civita, 2010; SI (Ribeiro, 2000; Frances et al., 2001; Stigter et al., 2006; Barroso et al., 2015) and DISCO (Pochon & Zwahlen, 2003; Pochon et al., 2008).

For GOD-S method no adaptation was made. For DRASTIC-Fm index, the original DRASTIC index was somewhat modified, taking into account the specificities of the fissured hard-rock aquifers. The fractured media parameter (Fm) was derived from the tectonic lineaments density map, and grouped into four classes, with rating varying from 4 to 10, according to the tectonic lineament density (Teixeira et al., 2015). Concerning SINTACS method, the multiplier weights of normal string were used (Civita, 2010). For SI method, the Land Use (LU) parameter was derived from land cover maps (Corine Land Cover, 2006—Caetano et al., 2009; Painho & Caetano, 2006; Carta de Ocupação do Solo, 2007—IGP, 2010). Finally, for DISCO method, is applied in the vulnerable springs (normal springs and hydromineral water wells) linked to a highly heterogeneous aquifer.

Hydrogeological background was on the basis of the computation for the vulnerability approach. Groundwater vulnerability was subdivided into several broad classes from ‘‘Very Low’’ to ‘‘Extremely High’’. The national color code for DRASTIC index ranges was applied. Finally, an integrated assessment between all the methods was made.

3.4 Results and discussion

3.4.1. Local hydrogeological framework

A hydrogeological inventory was performed in Caldas da Cavaca region (Fig. 44.a). The water points of the region are not distributed equally, being most of the shallow dug wells located in the higher planned surfaces. They are related to the agricultural sites, which have in this area a high demand of water, mainly in the spring and early summer. These structures have normally small depths (< 5 m), and are mainly fed by the unconfined aquifer (Carvalho et al., 2005a; Espinha Marques et al., 2008a,b; Teixeira et al., 2010, 2015). The horizontal water galleries, usually hand-made, are located at lower altitudes (550–600 m). Springs are relatively rare and basically located at altitudes between 650 and 700 m. These springs have very small yields (0.01–0.05 L/s), low temperature (< 17ºC) and very low electrical conductivities (< 50 μS/cm).

The normal waters of the Caldas da Cavaca area can be categorized by two main groups:

i. Groundwater from weathered or fractured granitic areas, with a pH ranging 5-6.5 and electrical conductivities of 20 - 50 μS/cm;
ii. Surface water and groundwater from alluvia, with pH ranging 5.5-6 and electrical conductivities up to 20 μS/cm.

As for hydrodynamic features, this aquifer is characterized by transmissivity values below 1 m^2/day and long-term well yields below 1 L/s. However, springs have lower values, usually below 0.1 L/s.
The hydromineral waters of Caldas da Cavaca are characterized by temperature around 30ºC, pH around 8.3 and electrical conductivity values ranging 400-450 μS/cm. The hydromineral water wells are located in the bottom of the valley, intersecting the alluvia deposits in the first meters, and reaching a maximum depth of 220 m, with yields between 1 and 4 L/s and transmissivities ranging 27-136 m^2/day (Carvalho et al., 2005a; Teixeira, 2011; Teixeira et al., 2015).
All the hydromineral water sites seem to be somehow related to the regional tectonic lineaments, and located very close (< 100 m) to the tectonic lineaments. The context of hydrogeological trap is observed particularly in the bottom of the valley, where the hydromineral water wells are situated.

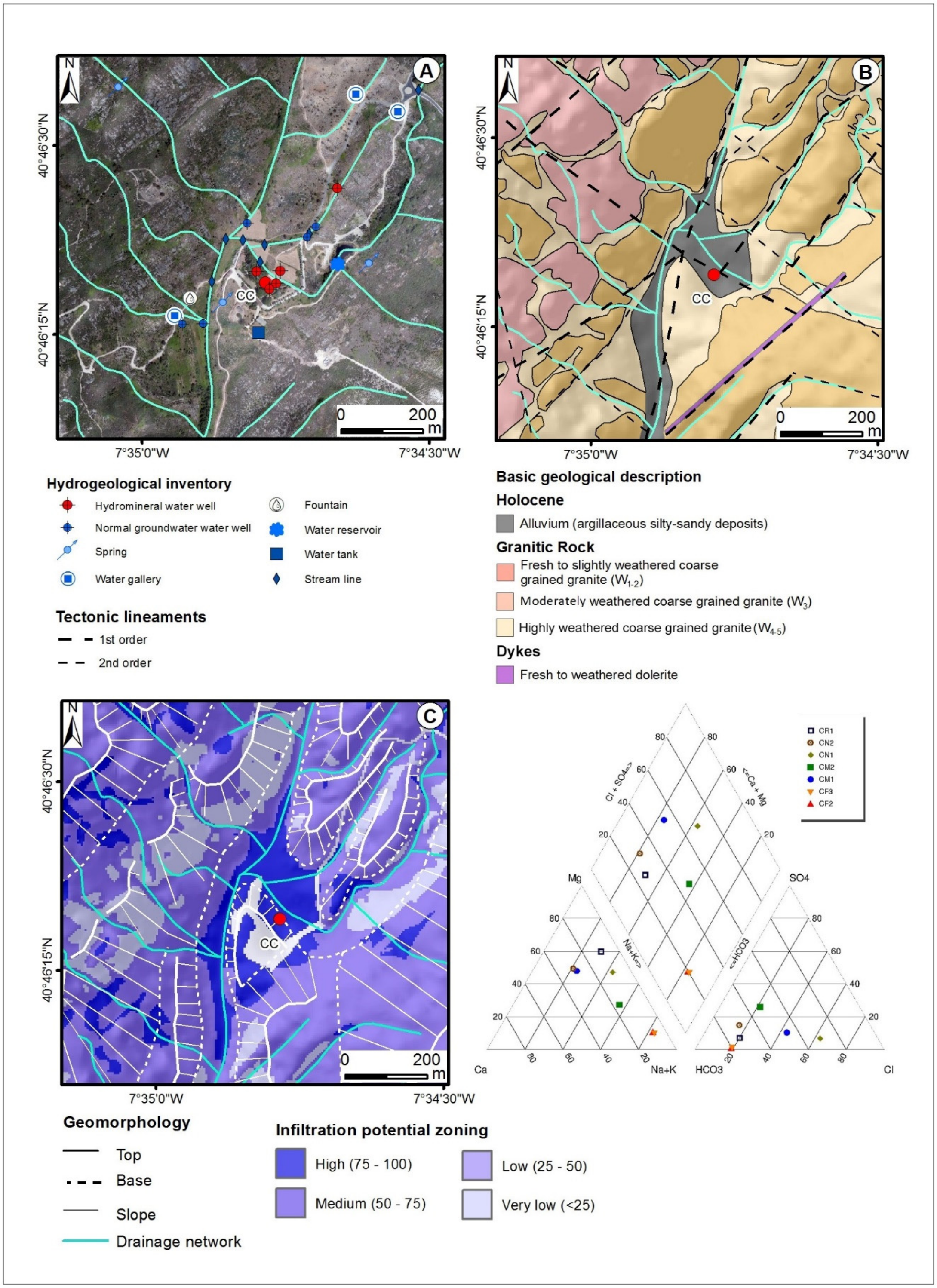


Figure 44. Local hydrogeological framework of Caldas da Cavaca site. Hydrogeological inventory (a); geological description (b); geomorphology and infiltration potential zoning (c); hydrogeochemical facies (d). Adapted from Teixeira (2011) and Teixeira et al. (2015).

The basic geological description in the study site was characterized by lithology, structure, weathering grade and fracturing degree (Fig. 44.b). Basically, a coarse grained granite dominates and it was categorized in three main groups, depending on its exposure weathering degree (Teixeira et al., 2010, 2015; Teixeira, 2011):

i. Fresh to slightly weathered coarse grained granite (W_{1-2}), occurring in the higher altitude zones (600–700 m) and showing moderate fracturing degree (F_3) to very close to close fracturing degree (F_{4-5}). This unit has a great morphological importance, determining core stones shaped forms in the granitic outcrops of the site;
ii. Moderately weathered coarse grained granite (W_3), found at lower altitudes (500–650 m), in a wide corridor (ca. 500–1,000 m), with a general NE–SW trend;
iii. Highly weathered coarse grained granite (W_{4-5}), which dominates in plateau regions. The mineralogy and grain size of this granite results, locally, in intense arenisation.

The rock mass W_{1-2}/W_3 are basically bordered by faults and fracture zones, with NNE–SSW to NE–SW, and NW–SE trends. Along these depressed regions, a lot of narrow corridors of highly weathered granite (W_{4-5}) surrounding the fresh rock masses were determined. The weathering grade is very intense and may reach depths of about 50 m, especially in the NNE–SSW trending megastructure, the so-called Ribeira de Coja fault zone (Carvalho et al. 2005a; Teixeira, 2011; Teixeira et al., 2015).

As for the dolerite dykes, they follow the general structural pattern, namely NE–SW and NW–SE orientations. These mafic deep structures have different weathering grade ranges, but in most cases are changed and present light green to orange color. Finally, the sedimentary cover is more important in the bottom of the Ribeira de Coja valley. The thickness of these silty–sandy deposits is thin and ranges 3–5 m (Carvalho et al. 2005a).

The local geomorphology (Fig. 44.c) reflects the regional morphological context. This surface has distinctive features characterized by regular top surface comprehending altitudes from 700-750 m. The regular surfaces are more extensive in the NW and in the SW sectors. Also there is a small ridge is appears in the W sector, with two plantation levels, around 650 and 700 m. This regional morphological unit is also characterized by the existence of some compact levels, from the top planned level, about 700 m, to the bottom of the Ribeira da Coja valley, around 521 m. The watercourses play a critical role, creating an important morphological feature, i.e., an entrenched valley with high slope values. The slopes show different patterns, related with their altitude, and topographic position. Near the top, between 650-700 m, the slopes are convex and have lower slope gradient; close to the valley bottom they are concave, leading also to the higher slope values of the study area.

As for the infiltration potential zoning (Fig. 44.c) it was shown that the most effective infiltration areas were located in the NW and SE sectors of the Caldas da Cavaca thermal site, specifically near the settlements of Quinta dos Matos, Quinta das Lameiras and Cavaca (see Fig. 3.2.). These zones, compatible with highly weathered granite with a high thickness arenisation, are located mainly in plateau areas. The less effective infiltration areas were found in an NE–SW corridor sub-parallel to the main tectonic valley and compatible with less weathered granites and higher slopes (Teixeira, 2011; Teixeira et al., 2010, 2015). The valley bottom also presented high infiltration potential, resulting from the combination of lithology (alluvial cover) and the very low slope (flattened valley bottom). However, the recharge area for hydromineral aquifer is probably located at higher altitudes (> 675 m).

The main features of the areas of higher infiltration potential were identified (Teixeira, 2011; Teixeira et al., 2015): (1) moderately to highly weathered granitic rock (including arenisation layers); (2) moderate to close fracturing degree; (3) low slope areas at the highest elevations; and, (4) agricultural and forest areas. Most of the water points (80 %) identified in Caldas da Cavaca study site are located in zones of high infiltration potential or in transition areas between the high and medium infiltration potential areas.

The drainage network density is also an important factor, that gives important clues about the surface and groundwater flows. In Caldas da Cavaca site, the higher drainage network density area follows the general trend of the main stream lines of the area, with a general direction approximately NE to SW. The higher values were registered in the SW area of Caldas da Cavaca (Fig. 44.c).

Concerning hydrogeochemical facies, the Piper diagram (Fig. 44.d) shows that the normal water of Caldas da Cavaca site have a sodium chloride to sodium bicarbonate facies, while the hydromineral waters have a sodium bicarbonate facies.

3.4.2. Local hydrogeomechanical framework

In order to characterize in hydrogeomechanical terms the Caldas da Cavaca site, three rock slopes were identified: Amores slope, A; Lagoa slope, L; and Cancela slope, C (details in Teixeira, 2011; Meirinhos, 2015). The slopes length have a total extension of 484 m and a height that varies from 1 to 7 m above the road, oriented mainly N45ºE/N60ºE (slopes A and L, respectively) and N80ºE/N110ºE (slope C) (Fig. 45). Some basic rock and soil geotechnics data and hydrogeomechanics data were compiled from the works of Teixeira (2011) and Meirinhos (2015), respectively.

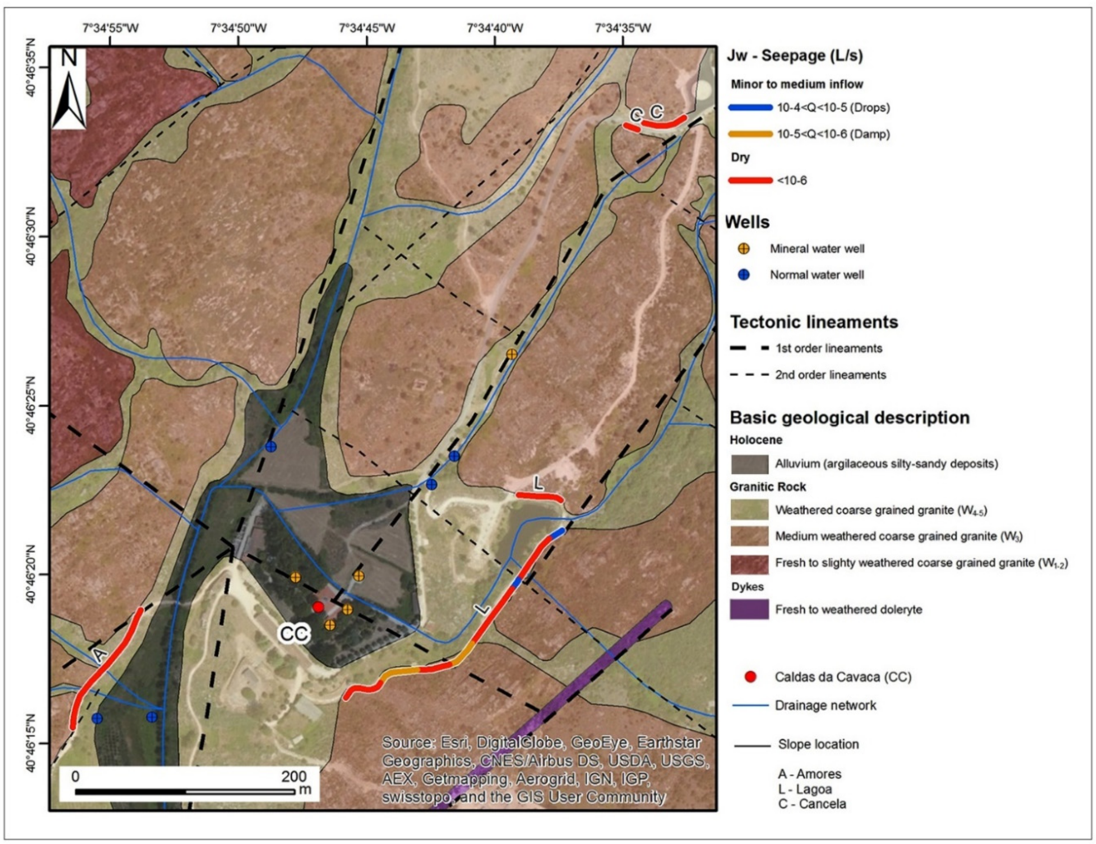


Figure 45. Location of the three studied slopes in Caldas da Cavaca site (after Meirinhos, 2015).

The main type of discontinuities presented in Caldas da Cavaca site is joints, being a small percentage faults and, in all slopes, their orientation is analogous. The first and dominant set of joints has a major joint orientation of N120º-150ºE (dipping 75ºNE/SW to 90ºNE/SW). The second set of joints has a general orientation trending N20º-80ºE (dipping 55º- 90ºSE). As for the weathering grade, these slopes exhibit, basically, a moderate weathering (W_3) with occurrences of highly to completely weathered ($W_{4\text{-}5}$) rock and, some clear occurrences of fresh to slightly weathered rock (W_{1-2}) on Amores and Lagoa slopes (Teixeira, 2011). The fracture interconnectivity has an important role on water flow in fractured medium, thus more frequent fracturing degree provides more paths for the water flow. In this site, the fracturing degree tendency showed a higher occurrence of wide spacing (F_{1-2}) discontinuities, to discontinuities with moderate spacing (F_3) and, a small percentage of close spacing discontinuities (F_{4-5}), (Meirinhos, 2015).

Regarding the water content, it is classified depending on the amount of water flowing through rock joints. Lagoa slope presented small sections classified as wet (10 ≤ drops/min < 100), as well as damp (1 ≤ drops/min < 10), although the most part of the slope was dry. A small section of Amores slope was classified as damp (1 ≤ drops/min < 10), while Cancela slope was entirely dry.

Tables. 22, 23 and 24 show an overview of the geomechanical basic parameters description for the three rock slopes.

Table 22. Basic geomechanical parameters for Lagoa slope, Caldas da Cavaca (adapted from Meirinhos, 2015).

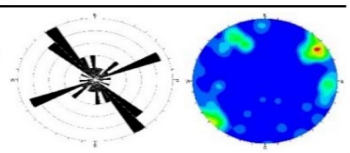
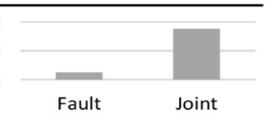
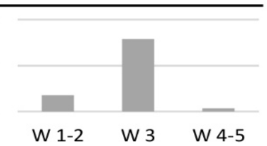
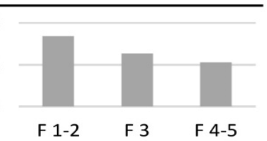
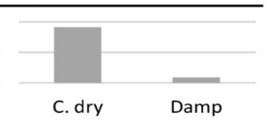
AMORES SLOPE: GEOMECHANICAL JOINT CHARACTERISTICS		Slope 1 (n=57)		
	Lithology	Two-mica granite, coarse grained		
	Joint sets	N130º-150ºE; 65º-85ºSW N60º-70ºE;60º-80ºSE		
	Discontinuity type	Fault	12,3%	
		Joint	87,7%	
	Weathering grade, W	W 1-2	17,5%	
		W 3	78,9%	
		W 4-5	3,5%	
	Fracturing degree, F	F 1-2	42,1%	
		F 3	31,6%	
		F 4-5	26,3%	
		Average value = 63,5 cm		
	Seepage	Completely dry (C. dry)	91,2%	
		Damp	8,8%	

Table 23. Basic geomechanical parameters for Cancela slope, Caldas da Cavaca (adapted from Meirinhos, 2015).

CANCELA SLOPE: GEOMECHANICAL JOINT CHARACTERISTICS

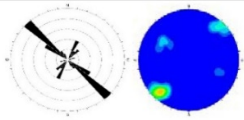
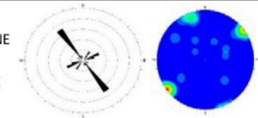
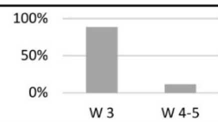
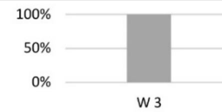
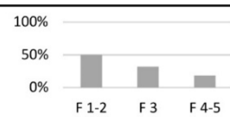
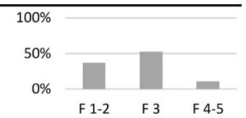
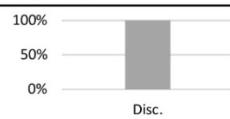
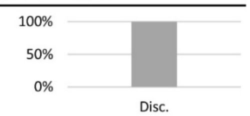
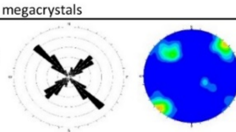
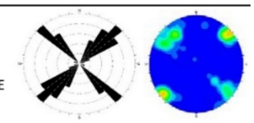
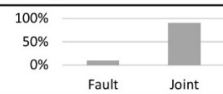
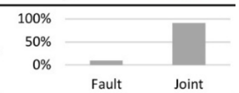
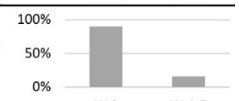
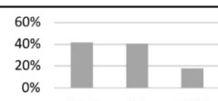
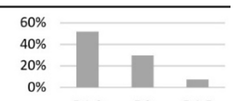
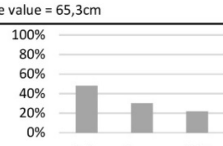
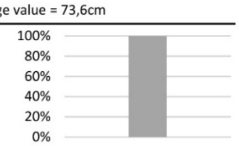
	Slope 1 (n=44)			Slope 2 (n=19)		
Lithology	Two-mica granite, coarse grained			Two-mica granite, coarse grained		
Joint sets	N120º-140ºE; 70º-90º NE N20º-40ºE; 55º-75º SE			N140º-150ºE; 80º-90º NE N60º-80ºE; 80º-90º SE		
Discontinuity type	Fault	4,5%		Joint	100,0%	
	Joint	95,5%				
Weathering grade, W	W 3	88,6%		W 3	100,0%	
	W 4-5	11,4%				
Fracturing degree, F	F 1-2	50,0%		F 1-2	36,8%	
	F 3	31,8%		F 3	52,6%	
	F 4-5	18,2%		F 4-5	10,5%	
	Average value = 71,7cm			Average value = 63,8cm		
Seepage	Completely dry (C. dry)	100,0%		Completely dry (C. dry)	100,0%	

Table 24. Basic geomechanical parameters for Amores slope, Caldas da Cavaca (adapted from Meirinhos, 2015).

LAGOA SLOPE: GEOMECHANICAL JOINT CHARACTERISTICS

	Slope 1 (n=183)			Slope 2 (n=54)		
Lithology	Two-mica granite, coarse grained, porphyritic with feldspar megacrystals			Two-mica granite, coarse grained		
Joint sets	N130º-150ºE; 75º-85ºNE N40º-60ºE; 60º-80ºSE			N40º-60ºE; 60º-80ºSE N130º-150ºE; 75º-85ºNE		
Discontinuity type	Fault	9,3%		Fault	9,3%	
	Joint	90,7%		Joint	90,7%	
Weathering grade, W	W 1-2	2,7%		W 3	90,2%	
	W 3	91,3%		W 4-5	15,7%	
	W 4-5	6,0%				
Fracturing degree, F	F 1-2	41,7%		F 1-2	51,9%	
	F 3	40,5%		F 3	29,6%	
	F 4-5	17,9%		F 4-5	7,4%	
	Average value = 65,3cm			Average value = 73,6cm		
Seepage	Completely dry (C. dry)	48,1%		Completely dry (C. dry)	100,0%	
	Damp	30,1%				
	Wet	21,9%				

All the rock/soil geotechnical and hydrogeomechanical surface data allowed to divide the slopes in hydrogeomechanical zoning and classified them by their similarity and behavior. The major consideration taking part on this distinction was the respective joint water content, separating, within each slope, zones containing equivalent water flowing values. This zone distinction allowed the creation of different seepage content zones called hydrogeomechanical zones (HGMZ).There are several hydrogeomechanical zoning considered for the three slopes (Table. 25), details in Meirinhos (2015).

Table 25. Summary of the basic hydrogeomechanical parameters from the studied rock slopes in Caldas da Cavaca (adapted from Meirinhos, 2015).

HYDROGEOMECHANICAL ZONING	Hydrogeomechanical Zone		Scanline section (Extension, m)	Joint Sets	Weathering grade, W	Fracture intercept, F	Seepage
LAGOA SLOPE	1		0 - 13,9	N140º-150ºE; 80º-90º NE; N30º-60ºE; 75-80º SE; N0º-10ºE; 50º-80º NW	Moderately weathered (W_3) to highly weathered (W_4)	Moderate to wide spacing (F_3 to F_2) but, sometimes, closed spacing (F_4); min: 10 cm, max: 130 cm; average value = 49,2 cm	Drops; 10<drops/min<100
			61,1 - 70,8				
	2		133,0 - 161,9			Wide to moderate spacing (F_2 to F_3) but, sometimes, closed spacing (F_4); min: 10 cm, max: 170 cm; average value = 68,7 cm	Damp; 1<drops/min<10
			192,0 - 230,0				
	3	Slope 1	13,9 - 34,5	N30º-50ºE; 60º-90º SE; N130º-150ºE; 70º-80º NE; N10º-20ºE; 30º-40º NW	Moderately weathered (W_3) to fresh-rock to slightly weathered (W_{1-2})	Moderate to wide spacing (F_3 to F_2) and rarely, closed spacing (F_4); min: 10 cm, max: 180 cm; average value = 60,1 cm	Dry
			86,5 - 98,0				
			161,9 - 186,1				
			242,0 - 268,3				
		Slope 2	0 - 39,0		Moderately weathered (W_3) to highly weathered (W_4)	Wide to moderate spacing (F_2 to F_3); min: 10 cm, max: 200 cm; average value = 72,1 cm	Dry
	4		34,5 - 61,1	Non available	Completely weathered rock (W_5)	Non available	Dry to minor inflow
			70,8 - 86,5				
			98,0 - 133,0				
			186,1 - 192,0				
			230,0 - 242,0				
AMORES SLOPE	1		0 - 32,6	N 130º-150ºE; 65º-85ºSW;	Moderately weathered (W_3) to fresh-rock to slightly weathered (W_{1-2})	Wide to moderate spacing (F_2 to F_3) but, sometimes, closed spacing (F_4); min: 5cm, max: 270 cm; average value = 73,7 cm	Mostly dry to damp (1<drops/min<10)
			85,4 - 125,8	N60º-70ºE; 60º80ºSE			
	2		32,6 - 85,4	Non available	Completely weathered rock (W_5)	Non available	Dry to minor inflow
CANCELA SLOPE	1	Slope 1	0 - 38,8	N130º-140ºE; 70º-90º NE; N20º-40ºE; 55º-75º SE	Moderately weathered (W_3) to highly weathered to completely (W_{4-5})	Wide to moderate spacing (F_2 to F_3) but, rarely, closed spacing (F_4); min: 20 cm, max: 152 cm; average value = 71,7 cm	Dry
		Slope 2	0 - 11,5	N140º-150ºE; 80º-90º NE; N60º-80ºE; 80º-90º SE	Moderately weathered (W_3)	Moderate to wide spacing (F_3 to F_2); min: 35 cm, max: 169 cm; average value = 63,8 cm	Dry

Concerning Lagoa slope, four hydrogeomechanical zones were determined depending on its water content (Meirinhos, 2015):

- HGMZ 1 includes the two sections that had the higher flowing water on all the slope length, with water drops ranging from 10 drops/min to 100 drops/min;
- HGMZ 2, less humid, with a flowing yield that ranges from 1 drop/min to 10 drops/min;
- HGMZ 3 includes only dry sections;
- HGMZ 4 comprises sections completely weathered where it was not possible to retrieve parameters.

As for the fracture intercept, HGMZ 1 had the lowest value in Caldas da Cavaca study site, 49,2cm (F_3). HGMZ 2 and HGMZ 3 had values of, respectively, 60 cm and 72 cm (F_2). Regarding the rock mass weathering degree, the zone HGMZ 1 supports the possibility of water seepage and infiltration, as it is mostly weathered to highly weathered (W_3 to W_4). HGMZ 3 showed a better rock quality, from weathered to fresh to slightly weathered (W_3 to W_{1-2}).

Concerning Amores slope (Meirinhos, 2015), two zones were determined, HGMZ 1 and HGMZ 2. Regarding HGMZ 1, although, there were some joints, conveying water to the outcrop surface, they were minimal and mostly wet, so this slope was considered mainly dry with a few spontaneous drops, varying from 1 drop/min to 10 drops/min. The rock mass is moderately weathered (W_3) with sections of fresh to slightly weathered (W_{1-2}). Also in this zone, the average fracture intercept value is 73.7 cm (F_2) with a maximum value of 270 cm (F_1). HGMZ 2 is a completely weathered zone, acting like a soil mass, where it was not possible to identify discontinuities.

Concerning Cancela slope (Meirinhos, 2015), the collected data was from two separated slopes and only one zone was determined, corresponding to a dry zone. The rock mass appeared to be moderately weathered (W_3) on both slopes, but sometimes highly to completely weathered (W_{4-5}) on slope 1. The average fracture intercept value for slope 1 was 71.7 cm having it, mostly, a wide to moderate spacing (F_2 to F_3). For slope 2 the average value of fracture intercept is 63.8 cm having a moderate to wide spacing (F_3 to F_2).

3.4.3. In situ hydrogeophysical data

The discharge area of the aquifer hydromineral was the target of two geophysical surveys using geoelectrical methods (details in Teixeira, 2011): (a) with electrical tomography (Espinha Marques et al., 2008a,b), (b) other with electromagnetic methods electromagnetic conductivity Geonics EM34-3 model (GeoSonda, 2004; TARH, 2005).

The electromagnetic survey culminated in a set of electromagnetic profiles over an area of approximately $3184m^2$(Figure 46). However, throughout the electrical and electromagnetic surveys, depths not exceeded 50 m. Through the electric conductivity maps, vertical dipole configuration, geoelectrical surveys defined structures were identified by alignments of high conductivity values, i.e., a structure with approximate geoelectric N-S direction NNE-SSW, which develops in depth. The orientation of this structure is consistent with a major tectonic lineament systems inferred by photo-interpretation and field mapping, the digital terrain model and the geostructural and geomorphological mapping, sometimes presented (details in TARH, 2005). However, the interpreted megastructure in the previous studies where the probable location was one of the criteria to locate the boreholes, appears to have more continuity, having been interpreted considering new data coming from new groundwater engineering operations

The presence of mineral water in boreholes enable the definition of a structure with an approximate direction N30ºE as the potential conditioner of groundwater flow in the area of Caldas da Cavaca, as it may correspond to a higher permeability zone in the granitic rock mass which allows the rise and the emergence of mineral water. This increased permeability is probably associated with a deep tectonic node originated by the intersection of two main families of deep fractures, one with direction N-S dipping 70º-80ºW and the other with direction NW-SE with subvertical tendency. It should be noted that there is another fracture family, discrete oriented to W-E. The strong hydraulic charges, combined with the density lowering caused by temperature and gases in solution, may be the cause for the rise of mineral water in a clear context of deep tectonic node and a crustal damage zone.

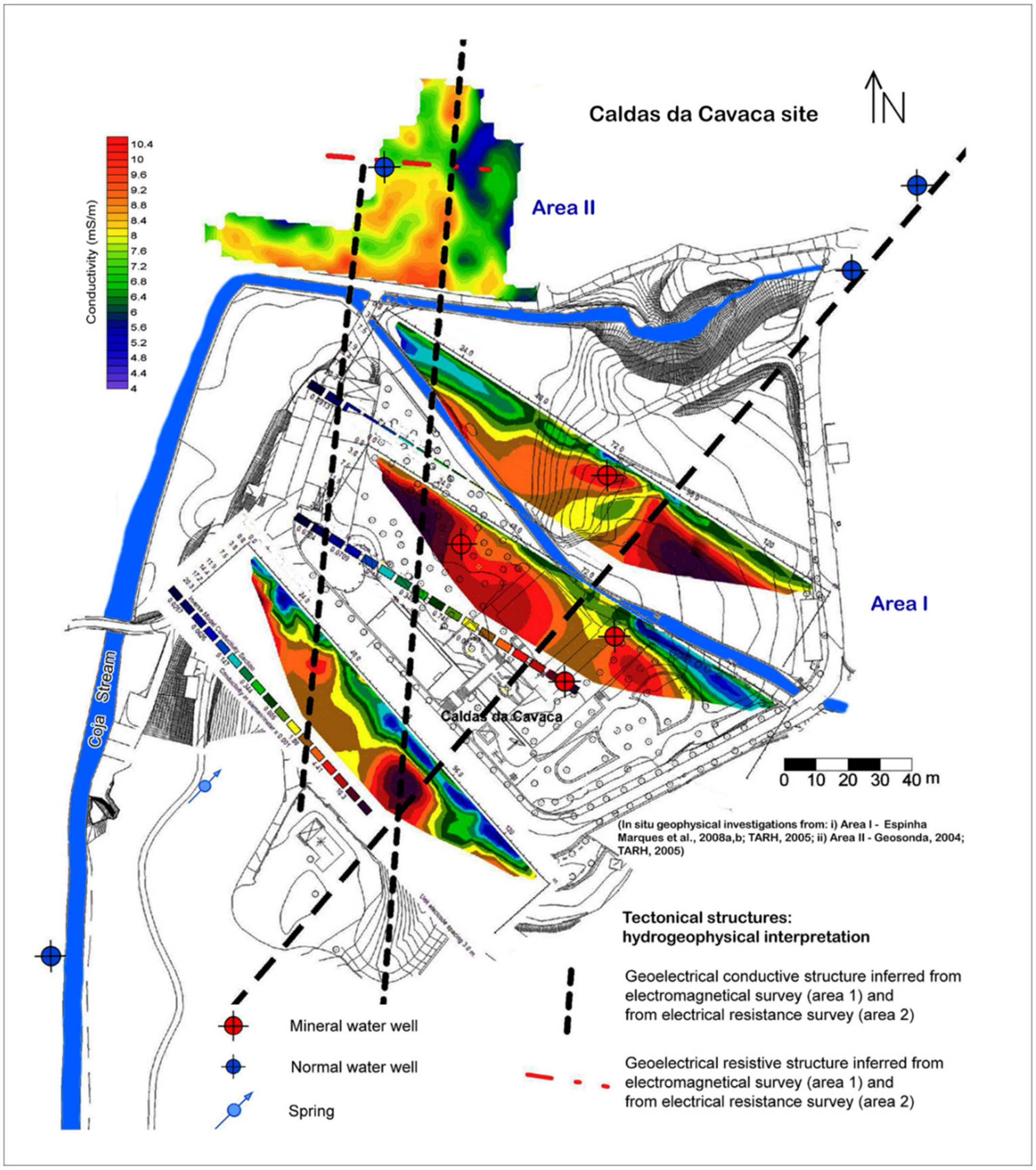


Figure 46. Synthetic interpretation of geophysical surveys in the area of Caldas da Cavaca (updated from Teixeira, 2011).

3.4.4. Vulnerability assessment

The intrinsic vulnerability assessment for the aquifer systems in Caldas da Cavaca was previously evaluated by Teixeira et al. (2015) based on GOD-S, DRASTIC-Fm, SINTACS and SI indexes. Tables 26, 27, 28 and 29 present a synthesis of the parameters description, along with the classification adopted for the four methods, GOD-S, DRASTIC-Fm, SINTACS and SI indexes (Fig. 47).

Table 26. GOD-S parameters used in the surrounding area of Caldas da Cavaca site (adapted from Teixeira, 2011 and Teixeira et al., 2015).

	HYDROGEOLOGICAL UNITS				
	Sands and gravels	**Highly weathered coarse grained granite (W_{4-5})**	**Moderately weathered coarse grained granite (W_3)**	**Fresh to slightly weathered coarse grained granite (W_{1-2})**	**Fresh to weathered dolerite**
G	unconfined	confined/semi-confined	confined/semi-confined	confined/semi confined	confined
O	Alluvial sands and gravels	igneous formations	igneous formations	igneous formations	igneous formations
D	< 5	5-20	5-20	< 5	5-20
S	silty sand	silty clay	silt	thin/absent	silty clay

Table 27. DRASTIC-Fm parameters used in the surrounding area of Caldas da Cavaca site (adapted from Teixeira et al., 2015).

	HYDROGEOLOGICAL UNITS				
	Sands and gravels	**Highly weathered coarse grained granite (W_{4-5})**	**Moderately weathered coarse grained granite (W_3)**	**Fresh to slightly weathered coarse grained granite (W_{1-2}))**	**Fresh to weathered dolerite**
D (see **D** GODS)	1.5 – 4.6	4.5 - 9	4.5 - 9	1.5 - 4.6	4.6 – 9.1
R	250	175	175	175	175
A	sand and gravel	igneous/weathered igneous	igneous/weathered igneous	igneous	igneous/weathered igneous
S (see **S** GODS)	sandy loam	clay loam	silty loam	sandy loam	clay loam
T*	0 - 60%	0 - 60%	0 - 60%	0 - 60%	0 - 60%
I (see **O** GODS)	sand and gravel with significant clay	sand and gravel with significant clay	igneous	igneous	igneous
C	< 4.1 m/day	< 4.1 m/day	< 4.1 m/day	< 4.1 m/day	< 4.1 m/day
Fm**	0 – 25 km of lineament/km^2	0 – 25 km of lineament/km^2	0 – 25 km of lineament/km^2	0 – 25 km of lineament/km^2	0 – 25 km of lineament/km^2

** Topography values are calculated for each pixel of the raster dataset*
*** Fm parameter varies for each pixel of the raster dataset*

Table 28. SINTACS parameters used in the surrounding area of Caldas da Cavaca site (adapted from Teixeira et al., 2015).

	HYDROGEOLOGICAL UNITS				
	Sands and gravels	**Highly weathered coarse grained granite (W_{4-5})**	**Moderately weathered coarse grained granite (W_3)**	**Fresh to slightly weathered coarse grained granite (W_{1-2})**	**Fresh to weathered dolerite**
Soggicenza (depth to groundwater) (m) See Depth to groundwater for DRASTIC	1.5 – 4.6	4.5 - 9	4.5 - 9	1.5 - 4.6	4.6 – 9.1
Infiltrazione (effective infiltration) (mm/y) See Net Recharge for DRASTIC	250	175	175	175	175
Tipologia della cobertura (soil /overburden attenuation capacity) See Soil media for DRASTIC	sandy loam	clay loam	silty loam	sandy loam	clay loam
Acquifero (satured zone characteristics) See Aquifer media for DRASTIC	coarse alluvial deposit	fissured plutonic rock	fissured plutonic rock	fissured plutonic rock	fissured plutonic rock
Conductivity (hydraulic conductivity) (m/s) See Hydraulic conductivity for DRASTIC	$5E^{-5}$ - $1E^{-4}$	< $5E^{-5}$	< $5E^{-5}$	< $5E^{-5}$	< $5E^{-5}$
Superficie topografica (topographic surface slope) (%) See Topography for DRASTIC	The rating for this parameter is variable since slope values are calculated for each pixel of the ArcGIS raster dataset				

Table 29. SI parameters used in the surrounding area of Caldas da Cavaca site (adapted from Teixeira et al., 2015).

	HYDROGEOLOGICAL UNITS				
	Sands and gravels	**Highly weathered coarse grained granite (W_{4-5})**	**Moderately weathered coarse grained granite (W_3)**	**Fresh to slightly weathered coarse grained granite (W_{1-2}))**	**Fresh to weathered dolerite**
D	1.5 – 4.6	4.5 - 9	4.5 - 9	1.5 - 4.6	4.6 – 9.1
R	250	175	175	175	175
A	sand and gravel	igneous/weathered igneous	igneous/weathered igneous	igneous	igneous/weathered igneous
T	The rating for this parameter is variable since slope values are calculated for each pixel of the ArcGIS raster dataset				
LU	The rating for this parameter is variable since land use is calculated for each pixel of the ArcGIS raster dataset				

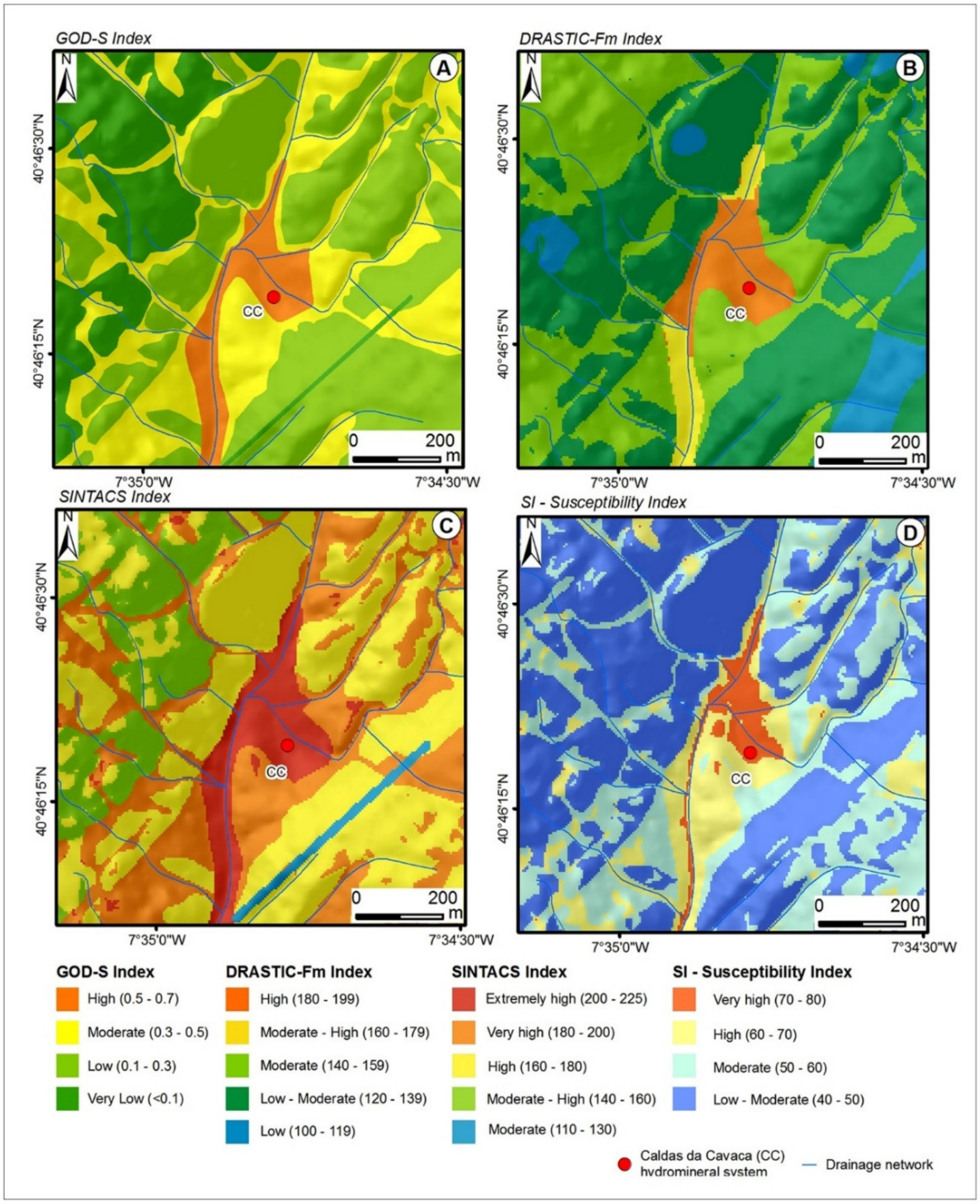


Figure 47. Vulnerability indexes from Caldas da Cavaca aquifer systems and surrounding area: a) GOD-S; b) DRASTIC-Fm; c) SINTACS; d) SI (updated from Teixeira et al., 2015).

According to GOD-S index (Fig. 47.a), most of the Caldas da Cavaca area fits in a moderate vulnerability category. This category is compatible with the highly weathered granite (W_{4-5}). The low and very low vulnerability categories are related to the moderately weathered (W_3) to slightly weathered (W_{1-2}) granite and with the dolerite dykes. On the contrary, the high vulnerability category compatible with the alluvia sedimentary cover, in a narrow strip along the bottom of the valley.

Considering DRASTIC-Fm index (Fig. 47.b), a clear dominance from the lithology becomes apparent and clear in the moderate-high and high vulnerability categories. Those categories are closely associated with the flat valley bottom, where the alluvia sedimentary cover prevails. The moderate vulnerability areas are located SE, N and NW of Caldas da Cavaca thermal site, mostly in large corridors with NE–SW trends. That is in relationship with the slope, the fracturing density and less weathered granite. Almost 50% of the area has low-moderate and low vulnerability. Those areas are located mainly in the NW and SE areas of the study region, close to the Quinta das Lameiras and Cavaca localities.

For SINTACS index, the very high and extremely high values (Fig. 47.c) are located mainly near the settlements of the study site (Quinta das Lameiras, Quinta dos Matos and Cavaca), and in the bottom of Ribeira de Coja valley. The low slope values and lithology (alluvia or highly weathered granite) are the main controlling factors. Higher slope values and less weathered granite are the main features of the moderate-high vulnerability areas, mainly in a large NE–SW corridor, along the valley slopes. The lower index values correspond to the dolerite rocks, and are related to the argillaceous weathering of these dykes.

Taking into account the SI index (Fig. 47.d) reveals a similar pattern with SINTACS. However, land use can be clearly seen as an important parameter, namely around the settlements, where the buildings and agricultural areas are concentrated. Besides, these high to very high vulnerability areas have low slope values. The high slope, rocky outcrops and less weathered granitic areas have moderate or low-moderate vulnerability values. The high vulnerability area showed in the other indexes is not clearly seen in SI index; only a very small area has high vulnerability, in the N of the Caldas da Cavaca thermal site. The figure 48 illustrates schematic block-diagrams with ground conditions and vulnerability index inputs (GOD-S, DRASTIC-Fm, SINTACS, SI).

In this work an exploratory assessment was developed considering the DISCO method (details in Pochon et al., 2008). Groundwater protection zones have been delineated for two groups of water points: the two hydromineral water wells (Figures 49, 50, 51 and 52) and one spring of normal groundwater (Figure 53). Various systems of structural discontinuities at the scale of the groundwater catchment, as well as at outcrop level have been observed. They dictate the location of the springs.

Both the hydromineral water wells and the springs are aligned along major deep crustal fractures, or are close to tectonic lineament nodes (i.e., fracture damage zones). Water wells collect groundwater from the fractured slightly weathered bedrock areas at deep depths (ca. 100-200 m) and the spring drains groundwater from the highly weathered granite. These aquifers are covered by ca. 2-5 m of alluvia sedimentary cover, mainly silty and sandy deposits (details in Carvalho et al., 2005a; Teixeira, 2011).

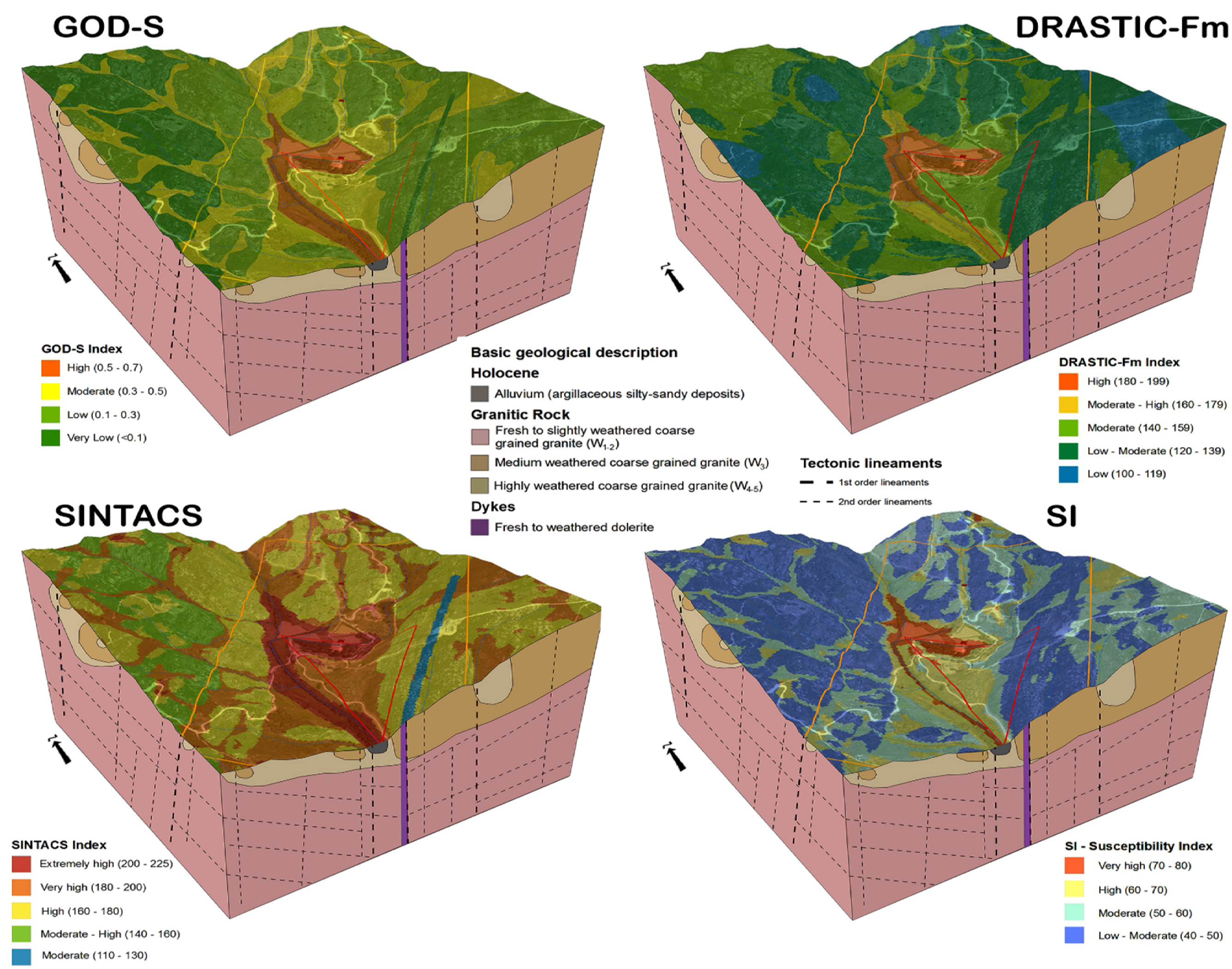


Figure 48. Ground conditions and vulnerability indexes mapping and : GOD-S, DRASTIC-Fm, SINTACS, SI.

The application of the DISCO method included three steps:

1) *Assessment of the discontinuities (DIS) and protective cover (CO) parameters*

The discontinuities parameter (*DIS*) was based on tectonic lineaments analysis, field survey, hydrogeological, hydrogeomechanical and hydrogeophysical data. With reference to the delineation of protection zones at the site, D_0, D_1, D_2 and D_3 were defined according to the rating and criterion defined by Pochon et al. (2008) (Fig. 49). Therefore, buffers were assigned for each category: 25 m for D_0, 10 m for D_1 and 5 m for D_2. D_3 was assigned to the rest of the area.

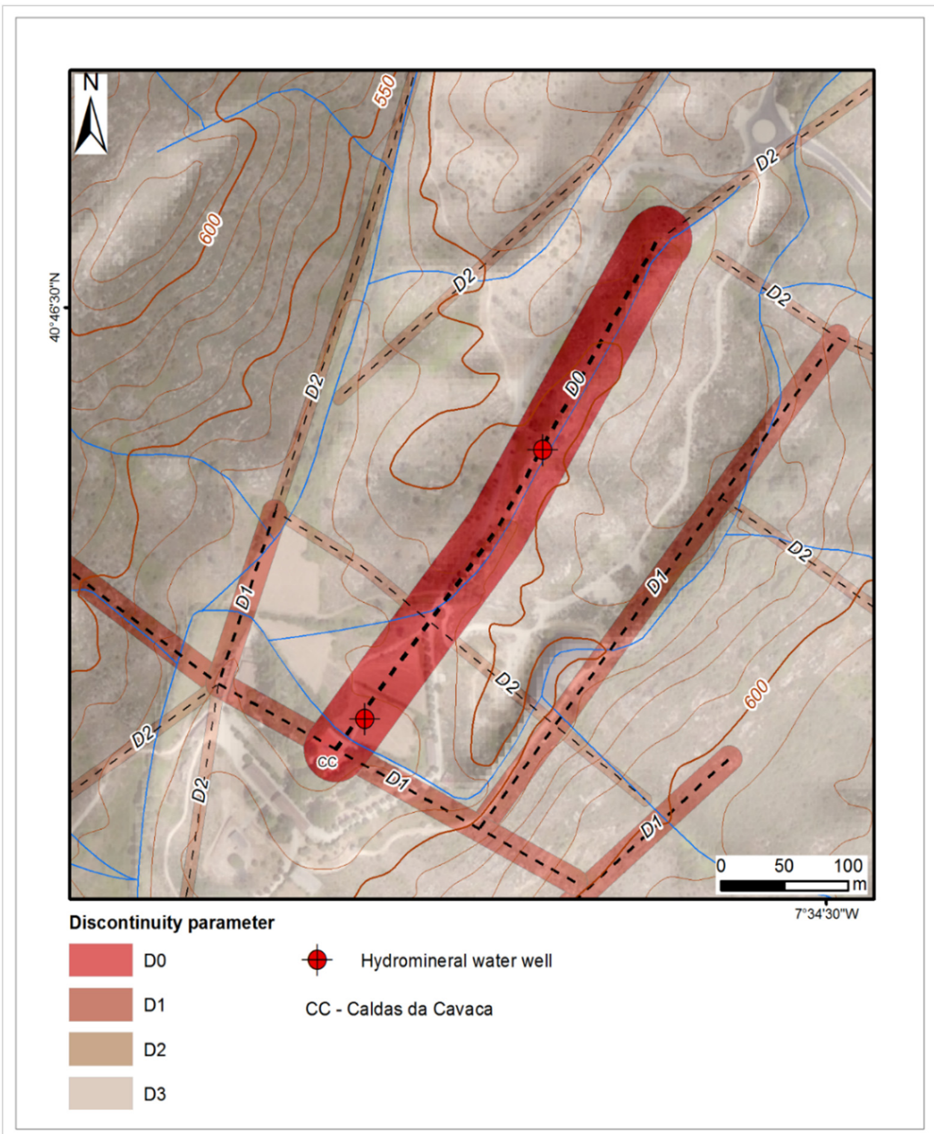


Figure 49. Map of the discontinuities parameter for the hydromineral water wells (Caldas da Cavaca site).

Protective cover parameter (CO) was based on soil analysis, geomorphological mapping, drilling and hydrogeophysics, and was defined according to the rating and criterion defined by Pochon et al. (2008), taking into consideration pedological soils and geological formations overlying the aquifer (Table 30).

Table 30. Protective cover parameter evaluation taking into consideration geological formations and pedological soils overlying aquifers in Caldas da Cavaca site.

		Hydrogeological units				
		Alluvia (argillaceous silty – sandy deposits)	**Highly weathered coarse grained granite (W_{4-5})**	**Moderately weathered coarse grained granite (W_3)**	**Fresh to slightly weathered coarse grained granite (W_{1-2})**	**Fresh to weathered dolerite**
Protective cover: pedological soil	**Description**	High permeability soil (sand, pebbles)	Moderate permeability soil (silt, loam)	Moderate permeability soil (silt, loam)	Moderate permeability soil (silt, loam)	Low permeability soil (loam, clay)
	Thickness (m)	> 5	> 1	0.2 - 0.5	0 – 0.2	> 1
	Class	P_1	P_1	P_0	P_0	P_3
Protective cover: geological formations	**Description**	Combined with P_1 soil	Combined with P_1 soil	Combined with P_0 soil	Combined with P_0 soil	Combined with P_3 soil
	Thickness (m)	> 2	> 2	1 - 2	< 1	> 2
	Class	P_3	P_3	P_2	P_1	P_4
Rating		3	3	2	1	4

Considering this approach, the rating values of “P” range from 1 to 4, with increasing values corresponding both to higher protective cover thickness and/or lower permeability of the deposits. This way, “P” areas correspond to (Fig. 50):

- P1 - fresh to slightly weathered coarse grained granite, covered by moderate permeability soils;
- P2 - moderately weathered coarse grained granite, covered by moderate permeability soils;
- P3 - highly weathered coarse grained granite and alluvia deposits, covered by moderate to high permeability soils;
- P4 - fresh to weathered dolerite, covered by low permeability soils.

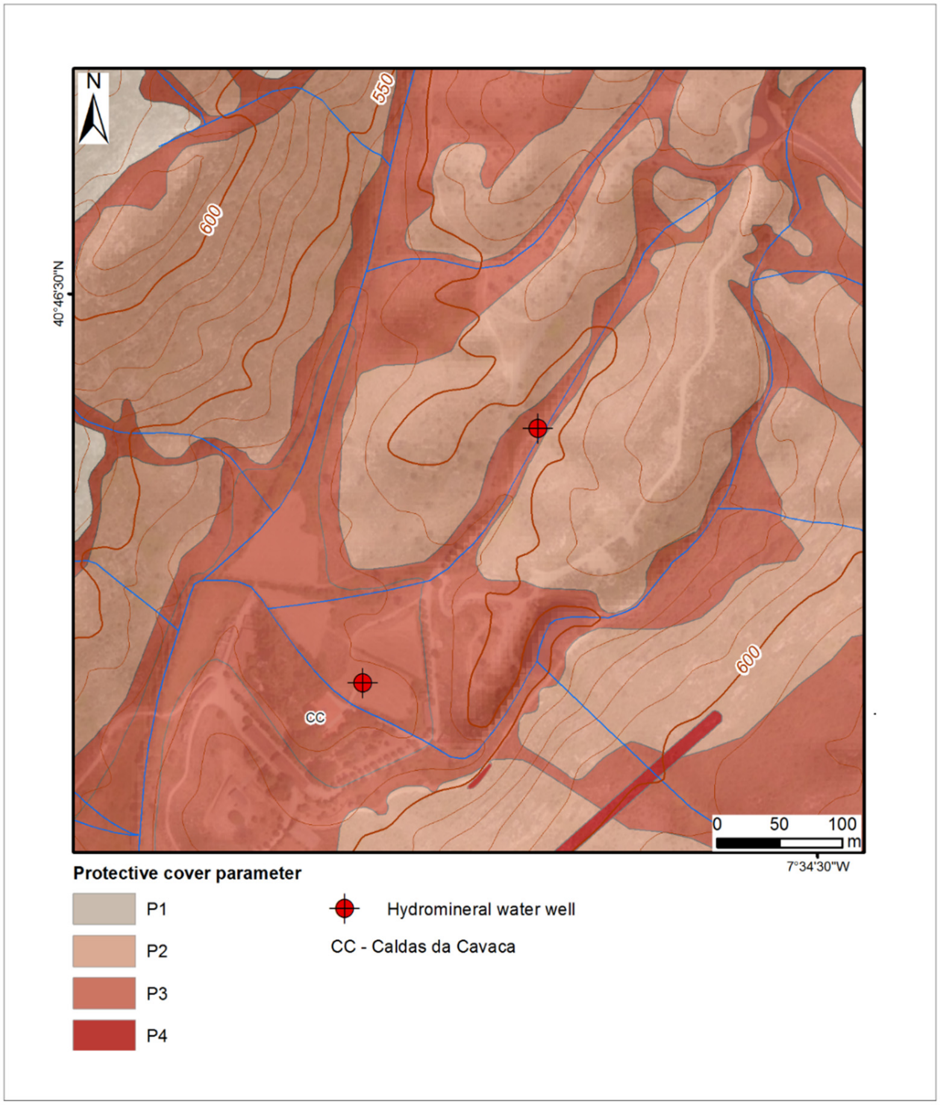


Figure 50. Map of the protective cover parameter for the hydromineral water wells (Caldas da Cavaca site).

2) Determination of the intermediate protection factor (F_{int})

Considering expression [24], previously presented in topic 2.11.5, it was possible to calculate the intermediate protection factor (F_{int}). Accordingly, this factor ranged from 2 (low protective effect) to 7 (moderate protective effect).

According to the conversion between the protection factor F and the groundwater protection zones presented in Table 20, the relation between F_{int} and groundwater protection zones (S) is the following (Fig. 51):

- Zone S_2 is compatible with F_{Low} (2, 3, 4) where the values 2, 3 and 4 are related with lineaments and to the moderately to highly weathered coarse grained granite (W_3 to W_{4-5});
- Zone S_3 is compatible with F_{Moderate} (5, 6, 7) where the values 5 and 6 are related with some lineaments and value 7 is related with the fresh to slightly weathered coarse grained granite (W_{1-2}).

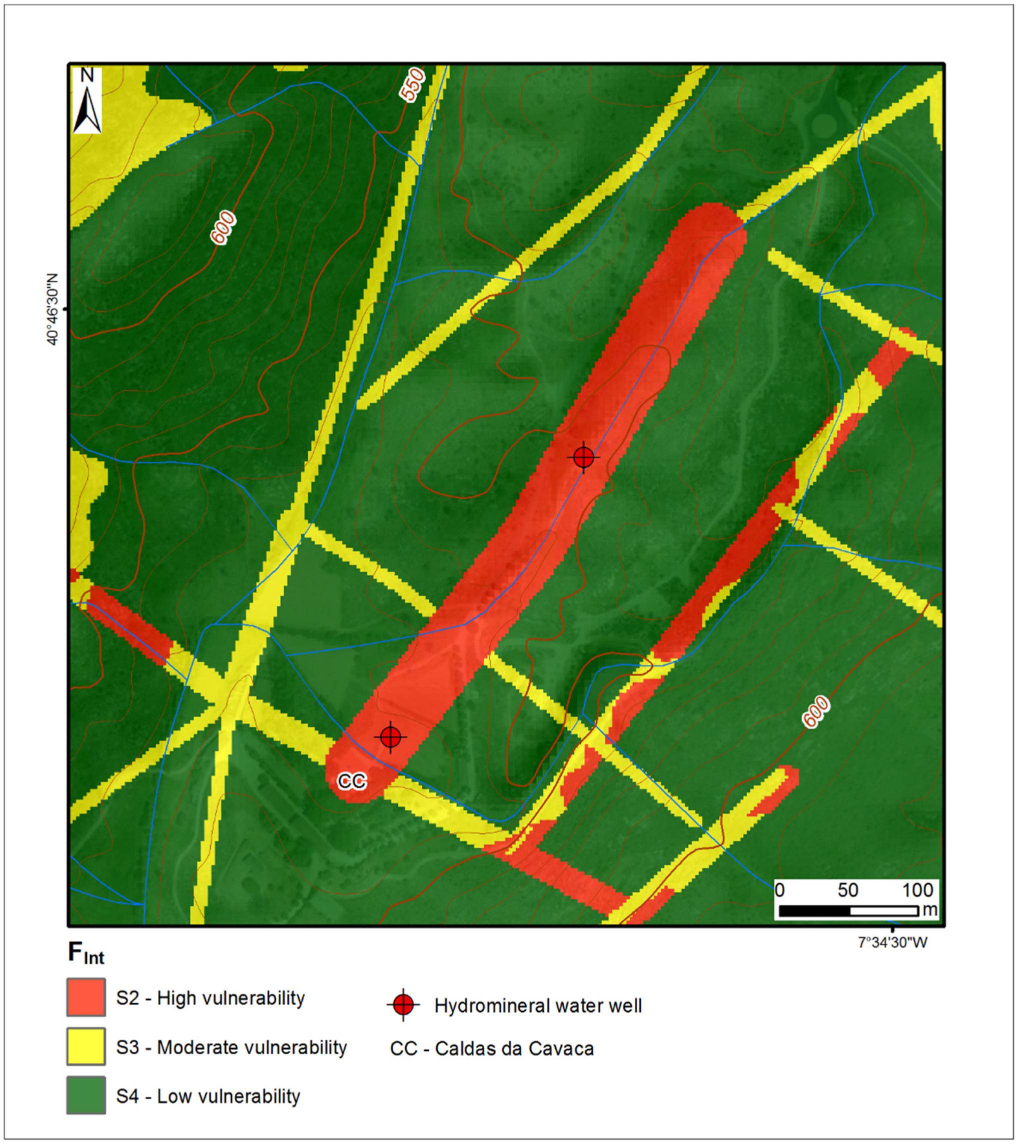


Figure 51. Map of the intermediate protection factor for the hydromineral water wells (Caldas da Cavaca site).

3) Protection zone delineation (F)

Due to the slope topography and the presence of low permeability cover over some parts of the area, it was necessary to adjust the F_{int} map, taking the runoff parameter into account. The protection zone map (Fig. 52) shows that S_2 zones (high vulnerability) were assigned to the most important draining discontinuities (first order lineaments), and the S_3 zones (moderate vulnerability) were assigned to the second order lineaments in the site; S_4 zones (low vulnerability) were assigned to the rest of the area.

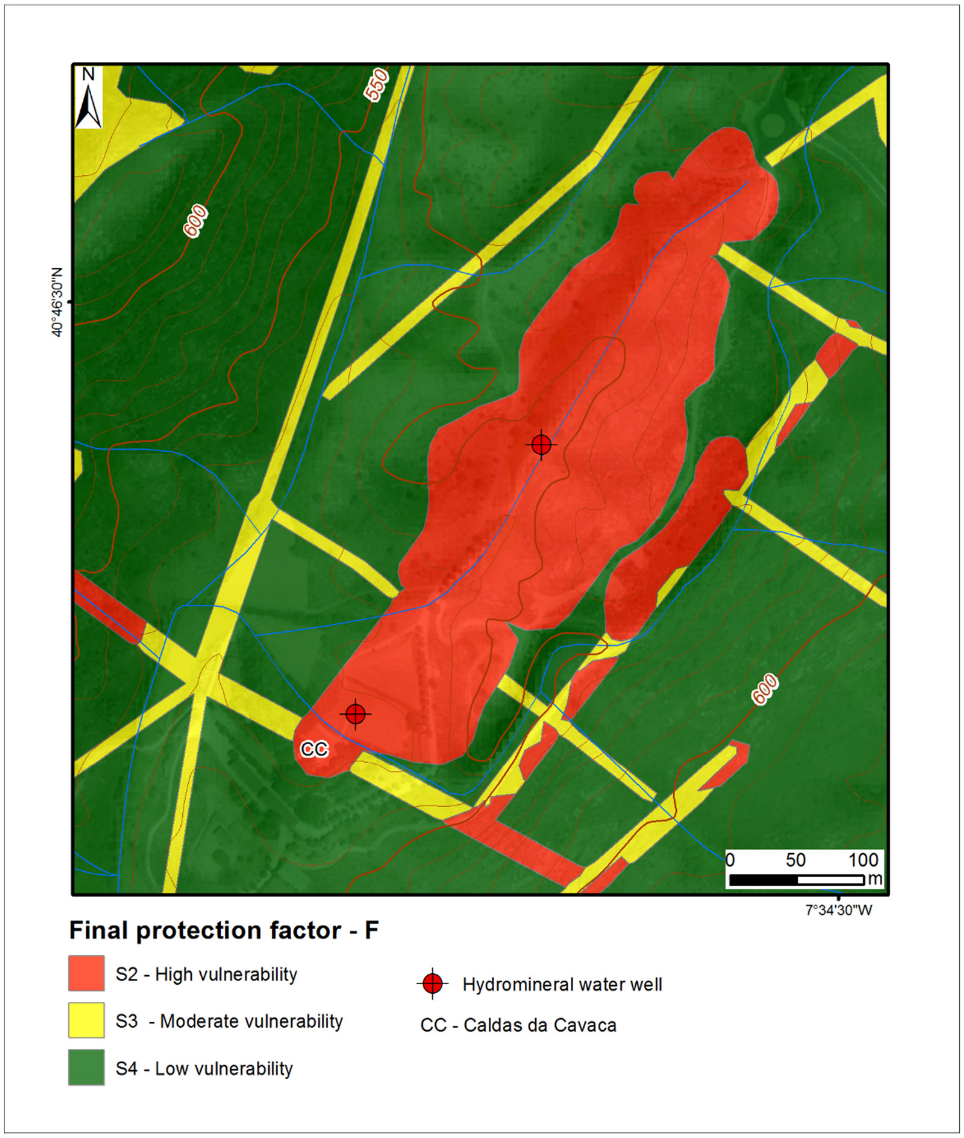


Figure 52. Map of the final protection factor for the hydromineral water wells (Caldas da Cavaca site).

A similar approach was applied to a spring of normal groundwater as it is presented in Fig. 53.

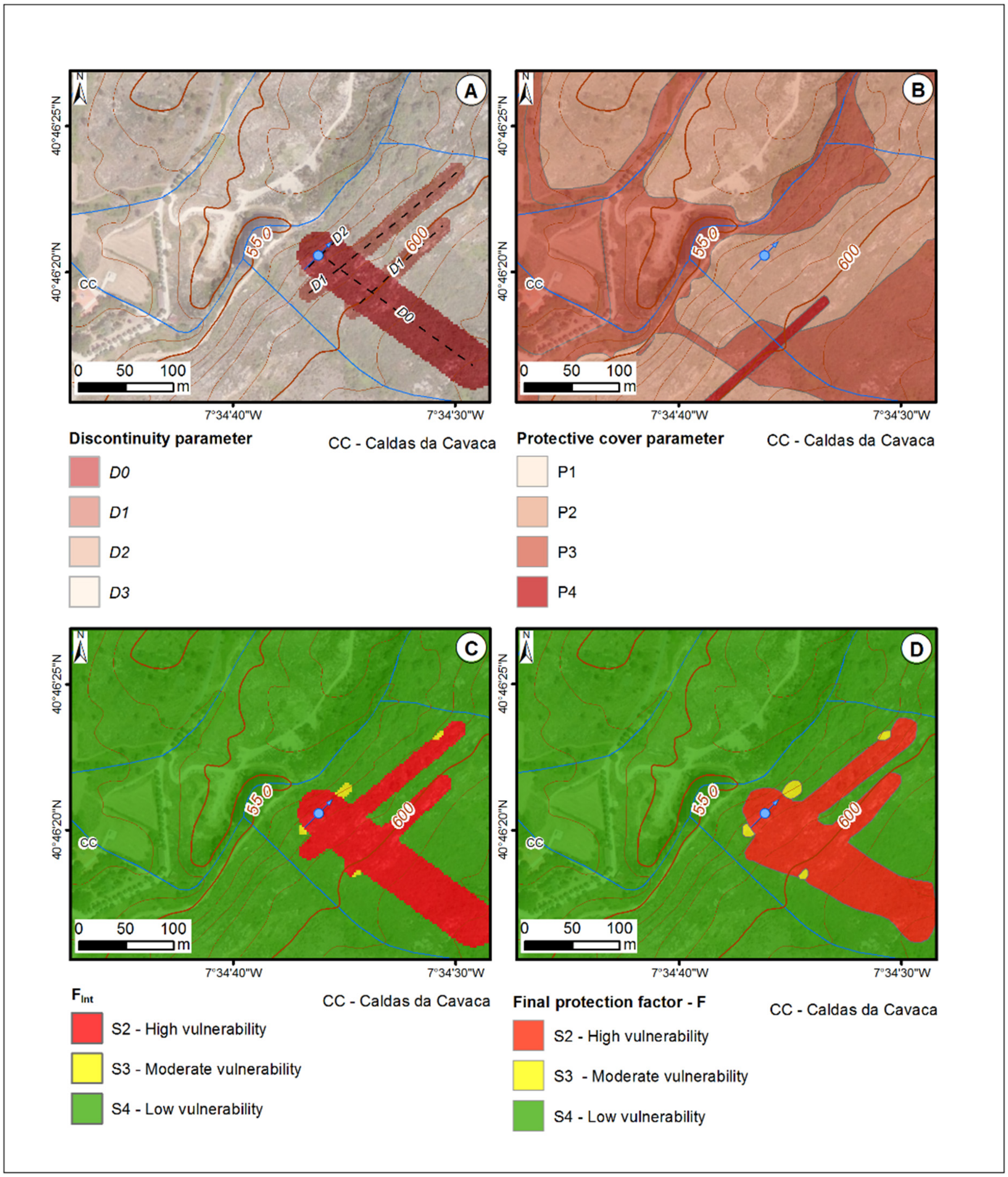


Figure 53. DISCO method applied to a spring at Caldas da Cavaca site: a) discontinuity parameter; b) protective cover parameter; c) intermediate protection factor (F_{int}); d) Final protection factor (F).

The wellhead protection areas established, by the technical director of the hydromineral resources, in 1996 by the Portuguese legislation for Caldas da Cavaca spa are presented in Fig. 54. These areas were proposed for the former hydromineral water well that was located inside the red triangle area.

Most of the groundwater protection S_2 zones (high vulnerability) defined for DISCO method (Fig. 52) includes the immediate and intermediate areas previously proposed in 1996. On the other hand, most of S_3 zones (moderate vulnerability) and S_4 zones (low vulnerability) are included in the extended area defined in 1996.

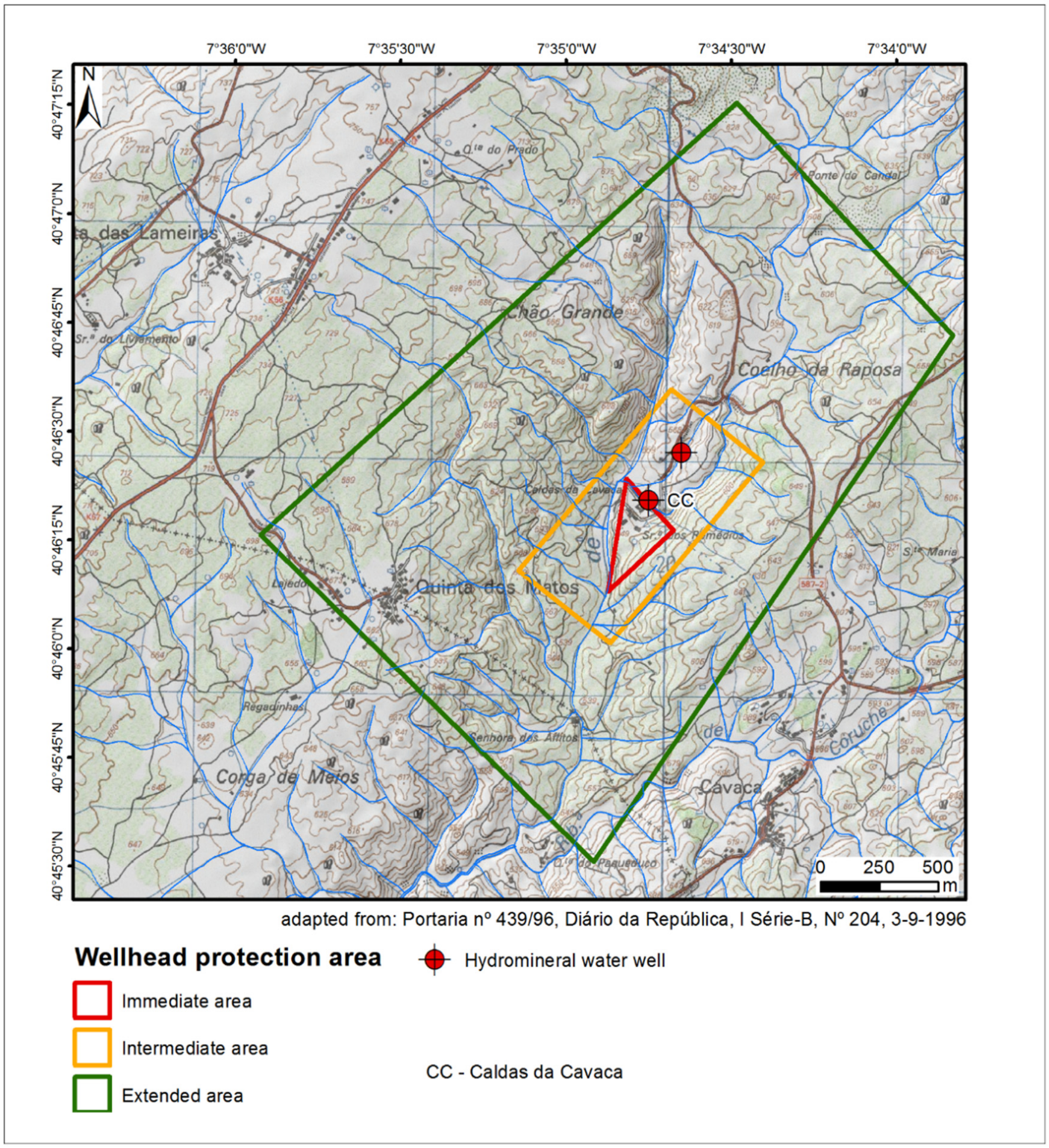


Figure 54. Wellhead protection areas defined in 1996 for Caldas da Cavaca spa.

3.5. Hydrogeology conceptual site model: inputs from vulnerability mapping

The Caldas da Cavaca hydromineral system discharge zone are constituted by the following main aquifer types (details in Carvalho et al., 2005a; Teixeira, 2011; Teixeira et al., 2010, 2015), see figure 55 (A, B):

i) Shallow, unconfined aquifer, related to the alluvia cover, and located in the valley bottom, near the Caldas da Cavaca thermal site; the groundwater has a pH 5 – 6.5 and electrical conductivity under 20 μS/cm (very low mineralization). Water temperature is strictly dependent of the air temperature;

ii) An unconfined to semi-confined aquifer, in the weathered rock mass and in fractured granite. These groundwaters have pH of 5 – 6.5 and electrical conductivity varying from 20 – 50 μS/cm (low mineralization). The water yields, in the measured springs, are very low (< 0.05 L/s), and the transmissivity is lower than 1 m^2/day;

iii) A deep confined hydromineral aquifer controlled by a deep fault zone, in the fresh granite. The hydromineral water has temperatures around 30ºC (mesothermal waters), higher electrical conductivities (350 – 400 μS/cm; medium mineralized waters) and pH around 8.4 – 8.6. These waters have an alkaline reaction, a sodium bicarbonate facies, fluoridated and sulphurous. The transmissivity in the hydromineral aquifer varies from 27 – 136 m2/day. The Ribeira de Coja fault zone, with general NNE–SSW trend, mapped around Caldas da Cavaca area, has a regional cartographic expression, and locally, fault gouge was observed. This may be the main structure controlling the occurrence of hydromineral waters in this site.

The hydrogeological parameters were assessed and, using the previously defined general hydrogeological conceptual model for Caldas da Cavaca hydromineral system by Teixeira (2011) and Teixeira et al. (2015), new information was plotted. Where the hydromineral system of Caldas da Cavaca characterized by precipitation range from 1150 – 1300 mm/year; actual evapotranspiration range from 575 – 600 mm/year; surface run off from 475 – 500 mm/year and recharge from 175 – 180 mm/year also the hydromineral water wells yield [Q] which is difference between Q = 1 L/s in the slope and Q = 4 L/s in the valley. All the previous properties established a clearer overview of the hydraulic behavior on Caldas da Cavaca area.

As it is possible to observe on the following Figure 55 (A,B), the geostructural framework, geological description of the site, hydrogeological inventory and rock mass geotechnical conditions was encompassed, which can contribute to a re-evaluation and/ or redefinition of wellhead protection areas, for hydromineral groundwater in the study site.

According to the vulnerability DISCO index (figure 55.C) it is possible to create a hydrogeological conceptual site model based on the final protection factor (F) for the Caldas da Cavaca site. Where figure 55 (C) show hydrogeological conceptual site model depending on the vulnerability DISCO index inputs. However, the DISCO index are in general accordance with the other vulnerability studied indexes (particularly, GOD-S, DRASTIC-Fm, SINTACS, SI); see figure 48. Where the high vulnerability were assigned to the most important draining discontinuities (first order lineaments), and the moderate vulnerability were assigned to the second order lineaments (and related fractures and joints) in the site and the low vulnerability were assigned to the rest of the area.

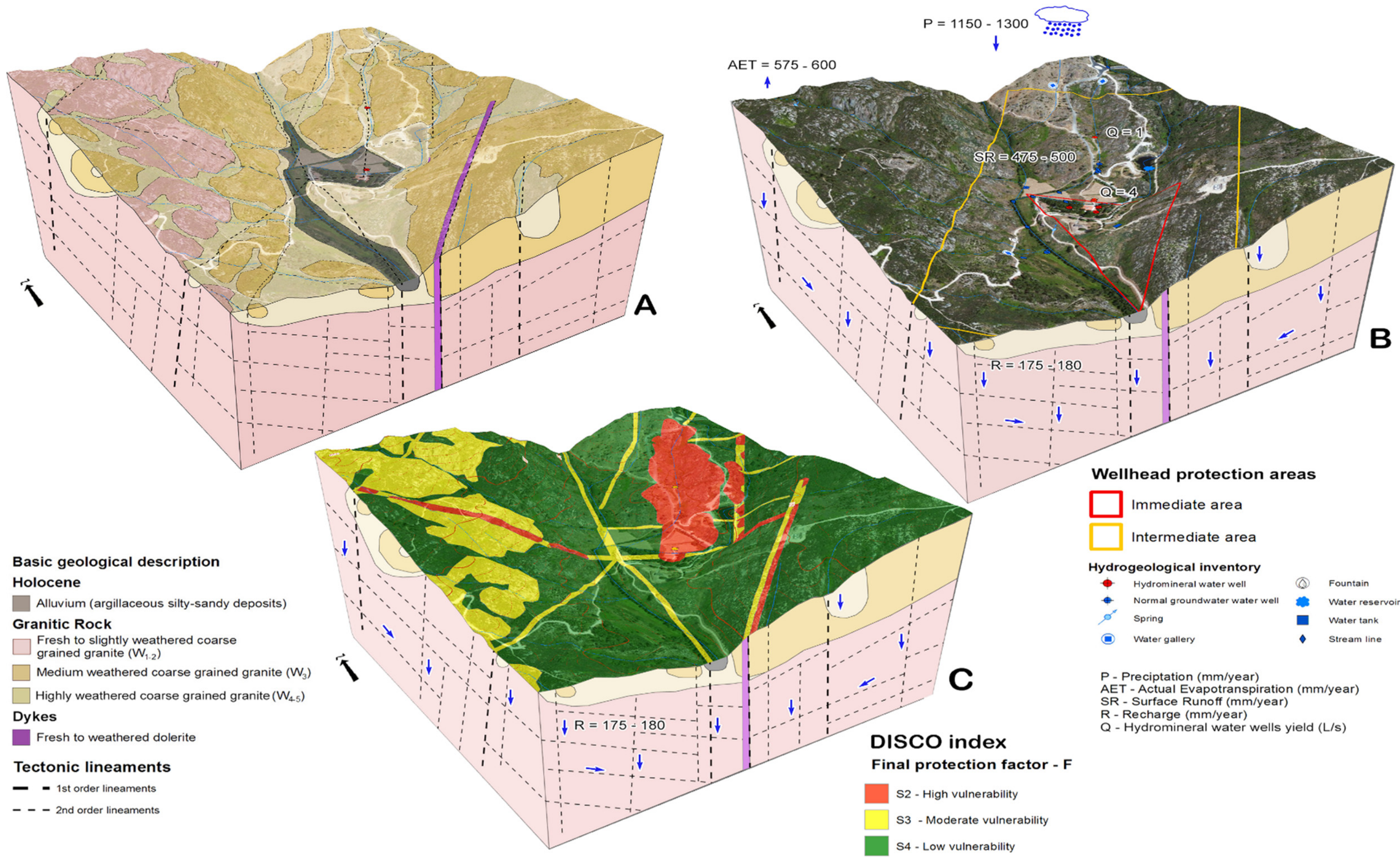


Figure 55. Hydrogeological conceptual model from Caldas da Cavaca hydromineral system: vulnerability DISCO index assessment input. A) general geological and surface geotechnical conditions; B) hydrogeological conceptual site model (adapted from Teixeira, 2011; Teixeira et al., 2015); C) vulnerability DISCO index inputs.

4. Conclusions

The evaluation of groundwater vulnerability to contamination through vulnerability assessment mapping provides a visual analytics and quantitative tool to help planners and decision makers faced with the increasing pressure of development and residential dependency on groundwater as primary source of drinking water and for the industry of hydromineral resources.

This work was focused on Caldas da Cavaca spa, which is located in the Central Portugal, in the municipality of Aguiar da Beira, and was based on a multidisciplinary approach including geotectonics, land cover, surface hydrology, hydrogeology, hydrogeomorphology, hydrogeophysics, hydrogeotechnics, and groundwater vulnerability to contamination. This study was performed using a GIS mapping technology which can provide an accurate method to assess hydrogeomorphological features that are suitable to infiltration and aquifer recharge or discharge. Furthermore, GIS contribution is important to build and improve the hydrogeological conceptual model of the study area. In addition, a groundwater vulnerability assessment, with the GOD-S, DRASTIC-Fm, SINTACS, SI and DISCO methods, was developed. This work was focused, particularly, in the use of the DISCO methodology on the well and spring areas.

The main factors controlling the infiltration and recharge in Caldas da Cavaca region are the highly weathered granite, the close fracturing degree, as well as the planned surfaces in the higher areas, especially when the land use corresponds to agricultural or forest areas. Regarding the discharge, it can be controlled by the fresh granite, in the areas with higher fracturing degree, and especially in the lower areas of the valleys.

Some recent studies achieved several important remarks concerning the hydrogeological and hydrogeomechanical framework of Caldas da Cavaca rock mass, such as:

- Identifying the geological description in the site (weathered coarse grained granite in addition to the dolerite dykes), the type of waters (normal and hydromineral water), the infiltration potential zoning (high infiltration potential) and the drainage network (high drainage network); details in Teixeira (2011);
- Determination for each of Amores, Lagoa and Cancela slopes the main type of discontinuities, weathering grade, water content, and the hydrogeomechanical zones (details in Meirinhos, 2015);

The intrinsic groundwater vulnerability assessment for the aquifer systems in Caldas da Cavaca area was evaluated based on GOD-S, DRASTIC-Fm, SINTACS, SI and DISCO indexes. GOD-S indicated that most of the Caldas da Cavaca area fits in a moderate vulnerability category and the high vulnerability category compatible with the alluvia sedimentary cover, in a narrow strip along the bottom of the valley; DRASTIC-Fm indicated that most of the Caldas da Cavaca area fits in a moderate-high and high vulnerability categories. Those categories are closely associated with the flat valley bottom, where the alluvia sedimentary cover prevails; SINTACS indicated that very high and extremely high values are located mainly near the settlements of the study site, and in the bottom of Ribeira de Coja valley; SI revealed a similar pattern with SINTACS. DISCO indicated that the zones of the hydromineral wells and the spring fit in a high vulnerability, and the rest of the area fits in a low vulnerability;

All these assessments permitted to rebuild and improve the hydrogeological conceptual model of the study area. This model is very useful in the decision-making process regarding the integrated management of the water resources. In addition, it may help to plan future hydrogeological investigations, and thus, reduce the costs of more advanced studies. Also, it may support the definition of the most vulnerable areas to contamination and to delineate wellhead protection areas, as well as to achieve a sustainable management of groundwater resources in this region.

For the improvement of the vulnerability assessment analysis in the future, research challenges can be found in the following aspects:

- Develop methods for accounting preferential flow pathways that can affect strictly the vulnerability;
- Define additional categories of vulnerability and determine which processes are most important to be incorporated into vulnerability assessment at different spatial scales;
- Studies must be more heterogeneous and more specific analysis, in order to obtain results as close as the inherent reality of the study;
- Establish conceptual and operational basis for combining vulnerability methods and the results of process based models.

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