HYDROGEOLOGICAL BASINS: CONCEPTS AND APPLICATIONS

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ABSTRACT

A hydrogeological basin represents a subsurface compartment, represented by an aquifer, a set of aquifers, or a part of a stratigraphic unit, which flow converges towards a single point or discharge area. Thus, an aquifer or aquifer system can either represent a single hydrogeological basin, or can be subdivided into different basins, depending on the divergent arrangement of the directions of the underground flow. Unlike a watershed that may have its exutory, represented by a point that represents the entire upstream area, the hydrogeological basins often have the discharge zone commonly represented by an area, a surface water body, or a surface watercourse segment. A set of hydrogeological basins can occur overlapped due to regional geological complexity, thickness of the strata, and surface relief. Determining the boundaries of the hydrogeological basins associated with an aquifer or set of aquifers is important to understanding the flow dynamics at subsurface and the relationship with the overlapping watersheds on the surface. Different techniques and methods can be applied to the determination and cartography of hydrogeological basin boundaries including, potentiometry, geophysics, hydrochemistry, hydrological techniques, tracer tests, isotopic hydrology, among others. However, despite its importance, this is not a recurring theme in the literature applied to groundwater resources, being a terminology still little used in scientific research. Most of the citations to this denomination only refer to aquifers, sets of aquifers, and hydrostratigraphic units, without considering the actual concept of hydrogeological basins. Considering these issues, the present paper proposes a review of the knowledge about hydrogeological basins to expand and update its concept and discuss its applications for different contexts, including water resources management, artificial recharge projects, estimation of water reserves, development of conceptual models and numerical simulations, among others.

Keywords: Groundwater basin; Watershed; Water resources; Management.

RESUMO

BACIAS HIDROGEOLÓGICAS: CONCEITOS E APLICAÇÕES. Uma bacia hidrogeológica representa um compartimento em subsuperfície, representado por um aquífero, conjunto de aquíferos ou parte de uma unidade estratigráfica cujo fluxo converge para um único exutório ou área de descarga. Assim, um aquífero ou sistema aquífero pode representar uma única bacia hidrogeológica ou pode ser subdividido em diferentes bacias, em função do arranjo divergente dos sentidos do fluxo subterrâneo. Ao contrário de uma bacia hidrográfica que pode ter seu exutório representado por um ponto que representa toda a área a montante, na bacia hidrogeológica a zona de descarga é comumente representada por uma área, um corpo hídrico de superfície, ou segmento de curso d'água superficial. Um conjunto de bacias hidrogeológicas pode ocorrer de forma sobreposta em função da complexidade geológica regional, da espessura dos estratos e do relevo na superfície. A determinação dos limites das bacias hidrogeológicas associadas a um aquífero ou conjunto de aquíferos é importante para o entendimento da dinâmica de fluxo em subsuperfície, além de auxiliar na compreensão da relação com as bacias hidrográficas que as sobrepõem em superfície. Diferentes técnicas e métodos de estudos podem ser aplicados para a determinação e cartografia dos limites das bacias hidrogeológicas incluindo, potenciometria, geofísica, hidroquímica, técnicas hidrológicas, testes de traçadores, hidrologia isotópica, dentre outros. Entretanto, apesar de sua importância este não é um tema recorrente na literatura aplicada aos recursos hídricos subterrâneos, sendo uma terminologia ainda pouco utilizada no meio científico. A maior parte das citações a esta denominação apenas se refere a aquíferos, conjuntos de aquíferos, unidades hidroestratigráficas, sem considerar o conceito da bacia hidrogeológica *sensu strictu*. Considerando tais questões, o presente trabalho propõe uma revisão do conhecimento a respeito das bacias hidrogeológicas, bem como expandir e atualizar seu conceito e discutir suas aplicações em diferentes contextos, incluindo gestão de recursos hídricos, projetos de recarga artificial, estimativa de reservas hídricas, desenvolvimento de modelos conceituais e simulações numéricas, dentre outras.

Palavras-chave: Bacia hidrogeológica; Bacia hidrográfica; Recursos hídricos; Gestão.

1 INTRODUCTION

Hydrogeological basins should be the basic unit for groundwater management on a local scale, in the same way that watersheds are the unit of surface water management. However, the concept of hydrogeological basin is not as well-defined in the literature as that of a watershed. Several works can be found on this theme, even when using automatic bibliometric systems. However, upon closer examination, these papers only refer superficially to the hydrogeological basin, without fully addressing the concept, or as a secondary part of a research which central theme does not refer to the subsurface basins (CASTANY 1981; PEREIRA et al. 2003; CAVALCANTE et al. 2006, 2007; VERÍSSIMO et al. 2007; ANANDAN et al. 2010; ALBUQUERQUE FILHO et al. 2012; ENGELBRECHT & CHANG 2015; ARAÚJO et al. 2016; MUÑOZ et al. 2016; GURITA 2020; BATJARGAL & BATSUKH 2022).

TIEDMAN et al. (1998) defined a hydrogeological basin as the limits and paths through which groundwater flows within an aquifer, including the recharge zones and specific discharge areas. Since TIEDMAN et al. (1998), there were no further studies that aimed to conceptualize and define the necessary tools for the delimitation of hydrogeological basins, until ARRAES (2008) and ARRAES & CAMPOS (2007, 2010) published research that deal with the proposition of criteria for the delimitation of these basins. These works proposed the use of the following techniques for the delineation of hydrogeological basins: potentiometric studies, hydrological studies, tracer tests, hydrochemical analyses, isotopic geochemistry, lineament analysis, and geophysical studies.

The boundaries of the watersheds and the underlying hydrogeologic basin may or not coincide, resulting in a symmetry or an asymmetry between these limits. When the boundaries coincide, they are referred to as symmetric limits, and when they differ, they are called asymmetric limits.

The definition of the lateral extension of hydrogeological basins is more abstract compare to that of watersheds, which can be obtained in a relatively simple and accessible way through the analysis of digital elevation models, where data such as slope, topography, and hypsometry are evaluated. However, in depth analysis, a hydrogeological basin may have a larger spatial extent compared to its overlapping watershed (TIEDMAN et al. 1998) (Figure 1). Conversely, a watershed can encompass several hydrogeological basins (Figure 1), which happens when the subsurface flow and the base flow present divergent patterns with different recharge and discharge points (ARRAES & CAMPOS 2007).

The dataset used for determining the boundaries of underground basins includes the following factors: single-point groundwater levels or potentiometric maps, hydrochemical

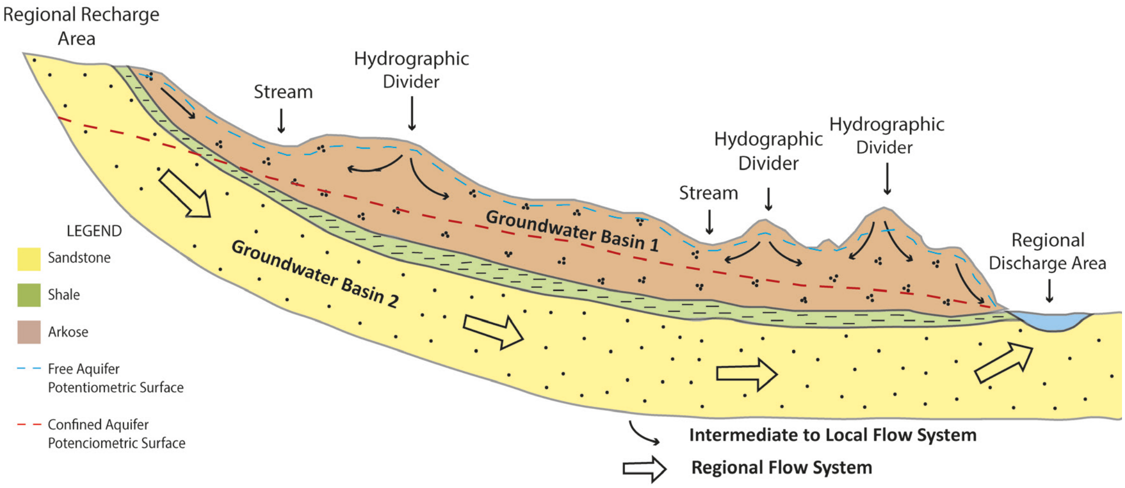

FIGURE 1 – Schematic illustration depicting a case where two hydrogeological basins, separated by a layer of shale, acting as an aquitard. The hydrogeological basin 1 is characterized by a local and an intermediate hydrogeological flow systems, while the hydrogeological basin 2 exhibits a regional flow. This is a case where the area of a single watershed corresponds to several watersheds. The red dotted line represents the potentiometric surface of the aquifer system 2, while the blue dotted line represents that of the aquifer system 1. Modified from ARRAES & CAMPOS (2007).

information, hydrographic elements, flow data from springs and surface watercourses, rock types, stratigraphy, geological structures (with emphasis on regional folds and main structural lineaments), as well as other complementary elements.

Another important aspect in distinguishing between hydrographic and hydrogeological basins involves the evaluation of aquifer systems, understanding that an aquifer system comprises different subtypes of aquifers, as seen in the Guarani or Urucuia aquifer systems. The Urucuia Aquifer System, for example, includes regional unconfined, perched, confined or semiconfined, and deep regional subtypes (GASPAR 2006, GASPAR & CAMPOS 2007). The Guarani Aquifer System consists of unconfined, semiconfined, and confined portions in its different areas of occurrence (ARAUJO et al. 1999, OLIVEIRA 2009). A hydrogeologic basin can be composed of a single subtype or multiple subtypes of the aquifer that makes up the system. This distinction will depend on the lateral and vertical organization of the units within the aquifer system as a whole.

Thus, the objective of this article is to contribute to the discussions about the concept, delimitation tools, and the implications of the knowledge about hydrogeological basins or underground basins.

The definitions of the main terms cited in this review work are presented to guide non-specialist users, who may come from different technical backgrounds and potentially require knowledge and applications on hydrogeological basins. These definitions are sourced from classic works of conceptual hydrogeology such as FETER (2001) and FREEZE & CHERRY (2017):

- Aquifer is any geological material (rock, soil, or altered rock) with the ability to accumulate and transmit water. Vertically, the aquifer is divided into three zones: the vadose or unsaturated zone (where water occurs as a moisture in the upper portion), the transition zone, and the saturated zone (where water occupies all the empty space, at the base of the system).
- Hydraulic conductivity represents the potential flow through the medium, and is measured in terms of length divided by time, e.g. m/s or cm/day. The concept of hydraulic conductivity should not be confused with flow velocity, since the distance of the flow through time depends on the hydraulic gradient and the effective porosity, which represents the portion

of the voids available for the movement of the water.

• Depending on the type of pore spaces in these materials, aquifers are classified into intergranular, fractured, or karstic. Intergranular aquifers have voids occurring between the constituent grains; fractured aquifers are associated with fractures in hard rocks; and karstic aquifers store water in dissolved rocks, resulting in large voids (cavities in the form of caves).

• Another important classification is based on the pressure to which groundwater is subjected. An aquifer is considered unconfined when the upper surface of the saturated zone is at the atmospheric pressure and confined when the top of the saturated zone is at pressures greater than atmospheric. A confined aquifer can be classified as fully confined or semiconfined, depending on the contrast in hydraulic conductivity between the aquifer layer and the overlapping bedrock. Thus, when the hydraulic conductivities present significant contrast, the system is defined as fully confined and the overlapping layer is classified as an aquifuge. When the contrast is reduced, the aquifer is classified as semiconfined and the top layer is referred to as an aquitard.

• The recharge area corresponds to the places where rainwater infiltrates to replenish the saturated zone of the aquifers. The discharge area or exutory is the region or point where the waters return to the surface and become part of the surface watercourses.

• In local hydrogeologic flow, the recharge area is close to the discharge site, and in this case, the waters are young, cold, and poorly mineralized. In regional flow, recharge takes place at the dividers of the basins, and the discharge areas are located in the main valleys. Generally, these areas have older waters with higher temperatures and higher mineralization, attributed to the longer contact time between water and rock.

• The water mineralization corresponds to the total of dissolved ions, being controlled by the types of minerals and their solubility in the aquifer, composition of the recharge water, climate, soils types, land uses, among other factors.

2 CONCEPTUALIZATION AND CRITERIA FOR DELIMITATION

The portion of an aquifer or set of aquifers that have a convergent flow to a common discharge area defines a hydrogeological basin. Thus, an individual aquifer or aquifer system can be subdivided into distinct hydrogeological basins. Therefore, a hydrogeological basin is not synonymous with an aquifer or a stratigraphic unit.

Hydrogeological basins can be vertically overlapped due to the stratigraphy of the basin, the presence of confined aquifers, and the occurrence of vertical upward or downward flow. A hydrogeological basin may contain or be subdivided into sub-basins as observed in watersheds.

A large river watershed may overlap different hydrogeological basins. Conversely, the surface relief generates different watersheds that overlap a single hydrogeological basin at depth, the opposite can be observed.

Dividers located in high-altitude regions between two lower-altitude areas define watersheds. The delimitation of the watersheds can be done directly on planialtimetric maps or satellite images using specific software.

Groundwater dividers commonly coincide with surface dividers primarily in intergranular and unconfined aquifers in flat-relief regions. However, the areas bordering aquifers often do not coincide with the surface drainage areas (WHITE 2002, GUNN 2007, PALMER 2010, DEMIROGLU 2016).

The delimitation of the hydrogeological basin is very important for the groundwater management guidelines and the limits of the hydrogeological basins may change over time, depending on the current exploitation in the area. The establishment of a regional depression cone can result in flow reversal, causing the watershed boundary to migrate laterally as a function of the drawdown.

The methods used to define the boundaries between hydrogeological basins are largely qualitative, but the integration of different techniques, even quantitative ones, can provide more accurate results. Before applying the delimitation methods, it is crucial to analyze the dynamics of local or regional underground flows, as well as overland flow, taking into account the classification of surface watercourses as effluent or influent.

2.1 Potentiometric studies

Groundwater moves through empty spaces within the rock framework, including interstitial spaces (intergranular aquifers), by fracturing (fractured and double-porosity aquifers), and by dissolution (karst and fissure-karst aquifers). This underground flow is driven by potential differences between points at different levels, where water flows from points of higher potential to points of lower hydraulic potential (FETTER 2001, FREEZY & CHERRY 2017).

The method involves three basic concepts, the potentiometric surface, equipotential surface, and equipotential line (FEITOSA 1997). The first consists of the geometric place formed by the points that determine the potentiometric elevations of an aquifer, which refer to a specific depth of the water level. The equipotential surface is a virtual surface where all points have the same hydraulic potential (or hydraulic head). The equipotential line is the projection onto the plane of the intersection of the potentiometric surface with a defined potentiometric elevation plane. Finally, the potentiometric map is the set of equipotential lines generated by the projection of several intersections of the potentiometric surface with planes of different potentiometric levels. Such maps allow the two-dimensional visualization of the groundwater flow direction and are elaborated from data of potentiometric levels collected from water points, including production wells (at pumping rest condition), monitoring wells, dig wells, and springs.

The elaboration of potentiometric maps is the main tool for determining hydrogeological basin boundaries, since they provide groundwater flow directions in two dimensions and allow the comparison with the flow directions of the overlying watershed. Thus it is possible to identify any asymmetry indicated by distinct flow directions. In addition to delimiting hydrogeological basins, potentiometric maps are also important for the aquifer monitoring programs, contamination plumes and remediation studies, characterization of the vulnerability of the aquifers, among other applications.

In compartmentalized aquifers, such as fractured and karst systems, potentiometric maps must respect the distinct blocks, which are determined from studies of regional structural lineaments on orbital images at different spatial scales (OLIVEIRA et al. 2022).

In cases where the number of wells is insufficient or poorly distributed across the aquifer's occurrence area, other tools should be used for the delimitation of the underground basins.

2.2 Hydrological studies

Hydrological studies are based on long-term monitoring of surface watercourse discharge and the relationships of discharge variations over time and space. The specific yield, which represents the discharge divided by the drainage area, is a useful parameter for understanding the relationship between the baseflow and the river flow in the hydrological cycle. Seasonal variations in flow are used to verify the regularization of the watercourses. In rivers with more regularized flows the differences between the maximum and minimum flows are small, indicating a greater contribution of the aquifer baseflow discharge. In rivers with extreme variations, runoff contributes more significantly compared to aquifer discharge. Long-term permanence flow measurements (such as Q_{90} or Q_{95}) also provide insights into the aquifer's contribution to the river during periods of rainfall recession.

The heterogeneities and anisotropies of the geological environment can often result in discharge measurements that differ from what is expected based on physiographic analysis of the terrain (ARRAES & CAMPOS 2007). The analysis of the specific yield in surface watercourses provides only an indication of the presence or absence of asymmetry between the boundaries of the basins, so this is not an accurate method of analysis for determining the hydrogeological basins. However, this criterion can be used for a first approximation for evaluating large river basins.

This tool is particularly useful for karst and fissure-karstic systems, where the conceptual model of the system itself is complex and difficult to predict, since a set of underground channel flows may present a convergent or even divergent patterns.

2.3 Tracer test

Studies using tracers, such as fluorescent dyes, salts or other substances, represent an excellent tool for delimitation of hydrogeological basins. They validate the boundaries indicated by other methods and precisely define the limits, as they require direct access to the aquifers, through sinkholes in karst aquifers or wells for other types of aquifers (ARRAES & CAMPOS 2007). The tracer tests also have the advantage of allowing the definition of the boundaries, when they vary spatially due to pumping of unconfined aquifers under intense exploitation.

Groundwater tracer tests provide data on flow patterns within the aquifer, average linear velocity of water transit, longitudinal and lateral dispersion, and other hydrodynamic parameters with great precision, such as conductivity and transmissivity (BENISCHKE et al. 2007, GOLDSCHEIDER 2015, CAO et al. 2020, BENISCHKE 2021). These tests require a large number of monitored wells and extensive data generation, making them suitable for studies in areas no larger than one km^2 and with specific objectives, such as the delimitation of boundary conditions in aquifer modeling projects for in situ remediation.

2.4 Isotopic hydrology

Isotopic studies in groundwater have a wide range of applications and are important for delimiting hydrogeological basins based on the determination of the isotopic signature of recharge waters or to define the age of the waters after they have transitioned from the atmospheric or surface environment and become integrated into the aquifer flow through natural recharge.

The radioactive isotopes of Carbon 14 and Tritium are widely used in water dating due to their half-lives, which fit the time intervals required for dating most groundwater, and they occur naturally in the water. Tritium, with a half-life of 12.3 years, is used for dating young water. Carbon 14, with a half-life of 5,730 years, is suitable for dating older samples, from 500 to 40,000 years (FEITOSA et al. 2008, SILVA Jr. 2021). The age of the waters is an important indicator in terms of flow dynamics, as it is associated with the time of residence of these in the aquifer. Younger waters show shorter residence times, which indicates proximity between the recharge and discharge areas, and therefore are less mineralized. The older waters show longer residence times, and their recharge and discharge areas are the dividers and main courses of the basin, respectively. These waters tend to be more mineralized because they remain longer in contact with the aquifer rocks.

The stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) are widely used in hydrogeology studies to differentiate groundwater recharge sources and possible mixtures, with surface and meteoric waters. The isotopic signature of oxygen and hydrogen in waters naturally varies due to the isotopic fractionation of these elements, and also by their transport within the hydrological cycle. The concentrations of these isotopes are measured as $\delta^{18}O$ and $\delta^{2}H$, which do not reflect absolute concentrations, but indicate deviations (in parts per thousand) from the isotopic ratios relative to a defined standard, known as SMOW- Standard Mean Ocean Water. The isotopic ratios are calculated as delta according to the equation: δ (‰) = $[R_{sample} - R_{standard}] / R_{standard}$ X 1000, where the ratio R is expressed by the quotient between the concentration of the heavy isotope by the respective light isotope.

The fractionation of stable isotopes occurs due to phase changes in the hydrological cycle, such as evaporation, condensation, and melting. This fractionation process results in a specific isotopic composition of the water, which indicates its source (CLARK & FRITZ 1997).

In general, these data are plotted on $\delta^{18}O$ versus $\delta^{2}H$ graphs and the results of the aquifer water samples are compared with global or local meteoric water lines. Deviations are interpreted based on physical processes, such as evaporation prior to water infiltration into the aquifer, water-rock interactions with mineral hydration, or even mixtures of older waters with modern or submodern circulation waters.

Thus, when the isotopic signal of the waters of a given portion of a hydrostratigraphic unit is very distinct from another portion, it can be inferred that they originate from distinct hydrogeological basins or sub-basins.

2.5 Structural lineament analysis

Lineament analysis is a useful technique in the delimitation of hydrogeological basins, as the asymmetry between surface and underground basins is frequently caused by the presence of large geological structures, such as regional faults, shear zones, or folds. Faults and fractures often result in the inversion of the underground flow, by the lateral flow of the infiltration waters towards the zones of greater hydraulic conductivity caused by the "damage zone" associated with these structures.

The analysis of lineaments is performed using orbital images or aerial photographs to highlight straight-lined structures, such as fault or fracture zones. Along these structures, the set of rocks underlying the soil covers presents higher hydraulic conductivity compared to their surrounding areas. Vertical drainage along regional lineaments (especially those located in regions of flattened relief) causes localized lowering of the potentiometric surface, which results in the differentiation of hydrogeological sub-basins.

In addition to the trace of these structures, the dip is also important, as the water that drains through the plane of the structures tends to migrate to the dip direction, resulting in the change of the flow direction and causing potential asymmetry between the overlapping watersheds.

3 ASYMMETRY BETWEEN SURFACE AND UNDERGROUND BOUNDARIES

The lack of overlap between the boundaries of the watershed and hydrogeological basins is referred to as the asymmetry between the surface and underground basins by ARRAES & CAMPOS (2007). Several factors may be responsible for the divergence between the boundaries of the surface and underground basins. The main factors include geological structures (faults and fractures), karst features (sinkholes and springs), stratigraphic heterogeneities (presence of layers with different hydraulic conductivities), and surface relief patterns (geomorphology).

3.1 Asymmetry caused by the presence of geological structures

The presence of geological structures such as folds, cataclastic zones, or faults may alter the flow dynamics in the underground environment, since they affect both the physical configuration of the medium and the arrangement of lithological layers with different properties (Figure 2).

For example, a fold can generate the repetition of the same hydrostratigraphic layer that would not exist if the substrate were not deformed, making the establishment of the boundaries of the hydrogeological basins more complex.

CORNIELLO et al. (2017) observed that the complex tectonic configuration of the studied area in the Campania region of southern Italy, with extensional faults associated with small cataclastic belts of low permeability, clearly interferes with the flow of groundwater, configuring a large number of distinct hydrogeological basins.

PUTRANTO & LUTHFI (2019) show the division of hydrogeological basins from the analysis of hydrogeological systems, recharge, and discharge areas in the Karankobar region, Indonesia.

The presence of anisotropy is associated with differences in hydraulic conductivity along

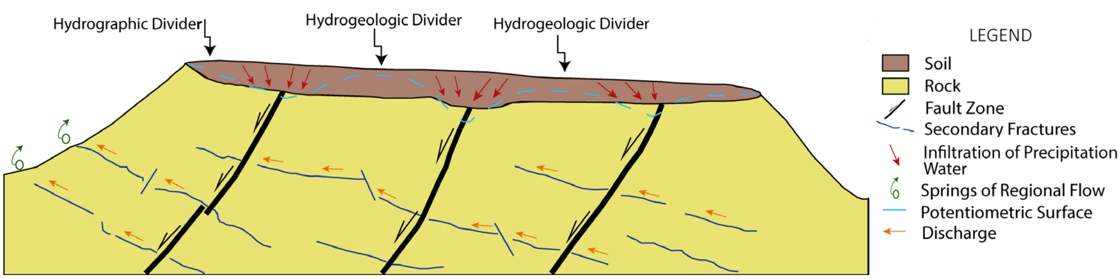

FIGURE 2 – Schematic illustration demonstrating how large geological structures can influence the establishment of asymmetries between hydrographic and hydrogeological dividers.

the directions represented by the main axes of brittle tectonic structures, such as fault zones and fractures (FEITOSA 1997).

3.2 Asymmetry caused by karst features

In the case of karst or fissure-karstic systems, the openings represented by planar structures such as faults and fractures, or by secondary structures, generated by the dissolution of carbonates, may represent directions of greater hydraulic conductivities, due to properties such as opening of the conduits and interconnection between the structures.

In karst systems, the dissolution of carbonate generates catchment zones represented by dissolution or collapse dolines and sinks (zones where the flow of rainfall runoff or watercourses becomes part of the underground environment).

Figure 3 illustrates a situation in which the hydrographic and hydrogeological dividers do not coincide due to the zone of higher conductivity generated by sinkholes in a karst system with a dip in the opposite direction of the surface runoff. This configuration is very common in karst environments and can result in wide offsets between the dividers.

3.3 Asymmetry caused by heterogeneities in aquifers

The heterogeneities in the underground environments are among the most common causes for the occurrence of asymmetry between watersheds and hydrogeological basins. They can be caused by intercalations between different hydrostratigraphic units, presence of impermeable or poorly permeable layers, or materials with a wide contrast in hydraulic conductivity (e.g., gravel lenses within clayey sandstones or silicified layers interspersed in unconsolidated sandstones).

In the example shown in figure 4, the asymmetry is due to the presence of the impermeable layer at the base of an unconfined aquifer. The arrangement of the layers results in an increased hydraulic gradient that shifts the hydrogeological boundary in relation to the hydrographic boundary. In this example, despite both watersheds having the same drainage area, the base flow of stream 2 should be greater than that observed in stream 1.

3.4 Asymmetry controlled by geomorphological feature

Regional geographical structures such as aligned mountain ranges (e.g., Serra Geral de Goiás), regional plateaus (e.g., Serra de Caldas Novas), plateau edges (e.g., the northern limit of Chapada da Contagem in the Federal District), regional tables (e.g.: Serra da Água Morna in the region of Posse, GO), among others, commonly determine the asymmetry between surface and underground basins in their lateral termination

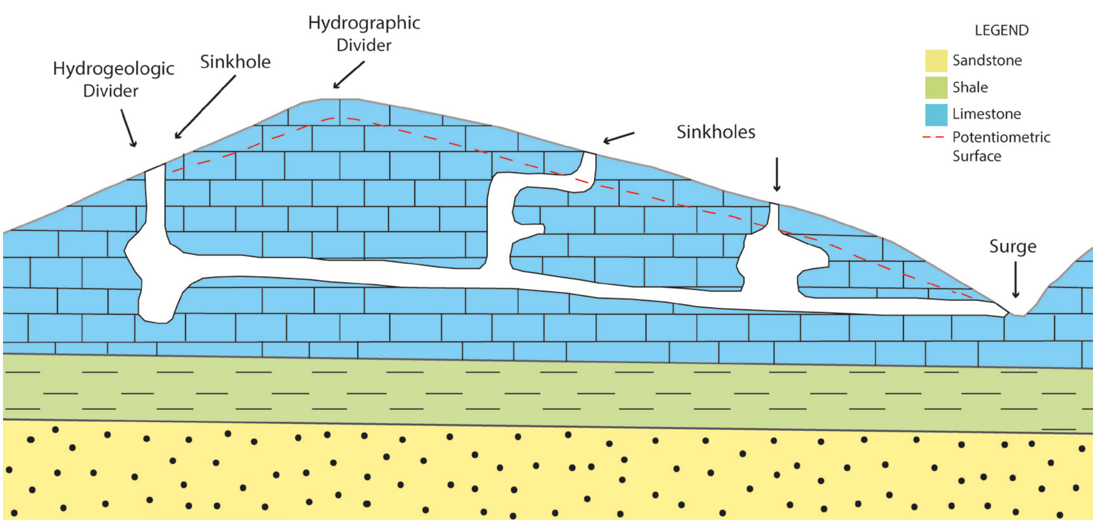

FIGURE 3 – Asymmetry in the karst system associated with the presence of sinks, which represent zones of higher hydraulic conductivity. The red dotted line represents the potentiometric surface of the aquifer system. Modified from ARRAES & CAMPOS (2007).

areas, as can be seen in figure 5. This control is linked to the high potential energy that results in the rapid lowering of the potentiometric surface of the aquifer towards the lower relief compartment.

GASPAR (2006) shows that the distribution area of the Urucuia Aquifer System presents a longitudinal divider approximately north-south that separates the system into two large hydrogeological basins with predominat westward and eastward flows. This underground divider is exclusively conditioned by the regional geomorphological pattern.

The rupture of the potentiometric surface causes the displacement of the hydrogeological boundary in the opposite direction to that of the abrupt breaking of the relief. In the most common context, the hydrographic boundary is located near the contour of the geomorphological compartment or the elevated regional structure.

4 IMPLICATIONS AND APPLICATIONS

The understanding of the hydrogeological basins is important for several practical applications, serving as one of the criteria for the definition of the aquifer or aquifer systems. In the following sections, it is briefly shown, and in some cases with examples, the main implications and applications of the knowledge

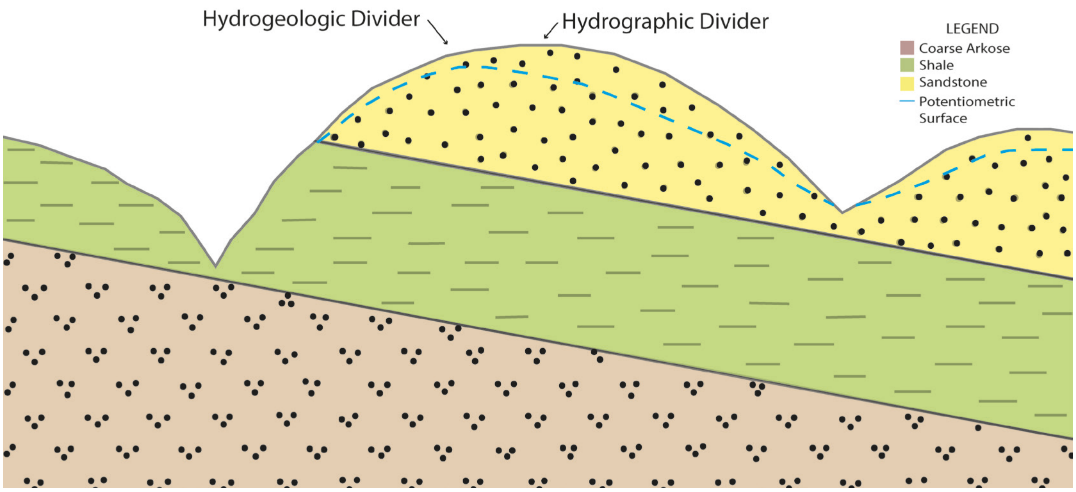

FIGURE 4 – This case shows an asymmetry between the hydrographic and hydrogeological boundaries caused by the presence of an impermeable layer of shale under an unconfined aquifer composed of sandstone. The blue dashed line represents the potentiometric surface of the aquifer system. Modified from ARRAES & CAMPOS (2007).

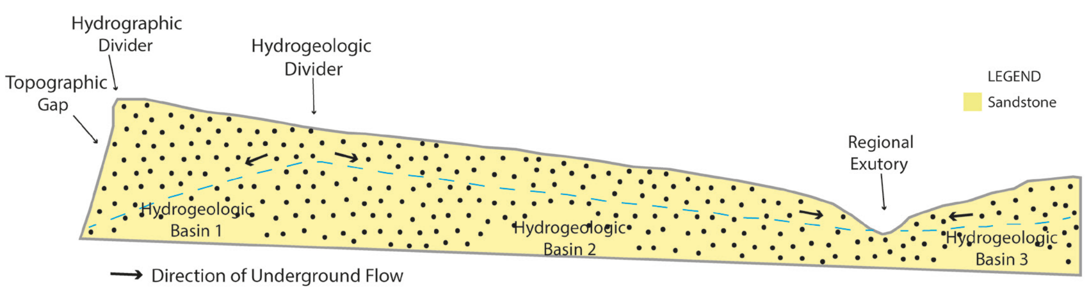

FIGURE 5 – Asymmetry caused by relief control associated to the presence of a edge of a regional plateau. In this case, the same watershed comprises three underlying hydrogeological basins. Modified from ARRAES & CAMPOS (2007).

regarding the boundaries of hydrogeological basins in studies related to water resources.

4.1 Integrated management of surface and groundwater resources

The implementation of groundwater management strategies, concerning the susceptibility of aquifers to contamination by elements present in soils or waters, requires that the individual boundaries of hydrogeological basins and sub-basins are previously established. In cases where there is an asymmetry between the hydrographic and hydrogeological limits, the area susceptible to aquifer water contamination may be considerably larger than expected from the analysis of surface dynamics alone, based on aerial and satellite images.

Moreover, surface and underground resources should be treated as a single unit when discussing an integrated management. It is not possible to manage groundwater without taking into account the recharge origins, the land surface use, and the relationships of hydrographic and hydrogeological boundaries. It is necessary to identify the discharge areas and the perennial or intermittent rivers supplied by the waters coming from the aquifers, which are effluent or influent. All these aspects are affected to some extent by the subsurface flow dynamics, and how it connects with the surface flow.

Therefore, the determination of the hydraulic connection between surface and groundwater resources is an important premise for integrated management, aiming at the preservation of both resources. In cases where there is no connection between the rivers and the deeper aquifers, the management can be carried out separately, since they are distinct reservoirs (BRASIL 1997; CNRH 2001, 2002).

To determine the hydraulic connection between the aquifer and the river, two technical procedures can be applied:

i) River flow measurements in a stretch without tributaries, in different segments from upstream to downstream. If the flow rates systematically increase or decrease, the connection is verified, which can define the river as effluent or influent, respectively;

ii) Potentiometric head measurements in wells located perpendicular to the river channel. In this case, the existence of multiple potentiometric surfaces and any confining layers should be verified, in addition to the constructive characteristics of the monitoring wells (soil and rock description, depth, and position of the screen sections).

One possible situation is the existence of overlapping aquifers associated with different hydrogeological basins, where there is a hydraulic connection with the shallower aquifers and disconnection with aquifers located at greater depths.

4.2 Transboundary aquifers

Worldwide, about 600 transboundary aquifers have been identified, according to VILLASEÑOR & MEGDAL (2021). However, out of these 600 aquifers, only six have formal binational or multinational cooperation agreements for the use and management of groundwater present in these shared reservoirs. These authors compare the numbers of existing agreements for the maintenance of reserves and use of groundwater with those for surface waters. This phenomenon is attributed to the lack of institutional capacity for the groundwater resources management, the absence of data or incongruity in assessing the groundwater reserves, unlike surface water resources that can be directly observed and analyzed.

The Transboundary Aquifer Assessment Program is a collaborative force between the United States and Mexico to study the shared aquifers worldwide and analyze the agreements established by other nations. The program also aims to establish robust binational cooperation in developing guidelines for managing the groundwater resources of the shared region between the two countries, taking into account aquifers as a fundamental unit of analysis. In this sense, the study of the Santa Cruz and San Pedro aquifers, shared between the state of Arizona (USA) with Sonora (Mexico), and the Mesilla and Hueco Bolson aquifers, shared between Texas and New Mexico (USA) with Chihuahua (Mexico) was authorized (VILLASEÑOR & MEGDAL 2021). In South America, a multinational study was also developed involving the countries of the Guarani Aquifer System (OAS 2009).

The evaluation and study of shared aquifer systems is an essential tool for enhancing the management of groundwater resources in any agreement.

In Brazil, the legislation defines that the groundwater belongs to the states of the federation. Therefore, when an aquifer crosses the geographical boundaries, the two geopolitical units must share the aquifers.

This is a sensitive subject, as it involves managers from different countries or states, with demands for various uses, with conflicting legislation, which can pose challenges for the effective management. Therefore, the process requires scientific basis, both for practices of exploitation and use of groundwater by the entities involved, as well as for attributions of responsibilities about the overexploitation of the aquifer by overstated pumping, development of activities that may lead to contamination of the soil and subsequent groundwater pollution, and criteria for granting the resources.

4.3 Remediation studies of contaminated aquifers

The determination of hydrogeological basins and sub-basins, especially those controlled by lineaments, is essential in the investigation of contaminated aquifers. The underground flow pattern plays an important role in understanding the interaction between contaminants and the underground medium, in addition to the intrinsic characteristics of the substances of interest. The presence of smaller order basins may explain changes in the dispersal pattern of contamination plumes, alterations in the direction of the contaminant flow, or even the presence of lateral barriers to flow. The distribution of the plume in different three-dimensional patterns is commonly attributed to the existence of hydrogeological sub-basins in the contaminated sites.

In addition, the development of an accurate conceptual model of groundwater flow is indispensable during the confirmatory investigation stage, guiding even subsequent decision-making stages, such as defining the sampling points in the vadose and saturated zones. The characterization of the environment as a whole is important, not only for investigation and definition of contamination, but also for remediation plans. These plans involve several techniques such as pumping and treatment, pumping and reinjection, in situ bioremediation, bioventing, volatile extraction, among others.

4.4 Aquifer protection

In general, groundwater has its specific legislation regarding its protection against contamination, inappropriate uses that can lead to overexploitation, reduction of recharge, or encroachment of the saline water in coastal aquifers, among other risks to which these resources are often exposed.

The groundwater regulation scenario is even more critical when compared to existing legislation for surface water. TOSCANO et al. (2008) analyzed the legislation for the protection of groundwater in Brazil, and compared with the existing laws in nations such as the United States and European countries. It was observed that the latter had standards that define criteria for the delimitation of protection perimeters, with the establishment of restrictions and control of land use, which was not observed in Brazil. At that time, only six Brazilian states had specific laws regarding the protection of groundwater, and five states included the subject only in the State Policies of Water Resource.

In Brazil, the federal environmental system has some legal documents, such as Resolution No. 396 of CONAMA (CONAMA 2008), which address specific issues related to the protection of groundwater, such as perimeters for the protection of supply wells, areas of restriction and control of the use of groundwater, and areas of aquifer protection. It should be noted that it was only with the 1988 constitution (BRASIL 1988) that groundwater ceased to be framed as a subsoil mineral resource belonging to the Union (Art. 176), and passed to the category of public good owned by the States and the Federal District (Art. 26, I).

More recently, the National Water Agency (ANA 2022) presents an update of the Brazilian legal framework related to the governance and protection of aquifers, highlighting as a premise the need to know the aquifers and their limits to achieve effective management results.

LOBO-FERREIRA (1998) and KOHNKE (2001) present discussions emphasizing that the knowledge of the boundaries of the hydrogeological basins is important for the aquifer protection studies.

4.5 Quantification of groundwater reserves

The lateral distribution area of an aquifer is one of the main parameters that must be considered for the calculations or estimates of water reserves within aquifers, in addition to their thickness and effective porosity or interconnected fracturing index. All the equations proposed for estimating the water reserves (COSTA 1998, 2000) of an aquifer and their adaptations to different types of aquifers, or the use of the water balance for this same purpose, require knowledge of the distribution area of the systems.

Thus, when possible asymmetries between the surface and underground basins are disregarded, significant errors can be generated and propagated in different scenarios.

CAMPOS & ALMEIDA (2012) estimated the groundwater reserves of the thermal aquifers of the Caldas Novas region, Goiás State. The areas of the different reservoirs were determined based on the proposed limits of the hydrogeological basins. JUNQUEIRA (2020) presented the estimates of water reserves of the thermal aquifer systems in the Chapada dos Veadeiros region, Goiás State, and the results were considered preliminary, considering that the hydrogeological basins have not yet had their limits minimally defined in this region.

4.6 Characterization of conceptual models of aquifers

The use of conceptual models is essential for understanding the functioning of hydrogeological systems and for developing guidelines and management plans for the water resources of a region. According to DEMIROGLU (2016), the term “conceptual model” encompasses characteristics related to the extension and spatial distribution of the system, including the three-dimensional limits of the aquifers. The elaboration of a conceptual model requires data on the study area, detailed information about the geology of the region, the underground flow dynamics, recharge, hydraulic parameters, and the well-defined limits of the hydrogeological basins (ROSEN & LEGRAN 2000). Therefore, defining the boundaries of the hydrogeological basins or sub-basins enables understanding of the occurrence and flow of groundwater, and comprises data on both the inflow (recharge) and the outflow (discharge) of the surface and underground system.

The conceptual characterization of aquifers encompasses all the different aspects related to the physical environment, the dynamics of underground flow, the interaction between the surface and subsurface environments, the determination of the water balance in the different compartments that make up the hydrological cycle as a whole, the identification and characterization of the recharge and discharge areas, the understanding of the thickness and parameters of the vadose zone, among other aspects.

Thus, in order to develop a conceptual model of an aquifer, the surface and subsurface media must be characterized. This characterization should specify the type of soil, its texture, structure, organic matter content, approximate thickness of the vadose zone, hydraulic conductivity, definition of the parental rock, and description of the soil horizons. After the characterization of the soils, it is important to understand the water balance in the different compartments involved in water transfer, including the time-spatial pattern of precipitation, and which portion of that undergoes evapotranspiration and interception by the vegetation. Finally, it is important to define the amount of water that (i) reaches the substrate, (ii) contributes to the surface runoff, (iii) infiltrates the soil and supplies the field capacity of the medium, and (iv) actually characterizes recharge to the aquifer. ROSEN & LEGRAN (2000) present the concept and the bases for the studies of conceptual modeling of aquifers. LOUSADA & CAMPOS (2005) and GOMES (2019) carried out works related to the proposition of conceptual models of flow in different hydrogeological contexts.

By analysing the flows of surface watercourses and decomposition of hygrograms, it is possible to separate the overland flow, interflow, and baseflow. Subsequently, potentiometric data can be used to define whether there is asymmetry between the boundaries of the watershed and hydrogeological basin, and to delimit the hydrogeological sub-basins. Finally, it characterizes the regional recharge areas, the discharge of the base flow, and the relationship with the saline wedge with the sea, in the case of coastal aquifers.

4.7 Numerical simulation of flow

The numerical models have a quantitative character, as they enable predictive simulation of contamination plume flow, aquifer recharge and discharge, elevation or lowering of the potentiometric surface in response to external influences, and other applications. These models are developed on conceptual modeling, which is considered as a qualitative representation of aquifers.

One of the major problems in developing a groundwater flow model that aims to represent the hydrogeological configuration of a specific aquifer or hydrogeological basin is the proposition of a conceptual model that accurately reflects reality (DEMIROGLU 2016). The accuracy of a conceptual model is intrinsically related to the use of equally accurate and detailed input data. Only in this way can the output data, which includes simulation and sensitivity analysis, be reliable (DEMIROGLU 2016).

For the elaboration of quantitative models, it is necessary to use hydrodynamic parameters, including hydraulic conductivity, storage coefficient, transmissivity, effective porosity, interconnected fracturing index, dispersivity, among others. This data is used as input information in numerical modeling software such as SWAT, FEFLOW, or MODFLOW.

One of the main imput datasets of the numerical aquifer models are the system boundaries, which make up the simulation boundary conditions, which are represented by the hydrogeological basin boundaries themselves. These data, ultimately, may be responsible for the greater or lesser sensitivity of the modeling, or even for the coherence of the results, since the inadequate selection of the systems limits can distort the outcomes. In addition to the limits, other factors also interfere with the results, including the quality of the input data, types of variables used in the modeling, accuracy of the recharge data, and density of the monitoring points, among others.

The data related to the polygonal of the aquifers (lateral distribution area) can be obtained from the modeling within a geoprocessing environment, projecting the aquifers limits onto the watershed limits. This method is consistent when both underground and surface basins share the same delimitation. In cases of asymmetry, the polygonal aquifers cannot be calculated directly, but can only be defined after an analysis that demonstrates the boundaries of the overlapping basins.

Numerical simulations can be highly inaccurate when performed in bordering areas where the watersheds and hydrogeological basins do not coincide. The same can occur in cases where the underground and surface basins are hydraulically disconnected.

4.8 Groundwater quality determination

CONAMA Resolution 396/2008 deals with the classification and environmental guidelines regarding groundwater quality determination. For the purpose of its application, some general guidelines are listed:

i) The classification of water bodies will be based on the hydrogeological characteristics of the aquifers and their respective uses;

ii) It should be considered that aquifers occur in different hydrogeological contexts and may exceed the limits of the watersheds;

iii) Groundwater presents intrinsic physical, chemical, and biological characteristics, with hydrogeochemical variations; therefore, it is essential that its quality classification takes into account these specificities;

iv) Issues related to pollution prevention and control are associated with the uses and classes of water quality required for a given groundwater body.

These points should be considered prior to the specific implementation of the defined water classification categories, and demonstrate the importance of the correct characterization of the hydrogeological context of the area, which should be integrated with the hydrographic context.

All these points also go through the definition of the boundaries of the hydrogeological basins, and the understanding whether or not there is an asymmetry between these limits and those of the watersheds, since the water quality classes are applied to a portion of an aquifer, and it is fundamental to delimit the areas of the aquifer with the same quality classes.

Activities that contribute to the degradation of groundwater quality may occur at specific locations, but the dispersion of contamination in the form of plumes may affect other portions of the aquifer within the same watershed. On the other hand, a source of contamination may migrate in the opposite direction of a watershed flow, if the boundary of the hydrogeological basin at depth is not superimposed on the hydrographic limit.

5 FINAL REMARKS

A hydrogeological basin represents a three-dimensional body in subsurface, represented totally or partially by an aquifer, set of aquifers, or a stratigraphic unit, where flow converges towards a single discharge area.

Among the main contrasts between watersheds and hydrogeological basins, the following stand out:

i) Surface basins are easily delimited from planialtimetric maps and satellite images, while delimiting hydrogeological basins is more challenging and requires subsurface studies to accurately map their boundaries;

ii) Watersheds have fixed boundaries, while hydrogeological basins may have their limits modified due to intense pumping;

iii) River basins may contain different hydrogeological basins in the subsurface and, conversely, a single hydrogeological basin may be superimposed by numerous watersheds;

iv) A watershed is always represented by a single area where runoff converges to a point, while hydrogeological basins can be vertically superimposed due to stratigraphic succession.

The determination of the boundary of a hydrogeological basin should be supported by different databases, including potentiometric mapping, the study of geological structures, hydrographic information, hydrochemical and isotopic data, as well as complementary documentation (satellite images, geomorphological maps, and digital elevation models).

The asymmetry between the boundaries of watersheds and hydrogeological basins can be determined by different controls: relief, anisotropies, geological structures, heterogeneities of aquifers, among others.

The identification of the boundaries of hydrogeological basins and their relationship with overlapping watersheds are important for different studies applied to aquifers, with an emphasis on transboundary aquifers, integrated management of water resources, remediation of contaminated aquifers, numerical simulation studies of flow, among other implications.

The relationships between the hydrographic and underground basins are more relevant in cases where there is an effective hydraulic connection between the aquifer and the surface watercourses. In cases of confined aquifers or deep fractured aquifers in regions with little pronounced relief, the physical separation of groundwater and surface reservoirs allows the boundaries to be treated as coincident.

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7 REFERENCES

ALBUQUERQUE FILHO, J.L.; BARBOSA, M.C.; AZEVEDO, S.G.; CARVALHO; A.M. 2012. Aspectos para a gestão estratégica das águas subterrâneas. *In*: ABAS, CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS, 17, Bonito, *Anais*, 4 p.

ANA – AGÊNCIA NACIONAL DE ÁGUAS E SANEAMENTO. 2022. *As águas subterrâneas na política nacional de recursos hídricos*. Série Capacitação em Gestão de Recursos Hídricos, 5, 220 p.

ANANDAN, K.S.; SAHAY, S.N.; KARTHIKEYAN, S. 2010. Delineation of Recharge Area and Artificial Recharge Studies in the Neyveli Hydrogeological Basin. *Mine Water and the Environment*, 29: 14-22. http://dx.doi.org/10.1007%2Fs10230-009-0090-8

ARAUJO, L.M.; FRANÇA, A.B.; POTTER, P.E. 1999. Hydrogeology of the Mercosul Aquifer System in the Paraná and Chaco-Paraná Basins, South America, and comparison with the Navajo-Nugget Aquifer System, USA. *Hidrogeology Journal*, 7: 317-336. https://doi.org/10.1007/s100400050205

ARAÚJO, P.P.; FREDDO, V.J.F.; FERREIRA, H.S.; ABREU, F.A.M. 2016. Cartografia das bacias hidrogeológicas usando os métodos potenciométrico e gravimétrico, nordeste do estado do Pará. *In*: ABAS, CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS, 19, Campinas, *Anais*, 10 p.

ARRAES, T.M. 2008. *Proposição de critérios e métodos para delimitação de bacias hidrogeológicas*. Instituto de Geociências, Universidade de Brasília, Brasília, MS Dissertation, 125 p.

ARRAES, T.M.; CAMPOS, J.E.G. 2007. Proposição de critérios para avaliação e delimitação de bacias hidrogeológicas. *Revista Brasileira de Geociências*, 37(1): 81-89.

ARRAES, T.M.; CAMPOS, J.E.G. 2010. Aplicação de ensaio de traçador e dados de potenciometria como ferramentas para a delimitação de bacias hidrogeológicas. *Geociências*, 29: 623-631.

BATJARGAL, D; BATSUKH, N. 2022. Calculation of Potential Groundwater Resources in Orkhon River Basin. *Mongolian Geoscientist*, 27(54): 9-19. https://doi.org/10.5564/mgs.v27i54.1126

BENISCHKE, R. 2021. Review: Advances in the methodology and application of tracing in karst aquifers. *Hydrogeology Journal*, 29: 67-88. https://doi.org/10.1007/s10040-020-02278-9

BENISCHKE, R; GOLDSCHEIDER, N; SMART, CC. 2007. Tracer techniques. *In*: N. Goldscheider & D. Drew (Eds.) *Methods in karst hydrogeology*. International Contribution to Hydrogeology, IAH, vol. 26, Taylor and Francis, Balkema, London, p. 147-170.

BRASIL. 1997. *Lei das Águas. Lei nº 9.433, de 8 de janeiro de 1997*. Brasília, DF, Presidência da República. Available at http://www.planalto.gov.br/ccivil_03/LEIS/L9433.htm. Accessed in 2 feb. 2017.

CAMPOS, J.E.G.; ALMEIDA, L. 2012. Balanço térmico aplicado à recarga artificial dos aquíferos da região de Caldas Novas, estado de Goiás. *Revista Brasileira de Geociências*, 42(1):196-207. http://dx.doi.org/10.5327/Z0375-75362012000500016

CAO, V.; SCHAFFER, M.; TAHERDANGKOO, R.; LICHA, T. 2020. Solute Reactive Tracers for Hydrogeological Applications: A Short Review and Future Prospects. *Water*, 12(3): 653. https://doi.org/10.3390/w12030653

CASTANY, G. 1981. Hydrogeology of deep aquifers, the Hydrogeological Basin as the Basis of Groundwater Management. *Episodes*, 3: 18-22. https://doi.org/10.18814/epiiugs/1981/v4i3/004

CAVALCANTE, I.N.; CAJAZEIRAS, C.C.A; VERÍSSIMO, L.S.; GUERRA JUNIOR, W.G.; MATTA, M.A.S.; ALMEIDA, F.M. 2006. Zoneamento hidrogeológico da faixa costeira de Caucaia, CE. *In*: ABAS, CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS, 14, Curitiba, *Anais*, 17 p.

CAVALCANTE, I.N.; COSTA, N.B.; GOMES, M.C.R.; MAIA, J.V.M.; FREITAS, L.C.B.; LEMOS, E.C.L. 2007. Aquífero costeiro na região de Paracuru, Ceará. *In*: SIMPÓSIO DE HIDROGEOLOGIA DO SUL – SUDESTE, 1, Gramado, *Anais*, 16 p.

CLARK, I.D.; FRITZ, P. 1997. *Environmental Isotopes in Hydrogeology*. CRC Press, Boca Raton, 352 p.

CNRH – CONSELHO NACIONAL DE RECURSOS HÍDRICOS. 2001. *Resolução nº 15, de 11 de janeiro de 2001*. Conselho Nacional de Recursos Hídricos, Diário Oficial da União, published in 22/01/2001.

CNRH – CONSELHO NACIONAL DE RECURSOS HÍDRICOS 2002. *Resolução nº 22, de 24 de maio de 2002*. Conselho Nacional de Recursos Hídricos, Diário Oficial da União, published in 04/07/2002.

CONAMA – CONSELHO NACIONAL DO MEIO AMBIENTE. 2008. *Resolução CONAMA n° 396, de 3 de Abril de 2008*. Conselho Nacional do Meio Ambiente, Diário Oficial da União, published in 7/04/2008.

CONAMA – CONSELHO NACIONAL DO MEIO AMBIENTE. 2009. *Resolução CONAMA n° 396, de 27 de Junho de 2009*. Conselho Nacional do Meio Ambiente, Diário Oficial da União, published in 29/06/2009.

CORNIELLO A.; DUCCI, D.; MONTI, G.M. 2017. An integrated approach for the delimitation of a groundwater basin: the case study of the Conca di Acerno (Campania, southern Italy). *Italian Journal of Engineering Geology and Environment,* Special Issue, 1: 17-28. https://doi.org/10.4408/IJEGE.2017-01.S-02

COSTA, W.D. 1998. Avaliação de reservas, potencialidade e disponibilidade de aquíferos. *In*:

ABAS, CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS, 10, São Paulo, *Anais*, 11 p.

COSTA, W.D. 2000. Uso e gestão de água subterrânea. In: F.A.C. Feitosa & J. Manoel Filho (Coords.) *Hidrogeologia: Conceitos e Aplicações*. CPRM – Serviço Geológico do Brasil, Rio de Janeiro, 2ª ed. Rev. e Ampl., p. 341-367.

DEMIROGLU, M. 2016. Identifying the groundwater basin boundaries, using environmental isotopes: a case study. *Applied Water Science,* 7: 1161-1167. https://doi.org/10.1007/s13201-016-0516-y

ENGELBRECHT, B.Z.; CHANG, H.K. 2015. Simulação numérica do fluxo de águas do Sistema Aquífero Urucuia na Bacia Hidrogeológica do Rio Corrente (BA). *Águas Subterrâneas*, 29(2): 244-256. https://doi.org/10.14295/ras.v29i2.28435

FEITOSA, E.C. 1997. Pesquisa de Água Subterrânea. *In*: F.A.C. Feitosa & J. Manoel Filho (Coords.) *Hidrogeologia: Conceitos e Aplicações*. CPRM – Serviço Geológico do Brasil, Rio de Janeiro, 2ª ed. Rev. e Ampl., p. 53-80.

FEITOSA, A.C.F.; MANOEL FILHO, J.; FEITOSA, E.C.; DEMÉTRIO, J.G.A. (Coord.). 2008. *Hidrogeologia: conceitos e aplicações.* CPRM/LABHID, Rio de Janeiro, 3ª ed. Ampliada e Revisada, 812 p.

FETTER C.W. 2001. *Applied Hydrogeology*. Prentice-Hall, Inc, New Jersey, USA, 4th ed., 691 p.

FREEZE, A.R.; CHERRY, J.A. 2017. *Águas Subterrâneas*. Tradução de *Groundwater*, Everton de Oliveira (coord.), Edição Instituto Água Sustentável, São Paulo, 698 p.

GASPAR, M.T.G. 2006. *Sistema Aquífero Urucuia: caracterização regional e propostas de gestão*. Instituto de Geociências, Universidade de Brasília, Brasília, PhD Thesis, 158 p.

GASPAR, M.T.P.; CAMPOS, J.E.G. 2007. O Sistema Aquífero Urucuia. *Revista Brasileira de Geociências*, 37: 216-226.

GOLDSCHEIDER, N. 2015. Overview of Methods Applied in Karst Hydrogeology. *In*: Z. Stevanović (Ed.) *Karst Aquifers - Characterization and Engineering*. Professional Practice in Earth Sciences, Springer Cham, Switzerland, p. 127-145.

GOMES, A.W. 2019. *Impactos da variabilidade temporal do regime pluviométrico da recarga de aquíferos: Estudo de caso em Caetité, BA*. Instituto de Geociências, Universidade de Brasília, Brasília, MS Dissertation, 108 p.

GUNN, J. 2007. *Contributory area definition for groundwater source protection and hazard mitigation in carbonate aquifers.* Natural and Anthropogenic Hazards in Karst Areas: Recognition, Analysis, and Mitigation. Geological Society, London, Special Publications, 279: 97-109.

GURITA, R.A. 2020. *Avaliação dos fatores condicionantes da favorabilidade hidrogeológica do sistema aquífero cárstico-fissural, região de Montes Claros, MG*. Departamento de Geologia, Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto, Undergraduate Dissertation, 78 p.

JUNQUEIRA, T.P. 2020. *Modelo conceitual das águas termais da região da Chapada dos Veadeiros (GO): estudos estruturais, hidroquímicos e isotópicos*. Instituto de Geociências, Universidade de Brasília, Brasília, MS Dissertation, 101 p.

KOHNKE, M.W. 2001. Atenuação natural de contaminantes, metodologias para a delimitação do perímetro de proteção de poços (PPP). *ABAS Informa*, 121: 9-10.

LOBO-FERREIRA, J.P. 1998. Vulnerabilidade à poluição de águas subterrâneas: fundamentos e conceitos para uma melhor gestão e proteção dos aquíferos de Portugal. *In*: APRH, CONGRESSO DA ÁGUA, 4, Lisboa, *Comunicações*, p. 1-16.

LOUSADA, E.O.; CAMPOS, J.E.G. 2005. Proposta de modelos hidrogeológicos conceituais aplicados aos aquíferos da região do Distrito Federal. *Revista Brasileira de Geociências*, 35(3): 407-414.

MUÑOZ, E.; ARUMÍ, T.; WAGENER, R; OYARSÚN, R.; PARRA, V. 2016. Unraveling complex hydrogeological processes in Andean basins in south-central Chile: An integrated assessment to understand hydrological dissimilarity. *Hydrological Processes*, 30: 4934-4943. https://doi.org/10.1002/hyp.11032

OAS – ORGANIZATION OF AMERICAN STATES. 2009. *Aquífero Guarani: Programa Estratégico de Ação. Relatório do Projeto de Proteção Ambiental e Desenvolvimento Sustentável do Sistema Aquífero Guarani*. OAS, Edição bilíngue, Brasil, Argentina, Paraguai, Uruguai.

OLIVEIRA, L.A. 2009. *O Sistema Aquífero Guarani no Estado de Goiás: Distribuição, caracterização hidrodionâmica, composição isotópica e CFCs*. Instituto de Geociências, Universidade de Brasília, Brasília, PhD Thesis, 188 p.

OLIVEIRA, O.A.; RODRIGUES, D.S.; CAMPOS, J.E.G.; UAGODA, R.E.S. 2022. Metodologia para Confecção de Mapas Potenciométricos em Aquíferos Cársticos e Físsuro-Cársticos: Estudo de Caso na Alta Bacia do Rio Corrente, Mambaí, GO. *Revista Brasileira de Geografia Física*, 15(5): 2327-2339. https://doi.org/10.26848/rbgf.v15.5.p2327-2339

PALMER, A.N. 2010. Understanding the hydrology of karst. *Geologia Croatica,* 63:143-148. http://dx.doi.org/10.4154/gc.2010.11

PEREIRA, R.; GUIMARÃES Jr., J.A.; SILVA Jr., G.C. 2003. Estado da arte da bacia hidrogeológica do Sistema Lacustre Bonfim – RN, Nordeste do Brasil. *Revista Águas Subterrâneas*,17: 41-47. https://doi.org/10.14295/ras.v17i1.1311

PUTRANTO, T.T.; LUTHFI, M.I.; QADARYATI, N.; SANTI, N.; HIDAJAT, W.K. 2019. Aquifer system, recharge-discharge zone and groundwater basin boundary mapping to support open and transparent water data, case study: Karangkobar Groundwater Basin. *E3S Web of Conferences*, 125: 01012. https://doi.org/10.1051/e3sconf/201912501012

ROSEN, L.; LEGRAN, H.E. 2000. Systematic makings of early stage hydrogeologic conceptual models. *Groundwater*; 38: 887-893. https://doi.org/10.1111/j.1745-6584.2000.tb00688.x

TIEDMAN R.C.; GOODE D.J.; HSIEH P.A. 1998. Characterizing a ground water basin in New England Mountain and valley terrain. *Groundwater*, 36(4): 611-621. https://doi.org/10.1111/j.1745-6584.1998.tb02835.x

TOSCANO G.L.G.; SANTOS K.M.; ALMEIDA C.N.; SILVA T.C. 2008. Uma Síntese Analítica sobre Legislação de Proteção das Águas Subterrâneas no Brasil. *In*: ABAS, CONGRESSO BRASILEIRO DE ÁGUAS SUBTERRÂNEAS, 15, Natal, *Anais*, 20 p.

SILVA Jr., G.C.; PITA, R.C.S.; CUNHA, C.M.B.; SILVA, T.A. 2021. Aplicação do isótopo radioativo de carbono (^{14}C) na determinação de tempos de residência em aquíferos. *Derbyana*, 42: e743. https://doi.org/10.14295/derb.v42.743

VERÍSSIMO, L.S.; CAVALCANTE, I.N.; AGUIAR, R.B.; MAIA, J.V.M. 2007. Recursos hídricos subterrâneos da Bacia Sedimentar do Araripe, Zona Leste do estado do Ceará. *In*: SIMPÓSIO DE HIDROGEOLOGIA DO SUL – SUDESTE, 1, Gramado, *Anais*, 11 p.

VILLASEÑOR, E.M.; MEGDAL, S.B. 2021. The U.S.-Mexico Transboundary Aquifer Assessment Program as a Model for Transborder Groundwater Collaboration. *Water*, 13(4): 530. https://doi.org/10.3390/w13040530

WHITE, W.B. 2002. Karst hydrology: recent developments and open questions. *Engineering Geology*, 65: 85-105. http://doi.org/10.1016/S0013-7952(01)00116-8

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