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Identification and characterization of regional water flows contributing to the recharge of an unconfined aquifer

Identificación y caracterización de flujos regionales de recarga de agua a un acuífero libre

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ABSTRACT: The aquifer recharge can be direct and diffuse, or can occur through interaction with surface water bodies, or from input of regional flows from remote areas according to the conditions of porosity and second permeability from the host rock. In this study, direct recharge areas and regional flow systems were determined for the Aburrá Valley-Colombia. Five factors were taken into consideration in order to identify recharge areas: location of the springs, weathering profiles, topography, structural patterns and infiltration. Hydrogeochemical and isotope methods were used in order to validate the model.

RESUMEN: La recarga a un acuífero puede ser directa y difusa produciéndose a través de la superficie donde este aflora, puede darse mediante la interacción con cuerpos de agua superficial o a partir de aportes de flujos regionales desde zonas distantes según condiciones de porosidad y permeabilidad secundaria de la roca encajante. En este estudio se determinó para el valle de Aburrá-Colombia, las áreas de recarga directa y las zonas de aporte por flujo regional. Para la identificación de las zonas de recargas se tuvieron en cuenta cinco propiedades del sistema: localización de manantiales, perfiles de meteorización, topografía, patrones estructurales e infiltración. Métodos hidrogeoquímicos e isotópicos se usaron para validar el modelo.

1. Introduction

Of all the liquid freshwater resources that exist on the planet, groundwater represents the most important reservoir. Its relative abundance and the natural conditions of its location, in theory, allow it to have excellent quality.

Within a hydrogeological system, the main source of direct recharge to a free aquifer is generally precipitation surplus [1, 2]; however, in aquifers with significant thickness, lateral contributions from the host rock or from regional flows are able to add a significant amount to the volumes of water that are stored and circulate through porous media and fractured rocks.They can also influence the water's chemical properties.

An analysis of the effect of regional flows in particular has hardly been studied or reported [3, 4]. The predominance of one or another source of water in the system depends on the geological, geomorphological, edaphological and climatological properties of the system.

The conceptual hydrogeological model is an essential tool in identifying areas of interest that contribute to the recharge of the aquifers and the measurement of their direct recharge. In general terms, the precipitations entrance through the unsaturated zone occurs according to the infiltration rate of the soil in the area around the surface of the aquifer [5-7], and depends on the quantity of precipitation [8, 9]. By means of direct and indirect calculation, it is possible to calculate and measure this recharge.

The lateral contributions become apparent through measurement of fluctuations in the piezometric level [10, 11], and they are tested with hydrochemical and isotopic analyses which show the water sources that are contributing in addition to local precipitation [12].

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The identification and determination of areas and sources of water contributing to hydrogeological systems is fundamental for determining the availability of the resource and for establishing protection measures that might guarantee the quality, and along with it, the sustainability of groundwater. Additionally, to detect instability factors that can trigger phenomena such as landslides or subsidence, and can eventually represent risks to human lives and civil works.

This article is a synthesis, examining the experience acquired through the studies Determinación y Protección de Zonas de Recarga en el Norte del Valle de Aburrá [13] and Determinación y Protección de Zonas de Recarga en el Centro y Sur del Valle de Aburrá [14]. It uses a methodology of analysis for determining and categorizing the areas of lateral contribution of groundwater to an aquifer, combining a series of technical procedures that until now have never been used together. This methodology becomes a proposal that can be used for the study of recharge of aquifers due to regional flows.

At the end, we present the results of the application of this methodology for a specific case in Aburrá Valley, Colombia.

2. Methodological synthesis

To adequately administer the resources that exist in aquifers, it is necessary to have a detailed knowledge of how the water flows occur in the soil and rocks. Additionally, to understand aquifer recharge and discharge, it is necessary to look at the boundary conditions that define the input and output flows to these units. Figure 1 is a diagram of these external boundary conditions and the way water can flow into an aquifer. The infiltration of water from precipitation to an aquifer can occur by direct recharge, indirect recharge from regional flow, and/or through flow from bodies of surface water. Direct recharge occurs when the water gains access by vertical percolation through an existing unsaturated zone above the aquifer. Indirect recharge from regional flow occurs by infiltration through permeable strata, weathered or fractured rocks. Finally, the recharge from surface bodies can arise from the interaction between surface water sources and the hydrogeological unity.

The identification and characterization of natural water flows that contribute to the recharge of an aquifer are indispensable for an adequate understanding of the size and availability of the water as a resource. Thus, there are various techniques that permit the estimation of the boundary conditions that allow the ingress of water. Figure 2 shows a conceptual diagram of the techniques that allow identifying the three kinds of natural water contributions to a free aquifer. The first corresponds to direct recharge areas that can be estimated by locating those places where outcropping of the aquifer occurs, and that are determined by hydrogeological exploration. A task that is part of the conceptual hydrogeological model. Secondly, we have areas that allow the flow of surface water to a hydrogeological unit and that can be estimated through piezometric monitoring, which gets the measurements of the groundwater level through time, and by inspection and comparisons of piezometric surfaces that allow determining possible interactions between surface water and groundwater. Finally, regional flows depend on the host rock, its primary and secondary permeability. Of the three forms of recharge, the latter has been shown in the context of regional flow systems [15]; however, it has hardly been evaluated or documented. It is particularly complex and it depends on multiple variables such as: the presence of springs, the characteristics of the weather profiles, terrain geomorphology, structural patterns and infiltration conditions. The use of hydrochemical and isotopic tracers permits verification of these flow routes. On a regional level, the areas that facilitate this type of recharge are extensive. These recharge areas by regionals flows influence the quality of the water that flows into the aquifer considerably. This is due to the possibility that contaminants infiltrate and reach the aquifer. Consequently, regional flows must not be neglected in an assessment of the groundwater resources of an area.

Recharge from regional flows can normally be seen when aquifer system host rocks have acquired conditions of porousness and secondary permeability. To identify the areas that have acquired these conditions, which turn them into a source of indirect recharge, in this study, we propose undertaking a cross-analysis of a series of hydrogeological characteristics units that serve as the base or host hydrogeological units for the underground reservoir (Figure 2). The hydrogeological characteristics are explained in the following:

- Location of the springs: since the springs are points where groundwater naturally outcrops, the possibility for using them to gauge the flow and take measurements of the water converts them into sources of information that show the transit route of the underground hydric resource. To locate the springs, field visits were done to make an inventory of the points where outcroppings of water were detected.

- Determination of weathering profiles: the evaluation of textural properties of the unsaturated zone, characteristics inherited from the mother rock based on the physical and the chemical meteorization

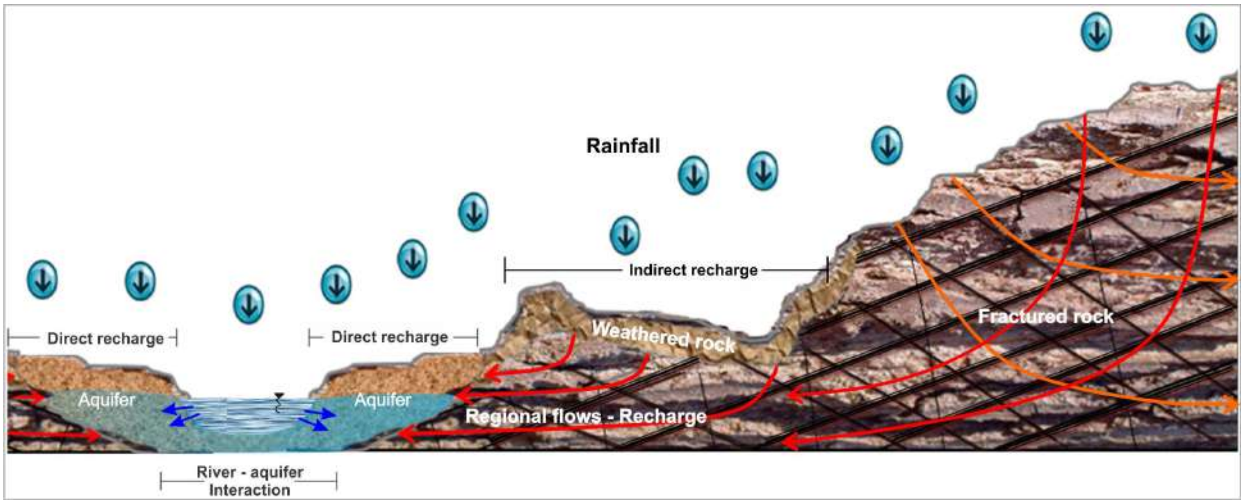

Figure 1 Scheme on direct and indirect recharge processes

processes it has undergone, gives clues for estimating the dimension that the vertical flow of water can cover through them as a potential source of recharge. For description of the profiles, some zones were identified in the field that permit analysis of the texture of the meteorized rock and its respective thicknesses.

- Identification of areas with adequate topography: the maps of slopes and transverse topographic sections permits the location of sectors with soft reliefs, steps and sinkholes in the slopes which allow for temporary surface storage on the surface that becomes the source of flow. To identify these zones, a digital elevation model (DEM) was used to obtain a map of the slopes and a side-view of the profiles toward the area of the aquifer.

- Evaluation of structural patterns: the objective of this activity is to identify jointing families and patterns that allow the regional flow toward the aquiferous units. Some aspects that must be considered include: directions and angles of pitch of the structures, density of the jointing, aperture of fractures, and joint roughness. To determine the structural patterns, rock outcroppings were located in the zone and measurements of pitches, paths, distancing and spacing for each jointing family were taken.

- Determination of infiltration conditions: in the zones where adequate topographical conditions are met based on weathering profiles and structural patterns that are conducive to infiltration, field infiltration tests were performed to evaluate the levels of hydraulic conductivity. For estimation of the infiltration capacity of the soil, two-ring hydraulic conductivity field tests were performed [16] in the zones chosen for likely having significant rates of infiltration, based on their topographical profiles.

Keeping the combination of hydrogeological characteristics in mind that are considered essential at different levels of importance for causing the entry and movement of water to the subsoil, we propose applying the Analytic Hierarchical Process (AHP), based on the work of Thomas L. Saaty [17], and the "outranking" approach, based on the work of Bernard Roy [18, 19] for determining the recharge zones that make up regional flows.

For implementation of the AHP methodology in the evaluation of regional flows and their contribution to recharge, we selected a representative sample made up of 18 experts in hydrogeology from Argentina, Mexico, France, Portugal and Colombia. We handed them a survey which allowed us to rank the essential factors for characterizing the recharge coming from regional flows in order of importance. More details about the methodology used for defining the weights assigned to each evaluated characteristic can be found in Escobar *et al.* [20].

Table 1 synthesizes the weights that were obtained. According to these results, the factor with the biggest importance in defining the recharge coming from regional flows is an adequate topography which allows water infiltration. The least important factor is the presence of springs. It is worth noting that this factor (location of springs) shows that a flow exists through the geological units, but indicates a discharge of groundwater.

We obtained a function that can be defined as an index of regional flows (1) and which helps us to categorize regional flows and their contribution to recharge considering the weight obtained from each factor. The function is applied per geological unit and consists of multiplying each factor,

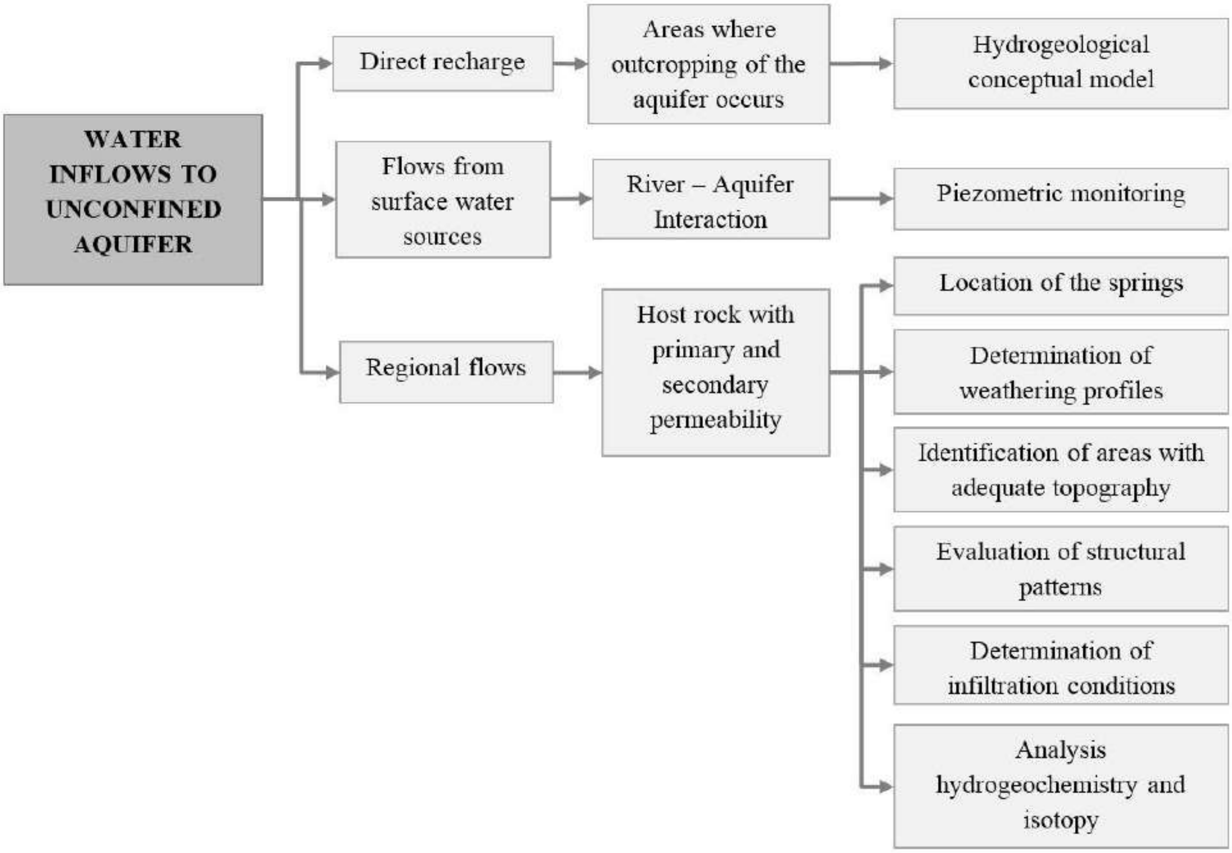

Figure 2 Conceptual diagram to identify natural inputs of water (contributions) to an unconfined aquifer

Table 1 Results of the weighting methodology for variables in the evaluation of regional flows and their contribution to recharge

Factor	Weights obtained
Identification of areas with adequate Topography (T)	0.26
Evaluation of Structural patterns (S)	0.23
Determination of weathering profiles for evaluation the Textural Patterns (TP)	0.21
Determination of Infiltrations conditions (I)	0.19
Location of the Springs (SP)	0.11

for the identification of regional flows, by the weight obtained by methodology AHP.

$$IRF = 0.26(T){+}0.23(S){+}0.21(TP){+}0.19(I){+}0.11(SP) \quad (1)$$

$Where$:
IRF: Index of regional flows
T: Topography
S: Structures
TP: Textural patterns
I: Infiltration
SP: Springs

Approximations in the same mode have been proposed by Zaidi *et al*. [21] for evaluating the handling of aquifer recharge.

Hydrogeochemistry and isotopy constitute methodologies for testing water sources and routes. Samples are taken of water sources that are put under hydrogeochemical isotopic analysis [22] to track flow routes. In the hydrogeochemical analysis, Piper diagrams are used to chemically characterize the water and to establish a tentative approximation of its origin and degree of evolution from interaction between water and rock along a flow line. In the isotopic analysis, a local meteoric line -LML- is defined with at least one year of monthly isotopic information, and the possible sources of recharge are defined on a graph δ18O vs.δ2H.

In mountain areas, the isotopic fractionation associated with altitudinal effects is an important indicator for the definition of recharge zones. The relationship between the isotopic composition of groundwater and rainfall data allows an establishment of the degree of closeness with an average composition, or the contrary with water coming from different sources of rain.

Once the recharge zones are identified according to the proposed criteria, a methodology of ranking is developed for the flows that contribute water either directly or indirectly to a free aquifer. To rank the recharge zones, we propose a system of 5 categories, in which category 5 corresponds to the most important zone and category 1 to the least important zone.

- Category 5 – Direct recharge: the most important recharge areas in terms of magnitude. They are considered the most important because through them the flow from surface to aquifer happens only by infiltration, and the lag time in relation to precipitation is minimal.
- Category 4 – Regional flows of high importance: group of areas geomorphologically adequate for temporary storage on the surface. Existence of weathering profiles with high hydraulic conductivity, which have associated springs. Structural patterns favoring underground flow in the direction of aquiferous units are favored.
- Category 3 – Regional flows of moderate importance: areas which are geomorphologically adequate for temporary storage on the surface. Existence of weathering profiles of moderate hydraulic conductivity. Structural patterns with some component favorable to the flow in the direction of some neighboring aquiferous units.
- Category 2 – Regional flows of low importance: areas geomorphologically adequate for short-term surface storage. Weathering profiles with low hydraulic conductivity. Structural patterns with some components that are favorable to the flow in the direction of the neighboring aquiferous units at a short distance.
- Category 1 – Regional flows of very low importance: areas which are geomorphologically adequate for short term storage on the surface. Meteorization levels with very limited hydraulic conductivity. Structural patterns favorable to flow being directed to the aquifer are scarce.

3. Application

3.1 Area of Study

The proposed methodology has been applied in the Aburr Valley. The Aburr Valley is located in the Colombian Central Andes, between geographic coordinates 6°30'25'' and 6°17'2'' N and 75°40'5'' and 75°13'30'' W. It is a natural basin of the Aburr-Medellín River, located in the middle of the Department of Antioquia. The Aburr Valley is a mountainous domain with altitudes varying from 1,300 m.a.s.l. to 3,100 m.a.s.l., and has slopes of up to 75°. In terms of geomorphology, the valley consists of three units with different landscapes, taking into account aspects of shape, width, orientation, and physiographic context. Temperature oscillates between 16 and 29 °C and relative humidity is 70%. The region is characterized by a humid, tropical climate with an average annual precipitation of 1,500 mm.

For Aburr Valley, a tectonic-sedimentary origin has been documented, with the effects of the fault being relevant and obvious in producing fracturing and jointing of hard rocks. A hydrogeological system has been detected in the valley in which a free aquifer, associated with alluvial deposits from the Medellin River, and debris can be identified.

The zone in which the application of the proposed methodology to determine regional flows was undertaken (Figure 3) has an area of 1,152 km2 and is home to approximately 3,306,490 inhabitants (94.5% in the urban area and 5.5% in the rural area) [23].

3.2 Hydrogeological Model

The free aquifer of Aburr Valley is associated with recent alluvial deposits of the river and its main tributaries. Moreover, it is connected to deposits from debris flows from the Neogene to Quaternary Ages. In terms of texture, these formations show the presence of facies with a sandy or sandy-silt matrix that confers characteristics of hydraulic conductivity that allow them to be considered aquifers. The aquifer reaches thicknesses of up to 68 meters, and the flow tendency of the groundwater is generally sub-parallel to the topographic slope; although occasionally there are gradients that allow flows from certain surface bodies to the subsoil. On average, the Medellin River has a hydraulic that captures the basal flow. Conditions of transmissivity are directly tied with the textural conditions of the hydrogeological formations, and vary between 0.01 and 9.64 m^2/day [14].

The entry of water into the system could occur from direct recharge and regional flows.

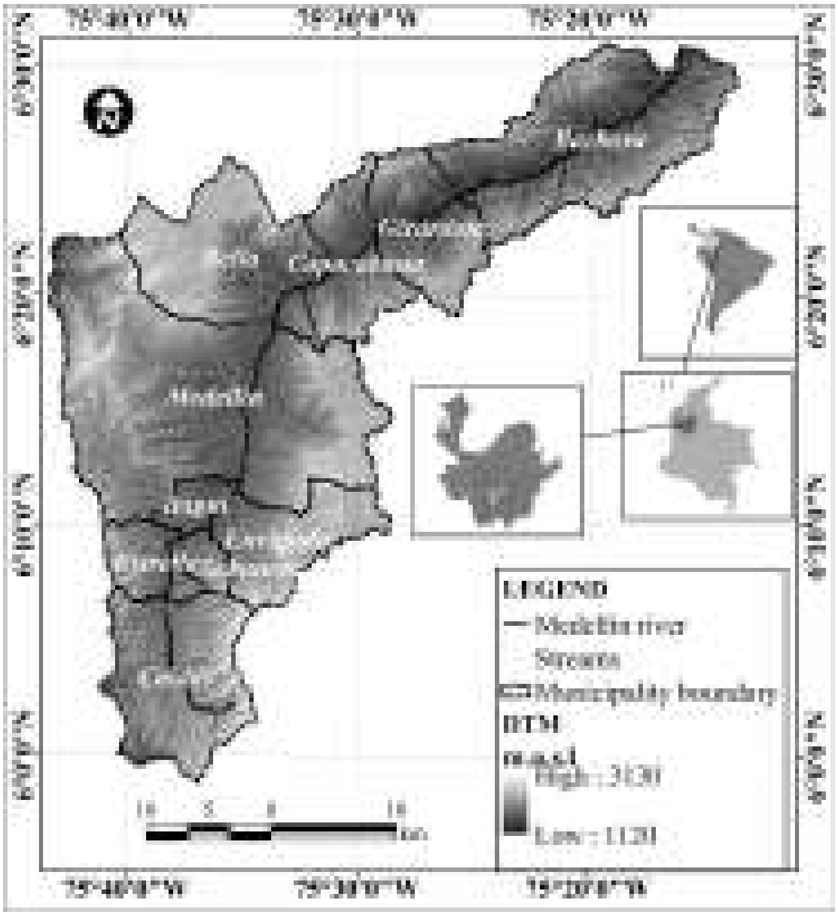

Figure 3 Location of the study area in the Aburrá Valley

per unit of soil method, Soil Water Balance (SWB), and using data from 8 hydrometeorolgical stations of the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) with daily measurements between 2000 and 2011, it has been estimated that direct potential recharge for dry scenarios (2000-2001) is on average 83 mm/year, 149 mm/year for a year with moderate precipitation, and 610 mm/year for a wet year (2010). On average, recharge makes up 20% of annual precipitation [14].

The hypothesis that there are regional flows that add water to the free aquifer of the Aburrá Valley is supported by the existence of springs, the tectonic characteristics of the base that hosts the aquiferous system, and the directions of flow which signal that source areas of recharge are located on the slopes of the valley.

The base of the hydrogeological system is made up of lithological units of intrusive igneous and regional metamorphic origin. Both types of rock are affected tectonically by the fault in a preferential SW-NE direction, with different pitch conditions. In addition, we know the physical meteorization conditions of these rocks and have identified cracks caused by dissolution processes from jointing. The most relevant rock units in terms of regional flow are Batolito Antioqueño, la Dunita de Medellín, las Anfibolitas de Medellín, el Stock de Altavista, Stock de Amaga, Tonalita de Ovejas, las Migmatitas de Puente Pelaez and the Esquistos de Cajamarca. The Batolito Antioqueño (KcdA), from the Cretaceous, is a phaneritic and equigranular granodiorite, with mainly medium to thick grain size. The Dunita de Medellín (JKuM) is a body with a tabular shape placed by overthrust in a SE-NW direction over the Colombian Central Andes; the dunite has gone through serpentinization and dissolution processes that make it a pseudokarst. Compared to the Anfibolitas de Medellín (TRaM), it is a rocky body arranged in a strip in a NW direction, and is a rock of medium to fine grain with euhedral shapes. The Stock de Altavista (KdA) is a plutonic to subvolcanic igneous body that is intensely meteorized, with high degrees of textural and granulometric variability. The Stock de Amaga (TRgA) is an equigranular rock with a medium phaneritic texture, mostly solid, granular to porphyritic, and medium to thick grain. The Tonalita de Ovejas (KtO) is a phaneritic and equigranular rock, of medium to thick grain with significantly deep weathering profiles that preserve the textural traits of the parent rock. The Migmatitas de Puente Peláez (TrmPP) have a migmatitic, folded texture, with the presence of fine grains and porphyritic bodies, as seen in some fault zones. The Esquistos de Cajamarca (TreC) are made up of low grade metamorphosis schists whose main composition is quartz-sericite, raphitic and cloritic [13, 14]. These schists show a development of residual soil which varies between the size of sand grains and smaller sizes. The detailed geology of the Aburrá Valley can be consulted in the study Microzonificación Sísmica del Valle de Aburrá [24].

3.3 Identification of source areas of regional flows

In accordance with the methodology proposed in this text, we describe the results of its application— step by step— in the geographic domain of the Aburrá Valley, a region selected as the pilot for identifying source areas with regional flows that contribute water to the aquifer.

The information registered for each of the hydrogeological characteristics that was considered in the classification and categorization of recharge zones by regional flows contributing to the recharge of an unconfined aquifer, was obtained through the studies for the identification and delimitation of recharge areas in the Aburrá Valley [13, 14].

Location of the Springs

The spatial distribution of 101 perennial springs that are recognized in the zone of study (Figure 4) is the first evidence for the existence of zones in the high parts and across the tributaries that border the Aburrá Valley from which infiltration is produced, and later, flow of groundwater comes. As shown in the map in Figure 4, springs are distributed over the different rock units. In addition, the network of drainage with a density of 7.2 km/km2 and more than 28,000 channels of order 1 reveals there is an outcropping point for water from the subsoil for each initiation of current.

3.2.1 Weathering profiles

Based on the profiles that were identified for the distinct units of rock of the zone of interest, the development of soil under the proper hydrological and topographical conditions allowing infiltration processes is established. In the Batolito Antioqueño (KcdA) diverse, deep weathering profiles were developed. Accompanied by spheroidal meteorization processes, horizons with outcroppings of fresh rock developed which have not been affected by jointing, or show only light jointing. In addition, horizons of friable saprolite were created that conserve the granitic texture of the rock, with silty granulometry; also, the sporadic occurrence of quartz grains of sand size along with horizons where the granulometry varies between sandy clay and sandy loam, with the frequent presence of quartz grains and gravel-size pieces of mica, with characteristic colors red and yellow, on occasion enter-mixed in the same horizon, giving it a mottled appearance.

Over the Dunitas de Medellín, in addition to serpentinization, meteorization processes have occurred that led to the development of soils with horizons of little thickness, and with nuclei of fresh rock immersed in a silty, reddish-brown matrix. In the Anfibolita de Medellín (TraM), the main type of horizon is one with saprolite of silty clay granulometry that is gray with white specks that keep the original texture of the rock. Moreover, we can find horizons with granulometry that varies between silt, clayey silt, and clay with a reddish-yellow and brownish-yellow color. In the Stock de Altavista (KdA), shallow layers of mature, homogeneous soil develop with a clayey silt character and clear color, followed by silt-clay saprolite that keeps the original texture and structure of the rock. These soils show a high degree of variability in terms of texture and granulometry. In the Stock de Amaga (TrgA), residual soils are most common over the fresh rock, with weathering profiles that are highly fractured, of dark or pallid yellow, with sandy granulometry and the development of gruss. Over the Tonalita de Ovejas (KtO), deep weathering profiles have developed, generally white in color, with horizons that keep the textural traits of the parental rock, silty granulometry, silty clay, firm consistency, low to zero plasticity and moderate cementation. In the Migmatitas de Puente Peláez (TRmPP), yellow and reddish residual soils form with fine (clay) and thick (sand) granulometry, with horizons characterized by the banding inherited from the parental rock, with white, dark gray and many shades of yellow and red color. Classification of the gneiss in each horizon depends on the degree of jointing and alteration in the fracture zones. Finally, the Esquistos de Cajamarca (TReC) have variable weathering profiles, with the development of a reddish-brown clayey silt that has no surface texture, followed by a material that keeps the original texture.

Identification of areas with adequate topography

The geomorphological characteristics that have shaped the landscape of the Aburrá Valley over the distinct types of rock, as much by the effects of meteorization as by tectonics, permit the identification and localization of sectors where the relief is favorable for temporary surface storage of water, allowing later infiltration. These traits basically correspond to the high sectors of the plateau, where the shallow watershed of the Aburrá Valley is

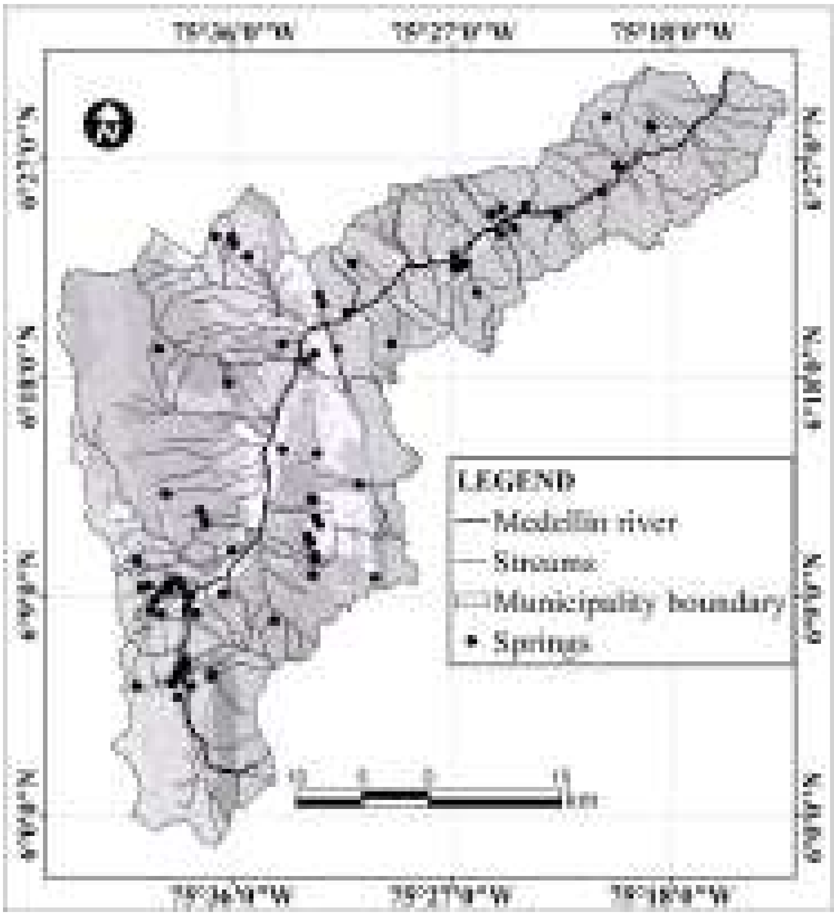

Figure 4 Springs Localization

located, and to the steps in the tributaries caused by the presence of saddles or alignments of fault traces. In the cut shown in Figure 5, an example of these characteristics can be seen.

Evaluation of structural patterns

Structural analysis was done in an independent manner for each geological unit, differentiating both tributaries of the river. The information used for this activity came from documentary sources [24] and from fieldwork. In total, we analyzed structures measured at 702 observation points. For each unit we obtained results such as those shown for the Anfibolitas de Medellín, on the right bank of the river (Figure 6). In this particular case, the systems from which the flow that feeds the aquifer can be expected are the jointing families with paths that oscillate toward the N-S, with pitches in the NW, SW, NW direction.

Determination of infiltration conditions

From the results of 57 two-ring hydraulic conductivity field tests performed at sites with distinct parental, material and different meteorization conditions [13,14], it was possible to establish that the entry values of water for the Batolito Antioqueño vary from moderate to slow, by taking various coverings of the soil into account and reconsidering contrasts in the topographic aptitude. As to the Anfibolitas de Medellín and the Migmatitas de Puente Peláez, the infiltration rate varies from moderately slow to impermeable, and for the Stock de Altavista and the Tonalita de Ovejas it is moderately fast [13, 14, 25].

3.4 Categorization of areas

The IRF function for categorization of regional flows and their contribution to recharge keeps track of and implements the weight of each determining factor and applies the function to a lithological unit. Each factor is scored on a scale from 5 to 1, depending on whether or not it facilitates the recharge of the aquifer.

The areas with adequate topography were assigned a value according to their degree of inclination, with 5 for flat zones (0°) and 1 for those with slopes of 90°. The structural patterns of each lithological unit are score-based and depend on how favorable its jointing families tend to

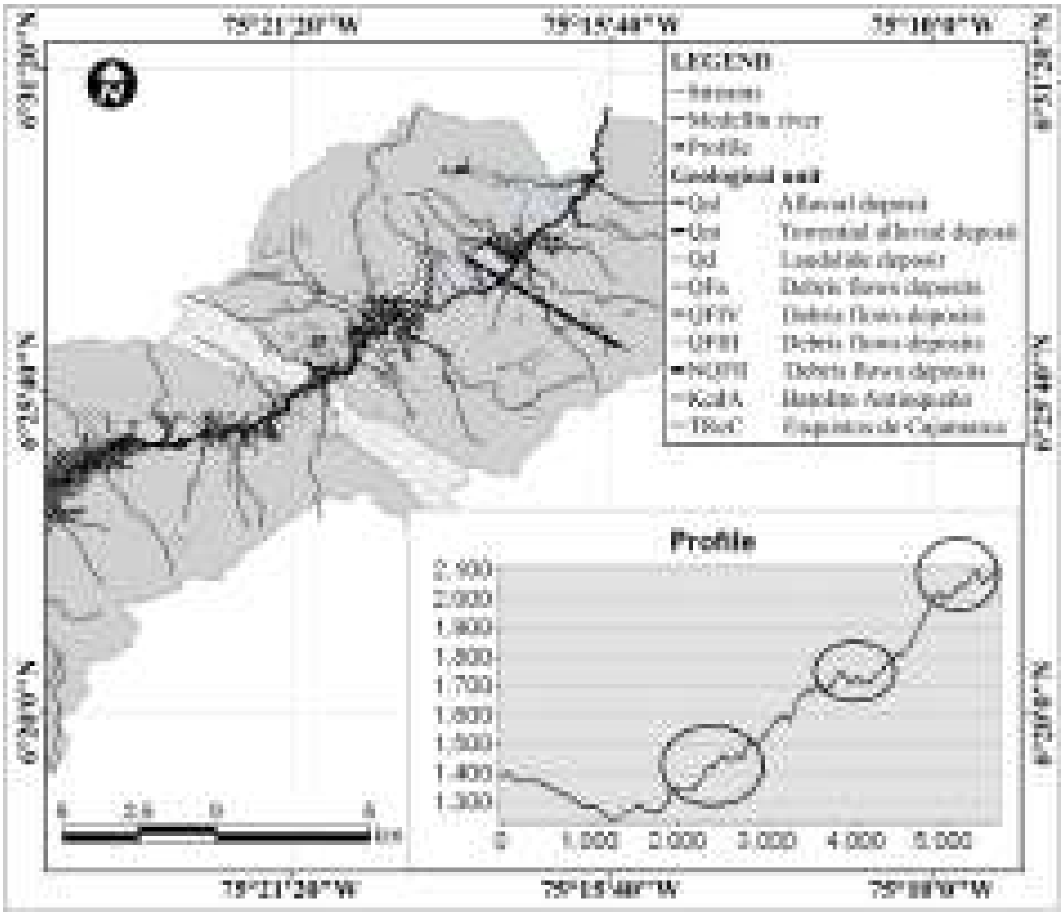

Figure 5 Geomorphology of the study area

be, the amount of jointing per meter present in its outcroppings, and its pitch. For these textural patterns, scoring is defined according to the granulometry of the soil, assigning 5 for thick grain sizes (gravel, sand, sandy gravel, fine sand, silty sand), 3 for textures with mixtures of types of sand with fine granular particles (silt, sandy silt, sandy clay), and 1 for fine sizes (clay). The infiltration rate is directly related to the texture of the material. Its score depends on the velocity of infiltration, with 5 for flows that vary from moderate to very fast, 3 for slow flows and 1 for impermeability. This model is based on the classification of quality and soil sanity of the soils (Table 2) [25]. For the last factor, and keeping in mind that springs have discharge zones, the lithological units are assigned a score of 5 if they don't have them, and a score of 1 if they do.

Once the values of the determining factors for the identification of regional flows are defined, they are multiplied by the weight found by using the Saaty AHP. The categorizations obtained from applying this methodology are grouped and ranges of 4 classes are established (scores between 1 and 4) for the zones identified with regional flows.

Table 2 Infiltration rate classification. Source: [25]

Infiltration rate (centimeters/hour)	Infiltration rate classification
>50.80	Very fast
15.24 – 50.80	Fast
5.08 – 15.24	Moderate fast
1.52 – 5.08	Moderate
0.51 – 1.52	Moderate slow
0.15 – 0.51	Slow
0.004 – 0.15	Very slow
<0.004	Impermeability

Based on the obtained IRF values, the recharges from regional contributions are ranked with different levels of importance i) High 4 to 5, ii) Moderate 3 to 4, iii) Low 2 to 3 y iv) Very low 1 to 2. In light of this methodology, the direct recharge zones will be considered as having the most importance (grade 5), because through them the flow from surface to aquifer takes place because of texture and infiltration, lessening the amount of time between the precipitation event and the contribution to the aquifer.

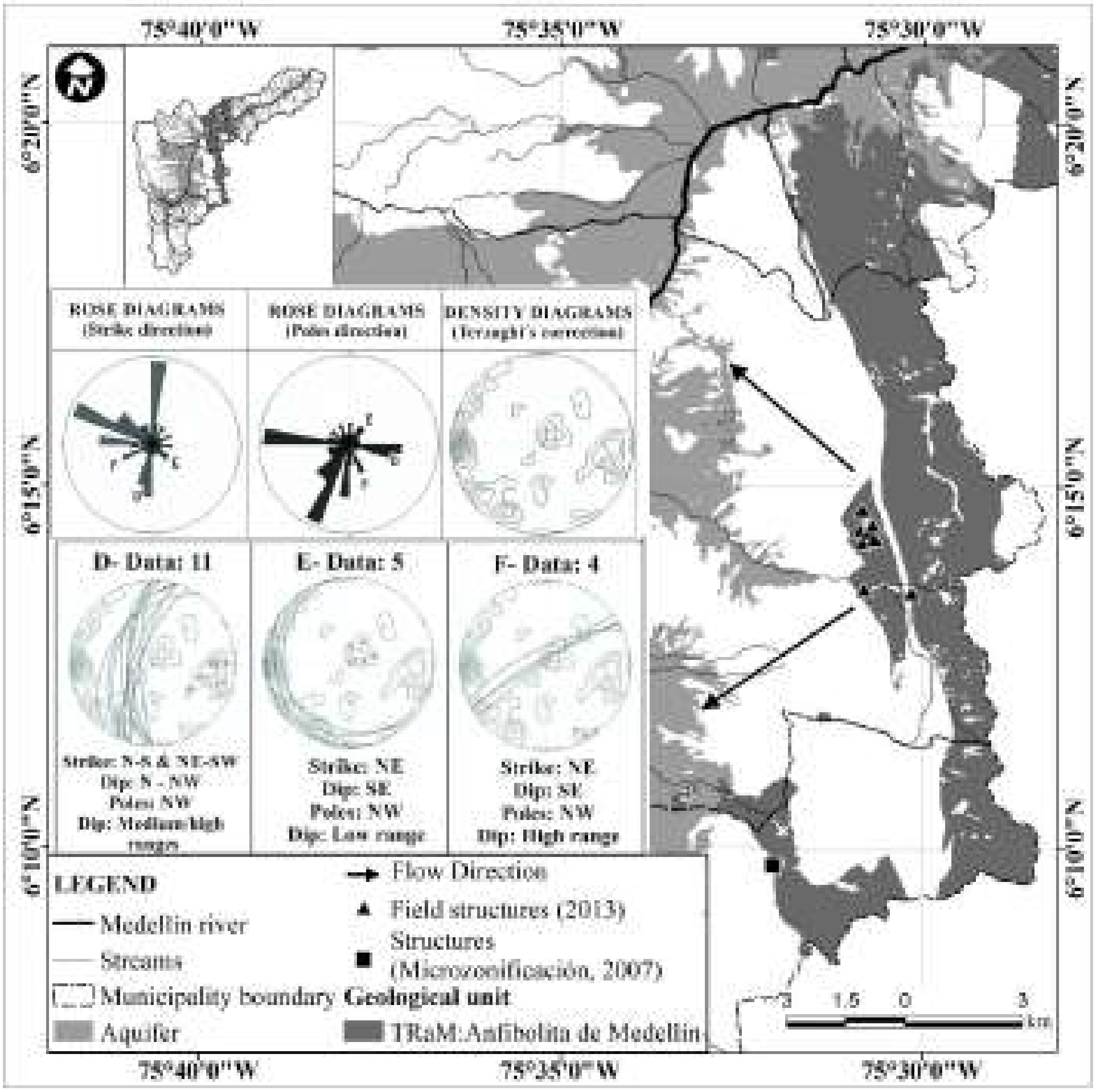

Figure 6 Structural patterns for Anfibolitas de Medellín, on the right bank of the river

Figure 7 shows the results of applying a map algebra function to calculate the IRF and proposed ranking in terms of the results from the study of the Aburrá Valley. The figure shows the category that corresponds to the direct recharge zone. It is located all along the banks of the Medellín River and its tributaries, and it is associated with some mass flows. The Dunita de Medellín also belongs to this category; the area of direct recharge (excluding the urban area) is 165.2 km2. The indirect recharge zone of high importance is in the Stock de Amagá (TRgA) and in the same units as the direct recharge, but in areas smaller than 2 km2. The category with the largest area is the recharge zone of moderate importance, which involves geological units such as the Batolito Antioqueño (KcdA), the Esquistos de Cajamarca (TReC), the Anfibolitas de Medellín (TRaM), the Migmatitas de Puente Peláez (TRmPP) and the Stock de Altavista (KdA). The zones of low importance are found in small areas of the municipalities of Caldas, Itagí, Envigado, Medellín, Bello and Copacabana.

3.5 Validation by hydrogeochemistry and isotopy

For validation of the recharge areas, transit and discharge of groundwater, it is important to keep the point of origin of the hydrogeological flow in mind that is obtained from information collected from the field during the inventory of springs and monitoring of levels that permitted the modeling of piezometric surfaces, according to which the groundwater flow orients itself toward the axis of the river, stemming from its left and right slopes.

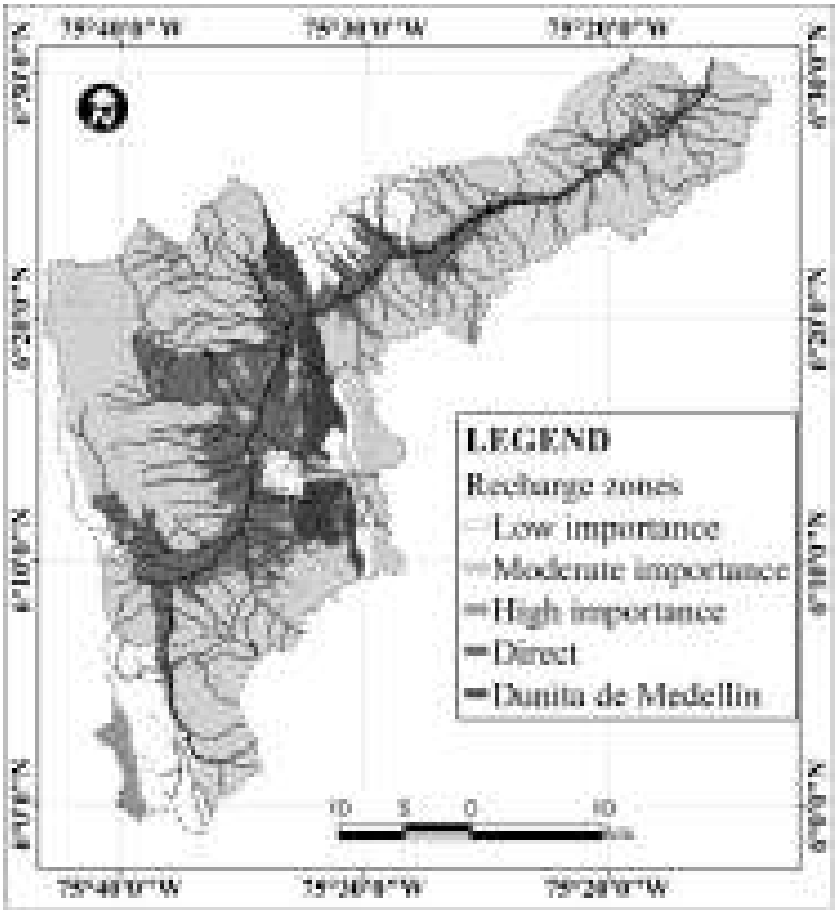

Figure 7 Recharge zones in the Aburrá Valley

This fact confirms that, based on hydraulics, there are recharge zones located on the slopes and in the high part of the valley. Then, hydrogeochemistry and isotopy verify this hypothesis in a more certain manner.

Geochemistry is the science that explores the processes that determine the chemical composition of groundwater [26]. To validate the recharge zones in Aburrá Valley using hydrogeochemistry, by means of hydrochemical analysis, we reviewed the results of 76 samples obtained during the RedRío Fase IV, Zonas de Recarga Fase I and II projects [13, 14, 27]. These consist of 15 springs, 4 wells, 53 cisterns and 4 piezometers.

The Piper diagram in Figure 8 shows that in the Aburrá Valley, there are five different chemical configurations in the groundwater. The most representative group (1) corresponds to the magnesium-calcium bicarbonate type (young waters with low residence time and quick circulation), the second group has a chemical composition of magnesic calcium, the third group has a composition of chlorinated, sulphated sodium, a fourth group belongs to the mixed bicarbonate type, and a fifth group has a sodium bicarbonate composition (the most evolved waters).

To validate the flow directions that exist in the Aburrá Valley and to find the relationships inside the water circulating in the system, the piezometric surfaces obtained in the RedRío Phase IV project [27] were used. Six lines of flow which respond to different patterns of evolution allowed its definition. Figure 9 shows the flow lines and the points where water samples were taken to perform the hydrogeochemical and isotopic analysis.

Evaluating hydrochemistry in light of the directions of hydrogeological flow and water-rock interaction, it is possible to explain the evolution and identify possible transit routes through units like Metabasitas del Picacho, el Stock de Altavista and las Milonitas de la Iguaná, located on the left slope of the river; similarly, a magnesic signature is detected on the right border of the river, which would indicate recharge coming from the Dunita de Medellín. Figure 10 shows the Stiff diagrams for some flow lines.

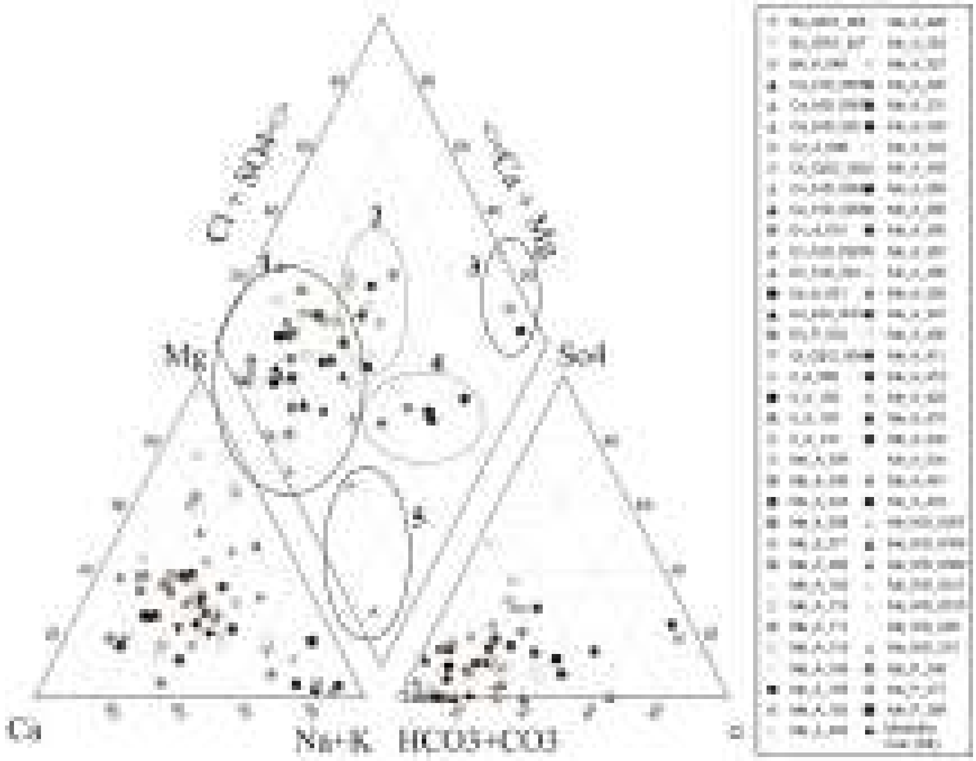

Figure 8 Piper diagram from monitoring hydrogeochemistry in the area of study

Isotopic hydrology is defined as the discipline that deals with using isotopic investigations for (re)solving a wide spectrum of hydrological problems related to surface and underground resources, and environmental studies in hydroecological systems. Some analyses of this type were used to try to test the hypothesis about the recharge area. To observe the relation between rain water and groundwater, a δ18O vs. δ2H graphic is evaluated. The position of the groundwater samples from each hydrogeological unit, with relation to meteoric tendencies that go along with the hypothesis of it being a source of recharge, are considered to determine the level of homogeneity of the data, which translates into an indication of how good the water mixture is in the aquifer. Also, it is necessary to identify whether the recharge is produced directly from precipitation or from sources that have undergone evaporation, according to how the samples are located above or below the local meteoric line [28].

Groundwater flow in Aburrá Valley was evaluated based on 90 isotopic analyses done using laser technology at the Instituto de Geocronología y Geología Isotópica (INGEIS), which is ascribed to the Facultad de Ciencias Exactas y Naturales (FCEN) of the Universidad de Buenos Aires (UBA) in Argentina. 24 samples correspond to rain water captured in the totalizers, one of which is located in the back of the valley at 1,450 m.a.s.l. (Universidad de Antioquia) and another one at 2,200 m.a.s.l (Localidad de Santa Elena), 8 samples from the Medellin River, 17 spring samples, and 40 groundwater samples. For effects of the analyses made here, data from the seasonal precipitation analyses made by Campillo in 2012 was evaluated [29].

The isotopic data from rain water obtained during the 2 years of monitoring permits a first approximation of the local meteoric line $\delta^2 H = 8.24 * \delta^{18} O + 13.7$. Figure 9 shows the data of the isotopic analysis for groundwater and surface water in relation to rain records and its average composition. A more detailed approximation makes it possible to observe certain details. Groundwater taken from the majority of the catchment shows a moderate average isotopic composition , between the averages of the rainwater from Santa Elena and Universidad de Antioquia (Figure 11), which confirms that the recharge to the hydrogeological system has a regional character, and that the water of the aquifer corresponds to a mixture of rain waters from high parts, down to the center and bottom of the Aburrá Valley. Two situations that deviate slightly from this generality are recorded for a few somewhat enriched samples and other somewhat impoverished samples.

Two springs and a cistern show a more enriched composition. Evaluating the relation of $\delta^{18} O$ vs Cl, we discard the possibility of evaporation being the source of this enrichment.

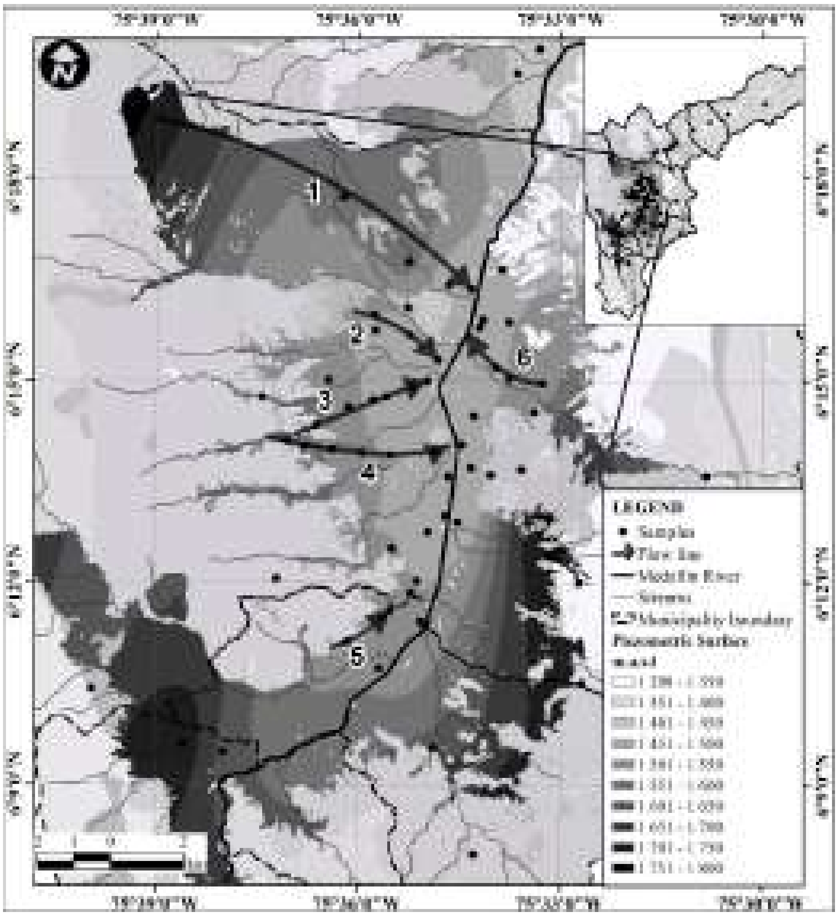

Figure 9 Flow lines in the area of study

New analyses will be necessary to evaluate the origin of this water and discern if its composition is the result of temporary effect, or if it is an indication of a different source of recharge. The most impoverished points imply a source of localized recharge at altitudes above 1,900 m.a.s.l. These sites correspond to some springs located on the right border of the Medellín river.

By tracking the isotopic characteristics of the groundwater samples through the various flow lines analyzed by means of hydrogeochemistry, the behavior of some lines stands out, in which all the points have an almost identical isotopic signature. This means that there's evidence of the existence of a single source of recharge. This can be observed in the flow line 3 (Figure 10).

4. Conclusions

The sustainability of hydrogeological resources is evaluated based on the available information about the origin of the water in aquifers, and for this reason it is fundamental to identify areas and sources of recharge and regional flows. This determination is supported by a number of factors that determine ingress of water to the subsoil and its transit through it.

The spatial representation of factors such as areas with adequate topography, structural patterns, weather profiles, infiltration rate, and presence of springs are essential for evaluating and prioritizing areas of infiltration and regional flow systems.

The geo-informatics tools that are currently available permit the development of complex, structured analyses of heterogeneous information which stems from various sources, with different scales and levels of detail. This proves to be very useful in hydrogeology and the study of aquifer recharge.

Analytic hierarchical processes, such as that of Saaty, with a wide enough survey size and expert, independent evaluators, allow assigning weights and guarantee a reasonable decrease in the so-called "decider's bias".

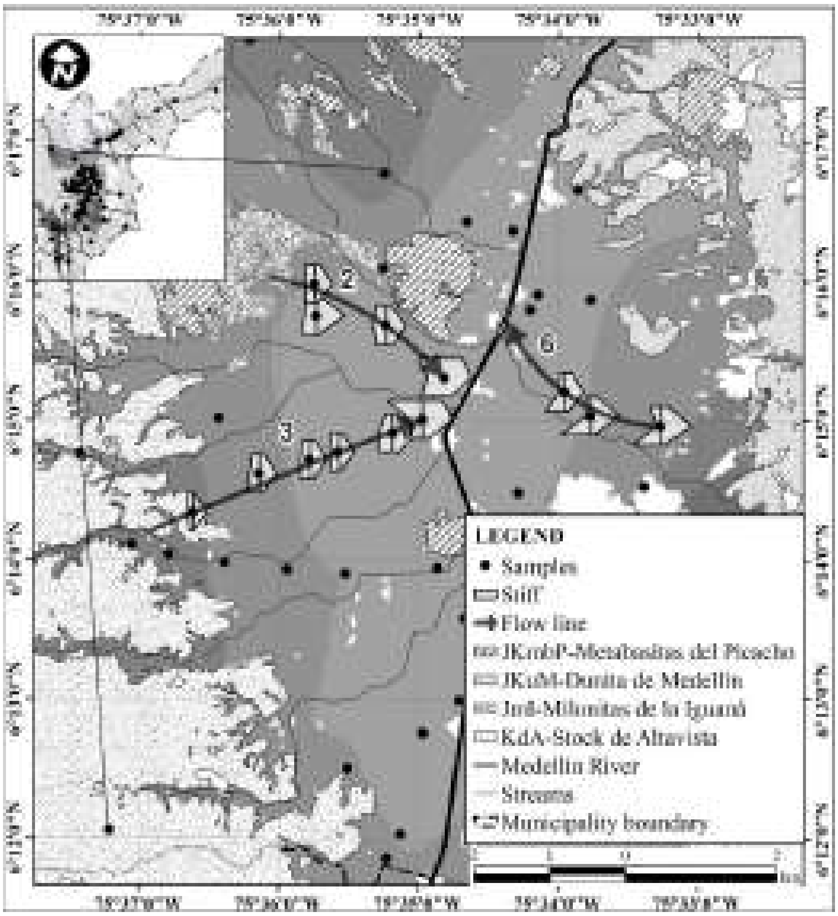

Figure 10 Stiff diagrams in the area of study

The determination of areas of recharge and regional flow systems in Aburrá Valley (Colombia) was possible by applying the superposition methodology and spatial analysis. The recharge zones were ranked in 5 categories, with direct recharge zones being the most important. For the regional contributions, four categories were defined and thereby designated as indirect recharge zones of high, medium, low or very low importance. Each condition is classified according to the ratio of occurrence of the five weighting factors.

From the collected information in the identification and characterization of the recharge zones of the Aburrá Valley, it will be possible to enforce the quantitative analysis that allows the development of isotopic and hydrogeochemical models.

The obtained results through the application of this proposed methodology to a case study in the Aburrá Valley, and its relationship with hydrodynamic methods and hydrogeochemical and isotopic information, validate the hypothesis of recharge and regional flows in the study area; it suggests that this methodology can be applied to other study cases even in different regions.

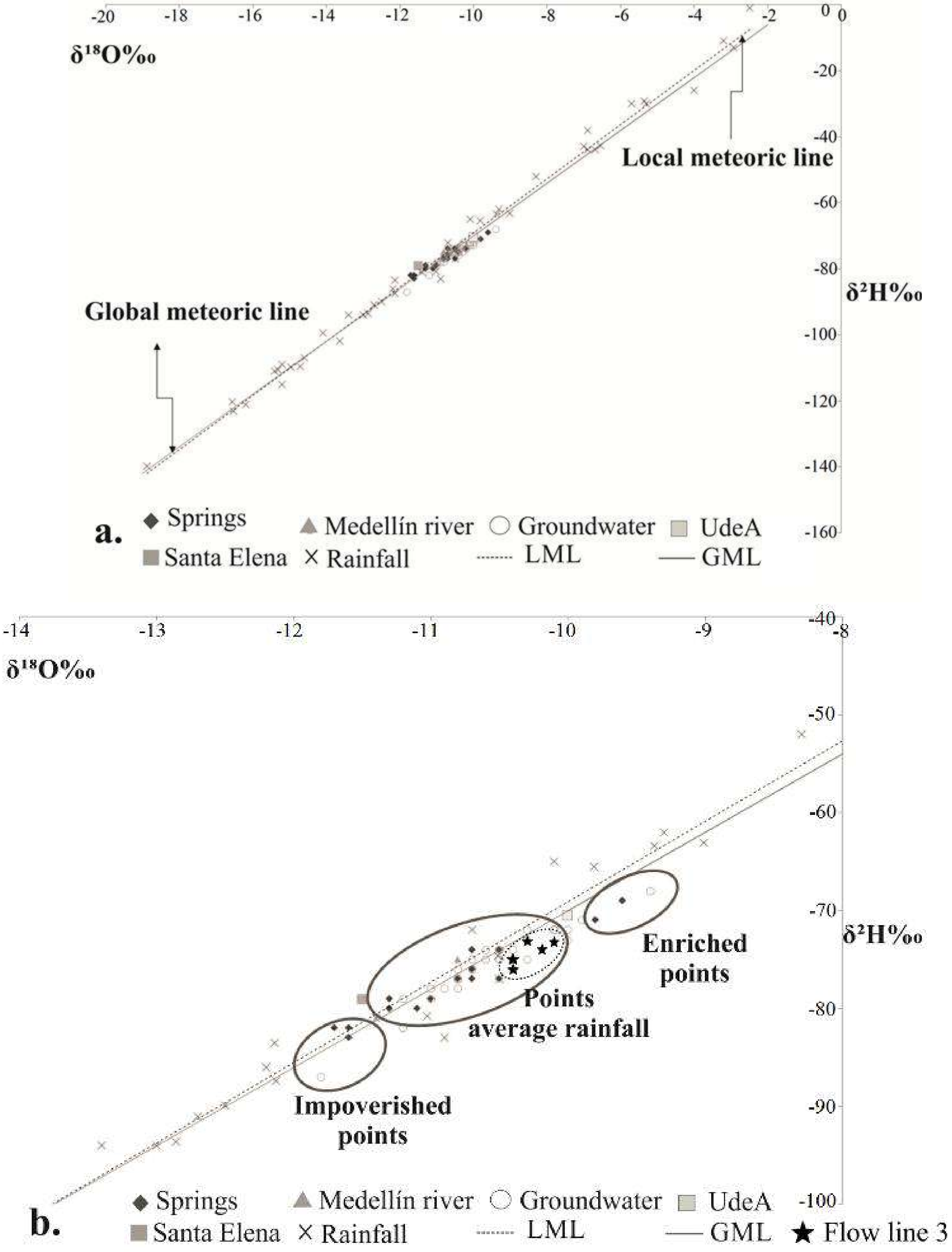

Figure 11 (a)Relationship between the isotopic composition of groundwater and Local Meteoric Line. (b) Detail Figure 11(a)

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