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Region-scale estimation of potential groundwater recharge in soft and hard rock formations through a distributed water balance in the area of influence of the tropical dry forest in the Cauca River canyon, Antioquia, Colombia

Estimaciones regionales de recarga potencial de aguas subterráneas en formaciones blandas y rocas duras, mediante un balance hídrico distribuido en zona de influencia del bosque seco tropical en el cañón del río Cauca, Antioquia, Colombia

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Abstract

Groundwater potential recharge is commonly estimated by water balances per hydrogeological unit. Most studies in Antioquia (Colombia) examine recharge in alluvial deposits or sedimentary rock units. The evaluation of the hydrogeological potential in the area of influence of the tropical dry forest in the Cauca River canyon, in the jurisdiction of Corantioquia, began in 2020, including regional estimates of potential recharge by precipitation. Recharge was estimated through a distributed soil water balance model at a daily time step, which efficiently incorporated the spatiotemporal variability of the meteorological conditions of the region as well as the spatial variability of the surface properties, such as soils, land cover and topography.

Between 2013 and 2020, annual recharge rates were estimated to vary spatially between 5 mm/year and 2000 mm/year, which represents between 0.4% and 45% of the annual precipitation, with a spatial and multiyear average of 342 mm/year (17% of precipitation). The aquifers of the Penderisco Formation are characterized by an average annual potential recharge of between 284 mm (to the northwest) and 756 mm (to the southwest), the aquifers of the Combia Formation show average annual recharge rates of 456 mm, and the unconfined aquifer of Western Antioquia and others associated with Quaternary deposits record average annual

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recharge rates of 36 mm. The recharge behavior in the area favors regional flows between hydrogeological units and confirms the considerable hydrogeological potential of various units of fractured hard rocks.

Keywords: potential recharge, distributed water balance, soft formations and fractured media, regional estimates, tropical dry forest, regional flows.

Resumen

La recarga potencial de aguas subterráneas se estima comúnmente mediante balances hídricos por unidad hidrogeológica. La mayoría de los estudios en Antioquia (Colombia) se refieren a la recarga en depósitos aluviales o unidades de rocas sedimentarias. En 2020 se inició la evaluación del potencial hidrogeológico en zona de influencia del bosque seco tropical en el cañón del río Cauca, en jurisdicción de Corantioquia, incluyendo estimaciones regionales de recarga potencial por precipitación. La estimación de la recarga se realizó a través de un modelo distribuido de balance de humedad en el suelo a escala diaria, en el que se incorporó de manera eficiente la variabilidad espaciotemporal de las condiciones meteorológicas de la región, así como la variabilidad espacial de las propiedades de superficie, como suelos, coberturas terrestres y topografía.

Entre 2013 y 2020 se estimaron tasas de recarga anual que varían espacialmente entre 5 mm/año y 2000 mm/año, lo que representa entre 0,4 % y 45 % de la precipitación, con promedio espacial y multianual de 342 mm/año (17 % de la precipitación). Los acuíferos de la Formación Penderisco se caracterizan por recarga potencial media anual entre 284 mm (al noroeste) y 756 mm (al suroeste); los acuíferos de la Formación Combia presentan tasas de recarga media anual de 456 mm; el Acuífero Libre del Occidente Antioqueño y otros asociados a depósitos cuaternarios registran tasas de recarga media anual de 36 mm. El comportamiento evidenciado de recarga en la zona favorece la condición de flujos regionales entre unidades hidrogeológicas y ratifica el potencial hidrogeológico significativo de diversas unidades de rocas duras fracturadas.

Palabras clave: recarga potencial, balance hídrico distribuido, formaciones blandas y medios fracturados, estimaciones regionales, bosque seco tropical, flujos regionales.

1. Introduction

Groundwater accounts for more than 96% of the planet's fresh water (Lamichhane and Shakya, 2019). Its movement through the soil is conditioned by the climatic, geological and hydrological characteristics present during the recharge, transit and discharge processes (De Vries and Simmers, 2002; Harlow and Hagedorn, 2018; Mussa et al., 2021). According to Hussin et al. (2020), groundwater extraction worldwide occurs at an approximate rate of 986 km^3/year, and its overexploitation has been causing problems in several regions, especially in arid and semiarid areas.

Groundwater recharge is a part of the hydrological cycle that has a significant contribution to the water balance at the local, regional and global scales (Fauzia et al., 2021). Those areas where the soil allows the infiltration and percolation of water through its layers until reaching the vadose zone or continuing to flow to an aquifer are identified as *potential recharge zones* (Ahmed et al., 2021). Understanding the recharge and discharge balance of the aquifers forms the basis of groundwater resource management (Moeck et al., 2020).

Measuring natural recharge directly and accurately is challenging because the processes vary spatiotemporally according to climate, soil and geology, surface topography, hydrology and vegetation (Barua et al., 2021; Harlow and Hagedorn, 2018; Hussin et al., 2020). To accommodate the specific site conditions, different methods involving different spatial and temporal scales, ranges and reliabilities are used to estimate groundwater recharge. The uncertainties in each approach to estimate the recharge underscore the need to apply multiple techniques to improve the reliability of the calculated estimates (Scanlon et al., 2002).

Among the methods cited in the specialized literature to evaluate recharge are the application of Darcy's law, the measurement of infiltration through lysimeters installed in the unsaturated zone, the measurement and modeling of soil moisture content, estimates of heat flow, basin-scale water balances, remote sensing, numerical models, the water-table fluctuation (WTF) method and balancing chlorides and/or radioisotope concentrations (Barua et al., 2021). Most of these techniques are reliable at the level of experimental plots or in studies that cover local areas.

Dos Santos et al. (2021) estimated two types of recharge for the Cerrado basin in Brazil and determined the potential recharge through distributed modeling and the effective recharge with numerical modeling, the WTF method and base flow separation. Oliveira et al. (2015) evaluated the influence of land cover on the water balance of an undisturbed area in the Cerrado. Wang et al. (2021) applied the concept of *stable base flow* to estimate groundwater recharge in ten hydrogeological regions in Taiwan under historical conditions and climatic scenarios. Peijun et al. (2021) used tracers (isotopes of water, chlorides and nitrates) to estimate the recharge rates with methods that consider the differences in deep and shallow rooted vegetation as well as in the unsaturated and saturated zones.

When covering areas of regional extension, in which geological, physiographic and hydroclimatological variations can be recorded and, consequently, different ecosystems evolve, the recharge distribution includes direct recharge, which is generated by rainfall (also called diffuse recharge) that reaches aquifers or generates deep percolation that, over time, takes part in regional flows. In this sense, it is notable that the study of classical hydrogeology has focused on the knowledge of hydrogeological units associated with primary porosity; however, the need for hydrogeological exploration in rocks that have acquired secondary porosity, which function as reservoirs, recharge and transit zones in regional aquifer systems and serve as water resources to the population, is becoming increasingly evident (Koïta et al., 2018).

Much of the water available in ecosystems such as the tropical dry forest (TDF) is found in lowlands, between 0 m and 1000 m of altitude, in tropical areas with temperatures above 24 °C and annual precipitation between 700 mm and 2000 mm; these areas experience one or two periods of marked drought per year–with less than 100 mm of precipitation—of at least five to six months (Mooney et al., 1995, cited by Pizano and García, 2014). Under these conditions, direct recharge is usually low. Thus, the sustainability of this ecosystem is generally dependent on groundwater contributions from adjacent hydrogeological units that have received direct recharge, which is then transported laterally through regional flows, depending on the structural patterns in the zone. In this article, *sustainability* refers to the water available to biological processes of the TDF ecosystem vegetation. Given these conditions, it is essential to further explore the estimation and calculation of recharge at the regional scale, where direct recharge flows in some areas can subsequently become indirect recharge flows for other areas that are geologically, geomorphologically and hydraulically connected.

Some studies have used numerical models of groundwater flow and have dynamically linked them with hydrological models to estimate recharge variations in different climatic and land cover conditions (Aguilera and Murillo, 2009; Herrera-Pantoja and Hiscock, 2008; Jabloun and Sahli, 2012). The soil water balance model has been widely used to evaluate recharge by precipitation and is generally combined with other techniques, such as geographic information systems (GIS) and numerical flow models (Melo et al., 2015; Vela Mayorga, 2001; Westenbroek et al., 2010). It should be noted, however, that the water balance method usually provides results for direct potential recharge and not actual recharge since it does not incorporate enough information from the saturated zone.

Thus, soil water balance models are currently the most useful (Xie et al., 2017) since they help to efficiently estimate the direct potential recharge associated with precipitation and its response to surface changes (land cover, land use, precipitation, evapotranspiration), which makes these methods valuable tools for the comprehensive management of water resources and projection of these resources over time (Ehlers et al., 2016; Harlow and Hagedorn, 2018; Mair et al., 2013; Westenbroek et al., 2010). Soil water balance models can be subdivided into *mathematical reservoir-type approximations* and *coupled mathematical models* (Xie et al., 2017). The former simplifies the medium into vertical cells where water is stored or discharged by inflow (precipitation), outflow (evapotranspiration) and excess storage capacity (recharge), while the coupled models represent the evapotranspiration process as a submodel (greater refinement) and transit the infiltration through the unsaturated zone as a response to the Richard equation for flow in the vadose zone (Ruiz et al., 2010; Turkeltaub et al., 2015).

Soil water balance (SWB) (Westenbroek et al., 2010) is a distributed model implemented and widely used by the United States Geological Survey (USGS) for different hydrological environments of the United States and also used in some areas of Korea and recently in regions of Colombia (Bastidas, 2019; Engott et al., 2017; Harlow and Hagedorn, 2018; Johnson et al., 2018; Bradbury et al., 2017; Mair et al., 2013; Oviedo, 2020; Patiño, 2021; Westenbroek et al., 2010, 2018). The most notable advantage of this model is its ability to evaluate and spatially incorporate the regional factors involved in the direct recharge process (Harlow and Hagedorn, 2018), in addition to allowing the simulation of this hydrological flow over long and continuous periods of time, such as several years and even decades, all at a detailed time step, such as the daily scale. Several authors have shown that direct recharge estimates, calculated at a monthly scale, differ significantly from those presented on a daily scale; the latter is the most recommended (Harlow and Hagedorn, 2018; Jasechko and Taylor, 2015; Scanlon et al., 2002).

The purpose of this work was to contribute to constructing a conceptual hydrogeological model in a complex geological, physiographic and hydroclimatological zone to estimate the direct potential recharge over the area and zone of influence of the TDF in the department of Antioquia. The results help identify the factors that contribute to the regional dynamics of groundwater flow and that can affect the sustainability of one of the most vulnerable ecosystems in Colombia. The SWB model described is the most relevant for achieving the defined objective since it can evaluate the impact of the variability of the different physical factors on the spatial distribution and magnitude of the recharge. The information necessary to characterize the water balance and, consequently, estimate the recharge is described in this article, as are the methods used for information collection, model execution, processing and analysis.

2. Reference framework

The study area (Figure 1) is demarcated in the department of Antioquia (Colombia, South America) by a polygon that brings together several hydrographic subzones of the Cauca River basin and that are directly or indirectly associated with the TDF ecosystem. Among the main tributaries along with the Cauca River are the Aurrá, San Juan, Piedras, Poblanco, Amagá and El Buey rivers (see Figure 3d).

The study area has been defined at the scale of basins afferent to the Cauca River canyon based on the hypothesis that the dynamics of the water supply of the TDF ecosystem depend not only on the underground water availability throughout the ecosystem but also on lateral contributions of groundwater due to conditions such as climatology, topography and hydrogeological units. As explained in the introduction, these contributions can come from the upper watersheds, as observed by Vélez and Rhenals (2008) in the aquifers of western Antioquia, which are part of the study area of this research.

The study area elevation ranges from 171 meters above sea level (masl) to 3609 masl, with an approximate area of 10 662 km^2. According to the precipitation and temperature data recorded in the *Statistical Yearbook of Antioquia* (Gobernación de Antioquia, 2018), the municipalities with the highest precipitation are within the upper slopes of the mountain ranges and record average values above 2000 mm/year; near the Cauca River (bottom of the canyon), precipitation tends to be less than 1000 mm/year. The maximum temperatures fluctuate between 27 °C and 29 °C at the bottom of the Cauca River canyon, while the lowest (<15 °C) occurs in the higher-elevation municipalities. Therefore, it is deduced that the spatial behavior of precipitation and temperatures in the study area is strongly marked by the topographic gradient. The regions with average temperatures above 24 °C are located at elevations below 1000 masl and where precipitation is less than 2000 mm/year (Murphy and Lugo, 1986), showing typical conditions of the TDF ecosystems. Specifically, the TDF is present in the territory of municipalities along the Cauca River and is connected, along the eastern slopes of the Western Cordillera and the Central Cordillera, with other related ecosystems.

Originally, there were 150 400 ha of TDF associated with the Cauca River in Antioquia, from the southern border with the department of Caldas to the north in the municipality of Valdivia. According to the current cover map (Pizano and García, 2014), only 44 485 ha, 30% of the original cover, remains; of this total, 17% is TDF and 13% is successional vegetation.

In this territory, anthropogenic intervention has increased with the development of road infrastructure projects; in addition, there is considerable pressure on the extraction of metallic minerals (copper and gold), which has triggered opposition by the people to some projects. The economic dynamics of the region are fundamentally related to the activities that occur in the northern, western and southwestern subregions of Antioquia, especially livestock and agriculture in the north and west; the dairy and meat industry in the north; tourism, mining and logging in the west; and coffee and mining in the southwest.

The geological characteristics of the study area provide important elements for determining potential hydrogeological conditions, including recharge.

Through exercises of superposition, comparison and adjustments to define units and employ standardized nomenclature, the *geological map of Antioquia* was modified (González, 2001) from the official cartography, at a scale of 1:100 000, available in the geoportal of the SGC (Calle and González, 1980, 1982; Hall et al., 1970a, 1970b; Mejía, 1984a, 1984b; Servicio Geológico Colombiano, 1979, 1996). As a result of this process, Betancur (2021) assembled a synthesized geological map for the study area, as shown in Figure 1. With hydrogeological criteria, the description of the geology focused on determining the conditions of porosity and permeability that are key in facilitating the storage and flow of groundwater. Both for deposits and clastic sedimentary rocks, as well as for hard rocks, the condition of the hydrogeological unit and its potential as an aquifer was determined.

The oldest units date from the Proterozoic and Paleozoic, which correspond to metamorphic rocks: migmatites (PєAmm); feldspathic and aluminum quartz gneisses (Pznf, Pznl); rocks of the Cajamarca Complex, such as quartz-sericite schist (Pzes), chlorite-actinolite schists (Pzev) and intercalated schists (Pzes + Pzev); and amphibolites are also recorded (Pza). Along the western flank of the Central Cordillera is a tectonically elongated belt of medium-pressure metamorphites called the Arquía Complex (Kica), which, due to its tectostructural involvement, has developed secondary permeability. Both flanks of the Central Cordillera are characterized by the presence of variable-sized bodies, elongated in the regional tectonic direction, of syntectonic intrusives of gneissic structure; their ages are Paleozoic, and they are found in Abejorral and

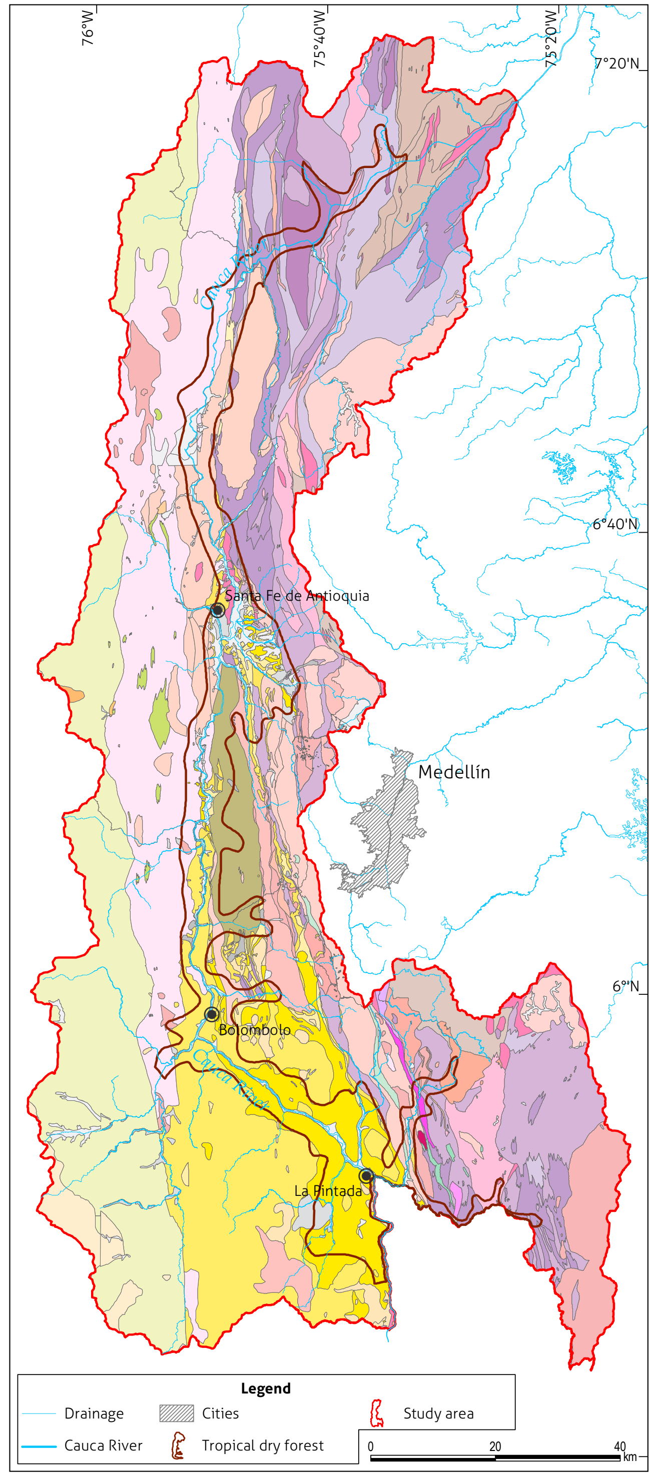

Figure 1. Delimitation of the study area and geological units present
Description of the complete geological legend available in the supplementary data. See legend in this kmz file (see in Google Earth). Source: modified from González (2001).

Alto de Minas (Pnim), Pantanillo (Pnip) and Río Verde (Pniv) (González, 2001).

Igneous activity in the Central Cordillera extended until the Triassic with the intrusion of adamellite stocks on the western flank of this mountain range (Honda Stock [TraH], Quebrada Liborina stock [TradL] and Buey stock [Trab]) and continued more intensely during the Jurassic with the intrusion of the Segovia and Sonsón batholiths (Jts), continuing until the end of the Cretaceous with the formation of the Antioquia Batholith (Ksta). A significant number of manifestations of igneous units complete the lithology of hard rocks (González, 2001).

Cretaceous sedimentary rocks are found in both the Central and Western Cordillera. According to their geographical or tectonic position and age, the following units were defined: San Pablo Formation, La Soledad Formation, Abejorral Formation (Kisa), Quebradagrande Group (Kisqg) and Cañasgordas Group (Urrao Member: Ksu; Cañasgordas Member: Ksn).

Belonging to the Cenozoic, the main soft formations (deposits, clastic sedimentary rocks and volcaniclastic rocks) are found in the Cauca River Valley in Antioquia. The accumulation of these materials was influenced by tectonism and subsequent magmatic activity; the Amagá Formation (lower member: Pgai; middle member: Pgam; and upper member: Ngas) and the Combia Formation (Ngc) stand out for their magnitude (González, 2001).

Quaternary deposits are mainly alluvial (Qal, Qat and Qt) and extend toward the flat areas of the department. Flow and colluvial deposits (Qcl), due to their extension, are not always represented on the map, although they may be locally important (González, 2001).

The crustal structure in the department of Antioquia is the result of the processes that were generated by the joining of the Nazca, Caribbean and South American plates. The Neogene and Quaternary deformations frequently overlap. Several fault zones with Quaternary displacement are located along the old shear zones that constitute subduction zones (González, 2001).

3. Materials and methods

3.1. Distributed soil water balance (SWB) model

The principle of soil water balance is based on applying the law of conservation of mass, which takes the first soil strata (soil–plant system) as the control volume and schematizes all the natural flows involved in the generation of recharge, as shown in Figure 2. For this research, the distributed SWB model was used (Westenbroek et al., 2010), which is deterministic, distributed and quasi-three-dimensional and operates on a daily scale; its spatial variability is given by a gridded arrangement in which various physical variables that influence the recharge process are configured, such as soil properties, land cover, topography (flow directions) and weather conditions (mainly precipitation and temperature).

The use of a distributed model to solve the water balance is pertinent given the considerable extent of the study area and the wide spatial variability presented by the physical variables that influence the recharge process. A distributed model allows the optimal incorporation and continuity of this variability to evaluate its impact on the spatial distribution of the magnitude of the recharge.

In the SWB model, the direct potential recharge is estimated as the remainder of the water balance in the defined control volume, where the vadose zone is conceptualized as a set of reservoirs in horizontal grid cells with variable thickness, depending on the depth of the roots. To solve the balance equation, a modified version of the Thornthwaite and Mather method is used to determine soil moisture and actual evapotranspiration at each time step and in each cell of the model domain (Bastidas, 2019). The soil water balance equation applied in the gridded cell SWB model is as follows:

$$DPR = Inflow - Outflow\text{-}\ Storage\ variation \quad (1)$$

$$DPR = (P + IF) - (Inp + ETa + DR) - \Delta H \quad (2)$$

where DRP: direct potential recharge; P: precipitation; IF: inflow from other cells; Inp: interception in the foliage; ETa: actual evapotranspiration; DR: direct surface runoff; ΔH: variation in soil moisture.

3.2. Information available and acquired

The information necessary to apply the distributed SWB model and thus obtain regional estimates of direct potential recharge is categorized into three large groups: soil and cover information, hydrometeorological data and geomorphological data. For the analysis of the water balance, it is assumed that the soil, cover and geomorphological data associated with the topography and the drainage network do not vary in time but do vary in space; therefore, they are called *static data* (invariant in time). While the hydrometeorological data vary in both space and time and are called *dynamic data*.

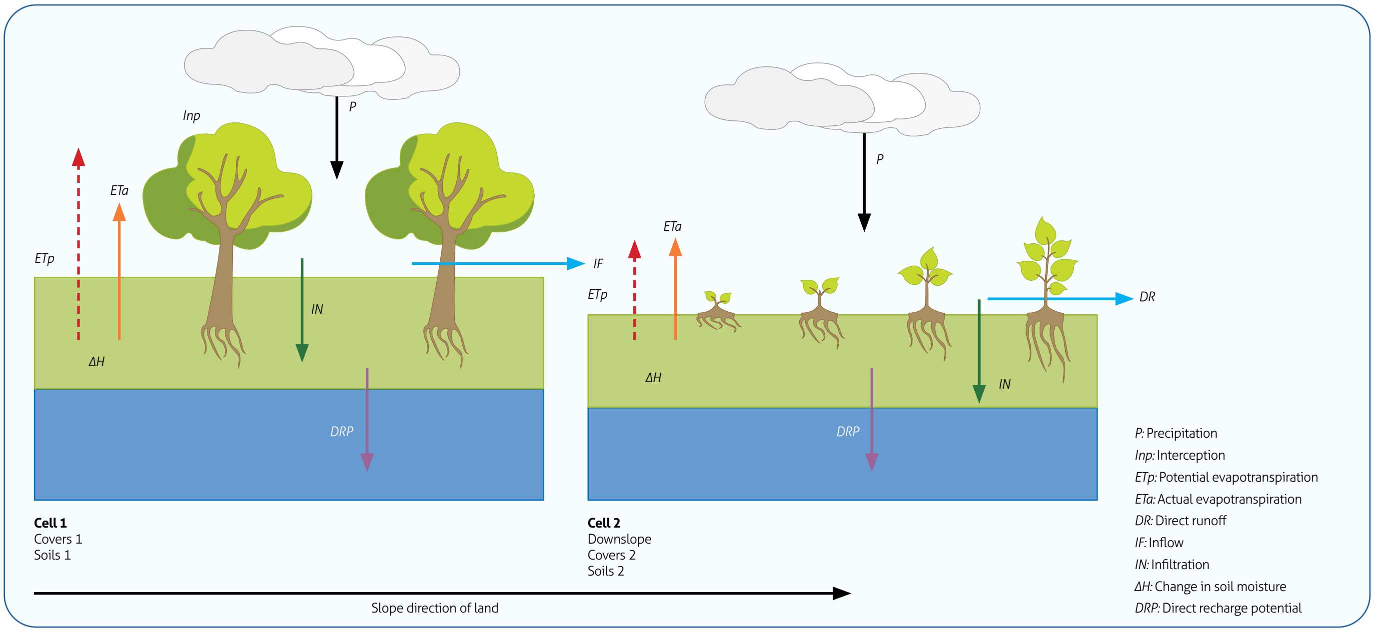

Figure 2. Diagram representing the soil–plant control volume cell by cell in the SWB model domain and the elements of the soil moisture balance involved in the estimation of the direct potential recharge. Source: Bastidas (2019).

Hydrometeorological data are an input for the application of the water balance, since precipitation is the main input to the control volume where the soil moisture balance is defined, and other hydrometeorological variables, such as temperature, solar brightness and relative humidity, are useful for the estimation of evapotranspiration. Based on this information, a clear and detailed hydroclimatological context for the region is constructed, which helps to better define the application scenarios of the water balance.

The hydrometeorological information consists of the daily records of the monitoring stations of the Institute of Hydrology, Meteorology and Environmental Studies (Ideam) (142 stations within and near the study area) and the Piragua monitoring network of Corantioquia (58 stations within and near the study area).

In total, information was obtained from 137 pluviometric and pluviographic stations and 35 weather and 28 limnigraphic and limnimetric stations. Of these 200 stations, 191 series of total daily precipitation were obtained, 23 of daily maximum temperature, 23 of daily minimum temperature, 24 of daily average flow and one of daily relative humidity. With this information from the hydrometeorological stations, whose locations are shown in Figure 3a, it was possible to obtain an adequate hydrometeorological context of the region and sufficient information for the application of the distributed water balance model.

The geomorphological data correspond to a digital elevation model (DEM) and a detailed surface drainage network. The DEM is obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite mission, which can be downloaded for free on the website http://asterweb.jpl.nasa.gov, and has a spatial resolution of 30 m × 30 m pixel size. This DEM is shown in Figure 3d, adequately representing the relief of the study area, and elevations ranging from 167 masl can be seen at the bottom of the canyon and toward the north, up to 3609 masl in the headwaters of the main tributary basins. The DEM was obtained from the Advanced Land Observation Satellite (ALOS), which collects terrestrial images through its Phased Array Type L-band Synthetic Aperture Radar (PALSAR) sensor (ASF DAAC, 2015), with a spatial resolution of 12.5 m × 12.5 m pixels, and was also initially considered for the study area; however, given its regional extension, it was considered pertinent to work at a coarser resolution to reduce the computational times of the model, so the ASTER DEM was selected.

Regarding the drainage network, information from two main sources was used: the double and single drainage network of the Agustín Codazzi Geographic Institute (IGAC) at a scale of 1:100 000 and the single and double drainage network of Corantioquia at a scale of 1:25 000. Figure 3 shows the cartographic generalities of the drainage network in the study area.

The soil information was obtained from *the General study of soils and land zoning of the department of Antioquia*, conducted by the Agustín Codazzi Geographical Institute (IGAC and Gobernación de Antioquia, 2007) at a scale of 1:100 000, which describes the soil mapping units of the entire department, and includes planning and management information for the watersheds (POMCA) of the Amagá River-Sinifaná Creek and the Aurrá River at a scale of 1:25 000 (Corantioquia et al., 2018a; Corantioquia et al., 2018b). For each mapping unit, various soil profiles surveyed in the field are presented in the framework of these studies; within the description of the profiles is the granulometry of these profiles at different depths and their textural classification.

In the study area, 41 soil mapping units are identified, which, in turn, are subdivided into 202 units differentiated by geomorphological phases (slope and erosion). In the study area and its surroundings, 157 soil profiles obtained from the IGAC study (2007) and 60 soil profiles obtained from the aforementioned POMCAs (21 from the Aurrá River POMCA and 39 from the Amagá River-Sinifaná Creek POMCA) were identified. From these profiles, it is possible to directly characterize 94 of the soil mapping units differentiated by geomorphological phases. Although there is a considerable number of profiles, these are distributed in such a way that they are not sufficient to adequately characterize the properties of the soil mapping units in the study area; as a result, there are various areas of spatial information gaps, mainly in the northern area. Therefore, in the framework of this research, soil samples were taken at 30 points in the field for particle-size analysis in the laboratory to refine and complete this information. The locations of the 217 profiles obtained from the baseline studies and the 30 soil samples are presented in Figure 3c.

Regarding land cover, three main sources of documentary information related to land cover in the study area were used: 1) *National land cover map of Colombia according to the Corine Land Cover methodology* (Ideam, 2010), 2) *POMCA - Planning and management plan of the hydrographic basin of the Amagá River and Sinifaná Creek* (Corantioquia et al., 2018b), 3) *POMCA - Aurra River Watershed Management and Landuse Plan* (Corantioquia et al., 2018a). Given the regional scale and the extension of the study area, the land cover is based on the national cover map, interpreted at level 3, which refers to the level of detail in the cartographic definition for each land cover unit. According to the *Corine Land Cover* methodology adopted by Colombia, the level ranges from 1 (general) to 6 (maximum detail). This map and its legend are shown in Figure 3b.

3.3. Data treatment and processing

Specific treatments were performed on the hydrometeorological, geomorphological, soil and cover data with the objective of preparing the information to be used within the distributed SWB model.

The hydrometeorological data were processed to obtain the average annual cycle of the main variables involved in recharge: precipitation and temperature (as an indicator variable for the estimation of evapotranspiration). The basic quality analysis of the records was performed, defining record length, coincident periods between stations and percentage of missing data. Subsequently, the graphical and statistical correlation of precipitation with the macroclimatic phenomenon El Niño-Southern Oscillation (ENSO), the main modulator of the interannual variability of the climate in Colombia, was analyzed (Poveda, 2004; Poveda et al., 2002; Poveda and Álvarez, 2012). Based on the quality analysis of the records and the correlation with ENSO, the simulation period of the water balance was defined, which captures contrasting hydrological years (dry, wet and normal years).

Subsequently, the reconstruction of missing data in the daily records of precipitation and maximum and minimum temperatures for the simulation period was performed. The data were reconstructed through the mean ratio method (Unesco and Rostlac, 1982) and inverse distance weighted (IDW) interpolation (Echavarría, 2013).

For the simulation period, a series of daily maps of precipitation, maximum temperature and minimum temperature were generated in the study area with the objective of capturing and incorporating the spatiotemporal variability of these variables in the SWB model. To this end, recurring daily interpolations of the aforementioned variables were performed based on the implementation of the deterministic technique of thin plate spline interpolation (TPS) (Nychka et al., 2015) incorporated into a recurring code programmed in R (Bastidas Osejo and Betancur, 2019). The TPS is part of the family of polyharmonic splines, is widely used for the spatial smoothing of dispersed data and is considered a good deterministic approach to the universal kriging geostatistical procedure for various applications (Donato and Belongie, 2002; Moreles and Mejía, 2010).

The interpolations were performed for a cell size of 100 m × 100 m, and with the use of control points in areas where the

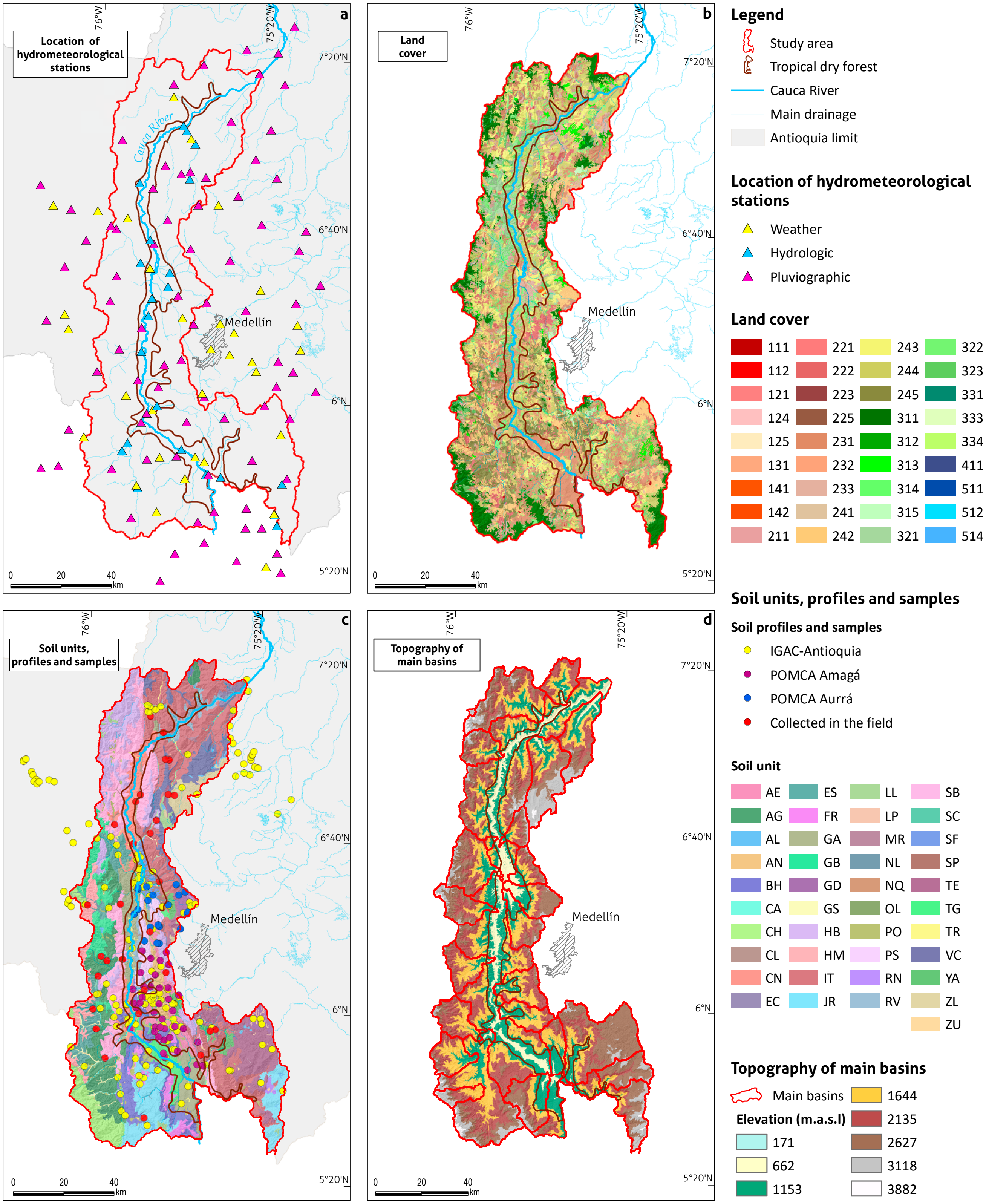

Figure 3. Graphic summary of the spatial information used for the implementation of the SWB model in the study area
Details of the stations used, description of the soil legend and description of the land cover are available in the supplementary data. See legend in this kmz file (see in Google Earth).

monitoring density was not sufficient; these were taken from the maps of the multiyear averages of the hydrometeorological variables generated in the framework of this research.

The geomorphological information was incorporated into the SWB model from the surface flow direction map (required in ArcGIS D8 format). The procedure for obtaining this information was described by O'Callaghan and Mark (1984) and Universidad Nacional de Colombia (2011) and is programmed in the *MapWindow software* with the *Watershed Delineation* tool. From the surface flow direction map, it is possible to outline the main hydrographic basins in the study area, which are shown in Figure 3d and generally correspond to hydrographic subzones defined by Ideam.

With the information of the 247 profiles and soil samples obtained in the study area, the soil properties required to run the SWB model were characterized: spatial distribution of soil textures (NRCS-USDA classification), spatial distribution of soils classified by hydrological group (according to the NRCS) and spatial distribution of the field capacity of the soils. These properties were particularly defined for each soil profile and sample in the study area , based on the reported particle-size composition (percentages of sands, silts and clays), with the use of the universally accepted textural triangle of the United States Department of Agriculture (USDA) (NRCS-USDA, 2018) and pedotransfer functions (Saxton and Rawls, 2006). The spatial distribution was determined from a geospatial analysis by soil mapping unit as follows: for each unit, a qualitative spatialization was carried out using the Thiessen (also known as Voronoi) polygons geometric technique (De Berg et al., 2008), with a subsequent adjustment to the limits of influence of each profile with geomorphological criteria (watershed divide, slope changes, drainage network, etc.). Finally, the mapping units differentiated by profile or area of influence were assembled in a single map following the methodology presented by Bastidas (2019).

The texture map obtained and used within the SWB model is shown in Figure 4a, in which a diversity of soil textures is observed, with a notable predominance of three types: sandy loam (29%), clay (20%) and clay loam (19%). These soil textures exhibit a defined spatial pattern, where the coarsest (loamy sand, sandy loam and loam) occur mainly in the upper part of the hydrographic basins associated with the Cauca River canyon. Among them are the upper part of the basins of the Arma River to the southeast, that of the San Juan River to the southwest, that of the Aurrá River between Sopetrán and San Jerónimo, that of the Tonusco River in Santa Fe de Antioquia and that of the Peque Creek and the Ituango River to the northwest. While the finest textures (clays and clay loams) are mainly present in the lower and middle parts of the basins, clayey textures are notably observed toward the bottom of the Cauca River canyon between Sabanalarga and Toledo and between clays and clay loams between Fredonia and Ebéjico.

The field capacity (FC) is the hydraulic property of the soil of greatest interest in the SWB model since it configures the maximum moisture capacity in the soil, which represents the threshold that must be exceeded for recharge processes to be generated. The FC was estimated from the textural data collected from the soils and with the application of the pedotransfer function of Saxton and Rawls (2006). Figure 4b shows the spatial distribution of the FC in the study area. It can be seen that the FC varies spatially between 16.7% and 48%, where the highest FC is recorded in the middle and lower parts of the basins, where there are finer textures, while the lowest FC occurs in the upper parts of the hydrographic basins, where coarser textures predominate.

3.4. Model settings

The SWB model version 1.0 estimates the surface runoff of grid cells using the *curve number* (CN) method (Cronshey et al., 1986); the estimated runoff in each cell runs downhill following the directions of surface flow (in D8 format), then becomes inflow to adjacent downslope cells and thus applies the algorithm described by O'Callaghan and Mark (1984) and the Universidad Nacional de Colombia (2011). The ability to route inflow in the model is considered an improvement in terms of traditional methods of estimating recharge by water balance (Harlow and Hagedorn, 2018). The model assumes that all the precipitation entering the model domain in one day is distributed in the different compartments and flows on the same day, including the total outflow of the runoff.

This model has five programmed methods to estimate potential evapotranspiration (ETp): Thornthwaite and Mather (1957); Turc (1961); Hargreaves and Samani (1985); Jensen-Haise (1963) and Blaney-Criddle (cited by Dockter and Palmer, 1994); for this research, the method of Hargreaves and Samani (1985) was used, mainly because it is the only one that allows the incorporation of the spatial variability of the ETp in the model and because of the amount of information required (daily maps of maximum and minimum temperature).

Part of the precipitated water can be intercepted by the plants before contacting the soil surface; this amount is called

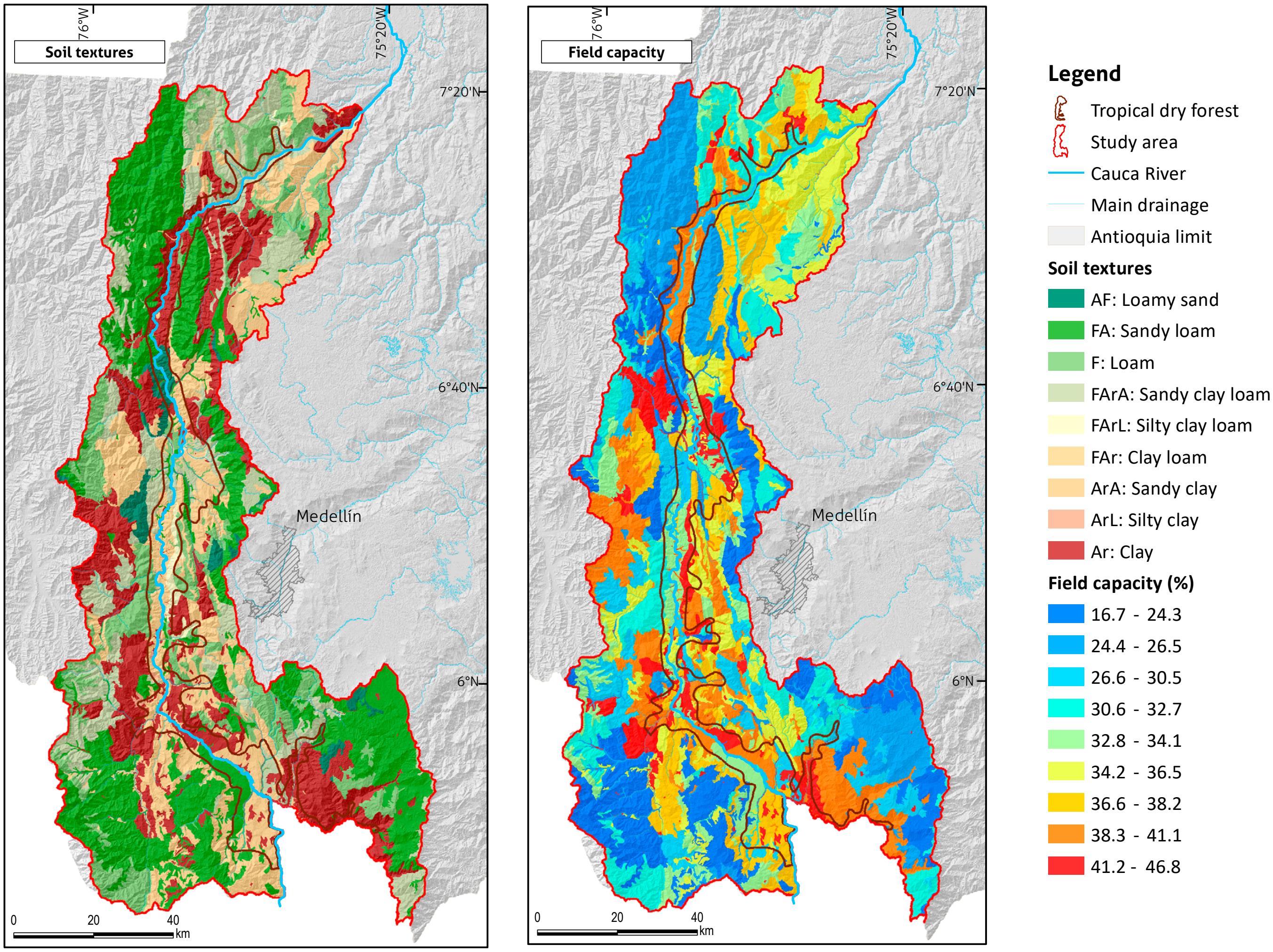

Figure 4. Spatial distribution of soil textures and field capacity in the study area
See legend in this kmz file (see in Google Earth).

interception by foliage, and within the SWB model, it is estimated in a simple manner from a reservoir approach (Westenbroek et al., 2010), based on thresholds that must be exceeded by precipitation, which depend on the type of land cover and hydrological conditions.

The joint occurrence of a specific type of soil and a specific type of cover defines various parameters of the SWB model, such as the CN for the three antecedent moisture conditions (normal CNII, dry CNI, wet CNIII) and the assumed percentage of impervious surface, maximum recharge rate (R_{max}) and rooting depth (RD). These factors determine the vadose zone thickness (VZT), where evapotranspiration occurs, and represent the soil–plant control volume for the model (Dripps and Bradbury, 2007; Mair et al., 2013; Westenbroek et al., 2010).

From the cross between the type of soil and the type of cover, the aforementioned parameters are obtained, and the reference values for each cross are obtained from Thornthwaite and Mather (1957); Mockus (1965); Cronshey et al. (1986); Dripps and Bradbury (2007); Westenbroek et al. (2010). The values assigned to the parameters of curve number CN, R_{max} and RD, among others, are presented in the supplementary data.

The SWB model is configured to continuously simulate several years at a daily time step. To define the simulation period, two main criteria have been taken into account: a) availability of information to construct the input variables of the SWB model, mainly hydrometeorological information, and b) a continuous period that allows the capture of the seasonal and interannual variability of the hydrometeorological vari-

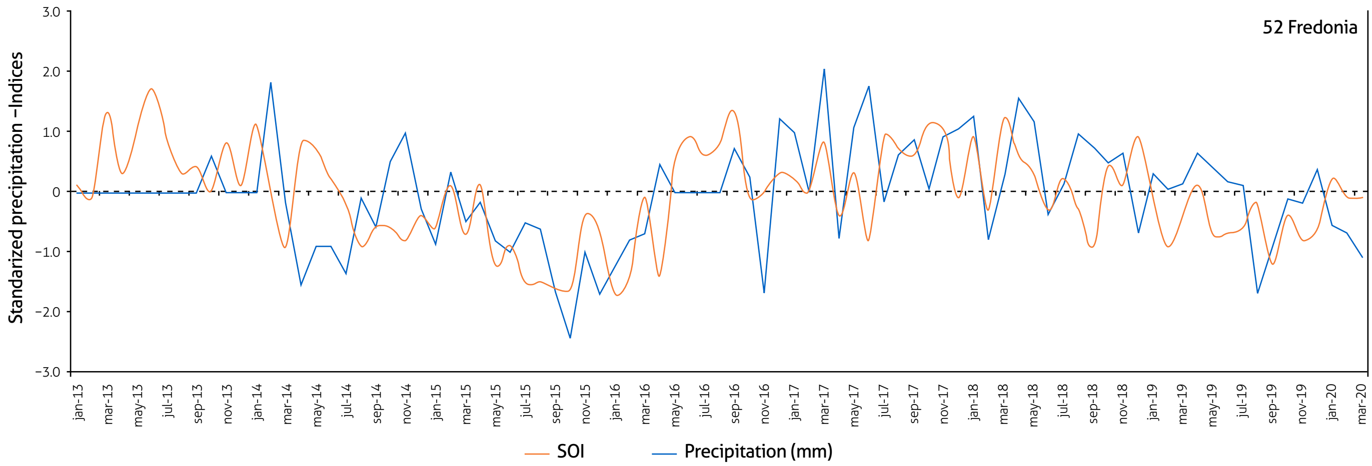

Figure 5. Standardized monthly precipitation at one of the stations in the study area (Station 52, Fredonia of Piragua) and its graphic temporal correlation with the occurrence of the ENSO phenomenon from the monthly series of the Southern Oscillation Index (SOI)
Positive values indicate the occurrence of the La Niña cold phase, and negative values indicate the occurrence of the El Niño warm phase.

ables; thus, a dry, normal and wet year is captured. In the study area, an important relationship has been found between the macroclimatic phenomenon ENSO and the hydrometeorological variables, mainly precipitation, as illustrated in Figure 5. Therefore, the selected simulation period is also related to the occurrence of the cold and warm phases of ENSO.

The specific simulation period selected corresponds to 2012-2020, where the SWB model is started in 2012, so that it loses sensitivity to the initial soil moisture condition (a factor of high uncertainty in the simulations) (Westenbroek et al., 2010). That is, this same year is used for the internal calculations of the model, but no results of the estimated flows in that year are exported, nor are they analyzed.

The year 2014 is characterized as normal (neutral phase of the ENSO); 2015, a dry year (very strong El Niño), and 2018, a wet year (weak La Niña). Since the simulation scale of the SWB model is daily, for the aforementioned period, the daily maps of maximum and minimum temperature and precipitation in the study area are generated, for which the previously mentioned methodology is followed, and 9864 maps are obtained, 3288 for each variable, which are stored in simple ASCII format, for a total storage volume of 323 GB.

Finally, Table 1 summarizes the SWB model applied to characterize the water balance in the study area.

4. Results

With all the inputs prepared for the study area, the SWB distributed model was executed in an approximate computation time of 72 hours (3 days) and the resulting file writing (monthly and annual potential recharge maps, actual evapotranspiration, potential evapotranspiration, interception by foliage, surface ru-

Table 1. General data of the specific SWB model settings to be applied to the study area

Coordinate system	Magna Colombia Bogotá Zone (3116)	Model operating units	inches (") and degrees Fahrenheit (°F)
Spatial domain of the model	Xmin: 774679	Model domain units	meters
	Ymin: 1094226	Number of rows	2149
	Xmax: 873479	Number of columns	988
	Ymax: 1309126	Cell size	100 m
Wet season	April-May and September-November	Precipitation (point or spatially distributed)	Distributed
Temperature (point or spatially distributed)	Distributed	Initial abstraction parameter	0.05
Evapotranspiration method	Hargreaves and Samani, (1985) (distributed)	Water storage capacity in the soil	Rooting depth by field capacity
Runoff method	Curve number	Time step	Daily
Initial soil moisture	At field capacity (100% FC)	Time scale of outputs	Monthly and yearly
Simulation period	January 2012 to December 2020	Output variables	Direct potential recharge, actual evapotranspiration, soil moisture, direct runoff, interception
Warm period	January 2012 to December 2012		

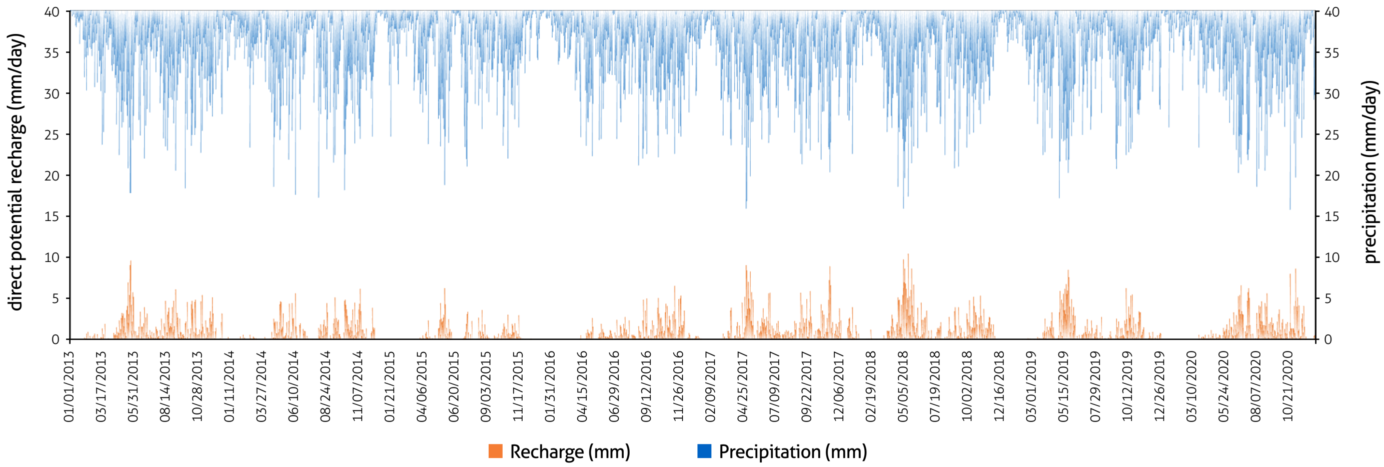

Figure 6. Daily direct potential recharge (DRP) series estimated as the spatial average for the study area (2013-2020)

noff and soil moisture) took approximately 48 hours (2 days). These execution times depend on the length of the model, the length of the study period and the computer equipment used. For this research, the model was run on a computer with 12 GB RAM and an AMD Ryzen 5 2500U processor (2.00 GHz).

The daily series of direct potential recharge (DRP) estimated with the SWB model for the spatial average of the study area (Figure 6) and the daily spatial average series for precipitation entered as a dynamic input to the model show a clear temporal coupling, which shows that the highest rates of DRP occur under the highest rates of precipitation, while in the absence of precipitation and even under the occurrence of low-magnitude precipitation, recharge flows are not generated. No temporal lag is observed in the recharge response to precipitation, which may be associated with a greater permanence of favorable soil moisture conditions in the study area.

Table 2 shows a statistical summary of the average daily recharge in the simulation period. On average, for the study area, the direct potential recharge represents 17% of the daily precipitation, while under maximum daily rainfall, the direct recharge represents 44% of the rainfall. Additionally, the great temporal variability of the DRP is highlighted as a response to the temporal variability of the rainfall and the other factors involved in the process (evapotranspiration, antecedent moisture, storage in the soil, direct runoff, etc.). This response is reflected in the high coefficients of variation for recharge (greater than 100%) being much greater than those of precipitation.

Figure 7 shows the spatial distribution of the DRP estimated for the average of each month in the analysis period (average annual cycle for 2013-2020). The monthly DRP presents a notable seasonality, similar to the seasonality of the rainfall, indicating that the lowest monthly recharge rates (<5 mm) occur during the January-March period. The recharge is even zero in large areas of the study area, especially during February, while between May and November, monthly recharge rates are higher, with two recharge peaks, the first in May (with a spatial maximum of 370 mm/month) and the second between October and November (with a spatial maximum of 220 mm/month), with a reduction in the larger-magnitude recharge areas in August. Likewise, in December, there is a significant reduction and a predominance of low- and medium-magnitude recharge rates (between 0 mm/month and 40 mm/month).

These findings show that, similar to regional precipitation, the regional behavior of the direct potential recharge in the basins associated with the Cauca River canyon in the study area is quasi-bimodal.

Table 2. Statistical summary of the average daily potential recharge (DRP) rate in the study area

	Precipitation [mm/day]	Recharge [mm/day]	DRP/P
Average	5.6	0.9	16.70 %
Maximum	24.1	10.6	43.80 %
Minimum	0	0	-
Standard deviation	4.4	1.3	-
Coefficient of variation	78 %	141 %	-

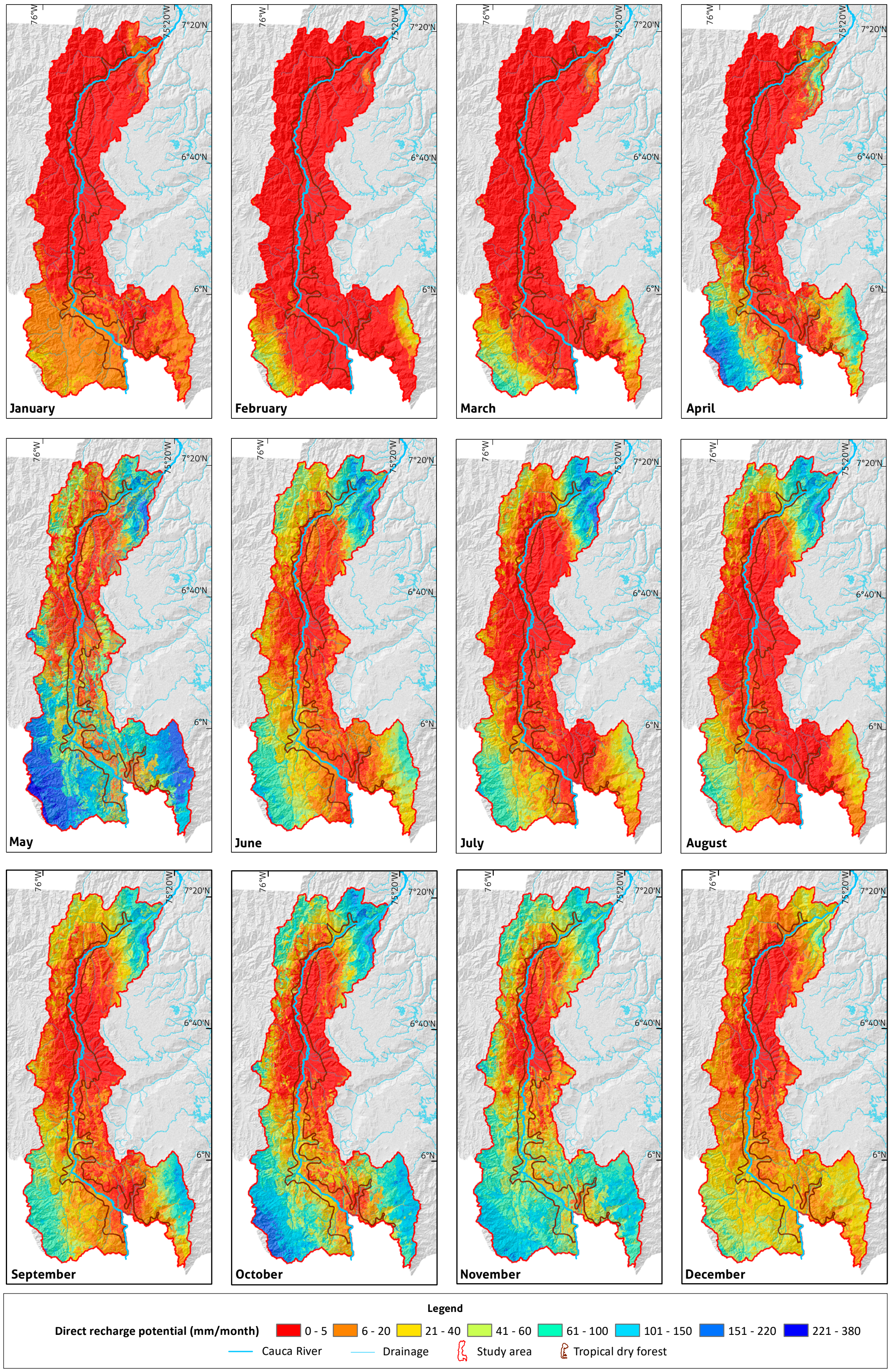

Figure 7. Spatiotemporal variability in the multiyear average monthly direct potential recharge (2013-2020) for the study area

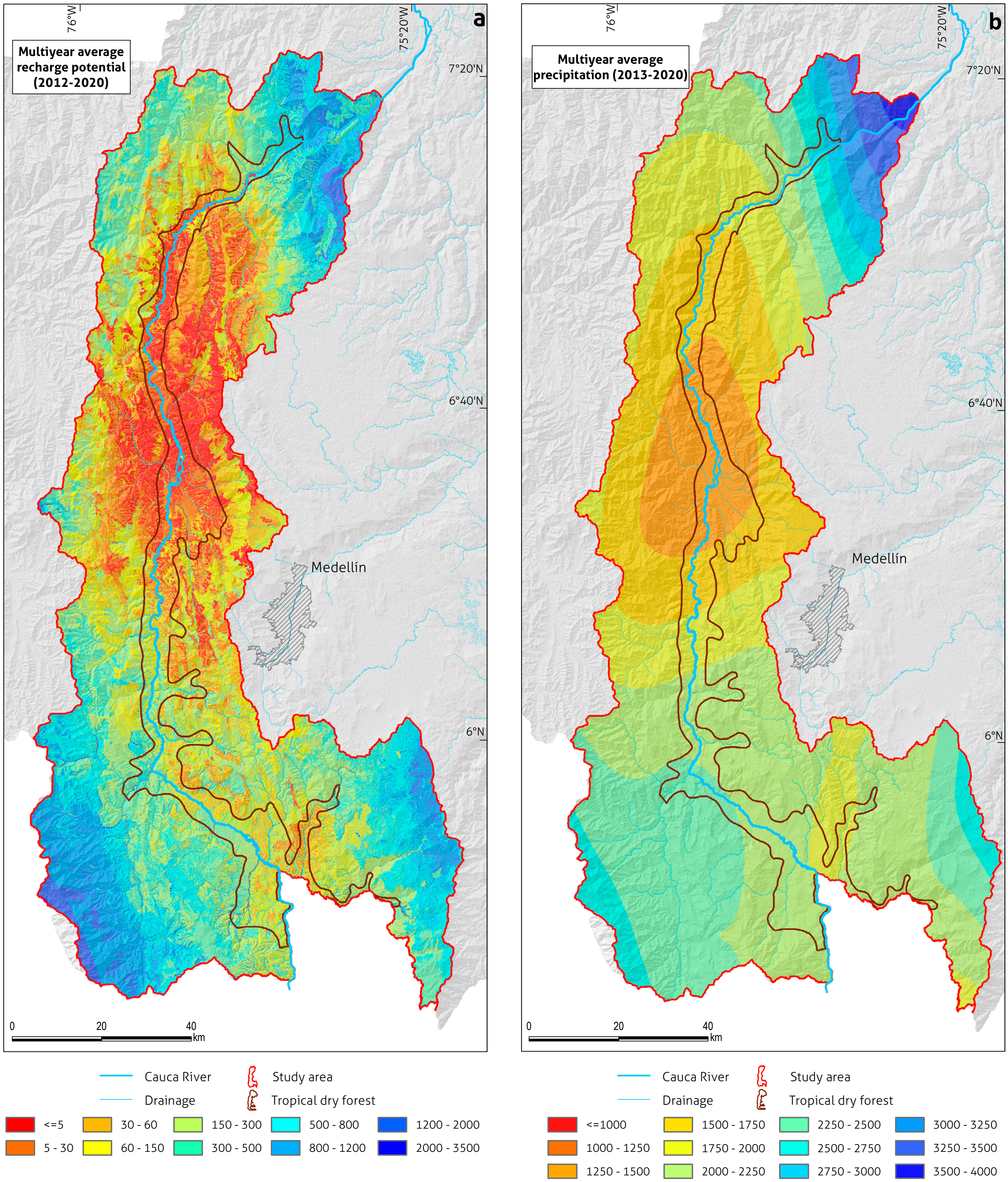

Figure 8. Spatial distribution of the average annual direct potential recharge in the study area between 2013 and 2020 and its spatial relationship with the average annual precipitation for the same period, units in mm/y

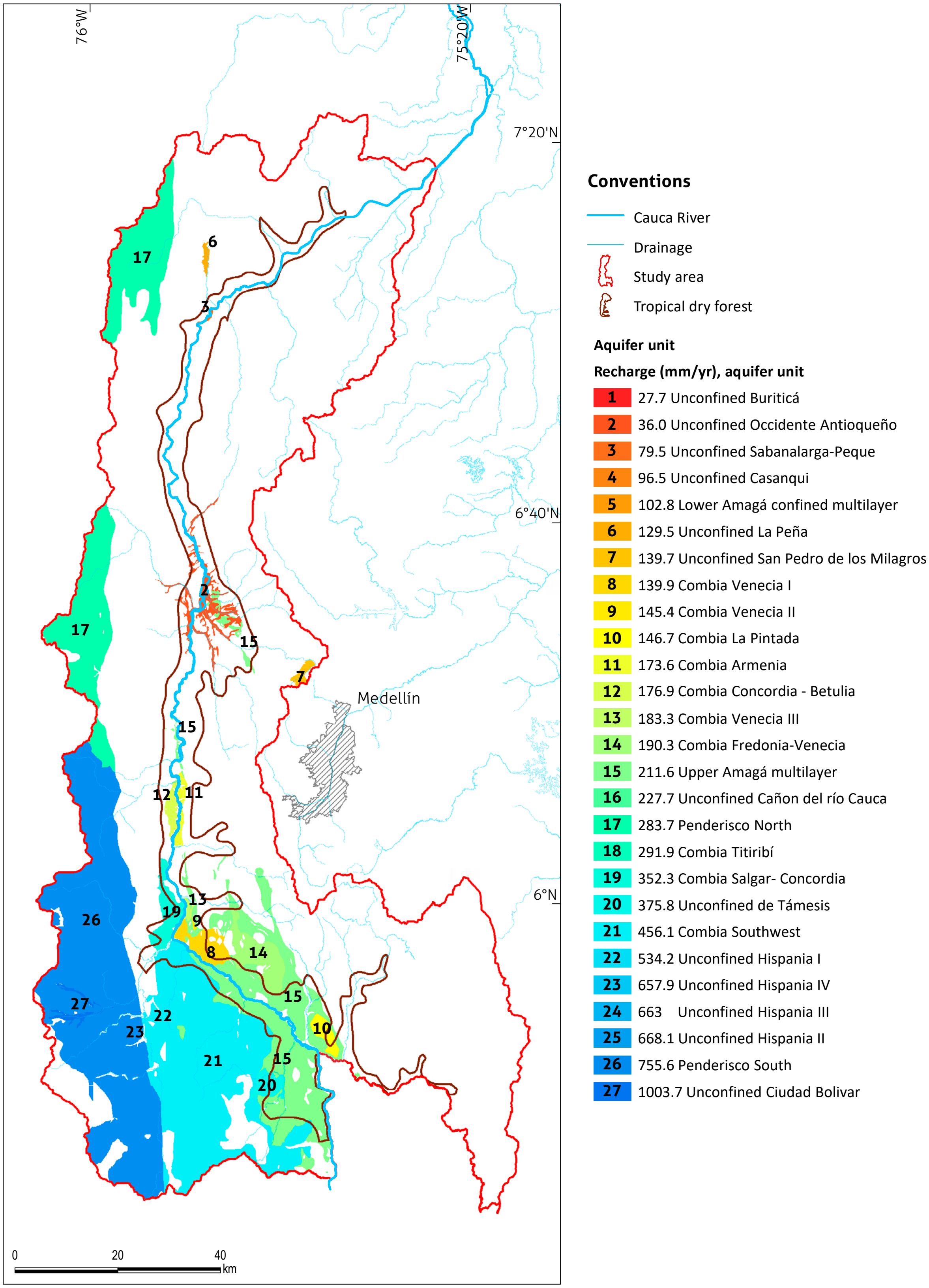

Figure 9. Spatial distribution of the average annual direct potential recharge (2013-2020) by hydrogeological unit in the study area
See legend in this kmz file (see in Google Earth).

Figure 8 illustrates the spatial distribution of the annual average direct potential recharge for the study area estimated between 2013 and 2020. The spatial variability of the recharge is also observed in detail, which has an important and close relationship with the spatial distribution of the average annual precipitation. Spatial patterns of the potential recharge are strongly related to the spatial variability of rainfall but also to the spatial variability of soil properties and type of land cover. It is also observed that the highest recharge rates, on the order of between 800 mm/year and 3500 mm/year, occur in the upper parts of the San Juan, Arma, Tonusco and Ituango river basins, as well as in the northern part of the study area in the municipality of Briceño and the Espiritu Santo River basin; in these areas, there is greater precipitation but also conditions of greater soil permeability and low field capacities. On the other hand, the lowest recharge rates (less than 5 mm/year) occur in the central region of the study area between the municipalities of Santa Fe de Antioquia, Olaya, Sopetrán and Liborina, mainly toward the bottom of the Cauca River canyon. In the upper part of the Aurra River basin, recharge rates are not as low, between 30 mm/year and 150 mm/year.

Regarding the spatial variability of the characterized and estimated hydrological flows, it is important to emphasize that in the direct extension of the TDF ecosystem, there are conditions of high temperatures and lower precipitation (spatial average of 1858 mm/year, compared to 2051 mm/year for the study area), high potential evapotranspiration rates (spatial average of 1793 mm/year, compared to 1591 mm/year for the study area) and low direct potential recharge rates (spatial average of 152 mm/year, compared to 342 mm/year for the study area), so direct water availability in this area is low, especially toward the central and north-central regions of the TDF extension.

From the regional estimates of direct potential recharge performed, the representative average precipitation potential recharge was obtained for each hydrogeological unit with aquifer potential in the study area (Figure 9). Notably, the aquifers associated with the Penderisco Formation to the northwest and southwest of the study area are characterized by a medium to high annual potential recharge, between 284 mm (northwest) and 756 mm (southwest). The aquifers of the Combia Formation to the southwest register high average annual recharge rates of 456 mm, while the quaternary units in relation to the direct potential recharge are behaviorally diverse, where unconfined aquifers associated with alluvial deposits are observed, with low annual recharge values, including the Buriticá Aquifer (28 mm), the Western Aquifer in Antioquia (36 mm) and the Sabanalarga-Peque Aquifer (80 mm). Unconfined aquifers mainly associated with alluvial terraces, with high annual recharge values, include the unconfined aquifer of Támesis (376 mm) and the unconfined aquifers of Hispania (534 mm to 668 mm). Finally, it is noteworthy that the unconfined aquifer of the Cauca River canyon has an annual direct recharge of 228 mm, which represents a moderate magnitude.

The state variable of the distributed SWB model is soil moisture, whose spatiotemporal behavior is highly variable and is strongly related to the temporal variability of precipitation (Figure 10). In periods of high rainfall, this humidity increases up to a storage limit defined by the field capacity, and under sustained conditions of low rainfall, soil moisture de-

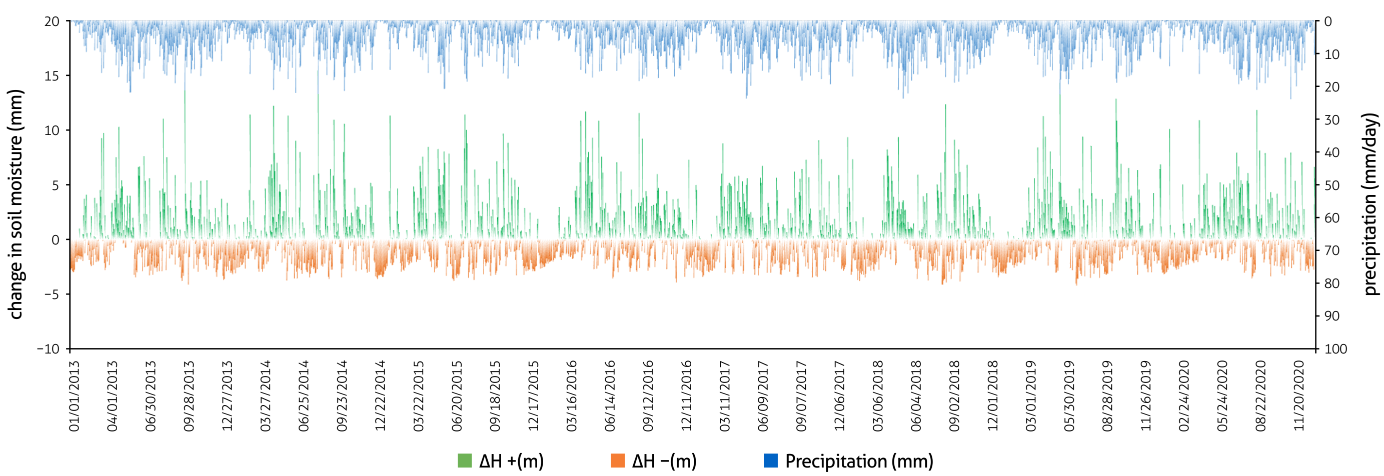

Figure 10. Daily series of soil moisture change (ΔH) estimated on average for the study area (2013-2020)

creases progressively and sustainably until a limit corresponding to the permanent wilting point, which shows a water discharge (negative change in storage) from the soil–plant control volume caused by the continuous requirement of the ETp.

Soil moisture and its temporal variation largely depend on the temporal variability of rainfall at the daily and monthly scales, which is also evident interannually (Figure 10). Between 2017 and 2018, characterized as wet years, there is generally higher soil moisture, with moisture conditions around field capacity for several continuous months, while between 2015 and 2016, dry years, there is generally less moisture in the soil, with considerable moisture loss mainly between December 2015 and January 2016. The positive changes in soil moisture (ΔH+) are generally of greater magnitude than the negative changes (ΔH-), which favors the generation of recharge, although the negative changes are more persistent in times of no rain, as is logical in relation to the action of the ETp.

Finally, Table 3 presents the total flows for each variable of the soil moisture balance, summarized as a percentage of precipitation. Balance closure tends to be adequate, with an approximate closure error of −0.4% (difference between inputs and outputs), which may be associated with changes in soil moisture storage, which in long-term periods (greater than ten years) should tend to zero, and/or to the systematic uncertainties of obtaining the input variables and of the operation of the submodels (e.g., NC method, Thornthwaite and Mather method, etc.).

All the terms of the balance vary temporally with precipitation. For example, in dry years, a greater percentage of rain becomes actual evapotranspiration (ETa) and is intercepted by foliage (Inp), and less is converted into direct surface runoff (DR) and DRP, while in wet years, the opposite occurs. In addition, the main flow is the ETa, which represents on average 56% of the precipitation and, in turn, satisfies on average 72% of the ETp. The next most important flow is interception with 17.6%, which, together with the ETa, can satisfy 95% of the ETp. Finally, the DRP represents an average of 16.4% of the precipitation and the DR, that is, on average 11.1% of the precipitation.

A fundamental aspect of the water balance analysis is the water deficit, which is the difference between the ETp and the ETa. When the availability of water is not sufficient for the ETa to satisfy the conditions of the ETp (positive difference ETp - ETa), water deficit conditions arise, which are directly related to the water stress of the plants. This research shows that the highest rates of water deficit are concentrated in the central part of the study area, at the bottom of the Cauca River canyon, mainly between Santa Fe de Antioquia, Olaya, Sopetrán and Liborina, with values between 500 mm/year and 900 mm/year of deficit, while the lowest rates of deficit are reported in the upper part of the basins, where the ETp requirements are low and the availability of water resources due to greater precipitation is high. It is important to note that, in general, the areas of high water deficit and low soil moisture coincide with the extension of TDF, so that together with the conditions of low water availability defined by lower precipitation, lower direct recharge by rain and greater ETp requirements, it is reasonable to think that the water sustainability of the TDF ecosystem cannot depend solely on direct water availability (direct recharge by rain in the polygon of the TDF ecosystem) since this source is limited.

5. Discussion

The spatiotemporal variability of recharge in the study area is dominated by the spatiotemporal behavior of precipitation, as is

Table 3. Summary of the main terms (as a percentage of precipitation) that make up the soil water balance (SWB) expressed as the spatial average for the study area.

Year	Potential evapotranspiration (ETp) [mm/year]	Precipitation (P) [mm/year]	Direct potential recharge (DRP)	Actual evapotranspiration (ETa)	Surface runoff (DR)	Foliage interception (Inp)
2013	1536	2210	18.90 %	52.10 %	13.50 %	16.70 %
2014	1595	1991	15.50 %	58.60 %	9.60 %	17.90 %
2015	1686	1704	10.40 %	66.80 %	9.50 %	18.50 %
2016	1667	1966	13.20 %	56.50 %	7.70 %	18.80 %
2017	1532	2254	19.30 %	52.40 %	12.40 %	16.90 %
2018	1597	2246	19.90 %	55.00 %	13.80 %	16.60 %
2019	1568	2035	16.70 %	54.90 %	12.30 %	17.40 %
2020	1551	2001	17.70 %	54.00 %	9.70 %	17.60 %
Average	1591	2051	16.40 %	56.30 %	11.10 %	17.60 %

common in tropical areas, where the availability of precipitation is the major determinant of recharge behavior (Bastidas Osejo et al., 2019; Koïta et al., 2018). The typical range of spatiotemporal variation in the estimated regional recharge is significant, between 5 mm/year and 2000 mm/year, which is consistent with the magnitudes of the potential recharge estimated in regions with weather conditions similar to those studied in this research (Andualem et al., 2021; Bastidas Osejo et al., 2019; Dos Santos et al., 2021; Hussin et al., 2020; Koïta et al., 2018).

The application of the distributed water balance model allows the determination of the direct potential recharge present in the study area. The high spatiotemporal variability of both precipitation and recharge is highlighted, which coincides with previous studies in several parts of the study area (Servicios Hidrogeológicos Integrales S. A. S. and Corantioquia, 2014; Universidad Nacional de Colombia and Corantioquia, 2004).

Regarding the magnitude of the direct potential recharge, the distributed balance model establishes that in the central region of the study area, between the municipalities of Santa Fe de Antioquia, Olaya, Sopetrán and Liborina, mainly toward the Cauca River canyon bottom, there are recharges between 30 mm/year and 150 mm/year and between 150 mm/year and 750 mm/year on the left bank of the Cauca River, between Támesis and southern Concordia. These values are similar to those obtained in studies carried out in 2004, 2014 and 2015 by Corantioquia, Universidad Nacional de Colombia and Servicios Hidrogeológicos Integrales S. A. S.

The results of the spatiotemporal distribution of the direct potential recharge in the study area provide elements that support the hypothesis initially proposed regarding the water availability of the TDF ecosystem, since the conditions of water availability directly in the extent of the ecosystem are limited. The lowest recharge rates in the study area, the highest potential evapotranspiration rates and the highest water deficit are reported. While in the middle and upper part of the basins associated with the Cauca River canyon, the direct potential recharge rates are high, these recharge flows could become regional and lateral for the aquifers located at the bottom of the Cauca River canyon, provided that there are hydrogeological conditions conducive to such interconnection, such as the degree of fracturing of the rocks, existence of regional geological structures, degree of permeability of the hydrogeological units and favorable topographic conditions. In the study conducted by the University of Antioquia and Corantioquia in 2021, various geological rock units with hydrogeological potential were defined, located in the upper part of the western slope of the Cauca River. Additionally, piezometric surfaces were modeled based on the data collected from a dense inventory of water points in the same study area, in which it was found that the general trends of the groundwater flow follow the topographic conditions, supporting the hypothesis that the direct potential recharge of the hydrogeological units of the upper part of the basins can become lateral and regional flows for the aquifers at the bottom of the canyon, where the TDF is located.

The recharge results in the study area are compared with those of previous hydrogeological studies in the aquifer system of western Antioquia (mainly Sopetrán, San Jerónimo and Aurra) and in the Valparaíso-La Pintada aquifer. Notably, in the case of western Antioquia, there is knowledge of the aquifers associated with alluvial deposits and the formulation of an aquifer environmental management plan (PMAA). Several areas of direct potential recharge located in the upper part of the basins of the study area, which have the potential to be areas of indirect recharge by regional flows, coincide with the location of recharge zones established in the area of Santa Fe de Antioquia and Olaya located between 1800 masl and 2400 masl and between 1100 masl to 1400 masl (Vélez and Rhenals, 2008), and in Valparaíso and La Pintada, where recharge is located in the upper parts of Cerro Amarillo and Farallones de la Pintada (Servicios Hidrogeológicos Integrales S. A. S. and Corantioquia, 2014).

The hypothesis that regional flows can feed the aquifers that provide water sustainability to the TDF finds local support from Vélez and Rhenals (2008), who, based on environmental isotopes estimated for the area between Santa Fe de Antioquia and Olaya, found the existence of regional flows from the high-elevation areas of the basin, especially from the Chico River basin.

The results of the present investigation constitute contributions at the regional scale to complement the hydrogeological knowledge of the previously studied regions, for which there are still no specific hydrogeological studies, making it possible to identify areas with greater hydrogeological potential based on their direct potential recharge. The estimates of direct potential recharge presented here should be validated through other estimation methods, such as those based on hydrographs of the surface currents receiving groundwater flows (Andualem et al., 2021; Dos Santos et al., 2021; Healy, 2010; Koïta et al., 2018; Scanlon et al., 2002; Vélez and Bastidas, 2018), those of piezometric oscillations (Bastidas Osejo et al., 2019; Dos Santos et al., 2021; Healy and Cook, 2002; Melo et al., 2015; Varni, 2013) and hydrogeochemicals and isotopes (Barua et al., 2021).

6. Conclusions

The geological synthesis shows that, given the technostructural characteristics of the central Andean region, there is a probable aquifer potential in the watersheds that demarcate the Cauca River canyon in Antioquia, which includes, in addition to the soft formations (sedimentary deposits), various units of hard fractured rocks that develop secondary permeability.

In this context, with the implementation of the distributed SWB model, it was possible to obtain estimates of direct potential recharge by precipitation in all geological units that have hydrogeological potential characteristics (which are listed and highlighted in Figure 9), in addition to understanding the spatiotemporal behavior of this recharge in the entire study area and the factors that most influence this behavior.

The high spatiotemporal variability of the potential recharge of the hydrogeological units associated with the basins of the TDF in Antioquia is confirmed, with typical ranges that oscillate between 5 mm/year and 2000 mm/year, characteristic of tropical climates, as highlighted in the discussion. This variability is mainly related to the spatial structure of rainfall and the permeability properties of soils and land cover. The interannual variability of the direct potential recharge is associated with the occurrence of the ENSO phenomenon. It is evident that under the El Niño phase, as was the case in 2015, the potential recharge tends to decrease, while under La Niña, as in 2018, the potential recharge tends to increase.

The potential recharge by precipitation shows a clearly defined spatial variability, with greater magnitudes toward the upper parts of the basins of the San Juan, Arma, Tonusco and Ituango rivers, as well as in the northern part of the study area, in the municipality of Briseño and the Espiritu Santo River basin. In these zones, greater precipitation is recorded, as are soil conditions with greater permeability and low field capacities. The lowest recharge rates occur in the central region of the study area between the municipalities of Santa Fe de Antioquia, Olaya, Sopetrán and Liborina, mainly toward the bottom of the Cauca River canyon. The spatial estimates of potential recharge allow us to conclude that the recharge in the extension of the TDF (152 mm/year on average) is much lower than that generated in the entire study area (342 mm/year on average), in which it is estimated that high recharge rates occur in the upper and middle parts of the basins afferent to the Cauca River canyon.

The general water balance for the study area allows us to conclude that most of the precipitation is converted into actual evapotranspiration, followed by interception by foliage, potential recharge and finally direct surface runoff. All balance terms vary temporally with precipitation. This pattern indicates that dry years lead to a higher percentage of rainfall being converted into actual evapotranspiration (ETa) and intercepted by foliage (Inp), and less rainfall becomes DR and DRP, while in wet years, the opposite occurs.

The highest rates of water deficit and lowest soil moisture content are concentrated in the central part of the study area, at the bottom of the Cauca River canyon. High water deficit and low soil moisture conditions coincide with the extension of the TDF, which is important in explaining that the water sustainability of this specific ecosystem may be related to the groundwater flows that are not directly generated in that area, given the low magnitude of recharge, but rather in the middle and upper part of the associated basins.

The spatial patterns of the direct potential recharge, its magnitudes and the spatial distribution of the other terms of the water balance allow us to conclude that there is a high potential for the generation of recharge by regional flows (lateral-indirect recharge) toward the hydrogeological units that are directly related to the TDF, since in the area covered by this ecosystem, the direct recharge is low; however, in the upper part of the associated basins, there are significant direct recharges that can become regional flows, depending on the structural patterns in the area and the direction of groundwater flow.

The regional recharge hypothesis derived from this research in the study area, as well as the magnitudes of regional recharge, are consistent with the results of local recharge estimates by various methods obtained from previous investigations in aquifers that are part of the study area, such as those of western Antioquia and Valparaíso-La Pintada.

7. Supplementary data

Supplementary data for this article can be found online at https://doi.org/10.32685/0120-1425/bol.geol.49.1.2022.625

The tables S1 to S7, in the supplementary data, provide information regarding the geological legend of Figure 1 and the information of the hydrometeorological stations used for the model, the description of the soil legend presented in Figure 3 and the description of the land cover in Figure 3, in addition to the values assigned to the parameters of the SWB model (curve number, daily recharge threshold, rooting depth).

Available data in kmz files

Figure 1. Delimitation of the study area and geological units present
Figure 3. Graphic summary of the spatial information used for the implementation of the SWB model in the study area
Figure 4. Spatial distribution of soil textures and field capacity in the study area
Figure 9. Spatial distribution of the average annual direct potential recharge (2013-2020) by hydrogeological unit in the study area

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