REPORT

Significance of river infiltration to the Port-au-Prince metropolitan region: a case study of two alluvial aquifers in Haiti

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Abstract

Mountain block recharge (MBR) mechanisms are an important component of the water budget for many alluvial aquifers worldwide. The MBR dynamics are complex, difficult to constrain, and quantification is highly uncertain. These challenges are magnified in data-scarce study areas, including the Cul-de-Sac and Leogane plains, two of Haiti's largest alluvial aquifers, which are flanked by the Massif de la Selle mountain block. The associated groundwater supplies the regional metropolitan area of Port-au-Prince (RMPP) and it is facing increasing pressure, requiring improved understanding of the aquifer system to guide management and protection. This report introduces the aquifers and investigates the significance of river infiltration from flows originating from the mountain block. The approach to derive important insight on recharge included analysis of broad datasets on piezometry, isotopes, hydrochemistry, and streamflow. The findings indicate that river infiltration is a major source of recharge to the alluvial aquifers. Grise and Blanche river infiltration may account for >80% of recharge to the Cul-de-Sac aquifer, exhibiting temporal variation correlated to climate events such as cycles of the El Niño/La Niña Southern Oscillations. Momance and Rouyone river infiltration may account for >50% of recharge to the Leogane aquifer. The results direct attention to the Massif de la Selle carbonate aquifer system, where bulk recharge is estimated to be four times greater than both alluvial aquifers. The Massif not only supplies the RMPP with ~65% of its water supply from karst springs, but its streamflow also recharges the alluvial aquifers that supply the balance of RMPP supply.

Keywords Haiti · Groundwater development · Groundwater recharge · Groundwater/surface-water relations · Mountain block recharge

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Introduction

More than 2.5 billion people worldwide rely on groundwater for basic water supply; however, aquifers around the world in both arid and humid regions, in developing and developed countries, are facing threats from overabstraction, contamination, and climate change (Mukherjee et al. 2020). Many areas of the world are increasing reliance on groundwater supplies—a global trend as precipitation and river flows are becoming less predictable (LaVanchy et al. 2021; Ostad-Ali-Askari and Shayannejad 2021). In Haiti, groundwater from wells and springs is the primary water supply for the entire country's population, which exceeds 11.38 million (Adamson et al. 2016; United Nations 2018). Groundwater is the water source for the regional metropolitan area of Port-au-Prince (RMPP), the country's capital and second-largest city of the Caribbean after Santo Domingo, Dominican Republic. The population of the RMPP is projected to increase from 2.84 million to 3.5 million

by 2030 (CIA 2020). This growth is coupled with the self-constructed, post-disaster settlement of Canaan that has transitioned from vacant land to an estimated population of 250,000 since the 2010 earthquake (Petter et al. 2020). Groundwater is an important dimension of securing access to clean water and sanitation (Vrba and Renaud 2016), this is especially the case in Haiti. The entire agenda of UN Sustainable Development Goals (SDGs) and human security is vitally related to clean water and sanitation (Taka et al. 2021).

The water demand of the RMPP is estimated in the range of 365,000 m³/day—(Agbar 2013; Emmanuel Moliere, CTE-RMPP [Centre Technique d'Exploitation de la Region Metropolitaine de Port-au-Prince], unpublished report, 2018). Municipal production from 2015–2018 averaged only 27–30% of average daily demand, or 107,000 m³/day. In 2018, the peak capacity of municipal wells and springs was reported in the range of 200,000 m³/day when all systems were in working order with reliable power (Emmanuel Moliere, CTE-RMPP, unpublished report, 2018). An additional six to eight municipal wells have reportedly been drilled since 2018 and are not included in the preceding estimate.

The gap between supply and demand inhibits progress towards 2030 sustainable development goals that are closely related to progress in national sovereignty, human security, health, education, work, and equality (UN-Water 2013). In this context, there is a critical need to secure additional water supplies for the RMPP, thus a prioritized query is dependent upon accurately estimating renewable quantities of groundwater in the alluvial plains.

For centuries, the Plaine du Cul-de-Sac (PCS) alluvial aquifer and the Massif de la Selle bedrock aquifer have supported the domestic, agricultural, industrial, and commercial demands of the RMPP. The RMPP system exploits ~35% of its supply from the PCS from ~26 municipal wells, and the Massif accounts for 65% from 15 springs, two tunnels, and one well. The Plaine de Leogane (PL) aquifer at the western limit of the RMPP supplies the City of Leogane, separate from the RMPP water system.

Prior studies have documented the occurrence and importance of streamflow infiltration for both the PCS and PL aquifers in Haiti (BRGM 1990; Gonfiantini and Simonot 1988; Northwater International and Rezodlo 2017; Northwater International and Rezodlo 2019a; Simonot 1982). Catchment-scale recharge and water balance estimates for PCS and PL aquifers are based on granular models that lack ground-truthing and may overlook or underestimate the importance of mountain block processes (Andreo et al. 2008; Akbari et al. 2019; Döll and Fiedler 2008; Farina and Gaspari 1990; Ghiglieri et al. 2014; Guardiola-Albert et al. 2015; Miner and Adamson 2017). This report aims to improve the understanding of groundwater availability by using ground-truthing methods to assess the component of recharge from streamflow infiltration originating from the

mountain block of the Massif de la Selle (hereafter referred to as the Massif or the mountain-block).

Feth (1964) introduced mountain-block recharge (MBR) based on research in the Wasatch Range of northern Utah, and a majority of MBR research has been focused on the western United States (Markovich et al. 2019). Since 2004, MBR studies have investigated aquifers around the world using broad methods with MBR estimates ranging from 5 to 62% of total aquifer recharge (Markovich et al. 2019; Manning and Solomon 2005). Mountain blocks feed rivers and can be a key groundwater balance component for downstream and lowland alluvial aquifers (Viviroli and Weingartner 2004). Groundwater contributions from mountain blocks to alluvial plains is difficult to quantify and estimates often have uncertainty, greatly affecting groundwater budgets and models (Hogan et al. 2004; Manning and Solomon 2004; Yu-Hsuan et al. 2012). Methods applied to improve estimations of MBR to alluvial aquifers are data intensive and include end-member mixing analysis, water tracers, streamflow analysis, rainfall analysis, chloride mass balance (CMB), and groundwater flow modeling approaches (Hogan et al. 2004; Markovich et al. 2019; Wilson and Guan 2004; Scanlon et al. 2002). Isotope data and mixing analysis have been used to estimate MBR in Ashikaga (Japan) and Taiwan (China) (Liu and Yamanaka 2012; Peng et al. 2016). Chloride data and mass balance have also supported MBR studies in Japan, the Boise Valley Aquifer in Idaho (USA), and the Adelaide Plains in Australia (Aishlin and McNamara 2011; Bresciani et al. 2018; Liu and Yamanaka 2012). In data-scarce study areas such as Haiti, estimating this unique source of recharge is especially challenging due to limited research and scholarship, and the lack of historical meteorological, streamflow, and piezometric data. This study was accomplished through a compilation of historical datasets and complemented with more recent unpublished data. Standard methods were applied, including analysis of piezometry, catchment scale CMB analysis, isotope partitioning, streamflow analysis, and baseflow separation. The results and conclusions highlight the importance of mountain block recharge (MBR) for the alluvial aquifers of the plains in the RMPP and potentially other mountain-block-associated alluvial aquifers of the Caribbean. The findings will support the government of Haiti, International Financial Institutions, and water managers in evaluating water supply alternatives and schemes to secure sustainable water supplies to meet the immediate and increasing water demands of the RMPP.

Study area

Setting and geography

The study area is geographically located between longitudes 72° 45′ W and 71° 50′ W and latitudes 18° 20′ N and
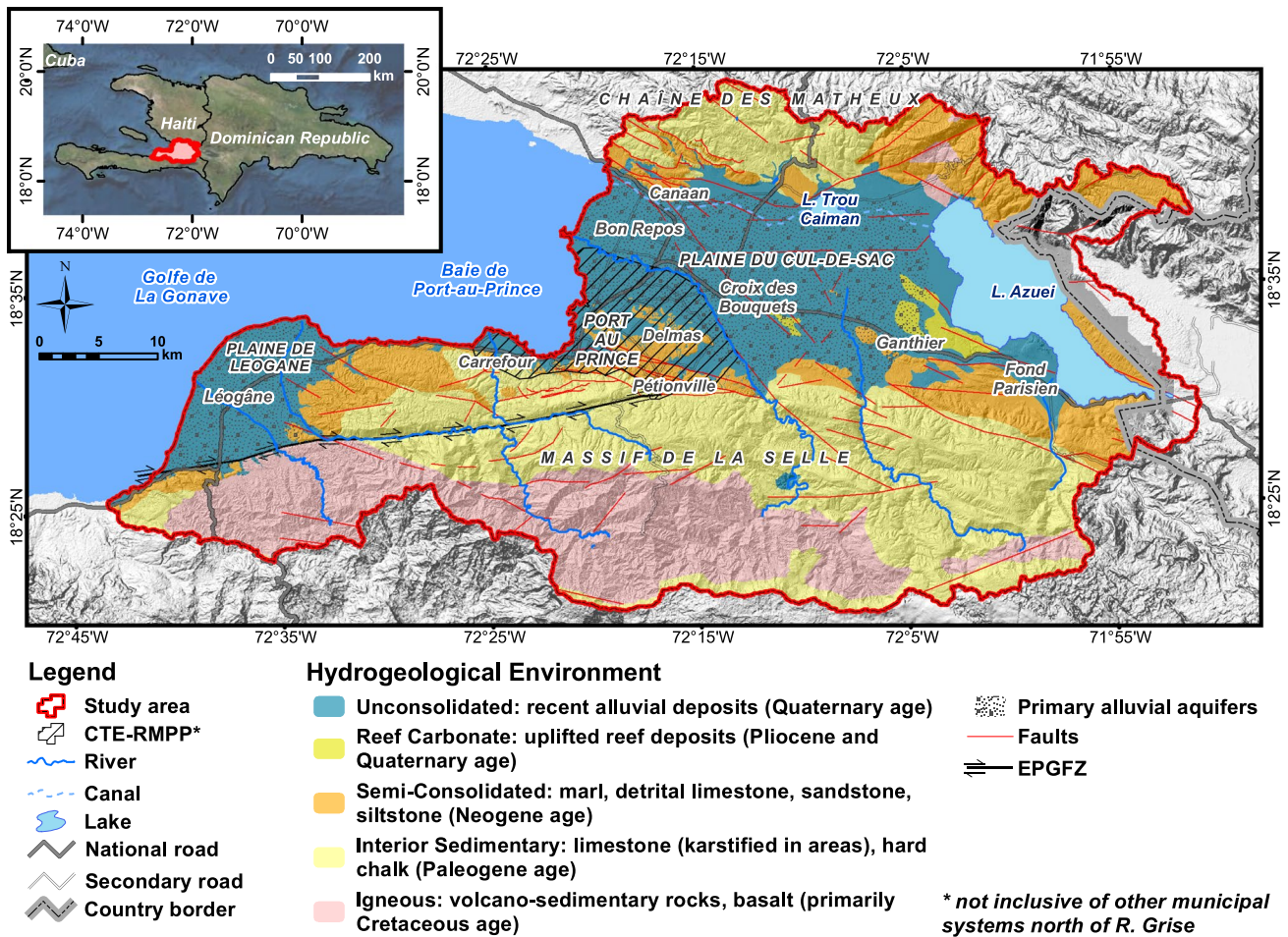
Fig. 1 Study area and geology of the catchments associated with the Plaine du Cul-de-Sac (PCS), Plaine de Leogane (PL) and Massif de la Selle

18° 45′ N in the Ouest Department of the Republic of Haiti (Fig. 1). A broad study area is defined for context which includes the alluvial aquifers of the PL and PCS and their hydrological basins which extend into the Massif. The two separate alluvial aquifers are both flanked by the Massif to the south; these mountains comprise the origin of alluvial sediments and streamflow that enter the plains.

The PL is an ~120 km² fan delta, the largest subaerially exposed such landform in the Caribbean region (Mann et al. 1995). It is bordered to the north and west by the Golfe de La Gonave, and to the east by its contact with semiconsolidated rocks (Fig. 1). The PCS is a ~360 km² basin nestled into the E–W trending linear ramp depression between the Haiti fold and thrust belt and the Massif de la Selle-Sierra de Baho-ruco. The depression is a former embayment of the Carib-bean Sea, since isolated by tectonic and geomorphological processes (Mann et al. 1984), and includes Lake Enriquillo in the Dominican Republic. The Chaine de Matheux moun-tains form the northern border of the PCS, and the Golfe de la Gonave and Baie de Port-au-Prince border the PCS to

the west. On the east of the plain, Lac Azuei (~155 km²) is a brackish lake with water surface elevations that oscillate between 19 and 23 meters above sea level (masl) (Moknatian and Piasecki 2019).

Topography varies from sea elevation near coastal extents to 2,671 masl in the Massif. The PL has a mean elevation of 23 masl and rises to 128 masl in its southern extent, while the PCS has a mean elevation of 47 masl and rises to 242 masl along its southern contact with the Massif.

The lower-latitude subtropical climate has a bi-modal temporal rainfall distribution (Fick and Hijmans 2017). Rainy seasons are typically April–May and August–October, and dry seasons November–March and June–August. Mean annual precipitation averages 1,300 mm/year, ranging from 730 mm/year in portions of the PCS to 1,900 mm/year in the Massif (Fig. 2). The mean annual precipitation in the PL and PCS is 1,212 and 970 mm/year, respectively (Fig. 2). Mean annual temperature across the PL and PCS is 26.5 and 27.0 °C, respectively, decreasing to 20.5 °C in the Massif. The evapotranspiration (ET) and relative humidity (RH) of the
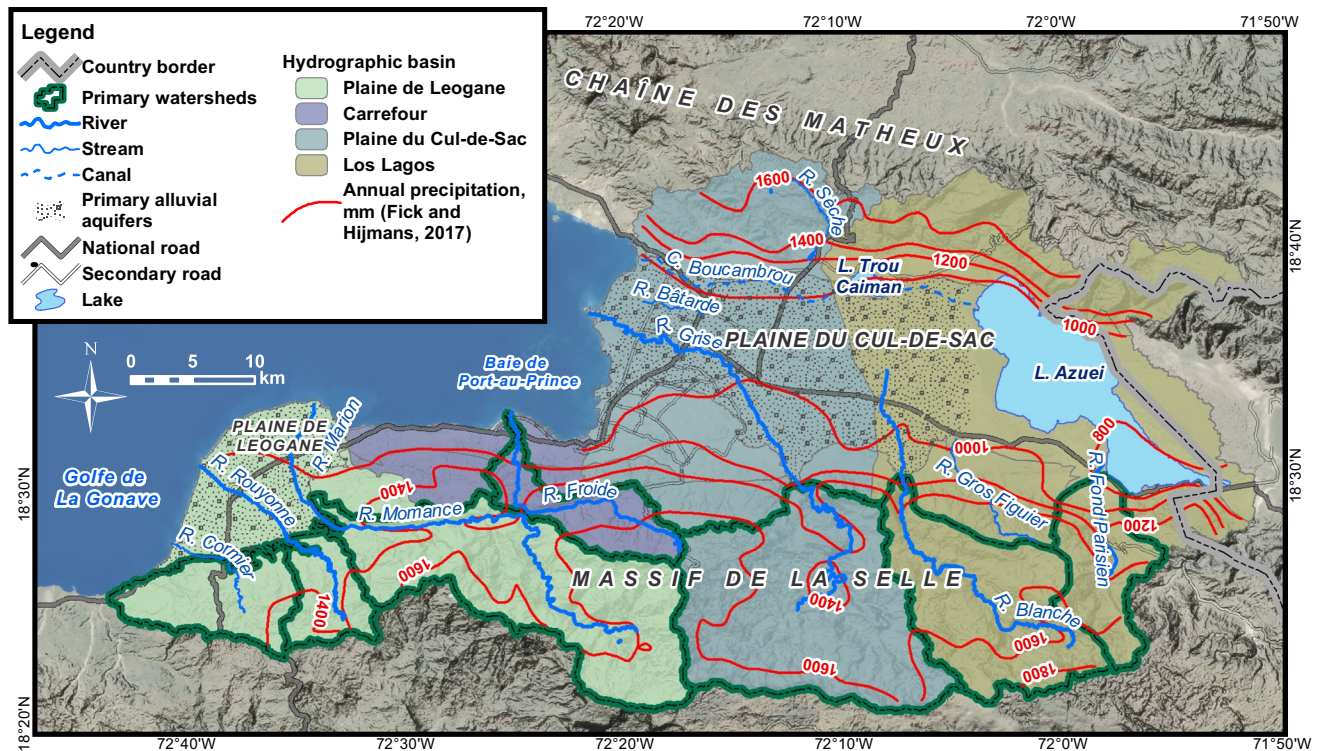
Fig. 2 Hydrographic basins, watersheds, rivers, and precipitation relevant to the regional metropolitan area of Port-au-Prince (RMPP). Source for precipitation data: Fick and Hijmans (2017)

study area is influenced by season, topography, and aspect. The PL and PCS have significantly higher ET and RH than the Massif (Trabucco and Zomer 2019).

The RMPP is contained within the study area and reflects high-density residential, commercial, and industrial land use across the southern portion of the PCS and the north-sloping flank of the Massif. Smaller communities and villages are scattered throughout the study area in a matrix of subsistence to commercial-scale agriculture in the plains. The foothills and mountains of the Massif are predominately isolated and rural with subsistence agriculture, charcoal cultivation, and natural areas. Protected and key biodiversity areas are present in the study area and represent important ecological resources with critically endangered, endangered, and vulnerable species (Timyan 2011).

Hydrology

Hydrographic basins in the study area are differentiated in Fig. 2. Los Lagos is the eastern-most basin and is considered the Haitian side of the transboundary aquifer system shared with the Dominican Republic. In Haiti, Los Lagos includes the eastern portion of the PCS aquifer and Lac Azuei and Trou Caiman. The principal rivers are River (R.) Blanche and R. Fond Parisien with watershed areas of 278 and 79 km^2, respectively, where they enter the plain from the

Massif. The PCS basin includes the western portion of the PCS aquifer and the mountainous watershed areas on both sides of the plain. The principal drainage is R. Grise, with a 279 km^2 watershed where it enters the plain from the Massif.

The PL basin and its associated aquifer have contributing watersheds comprised of R. Cormier, R. Rouyone, R. Momance, and R. Marion (from west to east). The largest is R. Momance, which flows westerly in the Enriquillo-Plaintain Garden fault zone (EPGFZ) for ~20 km prior to entering the plain and has a watershed area of 243 km^2 where it enters the plain. The remaining basin in the study area is Carrefour, which includes small drainages from the Massif and associated piedmont, and the R. Froide with its 65 km^2 watershed.

Geology

Geologically, the PCS and PL are bounded by mountains consisting of rocks of Neogene, Paleogene, and Cretaceous age (Boisson and Pubellier 1987). These rocks are differentiated into respective hydrogeological environments referred to as semiconsolidated, interior sedimentary, and igneous (Adamson et al. 2016; Fig. 1). The igneous and volcano-sedimentary Cretaceous rocks are the basement rocks of the Massif, outcropping in the high distal headwaters of the PL and PCS drainages. The southern side of the PL abuts igneous rocks which outcrop across a large portion of the PL watershed.

Paleogene sedimentary rocks blanket the Massif and Chaine des Matheux. The predominant lithology is thin-to-massive-bedded limestone exhibiting fractures and karst weathering (Woodring et al. 1924). Other rock types include shales, argillite, conglomerate, breccia, sandstone, chalk, and marl (Adamson et al. 2016; Butterlin 1960; Cox et al. 2011). The Neogene rocks are semiconsolidated and include colluvial and deltaic fans, marl, gypsiferous claystone, mudstone, shale, detrital limestone, and calcareous sandstone (Taylor and Lemoine 1949; Woodring et al. 1924; Cox et al. 2011). The low permeability rocks outcrop around the perimeters of the PL and PCS and underlie the alluvium of both plains with perhaps significant thickness. The PL and PCS are blanketed with layered coarse-to-fine-grained alluvium of Quaternary age. In the PL, the alluvium is coarser in the eastern and central portion of the plain and fines towards the coast and westerly (Northwater International and Rezodlo 2019a). Similarly, the PCS alluvium is coarser along the southern perimeter and fines northward and westerly towards the coast (Northwater International and Rezodlo 2017; UNDP [United Nations Development Program] 1990). Historical drilling records indicate alluvial thickness in the PCS extending up to 250 m (Northwater International and Rezodlo 2017). The thickness of alluvium of the PL is reported between several hundred meters (BRGM [Bureau de Recherches Géologiques et Minières] 1989; Northwater International and Rezodlo 2019a) and several thousand meters (Kocel et al. 2016). The latter estimates with seismic data are not validated with drilling and are believed to include semiconsolidated rocks of Pleistocene to Miocene age which are not considered part of the aquifer.

Hydrogeology

Both the PCS and PL aquifers are fluvial and deltaic origin sand and gravels with finer-grained layers of silt and clay. The PL aquifer is believed to have reef carbonate rocks of Quaternary age buried within the alluvium in some areas, possibly resulting from complex faulting concealed by the plain (Northwater International and Rezodlo 2019a).

Preliminary characterizations of the PL aquifer are documented by BRGM (1990) and Northwater International and Rezodlo (2019a), including data mining and a summary of historical records. Based on pumping tests of 16 wells provided by these sources, hydraulic conductivity ranges from 4.1 to 95 m/day ($\bar{x} = 43$), with transmissivity between 10 to 4,406 m^2/day ($\bar{x} = 1,120$). Drilled borehole depths range from 15 to 118 m ($\bar{x} = 37$, $n = 187$) and well pumping rates range from 0.2 to 420 m^3/h ($\bar{x} = 40$, $n = 21$). Airlift yields reported from 102 borehole records ranged from 0.2 to 68 m^3/h ($\bar{x} = 11$). The City of Leogane's municipal well is 48 m deep with a pumping rate of 23 m^3/h (Michel Jean-Baptiste, Foratech, 'Unpublished drilling, pumping and airlift yield and water level records for wells in Leogane and Plaine du Cul-de-Sac', unpublished data,

2019). Flowing artesian conditions are present in the northern aquifer limits where there are several springs and over 40 flowing wells, many within 200 m of the coast. Community hand pump wells, hand-dug wells, and private wells are located throughout the aquifer. Widmer et al. (2014) documented 345 water points in the plain, which were predominately hand-dug wells. Hand-dug wells are typically in a shallow superficial aquifer layer, less than 8 m deep and ~1.0–1.2 m in diameter.

The PCS aquifer is one of the largest aquifers in Haiti and supports domestic, agricultural, industrial, and commercial water supply. Several studies and modeling efforts have been conducted on the aquifer—(BRGM 1989; Eptisa 2015; Gonfiantini and Simonot 1988; Northwater International and Rezodlo 2017; Simonot 1982; Taylor and Lemoine 1949; Tractebel Development 1998; UNDP [United Nations Development Program] 1990, 1991). Groundwater flow models supporting groundwater balance estimates and municipal well pumping schemes have been developed by Tractebel Development (1998), Eptisa (2015), and Northwater International and Rezodlo (2019b). Hydraulic conductivity values in the aquifer range from 0.64 to 154 m/day ($\bar{x} = 28.2$), with transmissivities between 66 to 8,285 m^2/day ($\bar{x} = 1,980$) based on pumping tests of 35 wells. Drilled borehole depths are up to 236 m, and high-pumping-capacity large diameter (>8-inch casing) wells have an average depth of 95 m. Lower pumping capacity wells are not typically designed or equipped to pump greater than 20 m^3/h, have an average depth of 42 m, and are as deep as 156 m (Northwater International and Rezodlo 2017). Reported well yields range from 43 to 472 m^3/h ($\bar{x} = 166$) for high-capacity wells, and 1–19 m^3/h ($\bar{x} = 5.5$) for low capacity. Flowing artesian conditions occur in the Dessources and Sibert areas of the plain, where wells intersect deep sand and gravel layers in the lower extents of the aquifer and are hydraulically connected to the higher elevation recharge areas in the southern plain. The Dessources 2 irrigation well had artesian flows of 190 m^3/h in the 1940s and was measured at 7 m^3/h in 2016 (Northwater International and Rezodlo 2017). Groundwater abstraction from the PCS was estimated to be in the range of 30 million (M) m^3/year in 2018, with municipal abstraction accounting for ~13 Mm^3/year (Emmanuel Moliere, CTE-RMPP, unpublished report, 2018). Historical abstraction peaked in the 1970s and early 1980s and was estimated at over 100 Mm^3/year (Simonot 1982). During this period, power supply was more reliable, municipal pumping was higher, and the now inactive commercial sugar cane industry had pumping capacity up to 60 Mm^3/year from at least 57 wells. Aquifer impacts were pronounced during this period and included increasing salinity, lowering water tables, drawdown impacts and increasing salinity near the coast (Northwater International and Rezodlo 2017).

Considering that both the PCS and PL aquifers are bounded by the Bay of Port-au-Prince, saltwater intrusion is

a concern, especially with increased abstraction or upstream river modifications that may affect aquifer recharge. The coastal areas of the PL and PCS exhibit higher EC waters that exceed 1,500 µS/cm in the shallow surficial groundwater, and the water quality fluctuates seasonally. The deeper production wells in these areas have fresher water under pressure and are connected to upgradient recharge. In the PCS, historical EC values of several irrigation wells near the coast were as high as 1,450 µS/cm during a period of large-scale commercial sugar cane production (1920s–1980s). These wells reported EC values less than 400 µS/cm between 2000 and 2006, and also exhibited shallower static potentiometric surfaces than historically reported (Northwater International and Rezodlo 2017). Monitoring of municipal wells from 2006 to 2015 show stable EC at the "D" wells closest to the coast (<3.5 km), and increasing EC over time at the "F" wells which are 7–12 km from the coast. For example, the F4 well reported a gradual increase of EC from ~650 µS/cm to over 800 µS/cm between 2006 and 2012 before stabilizing through 2015. The origin of higher or increasing EC values may not always result from seawater intrusion, but also from multilayer aquifer dynamics and deeper bedrock origin groundwater that is brackish (Gonfiantini and Simonot 1988; Northwater International and Rezodlo 2017).

Based on a recent review of data, the PL aquifer is perceived to have limited saltwater intrusion affecting the primary production zones due to low levels of abstraction and the presence of flowing artesian wells and springs along the coast (Northwater International and Rezodlo 2019a). The shallow superficial layer near the coast can have higher EC values and is considered more vulnerable to seawater influence, especially during the dry season.

Materials and methods

Data supporting this study include piezometric, water quality, stable isotope, and river flow measurements. There is no systematic hydrological and hydrogeological research and monitoring in the study areas; most of the data were compiled from historical datasets, unpublished data, and consulting reports spanning different time frames. Sampling and monitoring campaigns were performed by the authors to support analysis and interpretations. Multiple methods were applied to derive preliminary insights on groundwater recharge. The isotope partitioning, chloride mass balance, and baseflow separation methods must be strengthened in future research with less reliance on historical data, assumptions, and extrapolations. Unless otherwise noted, the aquifer systems represented by the data and analysis are deeper-layer production zones accessed with drilled boreholes. They do not represent the shallow superficial aquifer that is accessed in lower-elevation and coastal areas with hand-dug wells.

Summary of datasets

Data sources and associated locations are outlined in Fig. 3, and Tables S1–S10 in the electronic supplemental material (ESM) include datasets applied in this report that are not published elsewhere. Historical data and drilling logs were compiled and applied to support analysis of groundwater flow for both aquifers. Data included discrete static water level (SWL) measurements from various time periods for 131 drilled boreholes in the PCS. For PL, the data included discrete SWL measurements for 33 drilled boreholes in 1989, 100 private wells between 2010 and 2017 (at time of drilling), and weekly SWL for 11 hand-dug wells from 2017 to 2018. SWL data were converted to groundwater head above sea level by subtraction of wellhead stickup (when known) and subtraction of water depth from ground surface elevation derived from 1.5 m resolution LiDAR data flown between 2014–2017 and made available by Mr. Boby Piard at Centre National de l'Information Géo-Spatiale (CNIGS). Piezometric contour maps to support analysis were developed using kriging interpolation methods in ArcGIS Desktop and Golden SURFER software.

Synthesis of water quality and stable isotope datasets included data collected from the 1980s to 2019. Figure 3 shows data locations including boreholes, hand-dug wells, springs, and several surface-water locations for which data are available. In-situ water quality, including pH and electrical conductivity (EC), were analyzed in October 2016 at 43 wells in the PCS (Northwater International and Rezodlo 2017) and in February 2019 at 75 wells in Leogane (Northwater International and Rezodlo 2019a). The Government of Haiti monitored groundwater monthly for principal ions, pH, and EC at 17 municipal boreholes in the PCS from 2006 to 2016 (CTE-RMPP, unpublished data, 2016). In 1989, BRGM (1990) measured EC at 18 boreholes once during the rainy season and once during the dry season in the PL. Weekly EC data from 2017–2019 were made available for 11 hand-dug wells in the PL (PIWAREC 2019). EC data were compiled and interpolated spatially for both aquifers using ArcGIS and Golden SURFER software.

Northwater International and Rezodlo (2017, 2019a) performed hydrochemistry sampling of 11 PCS boreholes in October 2016, and nine PL boreholes and two springs in April 2019. This included major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-), TDS, total hardness, and select metals. The aforementioned samples, plus eight additional boreholes and one river sample from the PL campaign were concurrently analyzed for stable isotopes (δ^2H and $\delta^{18}O$). The 11 stable isotope samples from PCS and 20 from PL are supplemented with published isotope data which include 87 data points from the PCS and 51 from the Massif (Gonfiantini and Simonot 1988; IAEA 2009). The isotope data represent the deeper aquifer units from drilled boreholes and not the
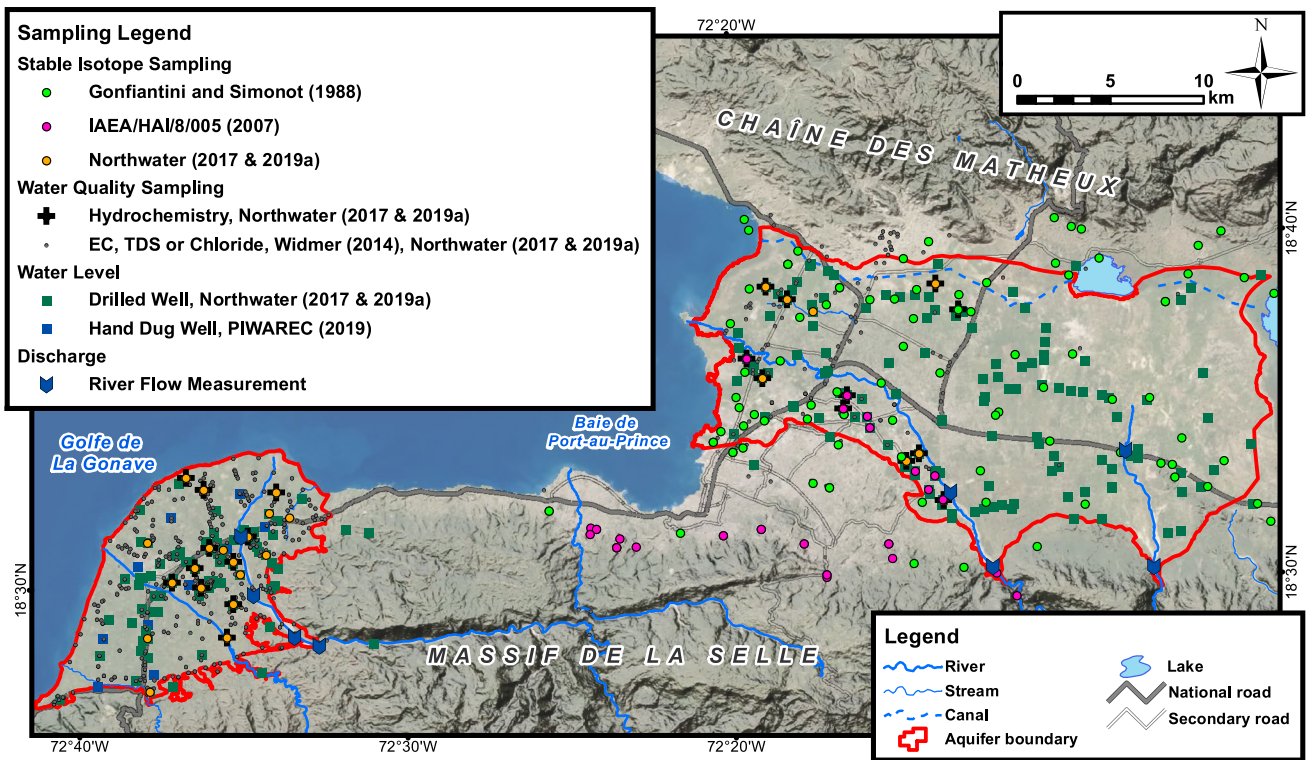
Fig. 3 Stable isotope, water quality, water level, and river discharge measurement locations with interpolated groundwater electroconductivity. Sources for sampling data include Gonfiantini and Simonot (1988), unpublished data collected by the International Atomic Energy Agency (IAEA 2009), Northwater International and Rezodlo (2017, 2019a), Widmer et al. (2014) and PIWAREC (2019)

shallow superficial waters. Based on analysis by Gourcy et al. (2022, this issue), change in stable isotope values has not been significant in the study area between the 1980s and recent datasets.

Between October 2016 and April 2019, 17 rainfall samples were collected and analyzed for chloride at several locations in the PCS, Massif, and PL at elevations ranging from 17 to 1,025 masl (Northwater International and Rezodlo 2019a, b). Rainfall chloride data were applied to support CMB analysis and recharge estimates.

Flow measurements of the primary rivers relevant to the PCS (R. Grise and R. Blanche) and PL (R. Momance) were compiled from historical datasets and recent measurement campaigns. Daily discharge values were available from 1919–1940 for R. Grise, 1923–1940 for R. Blanche, and 1921–1940 for R. Momance (DGTP [Republic of Haiti Public Works] 1918–1938). BRGM (1990) monitored daily discharge at multiple stations on R. Grise, R. Blanche, and one station on R. Momance during 1989. Irrigation diversions were also measured daily from all three rivers by BRGM in 1989. Discrete measurements of flow were made on R. Grise and R. Blanche in October 2016 at their points of entry into the plain from the Massif and at downstream locations in

the plain (Fig. 3; Northwater International and Rezodlo 2017). In the PL, discrete flow measurements were similarly made at multiple locations along R. Romance and R. Rouyone, and irrigation canals between 2018 and 2021. This included four events between April 2018 and April 2019, and five events between November 2020 and April 2021.

Analysis methods

Stable isotope partitioning

Stable isotope partitioning was performed to make preliminary estimates of the ratio of direct aerial recharge to streamflow infiltration for the aquifers using the mass balance equation described by Yeh et al. (2014). The equation is defined in Eq. (1), where X is the ratio of recharge from streamflow infiltration, and A, B, and C are the average $\delta^{18}O$ values of precipitation, rivers, and groundwater, respectively.

$$C = A(1 - X) + BX \qquad (1)$$

Isotope partitioning analysis applied kernel interpolation with barriers using ArcGIS for $\delta^{18}O$ values of drilled

boreholes throughout the PCS and PL aquifers. This included 99 and 20 data points for the PCS and PL aquifers, respectively. The δ^{18}O isolines are identical to those published by Gonfiantini and Simonot (1988) for the PCS resulting in a spatial average δ^{18}O value of –3.61‰. A secondary estimate representing the deeper confined layers of the aquifer was developed by averaging δ^{18}O results from four flowing artesian wells in the plain (–3.87‰). Groundwater δ^{18}O values for the PL were estimated by interpolation in the same manner as for the PCS for the aquifer extents east of R. Rouyone.

Average δ^{18}O of precipitation across the PCS of –3.1‰ (Gonfiantini and Simonot 1988) was used and applied for PL analysis as they are in close proximity, and have a similar setting and climate. The R. Grise δ^{18}O value was estimated at –3.7‰ based on two samples from 2007 (IAEA 2009) and the mean δ^{18}O of low EC (<1,500 µS/cm) groundwater from wells near the river documented by (Gonfiantini and Simonot 1988). Riviere Momance δ^{18}O was established at –2.68‰ based on a dry season sample (Northwater International and Rezodlo 2019a) which corroborates with the groundwater δ^{18}O isolines near infiltration areas of the river.

No direct Riviere Blanche δ^{18}O data were available; however, δ^{18}O was –4.3‰ at alluvial springs located downstream of the river's main losing section and applied for the analysis, and this was also assumed by previous researchers to represent the river (Gonfiantini and Simonot (1988). This value presents an assumption and method limitation; however, it corroborates with the spatial analysis of δ^{18}O for the plain groundwater and the isotopic enrichment observed at higher elevations and farther inland—for example, low EC (<1,500 µS/cm) karst springs near Fond Parisien reported δ^{18}O of –5.0‰.

This analysis applies limited data and also from different time periods for precipitation, river, and groundwater. Gourcy et al. (2022) reported similar isotope values in the study area comparing 1988 and 2016 data; however, with the assumptions outlined and reliance on δ^{18}O interpolation, the results must be considered preliminary and the data need to be strengthened in future research.

Streamflow analysis

Streamflow infiltration from the mountain block rivers into the alluvial aquifers was evaluated using direct measurements of discharge from several datasets using Eq. (2) and the monitoring stations shown in Fig. 4 with coordinates in the ESM.

The daily flux calculation is defined in Eq. (2), where Q_{flux} is the daily net gain or loss from the river between Q_{us} and Q_{ds}. Q_{us} is the river flow where the rivers enter the plain from the Massif, Q_{div} is the measured flow from irrigation
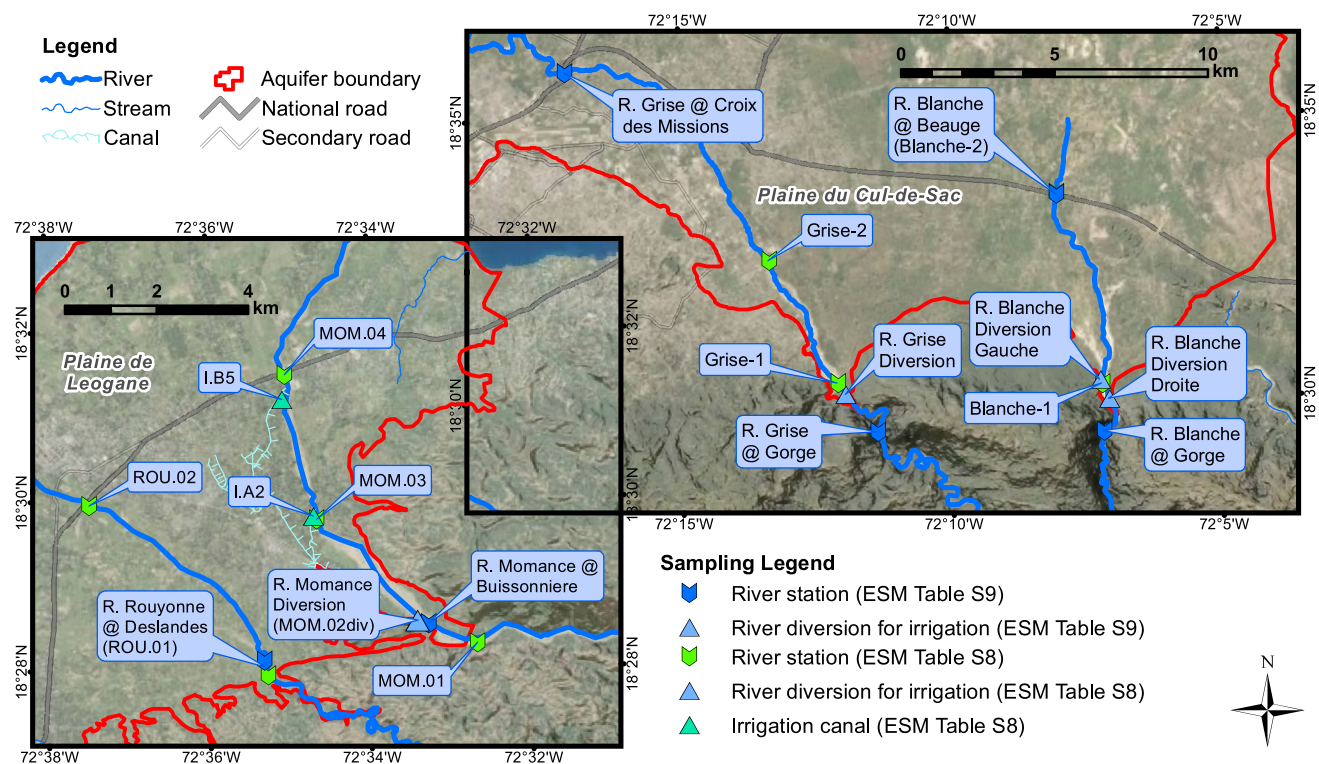

Fig. 4 Streamflow and diversion monitoring locations for the **a** Plaine de Leogane and **b** Plaine du Cul-de-Sac. Sampling data can be found in the ESM

diversions, and Q_{ds} is the downstream measured or interpolated river flow.

$$Q_{flux} = Q_{us} - (Q_{div} + Q_{ds}) \qquad (2)$$

Applying the 1989 BRGM data for R. Grise and R. Blanche, streamflow infiltration was calculated by subtracting the measured discharge from the most downstream location and irrigation diversions from the measured discharge where the rivers enter the plain from the Massif (Fig. 4).

For the R. Momance, discharge was only monitored at one location and at the irrigation diversion during 1989. A flow relationship was established between upstream and downstream reaches based on 2018–2019 measurements, this relationship was applied to interpolate downstream R. Momance flows for the 1989 monitoring period (Fig. 5).

The estimates for R. Momance corroborate river discharge monitoring for the period from November 2020 to April 2021 (Northwater International, unpublished data, 2021). Irrigation diversions have historically diverted river flows, affecting recharge processes and quantities. Diversions are still active on R. Momance, but not currently on R. Grise and R. Blanche due to hurricane-related damage to infrastructure in 2016.

Chloride mass balance

Chloride mass balance (CMB) is one of the most widely used methods for estimating groundwater recharge rates (Crosbie et al. 2018; Marei et al. 2010; Naranjo et al. 2015). A multicomponent CMB was applied for the PL aquifer due to the presence of multiple recharge sources and the availability of initial ranges for some components based on other methods and studies (Anderson et al. 2021). It was not performed for the PCS aquifer due to the

unavailability of chloride data to represent precipitation and river flows.

The balance based on Anderson et al. (2021) is defined in Eq. (3), where Q is volumetric annual flow, Cl is the average chloride concentration of respective waters, and subscripts gw represents groundwater, p represents precipitation, s represents streamflow (R. Momance). x is the balance of other recharge sources.

$$Q_{gw}Cl_{gw} = Q_pCl_p + Q_sCl_s + Q_xCl_x \qquad (3)$$

Baseflow separation

Groundwater recharge estimates in the R. Grise, R. Blanche, and R. Momance basins of the Massif were estimated using time-step digital filtering baseflow separation methods outlined by Eckhardt (2005) and Lim et al. (2005) and presented in Eq. (4), where b_t is baseflow, t is the time step, b_{t-1} is filtered baseflow, BFI_{max} is the maximum ratio between baseflow and streamflow, α is the filter, and Q_t is the total streamflow.

$$b_t = \frac{(1 - BFI_{max})x \propto + b_{t-1} + (1 - \propto)x\ BFI_{max}\ x\ Q_t}{1 - \propto x\ BFI_{max}} \qquad (4)$$

The maximum baseflow index (BFI_{max}) relates to hydrological and hydrogeological characteristics of the watersheds. A trial-and-error method was applied starting with BFI_{max} of 0.6 for all three watersheds. This value falls in the lower range of perennial streams with porous aquifers, whereas perennial streams in hard rock aquifers are in the range of 0.25 (Eckhardt 2005). The calibrated BFI_{max} values for R. Grise, R. Blanche, and R. Momance were 0.59, 0.57, and 0.48, respectively. R. Momance has a lower value due to the less porous watershed influenced by the igneous geology.

Results and discussion

Recharge dynamics

Groundwater flow

General interpretation of lateral aquifer flows in the primary production zones were interpolated using manual and kriging methods supported with ArcGIS software (Fig. 6). Estimated alluvial thickness is also presented based on North-water International and Rezodlo (2017). Steep hydraulic gradients in the aquifers occur where principal rivers enter their respective plains from the Massif mountain block due to the significant elevation differences between river beds and the piezometric surface of the aquifers in these braided
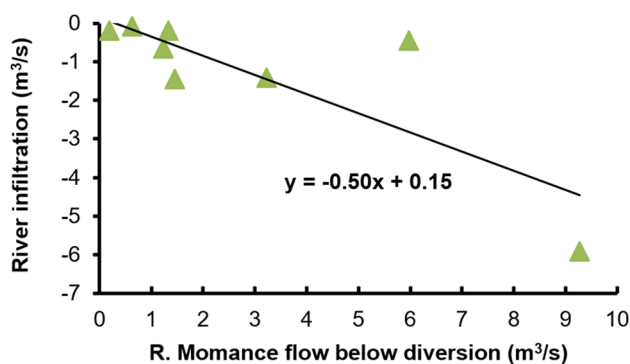

Fig. 5 River infiltration interpolation based on the relationship between upstream and downstream flows as measured in 2018–2019
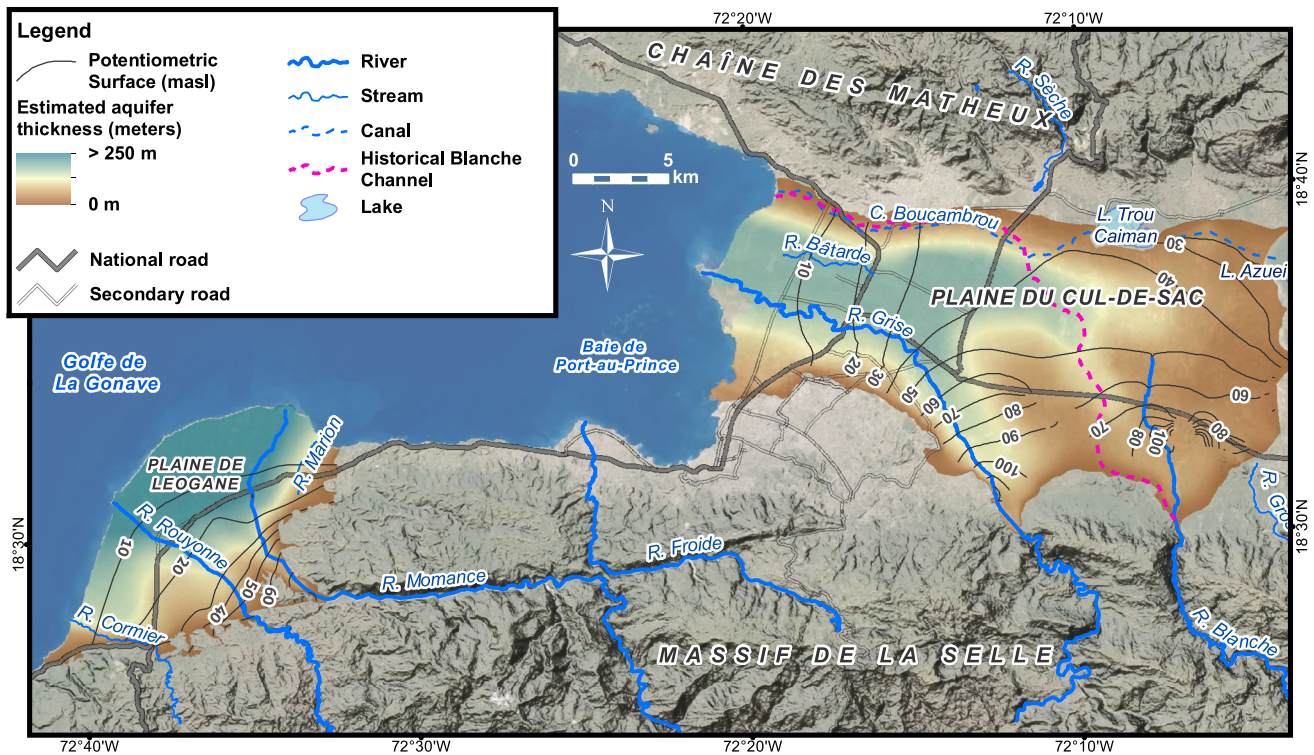
Fig. 6 Groundwater potentiometric surface in PCS and PL aquifers and estimated alluvial thickness. Potentiometric surface shown as contour lines and estimated alluvial thickness illustrated with color ramp

areas. These gradients, combined with the high-permeability strata, indicate river infiltration potential at a noteworthy scale along the southern perimeter of the respective plains, and even suggest that R. Grise and R. Blanche are perched high above the phreatic zone and that infiltration through unsaturated strata is occurring. The significance of groundwater mounding from streamflow infiltration of the two rivers promotes a groundwater divide that extends northward into the plain. Interestingly, this groundwater divide approximately corresponds to the surface watershed boundary transecting the plain between Lac Azuei/Los Lagos and the Golf de La Gonave. This boundary is where the eastern and western PCS aquifer is differentiated.

For R. Grise, a primary zone of infiltration is interpreted along the wide braided reach extending ~6 km from where the river enters the plain based on streambed morphology and flow measurements. This recharge flows northwestward where most of the wells and population are concentrated. The primary infiltration reach for R. Blanche is also interpreted to be ~6 km extending from its entry into the plain to National Route 8. Some of this river infiltration is rejected perhaps due to buried geological structures or limited aquifer storage, which results in several large springs near Ganthier. Streamflow infiltration from R. Blanche flows north and northeast towards Lac Azuei, Trou Caiman, Canal Boucambrou, and northwesterly in deep strata along the path

of the former R. Blanche channel and alluvial deposits as documented in a historical map (Hesse 1780; Fig. 6). Steep hydraulic gradients in the PL aquifer also indicate a zone of infiltration along a braided reach of the R. Momance extending ~5 km from where the river enters the plain. The first 3 km are braided and greater infiltration along this reach is interpreted. Seasonal fluctuations in groundwater level in both drilled and hand-dug wells are most significant in these areas, with fluctuations recorded up to 3 m (BRGM 1990; PIWAREC 2019), corroborating surface-water/groundwater interactions.

Hydrochemistry and stable isotopes

Spatial interpolation of groundwater EC data closely correlates with groundwater flow in both aquifers (Fig. 7). In the PCS, the freshest groundwater is along the southern edge of the plain and where hydraulic gradients are high, the influence of R. Grise infiltration is especially apparent on the level of groundwater mineralization. The north and northeast portions have mineralized groundwater due to lesser dilution from river infiltration and older brackish groundwater in bedrock under the plain (Gonfiantini and Simonot 1988; Simonot 1982). In the west, there is coastal influence of seawater mixing in shallower wells. In the PL, the freshest groundwater is in proximity to R. Momance and R. Rouyone
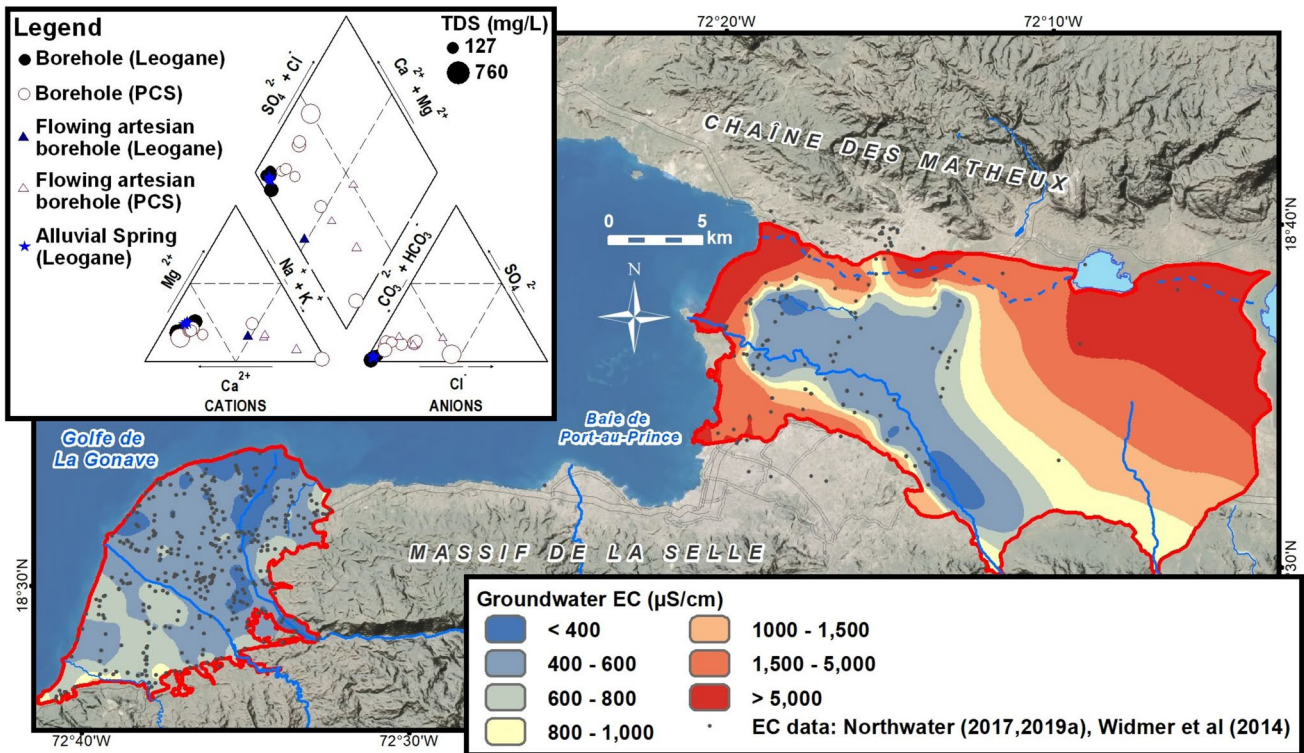
Fig. 7 Interpolated groundwater electrical conductivity (EC) with inset trilinear Piper diagram of PCS and Leogane boreholes, flowing artesian wells and alluvial spring. Sources: Northwater International (Northwater International and Rezodlo 2017, 2019a), Widmer et al. (2014)

and has similar EC values, suggesting streamflow infiltration. The EC increases westerly with distance from the rivers, where the hydraulic gradient is also lower and alluvium is finer-grained. EC values of groundwater across the PL were not documented above 1,000 µS/cm and the aquifer does not appear to have the dynamic mineralization influences as the PCS does. The groundwater in the PL exhibits a narrow range of calcium-bicarbonate facies, whereas the PCS groundwater has greater variability of hydrochemistry facies (Fig. 7). The calcium-bicarbonate facies also correlate to interpreted streamflow infiltration due to the carbonate makeup of the Massif.

Stable isotopes are useful tools to characterize water dynamics and origins (Ette et al. 2017), making them valuable for identifying groundwater recharge areas especially when complemented with hydrochemistry data (Montalvan et al. 2017; Sánchez-Murillo et al. 2019).

Statistical averages of stable isotopes for portions of the study area are plotted in Fig. 8 along with a local meteoric water line (LMWL) established for Haiti of $\delta^2H = 7.47\ \delta^{18}O + 10.05$ (Gourcy et al. 2022) and meteoric water line for Puerto Rico based on Global Network of Isotopes in Precipitation (GNIP) data of $\delta^2H = 7.852\ \delta^{18}O + 10.114$. Interpolated isolines of $\delta^{18}O$ for PCS and PL are plotted

in Fig. 9 and further corroborate recharge sources to the alluvial aquifers. The western portion of the PCS is well connected with the R. Grise infiltration area and the eastern portion of PCS shows $\delta^{18}O$ signatures from R. Blanche and perhaps R. Fond Parisien. Flowing artesian wells in the PCS have an isotopic signature closer to R. Blanche, suggesting its infiltration may comprise a greater proportion of recharge to deeper layers of the aquifer. Along the northern limits of the PCS, springs, and wells from the Chaine de Matheux exhibit signatures not represented in the alluvial waters, suggesting that a majority of PCS recharge originates from the Massif side of the plain. In the PL, the isotopic signatures in the east and near R. Momance show signatures similar to the river and from altitudes higher than the plain in the Massif. This corroborates with the other indicators of streamflow infiltration. The SW plain has more enriched isotopic signature, suggesting the influence of other water origins. The waters plot similarly to bedrock springs in the northern PCS, which were interpreted to have geothermal and fault influence (Gonfiantini and Simonot 1988). Seawater mixing could partially explain the enrichment in the SW based on where they plot in Fig. 8; however, the expected increase in EC of these waters was not observed. Hydrochemistry and stable isotope data are included in the ESM.
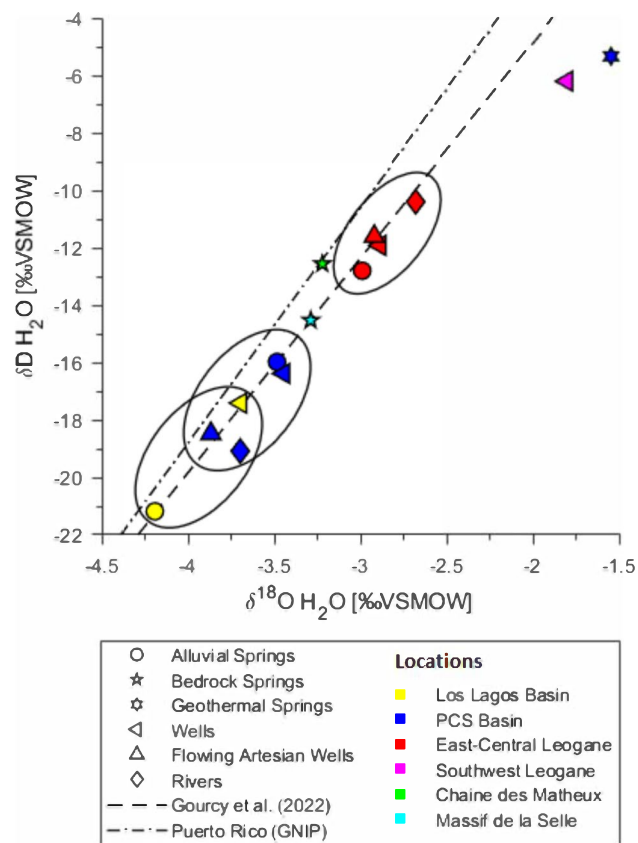
Fig. 8 Isotope plots for springs and boreholes in the PCS and PL

Streamflow analysis

Based on analysis of the 1989 BRGM dataset, R. Blanche results in the highest percentage of river loss to the aquifer (89%), followed by 58% for R. Grise and 28% for R. Momance (Fig. 10 and Table 1). The year-long dataset presented in Fig. 10 indicates that R. Grise and R. Blanche annual recharge to the west and east sides of the PCS aquifer is similar, 271,400 m³/day and 319,100 m³/day, respectively. Streamflow losses from the R. Momance into the PL aquifer is estimated at less than 72,200 m³/day.

These values corroborate with recent measurements from October 30, 2016, where infiltration was estimated at 290,400 m³/day from R. Grise, and 221,900 m³/day from R. Blanche (Northwater International and Rezodlo 2017). R. Momance monitoring events from 2018 to 2021 suggest 83,700 m³/day of infiltration (Northwater International, unpublished data, 2021), this campaign also introduces streamflow infiltration from R. Rouyone into the PL, estimated at 16,800 m³/day from direct measurements.

The difference between river infiltration recharge of the PCS and PL aquifers is partially due to their different watershed characteristics and provenance of alluvial sediments. The R. Grise and R. Blanche watersheds drain the highest

mountains of Haiti, predominately fractured and karst limestone, the rivers are of high gradient, transporting coarse alluvium into the plain. The R. Momance watershed has more igneous geology and the river has a lower gradient along the deeply incised EPGFZ before redirecting north into the PL.

Based on the Au Cadet (Lat. 18.4611°, Long. –72.2536°) and Furcy (Lat. 18.4205°, Long. –72.2999°), precipitation stations located in the Massif, 1988–1989 was a La Niña period of higher-than-average rainy season precipitation. Hurricane Gilbert also saturated the study area in September 1988; thus, the 1989 streamflow recharge simulations are likely high-end estimates expected on 3–7 year El Niño/La Niña Southern Oscillations (ENSO) cycles. The Massif de la Selle aquifer system response to ENSO cycles has been documented through analysis of spring flow of Tunnel Diquini (Miner et al. 2022, this issue). Tunnel Diquini discharged at approximately 2–4 times higher rates immediately after the 1988–1989 La Niña than in the preceding or proceeding 5-year periods, which included the El Niño periods of 1986–1987 and 1991–1993. Interestingly, due to the watershed characteristics of the R. Momance basin and its resulting flashiness, the ENSO influence appears muted when compared to R. Grise and R. Blanche of the PCS. The R. Momance streamflow infiltration estimates from 1989 may be closer to average or typical, while R. Grise and R. Blanche are higher-end estimates under more influence of the ENSO climatic event.

Despite the limited snapshot, the streamflow data that were available present direct evidence of the occurrence and scale of streamflow infiltration occurring in both aquifers. They also illustrate temporal dynamics, documented via annual time series that an important proportion of the PCS recharge occurs during the rainy season and during higher flow events of the R. Grise and R. Blanche. In the PL, the recharge is more temporally distributed, not fluctuating as episodically or at the magnitude of the PCS, although a majority of recharge still occurs during the rainy season.

Stable isotope partitioning

Based on δ¹⁸O partitioning, R. Grise infiltration to the PCS aquifer is estimated to represent 85% of recharge to most of the wells in the plain located on the western side of the aquifer (Table 2). The deeper aquifer layers and the eastern side of PCS have stronger signatures from R. Blanche infiltration and display greater isotopic depletion (Table 2).

In the PL, R. Momance infiltration is estimated to represent 61% of recharge in the east-central side of the plain (Table 2). The western side of the plain has a lesser
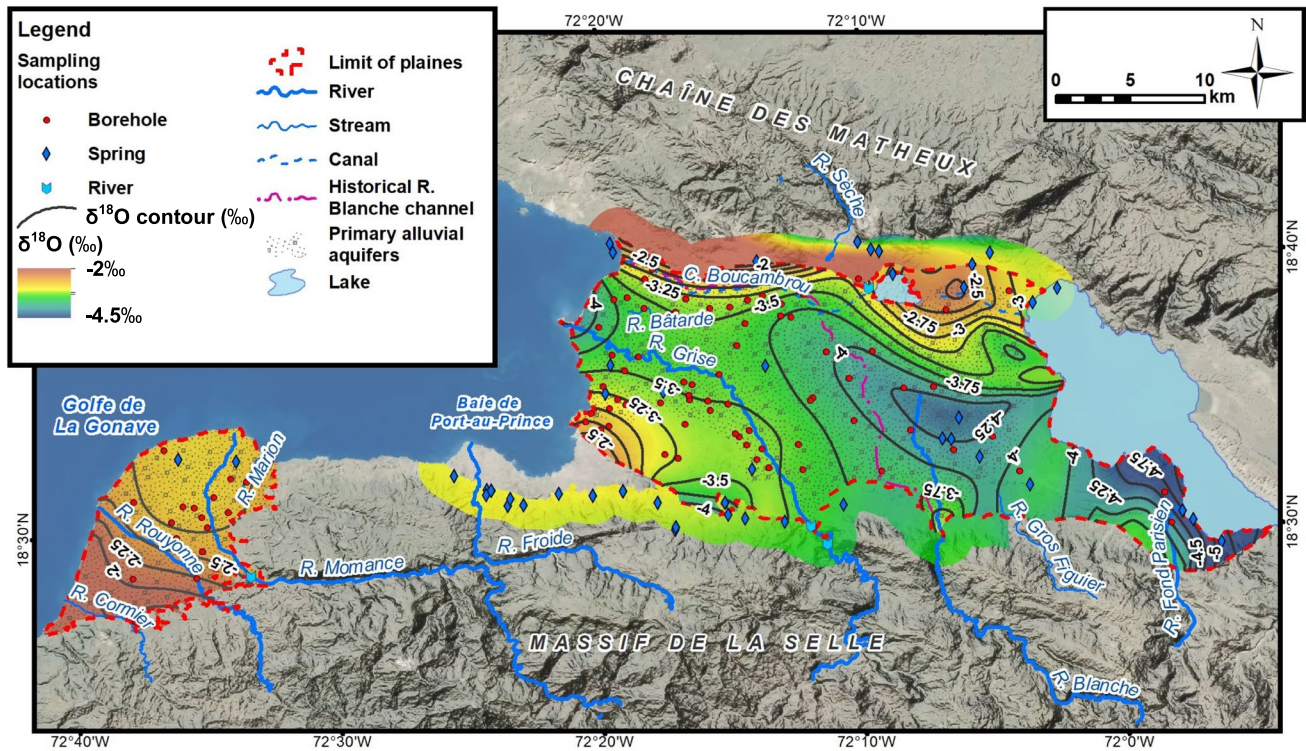
Fig. 9 Map of d[18]O isolines in groundwater of PCS and PL showing groundwater recharge primarily derived from R. Grise, R. Blanche in PCS and R. Momance in PL

proportion originating from R. Momance; however, infiltration is likely from R. Rouyone for which isotopic data were not available to represent the river waters. This analysis is limited by the dataset with few sampling events, especially of precipitation which is more temporally variable than river baseflow and groundwater. Further, the historical and current irrigation diversions of all three rivers would introduce recharge with increased isotopic enrichment versus its original river origin water. This would influence the values in groundwater, and may underestimate the contribution of streamflow infiltration from this analysis.

CMB Plaine de Leogane

As a supplemental means to evaluate recharge sources of the PL, a preliminary CMB partitioning analysis was performed due to the availability of low-level chloride analysis of rainfall, and chloride data for R. Momance and groundwater. Average chloride concentrations for groundwater, precipitation, and R. Momance waters were 13.6 mg/L ($n = 19$), 3.8 mg/L ($n = 13$), and 8.4 mg/L ($n = 3$), respectively (Table 3). Initial components applied include direct recharge (Northwater International and Rezodlo 2019a) and streamflow infiltration estimates (see sections 'Streamflow analysis' and 'Stable isotope partitioning'). The balance of recharge is inclusive of other sources such as irrigation canal water, R. Rouyone infiltration, and mountain block interflow and runoff.

The results indicate streamflow infiltration from R. Momance and direct infiltration from precipitation to be ~51 and ~14% of annual recharge, respectively (Table 3), which corroborate with other methodologies and historical estimates. The CMB suggests additional sources may account for ~35% (18.3 Mm³/year) of the recharge to the plain, contributing a higher chloride concentration (Table 3). Tractebel Development (1998) estimated such recharge sources to be in a similar range (15.7 Mm³/year). Riviere Rouyone streamflow infiltration and irrigation return flow estimates from 2020–2021 monitoring are estimated at 6 Mm³/year and 4.5–5.4 Mm³/year, respectively (Northwater International, unpublished data 2021). The remaining balance of ~8 Mm³/year is hypothesized to predominantly result from mountain block-related inflows.

Renewable groundwater resource estimates

Plaine du Cul-de-Sac

Estimates of direct aerial recharge and streamflow infiltration for the PCS are presented in Fig. 11. Direct aerial recharge is a small proportion of total recharge to the plain, between 5.5 and 6.5 Mm³/year, and is influenced by high evapotranspiration and lower precipitation in the plain (Northwater International and Rezodlo 2019b). Average annual streamflow infiltration from R. Grise and R.

Fig. 10 Streamflow infiltration analysis results for **a** R. Grise of the PCS, **b** R. Blanche of the PCS, and **c** R. Momance of the PL. The Au Cadet and Furcy precipitation stations are in the Massif de la Selle, within headwaters of the respective basins
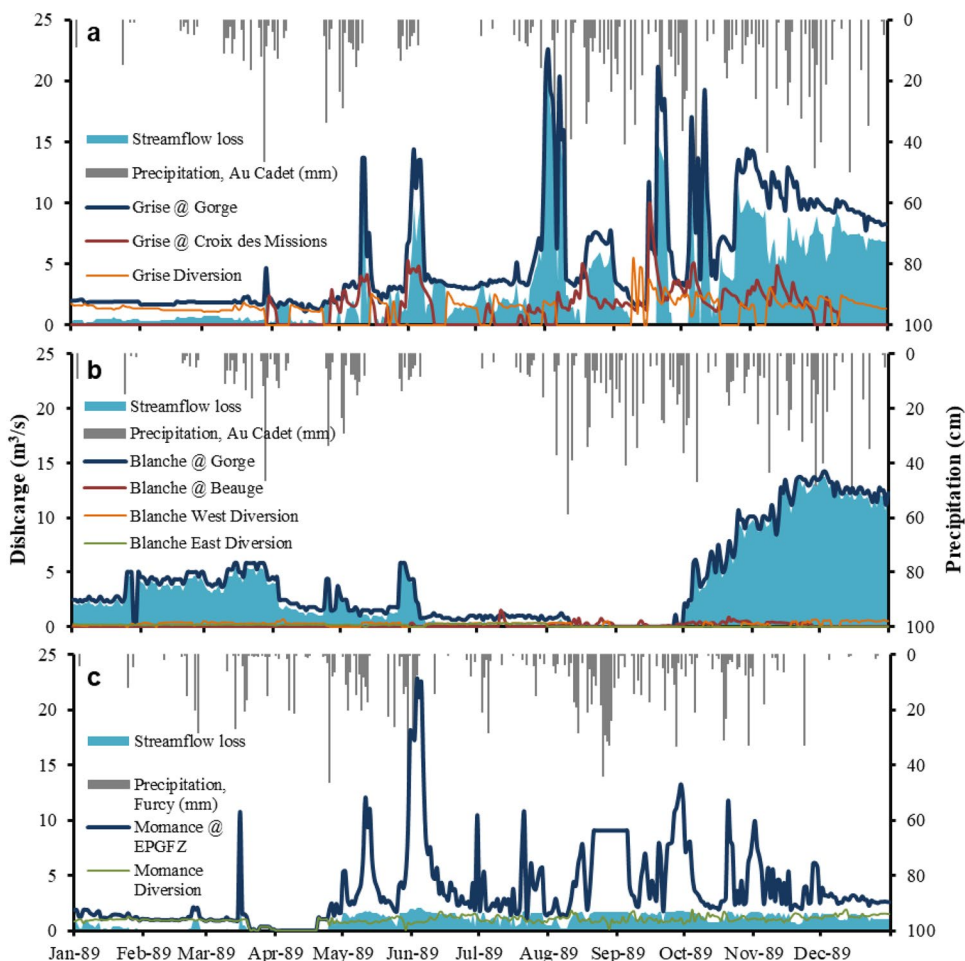

Table 1 Streamflow infiltration to alluvial aquifers based on 1989 daily discharge data

Parameter	Units	Plaine du Cul-de-Sac		Plaine de Leogane
		R. Grise	R. Blanche	R. Momance
Annual streamflow	Mm^3/year	171	131	94
Streamflow loss to aquifer	Mm^3/year	104	118	26.4
Streamflow gain from aquifer	Mm^3/year	4.5	1.2	NA
Net streamflow loss	Mm^3/year	99	116	26.4
	m^3/day (mean)	271,400	319,100	72,200
	Percent	58%	89%	28%

Table 2 Stable isotope partitioning results for the Plaine du Cul-de-Sac and Plaine de Leogane aquifers

Parameter	Plaine du Cul-de-Sac aquifer		Plaine de Leogane aquifer
	West aquifer and RMPP area	East aquifer and deep flowing artesian layers	East-central portion of the aquifer
Precipitation δ^{18}O (A)	−3.1‰	−3.1‰	−3.10‰
Streamflow δ^{18}O (B)	−3.7‰	−4.05‰	−2.68‰
Groundwater δ^{18}O (C)	−3.61‰	−3.87‰	−2.84‰
% streamflow infiltration (X)	85%	81%	61%

Table 3 Multi-component chloride mass balance results for Plaine de Leogane

Component	Mean chloride concentration (number of samples)	Estimated recharge volume	Chloride mass	Initial component source
	(mg/L)	(Mm³/year)	(kg/year)	
Leogane groundwater, average	13.6 (20)	–	–	Sampling data
Rainfall, Plaine de Leogane	3.8 (13)	7.29	27,702	GIS modeling and isotope partitioning
Riviere Momance (river water), average	8.4 (3)	26.4	221,760	River gain/loss and isotope partitioning
Other recharge sources (balance)	11.4	18.3	208,722	–
Total	13.6	52.0	458,184	–

Fig. 11 Estimated recharge from direct aerial and streamflow infiltration sources for the PCS aquifer, its west/RMPP portion, and its potential range. Estimates of groundwater pumping from the PCS aquifer are shown for comparison purposes; a majority of current and historical pumping is in the west/RMPP portion of the aquifer. ENSO = El Niño/La Niña Southern Oscillations
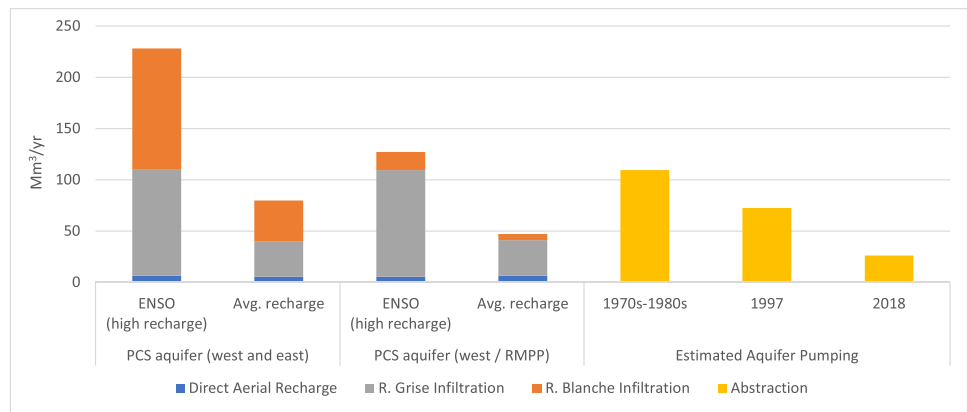
Blanche is estimated at 74.5 Mm³/year and may be much greater during La Niña periods or years with tropical storms and/or hurricanes (Fig. 11). The R. Blanche waters may not contribute significantly to available groundwater in the western portion of the aquifer and the RMPP area. Groundwater pumped from most RMPP wells is interpreted as R. Grise infiltration origin; thus, it is important to differentiate the west PCS zone as it is where the aquifer is predominately exploited and most high-capacity wells are located. Groundwater flow models result in more reliable simulations in the west PCS due to greater availability of data and drilling logs. The east PCS, including the area associated with Lac Azeui and Trou Caiman is data-scarce and conceptual models of geology and hydrogeology are inadequate. Based on past model results and analysis presented in this report, streamflow infiltration flowing towards the west PCS is predominately R. Grise infiltration and perhaps ~15% attributed to R. Blanche infiltration (Fig. 11).

The range of streamflow infiltration recharge is influenced by the Massif and the response of its carbonate aquifer system to climatic factors and ENSO cycles. The high-range estimates of infiltration may occur during La Niña episodes, and the lower-end estimates may be more representative of long-term average conditions. Severe El Niño events may

result in years with even lower streamflow infiltration; however, limited data are available to support such estimates.

The historical scale of abstraction has been greater than the average aquifer recharge quantities estimated from direct aerial and river infiltration. Recent abstraction estimates indicate a lower groundwater development ratio than historically, largely due to the inactivity of the sugar cane industry. Other sources of groundwater recharge including return flow of irrigation water, subsurface interflow from the Massif de la Selle bedrock, and return flow from bedrock springs are not accounted for in this analysis and should be addressed in future research.

Plaine de Leogane

Estimates of groundwater recharge to the PL aquifer are presented in Fig. 12. The long-term mean annual recharge is in the range of 42–52 Mm³/year, or 115,000–140,000 m³/day. Riviere Momance infiltration accounts for 26.4 Mm³/year, or 51–63% of mean annual recharge as supported by isotope partitioning, CMB analysis, and streamflow data. Direct aerial recharge for the PL is estimated at 7.29 Mm³/year (14–17%). This is a similar quantity to the PCS, however, more important for the PL as streamflow infiltration is less significant. Other recharge sources are estimated to provide
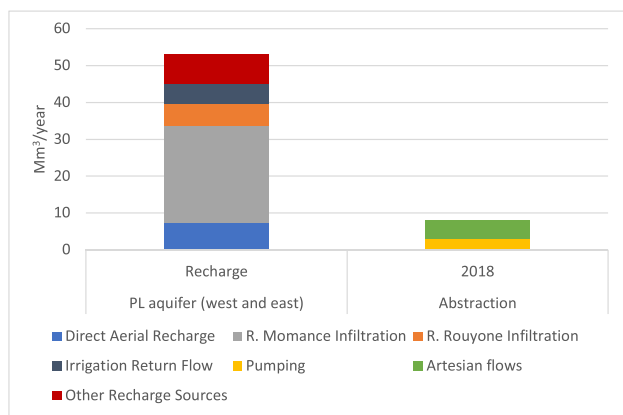
Fig. 12 Estimated long-term average recharge from direct aerial, streamflow infiltration, and irrigation return flow sources for PL aquifer. Estimates of groundwater pumping and artesian flows are shown for comparison purposes

an additional 16–18 Mm³/year (~35%). R. Rouyone infiltration and irrigation return flow estimates from 2020–2021 monitoring are 6 Mm³/year and 4.5–5.4 Mm³/year, respectively (Northwater International, unpublished data, 2021). The remaining balance of ~8 Mm³/year is hypothesized to predominately result from mountain-block subsurface inflows (Fig. 12).

Groundwater abstraction in 2018 was estimated to be in the range of 8.1 Mm³/year, which includes 3.1 Mm³/year from pumping wells and 5 Mm³/year from flowing artesian wells along the coast (Northwater International and

Rezodlo 2019a). Historical estimates of abstraction were not available.

Significance of the Massif de la Selle

The Massif de la Selle and its mountain-block carbonate aquifer system is a key component of recharge to the PCS and PL alluvial aquifers. The baseflow regression analysis was performed for the principal river basins that flow into the PCS and PL (Fig. 13). For the PCS, approximately 175 Mm³/year of baseflow is estimated to flow into the plain from R. Grise and R. Blanche. This baseflow indicates a long-term average recharge rate of 23% of annual precipitation in R. Grise basin and 27% in the R. Blanche basin.

For the PL, approximately 45 Mm³/year of baseflow is estimated to flow from the Massif into the plain from the R. Momance. This baseflow indicates a recharge rate of 12% of annual precipitation in the bedrock basin.

The difference in recharge estimates between the two areas can be explained by the geology. The mountain-block in the Grise and Blanche watershed is predominately karst limestone, whereas the Momance watershed has thinner and discontinuous limestone and more prevalent igneous geology.

Baseflow is assumed to primarily emanate from the carbonate portions of the watersheds which comprise 366 km² of the ~600-km² Massif de la Selle carbonate area; a minimum recharge rate for the Massif carbonates is 602 mm/year (0.6 Mm³/km²/year). This equates to 361 Mm³/year of
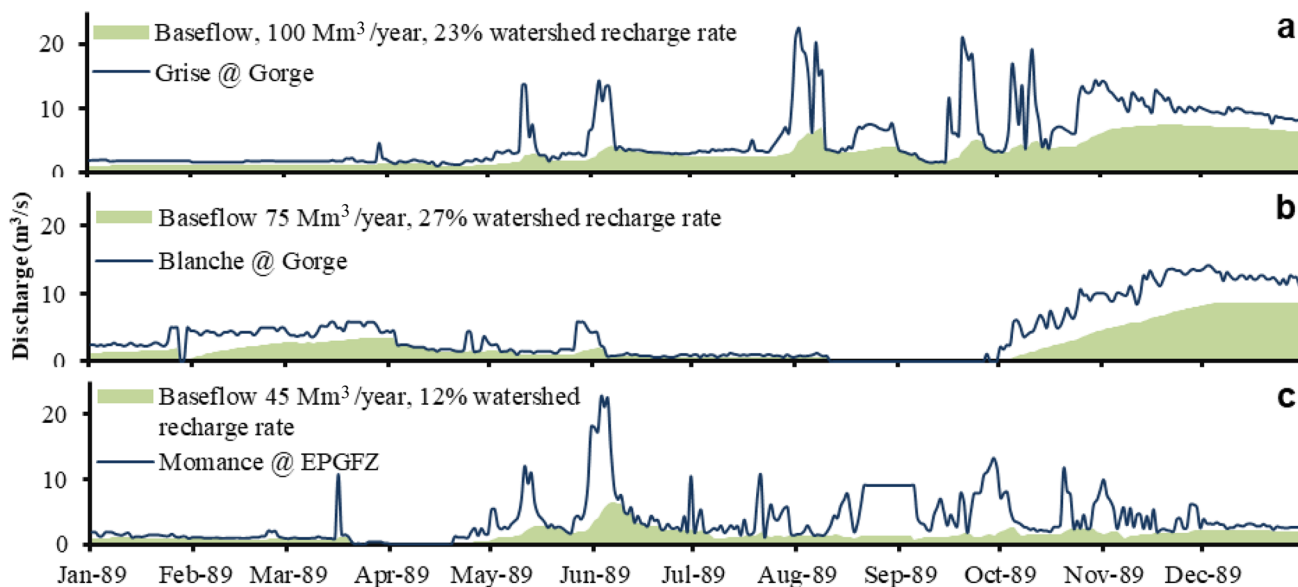

Fig. 13 Baseflow regression analysis of Massif de la Selle rivers at their entry points into the plains for **a** R. Grise, **b** R. Blanche, and **c** R. Momance

recharge, or 989,000 m³/day, which is 2–4 times greater than the estimated recharge to the western PCS and PL aquifers combined. These recharge rates for the Massif aquifer are comparable to those derived by Miner et al. (2022) for the region of the Massif near Carrefour, between the Momance and Grise rivers. There are few large-capacity pumping wells in the Massif de la Selle aquifer system. The municipal well in Turgeau (Port-au-Prince) is the only bedrock well associated with the RMPP water system; however, it was historically a flowing spring that now has to be accessed below the surface with pumping systems. The bedrock aquifer feeds several hundred springs along the northern flank of the Massif, the largest 15 of these springs and two water supply tunnels supplied an average of 29.2 Mm³/year (80,100 m³/day) to the Port-au-Prince water system between 2014 and 2018—CTE-RMPP, unpublished report (water supply production volumes), 2019. The RMPP region is fortunate to have access to this large bedrock aquifer system directly from the springs and indirectly from its flows that infiltrate into the PCS and PL.

Conclusions

The insights derived from this study based on analysis of isotopic, chloride, and stream flow data support the hypothesis that groundwater recharge resulting from river infiltration originating from the mountain-block of Haiti's Massif de la Selle is significant, and a primary source of recharge to the PCS and PL alluvial aquifers. R. Grise and R. Blanche may contribute over 80% of recharge to the PCS aquifer, exhibiting temporal variability correlating to climatic factors such as ENSO cycles. The R. Grise is interpreted to recharge the western portion of the aquifer, while the R. Blanche recharges deeper aquifer layers and the western portion of the aquifer. R. Momance may contribute 51–63% of recharge to the PL aquifer, and recent data suggest that R. Rouyone may also be an important source of recharge.

For both aquifers, the river infiltration is interpreted to occur along braided deltaic floodplains extending ~6 km into the plain from the mountain-block. Direct infiltration from precipitation is limited in both alluvial plains due to lower precipitation, higher ET, and confining layers between shallower superficial groundwater and deeper production zones. Absent of this MBR river infiltration, there would be scarce quantities of renewable freshwater available and saltwater intrusion risks would be of much greater significance than currently in the RMPP.

The Massif de la Selle mountain-block and its carbonate aquifer system not only plays a key role in directly supplying the RMPP with ~65% of its supply from 15 springs and two tunnels, but the aquifer also is a source of recharge for the PCS and PL aquifers. The bedrock aquifer provides

important storage and supplies river flows that ultimately recharge the plain aquifers. The permeable nature of the aquifer enables it to receive high quantities of recharge when water is available during La Niña episodes. Miner et al. (2022) estimated that 2–3 times more bedrock aquifer recharge can occur during these episodes compared to average years, similar to findings in other subtropical karst terrains (Hartmann et al. 2014). This present study brings emphasis and attention to the Massif de la Selle carbonate aquifer system and suggests that recharge to the regional bedrock aquifer system can be on the order of 4-times greater than both alluvial aquifers combined.

Managing the important recharge areas in the plain, as well as the contributing watersheds in the Massif, are important priorities for water planning and management. Aquifer vulnerabilities resulting from increasing aquifer pumping and the potential resurgence of commercial-scale irrigation (river diversions and groundwater pumping) warrant investments to advance research and establish monitoring programs to guide policies and water management. Diversions and other river modifications such as dams and impoundments in the Massif should assess and mitigate potential downstream impacts in the PCS and PL aquifers. River infiltration into the eastern PCS, especially from R. Blanche, are water sources to consider for further investigation. The infiltration of R. Blanche may also be important for Lac Azeui and Trou Caiman, which are identified as significant ecological resources of the Caribbean.

The standard methods for this study are simple and were applied to provide initial ground-truthing to advance insights regarding the significance and scale of streamflow infiltration recharge. The methods have limitations and assumptions due to the data scarcity and the reliance on historical data from broad sources, and limited datasets, often from different time periods. Monitoring and continued research is necessary to support improved portioning of MBR components of the aquifers, and to improve temporal and long-term average streamflow infiltration estimates.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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