



REPORT

Data and insights to advance characterization of groundwater resources in the Plaine des Gonaïves, Haiti

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Abstract

The Plaine des Gonaïves houses a regionally significant yet data-scarce coastal aquifer in one of the driest regions of Haiti. It is the primary source of water for the region, including Haiti's third largest city, Gonaïves. Pressure on groundwater resources will be compounded as municipal water services modernize and energy infrastructure enables the resurgence of commercial agriculture. In anticipation of increased stress and greater impacts, this study was undertaken (including data discovery, reconnaissance, and analysis) to gain insights and to advance understanding of the groundwater resources. The alluvial aquifer covers >115 km², exceeds 100 m thickness, and supports pumping yields as high as 532 m³/h. The heterogeneous multilayer aquifer exhibits hydraulic conductivities that range by an order of magnitude, influencing groundwater flow, residence times, and chemistry. Significant recharge occurs in the central and upgradient portions of the plain; river infiltration appears to be a more significant recharge source than direct infiltration. In the downgradient portion of the plain, confined aquifer pressure increases and discharge areas include the Quinte River, springs, wetlands, ditches and canals. Underlying the alluvium, discontinuous groundwater in bedrock with structural influence may mix with the alluvial aquifer, affecting isotopic composition and water chemistry. Increased abstraction, climate change, and intensification of agriculture and urban development could have consequential impacts on water quantity, water quality and ecosystems. The results, insights, and supporting datasets are a baseline to guide planning and to advance a hydrogeological conceptual model that supports sustainable and informed groundwater management.

Keywords Haiti · Groundwater management · Coastal aquifers · Developing countries · Data scarcity

Introduction

Many Caribbean island nations have limited freshwater resources and water security challenges are increasing due to land use changes, growing populations, climate change, pollution, and natural hazards (Campbell et al. 2010; Falkland 1999). The Caribbean islands have few regionally significant alluvial aquifers. Some of the largest aquifers are found on the island of Hispaniola, comprised of Haiti and the Dominican Republic. The aquifers are important resources that have fostered drought resiliency and shaped settlement

and development before and during colonialization (Gilboa 1980; Woodring et al. 1924). There are five major alluvial aquifers across Haiti: the Plaine du Cul-de-Sac, Plaine de Léogane, Plaine des Cayes, Plaine des Gonaïves, and Plaine du Nord-Massacre (Adamson et al. 2016). Aquifer management and protection in Haiti are inhibited by complex capacity, and socio-economic and political factors. However, data and knowledge scarcity fundamentally impede local and international investments to take informed measures that consider the sustainability of vital resources (Adamson et al. 2016).

The Plaine des Gonaïves (herein often referred to as the plain) has long been considered valuable for agriculture and food security in the semiarid climate and long dry season of NW Haiti (FAO 1969; Tippenhauer 1893; Woodring et al. 1924). Groundwater development opportunities in the late 19th and first half of the twentieth century are documented by Taylor and Lemoine (1949); Tippenhauer (1893), and Woodring et al. (1924). Starting in the late 1950s and

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1960s, groundwater development expanded significantly. The SEDREN mining company drilled domestic and irrigation wells during a period in which a copper mine operated in the region. In the late 1960s, the Food and Agricultural Organization of the United Nations (FAO) funded the drilling of irrigation wells to improve food security and mitigate drought-related emergencies (FAO 1969). In the 1970s and 1980s, the Organisme de Développement de la Plaine des Gonaïves (ODPG) commissioned at least 36 high-capacity irrigation wells and power infrastructure throughout the plain (Mission Technique Allemande, unpublished data, 1983). The plain has continued to evolve into a primary and critical water supply for public, domestic, commercial, and agricultural uses. Most of the high-capacity wells are not currently in operation due to a depressed economy, aging power infrastructure, and other issues. Currently, groundwater abstraction is low, estimated between 5,000 and 10,000 m³/day (J. Pierre, Gonaïves CTE, personal communication, 2018). This abstraction could increase towards 100,000 m³/day with unknown impacts if existing municipal and irrigation wells were recommissioned to historically documented pumping capacities.

Despite the regional significance of the plain in one of the most arid regions of Haiti, hydrogeological and hydrological data are scarce. The rivers and groundwater are ungauged and not monitored, and studies are few, unavailable or lost. Advancing a hydrogeological conceptual model for the plain is critical, as planned rehabilitation and expansion of municipal abstraction and possible resurgence of commercial agriculture could result in significant impacts on the coastal aquifer's water quantity and quality.

The Inter-American Development Bank (IDB) and Haiti's water and sanitation authority (DINEPA) supported a focused investigation to establish a baseline understanding of the groundwater resources of the plain to support planning for municipal water system expansion. The study approach applied an in-depth data discovery effort and a brief field reconnaissance mission, both supported by champions in local government and motivated stakeholders. The study applies historical, unpublished, and newly collected hydrogeological, hydrochemistry, stable isotope, and piezometric data towards this objective. These key data types are important for the advancement of conceptual models, especially in data-scarce regions (Boronina et al. 2005; Bredehoeft 2005; Dieng et al. 2017; Gonfiantini and Simonot 1987; Kresic and Mikszewski 2013; Stuyfzand 1999). In response to the prevalent issue of data scarcity in emerging nations, important outputs are Open Access publication and daylighting of data in a findable, accessible, interoperable and reusable (FAIR), compliant manner making it reliably available for continued application and research to build and strengthen the conceptual model. Without an objective to address data scarcity, this research might simply have served

as yet another batch of data and the gained knowledge could have been at risk of becoming lost, forgotten and as unseen as the aquifer itself.

Study area and setting

The Plaine des Gonaïves is over 115 km² in spatial extent and located entirely within the Gonaïves commune of the Artibonite Department. The plain is situated in a north–south oriented lowland and is approximately 13 km in length and its width extends to 10 km southerly towards the coast where it discharges into the Gonaïves Bay (Fig. 1). The elevation of the northern extent of the aquifer is approximately 130 m above mean sea level (masl). Approximately 20% of the plain extent comprises high-density residential, commercial, and industrial land use. The remaining plain is primarily agricultural and dispersed rural communities. National Route #1 transects the plain, connecting Gonaïves to Port-au-Prince and Cap-Haitien (Fig. 1). The city of Gonaïves is Haiti's third largest city with a population of 261,000 (Lozano-Gracia and Lozano 2017). The city lies along the west and SW margins of the plain, where the bedrock foothills and Morne Bienac support higher elevations protected from periodic catastrophic flooding that inundates the plain during hurricanes and tropical storms. The eastern margin is defined by two bedrock ridges that extend westerly from the Montagnes Noires. The plain is dissected by rivers that drain the surrounding mountains, converge in the plain and flow to the bay.

The population relies on the groundwater resources of the plain as a water supply. The methods of potable water access and delivery include private wells, community wells with hand pumps, commercial wells that supply water trucks, and a municipal water system that intermittently serves the city. Agricultural use of groundwater for irrigation mostly occurs in the dry season, however, abstraction is currently a small fraction of historical levels.

Climate

Based on datasets from 1960 to 1990, the mean annual precipitation across the plain is 544 mm with a mean temperature of 26.1 °C (Fick and Hijmans 2017), which is 6% less precipitation than the historical average of 580 mm/year based on records between 1906 and 1948 (Direction Générale des travaux publics 1918–1938; Taylor and Lemoine 1949). Potential evaporation across the plain ranges from 1850 to 1920 mm/year, with a semiarid aridity index of 0.3–0.39 (Trabucco and Zomer 2019). The rainy season is from May through October, and a long dry season extends from November through April, represented by an average precipitation of only 86 mm (Fig. 2). The plain is on the

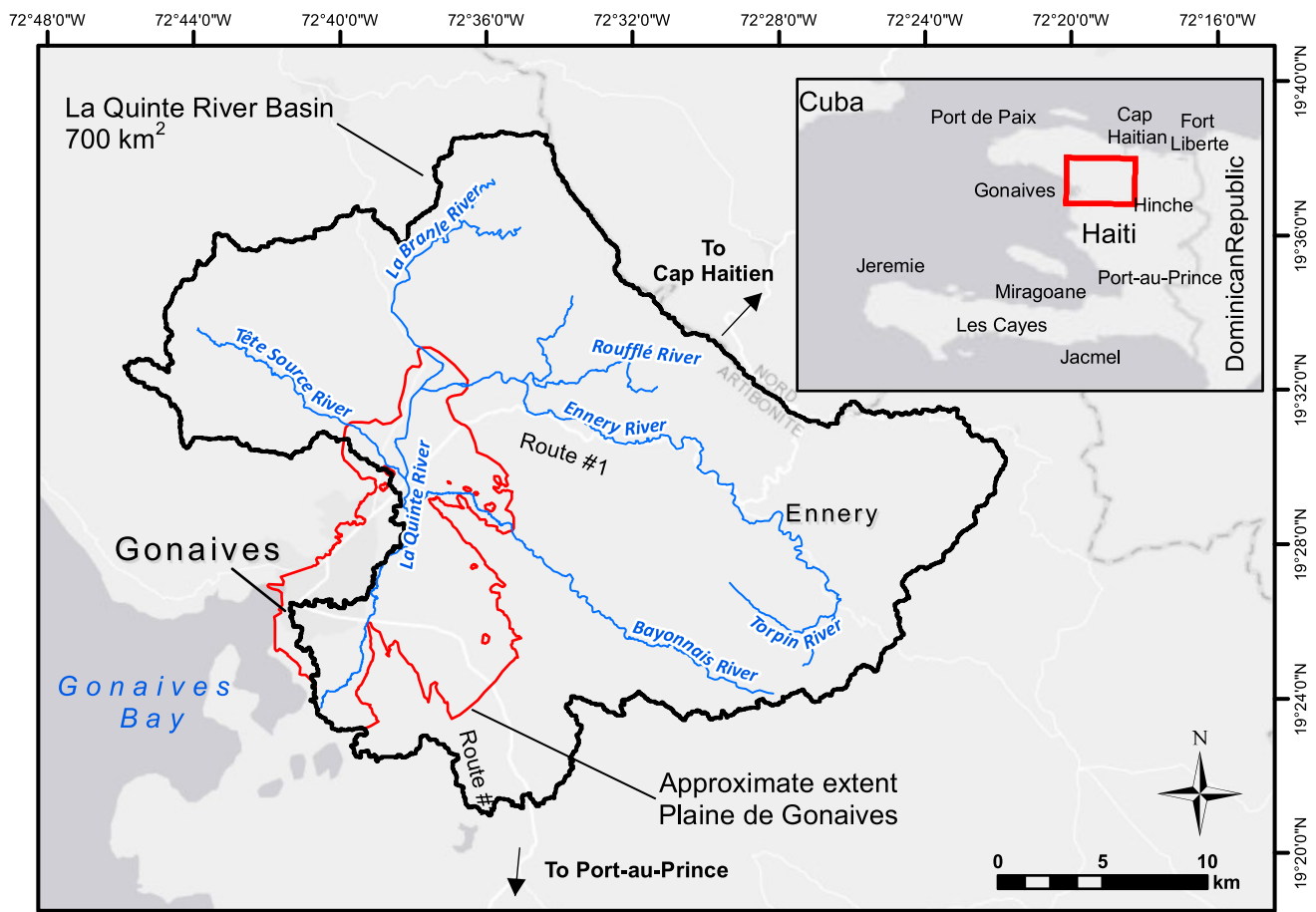


Fig. 1 Study area map showing the setting and extent of the plain, major rivers and the Quinte River basin

leeward side of the Massif du Nord, and rainfall is expelled from the northeasterly trade winds prior to reaching the plain. Coastal-origin storms, tropical storms and hurricanes from the south also contribute to the annual rainfall. The mountainous sub-watersheds within the plain exhibit humid aridity indexes, with significantly lower evapotranspiration and higher precipitation than the rest of the plain. The town of Ennery is located only 30 km northeast of Gonaïves and has 3 times more precipitation on the plain with an average precipitation of 1,450 mm/year and an aridity index of 0.76 (Trabucco and Zomer 2019). The influence of the dry season in Gonaïves on surface water and stream flows makes groundwater a critical resource.

Drainage

The plain is influenced by a drainage area of approximately 700 km²; the Ennery River and Branche River flow into the plain from the northern mountains and converge into the Quinte River. The Quinte River flows through the plain and is joined by the Bayonnais River and Deux-Bassins River prior to flowing into the Gonaïves Bay (Fig. 1; Table 1).

The Quinte River is a significant river system relevant to the plain, and is ephemeral in the upstream reaches extending into the mountains and intermittent to perennial in the lower reaches. The only known period of continuous-flow monitoring of the Quinte River was in 1965 and 1966; average annual flow was reported to be 13 m³/s, and low flow was 0.008 m³/s (Ministry of Environment (MDE), personal communication, 2018). There are several irrigation diversions located along the main channel as it flows through the plain, and a complex and aging system of canals and ditches interweave the plain and support irrigation, drainage of floodwaters, and high water tables. Canal irrigation infrastructure is augmented with many high-capacity irrigation wells; however, most of these wells were idle during the 2018 reconnaissance and had not been in operation for at least several years.

Geology and hydrogeology

A geological map of the study area is presented in Fig. 3. The plain and surrounding mountains result from complex tectonic, volcanic, and stratigraphic processes. The lowland

Fig. 2 Average monthly precipitation for the city of Gonaïves

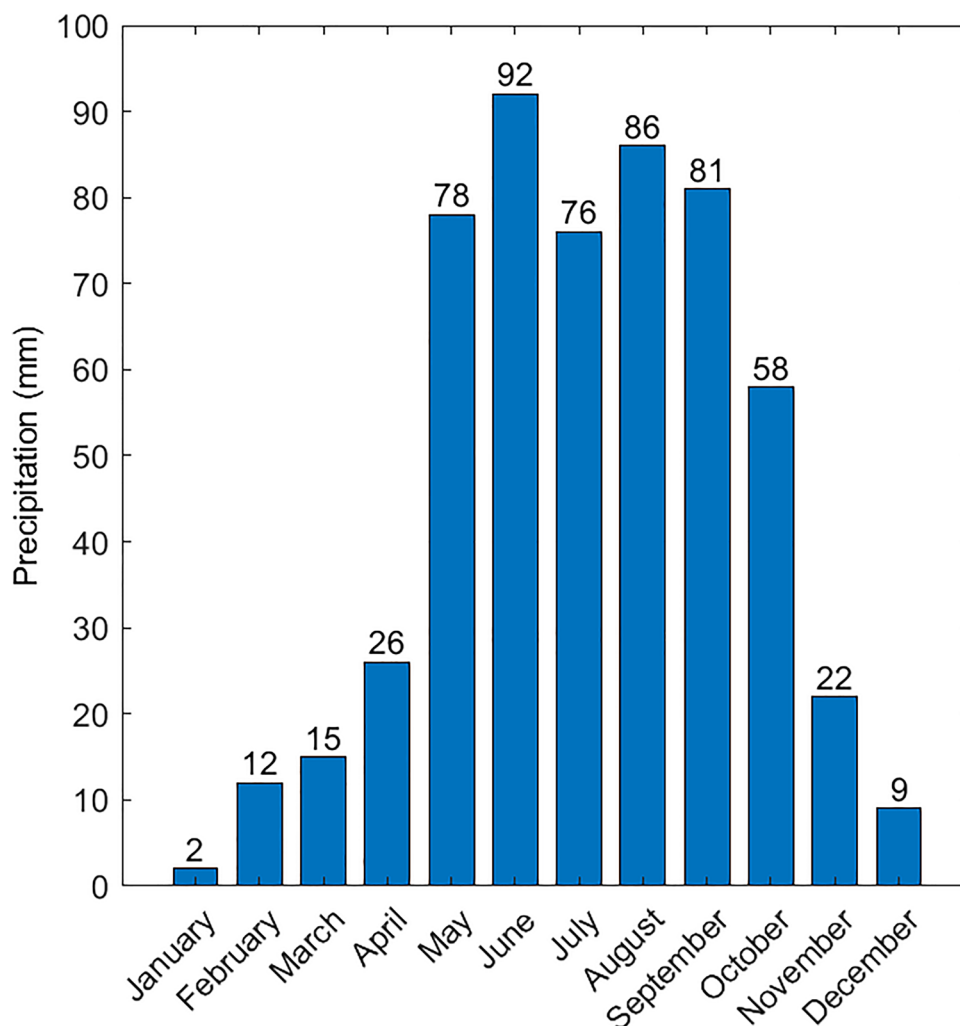


Table 1 Hydrologic basins and drainage areas relative to the Plaine des Gonaïves

Tributary	Approximate drainage area (km ²)
Quinte River ^a	700
Ennery River	240
Branle River	132
Bayonnais River	126
Deux-Bassins River	66

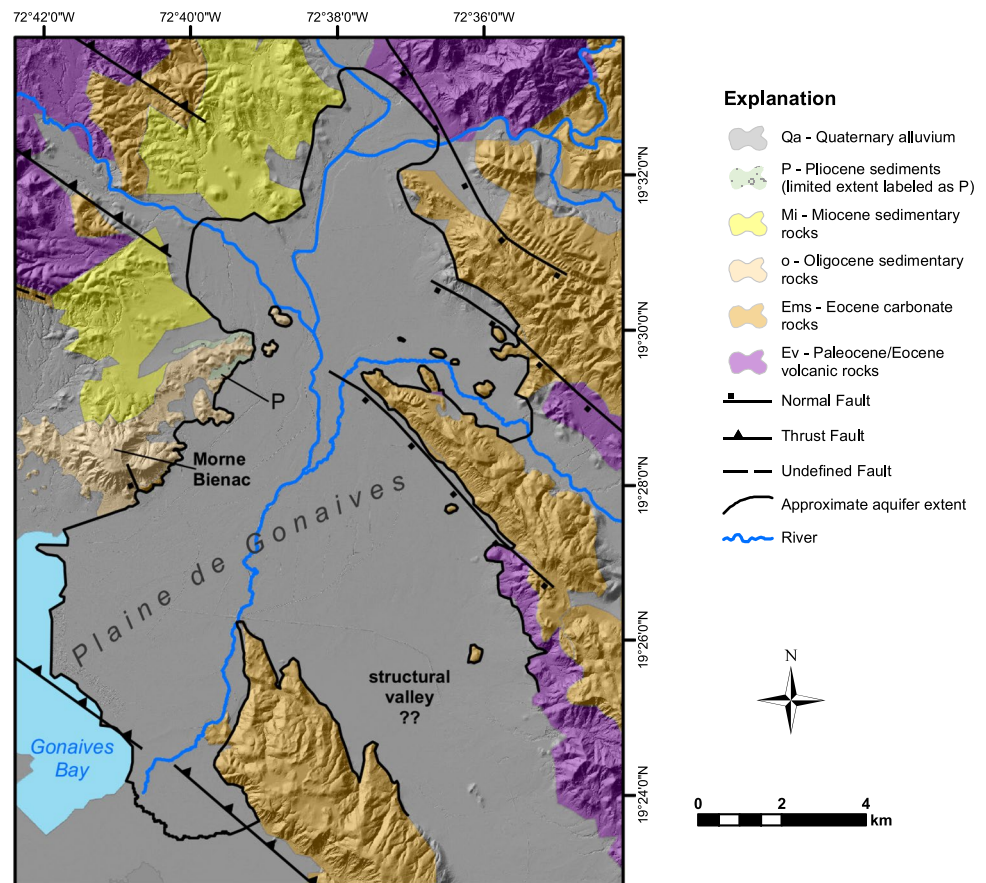
^aLa Quinte River basin includes all rivers (Ennery, Branle, Bayonnais and Deux-Bassins)

is believed to be the result of structural tilting of crustal blocks and associated normal faulting during the post-Miocene time that resulted in a series of grabens and extensional lineaments (Butterlin 1960; Woodring et al. 1924). Throughout the Pleistocene and recent times, the lowlands have accumulated alluvium from an array of depositional

environments, ranging from high-gradient mountain runoff and migrating river courses, extended periods of floodplain inundation from hurricanes and tropical storms, and a transgressing marine delta towards the coast. These processes have resulted in diverse and heterogeneous alluvium throughout the plain, much of which stores and yields regionally significant quantities of groundwater.

The basement rock of the region and mountains that surround and underlie the plain is primarily Cretaceous to early Eocene age volcanic rocks, consisting of andesite, basalt, and volcano-sedimentary agglomerate, tuffs, conglomerates, and breccias. Tertiary rocks of late Eocene and Oligocene age overlie the older volcanic rocks and consist of thin to massive cherty limestone with localized areas of karst. The Oligocene series is characterized as having shallower marine deposition and consisting of detrital limestone, calcareous/marly sandstone, shaly limestone, marl and shale (Taylor and Lemoine 1949). Miocene age semiconsolidated rock is present in some areas and includes marl, marly sandstone, siltstone and claystone.

Fig. 3 Geological map modified from Boisson and Pubellier (1987) showing surficial geology, regional structure, and interpreted aquifer extents. Hillshade derived from 1.5-m resolution LiDAR dataset



The alluvium of Quaternary age consists of gravel, sandy gravel, and sand beds of varying thicknesses that are separated by finer-grained aquitards predominately of clay and sandy clay but also varying composition of silts and fine sands. The alluvium is generally coarser grained and thinner in the northern and higher elevations of the plain, and grades finer and becomes thicker towards the coast.

Methods

An approach was developed that first included persistent research and data discovery to support interpretation and analysis, and to guide a focused data collection campaign in the field. Hydrogeological assessment included the analysis of drilling logs, pump test data, water levels, water quality, and stable isotopes which are presented in this report and in the electronic supplementary material (ESM).

Data discovery

Data discovery was supported through meetings and collaboration with DINEPA, Office régionale de l'eau

potable et de l'assainissement (OREPA), Centre Technique d'Exploitation (CTE)-Gonaïves, Ministry of Environment (MDE), and local drillers. In most cases, hard-copy documents were scanned and then transferred to digital format for analysis and interpretation. A dataset was compiled, consisting of ~90 well records, 40 of which included lithology, and historical pumping data (Haiti Foratech, unpublished data, 2006; Mission Technique Allemande (MTA), unpublished data, 1983; Soheco/Steaci, unpublished data, 2018; SEDREN, unpublished data, 1962). Data from the six municipal wells were compiled from CTE-Gonaïves and the drilling contractors. Many well records lacked coordinates and were spatially located using a combination of methods including interviews, historical maps, location descriptions, satellite imagery analysis, and field verification. Geological and hydrogeological maps with data representing the Gonaïves area were compiled (Boisson and Pubellier 1987; Butterlin 1960; Taylor and Lemoine 1949; Woodring et al. 1924; UNDP 1990) as well as 1.5-m resolution LiDAR data that was flown between 2014 and 2017 as part of the World Bank Disaster Risk Management and Reconstruction project. The basin is currently ungauged and no more river flow data were made available resulting from the data discovery process.

Field campaign

A field mission was performed in October 2018 to make hydrogeological observations throughout the plain, to inventory the wells and water features, and to interview government representatives and other stakeholders. The campaign is representative of the rainy season and included in-situ water quality analysis with a YSI ProPlus meter at 15 wells, three locations along the Quinte River, one spring, and two ditches. In-situ parameters included electrical conductivity (EC), temperature, pH, oxidation-reduction potential (ORP), and dissolved oxygen (DO). A subset of samples from eight wells were collected and analyzed for stable isotopes (δD , $\delta^{18}O$), principal ions (Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} , Na^+ , K^+ , Mg^{2+} and Ca^{2+}) and other inorganic parameters at IsoTech Laboratories (Illinois, USA) and ENCO Laboratories (North Carolina, USA), respectively. Samples were collected from wells after purging with existing pumping infrastructure or manually using 84-mm diameter polyethylene bailers. Samples were collected into laboratory-provided containers with designated preservative after a minimum of three well-casing volumes were purged and turbidity was less than 5 NTU. Mass balance error analysis for ions was performed to validate laboratory results (Freeze and Cherry 1979); no samples were excluded although two wells had a 6% mass balance error.

All six municipal wells were visited during the October 2018 campaign; the sixth municipal well (ID 4) referred to as “ODPG” was recently drilled and commissioned by the drilling company STEACI. The other five municipal wells were out of service with electrical or pump issues and had not been operating for at least 1 year. To avoid confusion, the ODPG well name is based on its location on Route ODPG and is not affiliated with the ODPG organization itself or the irrigation wells.

Flow measurements were made at three stations along the Quinte River and at two ditches by establishing cross-sections across the channels with a tape measure and measuring depth and velocity across the cross-section width with a US Geological Survey (USGS) top-setting wading rod and Marsh McBirney Flowmate 2000 electromagnetic velocity meter. Flow discharges were calculated using the USGS mid-section computation method (Rantz et al. 1982a, b).

Analysis and interpretation

Geological data and maps were refined at 1:50,000 scale to define aquifer limits and surrounding bedrock characteristics based on field observations and the digital terrain model (DTM) derived from 1.5-m resolution LiDAR data. Aquifer thickness and hydrostratigraphy were interpreted based on analysis of the well database and horizontal-to-vertical spectral ratio (HVSr) seismic geophysical data collected in the

area to support geological hazards assessment (Miner and Adamson, Northwater International, unpublished data, 2018).

A sample set of wells with a range of production capacity, well depths, and spatial locations were selected for hydraulic pump-test analysis to understand a range of aquifer properties representative of the aquifer. The wells had multiday constant-rate pumping test data available and specific capacities ranging from 3.9 to 74 $m^3/h/m$. Hydraulic analysis methods applied included Cooper-Jacob (1946) and Hantush-Jacob (1955).

Groundwater level data for the aquifer are scarce spatially and temporally; the intermittent data span various years and seasons dating back to the 1940s. Due to pumping equipment and other limitations, few measurements were possible during the 2018 campaign resulting in insufficient spatial coverage to develop a recent ‘snapshot’ of the potentiometric surface. A concept of groundwater flow was supported using historical measurements and by converting static water depths to elevation based on the geographical location of the well and the land surface elevation derived from the LiDAR dataset. All measurements used for interpolation represent static conditions when wells were first drilled before pumping, or what was interpreted here as nonpumping conditions. Geostatistical kriging and manual methods were applied to plot water-table elevations and present a general groundwater flow map for the plain. In areas absent of wells, contours were extrapolated by the authors, assuming rivers were proximate to the potentiometric surface. The resulting analysis correlates strongly with the few measurements made during the 2018 campaign.

Standard methods were applied to datasets to support analysis, interpretation, and presentation of the results. Well properties such as depth and specific capacity were analyzed and presented statistically. The limited hydrochemistry data were analyzed with statistical and graphical methods to derive interpretations and insights about the aquifer system. Geospatial analysis of mineralization was performed using EC as a proxy, and standard stable isotope data analysis strengthened the understanding of groundwater flow, aquifer heterogeneity, surface-water/groundwater interactions and recharge dynamics.

A chloride mass-balance (CMB) analysis was performed to support the preliminary recharge estimates. The CMB equation is defined in Eq. (1), where R is recharge (mm/year), P is rainfall (mm/year), Cl_p^- is average chloride concentration in rainfall (mg/L), and Cl_{gw}^- is average chloride concentration in groundwater.

$$R = P \times \frac{Cl_p^-}{Cl_{gw}^-} \quad (1)$$

Chloride concentration in groundwater is derived from the eight samples collected in 2018 and a limited dataset

of five rainfall samples collected in Anse-a-Galets and Gonaïves which ranged from 0.8 to 7.06 mg/L (Northwater International, unpublished data, 2018).

includes a compilation of well data compiled from various sources in addition to water quality data from the October 2018 sampling event.

Results

The results of the research and reconnaissance are synthesized in maps, plots, and tables. Two maps are presented to illustrate the topography, alluvial thickness, groundwater flow, and data locations throughout the plain (Figs. 4 and 5). The ESM

Aquifer limits and thickness

The plain alluvium is greater than 115 km² in spatial extent, extending from mountain valleys to sea level at the Gonaïves Bay. In its downgradient extents, the plain diverges south-easterly along a wide structural valley corresponding to where National Route #1 enters the plain (Fig. 3).

Fig. 4 Hillshade map from LiDAR dataset with interpreted depth to bedrock contours and alluvial thickness data points which include boreholes and horizontal-to-vertical spectral ratio (HVSr) geophysical soundings

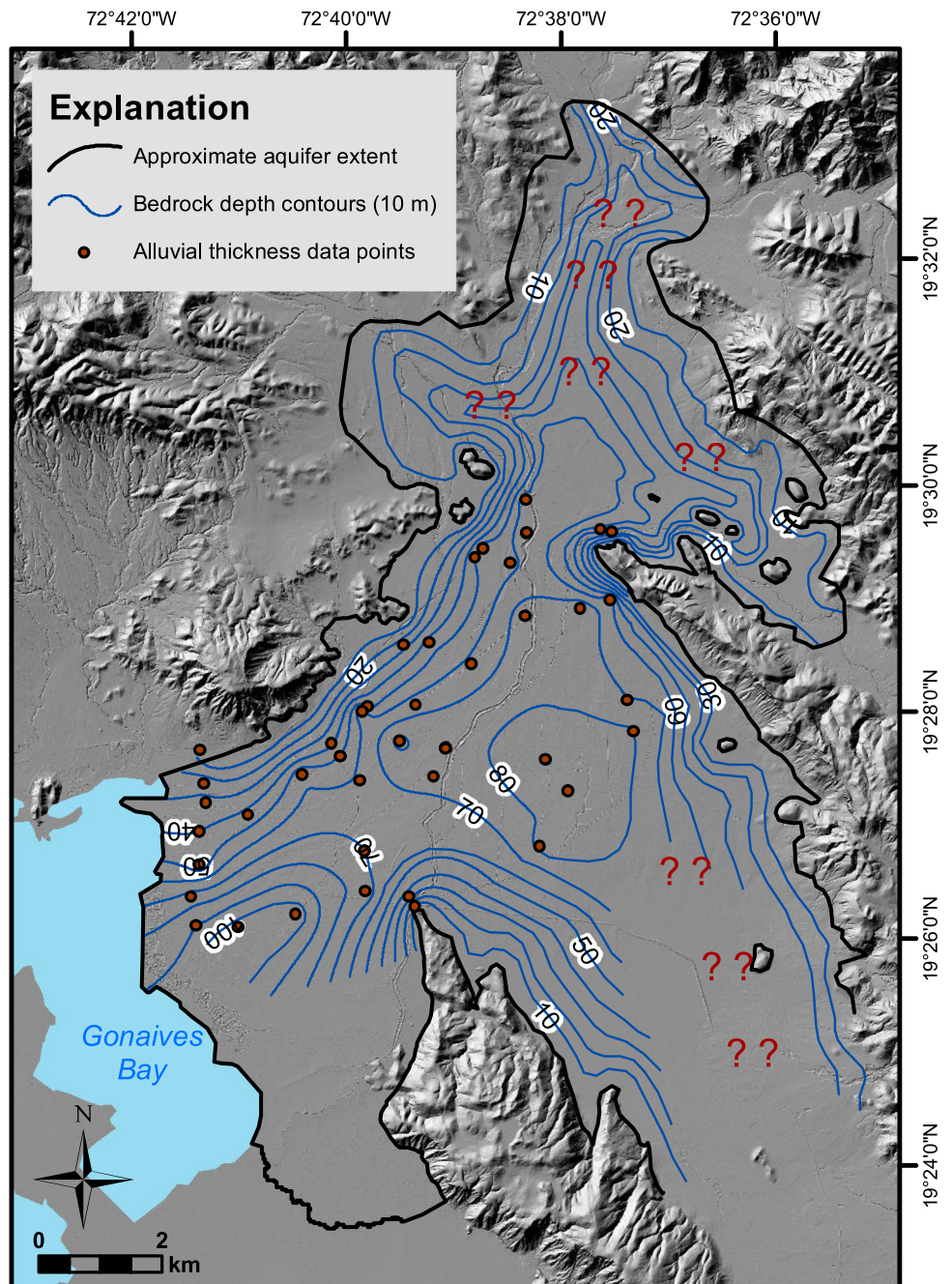
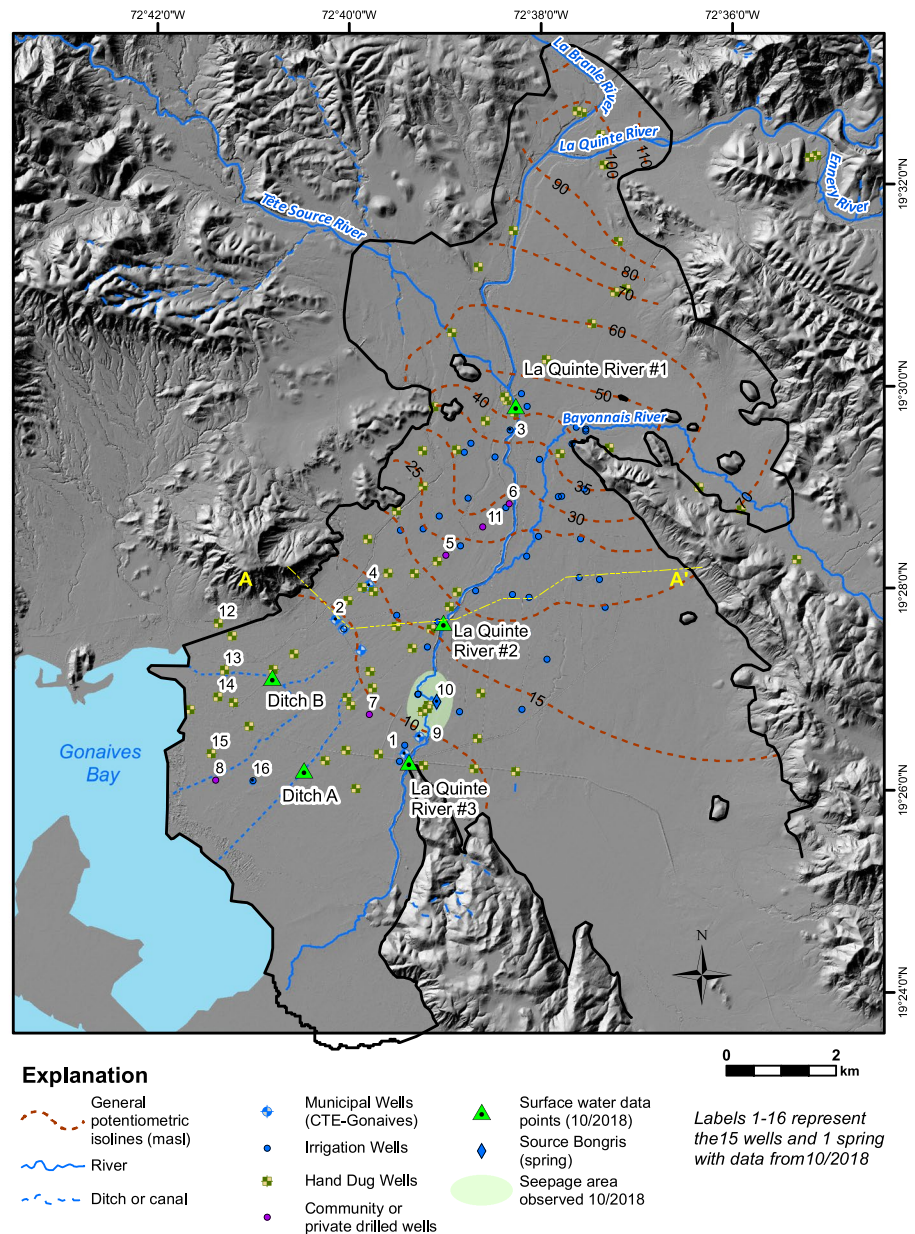


Fig. 5 Hillshade map illustrating groundwater flow, known well locations, and data collection locations from October 2018. The yellow line corresponds to the cross section presented in section ‘Hydrostratigraphy and aquifer properties’



Alluvial thickness was interpreted from 19 drilling logs that intersected bedrock and 15 HVSR seismic stations that interpreted the contact (Fig. 4). Based on these data points and statistical kriging, the thickness of alluvium averages 50–70 m, and exceeds 100 m towards the coast (Fig. 4). There is interpreted variability of alluvial thickness due to the irregular topography of the bedrock valley, influenced by geologic structure and erosional features.

Groundwater flow and surface-water observations

A general interpretation of groundwater flow across the aquifer is presented in Fig. 5 based on analysis of historical

and recent static water level data. Groundwater flow is from the north to south generally following topography, starting with a steeper gradient (0.01) and flattening (0.0036) as the plain widens towards the coast. Drilling-log and water-level data indicate confined conditions throughout the plain, with pressures increasing towards the coast. Flowing artesian wells have been reported in the coastal areas of the plain. A well in Jubilee Blanc (ID 8) was reportedly a flowing artesian well when drilled, producing from confined sand intersected at 36 m depth (Jubilee Kids Inc., personal communication, 2011). Unconfined conditions occur in shallow sand and sandy clay in the coastal areas, and typically have EC values that exceed drinking-water standards. The

upgradient, higher elevation areas of the aquifer may also exhibit unconfined conditions in some localities.

Based on three river-flow measurements along the Quinte River, there was a 15% decrease in flow estimated in the upper to middle portion of the plain, a difference of over 2,000 m³/h (Table 3). In the downstream portion of the plain, the river regained over 3,000 m³/h as dissolved oxygen and ORP decreased (Table 3). In this locality of the aquifer, the Bongris spring, perennial wetlands, and several ditches and canals had flowing water with no turbidity, low dissolved oxygen and EC values ranging from 989 to 1,455 µS/cm. The ditch/canal waters reported the only negative ORP, accompanied with the lowest dissolved oxygen measured (1.0 mg/L) and higher EC (1,455 µS/cm) than most other samples.

Hydrostratigraphy and aquifer properties

Historical drilling records support an understanding of aquifer hydrostratigraphy in the plain as a heterogeneous multilayer aquifer system. Production zones and aquitard layers have abundant pinchouts and discontinuities spatially and at depth. The upgradient stratigraphy has greater permeability, and up to 20-m-thick layers of medium-to-coarse gravel and sandy gravel with cobbles commonly reported up to 400 mm diameter. The production zones are separated by layers of clay, sandy clay, and silty strata that range from less than 0.5 to ~10 m. The water table or potentiometric surface is less than 5 m below ground and within permeable strata, and interpreted as semiconfined and unconfined in some localities. The thickness and number of production zones decreases towards the eastern and western edges of the aquifer, and the central plain where the alluvium is thickest is most productive. The stratigraphy of the central section of the aquifer is illustrated in Fig. 6. The production layers are deeper and thinner, with thicknesses that range from 1 to 16 m, averaging ~9 m. Wells intersect between two and six production zones separated by aquitard layers of clay,

sandy clay, sandy silt, clayey silt and silty sand. The production zones are described as well sorted, fine or medium to coarse gravels with fine-to-coarse sand; cobbles are commonly reported as 300 mm and up to 400 mm. The aquifer is confined in this portion of the aquifer, as the depth to first production zones can be upwards of 20 m below aquitard units and the potentiometric surface is typically less than 3 m below ground (Fig. 6). There are limited lithology logs in the downgradient aquifer towards the coast; the production zones are typically deeper (up to 40 m) and sandier with less gravel and cobbles. The aquitard layers are described as sandy clay and clays. Shallow layers of sand, producing brackish groundwater, are documented near the coast. Fresher groundwater is often found after drilling through a sandy clay or clay aquitard to the deeper production zones, and this water can be flowing artesian. The aquifer in the downgradient/coastal section is considered confined, as production zones are under notable pressure and the potentiometric surface is near or even above land surface.

Summary statistics based on analysis of drilling logs and pump test data are presented in Fig. 7. Borehole depths range from 60 to 152 m with water levels ranging from near land surface to 17 m (Fig. 7). Production occurs from multiple beds of medium-to-coarse sand and gravel up to 20-m thick. Production zones are separated by aquitard layers of clay and clay with sands, and several deeper wells also penetrate underlying bedrock (Fig. 6). The bulk thickness of the production zones averaged 48 m, ranging from 12.5 to 70 m. Towards the coast, gravel becomes less prevalent and beds are thinner and exhibit greater discontinuity (Fig. 6). Yields documented from pumping ranged between 66 and 532 m³/h and averaged 238 m³/h (Fig. 7; Table S1 of the ESM). Based on 72-h pumping tests, the specific capacities of wells average 14 m³/h/m and range between 3.9 and 74 m³/h/m (Fig. 7; Table S1 of the ESM).

Hydraulic conductivity averaged 60 m/day, ranging from 1.1 to over 137 m/day (Table 2). Transmissivity averaged >2,000 m²/day, ranging from 63 to 9,122 m²/day, and storativity ranged from 1.3 × 10⁻³ to 1.8 × 10⁻⁸ (Table 2).

Table 3 Flow and water quality data from surface water on 11 October 2018

Study ID/name	Type	Latitude (dd)	Longitude (dd)	Flow (m ³ /h)	Temp (C)	EC (µS/cm)	pH	ORP (mV)	DO (mg/L)
Quinte #1	River (upstream)	19.49763	-72.6387	16,095	27.7	403	8.04	127	6.65
Quinte #2	River (middle)	19.46204	-72.6517	13,268	27.1	478	8.07	122	7.92
Quinte #3	River (downstream)	19.43911	-72.6581	16,798	30.8	512	8.06	96.1	5.57
10 /Source Bongris	Spring	19.4490	-72.6531	35 ^a	28.8	989	6.83	79.8	1.13
Ditch A	Ditch/canal	19.45338	-72.6816	200	–	–	–	–	–
Ditch B	Ditch/canal	19.43808	-72.6763	655	28.6	1,455	7.48	-23.3	1.0

^aFlow was estimated not directly measured; – data not collected

Flow measurements and sampling followed a rainy period and data are not representative of baseflow conditions. Diversions taking less than 500 m³/h were present along the Quinte River between stations 1 and 2, and between stations 2 and 3. The Quinte River was turbid at all three sampling locations. The water was clear (<5 NTU) at Bongris spring and both ditch locations

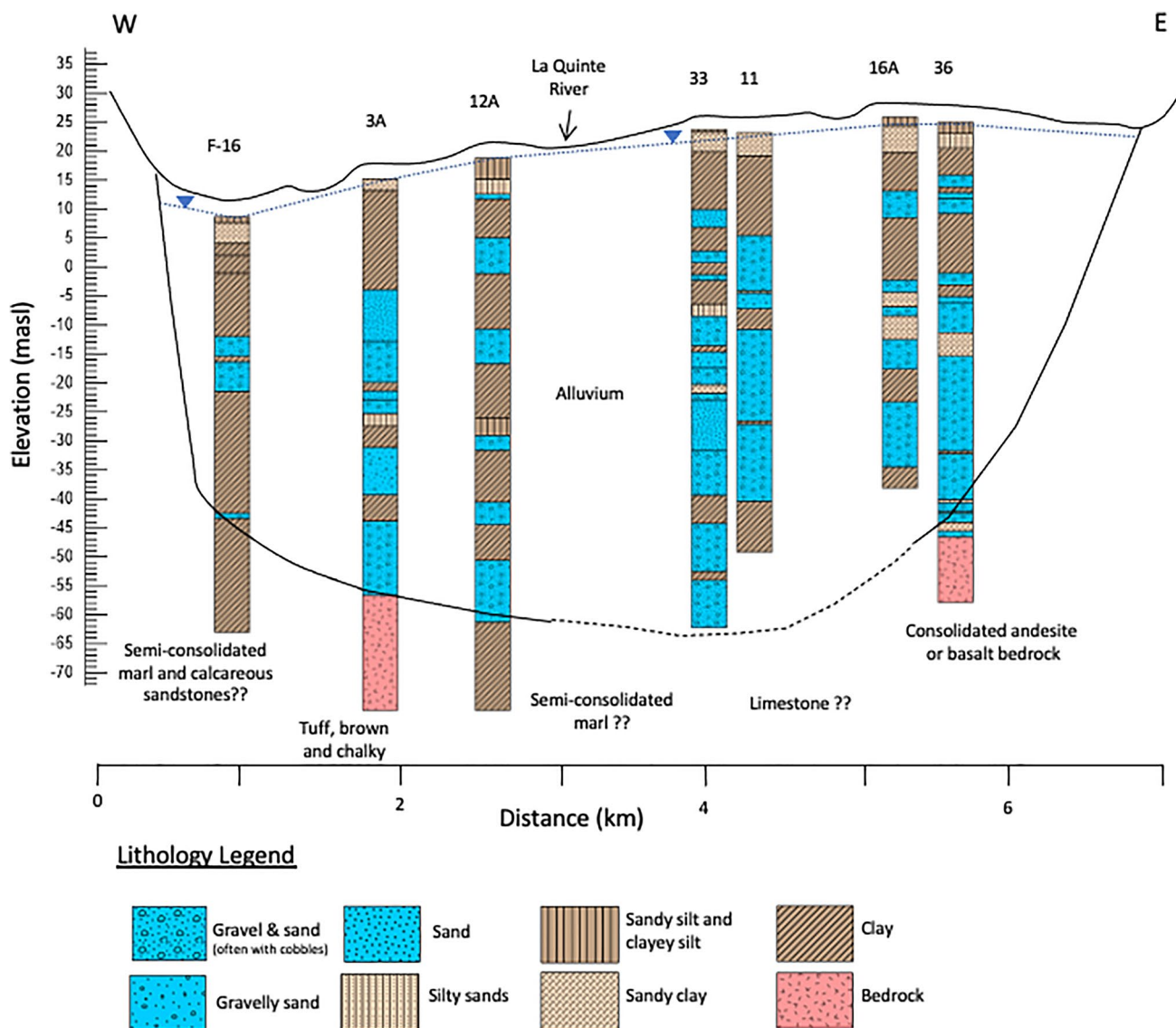


Fig. 6 Generalized cross section of the aquifer and hydrostratigraphy based on select lithology logs; section location is shown on Fig. 5 (vertical exaggeration is 40x). Table S1 in the ESM includes coordinates and other details regarding the wells presented

Hydrochemistry and water quality

Table 4 includes the field water quality results from 15 wells and one spring (ID 1–16). Groundwater showed a variability in EC ranging from 565 to 3,125 $\mu\text{S}/\text{cm}$, the range indicating various stages of mineralization and perhaps one result with seawater influence. Dissolved oxygen ranged from 1.1 to 5.1 mg/L; the higher result was likely affected by the high pressure experienced at the spigot when the sample was collected. ORP values of all well and spring samples were positive, ranging from 50.5 to 155 mV; however, the ditches had negative ORP. pH ranged from 6.82 to 8.81; interestingly, the highest pH is upgradient in the aquifer at a higher elevation (ID 3) and is similar to the Quinte River waters.

Groundwater temperatures ranged from 28 to 30.9 °C and correlated to elevation.

A subset of eight wells with hydrochemistry data indicate that most groundwater is Ca-HCO_3 and HCO_3 water types (Table 5; Fig. 8). One well (ID 8) was Na-HCO_3 water type (EC = 824 $\mu\text{S}/\text{cm}$) and is in close proximity to the coast. One hand-dug well (ID 12) with higher EC (3,125 $\mu\text{S}/\text{cm}$) is located along or perhaps outside the aquifer boundary and may indicate seawater influence in shallow unconfined sediments or perhaps bedrock units not diluted by alluvial waters. Hydrochemistry is spatially variable, more so in the downstream portion of the aquifer influenced by production zones at varying depths. Lower EC values are found in wells closer to the river, appearing more prevalent in the

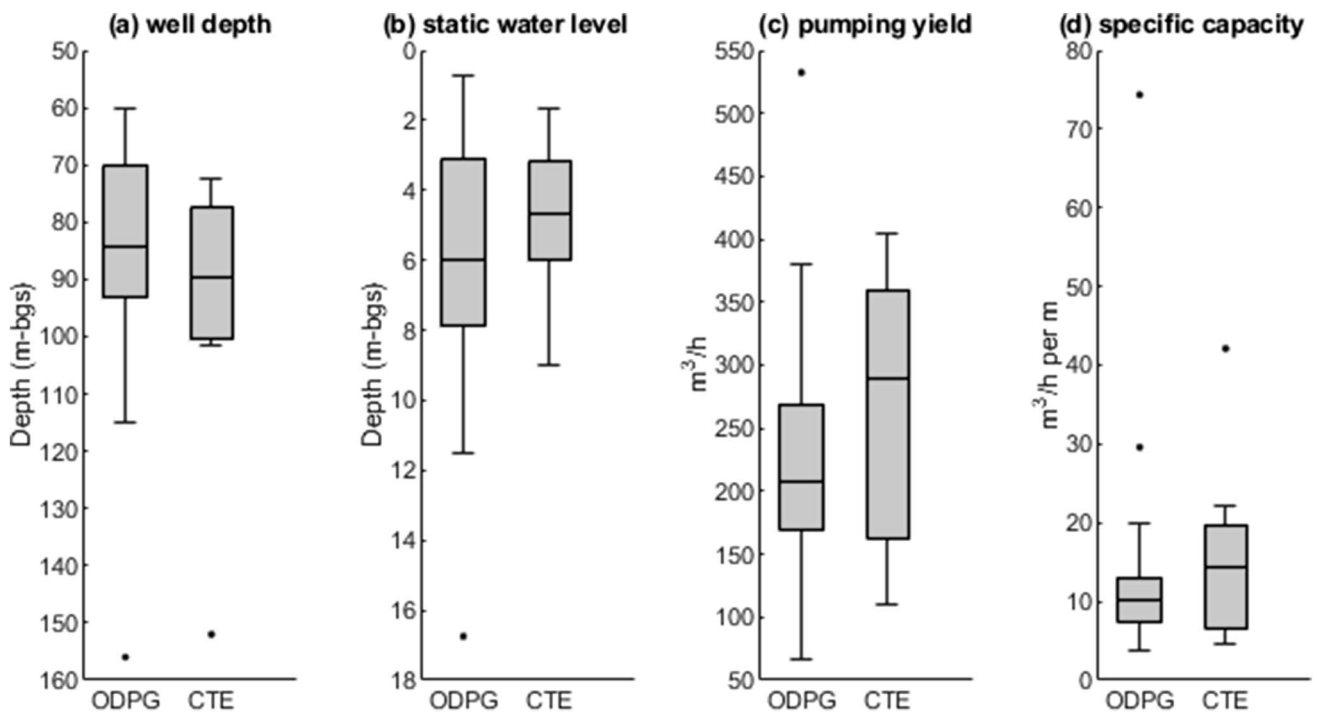


Fig. 7 a–d Box plots illustrating well properties for irrigation (ODPG) and municipal wells (CTE)

Table 2 Aquifer hydraulic properties based on analysis of select wells in the Plaine des Gonaïves

Study ID/well name	Specific capacity (m ³ /h/m)	Transmissivity (m ² /day)	Hydraulic conductivity (m/day)	Storativity
F16	12.7	1,138	114	–
PG2	17	1,366	26	1.3E-03
4A	42	9,122	137	–
19	3.9	63	1.1	2.1E-05
3A	74	6,991	106	7.7E-06
1A	9.4	671	13	2.3E-05
4/ODPG ^a	7.7	1,010	20	1.8E-08

^aAnalysis performed by STEACI, unpublished data, 2018

upgradient portions of the plain. Concentrations of agricultural and anthropogenic indicators such as nitrate, nitrite, total organic carbon, and other inorganic parameters were generally low. Nitrate (NO₃-N) values ranged from undetected to 4.35 mg/L, and averaged 2.73 mg/L (Table S2 of the ESM).

Multivariate analysis of groundwater chemistry indicates that most water exhibits higher Ca²⁺ coupled with lower Mg²⁺ and SO₄²⁻ (Fig. 9). This water is interpreted as mixed plain groundwater and is the predominant water type. Na²⁺ and K⁺ are the major ions that increase in an expected manner towards the coast. Well ID 8 near the coast has a strong correlation with upgradient groundwater, however, with a stronger K⁺ and Na²⁺ fingerprint than the rest of the aquifer. There are likely more clay minerals, evaporate and marine-origin sediment in the near-coast alluvium that alters the hydrochemistry of the aquifer as it gains residence time

in those sediments. Three wells in the central portion of the aquifer exhibit higher proportions of Cl⁻, Mg²⁺ and SO₄²⁻ (ID 2, 4, 7), which may indicate upwelling and mixing from underlying bedrock. Two of these wells (ID 2, 4) are proximate to the aquifer boundary and may intersect the bedrock and one (ID 7) is located centrally in the aquifer. Coincidentally, these wells are aligned with the NW–SE oriented boundary between the structural valley/depressional sink and bedrock ridge of Eocene carbonate bedrock. Well ID 3 is an isotopic outlier, exhibiting low mineralization, and is explained by its upgradient location, higher elevation, and proximity to the Quinte River.

Stable isotopes

With the absence of local precipitation data, a local meteoric water line (LMWL) relevant to Haiti of $\delta^2\text{H} = 7.47$

Table 4 In-situ field water quality data from wells (October 2018)

Study ID	Other ID	Type	Date (d/m/yyyy)	Lat (dd)	Long (dd)	Elev (m)	pH	Temp (°C)	Conductivity (µS/cm)	ORP (mV)	DO (mg/L)
1	PG1	Well	8/10/2018	19.4405	-72.6588	11.2	6.92	29.4	878	79.4	2.07
2	SP2bis	Well	8/10/2018	19.4628	-72.6705	11.3	7.65	28.7	1,071	112.1	4.1
3	IRR-1	Well	8/10/2018	19.4937	-72.6397	44.7	8.18	28	565	80.8	3.55
4	ODPG	Well	8/10/2018	19.4684	-72.6646	15.8	7.16	28.1	890	134	5.1
5	Kayon	Well	8/10/2018	19.4731	-72.6512	26	7.07	29.3	909	113	3.42
6	Haut Kayon	Well	8/10/2018	19.4815	-72.6401	34.8	7.06	29	877	106	4.2
7	Odivin	Well	10/10/2018	19.4470	-72.6649	10	7.1	29.9	1,148	114.1	1.89
8	Jubilee well	Well	10/10/2018	19.4366	-72.6918	1.1	7.61	30.9	824	91.7	2.5
9	PG2	Well	8/10/2018	19.4433	-72.6562	12.2	6.92	29.4	950	79.4	2.07
10	Sous Bongris	Spring	8/10/2018	19.4490	-72.6531	12.9	6.83	28.8	989	79.8	1.13
11	Soufra Feno Fausten	Well	8/10/2018	19.4778	-72.6447	29.9	7.1	28.7	863	50.5	2.5
12	Hand-dug well at home	Well	10/10/2018	19.4625	-72.6909	3.7	6.82	28.9	3,125	133	2.33
13	Hand-dug well at store	Well	10/10/2018	19.4547	-72.6900	2.1	7.12	29.5	1,401	155	2.54
14	Hand-dug well at home	Well	10/10/2018	19.4503	-72.6912	1.6	7.36	29	841	122	3.1
15	Hand-dug well at home	Well	10/10/2018	19.4410	-72.6924	1.2	7.74	30.7	1,450	80.5	1.1
16	Drilled well with handpump	Well	10/10/2018	19.4364	-72.6853	1.9	7.04	29.6	1,094	113	1.65

Table 5 Principal ions and stable isotope data from eight wells (October 2018)

Study ID	Other well ID	Lat (dd)	Long (dd)	Elev (m)	Hydro Facies	HCO ₃ ⁻ mg/L	Cl ⁻ mg/L	SO ₄ ⁻ mg/L	Ca ⁺ mg/L	Mg ⁺ mg/L	K ⁺ mg/L	Na ⁺ mg/L	TDS mg/L	δH ₂ O ‰	δ ¹⁸ O ‰
3	IRR-1	19.4937	-72.6397	45	HCO ₃ ⁻	180	27	36	45	8.4	3.6	44	210	-7.4	-2.16
5	Kayon	19.4731	-72.6512	26	Ca ⁺ /HCO ₃ ⁻	330	48	46	95	16	2.9	55	500	-13.9	-2.94
7	Odivin	19.4470	-72.6649	10	Ca ⁺ /HCO ₃ ⁻	430	72	62	102	27	2.8	72	652	-13.2	-2.85
6	Haut Kayon	19.4815	-72.6401	35	Ca ⁺ /HCO ₃ ⁻	330	36	37	88	13	2.5	62	494	-14.4	-2.99
2	SP2bis	19.4628	-72.6705	11	HCO ₃ ⁻	330	78	73	76	26	3.5	74	568	-12.9	-2.56
4	ODPG	19.4684	-72.6646	16	Ca ⁺ /HCO ₃ ⁻	380	78	72	103	26	3	71	628	-14.7	-3.08
1	PG1	19.4405	-72.6588	11	Ca ⁺ /HCO ₃ ⁻	330	45	47	94	20	2.5	54	512	-13.9	-2.93
8	Jubilee	19.4366	-72.6918	1	Na ⁺ /HCO ₃ ⁻	330	36	30	36	19	16	78	452	-15.0	-3.22

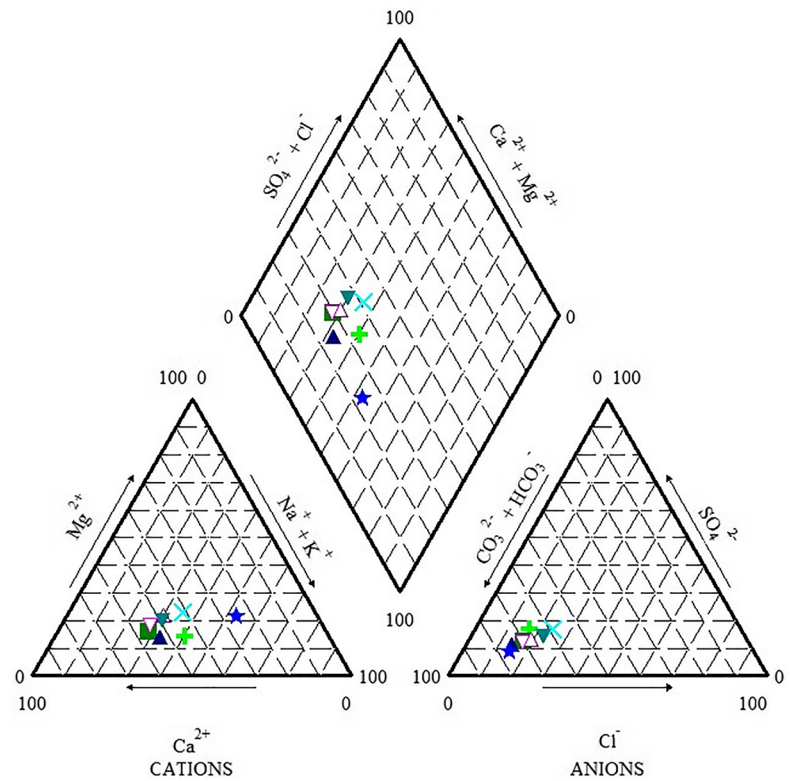
δ¹⁸O + 10.05 was derived from spring flows with low-EC waters and considered for analysis, and plotted in Fig. 10 (Gourcy et al. 2022, this issue). δ¹⁸O values in groundwater from the eight wells ranged from -2.16 to -3.22‰ and δH₂O ranged from -7.4 to 15‰ (Fig. 10; Table 5). Samples plot in a relatively narrow range, and most fall below the meteoric water lines, indicating evaporative influences and perhaps recharge origins from stream infiltration and flooding events. Surface-water infiltration and mixing is further supported by the relationship of mineralization (chloride and EC) and δ¹⁸O (Fig. 10b) where a consistent δ¹⁸O signature is exhibited in waters of varying mineralization. In the central portion of the aquifer, a municipal well (ID 2) and well ID 7 anomalously plot farther from the LMWL, also exhibiting more depleted δ¹⁸O signatures than other samples. Interestingly, a municipal well (ID 4) less than 1 km from well ID 2 plotted closer to the LMWL and was less depleted, despite

having similar hydrochemistry and chloride concentration as the latter (Fig. 10). These results suggest other water origins with greater evaporation exposure and perhaps originating from higher elevations. Lastly, well ID 3 has a heavier, more enriched isotopic signature versus the other samples. Consequently, it is also the most upgradient sample (45 masl), has the lowest EC of the sample set, and is in close proximity to the Quinte River. The isotopic composition, especially in recharge areas, may vary seasonally as the precipitation events originate from coastal, more enriched rain to depleted rains from inland origins.

The isotope and hydrochemistry trends point to the evolution of more recently recharged waters to relatively older waters. Two wells (IDs 4 and 8) have more depleted waters and are interpreted as older, with more distal recharge origin. Well ID 8 is very near the coast and does not show isotopic evidence of seawater influence. Well IDs 2, 4, and 7 in the

Fig. 8 Piper diagram illustrating major ions and Ca–HCO₃ and HCO₃ geochemistry of groundwater (October 2018)

- EXPLANATION
- ▽ IRR-1
 - × Kayon
 - + Odvin Hotel
 - ▼ Haut Kayon
 - SP2bis
 - ▲ ODPG
 - △ PG1
 - ★ Jubilee Well



central portion of the aquifer appear to have influences perhaps from the structural valley and carbonate bedrock ridge to the SE. Analysis and interpretation were limited due to the lack of local precipitation and surface-water data. Temporal data between dry and rainy seasons with more spatial coverage is necessary to strengthen isotopic interpretations.

Discussion

Current conceptual model

A conceptual schematic of the plain hydrogeology is presented in Fig. 11. Two aquifer systems are interpreted: (1) the alluvial aquifer, and (2) a discontinuous bedrock aquifer beneath part of the plain.

The plain is underlain with unconsolidated alluvial sediments housing production zones with higher permeability than most of the underlying bedrock of Tertiary to Cretaceous age, where the base of the aquifer is generally considered. Drilling log analysis suggests the presence of discontinuous groundwater in the underlying bedrock in some localities, typically where consolidated sedimentary rocks are documented. Other less permeable bedrock geology under the plain includes volcanic, volcano-sedimentary, and semiconsolidated marl strata which are not interpreted to store and yield significant groundwater. Several irrigation wells yield groundwater from both alluvium and bedrock,

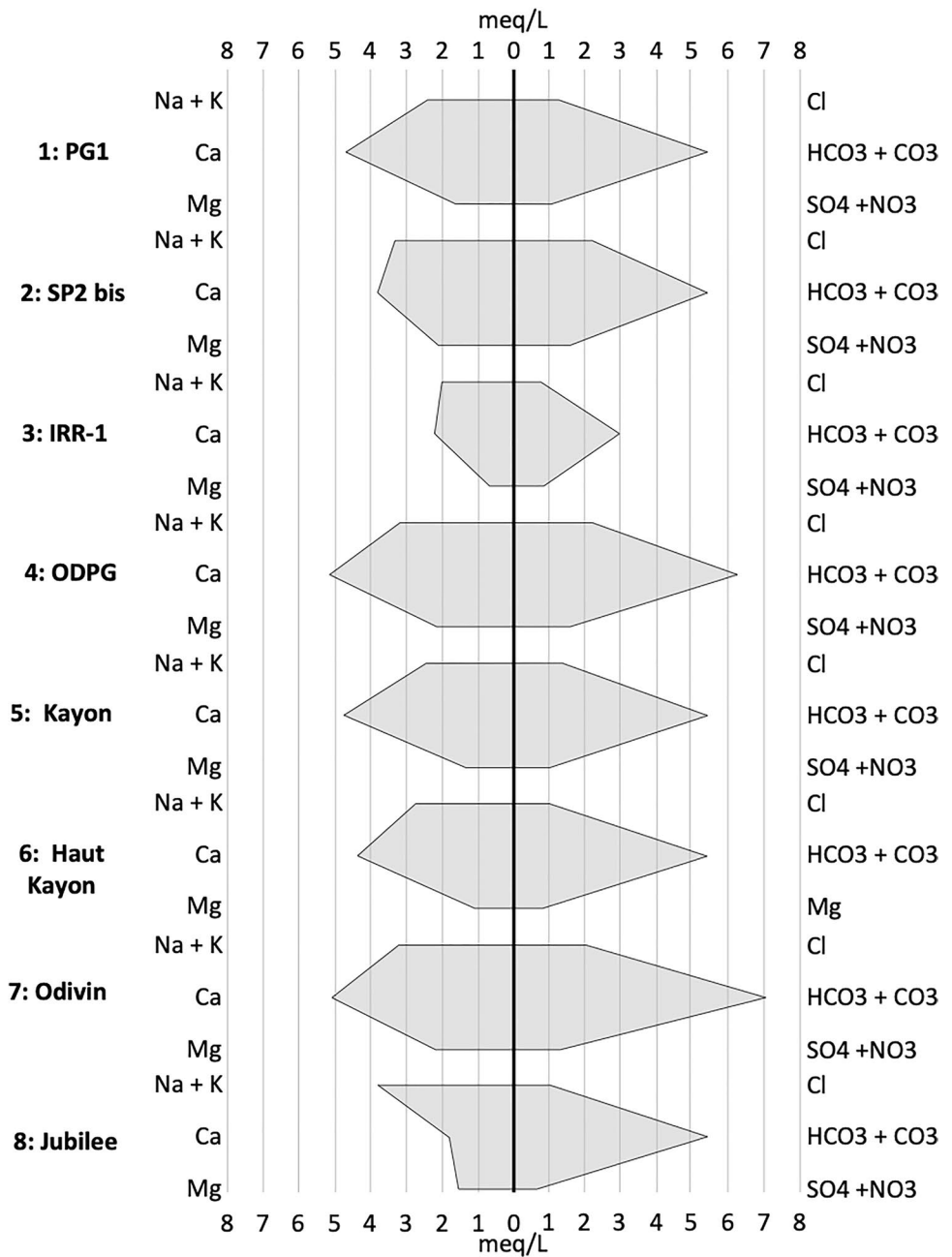
and such boreholes may enhance flow and connectivity between them. The bedrock and potential interconnection with the alluvium may influence renewable quantities of groundwater available throughout the plain.

Alluvial aquifer

The alluvial aquifer is stratigraphically heterogeneous and considered a multilayer system. The discontinuity of aquifer and aquitard strata with abundant pinchouts explain both the significant variability of aquifer hydraulic properties and pumping yields, and the generally well-mixed hydrochemistry. Recent drilling of the new municipal well (ID 4/ODPG) in 2018 was a disappointment for the city of Gonaïves, resulting in one of the lower yielding production wells in the plain. The findings of this study suggest that aquifer thickness and permeability were limited due to the proximity to the aquifer boundary. Few areas of the plain are absent of strata with hydraulic properties capable of supporting an aquifer system (Fetter 2001). Localized areas of unproductive permeability are possible towards the coast and where aquifer thickness tapers towards its boundaries. The subsurface characteristics of the structural valley extending south are unknown and may exhibit favorable permeability and thickness especially if the valley supported the drainage area of the Quinte River in the geological past.

With some exceptions, hydrochemistry and EC indicate a mixed and consistent signature defining most

Fig. 9 Stiff diagram illustrating variability ion chemistry of groundwater (October 2018)



groundwater in the alluvial plain. The waters are influenced by weathering, ion exchange in evaporative and low-permeability sediments, and mixing with other waters such as bedrock groundwater, seawater, surface water, floodwaters and rainwater. Groundwater age and mineralization generally increase towards the coast, with distance from the river and at greater depths in the aquifer. The range in EC across the aquifer results from dilution from rainwater and surface water and variability in water residence times influenced by aquifer heterogeneity. Waters interpreted as younger are found in shallower wells farther upgradient in the aquifer and closer to the

river systems. Drilling logs indicate semiconfined and confined conditions, with increased pressure occurring in aquifer layers towards the coast, where flowing artesian wells are documented. Shallow zones and upgradient areas at higher elevations can have localized unconfined conditions favorable for recharge, but more vulnerable to contamination. The shallow unconfined groundwater within the sands and sandy clay in coastal areas is commonly brackish, likely due to a combination of factors that may include residence times, high evapotranspiration, and seawater mixing. In these areas, fresher groundwater is present within deeper confined layers.

Fig. 10 Plot illustrating **a** stable isotopes $\delta^2\text{H}$ and $\delta^{18}\text{O}$, and **b** chloride and $\delta^{18}\text{O}$ for eight wells sampled in October 2018. The local meteoric water line (LMWL) is derived from Gourcy et al. 2022

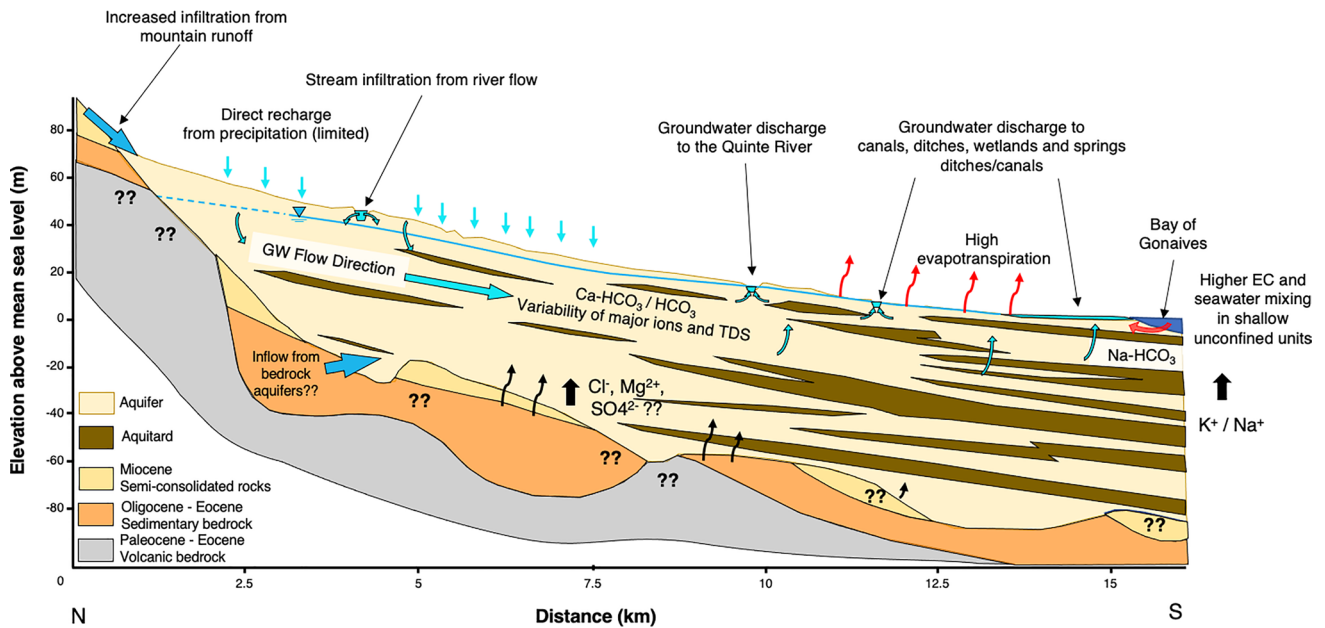
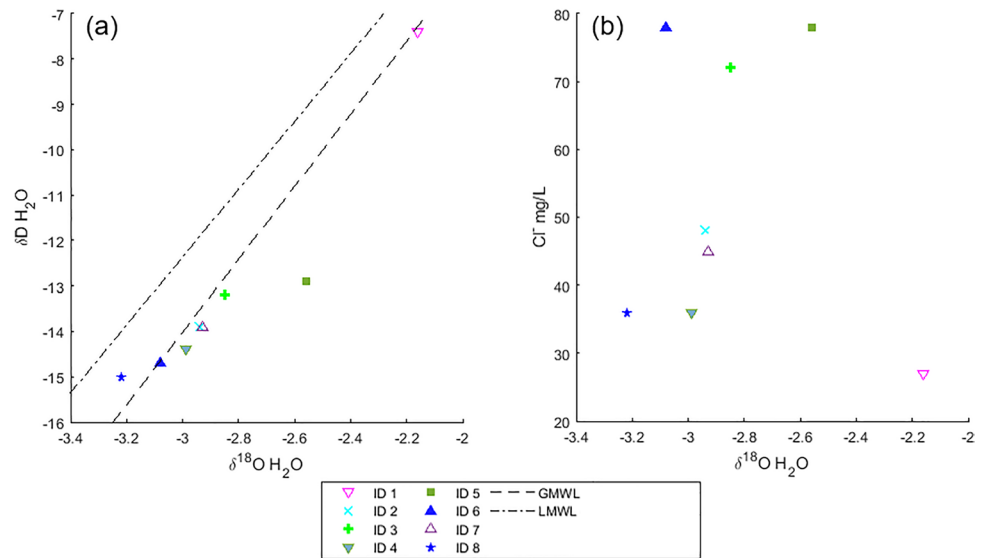


Fig. 11 Conceptual hydrogeological diagram of the Plaine des Gonaïves

Groundwater flow and surface-water/groundwater interactions

The alluvial aquifer flows towards the coast and a strong connection is interpreted between the aquifer and the river systems (Fig. 11). In the middle and upgradient portions of the aquifer, river-bed elevations are higher than the potentiometric surface and groundwater radiates from the rivers

due to river infiltration. River infiltration is evidenced by groundwater isotopes, indicating evaporative exposure prior to recharge. Hydrochemistry, field water quality, drilling logs, river flow measurements, and water level analysis corroborate this process and highlight this potentially significant source of groundwater recharge. Groundwater samples from some wells showed evidence of dilution in proximity to a river, further indicating direct infiltration from rivers. The

most significant dilution occurred at the furthest upgradient and highest elevation well sampled (ID 3); the water also had the most enriched isotopic signature. Coastal-origin storms produce enriched precipitation and may explain this outlier. A more depleted isotopic signature is expected from inland-origin precipitation events and in the drier season when river hydrology is supported by flows originating from the inland mountains.

The anomalous isotope and hydrochemistry signatures at wells in the central part of the aquifer may indicate an area with more prevalent mixing with other waters. This area coincidentally aligns perpendicularly to the south with the NW–SE oriented boundary between the ridge of Eocene carbonate bedrock and the structural valley. A depressional sink in this valley of ~8 km² in extent becomes inundated for long durations after floods as there is no topographic outlet. Inundated floodwaters of higher-elevation origin and increased ET exposure may locally recharge the fractured carbonate bedrock and/or alluvium in this area. Groundwater flow from this potential recharge area northward would likely intersect with the central portion of the plain.

Moving downgradient and at lower elevations towards the coast, the aquifer discharges to surface-water systems starting at elevations between 10 and 15 masl. In this zone, discharge occurs to the Quinte River, springs, perennial wetlands, and a series of ditches and canals. As observed in October 2018, flow increased in the lower section of the Quinte River, which was complemented with indicators of groundwater discharge that included decreases in turbidity, dissolved oxygen, and

ORP compared to upstream data. The Bongris spring and ditch waters had turbidity, dissolved oxygen, EC and ORP values that strongly indicate groundwater origin of the waters. Furthermore, the ditch waters (flowing at 238 L/s) had the lowest dissolved oxygen measured, higher EC than most wells (1,455 µS/cm), and the only negative ORP documented in the study area. This suggests upwelling from deeper zones and mixing with shallow waters and a possible redox front associated with the aquifer (Schuring et al. 2000).

Groundwater budget and recharge

Direct recharge from precipitation is not a significant source of aquifer recharge (Table 7). The preliminary CMB analysis suggests direct recharge in the range of 7% of annual precipitation, or 42 mm/year. Much lower estimates, in the range of 2%, were presented for the plain by Miner and Adamson (2017) based on water balance analysis and GIS modeling. This range of aerial recharge correlates with other alluvial aquifers in Haiti including the Plaine du Cul-de-Sac, Plaine de Leogane, and Plaine du Nord-Massacre (Adamson et al. 2022, this issue; Arnaud et al. 2022, this issue). The low average annual precipitation (544 mm), southern aspect, and high evapotranspiration of the plain combine to limit recharge rates, similar to the aforementioned alluvial aquifers. Direct recharge is higher in the upgradient portion of the plain, influenced by elevation, greater permeability of alluvium, and lower evapotranspiration. The high-end range of direct recharge equates to ~4,830 Mm³/year across the

Table 7 Groundwater budget illustrating significant data gaps and the potential of 15× more groundwater abstraction if existing irrigation and municipal infrastructure were to be restored. Subtotals are given *in italic*

Classification	Source	Amount (Mm ³ /year)	Uncertainty	Method
Recharge	Rainfall (direct recharge)	1,258–4,830	Moderate	CMB, Miner and Adamson (2017)
	Streamflow infiltration	10,000–30,000	High	Flow measurement
	Other ^a	Unknown	High	–
	Subtotal	<i>11,258–34,830+</i>	–	–
Discharge	Baseflow	Unknown	High	–
	Well pumping (current)	1,825–3,650	Moderate	Estimate based on CTE interview and windshield survey
	Well pumping ^b (recommissioning of all irrigation and CTE wells)	28,000	Low	Based on historically documented pumping rates
	Springs and ditches	3,000–8,000	Moderate	Flow measurement
	Other ^c	Unknown	High	–
	Subtotal	<i>4825–11,650+ (36,000++ with historical abstraction)</i>	–	–

^aIrrigation return flows, runoff from surrounding mountains, flooding and inundation events, inflow from bedrock

^bAssuming 126,000 m³/day abstraction during 6-month dry season based on inventory of 45 irrigation wells in the plain, and 6,200 m³/day abstraction if all CTE-Gonaïves municipal wells are operating 8 h/day

^cOcean, evapotranspiration

plain, which is not much greater than the groundwater discharging to the ditches measured in October 2018.

The preliminary groundwater budget presented in Table 7 exposes the importance of identifying and quantifying recharge sources to the aquifer. With a high level of uncertainty, aquifer recharge is estimated in the range of 11,000–35,000+ Mm³/year. Current well pumping is estimated as ~2,000 Mm³/year; however, if existing irrigation and municipal well pumping infrastructure is recommissioned it could increase by 10–15 times to over 30,000 Mm³/year. This scale of abstraction may result in an unsustainable groundwater development with significant impacts on the aquifer system, especially if it is determined that streamflow infiltration is towards the lower end of current estimates.

Other potentially important recharge sources requiring further investigation include: inflow from bedrock, infiltration of floodwaters, runoff into the plain from the surrounding mountains, and inflow associated with the valleys that converge into the plain. The plain is subject to extreme event flooding and inundation resulting from tropical storms, and hurricanes (CIAT 2013; Smith and Hersey 2008). Floodwaters could be important aquifer recharge events as documented in other systems (Mertes 1997). In addition to pumping, primary aquifer discharge occurs subsurface to the ocean as baseflow to the lower Quinte River, and to springs, wetlands, and ditches in the lower part of the aquifer.

Uncertainties and limitations

A hydrogeological conceptual model in a data-scarce region comes along with the extra baggage of uncertainties and limitations. The model relies significantly on historical unpublished datasets, some data spanning back several decades. Water level measurements from wells span a wide range of dates with limited spatial and vertical representation, supporting only a general interpretation of groundwater flow, which may not be representative of current conditions across the aquifer and not representative of seasonal fluctuations. Lithology logs and interpretations of subsurface strata and bedrock depth are not validated, and drilling logs are often made by drillers and others with limited experience and training. Accurate locations of wells and associated data are another source of uncertainty; geographic coordinates were not documented for most historical data. The authors ground-truthed and/or relied on others to verify well locations. There is no tracking or monitoring of groundwater abstraction or private wells; estimates are based on qualitative information from government officials and cursory observations of the authors during the brief reconnaissance.

The reconnaissance mission and associated data represent only one discrete sampling event and it occurred towards the end of the rainy season. The single snapshot of hydrochemistry and isotopic data and associated interpretations

introduce uncertainty and limitations. Data collection was also limited on the east side of the aquifer (east of Quinte River) as conditions restricted efficient access during the reconnaissance. Further, the single measurement of water quality and flow from springs, ditches and rivers during the reconnaissance strongly supports the current understanding of groundwater/surface-water interactions and groundwater budget. The lack of local chloride and isotope data from precipitation presents uncertainty related to isotopic analysis and chloride mass balance analysis.

While the study has identified the potential significance of streamflow infiltration and mixing from bedrock-origin groundwater, the quantification and differentiation of recharge sources and a more detailed assessment of groundwater/surface-water interactions is limited by the paucity and discrete nature of data. Addressing this important limitation demands further research and monitoring, and can also be enhanced with numerical groundwater flow modeling.

Continued research and monitoring

Data scarcity and lack of monitoring data limit the conceptual model. The most prevalent data gaps are: (1) hydrological, chemical and isotope data for river segments, (2) chloride and isotope data representing a range of precipitation in the plain and watershed, and (3) temporal monitoring of piezometry throughout the aquifer. The structural valley and bedrock ridge extending to the SE needs to be investigated in this context, as it may hold an explanation for the isotope and hydrochemistry anomalies in the central portion of the aquifer. In the short term, a dry season snapshot of river hydrology, chemistry and isotopes combined with an effort to measure water levels in wells across the aquifer would significantly strengthen the conceptual model, and support calibration and validation for numerical groundwater flow modeling. It is currently very difficult to measure water levels in wells throughout the plain. New production wells should include a monitoring tube, and designated monitoring wells should be prioritized near all of the municipal wells. The difficulty of efficiently collecting water level data is a major impediment to further studies and groundwater management. Groundwater abstraction estimates need to be improved with an inventory of private, commercial and industrial pumping wells.

Implications for groundwater management

In view of the semiarid nature of the study area, groundwater recharge could be limited and represents a concern for sustaining year-round and larger-scale groundwater abstraction. Recharge from stream infiltration, inflow from bedrock aquifers, and other recharge mechanisms (perhaps floodwaters) are more significant recharge sources than direct infiltration from precipitation. Until these recharge mechanisms

can be further studied and quantified, overexploitation should be considered a significant risk and could lead to lowered water levels, decreased well productivity, saltwater intrusion, and deleterious impacts to surface water and coastal ecosystems. Abstraction in the plain is currently low due to limited municipal pumping and inactivity of the irrigation wells. The reinvigoration of commercial agriculture, using existing idle well infrastructure, and the full-time pumping of municipal wells could result in abstraction in excess of what the aquifer can sustainably support. Additionally, global climate change models predict increasing temperatures, lower precipitation, and rising sea levels for this part of Haiti (CIAT 2013). Such impacts could lead to a further reduction of groundwater recharge and worsening of water quality in the coastal areas.

Groundwater in the study area does not presently show contamination of inorganic parameters; however, contamination is considered a risk given the high density of urban, peri-urban, and rural communities situated in the plain all lack sanitation and waste management infrastructure and associated practices. Urban expansion and/or agricultural development into critical recharge areas also pose a contamination risk. A resurgence of the commercial agriculture sector could introduce agrochemicals and nutrients, resulting in contamination pathways from both surface water and direct infiltration. Thus, aquifer management with regard to water quality is important, especially as it relates to land use practices in important recharge areas and the potential growth of commercial agriculture.

Conclusion

Historical and newly collected hydrogeological, hydrochemistry, isotope, and piezometric data contributed towards advancing knowledge and insights regarding the data-scarce aquifer system of the Plaine des Gonaïves, Haiti. The integrated approach combined an intensive data discovery effort and a reconnaissance mission in partnership with local government and stakeholders. The results highlight the efficacy and value of data discovery efforts and the importance of disseminating a foundation of aquifer data that is findable, accessible, interoperable, and reusable. This important and often neglected step will reduce duplicated and redundant efforts common in data-scarce regions and enable smarter investments that focus on critical data gaps and research questions. The study demonstrates that isotope and hydrochemistry data are valuable in advancing conceptual models and detecting interactions between surface water and groundwater, and may be especially useful in practice when piezometry data are scarce. The paper also exposes the challenge of advancing conceptual models and quantifying a groundwater budget absent of temporal piezometry, hydrology, and groundwater abstraction data.

The combination of highly permeable alluvium and potentially abundant river infiltration recharge supports one of Haiti's largest sources of freshwater. Indicators suggest the current condition of the aquifer to be good from sustainability and water

quality perspectives; however, current rates of groundwater development and agricultural production are at historical lows over the last decade. The aquifer system is considered vulnerable given its coastal setting, increasing drought intensity with climate change, and rapid urbanization lacking sanitation and waste management practices. Further, groundwater abstraction could increase 10 to 15× if existing well-pumping infrastructure in the plain is rehabilitated. The corresponding transition to commercial agriculture in the plain may also result in contamination and water quality risks that would further complicate groundwater management and sustainability. The results of this study are expected to serve as a foundation for continued research, monitoring, and modeling to address piezometric and hydrological data gaps and improve the understanding of groundwater flow, recharge dynamics, and quantify renewable resources. Advancement of these activities combined with a commitment to Open Access publications and FAIR compliancy of datasets will encourage and enable further research to address data gaps and research questions necessary for sustainable management and protection of the Plaine des Gonaïves aquifer system. Such data dissemination practices should be adopted by all geoscience researchers when working in data-scarce regions with limited institutional and data management capacity.

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Declarations

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

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