







American Red Cross

An evaluation of the Plaine du Cul-de-Sac aquifer and its potential to serve Canaan Department Ouest, Republic of Haiti



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Prepared by:

Northwater International

Rezodlo, S.A.

with support from V3 Haiti





FINAL REPORT

NORTHWATER INTERNATIONAL and REZODLO

For: Global Communities Financed by USAID and American Red Cross

An evaluation of the Plaine du Cul-de-Sac aquifer and its potential to serve Canaan

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UNITS & COMMON ABBREVIATIONS

CAMEP	Centrale Autonome Métropolitaine d'Eau Potable (former water utility for Port-au-Prince, now CTE-RMPP)
CERCG	Centre d'Etudes et de Réalisations Cartographiques Géographiques
CSAMT/MT	controlled source audio magneto-tellurics / magneto-tellurics
CTE-RMPP	Centre Technique d'Exploitation, Région Métropolitaine de Port-au-Prince
DINEPA	Direction Nationale de l'Eau Potable et de l'Assainissement
GC	Global Communities
ha	hectares
km, km ²	kilometre and square kilometre
L/s	litres per second
m	metre
mm	millimetre
mg/L	milligrams per litre
m^2	square metres
m	cubic metres
m ³ /y	cubic metres per year
Mm ³ /year	million cubic metres per year
MCL	maximum contaminant level, primary and secondary water quality standards established by the United States
	Environmental Protection Agency
PCS	Plaine du Cul-de-Sac
TDS	total dissolved solids
USAID	United States Agency for International Development
WHO	World Health Organization

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EXECUTIVE SUMMARY

This study focused on evaluating the feasibility and potential impacts of utilizing the Plaine du Cul-de-Sac (PCS) aquifer to support existing and future water demands of the rapidly growing Canaan area. The study was commissioned for the purposes of guiding the Haitian Government and stakeholders in making informed and sustainable groundwater management decisions. Support in the form of resources, data, and knowledge to guide groundwater management are unavailable, out of date, or are incomplete and sometimes conflicting. In this context, the study undertook a focused effort to compile, collect, and analyse a baseline volume of data and knowledge to generally characterize the current aquifer conditions and guide informed decisions for supplying water for the Canaan area.

Based on the study, indicators suggest that groundwater abstraction from the PCS aquifer to support Canaan is feasible. Properly guided abstraction from the aquifer will minimize impacts and foster a sustainable supply of freshwater that would provide tremendous public health and economic benefits for Canaan. The key observations that warrant the feasibility of developing groundwater supplies in the Canaan area are outlined below:

- Since the late 1980s, aquifer trends indicate recovering groundwater levels and improving water quality in the northern portion of the aquifer near Canaan. Saltwater intrusion is less pronounced now than it was in the 1970s and 1980s based on geophysics and water quality data. These positive trends are largely due to the decommissioning of high capacity HASCO irrigation wells, which formerly pumped 40 to 60 Mm³/year from the PCS aquifer. Some southern portions of the aquifer indicate trends of groundwater depletion and water quality degradation, thus, the condition of the aquifer varies spatially and is largely related to well density and the scale of groundwater abstraction.
- There is very little groundwater abstraction currently in the Canaan area, and there is a very low ratio of groundwater development in the northern portion of the aquifer. There is little risk of well interferences and no regularly operating high-capacity wells were observed that might have created local issues such as depletion or saltwater intrusion. There is a high ratio of groundwater development for the PCS aquifer as a whole, which is noted as a concern for the long-term sustainability of the aquifer.
- The current groundwater elevations in the Canaan area indicate that a hydraulic gradient condition exists that discourages seawater from entering the aquifer. Professionally specified pumping rates at a series of strategically located new boreholes and/or rehabilitated HASCO wells could range between 15 and 30 L/s and are not likely to promote localized saltwater intrusion issues.
- Hydrochemistry and isotope data suggests that the northern portion of the aquifer near Canaan relies significantly on streamflow recharge from the upper reaches of Rivière Grise and Rivière Blanche. This is favourable for Canaan since a large proportion of aquifer recharge flows towards the area.

Utilizing existing decommissioned HASCO wells and/or drilling new boreholes should be considered for Canaan. Recommended groundwater development zones were delineated that present the lowest risk and greatest potential based on the synthesized results from this study. Twenty high-capacity HASCO well records were thoroughly evaluated for wells that fell within or in close proximity to these recommended zones. Eleven of the wells have good hydrogeological suitability, five have moderate suitability, and four have poor suitability.

Based on this study, we recommend limiting total abstraction from the Sibert groundwater development area to $4,000 \text{ m}^3/\text{day}$ with a series of two to four wells. We recommend limiting total abstraction from the Dessources groundwater development area to $2,500 \text{ m}^3/\text{day}$ with a series of two or three wells. Guidance on establishing maximum suggested drawdown during pumping is included in this report to minimize the potential of negative impacts, such as well interference and saltwater intrusion. New boreholes drilled in any areas of the aquifer should avoid intersecting the Miocene age bedrock that underlies the aquifer. Groundwater in these lower units is known to be brackish and can negatively impact the water quality of the well during pumping and during periods of aquifer stress. Areas to avoid completing new large-capacity wells in proximity to Canaan are also discussed in section 4.2, as some areas are more susceptible to depletion and water quality issues, due to various geological and hydrogeological factors.

The potential for longer-term risks regarding Canaan are more difficult to evaluate due to the lack of aquifer monitoring and integrated water policy, planning and management. These factors are as follows:

• Future increases of groundwater abstraction from the aquifer overall, even outside of the Canaan area, will affect the water balance and may lead to depletion and greater vulnerability to degrading water quality in the Canaan area. The north and northwest portion of the aquifer is considered vulnerable due to its coastal setting and its down-gradient

position from a majority of aquifer withdrawals and recharge. Due to the time scale of groundwater flow, up-gradient changes to recharge and withdrawals could take decades before they are detected in the Canaan area.

- We were unable to evaluate the possibility that current abstraction and recharge conditions in the aquifer up gradient of Canaan could be seriously diverting ("robbing") the subsurface flow and recharge of freshwater to the Canaan area. Due to the time scale of groundwater recharge and flow, this situation could be occurring but it may take decades to observe the impacts. Numerical groundwater modelling would be necessary to evaluate this concern.
- The feasibility of sustainable groundwater abstraction to support Canaan is largely supported by the inactivity of the commercial sugarcane agriculture industry. Large-scale irrigation wells have been inactive for decades; many of these historical wells still exist and are within several kilometres of the Canaan area. Aquifer trends from historical records and recharge modelling suggest that the rate of groundwater abstraction should these wells be reactivated would be far greater than the renewable supply. Sustainable groundwater supply for the Canaan area would be compromised, if the unused capacity of existing irrigation well infrastructure were restored.
- The aquifer relies on streamflow from Rivière Grise and Rivière Blanche for at least an estimated 80% of its annual recharge. Changes to the streamflow regime due to climate change and irrigation diversion from rivers could result in serious consequences to the water balance and long-term sustainability of the aquifer. Due to the time scale of groundwater recharge and flow, it could take decades to notice the impacts, and thus take decades to rectify issues. The failure to maintain the major diversion infrastructure (dam) along Rivière Grise has probably been good for the long-term health and sustainability of the aquifer. We hypothesize that diversions over the last 100 years have negatively affected the long-term average recharge to the aquifer.

SECTION 1.0 INTRODUCTION

The Plaine du Cul-de-Sac (PCS) aquifer is one of the most important and largest aquifers of Haiti, supporting a population of over 2-million people and the agricultural, industrial, and commercial sectors. Rapid population growth has occurred in the Canaan area on the northern side of the PCS since the January 12, 2010, earthquake. This settlement is now estimated to have over 200,000 residents and no centralized water supply, electricity or waste disposal. The American Red Cross (ARC) and USAID have partnered with the Haitian government to support planning and implementation efforts in Canaan, and Global Communities (GC) is currently managing a phased USAID/ARC-funded program that includes establishing a water supply for Canaan. Northwater International was retained as water supply experts to evaluate the PCS aquifer and its suitability to serve the potable water needs of Canaan.

Major groundwater abstraction (pumping) in the PCS aquifer began in the early 1900s, when a strong sugarcane industry was supported by irrigation from high capacity wells throughout the plaine. The Haitian American Sugar Company (HASCO) was the largest company which operated through the late 1980s / early 1990s. At its peak, HASCO alone had over sixty high-capacity wells documented with peak abstraction estimated at 40 to 60 Mm³/year. The HASCO wells were decommissioned and many of them still remain in various conditions. Current groundwater abstraction is estimated at 63 Mm³/year, which includes agriculture, municipal supply, private pumper trucks, and private wells for industrial, commercial and residential use.

There have been great concerns about the PCS aquifer, its capacity and sustainability given its critical importance in supplying Haiti's largest metropolitan area. Several studies and investigations have noted aquifer problems, such as depletion and degrading water quality, and an extensive volume of research in the 1980s noted saltwater intrusion impacts in the coastal areas, and brackish groundwater in the bedrock underlying the aquifer. At least three major studies have been conducted on the aquifer, spanning from Taylor (1949) to the late 1980s (BRGM 1989, Simonot 1982, Simonot and Giofiantini 1989, and UNDP 1990). These studies provide valuable characterization and historical context from which to support an understanding of the current state of the aquifer. However, the PCS aquifer is a lot different currently than it was in the 1980s, especially from an abstraction / withdrawal standpoint, making it difficult to rely on 25+ year-old data and conclusions to guide decisions today. Supporting informed decisions today regarding the aquifer is further challenging because there has been no centralized aquifer monitoring, a repository of data and knowledge is unavailable, and tracking and permitting of wells and abstraction does not occur. As a result, an extensive body of professional work was required just to provide a basic level of sufficient knowledge to guide informed decision-making regarding groundwater development.

The primary objective of this study is to provide an assessment of the feasibility for the PCS aquifer to support increased groundwater abstraction to serve Canaan. While the primary focus is necessarily on a local section of the aquifer, the Canaan area does not function in isolation from the rest of the aquifer and thus a notable effort was necessary to craft a basic understanding of the overall aquifer in its current condition. The study included the following components:

- 1. Desk study & research compile and review available resources and data to support the study (Table 1)
- 2. Hydrogeological data collection reconnaissance, mapping, water point mapping, water sampling, vertical conductivity profiles of wells, windshield survey of water users, hydrochemistry and stable isotope analysis
- 3. Site-level geophysical investigation electromagnetic geophysics to characterize the subsurface conditions near Canaan and guide recommendations
- 4. Analysis and reporting Results and recommendations based on analysis and synthesis of research, hydrogeological data collection and geophysical investigation

Figure 1 provides an overview of primary points of interest within the aquifer. Much effort was invested into crafting a general characterization regarding the PCS aquifer. This was necessary in order to adequately inform planning and decision making for Canaan. This report presents this general characterization, however, this report is not intended to serve as a conclusive characterization of the aquifer, nor shall this be considered a complete and comprehensive study for the aquifer. This study did, however, produce a great volume of work, including recent data collection, and collation of historical data that will support future efforts. A much larger program of fieldwork, data collection, monitoring and analysis is necessary to characterize the aquifer and establish a monitoring program to support integrated planning and management of the aquifer and its users.

This report is structured in order to encourage brevity and, thus, many additional tables and figures are presented in the appendix for readers that desire supporting data and resources. Table 1 provides a list of key sources for this study, and a full references section is included at the end of the report.

This study focused on the PCS aquifer and did not specifically analyse the northern and southern mountain carbonate bedrock aquifers. The former supplies many low-yielding wells in the Canaan area, and the latter supplies a major component of the Portau-Prince municipal supply via springs. Historical trends indicate decreasing spring flow and lowering water tables, likely tied to landuse and climate changes. Further studies and investigations are warranted for the carbonate bedrock aquifers, as they are considered a major part of the solution for meeting future water demands and mitigating stress and reliance on the PCS aquifer.

		Table I - Key	
Author ¹	Work Product	Year(s)	Summary & Conclusions
Woodring, et al	Geology of the Republic of Haiti	1924	Performed the first countrywide geologic mapping of Haiti. Detailed report provides basic geologic context of study area, and well and hydrogeological data from the beginning of the 20^{th} century.
CERCG	Carte Géologique de la République d'Haïti	1989	Compiled a geologic map which synthesized several prior mapping efforts. Currently primary geologic map for entire country.
UNDP	Carte Hydrogéolique République d'Haïti	1990	Hydrogeologic map of Haiti 1:250,000 scale
Gonel	Étude du potentiel des eaux de surface à Haïti pour répondre aux problèmes de pénurie d'eau potable	1919-1943, 1962-1966, 1976-83, 1988-1990	Average, minimum and maximum annual flow rates for 39 rivers at 44 gauge stations, primarily from 1920s, 30s and 40s
Taylor and Lemoine	Groundwater in the Cul-de- Sac Plain, Haiti	pre-1949	Performed hydrogeologic mapping and characterization. Also summarized irrigation water use
Gonfiantini and Simonot	Isotopic Investigation of Groundwater in the Cul-de- Sac Plain, Haiti	1980's	Confirmed earlier hydrogeological hypothesis of groundwater recharge occurring primarily from the Rivières Grise and Blanche
DINEPA, BID, AECID	AOPI 04-08-12, Réalisation d'Etudes Hydrogéologiques	1990's	Average capacity of 19 springs in RMPP; no dates of measurement provided
Coletti et al, Oxfam	Carte Géologique de Canaan, Jérusalem, Corail et Onanville	NA	1:10,000 scale geologic mapping of NW portion of study area (Canaan)
Cox et al	Géologie de Port-au-Prince	NA	Shapefile of updated geologic mapping in the Port-au-Prince area
FAO	AQUASTAT data, online	NA	Precipitation, temperature and evapotranspiration data for various unknown years in Haiti
Hijmans	Very high resolution interpolated climate surfaces for global land areas	1960-1990	Modeled precipitation for entire country based on FAO statistics at approximately 900 m grid spacing
Polidori	BVH_PhaseII	NA	Delineated 75 primary basins for Haiti, including several for PCS area
MDE	Integrating the Management of Watersheds and Coastal Areas in Haiti	NA	Description and statistics for several basins and river flow rates
HASCO	Well Records	1950s-1980s	Well completion, service and maintenance records for 57 HASCO wells
Emmanuel et al	Trend analysis of the groundwater salinity of the Cul-de-Sac Aquifer in Haiti	1999-2003	Analyzed changes in groundwater salinity for 16 boreholes in PCS
BlueRidge Drilling	Well Logs	2009-2016	Well records for some hand pump wells in PCS basin
Living Water International	Well Logs	2004-2016	Well records for some hand pump wells in PCS basin
LGL, CTE	Phase 1: Collecte des données et Analyse Diagnostic Rapport no 1.4 Étude des ressources en eau	NA	Characterized springs, provided drilling recommendations in Massif de la Selle and produced initial modeling of aquifer which suggested a total annual recharge of 99 Mm3/y for alluvial aquifer, with 71 Mm ³ /y from the Rivières Grise and Blanche. Also cited 1997 estimate of 72.5 Mm ³ /y abstraction from alluvial aquifer.
МТРТС	Évolution du niveau de service de la CAMEP au cours des années 1996-1999	1996-1999	Cited 1996 usage at 264 L/s for 5 wells and 923 L/s for 18 springs in Massif de la Selle. Cited a figure for average daily production of 128,292 m^3 /day from 18 springs and 12 wells.
Adamson, et al.	Summary of groundwater resources of Haiti	2016	Peer reviewed publication with the Geological Society of America. Provides characterization of Haiti's hydrogeological environments, aquifer characteristics by area and aquifer type and discussion of opportunities and challenges for groundwater in various localities and rock types. Also provides country-scale hydrogeological map and recharge modeling to support decision making.

Table 1 - Key literature & data reviewed

¹ Additional bibliographical information provided in References Section at end of report



Plaine du Cul-de-Sac Aquifer

Figure 1 - Setting and major features of the Plaine du Cul-de-Sac aquifer

SECTION 2.0 AQUIFER AND BASIN CHARACTERIZATION

SETTING

The PCS basin is approximately 1726 square kilometers; the center of the basin houses the PCS alluvial aquifer that spans 376 square kilometres (Figure 1 and Figure 2). The basin primarily drains coastward to the west, however, a significant portion of the eastern drainage also feeds Lac Azuei, a brackish lake forming the eastern boundary of the basin. The plain is flanked to the south by the mountains of the Massif de la Selle, and to the north by the mountains of the Massif Matheux and Trou d'Eau.

Basin Setting - There are two primary rainy periods; from April to June and from August to October, with average annual rainfall ranging from 850 mm in the plain up to 3000 mm in the high mountains of the Massif de la Selle (Table 12 and Figure 24). Modeled average annual precipitation for the entire basin was 1521 mm (Hijmans, 2005). Annual average temperatures range from 12.4 C in the high mountains to 27 C in the eastern part of the plain and the hottest months are typically June through October (Table 13). Actual evapotranspiration was modeled across the entire basin and ranged from 434 mm/year to 2532 mm/year with a basin-wide average of 1060 mm/year. Elevations range from sea level in the western part of the plain up to 2675 m in the southern mountains of the Massif de la Selle. While the average elevation for entire basin is 508 m, the plain ranges from 0 to 200 m.

The PCS basin was subdivided into nine primary watersheds and numerous sub-watersheds (Figure 24), ranging from 958 km² to 12 km². The primary drainages of the Rivière Grise and Rivière Blanche encompass 277 km² and 173 km², respectively, of the Massif de la Selle prior to entering the plain. Table 16 in Appendix 1 includes supplemental data regarding the basin characterization.



Figure 2 - Geology, primary basins and aquifer limits for the Plaine du Cul-de-Sac; see detailed geologic map (Figure 25 in Appendix 1) for explanation of the surficial geologic units.

WATER POINT SUMMARY

The literature review, desk study and field reconnaissance allowed for the compilation of a partial database of water points in the PCS aquifer. Table 2 summarizes the compilation of water point records and the volume of water point data available to support the characterization of the aquifer. Figure 3 illustrates all the wells and springs which were evaluated as a part of this study and shows the water points (with locational information) gathered from previous studies. Data from wells and springs are central to understanding aquifer characteristics and trends; piecing together a chronology of records, sometimes back to the 1920s, helps identify possible trends to support aquifer characterization and can indicate issues, risks, and also opportunities. The data is also critical to support an estimation of groundwater abstraction, necessary for the water balance analysis and evaluating local potential.

Table 2 - Water point records

Reference	Summary
Taylor (1949)	66 wells, 38 springs, 8 well fields
Gonfiantini and Simonot (1988)	60 wells, 40 springs
CTE-RMPP	17 production wells, 17 piezometers
V3 Companies (2013)	19 wells
HASCO maintenance records	57 irrigation wells
Blue Ridge Missions	73 low-capacity wells
Living Water International	519 low-capacity wells
LGL, CTE (2011)	20 planned production wells
DINEPA (2011)	38 high-capacity private wells
Current Study	53 private wells, 21 high-capacity wells and piezometers

72°22'0"W 72°20'0"W 72°18'0"W 72°16'0"W 72°14'0"W 72°12'0"W 72°10'0"W 72°8'0"W 72°6'0"W 72°4'0"W Port de Paix 3 5 0 PCS Aquifer Boundary 1 2 4 🔶 CTE-RMPP Municipal 🕂 Well Batteries Cap Haitia km 💋 Canaan Private High Capacity Well CTE Planned Well ãO Fort Libe 1:150,000 • Private hand pump well **Primary Routes** Diffuse Spring Hydrochem or Stable Isotope Sample Site (2016) Hinch Spring ٥ High Capacity Well Source 18°40'0"N Port-a Puentes. Mirago Sources Les Cayes HAITI Source C Hotte Source Secant Dumornay Diacroix Source Sibert A3 Trou Sibert A2 Caiman HASCO Source 0 0 Sibert A7 Pascher Lago 0 Sources N0.6 Sibert A4 Sibert A Manneville Dessources No.12 Artesian 20 ibert Bf Source Balangnie La Serre Source 2#4 La Serre 2#3 Oranger Source Latha Vaudreuil HASCO #2 ources Vaudreuil, Papeau å HASCO #4 F3 Source HASCO #1 Vaudreuil Dame Marie La Serre 1#2 Sonnett Sources Source (Caseau Despuseau Source ŝ Zabette Source Source Babaco D'allamond GWS Delmas 31 Source Source Puits 0 Madame Blanc Beauge ŝ ٥ Sources Freres Source Source Source Digue Carnaut Dumay Source Source Dupon Source Gros ٥ **Metivier** Lower Jean Source 6 Source Millet Source Metivier Upper Northwater International 2017 Bauduy Source

Plaine du Cul-de-Sac Aquifer

Figure 3 - Water point map of wells and springs uncovered through the desk review. The eastern portion of the PCS aquifer was not researched in detail and few well locations/records were uncovered for private wells (commercial, industrial, residential).

GROUNDWATER SAMPLING

A limited groundwater sampling effort was performed to document the current conditions at select high-capacity wells in the PCS aquifer. Figure 3 shows the sample locations, and the results are presented in Table 6 and Table 7 and in Figure 15. Many of the wells sampled had water quality or isotope data from historical studies and records which supported an analysis of trends and aquifer changes. Major cations and anions, select metals, physio-chemical parameters and Tritium (H3) were measured at eleven wells, and stable isotope analysis for δD and $\delta^{18}O$ at twelve wells. Four rainfall samples were collected to support chloride mass balance analysis to support recharge estimates. Many of the decommissioned high-capacity HASCO wells for which records exist were not found in the field, or were inaccessible; however, the available wells provided pertinent information.

Windshield survey and north-south water point transects across the PCS were performed on October 21, 22 and 24 to better understand the distribution of wells, abstraction rates, and provide supplemental field water quality data. Forty-three (43) functioning and accessible wells were identified during this effort, and pH, temperature, conductivity, and hardness were measured. Compartment bag testing (CBT) for E. coli was also performed at these wells and the results are detailed in the water quality portion of this section. Supporting data is also included within Appendix 1.

VERTICAL CONDUCTIVITY PROFILES IN WELLS

Vertical groundwater conductivity and temperature profiles were collected at 21 wells or piezometers in the southern and western portion of the aquifer in November 2016. The goal of this work was to better understand the water quality between productive zones within the aquifer. Seventeen of the profiles were at CTE-RMPP monitoring piezometers that were installed in 2013. The results show zones of higher or lower groundwater conductivity within the well-bore which are related to changes in water quality in the different aquifer layers. Many of the piezometers showed anomalies in conductivity ranging up to 306 μ S/cm and temperature swings of up to 1.5 C. The majority of conductivity anomalies occurred in the D and T CTE-RMPP wells. In general, it appears that higher conductivity groundwater appears in thin aquifer layers in the coastward wells (CTE D wells), while conductivity generally increased with depth in the Tabarre area (T wells). See Appendix 2 for the full conductivity profiles.

GEOPHYSICAL INVESTIGATION

The primary goals of applying electromagnetic geophysics were to: i) characterize the resistivity of hydrogeological units, ii) aid in finding favourable groundwater zones, iii) investigate the current potential of saltwater intrusion, iv) locate the northern edge of the PCS aquifer near Canaan and v) test various methods of analysis to determine drilling potential. A total of 13 CSAMT/MT soundings were conducted for this assessment and another five soundings were available from previous studies performed by Northwater in the Canaan/Jerusalem area. Nine of the soundings were located near HASCO wells in order to aid in calibration and analysis. The location of each CSAMT/MT electromagnetic sounding is shown in Figure 4 below, and Table 19 in Appendix 1. The geophysical results of each station were modeled into four resistivity cross-sections (lines) to assist in data visualization (Figure 5 through Figure 8). Appendix 3 presents resistivity-depth logs for each sounding.

The geophysics resulted in overall low resistivity, with pockets of very low resistivity in zones of unproductive, fine-grained materials or brackish groundwater. Saltwater intrusion did not appear to be a major concern in the northwest part of the aquifer along modeled line 1; however, some deeper zones of low resistivity may contain brackish water which aligns with drilling logs for wells such as Sibert A4 (CSAMT/MT sounding 4). The northern edge of the PCS aquifer also appears to be interfingered with fine-grained fan material deposited by the Ravine La Couline in Canaan. However, a fault is present between sounding 9 and sounding J5 that displaced the geological beds, disrupting southerly groundwater flow from the Massif Matheux. This structural area near the northern aquifer boundary also appears to have worse-quality groundwater at depth (conductivity, sulphur). There are a range of hypotheses to explain this, but an important takeaway is that drilling or utilizing high-capacity wells near the northern aquifer boundary is not recommended.

Outside of the PCS aquifer, moderately productive carbonate bedrock aquifer materials were discovered by drilling near sounding J2, however, the geophysical data indicate that this carbonate bedrock is steeply dipping and likely at inaccessible depths further to the south beneath the Plaine. The high resistivity anomaly below sounding 10 is intriguing, however, and may warrant further investigation.

The geophysics results are valuable and effective for the following reasons:

- Supported identification of which areas to avoid for large-capacity wells in the Canaan area, areas that could be low yielding or have a greater potential to produce more brackish groundwater now or in the future
- Supported determination the northern edge of the PCS aquifer. It was also good for identifying the depth to the bedrock underneath the aquifer. This is important because intersecting the bedrock can lead to water quality issues
- Evidence of saltwater intrusion in the alluvium was not evident from the results, a favourable result for considering groundwater abstraction in the area

• A statistical trend was found between mean subsurface resistivity and specific capacity (Figure 9), however, the results were not as strongly correlated above resistivity of 10 ohm-m. This geophysical method would provide a useful screening tool, if applied to target areas of higher potential for future drilling in the PCS aquifer.

Figure 10 displays the inverse trend relationship between groundwater conductivity and subsurface resistivity, as measured by the geophysical equipment. Because high conductivity should be avoided, this tool can provide a useful screening method to avoid areas and depth intervals that may have water quality issues now or in the future.

Plaine du Cul-de-Sac Aquifer



Figure 4 - Geology of the northwestern PCS aquifer showing geophysical soundings and lines



CSAMT/MT Line 1 shows modeled results from near the coast (Sibert A7) and traversing NE toward Canaan and up to near the Ravine La Couline in northern Canaan. Higher resistivities (blue) are likely indicative of bedrock, which is known to be of Oligocene age carbonates under Station J1 and J2, but may be Miocene units containing poor quality water influenced by the micro-plate fault system noted between Station 9 and J5. Dark red (very low resistivity) is indicative of surficial clays and fine grained material near the surface, and likely poor quality groundwater at depth. It is likely that a majority of the freshwater produced from old wells is produced from the zones of moderate resistivity (yellow) in the top 100 meters. The complex boundary between the PCS aquifer and the Canaan area is indicated by the two annotated faults and anomalies in resistivity.



Figure 6 – CSAMT/MT modeled line 1A

CSAMT/MT Line 1A shows modeled results from Line 1 expanded for greater clarity between the coast and Route 1. Higher resistivities (blue) are likely indicative of bedrock, which near Station 9 and 10 may be Miocene units containing poor quality water influenced by the micro-plate fault system noted north of station 9. Dark red (very low resistivity) is indicative of surficial clays and fine grained material near the surface, and likely poor quality groundwater at depth. It is likely that a majority of the freshwater produced from old wells is produced from the zones of moderate resistivity (yellow) in the top 100 meters.



CSAMT/MT Line 2 shows modeled results along Route 9 in the Sibert locality. Red and orange (low resistivity) is indicative of surficial clays and fine grained material near the surface, and likely poor quality groundwater at depth. It is likely that a majority of the freshwater produced from old wells is produced from the zones of moderate resistivity (yellow) in the top 100 meters. Note that records for Sibert A7 indicate very poor quality water from a zone at depth which is annotated in Figure 7. The relatively high resistivity below Sibert A1 (Station 5) was not expected and may result from fresher water which is pressurized and proximity to the Rivière Batarde / Rivière des Oranges.





CSAMT/MT Line 3 shows modeled results in the Pascher and Dessources localities. Red (very low resistivity) is indicative of surficial clays and fine grained material near the surface, and poor quality groundwater at depth. All three wells in this section are flowing artesian, with the greatest yield at Dessources No.2. While groundwater quality is currently good, conductivity was significantly higher in these wells when heavily pumped. The annotated geologic contacts provide an approximate depth to the Miocene-aged sediments which likely contain the higher conductivity water.



Figure 9 – The relationship between mean subsurface resistivity collected with geophysical equipment and specific capacity of wells. This geophysical method could provide a useful screening tool to site future drilling locations for high-capacity wells. It could also be a cost-effective means to better characterize the aquifer in areas where drilling records and data are unavailable.



Figure 10 – The relationship between minimum subsurface resistivity collected with geophysical equipment and groundwater quality. Because groundwater with high conductivity should be avoided, this tool can provide a useful screening method to avoid areas and depth intervals that may have water quality issues now or in the future. It could also serve a cost-effective means to better characterize the aquifer in areas where drilling records and data are unavailable.

AQUIFER BOUNDARIES AND GEOLOGY

The PCS aquifer covers approximately 376 km^2 and stretches from the Baie de Port-au-Prince to near the western shore of Lac Azeui (Figure 1). The aquifer is bounded to the north by the low foothills and fans that emanate from the Massif Matheaux and Montagnes Trou d'Eau. National Route 3 forms an approximate northern boundary in the areas of Canaan to Onanville. To the southwest, the aquifer extends just past the airport, curving along near the Avenue Mais Gate and along Boulevard 15 Octobre until connecting to the southern foothills near to where the Rivière Grise enters the plain. East of the Rivière Grise, the boundary near follows the northern edge of the foothills and continues past the Rivière Blanche toward Ganthier and to its eastern boundary near Lac Azuei.

Geologically, the Plaine du Cul-de-Sac is a syncline and graben bounded between two anticlines; to the south lies the Massif de la Selle and to the north lies the Massif Matheux and Montagnes Trou d'Eau. Both mountain ranges are predominately Eocene carbonate limestone and basalt basement rock of Cretaceous age. The trough is believed to be a sea arm that transitioned to its current position due to uplift and sea level decline during the early Quaternary period. The PCS aquifer is the result of sediment deposition in this trough from the drainages originating from the mountains.

Thus, the lower units of the aquifer are partly marine-derived and include semi-consolidated siltstone, sandstone and limestone deposits of Miocene age. Overlying the Miocene bedrock, thin layers of sand and gravel, with thicker layers of silt and clay, are prevalent through the plain. Taylor (1949) estimated that there are several (1 to 8 m) layers of sand and gravel; many of the deeper wells in the aquifer intersect multiple of these sand and gravel layers. Some wells also intersect the deeper Miocene bedrock, contributing higher dissolved solids in some wells (Figure 17). For the purposes of this report, the entire thickness of the permeable upper layers of the Miocene, up to the surface layers of recent alluvium, are considered the Plaine du Cul-de-Sac aquifer.

The sediments that form the Plaine du Cul-de-Sac aquifer are derived from the limestone carbonate and basalt mountains of the Massif de la Selle and the limestone carbonate Montagnes Trou d'Eau. Much of the sand and gravel is limestone origin and the various permeable layers are believed to be connected to the coarse gravels deposited by the energetic Rivière Grise and Rivière Blanche, and historical streams that may have flowed into the basin. As these rivers deposited sediment over geologic time, their channels moved back and forth, creating the alternate layers of thick silts, sands and clays and the sand and gravel lenses which store and yield a majority of the groundwater. In general, the deeper sand and gravel deposits are connected to their source of recharge farther to the south and at higher elevations, thus, deeper drilling results in confined or even flowing artesian groundwater conditions (Figure 17). A secondary result of this hydrogeological structure is that deeper water has travelled longer underground and is, thus, often higher in dissolved solids content. Increased salinity is, therefore, in part due to the age of the groundwater in different layers.

Figure 2 presents updated basin-wide geology and Figure 4 presents the geology near Canaan along with the aquifer boundaries and other points of interest. A full, updated surficial geologic map is also presented in Figure 25 of Appendix 1. The updated geologic map was developed based on field work and synthesis of at least four previous mapping efforts by Taylor (1949), the country-wide compilation produced by the CERCG (1989), Cox et al. in Port-au-Prince (2011) and Oxfam in Canaan (2014). The symbols in Figure 2 and Figure 4 are explained in the legend of Figure 25.

AQUIFER PROPERTIES

The PCS aquifer is one of the largest and most productive aquifers of Haiti. Details from 686 wells were available to support aquifer characterization. The potentiometric surface (static water level; groundwater elevation) was interpolated across the aquifer from recent measurements from over 80 wells (Figure 11) and the specific capacity was similarly interpolated across the western end of the aquifer based on data from over 60 wells (Figure 12). Data for depth, static water level, yield and specific capacity were analysed based on the type of well and its spatial location (Table 3). Lower-capacity private and community wells require smaller yields and are not typically constructed, reported, or tested in a manner to support characterization of aquifer properties, however, they do often provide important lithology and static water level data. They also help to fill data gaps in the aquifer, as they are more numerous than high-capacity wells.

The analysis points to several important properties of the aquifer:

- 1. Deeper wells (generally high-capacity) tend to have higher static water levels than shallow wells.
 - a. This is likely due to the deeper layers receiving their primary recharge at higher elevations, such as the high gradient alluvial fans where the Rivière Grise and Rivière Blanche enter the plain.
- 2. Many wells source a majority of their production from the deeper layers of sand and gravel which overlie the older Miocene age sediments. These beds may provide a helpful marker that can be interpreted with geophysical studies, and indicate where drilling should terminate to avoid water quality issues from the underlying Miocene bedrock.
- 3. Yields from similar areas within the aquifer vary significantly, indicating the aquifer is not homogenous. The yields are also variable depending on the well construction and the drilling depths. This reinforces the importance of an informed program for drilling wells that achieve the outcomes desired.
- 4. Aquifer properties for the high-capacity wells in the northern portion of the aquifer are shown in Table 3. The northern section has excellent capacity and hosts a majority of the flowing artesian wells. Due to the recharge dynamics of the aquifer, the northern section of the aquifer is also considered vulnerable to depletion and water quality impacts, as it is on the down gradient of all other wells and the sources of groundwater recharge. This is further discussed in section 4.0.

Table 3 - Summary of aquifer properties												
Parameter	De	pth	Sta	atic	Yie	əld	Specific Capacity					
	(n	n)	(n	n)	(L/	/s)	(L/s per meter)					
Well Category	Low High Capacity ¹ Capacity ²		Low Capacity ¹	High Capacity ²	Low Capacity ¹	High Capacity ²	Low Capacity1	High Capacity ²				
Geometric Mean	42	95 (107)	25	4 (2)	1.5	46 (44)	NA	4.3 (4)				
Maximum	156	236 (201)	85	114 (7)	5.1	131 (131)	NA	52.8 (11.8)				
Minimum	1	9 (9)	2	0 (flowing)	0.3	12 (13)	NA	0.7 (0.9)				
Median	45	102 (107)	30	3 (2)	1.9 46 (39)		NA	4.2 (5)				
Count	564	122 (41)	65	81 (25)	65	74 (20)	NA	74 (7)				

(107) Values in parenthesis are the subset representing the northern portion of the aquifer

¹ Low-capacity wells are mostly private and hand pump wells that require smaller yields and are not typically constructed, reported, or tested in a manner to support characterization of aquifer properties, however, they do often provide important lithology and static water level data

² High-capacity wells are mostly irrigation or municipal wells that were drilled and tested in a manner to produce large yields and support characterization of aquifer properties



Figure 11 - Potentiometric surface map based on recent water level data from 2005 through 2013



Figure 12 - Modeled specific capacity distribution in the western portion of the PCS aquifer

GROUNDWATER QUALITY

Groundwater quality varies greatly throughout the PCS aquifer, both spatially and with depth. Field water quality data from over 90 well records were analysed, along with eleven wells selected for hydrochemical and stable isotope analysis (Table 4 & Figure 15). The new data was compared to 105 wells and springs sampled by Simonot and Giofiantini (1988) to support the identification of trends. Similar to the aquifer properties section, the results were analysed separately depending on whether wells were low or high capacity. Due to the spatially variable water quality data and expressed concerns about water quality in the aquifer, an effort was made to model groundwater conductivity (Figure 13). Aquifer water quality trends are discussed in Section 3.0.

The analysis points to several key points of discussion:

- 1. Conductivity and hardness of groundwater generally follows trends of aquifer flow; conductivity is shown in Figure 13 and aligns with interpretations by Simonot and Giofiantini (1988) using stable isotope analysis. Conductivity is generally lower through the center and western portion of the aquifer in the zones of the Rivière Grise and Rivière Batarde. Conductivity increases near the northern and southern aquifer boundaries, along the coast and near Lac Azuei. Limited data were uncovered for the eastern portion of the aquifer due to the westerly study focus. Conductivity likely varies in the east depending on hydrogeological influences from Rivière Blanche and Lac Azuei.
- 2. E. coli bacteria were only detected at shallow, lower-capacity wells. Sibert A6 was the only deeper, high-capacity well that was positive; this well was contaminated because it was not sealed and open. The bacteria analysis results are summarized in Table 5 and detailed in Appendix 1, Table 18.
- 3. Stable isotope data is a mechanism to better understand the origin, age and flow of groundwater. The data from this study indicates similar spatial trends as shown by Simonot and Giofiantini (1988), however, the levels of δD and $\delta^{18}O$ were slightly higher overall. This could be associated with the changes in abstraction relative to the 1980s. There is also a direct relationship between $\delta^{18}O$ and chloride (Figure 16). Considering that elevated $\delta^{18}O$ indicates less exposure to evaporation, some wells may rely more on direct recharge now than historically. Because direct recharge occurs at a significantly lower rate than streamflow infiltration recharge, the resulting chloride values are greater. The artesian wells have some of the greatest deflections from the meteoric water line and, thus, indicate high exposure to evaporation, again linking the artesian wells in the north and west of the aquifer to the stream infiltration in the south-central area of the aquifer (Figure 15).
- 4. Based on the eleven wells analysed, the groundwater is primarily a calcium-bicarbonate type. One well was sodiumpotassium-bicarbonate (T2 Piezometer), and 5 wells were a calcium-chloride type (Figure 15 and Table 6). This is generally to be expected with the high carbonate content of the alluvium and underlying marine-origin sediments. Overall, the primary driver of increased conductivity and chloride values appears to be associated with deeper, older water and proximity to the marine-origin or Miocene age geology. T2, for example, has the highest chloride level and is far from the coast, but near the southern boundary of the aquifer where the Miocene age bedrock is shallower.
- 5. Vertical conductivity profiles from wells tests that were performed for this study are presented in Appendix 2 and suggest that in some locations, particularly near the coast, groundwater conductivity can vary greatly between production zones. Two wells in the Duvivier locality had conductivity spikes of 400 and 500 μ S/cm between depths from 20 to 70 m. In the Tabarre locality, piezometers showed a general trend of increasing conductivity with depth. We hypothesize that a trend of increasing conductivity in the F wells and the higher conductivity at depth in the T wells is due their position near the aquifer boundary; with limited recharge, the shallower units become depleted and a greater proportion of deeper, more brackish groundwater enters the well.
- 6. While high-capacity wells tend to be deeper, they do not necessarily have poorer water quality: both total hardness and conductivity were, on average, lower in the high-capacity wells.
- 7. Four of the CTE wells were found to have iron concentrations above the DINEPA standard of 0.2 mg/L. This does not pose a health risk, but may be an aesthetic and management concern. Wells in the northern and northwestern portion of the aquifer did not have elevated iron. Arsenic was detected at Sibert A7 (0.25 mg/L) at levels slightly above the WHO guideline of 0.2 mg/L. Arsenic detection in an alluvial aquifer in Haiti is a rare situation, but underscores the importance of thorough water quality testing before groundwater is distributed for potable use. Sibert A7 is currently being used primarily as an intermittent source of irrigation, but some locals are also likely drinking from it. Resampling of this well is recommended along with notification of the owner, in order to determine its potability for local consumption.
- 8. Field water quality statistics for high-capacity wells in the northern portion of the aquifer are shown in Table 4. Conductivity, temperature and pH are all slightly higher in the northern zone, indicating that the groundwater is likely

older and of deeper origin. Structural geology influences are also possible, as many of these wells lie near the same fault system that influence Source Puantes and the Hatte Lathan well.

Table 4 - Summary of aquifer water quality												
Parameter	р	Н	Temp	erature	Cond	uctivity	Hardness					
	(s.	u.)	('	°C)	(µs	/cm)	mg/I as CaCO3					
Wall Catagory	Low	High	Low	High	Low	High	Low	High				
Well Category	Capacity	Capacity	Capacity	Capacity	Capacity	Capacity	Capacity	Capacity				
Geometric Mean	7.8	7.8 8.2 (8.5)		28.6 (29.1)	692	660 (717)	208	108 (46)				
Maximum	8.6	8.8 (8.8)	31.0	30.2 (30)	2520	15909	578	279 (81)				
Minimum	7.4	7.3 (7.7)	27.7	26.6 (27.9)	348	191 (250)	71	16 (16)				
Median	7.8 8.3 (8.6)		28.6	28.3 (29.3)	662	522 (530)	241	120 (67)				
Count	29	14 (7)	33	15 (8)	33	54 (19)	30	13 (5)				

Table 5 - Statistics for E. coli results (Aquagenx CBT test)

Well Type	Quantity Tested	Quantity E. coli present	Quantity Intermediate Risk (MPN < 10)	High Risk (MPN > 10)						
PVC Handpump	8	4	2	2						
Mark II Handpump	20	0	0	0						
Municipal Production	7	0	0	0						
Private or Institutional	5	2	0	2						
Uncovered well	3	2	1	1						
All Types	43	8	3	5						
Note: full results presented in Appendix 1, Table 18										



Figure 13 - Interpolated groundwater conductivity in the Plaine du Cul-de-Sac aquifer



Figure 14 - Stable isotope plot of 12 well samples collected October 2016. Deviations from the linear meteoric line indicate groundwater that was historically exposed to evaporation, suggesting a stream infiltration origin.

Legend

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Figure 15 - Piper diagram of 11 wells sampled for hydrochemical analysis. Sampled October 2016. The plot shows that PCS groundwater is primarily a calcium-bicarbonate type. One well was sodium-potassium-bicarbonate (T2 Piezometer) and 5 wells were a calcium-chloride type.



Figure 16 - (Left) relationship of chloride to Oxygen-18 and (Right) Oxygen-18 vs Deuterium, sampled October 2016. The positive trend of chloride and Oxygen-18 likely indicates that higher chloride levels are, in part, due to wells that rely more on direct recharge which occurs at a slower rate than streamflow infiltration recharge. Oxygen-18 to Deuterium ratios show the extent of deflection from the meteoric water line; the artesian wells consistently show greater deflection, indicating they receive recharge exposed to evaporation, which is likely stream infiltration in the south-central area of the aquifer.

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Plaine du Cul-de-Sac Aquifer

Table 6 - Hydrochemistry of select water samples

Parameter	Units	DINEPA Standard	WHO Guidelines	USEPA MCL	USEPA Secondary MCL	D2 Production 18.60760 -72 32556	Sibert A1 Artesian 18.56042 -72 23871	F3 Production 18.64242 -72 22909	T2 Production 18.62987 -72 21766	Source Ti Puits/Pascher No. 6 18.53765 -72 22666	D5 Production 18.63590 -72 30446	T1 Piezometer 18.58259 -72 27686	T6 Piezometer 18.64220 -72 31539	F2 Piezometer 18.55687 -72 24516	Dessources No 2 Artesian 18.58901 -72 27460	Sibert A7 18.59797 -72 31775
Data Collected						10/27/2016	10/27/2016	10/27/2016	10/27/2016	10/28/2016	10/27/2016	10/27/2016	10/27/2016	10/28/2016	10/29/2016	10/20/2016
Alkalinity Total (CaCO3)	ma/l	500				200	10/27/2010	210	270	130	190	190	220	10/20/2010	10/20/2010	360
Bicarbonate (CaCO3)	mg/L					200	120	210	270	130	190	190	220	150	100	360
Chloride	mg/L	250	250		250	27	12	47	170	28	43.6	8	9.2	11	49.6	20.8
Conductivity	umhos/cm					480	266	640	1110	354	557	397	442	353	410	690
Fluoride	ma/L	2	1.5	4		0.3	0.33	0.17	0.28	0.54	0.24	0.17	0.39	0.24	0.31	0.85
Ammonia (N)	ma/L					<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Nitrite (N)	ma/L	3	3	1		< 0.01	< 0.01	< 0.01	< 0.01	0.03	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Nitrate (N)	ma/L	50	50	10		0.61	0.61	6.17	6.96	0.36	5.86	3.06	1.91	2.39	1.35	0.19
pH @ 25°C	Units					8.01	8.13	7.6	7.48	7.88	7.84	7.79	7.92	7.89	7.98	8.48
Sulfate	ma/L	250	500		250	29	25	36	25	20	37	22	34	23	29	30
Silica (SiO2)	ma/L					58.6	16.6	34	54.9	19.8	40.9	28.8	29.7	28.8	22.1	41.4
TOC	mg/L					0.4	0.3	0.4	1.1	0.4	0.2	0.3	0.4	0.3	0.1	0.3
Antimony	mg/L		0.02	0.006		<0.006	<0.006	< 0.006	< 0.006	<0.006	< 0.006	< 0.006	< 0.006	< 0.006	<0.006	<0.006
Arsenic	mg/L		0.01	0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.025
Barium	mg/L		0.7	2		0.009	< 0.005	0.026	0.302	< 0.005	0.017	0.017	0.04	0.041	<0.005	<0.005
Beryllium	mg/L			0.004		< 0.005	< 0.005	< 0.005	< 0.005	<0.005	< 0.005	<0.005	< 0.005	< 0.005	<0.005	< 0.005
Cadmium	mg/L		0.003	0.005		< 0.005	< 0.005	< 0.005	< 0.005	<0.005	< 0.005	<0.005	< 0.005	< 0.005	<0.005	< 0.005
Calcium	mg/L	100				28.2	14	89.1	158	8.1	57.3	57.3	74.1	48.6	19.4	2.5
Chromium	mg/L		0.05	0.1		< 0.005	0.009	0.006	< 0.005	<0.005	0.011	0.011	0.006	0.008	<0.005	< 0.005
Copper	mg/L	1	2	1.3		< 0.005	< 0.005	< 0.005	0.014	<0.005	< 0.005	<0.005	0.008	< 0.005	<0.005	< 0.005
Iron	mg/L	0.2			0.3	< 0.05	<0.05	< 0.05	< 0.05	<0.05	0.43	0.43	1.34	0.41	<0.05	<0.05
Lead	mg/L	0.01	0.01	0.015		<0.005	<0.005	<0.005	< 0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Magnesium	mg/L	100				14.4	4.9	18.3	20.2	3.1	10.5	10.5	13.9	8.6	8	1.7
Manganese	mg/L		0.5		0.05	<0.005	<0.005	<0.005	< 0.005	<0.005	0.015	0.015	0.027	0.008	<0.005	<0.005
Potassium	mg/L					4.9	0.9	0.7	1.6	0.6	1.6	1.6	1.8	1.3	1	0.8
Silver	mg/L				0.1	<0.005	<0.005	<0.005	< 0.005	<0.005	< 0.005	<0.005	< 0.005	< 0.005	<0.005	<0.005
Sodium	mg/L					49.8	33.9	24.7	29	58.3	13.6	13.6	19.7	20.9	50.3	158
Thallium	mg/L			0.002		<0.01	<0.07	<0.05	<0.10	<0.08	<0.02	<0.09	<0.11	< 0.04	< 0.03	<0.06
Zinc	mg/L	3			5	0.016	<0.01	<0.01	0.03	<0.01	0.037	0.037	0.064	0.023	<0.01	<0.01
Total Hardness	mg/L	300				130	55	298	477	30	205	186	242	157	81	13
(CaCO3) Mercury	ma/l		0.0005	0.002		<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Field Temperature	C C		0.0005	0.002		<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0000	<0.0005
Total Dissolved Solids	mg/l	600	1000		500	222	148	303	760	175	225	211	277	200	127	461
	iiig/E	000	1000		300	JLL	140	555	700	175	555	211	211	203	121	401
NOTE:	0.09	constituent	detected													
	125	exceeds D	INEPA reference	e standard												
	0.012	exceeds W	HO guidelines													

Plaine du Cul-de-Sac Aquifer

Std.

Dev.

0.3

-19.9

-3.71

Table 7 - Major cations, anions and stable isotopes of select water sources HCO3 Cl SO4 K^{+} d¹⁸O H₂O Elev Hydro Ca⁺ Mg⁺ Na⁺ TDS Name Date dD H₂O Tritium Туре Lat Long (m) mg/l mg/l mg/l mg/l mg/l ‰ facies mg/l mg/l mg/l Rainfall Laboule 10/19/16 10/19/2016 Rainfall 18.495119 -72.315372 850 < 0.7 -65.2 -8.95 10/4/2016 850 -8.60 Rainfall Laboule Matthew Rainfall 18.495119 -72.315372 < 0.7 -67.4 Rainfall Laboule 10/24/16 10/24/2016 18.495119 -72.315372 850 Rainfall < 0.7 -48.9 -8.24 Rainfall Clercime 10/30/16 10/30/2016 18.574852 -72.276767 Rainfall 42 < 0.7 -16.8 -3.80 Production D2 Production 10/27/2016 18.607603 -72.325560 11 Ca-Cl 244 27 29 28.2 14.4 4.9 49.8 322 -16.9 -3.38 < 0.71 Well Flowing Sibert Al Artesian 10/27/2016 Artesian 18.635898 -72.304459 12 Ca-Cl 146 25 -19.0 < 0.54 12 14 4.9 0.9 33.9 148 -3.97 Well Production 10/27/2016 18.589009 -72.274604 F3 Production 39 CA-HCO3 256 47 36 89.1 18.3 0.7 24.7 393 -17.0 -3.37 1.08 Well Production Na-K-10/27/2016 18.556874 -72.245163 T2 Production 69 170 329 25 158 20.2 1.6 29 760 -11.5 -2.84 < 0.89 Well HCO3 Flowing Source Ti Puits/Pascher 6 10/28/2016 Artesian 18.642419 -72.229091 27 Ca-Cl 159 28 20 8.1 3.1 0.6 58.3 175 -16.0 -3.67 < 0.86 Well Production 10/27/2016 18.597966 -72.317751 CA-HCO3 D5 Production 7 232 43.6 37 57.3 10.5 1.6 13.6 335 -18.8 -3.64 < 1.01 Well T1 Piezometer 10/27/2016 Piezometer 18.560423 -72.238709 77 CA-HCO3 232 8 22 57.3 10.5 1.6 13.6 211 -20.0 -3.78 < 0.88 T6 Piezometer 10/27/2016 Piezometer 18.537653 -72.226656 101 CA-HCO3 268 9.2 34 74.1 13.9 1.8 19.7 277 -18.6 -3.68 < 1.12 F2 Piezometer 10/28/2016 Piezometer 18.582588 -72.276863 30 CA-HCO3 183 11 23 48.6 8.6 1.3 20.9 209 -18.0 -3.60 < 0.56 Flowing Dessources No. 2 Artesian 10/28/2016 Artesian 18.629867 -72.217658 30 Ca-Cl 122 49.6 29 19.4 8 1 50.3 127 -18.9 -3.82 < 0.52 Well Sibert A7 10/29/2016 Well 18.642202 -72.315389 9 Ca-Cl 439 20.8 30 2.5 1.7 0.8 158 461 -19.9 -3.94 < 0.43

CA-HCO3

15

10/29/2016

Well

18.630079 -72.291418

Sibert B6

GROUNDWATER RECHARGE

Based on modelling and analysis performed for this study, total long-term average annual groundwater recharge to the PCS aquifer is estimated at between 73 and 100 Mm³/year (2.35 and 3.18 m³/s). Recharge is believed to occur through two primary modes: direct infiltration of precipitation and infiltration of stream flow, the latter serving as the primary mechanism for the PCS aquifer. Infiltration of irrigated waters may also play a role in recharging the shallower aquifer layers, however, given the generally fine-grained nature of the upper layers, this contribution is assumed to be minimal.

- Direct infiltration in the plain was modeled to be approximately 12.6 Mm³/year or 3.4% of annual precipitation on the plain (Figure 26, Appendix 1). Direct recharge in the Sibert to Dessources area ranges from very low to 72 mm/year, with a mean of 24 mm/year. For the plain, the mean direct recharge rates for fine alluvium (Qaf) are 23 mm/year, medium alluvium (Qam) 53 mm/year, and coarse alluvium (Qac) 75 mm/year.
- Streamflow infiltration of 'losing' streams into the aquifer is dependent on many variables and requires a detailed study to adequately characterize and quantify. For the purposes of better understanding this important factor, we applied imagery analysis, streamflow records, and field reconnaissance to estimate total streamflow recharge to the PCS aquifer. The estimate suggests that between 61 Mm³/year and 88 Mm³/year enters the PCS aquifer from streamflow infiltration. The range considers the uncertainties related to irrigation diversions from Rivière Grise and the changing hydrologic regime of the river systems.
 - The Rivière Grise is the dominant recharge mechanism to the PCS aquifer. This finding aligns with past research, and the analysis of new and historical data further validates this conclusion.
 - The streamflow from Rivière Blanche entirely infiltrates during baseflow conditions and a portion recharges the PCS aquifer. A portion may not enter the aquifer and flow subsurface towards Lac Azuei or Trou Caiman.
- The timescale of groundwater recharge for the aquifer is on the range of decades to thousands of years, largely depending on the different aquifer beds, their pressure, and hydraulic conductivity. Groundwater age dating from the aquifer presented by Simonot and Giofiantini (1988) noted a mean age of approximately 560 years, with water age ranging from modern to 17,000 years. These groundwater ages imply that changes in the aquifer, such as decreased recharge or increased abstraction, may not be felt for decades or longer depending on location and extent.

While recharge primarily occurs along the southern boundary of the aquifer where the rivers enter the PCS, it is possible that recharge to progressively shallower layers occurs as the Rivière Grise flows toward the coast. These lower reaches are believed to interact freely with the river: during the rainy seasons the river loses water to the aquifer, while during the dry season the river gains water from the aquifer. The balance of these dynamics was not a focus of this study, as our field reconnaissance indicated that a majority of the recharge occurs within the first several kilometers from where the stream enters the plain.

Based on historical maps from the late 1700s, the Rivière Blanche used to flow northward and then curve westward along the current path of the Canal Boucambrou. This routing indicates that the Blanche River is likely the primary source of coarse sediment along the northern zone extending towards Dessources. This is a key finding in that it implies that the hydrogeologic connection between the northern aquifer and the Rivière Blanche is likely strong and that the artesian wells in the Dessources area may be primarily sourced from recharge which occurs along the Rivière Blanche. So, even though the Rivière Grise is the dominant source of recharge to many parts of the aquifer, the northern zone may be especially impacted by changes in the Rivière Blanche.



Figure 17 - Generalized aquifer cross section showing recharge, flow and well characteristics

GROUNDWATER FLOW

Groundwater in the Plaine du Cul-de-Sac aquifer generally flows from the southern edge of the aquifer toward the north and west. Figure 11 shows the interpolated groundwater elevation map for the aquifer. Given the aquifer structure and properties, as generalized in Figure 17, the high gradient and significant recharge along the southern boundary leads to pressurized confined beds of sand and gravel in the distal (north and west) sections of the aquifer. There are several key considerations to be drawn from the data:

- It is estimated that the time it takes for groundwater to flow from the distal recharge areas to the coast is on the order of hundreds of years; an estimate of 300 - 500 years is presented based on flow calculations and groundwater age dating. The zones of lower permeability and the deeper beds of Miocene age can potentially take 600 to over 1-million years to flow from the recharge zones to the coast.
- 2. Groundwater flow direction and recharge is apparent from the potentiometric map; the Rivière Grise is a dominant source of recharge, especially in the first 6-12 km after leaving the Massif de la Selle. A higher gradient around the alluvial fans of the Rivière Blanche and especially the Rivière Grise support the understanding that these upper zones are the primary source of recharge for the aquifer.
- 3. Flow patterns from south to north and west imply that recharge from stream infiltration reaches the northern area of interest near Canaan after traveling through areas of high potential abstraction. Thus, the aquifer must be managed and monitored in order to avoid depletion of the northern section, if significant development occurs.
- 4. As noted in the preceding section, the Rivière Blanche is likely a primary source of recharge to the northern zone; this is perhaps good news for the north-central portion of the aquifer near Dessources. However, the northern Sibert and Bon Repos area may receive a mix of recharge, more dominant from Rivière Grise infiltration. If groundwater abstraction upgradient approaches or exceeds a certain threshold, the down-gradient northwestern corner will be slow to feel the effects due to groundwater travel times, but negative impacts could occur. Further investigation is necessary to understand this risk.
- 5. Freshwater and saline seawater are held in a dynamic balance by the pressure, or flow, of fresh groundwater toward the sea. When fresh groundwater levels drop, a significant rise in the elevation of the mixing zone of fresh and saline water

can occur. Given low pumping rates in the northwestern portion of the aquifer, this does not appear to be a current concern; however, if water levels consistently drop due to pumping, the mixing zone may rise too and adversely affect water quality.

6. Due to the variable potentiometric levels in each of the water-producing layers of the aquifer, there are pressure gradients which drive flow between layers when they are connected by wells or well screens. When wells penetrate and screen multiple sand and gravel layers, a conduit is formed which allows pressurized water from lower aquifers to flow upward into higher layers. V3 (2013) noted up to several hundred gallons per minute flowing vertically upward through some production wells during rehabilitations of CTE-RMPP wells. This observation suggests that as the upper and more accessible zones of sand and gravel are depleted, wells will more greatly rely on the deeper zones.

GROUNDWATER ABSTRACTION & LEVEL OF GROUNDWATER DEVELOPMENT

Groundwater abstraction rates were estimated for primary water use types in the PCS aquifer. The lack of data surrounding groundwater pumping in the aquifer makes estimation very difficult. Municipal pumping rates were averaged for data provided by CTE-RMPP from 2011 through 2016. The remaining categories were estimated based on water point data, a windshield survey, interviews with drillers and businesses, and analysis of satellite imagery to estimate agricultural areas.

Table 8 presents an estimated groundwater development ratio for the aquifers, given the modeled recharge rates and estimated abstraction rates. Total groundwater use is currently estimated at $173,000 \text{ m}^3/\text{day}$ ($63 \text{ Mm}^3/\text{y}$). Compared to the annual recharge rate of 203,000 m³/day, this yields a groundwater development ratio of 0.92 or, stated another way, 92% of the PCS aquifer's renewable groundwater supplies are currently being exploited. It is important to note that current groundwater use is lower than many previous periods (as will be further discussed in Section 3) and groundwater recharge also has the potential to vary significantly, due to the diversion of streams for irrigation, and climate and landuse changes affecting streamflow. Although the aquifer, as a whole, does not appear to be fully exploited, groundwater flow dynamics and areas of concentrated pumping results in many areas being over-exploited with others less-exploited (Figure 18). Due to the decommissioning of HASCO wells in the Sibert and Dessources area, the northern portion of the aquifer currently has a low level of groundwater development; much higher exploitation is occurring towards the south.

	Area (km2)	Rech	arge	Natural Estimated Withdrawals / Abstraction										
Aquifer System		Effective infiltration	Streamflow infiltration	Sea, lakes, rivers	Total withdrawals	Irrigation	,	Municipal Potable Water	(CIE-KIMPP)	Private Potable Water	(Trucking & Bottling)	Private Wells (Commercial,	Industrial, Kesidential)	Ratio of Groundwater Development
		m3/day	m3/day	m3/day	m3/day	m3/day	%	m3/day	%	m3/day	%	m3/day	%	
Plaine du Cul-de-Sac Aquifer	376	34,500	168,192	14,000 - 80,000 ?	172,600	54,795	32%	33,600	19%	23,164	13%	61,041	35%	0.92
Massif de la Selle Carbonate	905	200,543												
Massif Matheux & Trou d' Eau Carbonate	445	48,645												

Table 8 - Estimated Ratio of Groundwater Development, Plaine du Cul-de-Sac Aquifer

* Irrigation and private (commercial, industrial, residential) abstraction estimates are considered estimates based on windshield surveys, discussions with drillers, and recent estimates of land use in the PCS. Municipal estimates are directly from CTE-RMPP, and private potable water estimates are based on independent research performed by one of the authors. This table is intended for visualization and planning purposes and should not be adapted as a formal water balance for the aquifer.



Figure 18 - Schematic illustrating the level of groundwater development and exploitation in the PCS aquifer

SECTION 3.0 AQUIFER TRENDS

We evaluated historical data and incorporated our new datasets to look for aquifer trends and indicators that could help this evaluation determine the aquifer's current condition and support the discussion of environmental and aquifer risks and vulnerabilities.

WATER QUALITY

A range of water quality data was reviewed and collected to evaluate trends and indicators that could help understand the aquifer's current condition and support decision making. Based on this review, the key findings are:

- Conductivity of groundwater has decreased (improved) in some parts of the aquifer since the late 1980s when the HASCO irrigation pumping was suspended. This is most notable in the coastal area of Sibert and Route 9. This is due to lower pumping stress, recovery from saltwater intrusion, and a lesser influence from deeper, older groundwater that is higher in dissolved solids.
- Conductivity of groundwater is highly variable spatially and at depth. The spatial variations in conductivity are illustrated in Figure 13; conductivity is higher along the coast and along the northern and southern aquifer boundaries. A review of hydrogeological well tests on CTE wells from 2013 illustrates that conductivity can vary significantly between these layers at different depths, and typically the deeper beds have higher conductivity.
- Due to limited time-series data, temporal changes in water quality are difficult to evaluate. Over the last 10 years, some portions of the aquifer appear to be experiencing a gradual increase in conductivity, while other areas appear to be stable. The CTE-RMPP F wells are primarily located east of the airport and show a strong trend of increasing conductivity from

2006 to present. The conductivity at these wells ranged between 400 to 835 μ s/cm, with an average increase of about 1.2 percent/year (Figure 19).

- Farther to the southeast, the CTE-RMPP T wells have more stable conductivity over the same period, with the exception of T8. The D wells, which are closer to the coast than the T and F wells, also show a trend of more stable conductivity through the same period, however, data was limited for the D wells.
- Trends were analysed for HASCO wells where four or more data points were available from various sources starting in 1948. Based on fourteen different wells, higher conductivity in the period from 1948 through the 1980s is illustrated, and then notable decreases in conductivity based on recent measurements (Figure 20). The Sibert wells illustrated the greatest changes. Sibert A3 and A4 reported values over 1000 µs/cm in the 1980s and they were recently reported at 306 µs/cm (2013) and 258 µs/cm (2016), respectively.
- Stable isotope results from similar locations between 1987 and 2016 indicate increases (less negative) of 18O, especially in the southern portion of the aquifer. The increases are greater in the easterly direction. This trend may indicate that a greater proportion of deeper groundwater is flowing to the wells currently, as the shallower zones have become depleted in the southern portion of the aquifer over time.



Figure 19 - Conductivity data from CTE-RMPP F Wells from 2006 to 2016



Figure 20 - Potential trends of improving conductivity at select HASCO wells

WATER TABLES / POTENTIOMETRIC SURFACE

Trends regarding groundwater elevations were difficult to evaluate, as limited time-series data was available. Observations are based on very limited datasets and are summarized below.

- Taylor (1949) noted a trend of rising static water levels in some HASCO wells based on measurements taken in the 1920s and 1940s. For example, Siebert A4 reported a static depth of 5.2 meters in 1927, 2.7 meters in 1937, and 2.5 meters in 1976. The trend is unexplained, because well pumping significantly increased during that period. A possible hypothesis proposed by our team is that since the new boreholes interconnected multiple confined beds of sand and gravel, the deeper beds under higher pressure may have contributed to this overall trend as the aquifer restored its new equilibrium.
- Water levels in the HASCO agricultural areas have recovered since pumping was suspended in the 1980s. Figure 21 illustrates this trend across several wells in the Sibert area in the northwest portion of the aquifer; an average of 2.5 meters of water table recovery is estimated, with some areas significantly greater or lower.
- Limited water level data from well service reports were pieced together for several CTE-RMPP wells. Dating back to the 1970s, a possible trend of lowering water tables in the F, T, and D wells was noted. In 2013, monitoring wells were installed at most of the CTE-RMPP wells and water table monitoring programs have recently been initiated.
- Dessources 2 is an artesian well that flowed at 52 L/s in the 1940s and now flows at about 7 L/s. This illustrates that the pressure in deeper beds of sand and gravel has been decreasing over time, which is the result of groundwater abstraction and reduced recharge. Sibert A7 was an artesian flowing well in 1973. Due to pumping influences, the water table dropped to 4.2 meters in 1982. The water table was recently measured (October 2016) at 1.15 meters with no pumping occurring in the area.
- Qualitative comparisons were made between recent groundwater elevation isopachs (Figure 11) and UNDP (1990) isopachs. Regionally, the flow directions and groundwater elevations were similar between the datasets. The recent isopachs indicated lower groundwater elevations in some southern and central areas of the aquifer, while the coastal area near Sibert illustrated areas with higher groundwater elevations. The recent isopachs contours also suggest greater pumping impacts in the southern and central portion of the aquifer. Due to the different methods and datasets used in modelling, it is not suggested to consider these interpretations as conclusive.



Figure 21 - Water table depths at select HASCO wells over time

GROUNDWATER ABSTRACTION

Groundwater abstraction from the PCS aquifer has varied greatly since the early 1900s. The peak abstraction from the aquifer was well over 100 Mm³/year in the 1970s and 1980s when HASCO irrigation wells were reportedly abstracting 40 to 60 Mm³/year, and the CAMEP municipal wells were operating more reliably than they are today (Figure 22).

Abstraction decreased significantly after the decommissioning of the HASCO irrigation wells. An abstraction estimate from 1997 suggested a total of 72.5 Mm³/year (CTE 2011). This current study estimates 65 Mm³/year This is lower than the 1997 estimate as irrigation withdrawals have decreased throughout the plain and the CTE-RMPP municipal wells are pumping less due to operational issues.

Future abstraction is planned by DINEPA and CTE-RMPP (Figure 22). It is estimated that an additional 11.6 Mm³/year will be abstracted from planned municipal wells (G1-G7 and P1) in the short-term, and an additional 16.42 Mm³/year in the medium-term. CTE-RMPP is reducing its reliance on the PCS aquifer by investing in wells targeting the Massif de la Selle limestone aquifer to the south. Abstraction for industrial, commercial and residential will also increase as Port-au-Prince continues to grow to the north and east.

One notable abstraction risk related to the aquifer is to commercial agriculture. Currently, the groundwater abstraction for irrigation is low considering there is close to 150 km^2 of agricultural land in the plain. The resurgence of this industry could potentially increase groundwater abstraction by 40 to 100 Mm³/year. The decommissioned HASCO wells alone have the capacity to abstract 40 to 60 Mm^3 /year.

To put this back into perspective, the total long-term average groundwater recharge to the aquifer is estimated at 74 Mm³/year. In principle, the concept of aquifer sustainability is connected to the relationship of **total** abstraction of groundwater from the aquifer and the **total** recharge replenishing the aquifer. When these are out of balance, there is greater potential for negative impacts and groundwater management is necessary to understand and mitigate the risks.



Figure 22 - Historical and possible future groundwater abstraction based on various sources. Estimated groundwater recharge rates are illustrated with and without river diversion to visually compare withdrawals with renewals. River diversions are defined as current and historical diversion of streamflow for irrigation use. Diverting this water makes it unavailable to recharge the aquifer.

SECTION 4.0 CONCLUSIONS & RECOMMENDATIONS

4.1 CONCLUSION

This evaluation focused on the capacity of the PCS aquifer to support groundwater abstraction to serve Canaan. In order to accomplish this, much effort was needed to characterize the entire aquifer and contributing basins. Many observations and conclusions are shared between the entire aquifer and the zone near Canaan, but there are unique challenges and considerations for groundwater in the Canaan area, specifically, the area between Sibert and Dessources.

The range of observations listed below suggest that groundwater abstraction from the PCS aquifer to support Canaan is feasible.

- Aquifer trends in the north and northwest portion of the aquifer suggest improving conditions over time, since the HASCO wells were decommissioned
- There is a low level of groundwater development currently in the Canaan area compared with other areas of the aquifer
- Current saltwater intrusion processes were not detected in the northern portion of the aquifer near Canaan based on this evaluation. The groundwater gradient, water quality data, and geophysical soundings indicate saltwater intrusion processes have receded significantly since the HASCO wells were decommissioned
- A large proportion of the PCS aquifer recharge flows towards the Dessources and Canaan area.

Properly guided abstraction from the northern portion of the aquifer will minimize impacts and foster a sustainable supply of freshwater that would provide tremendous public health and economic benefits for Canaan. Section 4.2 outlines specific recommendations related to groundwater development and management for the Canaan area, and the aquifer as a whole.

Short-term risks of utilizing the PCS aquifer to supply Canaan are considered limited and manageable. The main short-term risk is related to physiochemical water quality. Improperly informed and managed drilling and pumping in this area of the aquifer could result in groundwater becoming brackish due to the unique geological setting and/or coastal position of the area. These issues have been observed and documented historically and need to be seriously considered. They can be effectively managed and mitigated starting with recommendations outlined in this report.

The potential for longer-term risks regarding Canaan are very serious and difficult to evaluate due to the lack of aquifer monitoring and integrated water policy, planning and management. These factors are discussed below and summarized in Section 4.4 and in Table 11.

- Future increases of groundwater abstraction from the aquifer overall, even outside of the Canaan area, will affect the water balance and may lead to depletion and greater vulnerability to degrading water quality in the Canaan area. The north and northwest portion of the aquifer is considered vulnerable due to its coastal setting and its down-gradient position from a majority of aquifer withdrawals and recharge. Due to the time scale of groundwater flow, up-gradient changes to recharge and withdrawals could take decades before they are detected in the Canaan area.
 - We were unable to evaluate the possibility that current abstraction and recharge conditions in the aquifer upgradient of Canaan could be seriously diverting ("robbing") the subsurface flow and recharge of freshwater to the Canaan area. Due to the time scale of groundwater recharge and flow, this situation could be occurring but it may take decades to observe the impacts. Numerical groundwater modelling would be necessary to evaluate this concern.
- The feasibility of sustainable groundwater abstraction to support Canaan is largely supported by the inactivity of the commercial sugarcane agriculture industry. Large-scale irrigation wells have been inactive for decades; many of these historical wells still exist and are within several kilometres of the Canaan area. Aquifer trends from historical records and recharge modelling suggest that the rate of groundwater abstraction, should these wells be reactivated, would be far greater than the renewable supply. Sustainable groundwater supply for the Canaan area would be compromised, if the unused capacity of existing irrigation well infrastructure were restored.
- The aquifer relies on streamflow from Rivière Grise and Rivière Blanche for at least an estimated 80% of its annual recharge. Changes to the streamflow regime due to climate change and irrigation diversion from rivers could result in serious consequences to the water balance and long-term sustainability of the aquifer. Due to the time scale of groundwater recharge and flow, it could take decades to notice the impacts, and thus take decades to rectify issues. The failure to maintain the major diversion infrastructure (dam) along Rivière Grise has probably been good for the long-term health and sustainability of the aquifer. We hypothesize that diversions over the last 100 years have negatively affected the long-term average recharge to the aquifer.
4.2 RECOMMENDATIONS

SUMMARY

Utilizing existing decommissioned HASCO wells can be considered for Canaan. Table 9 and Table 10 outline potential wells in the Sibert and Dessources areas and comments on their suitability. The current condition of these wells needs to be evaluated and validated by a certified well contractor, and it should be assumed that cleaning, development and rehabilitation will be necessary for wells that can be used. Land ownership and easements are another factor that needs to be addressed. It should be noted that some of the well records, data, and locational information could be erroneous. Some wells may no longer exist or function as previously reported.

Drilling of new wells can also be considered; Figure 23 illustrates areas that would be recommended for new water supply wells. The mapped zones are based on the data analysed from this study. They represent areas of lower risk in terms of drilling success, water quality, and sustainability. New water wells drilled in the aquifer should avoid drilling into the Miocene age bedrock that underlies the aquifer. Groundwater in these units is known to be brackish and can negatively impact the water quality of the well during pumping and during periods of aquifer stress. The geophysical method utilized in this study can be an effective method for evaluating potential sites for drilling to optimize yield and water quality, and estimate the depth to the bedrock.

ABSTRACTION / WITHDRAWALS

Considering the limitations of this study, it is recommended to limit total abstraction from the Sibert area to $4,000 \text{ m}^3/\text{day}$, and $2,500 \text{ m}^3/\text{day}$ from the Dessources area. This abstraction represents a fraction of historical pumping rates from the area, and is based on a phase that would include a few production wells with managed withdrawals based on drawdown. Achieving this abstraction may require two to four production wells in Sibert and two or three production wells in Dessources. These suggested limits are considered conservative to account for limited data and resources to guide sustainable withdrawals while minimizing impacts. Further studies and monitoring can better refine these suggestions and guide long-term sustainability for these areas of the aquifer, and the aquifer in its entirety.

As general guidance to avoid negative impacts, well pumping (dynamic) water elevations should not fall lower than 3 meters above sea level in the Sibert area. Based on the well data reviewed, this would allow for an average of 5 meters of drawdown, and pumping rates from individual wells ranging from 15 to 30 L/s. In the Dessources area, we recommend limiting water table drawdown in order to reduce the potential for impacting free-flowing artesian wells that currently serve the communities in the area. Some simple groundwater modelling can establish these guidelines.

SIBERT AREA

The Sibert area located along the northern portion of Route 9, north of Rivière Batarde (Rivière des Oranges), offers great potential for using existing wells or drilling new wells. There were historically nearly a dozen HASCO irrigation wells in this area, and there has been very little abstraction since the late 1980s. Table 9 outlines the wells and their potential suitability for Canaan. It is not recommended to invest in drilling production wells anywhere north of Sibert A3 or west of Sibert A4. Although these wells currently report good quality water, the sustainability and potential for pumping impacts are of concern, especially in the future if exploitation was to increase in the area.

DESSOURCES AREA

The Dessources area is located on the eastern side of Canaan, about 6 km east of Sibert. Several HASCO wells are in this area, including seven free-flowing artesian wells. This area also offers great potential for rehabilitating existing wells or drilling new wells. Table 10 outlines the wells and their potential suitability for Canaan. The local populations currently use most of the wells, as they do not require pumping, and this could present a challenge for adopting these wells for Canaan. Further, there is limited knowledge about the wells and an investment would be necessary to evaluate and test them to determine their condition and suitability for Canaan.

As a consideration for future redundancy and resiliency, supply wells in this area, in addition to the Sibert area, may have advantages. It is likely that the two zones have different recharge areas and may respond differently to future stresses on the aquifer system. As noted above, drilling new wells in this area should avoid drilling into the underlying bedrock.

LEREBOURS

The Lerebours area is located south of the Rivière Batard from the Sibert wells, and several HASCO irrigation wells are located on either side of Route 9. This area also offers great potential for rehabilitating existing wells, or drilling new wells. However, this area is farther away from Canaan, thus, Sibert presents better options in the short-term.

AREAS TO AVOID

The northern and western perimeters of the aquifer should be avoided due to a greater potential for water quality issues. These areas also generally produce lower yields. In the northern extent of the aquifer, there are several risk factors: recharge is limited; seawater may intrude into the aquifer more easily along the northern aquifer boundary; there is older brackish water entrapped in underlying Miocene age bedrock (which are at shallower depths towards the aquifer boundary); and there is a plate boundary (fault) in this area that connects to deeper sulphurous geothermal water that is brackish and not potable (Sous Puantes, and the Hatte Lathan well). The Golfe de la Gonave bounds the western boundary of the aquifer, and the saltwater interface is shallower towards the coast and pumping regimes are more likely to encourage localized seawater intrusion.

As previously mentioned, new boreholes drilled in the aquifer should avoid drilling into the Miocene age bedrock that underlies the aquifer. Older brackish groundwater is trapped within these units, and can negatively impact the water quality of the well during pumping and during periods of aquifer stress.



Figure 23 - Recommended zones for groundwater development to serve Canaan. Also shows potential suitability of select HASCO wells to serve Canaan. Both Zone A and B are considered good areas to develop groundwater resources, however, Zone A is considered to have a lesser degree of long-term risks.

Table 9 - Summary of select HASCO wells in the Sibert Zone and their potential for Canaan

			Flov	Static	Suitability	
Well	Latitude	Longitude	(m)	Water	Ranking for	Notes
			(III)	Depth	Canaan	
Sibert A1 ¹	18.635898	-72.304459	12	Artesian (2016)	Good	Existing HASCO well currently flowing artesian. Records indicate it is 174 m depth, and reported a yield of 35 L/s with 7 meters of drawdown. TDS was 335 mg/L on 27-Oct 2016. Recommend limiting drawdown to 5 meters, which may support a pump rate up to 20 L/s.
Sibert A2	18.640793	-72.301742	9	0.9 m (1946)	Good	This area was suggested by DINEPA to Global Communities as a location for exploiting the aquifer for Canaan, perhaps due to the existing well. Historical records report it is 61 m deep, and reported a yield of 38 L/s with 14 meters of drawdown. Recommend limiting drawdown to 5 meters, which may support a pump rate up to 22 L/s.
Sibert A3	18.64475	-72.299611	10	2.32 m (2013)	Moderate	Existing HASCO well. Recent well service in 2013 reported a depth of 70 m, and included a 65 L/s pump test and 8.7m of drawdown. Recent water quality at this well is considered good (conductivity of 306 us/cm in 2013), however, historical records reported conductivity of 1300 us/cm in the 1970s when there was more aquifer stress in the area. This approaches drinking water guidelines limits; future stress on the aquifer could potentially affect this well more than others in the area. Recommend limiting drawdown at this well to 4 meters, which may support a pump rate up to 30 L/s.
Sibert A4	18.640829	-72.307419	8.4	0.35 (2016)	Poor	Existing HASCO well, verified but has largely collapsed and has minimal depth. Records indicate 200 m depth, and reported a yield of 12 L/s with 14 meters of drawdown. This well is not recommended for serving the Canaan area due to water quality and specific capacity concerns.
Sibert A7 ¹	18.642202	-72.315389	9	1.15 m (2016)	Poor	Existing HASCO well. Records indicate this well was artesian in 1973, but is not currently. Limited data was uncovered for this well, and due to its proximity to the coast and reports that noted more brackish and sulfurous groundwater at 150 m depth, this well is not recommended. 2016 sampling also resulted in Arsenic concentrations above WHO guidelines.
Sibert B1	18.633277	-72.291703	13	2.4 m (1940s)	Good	Existing HASCO well, currently utilized by DINEPA during dry season. Records report 103 m depth, and a yield of 85 L/s with 7.6 m of drawdown. Water quality has historically been below 400 mg/L of TDS, even during periods of high aquifer stress in the 1970s and 1980s. Recommend limiting drawdown to 4.5 meters, which may support a pump rate around 24 L/s.
Sibert B2 (Formerly Bon Repos #3)	18.636503	-72.290501	13	7.3 m (1926)	Good	Unverified HASCO well, may no longer exist. Records report 109 m depth, and a yield of 19 L/s with 4.6 m of drawdown. Limited data was discovered for this well. Recommend limiting drawdown to 4.6 m which may support a pump rate of around 19 L/s.
Sibert B3	18.636627	-72.285474	10	3.4 m (1992)	Moderate	Existing HASCO well currently used for intermittent irrigation. Records report 149 m depth, and a yield of 15 L/s with a drawdown of 8.9 m. Water quality was good as reported in the 1970s and 1980s, not exceeding 450 mg/L of TDS. This well could be considered a candidate for Canaan; however, it is one of the lower yielding wells.
Sibert B4	18.639073	-72.280142	15	8.2 m (1927)	Poor	Unverified well. Records report depth of 105 m, and a large yield of 58.6 L/s with a drawdown of 7 m. Water quality at this well has historically been higher in chloride, with a TDS concentration of 850 mg/L reported in the 1940s. This well is not recommended for Canaan due to the water quality.
Sibert B6	18.629048	-72.290489	11	3.7 m (1952)	Good	Existing HASCO well. Records report 93 m depth, and a yield of 37 L/s with a drawdown of 10 m. Water quality was reported at 320 – 360 mg/L of TDS in the early to mid 1980s. This well could be considered for Canaan. We would recommend limiting drawdown to 6 m which may support a pump rate around 20 L/s.

 $^{-1}$ – Hydrochemistry sample collected as part of this study (Table 6).

Table 10 - Summary of select HASCO wells in the Dessources Zone and their potential for Canaan

Well	Latitude	Longitude	Elev (m)	Static Water Depth	Suitability Ranking for Canaan	Notes
Dessources 1	18.6272	-72.2189	12	Artesian (2016)	Good	Unverified HASCO well. Records indicate it is 152 m depth, and flowed at about 1 L/s in 1921. TDS was reported at 340 mg/L in 1982. Data was not found regarding yield and capacity; however, a pump was reportedly pumping at 70 L/s in 1992.
Dessources 2 Artesian ¹	18.6292	-72.2174	24	Artesian (2016)	Good	Existing HASCO well. Yielded 53.5 L/s with a pump in 1945. Water quality has been good and TDS was 277 mg/L in October 2016. Locals currently use the well, as it is free-flowing artesian at about 7.5 L/s (2016).
Dessources 2 (west)	18.6245	-72.2288	25	1.2 m (1945)	Moderate/Good	Unverified HASCO well. Yielded 53.5 L/s with a pump in 1945. More detailed records were not found for this well.
Dessources 3	18.6289	-72.2165	22	Artesian (2016)	Good	Existing HASCO well. Records indicate 172 m depth in 1945, and 81 m depth in 1992. In 1921, the well flowed at about 3.3 L/s. The well had a pump installed and was reportedly pumping at 50 L/s in 1983. In October 2016, the artesian flow was 1.25 L/s.
Dessources 4	18.6284	-72.2154	25	Artesian ²	Good	Unverified HASCO well. Conflicting records indicate 91 and 155 depth. The well reportedly flowed at 0.7 L/s in 1921. TDS was 385 mg/L in 1983, and 300 mg/L in 1992.
Dessources 5	18.6295	-72.2183	24	Artesian (1920), 2.4 m (1992)	Moderate	Unverified HASCO well. Records indicate an artesian well 106 m depth, and a pumping yield of 8 L/s with 6.7 m of drawdown. In 1920, it reportedly flowed at 1 L/s without pumping. 1992 records suggest pumping was occurring at 47 L/s.
Dessources 6	18.6307	-72.2213	23	Artesian ²	Good	Unverified HASCO well. Records indicate an artesian well 91 m depth; it reportedly flowed at 1 L/s without pumping in 1920. Well records note the major water-producing zone was at 68 m depth.
Dessources 7	18.6313	-72.2168	24	Artesian	Good	HASCO well. Records indicate an artesian well 91 m depth; it reportedly flowed at 1.3 L/s without pumping in 1920. Artesian flow was estimated at 0.6 L/s in October 2016.
Pascher 1	18.6261	-72.2338	24	0.6 m (1948)	Moderate	Unverified HASCO well. Records report 98 m depth, and a yield of 33 L/s with a drawdown of 8.5 m. Another test reported a yield of 59 L/s with a drawdown of 15.6 m. Water quality was good as reported in the 1970s and 1980s, not exceeding 310 mg/L of TDS.
Pascher 6 / Source Ti Puits ¹	18.6424	-72.2290	27	Artesian	Poor	Existing HASCO well. Flowing artesian at 4 L/s in 2016 with conductivity of 354 μ S/cm. Conductivity was 2110 μ S/cm during the 1980s. Well was suggested by DINEPA due to proximity to Canaan. Could not locate records. Well would need pump testing to determine safe pumping yield. Water quality may decrease with pumping and, thus, may not be a good option for Canaan.

¹ – Hydrochemistry sample collected as part of this study (Table 6).

4.3 RECOMMENDATIONS FOR FURTHER STUDIES & MANAGEMENT

The sustainability of water supply for Canaan is largely dependent on factors that are occurring outside of Canaan. Recharge to the aquifer mostly occurs far away, and other wells and groundwater withdrawals up-gradient can significantly affect the availability of groundwater for Canaan in the future. As a result, recommendations need to consider the Plaine du Cul-de-Sac aquifer as a whole.

- 1. Develop an open and available data repository for the PCS aquifer to support informed decision making without requiring major efforts. There should be a formal study of the aquifer in its entirety in order to form a common consensus on current conditions to complement and update past studies.
- 2. Development of groundwater policy and stakeholders for the PCS aquifer; this should be led by the appropriate national authorities. Policy and regulatory mechanisms are required to keep track of wells and abstraction in order to manage the aquifer and minimize the risk for negative impacts.
- 3. Water balance studies to better quantify the current level of development in the aquifer.
- 4. Studies to better estimate the quantities of recharge from streamflow infiltration.
- 5. Delineate and protect critical recharge areas, and implement river irrigation diversion allocations that sustain adequate recharge to the aquifer.
- 6. Climate change impacts study to evaluate impacts to the PCS aquifer; specifically, reduced streamflow infiltration is a concern.

- 7. Monitoring of streamflow of Riviere Bartarde, Riviere Grise and Riviere Blanche.
- 8. Design and implementation of groundwater and surface water monitoring network for the PCS aquifer. This is needed to guide adaptive groundwater planning and management

Specifically for Canaan, the following items are suggested:

- 1. Design and implement groundwater monitoring network to include water tables and water quality. This will support adaptive groundwater management and allow for the detection or indication of issues before they become a major problem.
- 2. Monitor streamflow in Riviere Batarde and Riviere Grise.
- 3. Maintain records of daily abstraction from each production well.
- 4. Foster leadership in the sector for groundwater management and engage as a stakeholder regarding activities that require groundwater abstraction in the Canaan area and the PCS aquifer.

4.4 ADDITIONAL CONSIDERATIONS

CONSIDERATIONS FOR CANAAN

Considerations for the northern zone of the PCS aquifer stretching from Sibert (Route 9) east to Dessources are summarized:

- Recharge occurs distal to the Canaan area and groundwater flow passes numerous areas of current or future abstraction on its way to Canaan. Increases in overall aquifer abstraction will impact water levels and available resources for Canaan.
- Groundwater quality varies with depth and extraction rates. The primary driver of increased salinity appears to be deeper Miocene-aged bedrock which many of the current high-capacity wells intersect and source proportionally more water from under high extraction rates. Future development should avoid these deeper layers in order to maintain better water quality.
- Siting of new wells would benefit from further electromagnetic geophysical soundings to optimize well yields and avoid water quality issues.
- The source of recharge to the Dessources area varies from that of Sibert. Implementation of CTE-RMPP plans for G8-G19 will likely extract groundwater on its way to Dessources, which could reduce the available supply resulting in lowered water tables and decreased water quality.
- The Sibert area along Route 9 has aquifer properties suitable for significant extraction, however, water quality and water tables need to be monitored carefully to avoid pulling water from deep brackish sediments or lowering water tables such that saltwater intrusion occurs. With proper well completion and testing of new wells, and on-going monitoring, these risks can largely be mitigated.
- If future extraction of the PCS aquifer leads to over-exploitation and issues for Canaan, opportunities can be explored to supply groundwater from the Massif Matheux limestone, north of Canaan.

CONSIDERATIONS FOR PLAINE DU CUL-DE-SAC AQUIFER

Although this study did not focus on characterizing the entire PCS basin and aquifer, some key considerations can be developed from the analysis performed:

- Groundwater recharge occurs primarily from infiltration of the Rivière Grise and Rivière Blanche; surface water diversion from these rivers reduces the flow available for recharge.
- Water quality changes within the aquifer appear to be primarily driven by localized abstraction which draws from deeper water-bearing layers, especially on the southern and northern periphery.

- Aquifer management should be centrally coordinated for all stakeholders, including agriculture, industry and potable users, in order to provide comprehensive information to guide extraction rates and river diversion.
- Streamflow measurement at multiple points along the river courses is a critical component necessary to increase the accuracy of actual groundwater recharge, both spatially and temporally. This study was severely limited by the lack of current or time-series hydrograph data for the Rivière Grise and Rivière Blanche.
- Groundwater level and conductivity monitoring should be expanded beyond the CTE-RMPP wells in order to have representative wells from all zones of the aquifer.
- Although saltwater intrusion was not apparent from this study, groundwater abstraction near the coast is currently fairly limited. Increased abstraction must be coupled with strong enforcement of safe water levels in order to keep the saltwater mixing zone away from wells.
- The Massif de la Selle aquifer provides a parallel source of groundwater to populations on the plain and also provides the streamflow which recharges the PCS aquifer. Trends of decreasing spring flow in the Massif de la Selle indicate that the recharge dynamics have shifted considerably with land use, specifically, deforestation. If left unchecked, this will add increasing stress to the PCS aquifer. In addition to coordinated management of the PCS aquifer, we recommend a thorough evaluation of the entire PCS basin in order to better understand the dynamics at work and manage the water resources in an integrated manner.

SUMMARY OF RISK FACTORS

	Short-Term	Medium-Term	Long-Term
Physiochemical Water Quality	Moderate increasing to High monitoring is important in both Sibert and Dessources	of conductivity and other parameters	Very High , monitoring of conductivity and other parameters is critical in both Sibert and Dessources areas
Water Table/Potentiometric Surface	Low , monitoring of piezometric levels recommended in Sibert and Dessources area to avoid water table lowering that could lead to saltwater intrusion or abstraction of deeper Miocene groundwater in Dessources	Moderate , monitoring of piezometric levels recommended in Dessources but, especially, Sibert areas to avoid water table lowering that could lead to saltwater intrusion	High , parallel growth of abstraction in region will make aquifer-wide piezometric monitoring critical to a resilient supply as groundwater flow to Dessources and, especially, Sibert will decrease, if abstraction in the central or southern regions increase
Contamination	Low , low permeability surface layers however, development near the recharg potential to inject contaminated groundwa mean this may not be noticed for many year	help protect the confined aquifer, ge zone of the Rivière Grise has ater into deeper layers. Travel times ars	Moderate , industry growth and increased well density will raise the risk of contaminants travelling down poorly completed wells
Well & Spring Interference	Low , groundwater which feeds springs in of recharge to the PCS aquifer	the northern Massif Matheux and Mc	ontagnes Trou d'Eau is not a primary source
Groundwater Depletion	Low, with proper wells spacing and monitoring of groundwater levels, there should be sufficient water to serve Canaan	Moderate , as other parts of the aquifer are more heavily exploited, depletion will become a concern, especially in Sibert	High , regional growth in population, industry and agriculture put the aquifer at major risk of depletion, if not managed as an integrated basin
Recharge and Flow	Low , recharge highly dependent on streamflow along the southern boundary of the aquifer, and effects of changes in recharge will be slow to occur in Sibert and Dessources	Moderate , increased growth, especially of agriculture, will add pressure to divert river flow, which will decrease groundwater recharge	High, climate change and precipitation intensity will likely lead to 'flashier' hydrology in the southern watersheds which recharge the aquifer, thus reducing baseflow and streamflow recharge. Agricultural growth and increased aridity will increase demands on river diversions which will also reduce groundwater recharge

Table 11 - Summary of risk factors for development of PCS aquifer to serve Canaan

Note: these estimations of risk were compiled for the development of a water supply for Canaan, not the entirety of the PCS aquifer. However, aquifer management must also occur throughout the aquifer.

4.5 LIMITATIONS OF EVALUATION

Aspects of the assessment were especially limited by the unavailability of data and resources regarding the Plain du Cul-de-Sac aquifer. The lack of monitoring and records made it especially challenging to quantify the current health of the aquifer and its sustainability. A focused and basic level of analysis and synthesis was applied throughout the report with the primary objective to evaluate the potential for securing large quantities and yields of good quality and sustainable groundwater for Canaan.

This assessment was performed using the degree of professional care and skill ordinarily exercised, under similar circumstances, by experienced geologists and geophysicists practicing in this or similar locations with very limited sources of data and resources. Changes in analysis and interpretations can and will occur with the acquisition and analysis of new data, such as drilling results or other geophysical methods. Analysis and interpretations presented in this report must be considered fluid and subject to review and revision as additional data is compiled. Analysis and interpretations described in this report may be invalidated wholly or partially by the results of continued data collection and observations.

Much effort went into crafting a general characterization regarding the PCS aquifer; this was necessary in order to adequately inform basic-level planning and decision making for Canaan. This report presents this general characterization, however, this report is not intended to serve as a conclusive characterization of the aquifer, nor shall this be considered a complete and comprehensive study for the aquifer. The study did, however, produce a great volume of work, recent data collection, and collation of historical data that will support more formal scientific characterization in the near future.

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APPENDIX 1

SUPPLEMENTAL TABLES & FIGURES

Table 12 - Monthly precipitation measurements for towns in or near study area

Station	Elevation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Years of Record
Cabaret	81	20	26	54	76	174	84	85	114	137	100	53	22	945	30
Chauffard	1300	14	39	68	231	363	273	245	359	285	226	89	68	2260	11
Cornillon	1000	29	57	53	163	197	128	174	211	201	138	125	47	1523	6
Croix-des- Bouquets	50	18	31	50	103	176	70	59	123	121	116	50	21	938	37
Despuzeau	40	11	23	31	79	129	58	49	96	99	156	56	22	809	25
Duvalierville	70	22	32	66	104	184	166	105	138	151	147	80	25	1220	9
Furcy	1540	30	49	68	129	310	254	155	200	279	255	126	33	1888	38
Ganthier	70	11	22	38	101	145	49	35	68	106	125	56	56	812	52
Grand-Bassin	75	21	71	53	106	175	139	49	66	89	193	107	56	1125	10
Juvenat-Haiti	300	31	45	71	199	233	113	85	139	173	181	95	23	1388	20
Kenscoff	1400	18	39	53	206	334	184	104	181	252	254	67	46	1738	13
Pétion-ville	399	24	46	86	192	256	125	86	152	187	179	78	30	1441	61
P-au-P Airport	34	38	33	30	108	117	49	67	91	102	102	100	18	855	30
Seguin	1680	35	38	74	125	237	175	166	181	180	391	98	33	1733	15
Note: All values in mm (FAO, 2000).															



Figure 24 - Annual precipitation in Cul-de-Sac basin, modified from Hijmans (2005) and basins used for analysis

Table 13 - Monthly temperature measurements for towns in or near study area

Station	Elevation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Cabaret	81	25.0	25.6	26.1	26.7	27.1	27.8	28.4	28.1	27.4	27.0	26.2	24.9	26.7
Chauffard	1300	15.9	16.4	17.1	17.5	18.2	19.2	19.4	19.6	19.4	18.6	17.6	16.7	17.9
Cornillon	1000	20.9	21.1	22.2	22.9	23.4	24.2	24.8	24.7	24.7	23.6	22.6	21.7	23.0
Croix-des-Bouquets	50	23.9	24.2	24.9	25.7	26.4	27.2	27.4	27.5	27.3	26.9	25.7	24.5	25.9
Despuzeau	40	24.0	24.3	25.0	25.8	26.5	27.3	27.5	27.6	27.4	27.0	25.8	24.6	26.0
Duvalierville	70	25.1	25.5	26.9	26.8	27.5	28.2	28.4	28.5	28.0	27.5	26.3	25.6	27.0
Fonds Parisien	30	23.8	23.7	25.8	26.0	26.8	27.0	27.5	27.9	27.6	25.0	24.3	24.7	25.8
Furcy	1540	14.4	14.9	15.6	15.9	16.6	17.6	17.8	18.0	17.9	17.0	16.0	15.1	16.4
Ganthier	70	25.3	26.0	26.8	27.4	27.7	28.2	28.6	28.5	28.1	27.7	26.8	25.4	27.2
Grand Bassin	75	23.8	24.1	24.8	25.6	26.3	27.1	27.3	27.4	27.2	26.8	25.6	24.4	25.8
Kenscoff	1400	15.9	15.2	16.0	16.7	17.5	18.2	18.4	18.2	18.6	18.0	17.4	16.2	17.2
Pétion-ville	399	22.9	23.3	23.9	24.6	25.2	25.8	26.4	26.4	25.9	25.1	24.1	23.2	24.7
P-au-P (aéroport)	34	25.4	25.7	26.4	27.0	27.3	28.2	28.7	28.5	27.9	27.2	26.6	25.8	27.0
Seguin	1680	10.2	11.2	11.2	11.7	12.3	13.8	14.4	14.8	14.2	13.3	12.6	10.7	12.4
Sources Chaudes	6	23.7	24.0	24.7	25.4	26.1	27.0	27.1	27.3	27.0	26.6	25.4	24.2	25.7
Note: Source (FAC	, 2000)													

Table 14 - Monthly evapotranspiration estimates for towns in or near study area

Station	Elevation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Cabaret	81	106	116	125	136	144	159	172	165	150	142	127	104	135
Chauffard	1300	52	55	60	62	67	74	75	77	75	70	63	57	65
Cornillon	1000	70	72	83	90	96	105	112	111	111	98	87	78	92
Croix-des-Bouquets	50	92	96	107	119	131	146	150	152	148	141	119	101	123
Despuzeau	40	93	97	108	121	133	148	152	154	150	142	121	102	125
Duvalierville	70	106	113	139	137	152	168	172	175	163	152	128	115	141
Furcy	1540	49	51	56	57	62	68	69	70	70	64	58	53	60
Ganthier	70	108	121	136	149	156	167	177	174	165	156	136	110	144
Grand Bassin	75	91	96	106	118	130	145	148	150	146	139	118	100	122
Kenscoff	1400	55	51	55	60	65	69	71	69	72	68	64	57	63
Pétion-ville	399	85	89	97	106	115	124	133	133	125	113	100	88	108
P-au-P (aéroport)	34	111	116	129	141	148	168	180	175	161	145	133	118	142
Seguin	1680	40	45	45	48	51	59	62	64	61	56	52	43	52

Note: based on Thornwaite method (FAO, 2000)

Table 15 - Primary	watersheds of th	e Cul-de-Sac ba	asin used for analysis

Basin ID	Basin Area (km ²)	Subbasin ID	Subbasin Area (km ²)	Basin ID	Basin Area (km²)	Subbasin ID	Subbasin Area (km ²)
А		A1	641.6	С		C5	22.3
А		A2	173.3	С		C6	6.2
А		A3	72.6	С		C7	3.9
А	059.1	A4	26.9	С	249.5	C8	59.6
А	958.1	A5	24.0	С	248.5	C9	29.6
А		A6	4.7	С		C10	5.6
А		A7	5.6	С		C11	5.1
А		A8	9.4	С		C12	5.0
В		B1	29.0	D		D1	9.4
В	321.1	B2	14.6	D	93.5	D2	13.0
В		B3	277.6	D		D3	71.1
С		C1	44.8	E	41.9		
С		C2	11.0	F	18.8		
С		C3	34.8	G	12.2		
С		C4	20.6	Н	13.4		
				I	18.4		
					Total Area	1725.9	km ²

Name	Ave	rage Flow Rate	Drainage Area	Surface Area				
	Mean (m ³ s ⁻¹)	Max (m ³ s ⁻¹)	Min (m ³ s⁻¹)	(km²)	(km²)			
Riviere Grise	4.2	29.4	0.94	276				
Riviere Blanche	1.9	14.9	0.92	170				
Lac Azuei					115 (137) ²			
Trou Caiman					4.5			
¹ Flow rates calculated from Gonel (2006), measurement years 1919-1940 and 1976-1981 ² Historical area and (current area)								

Table 16 - Characteristics of primary rivers and lakes in study area



2*22'0'W 72*20'0'W 72*18'0'W 72*16'0'W 72*14'0'W 72*120'W 72*10'W 72*10'W 72*8'0'W 72*6'0'W 72*40'W 72*2'0'W 72*0'W 71*58'0'W 71*58'0'W 71*56'0'W 71*50'0'W 71*50'UW 71*50'0'W 71*50'UW 71*50'UW

Figure 25 – Updated geologic map of Plaine du Cul-de-Sac Basin based on Taylor (1949), CERCG (1989), Cox et al (2011) and Oxfam (2013)

Table 17 - Rainfall chloride measurements Lat Date Elev (m) Chloride (mg/l) Location Long Laboule 10/19/2016 18.4951 -72.3154 850 < 0.7 Laboule¹ 10/4/2016 18.4951 -72.3154 850 < 0.7 Laboule 10/24/2016 18.4951 -72.3154 850 < 0.7 18.5749 -72.2768 42 Clercine 12 10/30/2016 < 0.7 45 Cabaret #1 9/16/2015 18.7360 -72.4175 1.32 Cabaret #4 3/6/2016 18.7360 -72.4175 45 3.91 Cabaret #2 45 2/2/2016 18.7360 -72.4175 14 Lafito 2/11/2016 18.6966 -72.3494 22 29.00 Geometric Mean 1.8 Note: assumes chloride values for Laboule and Clercine 12 are approximately 0.5 mg/L $^{\rm 1}$ Sample taken during Hurricane

Matthew

Table 18 - Results of E. coli testing during water point transects

		Tuon	io nesuna		ing during water p	contra danseets		
#	Echantillon	MPN/100 ml	Latitude (dd)	Longitude (dd)	Zone	Туре	Appartenance	Date
1	Entrée Duvivier	0.0	18.60025	72.32233	Route neuf	Mark II Handpump	Communautaire	10/21/2016
2	Do rigol	0.0	18.60655	72.31969	Route neuf	Mark II Handpump	Communautaire	10/21/2016
3	Fougy	0.0	18.61185	72.31733	Route neuf	Mark II Handpump	Communautaire	10/21/2016
4	Leurbourg	0.0	18.62346	72.31092	Route neuf	Mark II Handpump	Communautaire	10/21/2016
6	Nan 10	0.0	18.63222	72.30632	Sibert	Mark II Handpump	Communautaire	10/21/2016
7	Bo Izin	0.0	18.62710	72.30175	Sibert	Mark II Handpump	Communautaire	10/21/2016
9	kafou Fougy	0.0	18.61415	72.31509	Route neuf	Mark II Handpump	Communautaire	10/21/2016
10	Pwa Kongo	0.0	18.60733	72.31953	Route neuf	Mark II Handpump	Communautaire	10/21/2016
11	Route rail	0.0	18.59486	72.88581	Croix des Missions	Mark II Handpump	Communautaire	10/22/2016
14	Route Nationale #1	0.0	18.60710	72.28009	Marin	Mark II Handpump	Communautaire	10/22/2016
17	Impasse Antoine	0.0	18.61963	72.27782	Lizon	Mark II Handpump	Communautaire	10/22/2016
21	Impasse mavilus	0.0	18.63993	72.26289	Bon Repos	Mark II Handpump	Communautaire	10/22/2016
24	Ruelle Shalom	0.0	18.58936	72.22598	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
25	Nan 2 /Dessources	0.0	18.62887	72.22948	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
26	Lilavois 64	0.0	18.60906	72.23067	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
27	Lilavois 68	0.0	18.60737	72.22064	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
28	Rue Thélémaque	0.0	18.60456	72.22202	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
30	Beudet 9	0.0	18.60245	72.22760	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
31	Beudet 7	0.0	18.59973	72.22359	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
33	Savane Blonde/Ti Boule	0.0	18.58568	72.22687	Croix des Bouquets	Mark II Handpump	Communautaire	10/24/2016
34	F3	0.0	18.58900	72.27460	Clercine	Municipal Production	CTE/RMPP	10/27/2016
35	T2	0.0	18.55687	72.24516	Tabarre	Municipal Production	CTE/RMPP	10/27/2016
36	Т6	0.0	18.53770	72.22679	Tabarre	Municipal Production	CTE/RMPP	10/27/2016
37	T1	0.0	18.56044	72.23869	Tabarre	Municipal Production	CTE/RMPP	10/27/2016
38	D2	0.0	18.60765	72.32560	Duvivier	Municipal Production	CTE/RMPP	10/27/2016
39	D5	0.0	18.59795	72.31779	Duvivier	Municipal Production	CTE/RMPP	10/27/2016
41	F2	0.0	18.58258	72.29309	Clercine	Municipal Production	CTE/RMPP	10/28/2016
5	Centre Sportif	0.0	18.65388	72.29050	Route neuf	Private or Institutional	CIO	10/21/2016
13	Mag Bon Dlo	0.0	18.60381	72.28175	Shada	Private or Institutional	Entreprise Privée	10/22/2016
29	Ecole notre Dame	0.0	18.60764	72.21938	Croix des Bouquets	Private or Institutional	Institution Privée	10/24/2016
18	Impasse Omega	>100	18.62475	72.26971	Lilavois	Private or Institutional	Maison privée	10/22/2016
32	Sténio Vincent #36	>100	18.59725	72.22442	Croix des Bouquets	Private or Institutional	Maison Privée	10/24/2016
8	Impasse Jean Noel	>100	18.61423	72.31079	Marin	PVC Handpump	Maison privée	10/21/2016
12	Impasse Gérard	0.0	18.60304	72.28379	Shada	PVC Handpump	Maison privée	10/22/2016
15	Impasse Moise	1.2	18.60666	72.28292	Marin	PVC Handpump	Maison privée	10/22/2016
16	Rue Lèo	1.2	18.61542	72.27306	Lizon	PVC Handpump	Maison privée	10/22/2016
19	Impasse Clément	0.0	18.22686	72.27004	Bon Repos	PVC Handpump	Maison privée	10/22/2016
20	Rue Rossini	0.0	18.63272	72.26947	Bon Repos	PVC Handpump	Maison privée	10/22/2016
22	Rue Libellule	0.0	18.64058	72.26316	Bon Repos	PVC Handpump	Maison privée	10/22/2016
23	Rue Lumière	>100	18.64552	72.25910	Bon Repos	PVC Handpump	Maison privée	10/22/2016
40	Sibert A1	0.0	18.63589	72.30445	Route neuf	Uncovered well	Ancien HASCO	10/27/2016
42	Sibert #6	>100	18.63012	72.29309	Route neuf	Uncovered well	Ancien HASCO	10/29/2016
43	Sibert #7	2.4	18.64215	72.29309	Route neuf	Uncovered well	Ancien HASCO	10/29/2016

			Surface	
Station	Longitude	Latitude	Elevation	Location Notes
			(m)	
1	-72.28585	18.63716	10	Near HASCO Sibert B3
2	-72.29155	18.63934	12	Near old canal, aerial may show an old well here but could not be verified
3	-72.31521	18.64198	8	Near HASCO Sibert A7
4	-72.30866	18.63926	7	Near HASCO Sibert A4
5	-72.30509	18.63630	14	Near HASCO Sibert A1 flowing artesian well
6	-72.30169	18.64084	15	-
7	-72.29976	18.64458	13	Near HASCO Sibert A1
8	-72.29709	18.64953	10	In salt flat exposed area to west of route 9, North of HASCO Sibert A3
9	-72.27959	18.64022	13	Possibly near Sibert A4 well, unverified
10	-72.27590	18.64088	16	
11	-72.22896	18.64242	27	Near HASCO Pascher 6 (Source Ti Puits)
12	-72.22281	18.63685	21	Near HASCO Pashcer No. Unknown, Taylor No. 70
13	-72.21788	18.62951	24	100 ft South of flowing artesian HASCO Dessources No. 2
J1	-72.24310	18.66954	97	Near top of ridge
J2	-72.24775	18.66772	81	Old broken well nearby
J3	-72.25269	18.66277	47	Near hand pump well
J4	-72.25291	18.65707	36	Near brackish well
J5	-72.25486	18.65269	27	Near brackish well

Table 19 - Locations of CSAMT/MT electromagnetic geophysical soundings



Figure 26 - Modeled annual effective infiltration in mm

APPENDIX 2

VERTICAL CONDUCTIVITY DEPTH PROFILES OF WELLS
















































Type de Tubage	Tubage	Depth	Conductivite (2013)				Conductivite (2016)					
	1	1:200	400 us/cm 650			400 us/cm			650			
			Temperature (2013)			Temperature (2016))				
			28		С		32	28		С		32
		- 36 -									_/	/
Crepine nervures-rep. Inox-indetermine Tube-plein Inox-indetermine Qualite variable du adherence du ciment au casing 45.6 m		- 40 - - 40 - - 44 -										
Adherence bon du ciment au casing 43.3 - 46.0 m												
Generalement une bonne adherence du ciment a la faible vitesse a argile et sable		- 48 -										
Crepine nervures-rep. Inox-indetermine		- 52 - - 52 - - 56 -										/
Tube-plein Inox-indetermine Pas de donnees		- 60 -										
		_	28 C 32			28 C			32			
	1	⊣ 1:200	Temperature (2013) 400 us/cm 650				400	Tempe	erature (2016) us/cm)	650	
Type de Tubage	Tubage	Depth	Conductivite (2013)				Conductivite (2016)					





















Type de Tubage	Tubage	Depth		Conductivité (2013))	Conductivité (2016)			
	1	1:200	400 us/cm Temperature (2013)			400 us/cm 700 Temperature (2016)			
			24	С	29	24	С	29	
			24	С	29	24	С	29	
				Temperature (2013))	Temperature (2016)			
		1:200	400	us/cm	700	400	us/cm	700	
Type de Tubage	Tubage	Depth		Conductivité (2013)		Conductivité (2016)			

















Type de Tubage	Tubage	Depth		Conductivite (2013)		Conductivite (2016)				
	1	1:200	300	us/cm 650 Temperature (2013)		200	650			
			27	С	32	27	С	32		
Tube-plein PVC										
		- 84 ·								
		- 88 -								
Crepine fentes PVC	- 92 -									
		- 96 -								
Tube-plein PVC		- 100 -								
<u> </u>			27	С	32	27	C	32		
		1:200	Temperature (2013) 300 us/cm 650			Temperature (2016) 200 us/cm 650				
Type de Tubage	Tubage	Depth		Conductivite (2013)		Conductivite (2016)				









APPENDIX 3

RESISTIVITY DEPTH LOGS (CSAMT/MT GEOPHYSICAL SOUNDINGS)
























