GEOLOGIC HAZARD ASSESSMENT AND RESERVOIR SITE CHARACTERIZATION – REPORTS I & II

August 31, 2018

PROJECT: GEOLOGICAL ASSESSMENT TO SUPPORT THE PREPARATION OF THE OPERATION HL-L1135, HAÏTI

PREPARED FOR:
INTER-AMERICAN DEVELOPMENT BANK

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EXECUTIVE SUMMARY

This report presents the results of a Geologic Hazards Assessment of the proposed Cap-Haitien water system. The goal of this report is to aid the Bank in the Environmental Safe Guards (ESG) process and to provide recommendations pertinent to the design and construction of the water system. Three primary components of the proposed Cap-Haitien water system were reviewed within the context of geologic hazards: i) the reservoir site in Bel-Aire, ii) the supply pipeline from the Balan well field to the Bel-Aire reservoir, and iii) the primary distribution pipelines from the Bel-Aire reservoir to service areas.

The assessment concludes that the project is in a high geological hazard risk zone. Several specific hazards were identified and should be appropriately considered as the operation advances. Our key recommendations are outlined below; the Bank should consider appropriate financing to assure appropriate expertise and resources are available throughout construction and that mitigation alternatives can be applied where feasible and appropriate.

Design for redundancy – The variety and spatial distribution of geologic hazards in the study area warrants that redundancy be a primary design consideration for the water system. Secondary infrastructure for supply, storage and distribution should be considered in a phased approach to achieve redundancy.

Design for rapid service recovery – It is probable that geologic hazards will cause water service disruption sometime in the future. System design and management must consider the greatest vulnerabilities in the system related to geologic hazards to mitigate the extent and duration of water service disruptions should an event occur. Incorporation of design and management features which mitigate both the extent and duration of disruption is needed.

Reservoir & Storage – The reservoirs in Bel-Aire require detailed analysis due to the identification of a potential fault zone beneath the site. In the context of this hazard, we recommend that an in-depth structural, geological and geotechnical analysis be performed to direct next steps related to the feasibility, costs and preferred design/construction solutions to reinforce and rehabilitate the existing reservoirs. Set-back distances should be established if future investments are to be made in Bel-Aire related to increasing storage.

- During subsequent operations, secondary areas should be evaluated for additional reservoirs and preferred locations selected. Establishing secondary and additional storage is an important activity to strengthen the system resiliency to geological hazards.
- Consider the option to design emergency pumping/pressurization functionality that would allow the well field to directly pressurize the distribution network if the reservoirs are damaged.

Site-level design – Areas of increased geologic hazards, especially near fault crossings and zones of potential liquefaction may require site-level assessment and design. We recommend that the supervision and contractor contracts include line-items for geotechnical assessment to guide site level design and construction adjustments. In defined

hazard areas, robust oversight and supervision by a geotechnical or geological engineer with experience in geologic hazard mitigation is recommended.

Materials, technologies and best practices – System design should incorporate appropriate, cost effective, and available materials and technologies that consider the hazards, especially in the specific locations of concern identified in this report such as fault crossings and zones of potential liquefaction.

- While some mitigation measures may be most efficiently designed with site-level geotechnical data, there are many measures which should be immediately integrated in the design moving forward. These measures are discussed in Section 7.1 and 7.2.
- In order to facilitate clear and efficient field design and installation we recommend that the bill of quantities include estimated amounts of specialized mitigation materials and methods so that per-unit pricing is established prior to site-level design.

Supervision, technical expertise and experience – Successful and durable design and construction of water infrastructure requires robust supervision, continuity and ownership. These factors are often lacking in Haiti water infrastructure projects. One method to encourage this ownership and continuity is the build-operate-train model in which the eventual system operator is involved in a supervisory and design role throughout the project implementation. This ensures that standards conducive to water system use and management are employed, as the operator has a keen interest in the quality of the system.

- Given the specific hazards present, we recommend that the supervisory firm has expertise in geological and geotechnical engineering, hazard investigation and mitigation, subsurface investigations, geophysics and pipeline design. The supervisory firm will also need water system design capabilities in order to approve and have input into field design decisions based on field results during construction.
- As this system will be approached in phases, it may be beneficial for the supervisory/operator firm to lead the design of the Phase 2 infrastructure including a second supply line and reservoir which will further encourage ownership and the quality needed for long term system functionality and maintenance.

It is important to note that this report focused on *identifying* geologic hazards and full characterization of each hazard and specific design recommendations were beyond the scope of this consultancy. Public datasets, governmental research and geotechnical information related to hazards and mitigation is not available in Haiti. As a result, it is cost and time prohibitive to characterize all of the hazards. The authors emphasize that further study of some hazards, particularly fault rupture, liquefaction and tsunami scour would be recommended if additional resources were available. In the absence of such studies, we recommend a watchful eye during construction and trenching, especially in potential hazard zones. Based on such observation, focused geotechnical assessments and appropriate mitigation practices can be applied when directed and appropriate.

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SECTION 1 – INTRODUCTION

The Inter-American Development Bank (IDB) commissioned a Geologic Hazards Assessment (GHA) for components of the proposed Cap-Haitien Water System in order to aid in the Environmental Safe Guards (ESG) process.

The purpose of this study is to evaluate the potential geologic hazards and better understand the geotechnical conditions for three primary components of the proposed Cap-Haitien Water System, which include:

- Reservoir site
- Supply pipeline, from Balan area supply wells to reservoir
- Primary distribution pipelines from reservoir to service areas

The study expresses professional opinions regarding geologic hazards to the water system based on limited data and a brief field reconnaissance. As part of this GHA scope of work, no statements or opinions made refer to the suitability or integrity of existing infrastructure.

Activities performed include:

- Research, desk review and digitization of existing hazards mapping
- Identification of key data gaps to be reviewed in the field
- Terrain and satellite imagery analysis
- Two brief field reconnaissance missions to observe local geologic conditions and perform a short geophysical survey.

Following these activities, all available data was synthesized in order to assess potential geologic hazards related to the proposed water system infrastructure. Figure 9 and Table 8 at the end of the report summarize the key geologic hazard zones for the water system along with recommendations for further investigation and mitigation strategies. Detailed recommendation descriptions can be found in Appendix A.

SECTION 2 – PROJECT DESCRIPTION

The study area is located in Cap-Haitien, in the Departement Nord, Republic of Haiti. Cap-Haitien is the second largest city in Haiti, and the capital of the Departement Nord, with an estimated population of 400,000 people. Based on water demand analysis provided by IDB, the 2025 water demand is 18,835 m3/day, and the 2035 demand is 35,338 m3/day.

The water infrastructure plan was developed by an IDB engineering consultant and was provided by the IDB as the basis for this assessment. Based on the information provided and conversations with DINEPA, the proposed supply line extends from several production wells in the Balan area to an elevated reservoir site in the Cap-Haitien suburb area of Bel-Aire. The proposed reservoir site has an existing 2,500 m^3 reservoir that was

constructed between 2009 and 2012 by GRETCO. Another smaller reservoir is located 70 m west of the proposed reservoir site on a 500-m^2 land parcel. This smaller reservoir appears to have been constructed around the same time as the larger one. Our team enquired with GRETCO regarding reservoir design and construction documentation, GRETCO informed us that all records were destroyed in the 2010 earthquake.

Together, the two existing reservoirs have a reported capacity of 4,250 m^3; 2500 m^3 at the lower (larger) reservoir and 1750 m^3 at the upper (smaller) reservoir. Preliminary water system design documents specify a system storage capacity of 40% of daily consumption. This would suggest that nearly double the current storage is necessary to meet 2025 demand and approximately 3-times the current storage to meet 2035 demand.

For clarity and brevity, this report refers to the proposed reservoir site as the larger 2,000-m^2 land parcel that currently houses the 2,500-m^3 existing reservoir.

The supply and primary distribution pipelines connect to the reservoir sites from a junction at Route L. At the Route L junction, the proposed distribution system branches into three zones, one to the north (Centre Ville), one to the east (Petite Anse) and the other to the south (Haut du Cap). Figure 2 illustrates the alignment of the proposed water system.

TABLE 1 – PROPOSED WATER SYSTEM DETAILS

Infrastructure	Design Summary
Supply Pipeline	• Total length of 7,200 meters (approximate) • Planned 500 mm diameter cast-iron pipe from well field to reservoir • Elevation along line ranges from 4-m AMSL to 49-meters AMSL at the reservoir
Main Distribution Pipeline	• Approximate total length of 248,161 meters o 164,804 meters of Ø 63mm HDPE or PVC o 37,594 meters of Ø 110mm HDPE or PVC o 11,488 meters of Ø 160mm HDPE o 17,981 meters of Ø 200mm HDPE o 5,427 meters of Ø 250mm HDPE o 1,001 meters of Ø 300mm HDPE o 7,267 meters of Ø 355mm HDPE o 1,113 meters of Ø 400mm HDPE o 1,486 meters of Ø 500mm HDPE • Proposed system would provide distribution to service areas at 41-meters AMSL or lower
Reservoir (Bel-Aire)	• Approximate site area of 2,000 m^2 at proposed reservoir location • Approximate site area of 5,00 m^2 at second reservoir location • Existing capacity total of 4,250 m^3 at two existing reservoirs (reported) • Additional needed capacity (being reviewed, assumes 40% daily storage): o 2025: 3,284 m^3 (7,534 m^3 total) o 2035: 9,885 m^3 (14,135 m^3 total) • Proposed site elevation : 48 to 51 m AMSL • Secondary reservoir site elevation: 54 to 56 m AMSL • No details were available at the time of writing as to the proposed design of new reservoirs

SECTION 3 – FIELD PROGRAM

A brief field program was conducted on June 8-9 and July 24-25, 2018 in order to document field observations in key areas, and to assist in filling data gaps to support the hazard assessment. Figure 1 shows the locations of the field reconnaissance activities and where seismic geophysical data collection occurred. It is important to note that no geotechnical borings or laboratory materials testing were performed or acquired as a part of this study. The field program included:

- Site-level geologic, structural and geo-mechanic mapping near the existing reservoir site in Bel-Aire
- Geophysical surveys across the Bel-Aire valley using seismic methods including compressional (P) and shear (S) wave refraction and Horizontal to Vertical Spectral Ratio (HVSR). A total of six HVSR stations, one P-wave refraction line and one S-wave refraction line were completed. HVSR stations were modeled into a 2D profile in order to estimate unconsolidated material thickness and assess potential faults.
- Geophysical survey along the primary supply line from the F10 supply well to the Bel-Aire reservoirs. A total of seven HVSR stations were completed and modeled to infer sediment thicknesses and characteristics.
- Observation of key locations where mapped hazard zones intersect the supply or main distribution lines. Locations included debris-flow and drainage crossings of the main distribution line along National Route 1, the supply line crossing of Riviere Haut du Cap, and the area uphill from the Bel-Aire reservoirs.

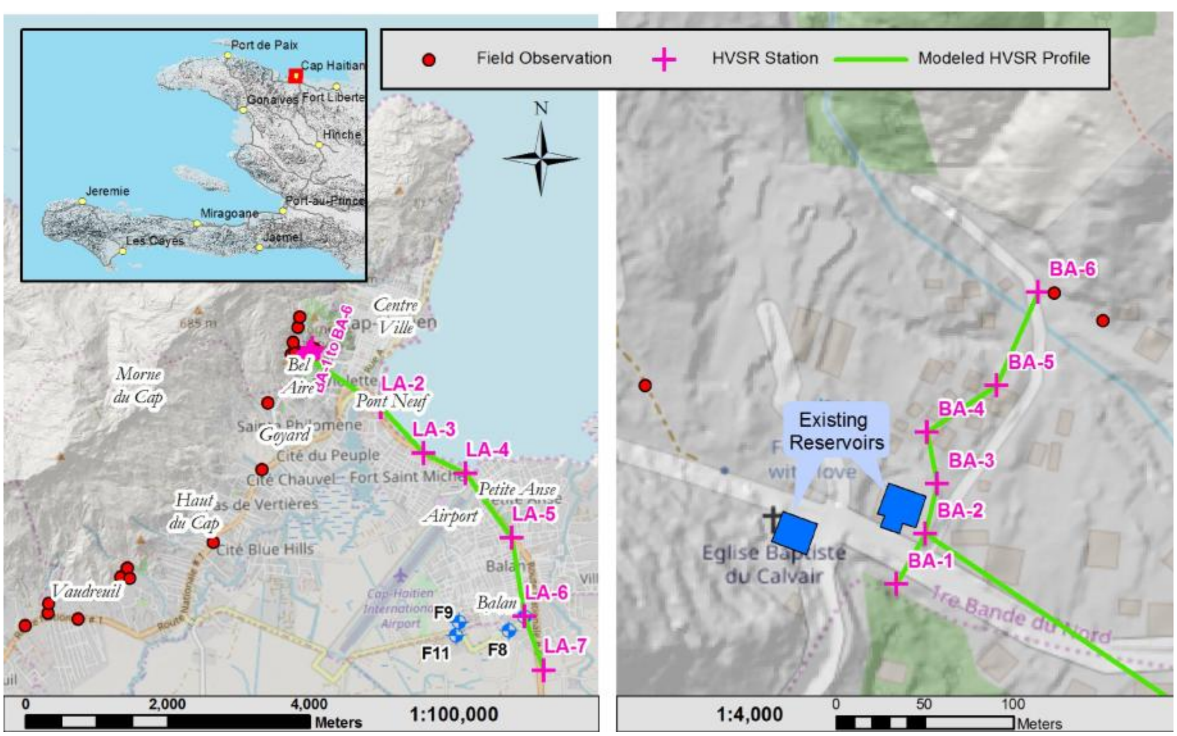

FIGURE 1 – LOCATION MAP OF FIELD OBSERVATIONS AND HVSR GEOPHYSICAL STATIONS

SECTION 4 – GEOLOGIC CONDITIONS

Section 4.1 – Regional Geology

The site has complex geology due to the tectonic, volcanic and stratigraphic history. The northern coast of Haiti is comprised of several mountain ranges with plains and valleys formed by tectonic and geomorphic processes. The basement rock of the region is primarily of Cretaceous-aged volcanic rocks consisting of andesite, rhyodacite and volcano-sedimentary conglomerates and breccias. Recent mapping by BRGM (Monthel et al, 2013) indicated that the Morne-du-Cap area was also intruded by tonalite. During the Late Cretaceous and Paleogene, thick units of volcano-sedimentary and sedimentary rocks were deposited concurrently as active tectonic processes occurring, including terrane accretion, strike-slip faulting, and regional uplifting.

The structural plains and valleys have been filled in with thick blankets of Miocene to Quaternary and recent sediments of both marine and terrestrial origin. The older Miocene sediments are semi-consolidated and predominately of marine origin. The Plaine du Nord alluvial plain has experienced several periods of transgression and regression from the Pliocene and Pleistocene Epochs to present.

The northern coast of Haiti is flanked by one of the two primary fault zones of Hispaniola: the Oriente-Septentrional Fault Zone (OSFZ). Near Cap Haitien, the OSFZ is primarily left-lateral strike-slip with ancillary thrust, strike-slip and normal faulting (Figure 3). The OSFZ is a very active fault system, with slip rates of up to 9 to 11 mm/year (Calais, 2015). Ruptures along the OSFZ have historically caused major damage to coastal towns like Cap-Haitien (1842), Mole Saint Nicolas (1887), Port de Paix and Jean Rabel (1956). Recent modeling by Torres et al (2016) indicated that the OSFZ could produce a 7.9 magnitude earthquake 10-km from Cap-Haitien at a depth of 20-km. Torres et al (2016) also modeled the destruction to Cap-Haitien from such a rupture, suggesting an estimated 13,500 buildings, or 47% of the city would be destroyed.

Section 4.2 – Site Geology

The project site has several different geological settings, primarily due to length and alignment of the supply and distribution pipelines. The site geology is outlined based on synthesis of a modified version of the CERCG (1989) 250K scale geological map with geologic mapping performed by BRGM (Gilles, 2014) in the Morne-du-Cap area, and also supported by field observations and terrain analysis by the authors. There were no soil or geotechnical borings performed, or detailed geological mapping performed to validate or verify the geological units and their contacts. Table 2 describes the geological units present in the project site, and Figure 2 illustrates the surficial geology of the project area.

The supply pipeline is primarily underlain by Quaternary-aged alluvial deposits (Qam), the last kilometer towards the reservoir is underlain by Quaternary-aged colluvial deposits on top of bedrock.

The distribution pipeline is primarily underlain by Quaternary age alluvial deposits (Qam) in the Centre Ville and Petite Anse sections. In the Haut-du-Cap section, the predominant surficial geology is Quaternary age colluvial deposits (Qcl) that overlie bedrock.

The reservoir is underlain by a thin veneer of Quaternary-aged colluvial deposits (Qcl) with fractured Cretaceous-aged andesite bedrock below. The thickness of the unconsolidated colluvial deposits is estimated to be between 5 and 10 meters thick under the existing reservoir.

Table 2 describes the geological units present in the project site, and Figure 2 illustrates the surficial geology of the project area.

TABLE 2 – GEOLOGIC UNITS PRESENT AT STUDY SITE

Geological Unit	Description
Qan	Anthropogenic fill, primarily around the harbor
Qam	Quaternary-aged alluvial deposits of moderate to high permeability. Grades from coarse sand and cobble in the south to fine to medium sand with beds of silt and clay near the coast.
Qcl	Quaternary-aged colluvial deposits, primarily shed from the Morne-du-Cap andesites, volcano-sedimentary units and carbonate float.
Ems	Middle to Upper Eocene-aged carbonate rock, observed to be micritic or brecciated, lies unconformably over Paleocene and Cretaceous units.
Ep	Paleocene to Lower Eocene-aged volcano-sedimentary rock, volcano-breccia and turbidite sequences
Cf	Upper Cretaceous age conglomerates and limestones
a	Cretaceous volcanic rock, primarily andesite with some zones vesicular and of pyroclastic origin.
Et/Gd	Likely Eocene-aged tonalites which intruded the cretaceous volcanics during the Eocene, helping to form the core of Morne-du-Cap. Emplacement is poorly constrained and may also be older and part of the *Gd* Cretaceous--aged formation.
Sources: visual observation, CERCG (1989) and Monthel (2013)	

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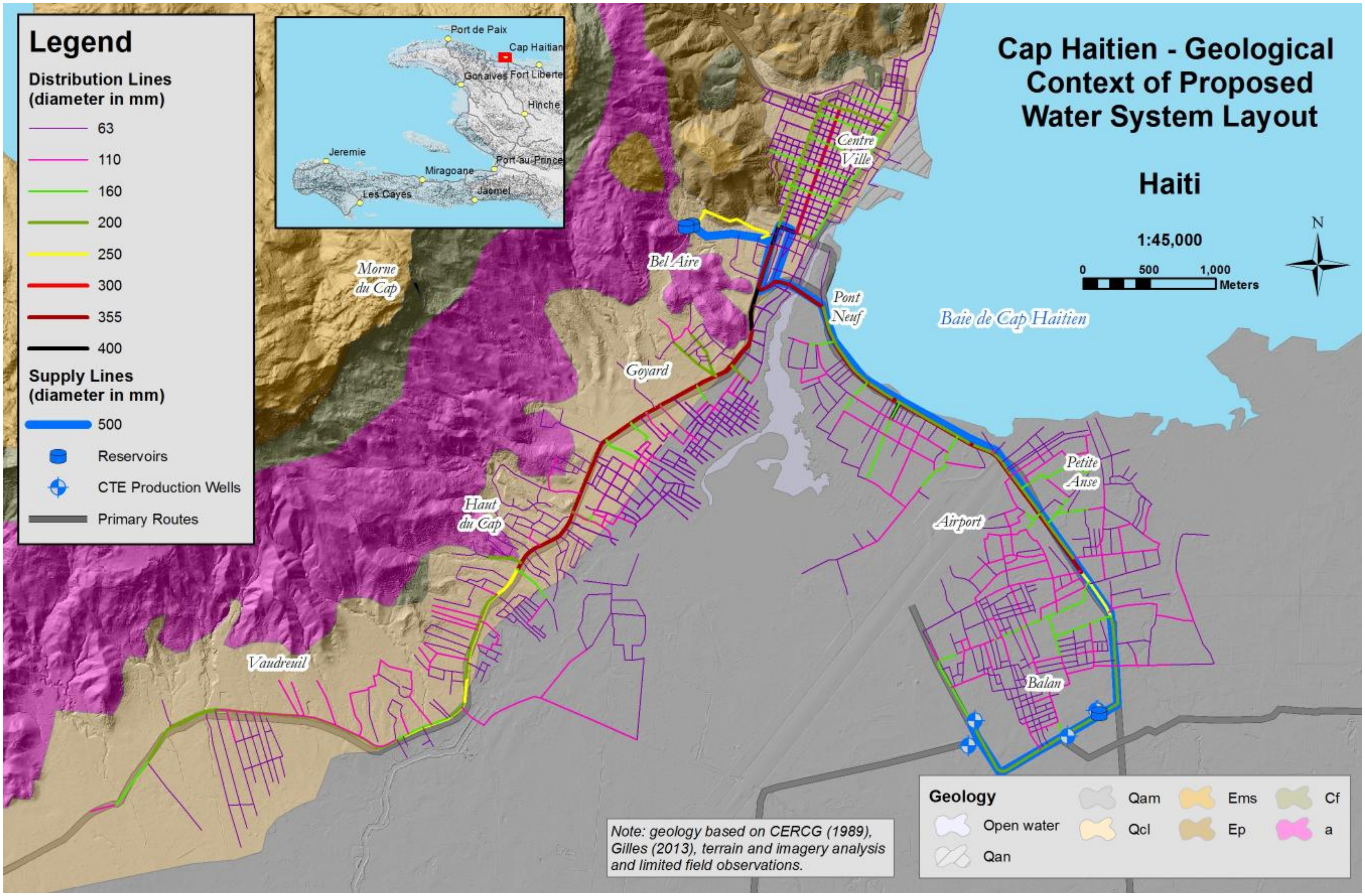

FIGURE 2 – PROPOSED WATER SYSTEM LAYOUT AND GEOLOGIC SITE CONDITIONS

SECTION 5 – GEOLOGIC HAZARDS FOR CAP HAITIEN WATER SUPPLY

Section 5.1 – Seismic

The seismic hazards evaluated in this section include the potential for ground shaking and rupture due to seismic events, liquefaction, and tsunamis/sea waves.

Historical Seismicity

Most of the major earthquakes in the study area are believed to originate in the submerged OSFZ associated with the Cayman Trough (aka Bartlett Trough). This fault zone and the trough are located offshore from Cap-Haitien between the mainland and the island of La Tortue. Vertical displacement in this fault zone results in high magnitude events, and great potential for tsunamis and sea waves. Other major fault zones relevant to the site include the North-Hispaniola Fault Zone which lies north of the OSFZ, and the Central Haiti Fold and Thrust Belt which formed the parallel ridges of the Central Plateau and Chaine-des-Matheux Mountains.

Seismic monitoring and published bulletins from 1909 to 1921 indicated 18 earthquakes recorded in Cap-Haitien, no seiches or tsumanis were documented in historical records for these events. Table 3 includes a list of historic earthquakes relevant to Cap-Haitien with magnitudes greater than 4.5. This list is derived from the USGS dataset (2018), historical records summarized by Woodring et al (1924) and records compiled by CIAT-BRGM (2017). It is not considered a comprehensive inventory of seismic history, but to be used as a guideline for understanding seismic history for the site.

Perhaps the most notable earthquake for Cap Haitien occurred in 1842 and is attributed to a rupture in the OSFZ which generated between a 7.6 and 8.0 magnitude earthquake. Reports indicate the town was completely destroyed and many thousands of lives were lost.

TABLE 3 – HISTORICAL EARTHQUAKES NEAR CAP HAITIEN

Date	Lat. (dd)	Long. (dd)	Magnitude (M)	Depth (km)	Approximate Distance (km)	Notes
May 7, 1842	19.8	-72.2	7.6-8.0	NA	NA	Cap-Haitien completely destroyed, ½ of population killed, tsunami recorded in Port-de-Paix
September 23, 1887	19.95	-73.73	6.7-7.8	NA	NA	Damage in Cap-Haitien, destroyed Mole St. Nicolas. Tsunami / sea wave reported
August 11, 1911	NA	NA	NA	NA	NA	IV on Rossi-Forel scale (likely IV on Modified Mercalli scale), unknown number of victims
October 11, 1911	NA	NA	NA	NA	NA	VII on Rossi-Forel (likely VIII on Modified Mercalli scale), unknown number of victims
September 6-7, 1912	NA	NA	NA	NA	NA	VI on Rossi-Forel (likely VI or VII on Modified Mercalli scale), unknown number of victims
July 26, 1917	NA	NA	NA	NA	NA	VI on Rossi-Forel (likely VI or VII on Modified Mercalli scale), unknown number of victims
July 9, 1956	20	-72.95	6.2	39	NA	Damage primarily in Port-de-Paix and Jean Rabel, unknown number of victims
April 20, 1962	20.38	-72.2	6.6	25	NA	Moderate damage in villages along the north coast, unknown number of victims
August 3, 1973	NA	NA	5.2	37	NA	Unknown damage or deaths
June 24, 1974	NA	NA	4.7	33	25	Unknown damage or deaths
August 12, 1982	NA	NA	4.6	33	20	Unknown damage or deaths
March 2, 1994	NA	NA	5.4	59.2	NA	Unknown damage or deaths
Sources: USGS Earthquake Hazards Program, Woodring et al (1924), CIAT-BRGM (2017), EM-DAT (2018)						

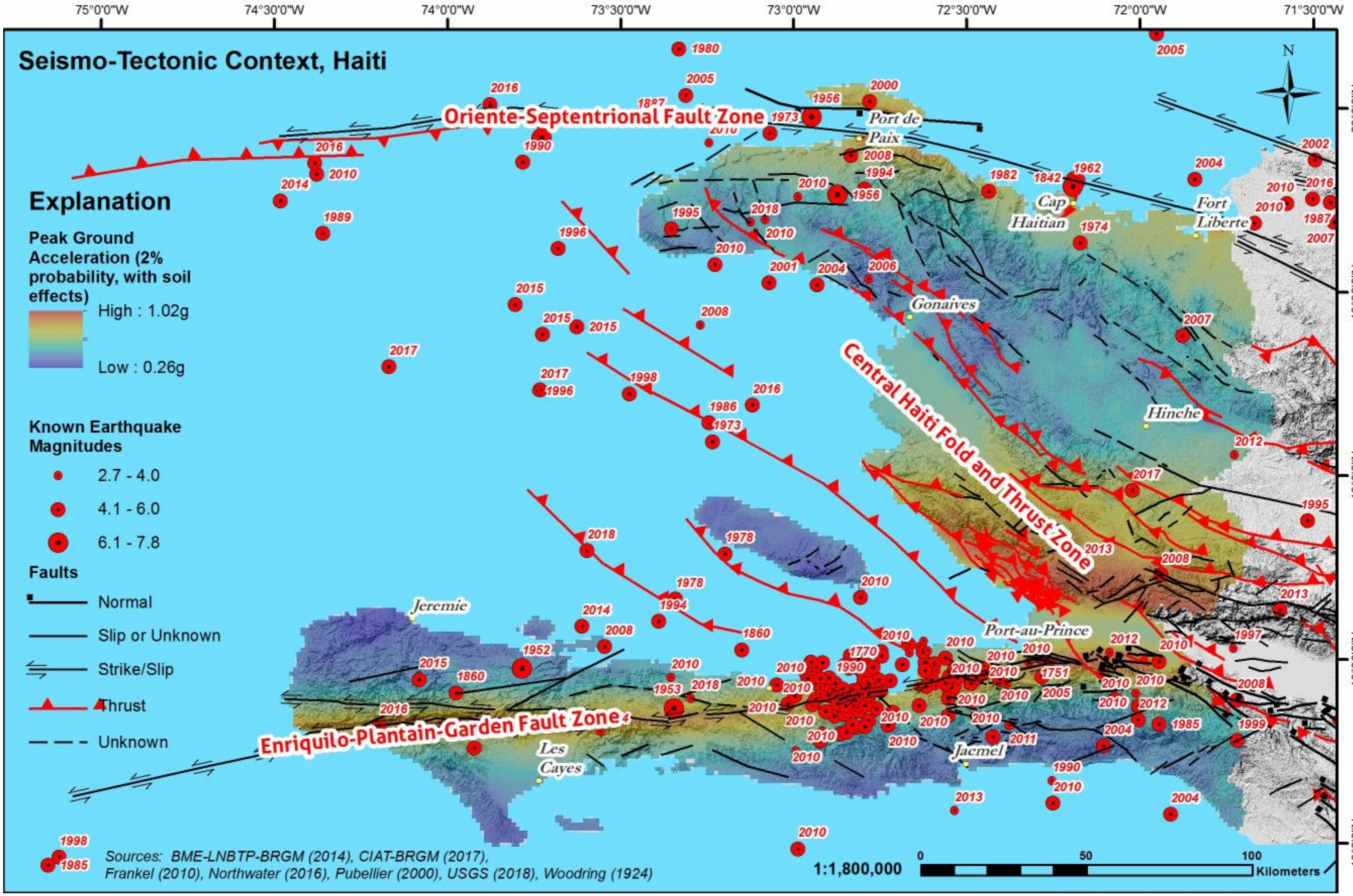

FIGURE 3 – SEISMO-TECTONIC CONTEXT OF CAP HAITIEN, HAITI

Shaking (Peak Ground Acceleration)

Regional-scale modeling of peak ground acceleration (PGA) due to ruptures along the OSFZ have been modeled by USGS (2010), Gilles et al (2014) and Torres (2016). The pipelines are less susceptible to shaking and acceleration than the reservoirs or associated support buildings due to burial which typically reduces the inertial forces relative to above-ground structures. As work progresses on this project, estimates of peak ground acceleration and the spectral response of the reservoir site should be refined to guide structural design.

Based on our evaluation, we believe that the regional faults present an overall moderate ground shaking hazard to the water system in the study area, with increased hazard in areas blanketed with unconsolidated materials and high groundwater tables. Acceleration increase due to site effects such as soil resonance do not appear to be a major issue for the reservoir site as long as the reservoir is designed as a low structure. Design complexity to accommodate seismic considerations will increase with reservoir height. Relatively large horizontal to vertical ratios for the reservoirs are recommended but will increase the required space per storage volume, possibly limiting the feasible storage capacity at the proposed site.

Liquefaction and Settling Potential

Seismic events can trigger a sudden change in the shear strength of unconsolidated sediments and soils. Liquefaction can occur in saturated soils with low plasticity (silts, and sands), and strain softening can occur in more cohesive soils. Soil bearing capacity and soil strength is significantly affected under these processes, and the ground surface can experience lateral displacement and subsidence.

Based on our first-hand knowledge of the alluvial deposits of the Plaine-du-Nord, we consider that some of the stratigraphy may conform to industry standard characteristics of liquefiable soils. The project site is located within a documented hazard zone (Gilles, 2014) which is illustrated in Figure 6. Supplemental HVSR geophysical data (Figure 4) along the main supply line also suggests up to 20 meters of low density sediment from near the Riviere Haut-du-Cap eastward to near the airport. This low density sediment appears to thin southward past the airport towards Balan.

There was insufficient soil property data available to make a determination with regards to strain softening of cohesive soils. Based on our knowledge of the alluvial deposits of the Plaine-du-Nord, the cohesive layers are typically a silty clay matrix with sand or gravel and are normally consolidated and wet. It is possible that some of the cohesive layers are of marine origin, which would increase the risk of highly sensitive soils.

Based on our evaluation, we would regard liquefaction, strain softening, and related hazards as a design consideration for sections of the pipelines underlain by unconsolidated alluvial deposits especially between the Riviere Haut-du-Cap and Petite Anse. A geotechnical investigation that includes borings with sediment characterization and SPT is recommended along the length of the supply line to better characterize the liquefaction hazard and design adequate mitigation structures. The cost of the liquefaction

investigation will likely result in cost-savings relative to the higher cost of installing conservative mitigation measures. We consider the liquefaction hazard to be a greater than the strain softening hazard.

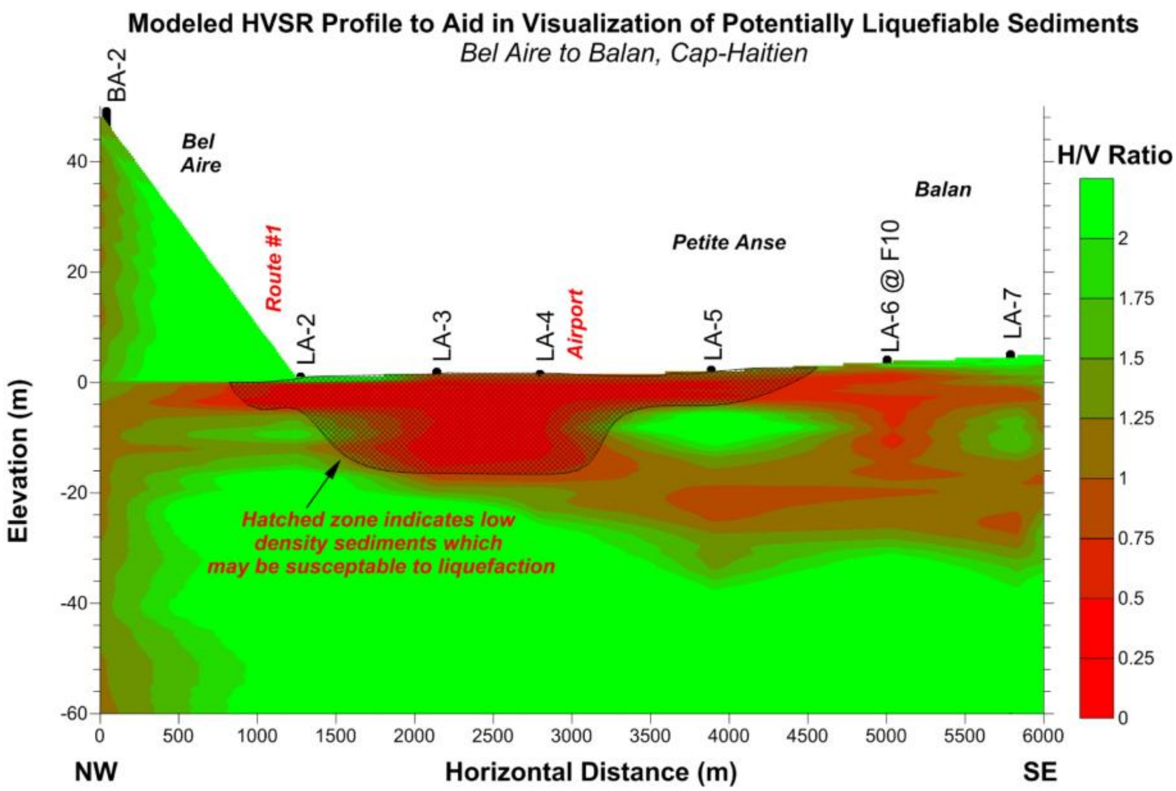

Figure 4 – Modeled HVSR Profile From Bel Aire to Balan, Dark red zones indicate potentially low density sediment which may be susceptible to liquefaction.

Ground Surface Rupture (Faulting)

There are numerous mapped and inferred faults in this part of Haiti, and likely many more that are yet undocumented. Faults are classified as active, potentially active or inactive. Active faults have ruptured during the most recent Epoch (Holocene Epoch, < 12,000 years before present). Potentially active faults show evidence of movement during the Quaternary Period, which spans the last 2.6 million years. Inactive faults have no evidence of movement within the Quaternary period.

Potentially active faults and fault zones relevant to the study area are illustrated in Figure 6. There are three primary types of faults in proximity or intersection with the pipelines or reservoir:

1. Normal faults result from tensional stresses and typically have steep fault planes in which the hanging-wall slides downward relative to the foot-wall
2. Strike-slip faults result from compressional or transpressional stresses and result in steep fault planes where each side moves roughly horizontally relative to the other.

3. Reverse or thrust faults result from compressional stresses that either re-activate old normal fault planes in an the reverse direction or cause folding and buckling which causes a curvi-planar fault surface with the hanging-wall moving upward relative to the foot-wall.
4. Many faults accommodate both strike-slip and reverse movement, with their classification being based on the more dominant movement type.

Based on our preliminary understanding of the site geology, potentially the most active fault which crosses the pipeline is a thrust fault which accommodates the transpressional stress caused by the OSFZ. This structure is believed to have contributed to the arching of Morne-du-Cap and is aligned approximately parallel to National Route 1. The supply line crosses this fault near the National Route 3 bridge over the Riviere Haut-du-Cap. The distribution lines likely intersect or are in close proximity to this fault at several locations along National Route 1.

A branch fault to the previously mentioned thrust fault was interpreted by Gilles (2014) near the site of the existing Bel-Aire reservoirs. Geophysical HVSR reconnaissance conducted by the authors across the Bel-Aire valley indicate a likely zone of faulting or fracturing that is buried by recent colluvial deposits. The faulting/fracture zone appears to directly underlie the reservoir site (Figure 5). This observation leads to several possible options, or a combination of options, for the water system:

- *Setback distance:* If large investments in water storage infrastructure are desired in the Bel-Aire area, establishment of a setback distance from the fracture zone for any further investments in water infrastructure is recommended. Establishment of the set-back distance would benefit from a detailed geologic study to more precisely describe the location and alignment of the potential fault.
- *Relocation* of the primary water storage infrastructure away from Bel Aire, with the option of secondary or tertiary storage at the existing reservoirs.
- *Seismic retrofit:* Conduct structural assessments of the existing reservoirs in combination with a more detailed geologic study of the fault location and alignment in order to determine the feasibility or design components necessary for seismic *retrofits* which take into account the increased fault rupture hazard. Depending on the feasibility of the retrofits, the existing reservoirs would either be incorporated as the initial storage infrastructure for the water system or as secondary or tertiary storage if alternate locations are selected.

In terms of ground surface rupture, it is our opinion that local faults do present a potential hazard for specific areas associated with the reservoir, supply pipeline and distribution pipeline. Areas of proposed water infrastructure that are underlain by active or potentially active faults require special design considerations which are further discusses in Table 8 at the end of this report.

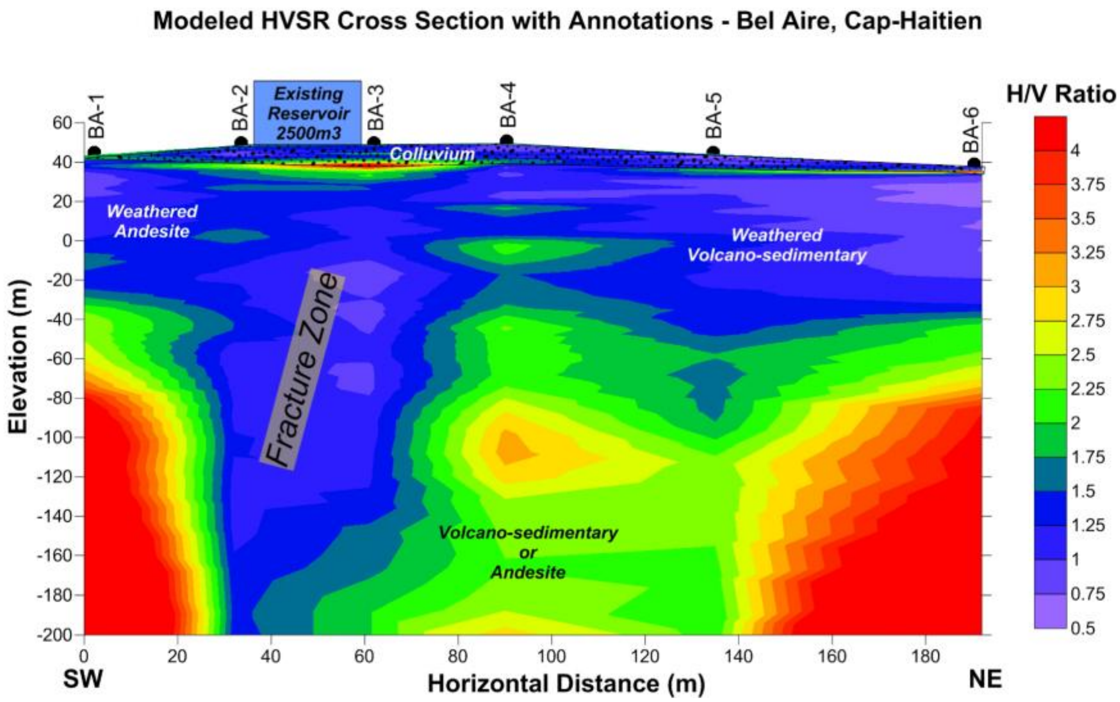

FIGURE 5 – MODELED HVSR PROFILE ACROSS BEL AIRE VALLEY. BLUE AND PINK ZONES AT DEPTH LIKELY INDICATE HIGHLY FRACTURED BEDROCK, POTENTIALLY DUE TO FAULTING.

Tsunami (Flooding, Scour and Disruption)

Tsunamis are low amplitude waves caused by the displacement of large amounts of water during a submerged fault rupture or submarine mass wasting event. They are often compared to a rapid and very large tide and can rapidly deliver tens of meters of water into low-lying areas. Tsunamis have been reported during several of the larger historical earthquakes in Haiti including the 1842 event that destroyed Cap-Haitien. Modeling presented by CIAT-BRGM (2017) delineates the potential tsunami inundation and wave velocity associated with an earthquake of similar magnitude as the event modeled by Torres (2016). For the project site, wave heights of up to 10 meters are possibly with corresponding velocities greater than 3 m/s (Figure 8). The primary hazard to the water system from tsunamis would be the compromise of above grade or exposed pipelines (such as bridge crossings).

Scouring is also a hazard due to the shear stresses resulting from wave velocity and water depth, certain areas could be subject to rapid soil erosion and compromise buried pipes.

Site-level design in areas of high tsunami potential may include concrete pipe cover, flexible joint piping such as earthquake resistant pipe, increased armoring of bridge and pylon abutments, isolation valves and outlet manifolds.

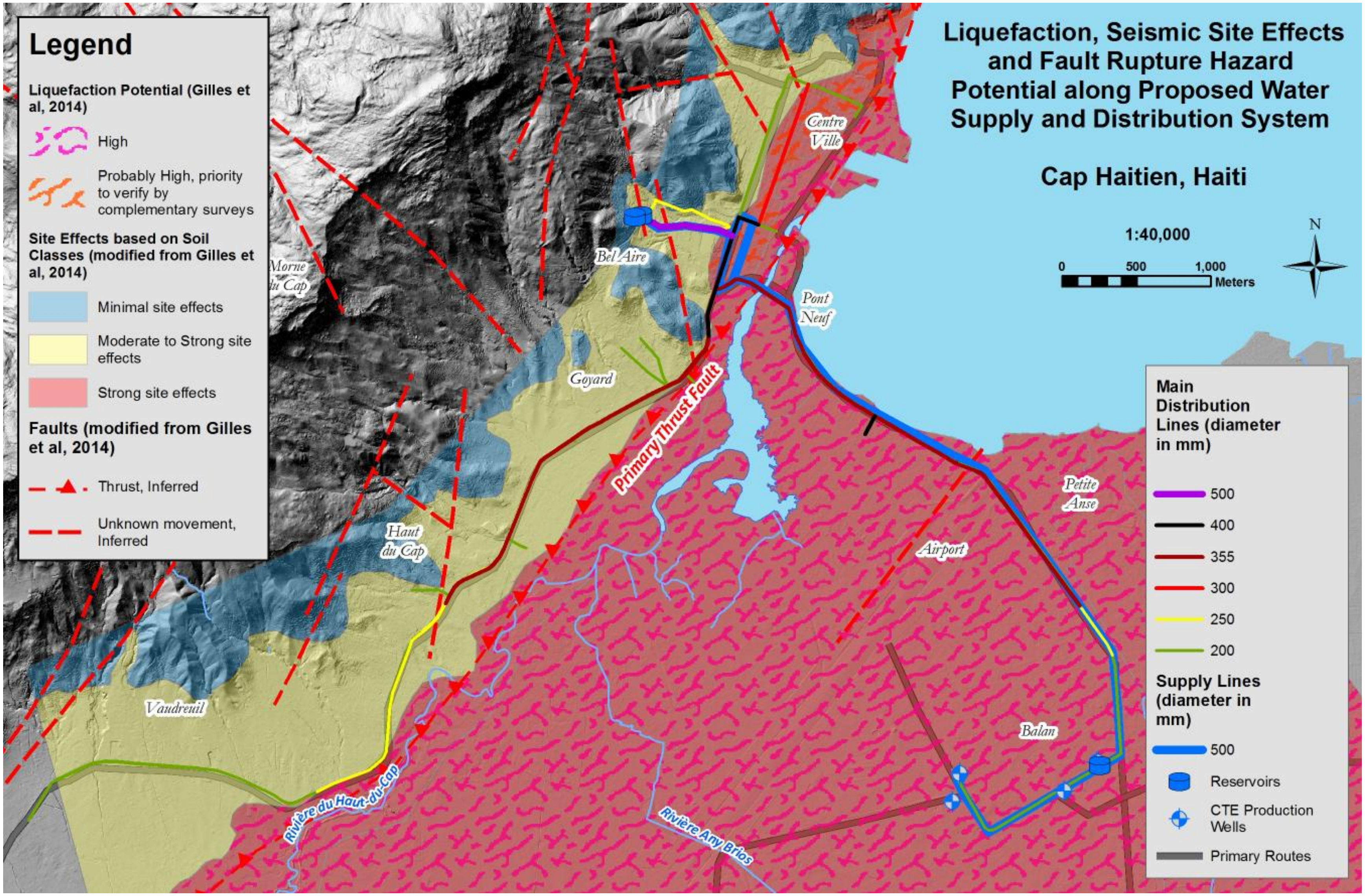

FIGURE 6 – SEISMIC HAZARDS TO PROPOSED WATER SYSTEM: LIQUEFACTION, SITE EFFECTS AND GROUND SURFACE RUPTURE (FAULTING)

Section 5.2 – Slope Stability

A large portion of the project site is on the relatively flat alluvial plain and does not present indicators of landslide or slope stability hazards. With regards to the supply pipeline and distribution pipeline located in the alluvial plain, we do not believe slope stability needs to be a design consideration.

Slope stability is a concern for other areas of the project site and reservoir site. Review of 1.5m LiDAR elevation data illustrates a very dynamic south and east facing slope of Morne-du-Cap. A long history of landslides, rock fall, and debris flows are evident along this mountain-side, some of which have been reported in Table 4.

This particular area was the focus of a recent landslide mapping activity (BME-LNBTP-BRGM, 2014, reproduced in CIAT-BME, 2017). This landslide mapping was applied to delineate various levels of geologic hazard along the pipeline routes, and at the reservoir site which are illustrated and documented in Figure 7.

Slope instability is often triggered by one or a combination of factors:

- Elevated shallow subsurface moisture levels due to high amounts of precipitation which decrease soil effective stress
- Seismic acceleration during an earthquake
- Loading of the landslide head or undercutting of the toe, both potentially due to construction, urbanization and increased runoff and erosion

Based on our evaluation, we regard slope stability hazards, especially debris flows, as an important design consideration for defined sections of the pipelines and the reservoir site. Investigation and mitigation recommendations are provided in Table 8 at the end of this report.

TABLE 4 – KNOWN HISTORICAL SLOPE INSTABILITY NEAR CAP HAITIEN

Date	Location	Notes
February 9-10, 1764	Morne du Cap	Rockfall and debris flow of 500 m^3
December, 2003	Cap Haitien	Landslide after heavy rain
2005	La Vigie, Cap Haitien	Rockfall, 2 deaths, 1 house destroyed
February 15, 2010	Careage, Cap Haitien	Rockfall, 4 deaths
May 25-26, 2011	Bel Aire, Cap Haitien	Landslide, 3 deaths, 1 house destroyed
November, 2012	Haut Charrier	Debris flow, 8 deaths
Unknown	Calvaire Jouissant	Rockfall, 2 deaths, 1 house destroyed
Source: CIAT-BRGM (2017)		

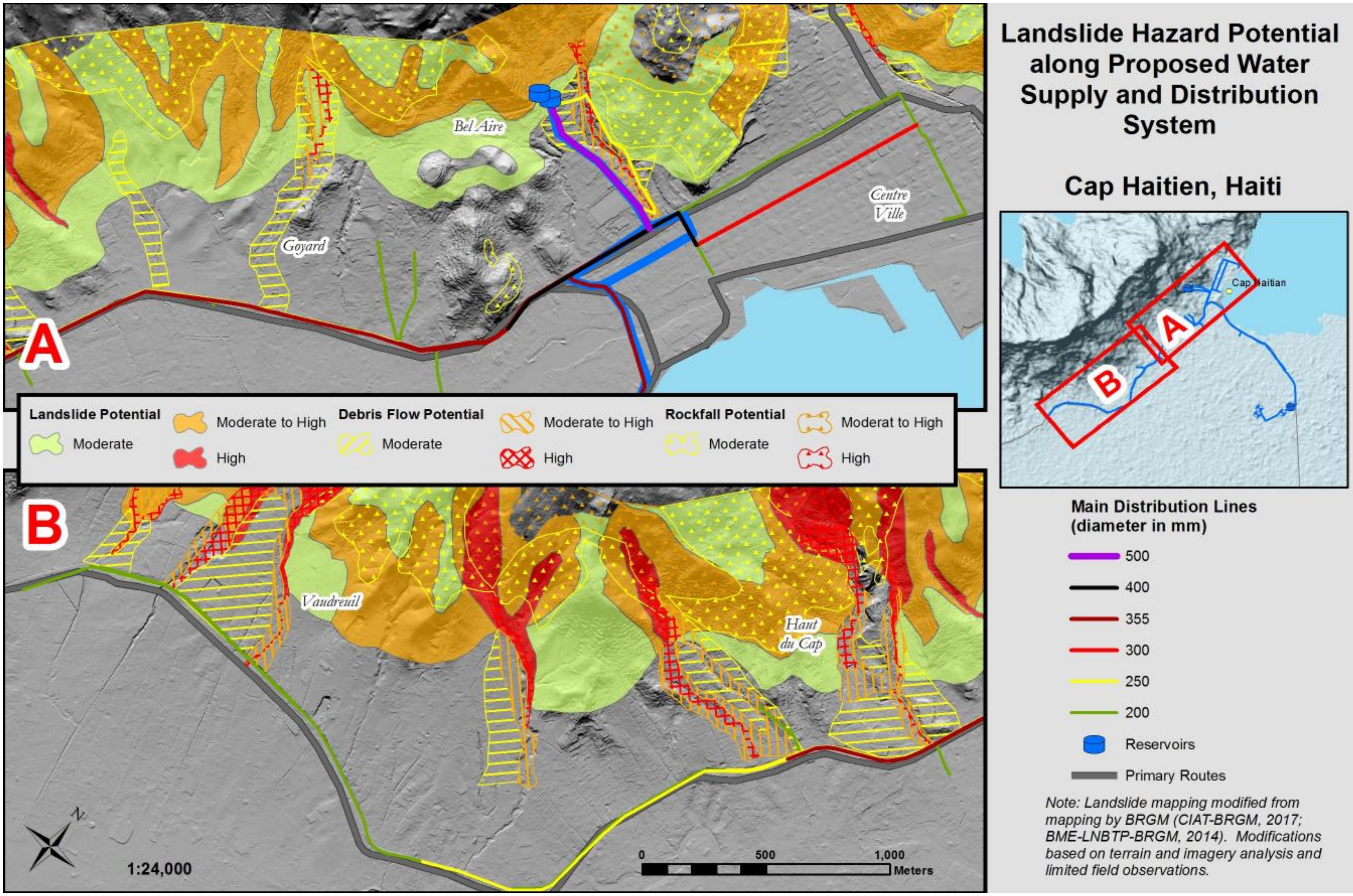

FIGURE 7 – SLOPE STABILITY HAZARDS TO PROPOSED WATER SYSTEM: LANDSLIDE, DEBRIS FLOW AND ROCK FALL

Section 5.3 – Flooding and Erosion

There are two primary mechanisms of flooding hazard in the study site: overbank flooding due to high rainfall events associated with the river drainages and tsunamis originating from the ocean (seismic triggered sea wave). The primary hazard to the water system during both types of flood events is due to scouring of soils which could expose and damage pipelines or erode the foundations of abutments and piles that support river and drainage crossings. A secondary hazard related to tsunamis is the near-simultaneous occurrence of seismic related hazards, a tsunami and its associated damage may inhibit the access to pipelines, valves and other critical water infrastructure that may have been compromised due to other seismic hazards.

In the plain, special design considerations will be necessary near drainages in order to protect the pipelines from scour and ensure access to critical infrastructure such as isolation valves in the event of high water. Drainage crossings, especially the Riviere Haut-du-Cap along National Route 3, will require site investigations to design appropriate support structures that are resilient to floodwaters traveling both directions along the channel and to accommodate the shear stress and flow velocities anticipated during an extreme event. Earthquake resistant pipe joints may be considered in order to allow for some movement during such events.

In the colluvial and bedrock hill slopes associated with Morne-du-Cap, the primary flood risk is constrained to high-gradient ravines which are susceptible to flash-flooding and debris flows. Final design and construction practices should especially consider this hazard along the primary distribution pipeline that runs parallel to National Route 1 and Route L. When above grade drainage crossings are required, site-level investigation and engineering is recommended to specify pipeline material and design appropriate support structures to accommodate the hazard and associated risk.

Over thirty major storms or hurricanes (cyclones) are recorded to have struck Haiti since the early 1900's (EM-DAT, 2018). Many of these recorded storms have caused deaths and destroyed infrastructure in Cap Haitien, both due to flooding and also due to high winds. It should be assumed that major hurricanes will strike near Cap Haitien within the project life of the water system and appropriate mitigation should be incorporated in the final design.

Based on our evaluation, we regard the scouring and erosion related to flooding and tsunamis to be a low to moderate hazard in the bedrock and colluvial sections of the line and a moderate hazard in the plain. We recommend that final designs incorporate mitigation techniques in specific zones which are described in Section 7.

TABLE 5 – FLOODING EVENTS RECORDED NEAR CAP HAITIEN

Date	Location	Cause or Mechanism	Victims
1942 and 1943	Old town center	Heavy rains and runoff	Unknown
November 14, 1963	Grande Rivière du Nord		Nearly 500 victims
November 22, 1968	Cap Haitien		Unknown
March 29-30, 1993	Lower section of town	Strong rains	6 deaths
May 8, 1993	Lower section of town	Rainfall, not a cyclone	Unknown, possibly up to 500 deaths in surrounding area based on EM-DAT
January 10, 1996			8 victims
November 1-2, 2000	Lower section of town flooded		16 deaths, 26,000 people affected
December 21-22, 2003	Lower section of town flooded	1 week of continuous rain	4 deaths, 34,000 people affected although some sources indicate as many as 300,000 people in the north were affected.
September 13, 2004	Precise location undefined	Tropical storm	Unknown
March 17, 2007	Cap region	1 week of continuous rain	
October 29-30, 2007	Precise location undefined		Unknown
November 10, 2007	Quartier Shadda, lower town, Haut du Cap, Petite Anse and the historic downtown completely under water	No information	2 deaths, likely many more in surrounding area based on EM-DAT.
November 7-8, 2012	Entire town flooded	Extremely heavy rains over 2 days. Peak at 282 mm on 8/11/12, and 584 mm for the month (absolute record according to FIC data). 440 mm over 4 days of 7 to 11/11/12	13 dead, 1 missing, 2,336 flooded houses, 2,350 affected families and 3496 people staying in 25 shelters. EM-DAT indicates up to 42 deaths.
July 10, 2013	In the foothills of Haut du Cap and Quartier Cité du Peuple, Bas de Vertiìeres, de Champin and Blue Hills	20 minutes of, Runoff and clogging of drainages because of garbage stored on National Route 1 despite the small rainfall rain	Overflow of channels and drains caused by rubble and non-hazardous waste which was dug out but fell back into canals
November 1-4, 2014	North region	Extended rain for 5 days and very heavy rain on Nov. 3 on the order of 120 mm. Flooding accentuated in the Riviere Haut-du-Cap due to a temporary construction dam for a bridge	2 deaths, one due to runoff and the other due to a collapse. EM-DAT indicates up to 12 deaths and 30,000 affected
Sources: Translation and reproduction from CIAT (2015) with additions from EM-DAT (2018			

TABLE 6 – CYCLONES AND TROPICAL STORMS RECORDED IN HAITI

Year	Name (hurricane, storm)	Affected areas	Deaths (EM-DAT, 2018)	Estimated Damage (USD), EM-DAT (2018)
1909	Unnamed cyclone	Unknown	150	
1915	Unnamed cyclone	Unknown	1600	
1935 (October)	Unnamed	Jérémie	2150	
1954 (October)	Hazel	Grande Anse, Ouest, Artibonite, Nord-Ouest (very widespread)	410	
1963 (October)	Flora	Grande Anse, Ouest, Cote sud (Cayes)	5000	180,000,000
1964 (September)	Cleo	Grande Anse	100	10,000,000
1966 (September)	Inès	Sud and Ouest	480	20,000,000
1979 (August)	David	Limited impact on Nord-Ouest	8	
1980 (August)	Allen	South coast (Cayes)	220	
1988 (September)	Gilbert	Primarily Sud	54	91,286,000
1994 (August)	Gordon	Jérémie (192 deaths)	1122	50,000,000
1996	Unnamed cyclone	Unknown	26	100,000
1998 (September)	Georges	Ouest – Centre	190	180,000,000
2001	Unnamed cyclone	Unknown		20,000
2002	Unnamed cyclone	Unknown	4	
2003	Unnamed storm	Unknown	26	
2004 (September)	Jeanne	Nord – Haut Artibonite (Gonaïves hard hit)	2757	51,000,000
2005	Five cyclones	Unknown	71	50,500,000
2006	Unnamed cyclone	Unknown	5	
2007	Three cyclones	Unknown	102	
2008 (August)	Fay	Entire country	698	
2008 (August)	Gustav	Sud and Grande Anse		
2008 (August)	Hanna	Artibonite and Nord Est (City of Gonaïves hard hit)		
2008 (September)	Ike	Brushed past the north - (City of Cabaret affected)		
2010	Unnamed storm	Unknown	6	
2010 (November)	Tomas	Sud	21	
2012 (August)	Isaac	Sud-Est and Ouest	88	254,000,000
2012 (October)	Sandy	Sud, Ouest and Grand Anse		
2015	Unnamed storm	Unknown	5	
2016 (October)	Matthew	Sud, Grand Anse, Nippes, Ouest, La Gonave, Nord-Est	546	2,000,000,000
2017 (September)	Irma	Nord	4	

Sources: EM-DAT (2018) and NATHAT (2010)

Section 5.4 – Groundwater

Aside from role of groundwater in other hazard categories, groundwater itself does not present a direct hazard to the project. Shallow groundwater tables are expected for all of the trenching and excavation in the project areas underlain by unconsolidated alluvial deposits.

A possible hazard to the project that should be documented is the potential risk of local ground subsidence resulting from aquifer drawdown from pumping. The dewatering of fine-grained beds could lead to hydrocompaction and localized ground subsidence. Some portions of the project site are underlain by the large regional Plaine-du-Nord alluvial aquifer with a very shallow water table.

Based on our evaluation, we would regard subsidence due to groundwater pumping as a low hazard for the project, but it may warrant some design consideration in the affected drawdown area associated with the municipal production wells and other potential well fields associated with the agricultural and industrial sectors.

In order to further evaluate the hazard, a geological engineering and geotechnical study would be necessary to characterize the soil layers that could be desaturated from aquifer drawdown.

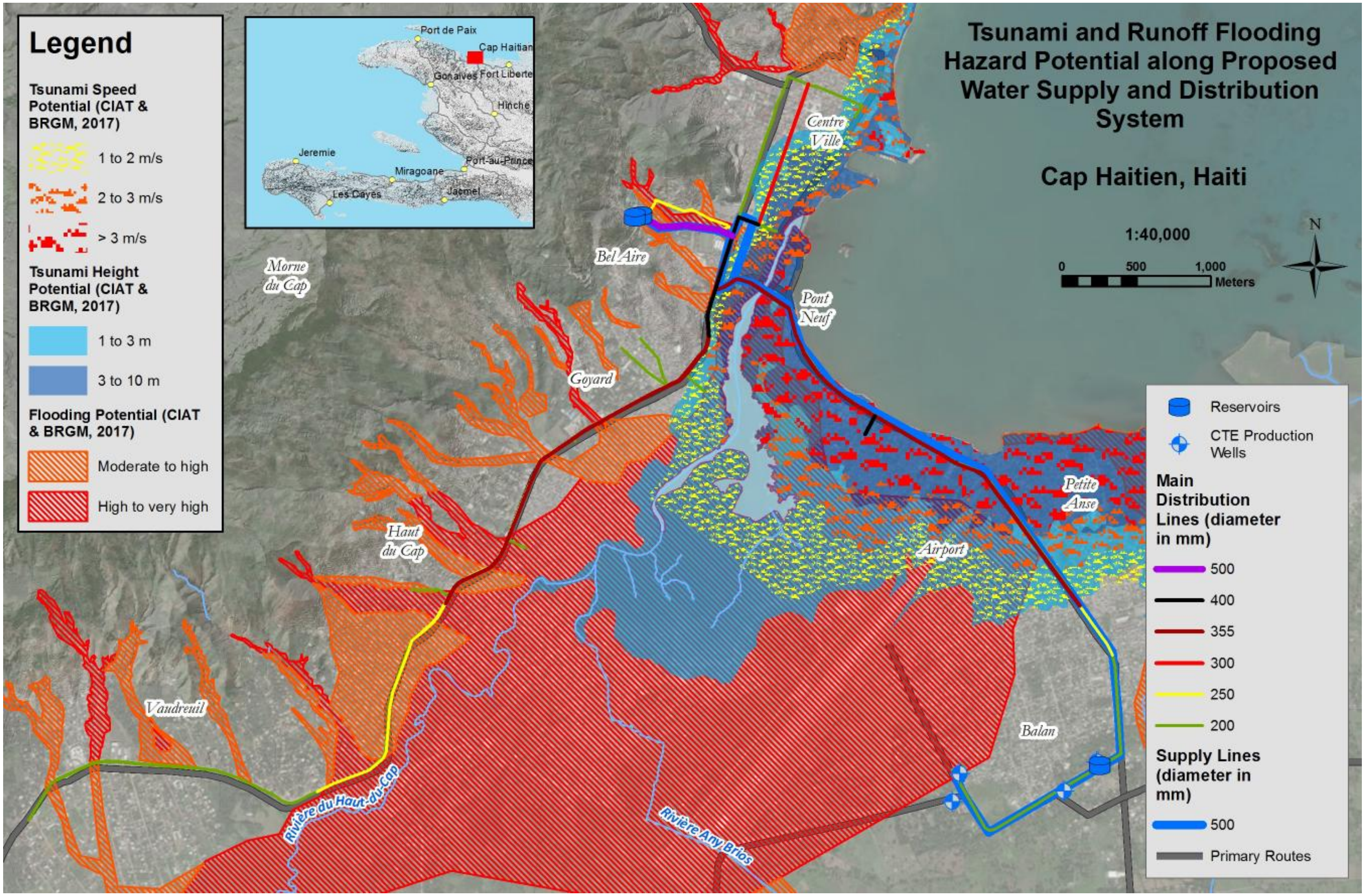

FIGURE 8 – SURFACE WATER HAZARDS TO PROPOSED WATER SYSTEM: TSUNAMI AND RUNOFF FLOODING

SECTION 6 – CONCLUSIONS

Based on the available data, it is our opinion that there are several primary geologic hazards in the project area that warrant design consideration. These key hazards are listed below and summarized in Table 7:

- Primary geologic hazards to the Bel-Aire reservoir site:
    - Seismic shaking (peak ground acceleration) and associated sloshing of stored water, also a primary hazard at the existing elevated reservoir site in Balan.
    - Surface rupture due to a potentially active fracture zone underlying the Bel-Aire reservoir site.
- Primary geologic hazards to supply and distribution pipelines in the plain and Ville-du-Cap Haitien:
    - Liquefaction and seismic settling particularly between National Route 1 and the airport.
    - Surface rupture due to a thrust fault which is believed to approximately parallel the Riviere Haut-du-Cap.
    - Scour, erosion and access interruption due to tsunami or flooding particularly near the coast or the Riviere Haut-du-Cap.
- Primary geologic hazards to supply and distribution pipelines in the colluvial fans and bedrock zones:
    - Debris flows along the distribution main on National Route 1 and Route L.

Based on the available data, it is our opinion that these factors are of low hazard potential to the water system:

- Of low hazard to the reservoir site:
    - Liquefaction, rockfall, landslide, debris flow, tsunami and flood scouring, groundwater hydrocompaction or settling.
- Of low hazard to supply and distribution pipelines in the plain and Ville-du-Cap Haitien
    - Seismic shaking (peak ground acceleration) except where pipeline above ground or at transitions.
    - Landslide, debris flow and rockfall.
    - Groundwater hydrocompaction and settling.
- Of low hazard to supply and distribution pipelines in the colluvial fans and bedrock zones
    - Seismic shaking (peak ground acceleration) except where pipeline above ground or at transitions.
    - Liquefaction.
    - Scouring and interruption due to tsunami.
    - Flood scouring outside of high gradient channels.
    - Groundwater hydrocompaction and settling.

It is worth noting that additional hazards may be present and impact the construction phase; however this consultancy focused on natural hazards at the design level of the water system.

TABLE 7 –EVALUATED HAZARD LEVELS TO THE PLANNED CAP HAITIEN WATER SYSTEM

Hazard	Supply Pipeline		Reservoir (Bel Aire)	Main Distribution Pipelines	
	Plaine and Centre Ville	*Colluvial fans and Bedrock*		*Plaine and Centre Ville*	*Colluvial fans and Bedrock*
Shaking (earthquake)	**Low**	**Low**	**Moderate**	**Low**	**Low**
Liquefaction (earthquake)	**High**	**Low**	**Low**	**High**	**Low**
Surface Rupture (earthquake)	**Moderate**	**Low to Moderate**	**High**	**Moderate**	**Low to Moderate**
Tsunami	**Moderate to High**	**Low**	**Low**	**Moderate to High**	**Low**
Landslide, Debris Flow and Rock Fall	**Low**	**Moderate**	**Moderate**	**Low**	**Moderate**
Flooding & Erosion	**Moderate**	**Low to Moderate**	**Low**	**Moderate**	**Low to Moderate**
Groundwater	**Low**	**Low**	**Low**	**Low**	**Low**

Note: Natural hazards were evaluated within the context of an installed and operational future water system. Other hazards which were not evaluated may affect the project construction.

SECTION 7 – RECOMMENDATIONS AND POTENTIAL MITIGATION STRATEGIES

The assessment concludes that the project is in a high geological hazard risk zone. Several specific hazards were identified and should be appropriately considered as the operation advances.

Section 7.1 – Summary

Our key recommendations are outlined below, the Bank should consider appropriate financing to assure appropriate expertise and resources are available throughout construction and that mitigation alternatives can be applied where feasible and appropriate.

Design for redundancy – The variety and spatial distribution of geologic hazards in the study area warrants that redundancy be a primary design consideration for the water system. Secondary infrastructure for supply, storage and distribution should be considered in a phased approach to achieve redundancy.

Design for rapid service recovery – It is probable that geologic hazards will cause water service disruption sometime in the future. System design and management must consider the greatest vulnerabilities in the system related to geologic hazards to mitigate the extent and duration of water service disruptions should an event occur. Incorporation of design and management features which mitigate both the extent and duration of disruption is needed.

Reservoir & Storage – The reservoirs in Bel-Aire require detailed analysis due to the identification of a potential fault zone beneath the site. In the context of this hazard, we recommend that an in-depth structural, geological and geotechnical analysis be performed to direct next steps related to the feasibility, costs and preferred design/construction solutions to reinforce and rehabilitate the existing reservoirs. Set-back distances should be established if future investments are to be made in Bel-Aire related to increasing storage.

- During subsequent operations, secondary areas should be evaluated for additional reservoirs and preferred locations selected. Establishing secondary and additional storage is an important activity to strengthen the system resiliency to geological hazards.
- Consider the option to design emergency pumping/pressurization functionality that would allow the well field to directly pressurize the distribution network if the reservoirs are damaged.

Site-level design – Areas of increased geologic hazards, especially near fault crossings and zones of potential liquefaction may require site-level assessment and design. We recommend that the supervision and contractor contracts include line-items for geotechnical assessment to guide site level design and construction adjustments. In defined hazard areas, robust oversight and supervision by a geotechnical or geological engineer with experience in geologic hazard mitigation is recommended.

Materials, technologies and best practices – System design should incorporate appropriate, cost effective, and available materials and technologies that consider the

hazards, especially in the specific locations of concern identified in this report such as fault crossings and zones of potential liquefaction.

- While some mitigation measures will be most efficiently designed with site-level geotechnical data, there are many measures which should be immediately integrated in the design moving forward. These measures are discussed in Section 7.1 and 7.2.
- In order to facilitate clear and efficient field design and installation we recommend that the bill of quantities include estimated amounts of specialized mitigation materials and methods so that per-unit pricing is established prior to site-level design.

Supervision, technical expertise and experience – Successful and durable design and construction of water infrastructure requires robust supervision, continuity and ownership. These factors are often lacking in Haiti water infrastructure projects. One method to encourage this ownership and continuity is the build-operate-train model in which the eventual system operator is involved in a supervisory and design role throughout the project implementation. This ensures that standards conducive to water system use and management are employed, as the operator has a keen interest in the quality of the system.

- Given the specific hazards present, we recommend that the supervisory firm has expertise in geological and geotechnical engineering, hazard investigation and mitigation, subsurface investigations, geophysics and pipeline design. The supervisory firm will also need water system design capabilities in order to approve and have input into field design decisions based on field results during construction.
- As this system will be approached in phases, it may be beneficial for the supervisory/operator firm to lead the design of the Phase 2 infrastructure including a second supply line and reservoir which will further encourage ownership and the quality needed for long term system functionality and maintenance.

This section further details the design considerations resulting from these key recommendations.

Section 7.2 – Conceptual Considerations

Our strongest recommendations regard overall redundancy and resiliency in the system to overcome impacts and minimize the areas and duration of service interruption. Given the study site, it is inevitable that the water system will one day be compromised by a geologic hazard.

Redundancy

Redundancy is often the key to resiliency during and after a geo-hazard event. Conceptual design aspects that address system redundancies such as looped systems with isolation valves, multiple reservoir locations, multiple water source locations and multiple supply pipelines will strengthen the resiliency of the system. It is likely that 2025 demand will warrant secondary storage areas, and additional sources of water, so it is recommended that system redundancies be prioritized in next phases.

<u>Reservoir Redundancy</u>

The reservoir site is a key aspect of system resiliency. Some seismic retrofits and design modifications may be considered for the existing reservoirs to serve an important role for the water system. Large investments enhancing storage in Bel-Aire are not recommended unless a desirable setback from the fracture zone can be achieved or the hazard can be better characterized or mitigated for. Location 1 in Table 8 and Figure 9 correspond to this hazard and further details are provided in Appendix A.

Due to our concerns regarding the existing reservoir site in Bel-Aire, our knowledge of the proposed water system, and conversations with OREPA Nord, we considered potential reservoir sites as we performed our reconnaissance work. Three potential options were noted during the course of this consultancy and are labeled and discussed in Table 8, Figure 9 and Appendix A.

<u>Water Supply Redundancy</u>

It is our opinion that emphasis should be placed on not only expanding the Balan well field but also on developing a second, independent well field for redundancy. A second well field could feed a secondary supply line connected to future reservoirs perhaps located in the foothills between Haut-du-Cap and Centre Ville.

<u>Supply Pipeline Redundancy</u>

The preliminary water system plan includes a single supply line which crosses zones of high liquefaction potential, thrust fault rupture, and flooding/tsunami potential. While the geometry of the plain and urban centers make re-alignment away from these hazards impractical, redundancy could be added via a second supply line from a well field in the plain towards the Haut-du-Cap area during a later phase of expansion. Traversing these hazards in areas of lower population density and farther from the most intense geological hazards near the coast may allow for more design flexibility. Added benefits of a secondary supply line include:

- Lower population and infrastructure density reduce the risks development imposed damage to the pipeline.
- Increased ease of access for repairs and maintenance if needed after a geo-hazard event.

- Reduced potential for disruption of repair works by flooding or tsunami which may allow for faster system recovery.
- Increased feasibility to cross the thrust fault zone near the Riviere Haut-du-Cap at an angle more favorable than the perpendicular alignment on National Route 3.

Rapid Recovery Post Disaster
It is often not feasible to design for no service interruptions after a large geo-hazard event such as an earthquake, especially in the context of Haiti. Due to this, a focus of design often includes infrastructure and planning to allow for rapid restoration of a limited water service while larger repairs are performed over a period of time. There are many techniques, materials and technological solutions that can be applied to mitigate hazards and reduce the level of risk and magnitude of impacts in the event of a geological hazard. Some common industry applications are outlined below:

- Design and installation of isolation structures and outlet manifolds to allow for flexible surface hose to bypass damaged sections of supply or distribution piping. This is a recommendation for many of the locations listed in Table 8 and Appendix A.
- Furnishing of seismic and flood resistant backup power and fuel supplies to critical infrastructure such as wells and any automated valve systems as grid power will often remain down for extended periods after a major geo-hazard event.
- Consider remote monitoring and control of flow rates, pressures and water levels via a Supervisory Control and Data Acquisition (SCADA) system in order to quickly isolate problem areas.
- Consideration of pipe materials which are especially suited to each type of hazard zone. Engineered steel pipe, ductile iron and HDPE pipe materials have various characteristics which allow for increased flexibility or strength when dealing with the transient and permanent deformations of geo-hazard events. Examples of potential pipe selection include:
  - Earthquake resistant pipe or chain-structure pipelines of ductile iron or steel with NS, S-II, S, flex-ring or GENEX® joint types in locations of high surface rupture or slope stability hazards.
  - Butt-fused and thick-walled HDPE in areas of high liquefaction or settling potential.
- Pipe selection also needs to take into account the managing authority’s familiarity with the material and ease of repair. In Haiti, this may advantage HDPE over ductile iron or steel, however, especially in fault rupture zones, steel and ductile iron with flexible joints are preferred.
- Designing to have particular areas with uninterrupted service provides an access point for emergency needs and a starting point to repair the system.

Section 7.3 – Site Specific Considerations

Key hazard zones and associated potential mitigation and assessment options are presented in this section. Figure 9 shows the location of each of the primary hazard zones and Table 8 defines our opinion of the hazard level and a summary of recommendations. Appendix A provides a more detailed discussion of the recommendations.

It is important to note that this report focused on *identifying* geologic hazards and full characterization of each hazard and specific design recommendations were beyond the scope of this consultancy. Within the context of Haiti, and specifically this project, it is understood that detailed characterization and refinement of these hazards may not be feasible. Public datasets, governmental research and geotechnical information related to hazards and mitigation is not available in Haiti, as a result, it is cost and time prohibitive to characterize all of the hazards. The authors emphasize that further study of some hazards, particularly fault rupture, liquefaction and tsunami scour would be recommended if additional resources were available. In the absence of such studies, we recommend a watchful eye during construction and trenching, especially in potential hazard zones. Based on such observation, focused geotechnical assessments and appropriate mitigation practices can be applied when directed and appropriate.

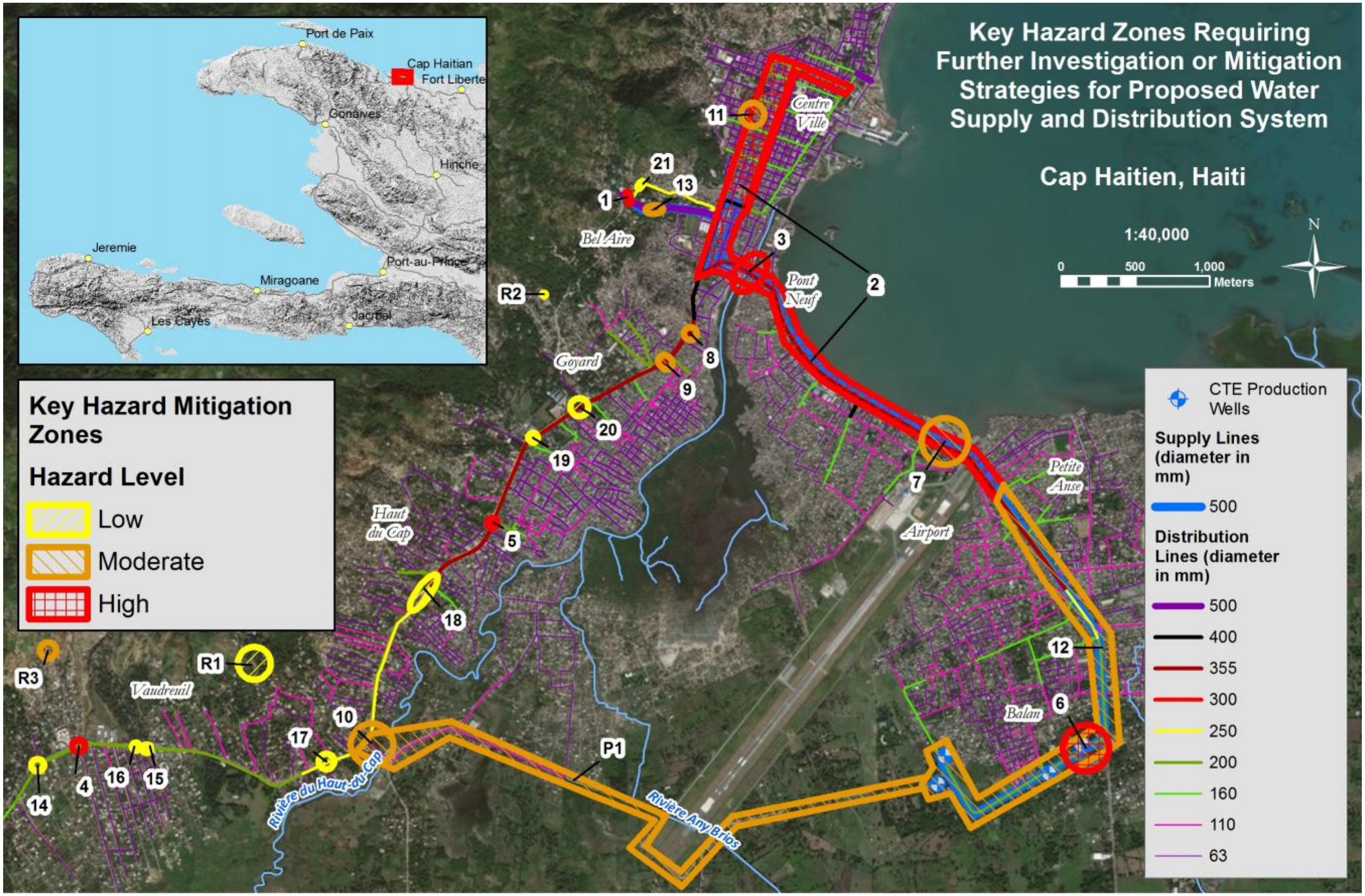

FIGURE 9 – KEY HAZARD ZONES TO BE CONSIDERED DURING DESIGN AND CONSTRUCTION

TABLE 8 – SUMMARY OF KEY HAZARD MITIGATION ZONES WITH POTENTIAL MITIGATION STRATEGIES AND CONSIDERATIONS (SEE APPENDIX A FOR MORE DETAILED DISCUSSION)

Location ID	Hazard Level	Hazard Type	Location	Recommended Mitigation Strategies or Assessments
1	High	Fault-Rupture	Bel-Aire, existing reservoir	• Structural and geotechnical analysis of the existing reservoirs. • Seismic retrofits to the existing reservoirs. • Geological mapping to better constrain the location and alignment of the fault and estimate a setback distance. Setback distance from the delineated fracture/fault zone may be a challenge due to high population density in the area. • Consider re-locating the primary storage capacity of the water system during later phases.
2	High	Liquefaction Shaking Tsunami	Petite Anse, Airport, Centre Ville	• Flexible continuous pipe sections such as butt-fused HDPE in coarse backfill. • Periodic isolation valves and bypass manifolds. • Flexible connections to all above-ground structures. • Site-level geotechnical assessments may refine the the liquefaction hazard along the coastal stretch of the supply line towards Balan and reduce the zone of necessary mitigation farther from the coast.
12	Moderate	Liquefaction Shaking	Balan	
4	High	Debris-Flow Flooding	Haut du Cap	• Additional anchoring and protection when crossing these drainages including thick-walled, strong pipe or pipe-sleeve. • Periodic isolation valves and bypass manifolds.
5				
6	High	Shaking	Balan	• Structural review of existing elevated reservoir in Balan at the F10 supply well if it is to be incorporated into new water system.
3	High	Flooding Tsunami	Pont Neuf, Riviere Haut du Cap	• Install shutoff valves, outlet manifolds, vault boxes and vaults with flexible hose storage on either side of river and potential river crossing support structures in the event of bridge failure. • Later phases may consider relocation of the primary supply line away from coastal hazards or an analysis of existing bridge capacity to support the additional supply and distribution lines in a flood or tsunami event.
3	High	Fault-Rupture	Pont Neuf, Riviere Haut du Cap	• It is possible that acceptable levels of mitigation may be achieved using flexible piping such as HDPE in oversized trenches with loose coarse granular fill and geomembrane liner. However, we also recommend that the design engineer evaluate the feasibility of using ductile iron or steel pipe with flexible joints to cross fault zones. • Install shutoff valves, outlet manifolds, vault boxes and vaults with flexible hose storage. • In zone 3, in the absence of a more detailed fault location study, treat the entire pipeline length (roughly 500m) from the intersection of Route 3 with Route 1 / Route L to the Pont Neuf traffic circle as a possible fault rupture zone. • Although potentially not feasible given project budget and time constraints, a geological investigation focused on refining fault locations would potentially reduce the length of mitigation measures needed. • Later phases may consider an additional supply line located away from coast in order to reduce fault crossings and have more flexible alignment.
7	Moderate		Airport	
8 - 11	Moderate		Route 1, Centre Ville	
13	Moderate		Bel-Aire	
14 - 21	Low	Debris-Flow Flooding	Haut du Cap, Vaudreuil	• Typical engineering design for drainage crossing and bridge/culvert support. • Standard drainage crossing protections such as steel or ductile iron pipe in exposed or erodible areas or concrete cap and anchoring to down-gradient sides of support structures such as bridges or culverts. • Periodic isolation valves and bypass manifolds.
R1	Low	Fault-Rupture Slope-Stability	Haut du Cap	Reservoir Site Evaluations – As noted in Section 7.1, three possible reservoir sites are provided based on our reconnaissance activities. Phase 2 should include reservoir site characterization studies in order to vet their suitability for incorporation into the existing system and potential geologic hazards. Site R1 is initially the preferred location based on elevation, slope stability and elevation.
R2			Goyard	
R3	Moderate		Vaudreuil	
P1	Moderate	Liquefaction Fault-Rupture	Plain south of airport	Alternate Supply Pipe Alignment Evaluation- This corridor or a second one further to the south provide an alternate/secondary supply line alignments which provide redundancy and potentially lower geological hazard levels. Phase 2 system design should include assessments of these alignments within the context of liquefaction and fault hazard and to plan the best alignment and support structure to cross the thrust fault near Riviere Haut-du-Cap in Haut-du-Cap. Especially of interest if an alternate well field is developed southwest of Balan.

SECTION 8 – LIMITATIONS OF THE INVESTIGATION

This geologic hazard memorandum was prepared using the degree of care and skill ordinarily exercised, under similar circumstances, by experienced engineers and geologists. The findings and interpretations apply data and records provided by others and assumptions were necessary due to the lack of public data available regarding geotechnical conditions, fault and landslide activity and other factors pertinent to water system design. No statements or opinions made refer to the suitability or integrity of existing infrastructure. These findings and recommendations are expected to change and be refined by further work and some recommendations require specific site investigations to provide data necessary for final design.

It is important to note that this report focused on *identifying* geologic hazards and full characterization of each hazard and specific design recommendations were beyond the scope of this consultancy. Within the context of Haiti, and specifically this project, it is understood that detailed characterization and refinement of these hazards may not be feasible. Public datasets, governmental research and geotechnical information related to hazards and mitigation is not available in Haiti, as a result, it is cost and time prohibitive to characterize all of the hazards. The authors emphasize that further study of some hazards, particularly fault rupture, liquefaction and tsunami scour would be recommended if additional resources were available.

Signed: ....

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Signed..

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Professional Geologist

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APPENDIX A:

KEY HAZARD MITIGATION ZONES, CONSIDERATIONS AND POTENTIAL MITIGATION STRATEGIES

<table>
<tr><th>Location ID</th><th>Hazard Level</th><th>Hazard Type</th><th>Location</th><th>Recommended Mitigation Strategies or Assessments</th></tr>
<tr><td>1</td><td>High</td><td>Fault-Rupture</td><td>Bel-Aire, existing reservoir</td><td>A structural and geotechnical analysis of the existing reservoirs is warranted in order to determine the feasibility of structural retrofits to withstand permanent ground deformation and the dynamic loads associated with shaking.

Geological mapping or geophysical surveys could better constrain the location and alignment of the fault which traverses north-south through Bel-Aire. The goal of such a study would be to define a setback zone from the fault for further water storage infrastructure. Determination of the fault activity may not be feasible or necessary with a setback distance.
If feasible and cost-effective, install seismic retrofits to the reservoirs and connected infrastructure. Structural analysis of the existing reservoirs in the context of the possible fracture / fault hazard should guide planning and decision making.

Setback distance from the delineated fracture/fault zone for any future reservoirs. This is challenged by the high population density of the area.

The primary mitigation strategy is to consider re-locating the primary storage capacity of the water system. Based on the observations of this assessment, it may not be advisable to rely upon the existing reservoir site to serve such a key component of the system.</td></tr>
<tr><td>2</td><td>High</td><td>Liquefaction Shaking Tsunami</td><td>Petite Anse, Airport, Centre Ville</td><td rowspan="2">Some potential mitigation strategies include:
• Flexible continuous pipe sections such as butt-fused HDPE.
• Subsurface conditioning techniques such as pore-pressure reduction strategies including coarse trench backfill with geotechnical membrane and vertical drains such as gravel of slotted PVC.
• Installation of periodic isolation valves and manifolds for temporary hose connection to bypass ruptured areas.
• Flexible connections between all above-ground structures such as well houses or reservoirs and all rigid infrastructures like valve or manifold stations.
• Consider reinforced concrete trench cover in order to reduce potential for scouring during tsunami.

Site-level geotechnical assessments and field observation during trenching is recommended in order to better constrain the liquefaction hazard along the coastal stretch of the supply line towards Balan. A geological engineer or geotechnical engineer experienced in liquefaction should be a part of the supervisory team and oversee the geotechnical data collection. Potential activities include borings using SPT sampling techniques, soil laboratory testing and use of geophysical techniques to efficiently estimate the lateral continuity of potentially liquefiable layers. Site-level pipeline construction and design should incorporate the geotechnical results. Based on preliminary geophysical data, the liquefaction potential is likely greatest along the coastal stretch, decreasing toward Balan.</td></tr>
<tr><td>12</td><td>Moderate</td><td>Liquefaction Shaking</td><td>Balan</td></tr>
<tr><td>4</td><td>High</td><td>Debris-Flow Flooding</td><td>Vaudreuil</td><td rowspan="2">High hazard potential for torrential flooding and debris flow. Pipeline requires additional anchoring and protection when crossing these drainages.
• Installation of shutoff valves, outlet manifolds, vault boxes and provision of flexible hose to by-pass ruptured section along drainage.
• Use of thick walled and strong pipe such as ductile iron or butt-welded steel needed if any section of pipe is exposed.
• Encasing pipe in thick concrete is also an option.</td></tr>
<tr><td>5</td><td>High</td><td>Debris-Flow Flooding</td><td>Haut du Cap</td></tr>
</table>

Location ID	Hazard Level	Hazard Type	Location	Recommended Mitigation Strategies or Assessments
6	High	Shaking	Balan	Structural review of existing elevated reservoir in Balan at the F10 supply well. Based on the structural review of the existing reservoir and the seismic stresses anticipated by the design event, retrofitting of the reservoir may be advisable if it is to be incorporated into the planned water system. Further, this reservoir could be at risk if land subsidence occurs due to groundwater pumping impacts.
3	High	Flooding Tsunami	Pont Neuf, Riviere Haut du Cap	Initial flood and tsunami potential mapping indicates high susceptibility to flooding and inundation of 3-10 meters depth with tsunami velocities greater than 3 m/s. Considerable forces would be exerted on any exposed pipeline or support structure (such as the existing bridge) in such an event. Primary mitigation strategies include: • Regardless of the suspension method used to cross the drainage and hazard zone, it is advisable to install shutoff valves, outlet manifolds, vault boxes and vaults with flexible hose to transmit water across the affected area. This may require temporary suspension of large diameter (12-18 inch) hose across a 60-80 meter span of the Riviere Haut-du-Cap at National Route 3 or suspension on the existing bridge. • Above-ground pipelines should be steel or ductile iron with flexible joints. • Support columns and anchoring should be designed to accommodate the potential forces. The design of support infrastructure to withstand such an event may benefit from a more detailed analysis of the hazard in terms of height, velocity and duration. The design and current condition of the existing National Route 3 bridge was not reviewed in this consultancy; a structural and conditions analysis of the current bridge may help guide mitigation approaches. Existing 12-inch supply lines are installed in constructed channels in the existing bridge which have been paved-over. The proposed 18-inch supply line and accompanying distribution lines will require a separate support structure or installation of side-mounted support brackets to the existing bridge. Considering an analysis of the existing bridge capacity to support the additional supply and distribution lines in a flood or tsunami event, a second support structure could be designed to withstand the refined hazard stresses. Later phases should consider addition of a second supply line away from the main tsunami and flood scouring hazard. One option would be crossing the Riviere Haut-du-Cap farther south in the Haut du Cap area.
3	High	Fault-Rupture	Pont Neuf, Riviere Haut du Cap	Geological investigations would be beneficial to more specifically define the location of faults which may intersect pipeline alignments, however general mitigation strategies can be employed in wide zones of potential rupture. Some potential mitigation strategies for fault rupture along a pipeline include: • Alignment so pipe is in tension rather than compression during fault displacement. For the primary reverse fault (Zone 3, 8-11), this would be when the intersection angle is small (sub-parallel) to fault. High urban density may reduce re-alignment feasibility in Zone 3. • It is possible that acceptable levels of mitigation may be achieved using flexible piping such as HDPE placed in oversized trenches with loose coarse granular fill and geomembrane liner. o Thick-walled and butt-fused HDPE pipe is recommended to withstand the tensile strain of faulting,

Location ID	Hazard Level	Hazard Type	Location	Recommended Mitigation Strategies or Assessments
7	Moderate	Fault-Rupture	Airport	increase wall thickness within 50m on each side of fault zone. Butt fusion provides higher strength. o Loose backfill reduces the interface friction, o Medium coarse low-angularity granular soil without cobbles or fines recommended for backfill material. o Oversized trenches with side slopes of 45-60 degrees potentially advisable to accommodate lateral and vertical displacement. o Double-layer geomembrane liner around pipe to decrease interface friction. • Installation of shutoff valves, outlet manifolds, vault boxes and provision of flexible hose to by-pass any rupture prone section. • As much as possible, avoid abrupt changes in direction and field bends, elbows or flanges which reduce the pipes ability to move in fault zones. • In areas of well-defined and maximum deformation, ductile iron or steel pipe using flexible joints such as NS, S-II, S, GENEX or flex ring type joints may be preferred, however the cost is higher than HDPE and would likely justify studies to better constrain the fault locations. If an alternate supply line from Balan or future well fields is selected, a potential fault-crossing could occur across the Riviere Haut du Cap in Haut du Cap and similar alignment considerations would be warranted, however the urban density would potentially lead to better feasibility. Zone 3: Without further study, it is advisable to treat the entire pipeline length from the intersection of Route 3 with Route 1 / Route L to the Pont Neuf traffic circle as a possible fault rupture zone (roughly 500m). Zone 7: Likely that fault movement is reverse or normal, not strike-slip. Better constraint of the location could be used to design flexible piping in the zone of most probable rupture and isolation valves for temporary hose installation. Zone 8, 9 & 10: If the fault lies to the southeast of the pipelines, then likely no special mitigation is necessary for fault rupture. However, wherever the fault is found to cross the main distribution line it may be advisable to consider the mitigation options presented. Zone 11 & 13: The mitigation strategies noted above may be sufficient without further investigation.
8	Moderate	Fault-Rupture	Goyard	
9				
10			Haut du Cap	
11			Centre Ville	
13	Moderate	Fault-Rupture	Bel-Aire	
14, 15, 16, 17, 18, 19, 20, 21	Low	Debris-Flow Flooding	Haut du Cap, Vaudreuil, Goyard, Bel-Aire	Standard drainage crossing protections such as steel or ductile iron pipe in exposed or erodible areas or concrete cap and anchoring to down-gradient sides of support structures such as bridges or culverts. Isolation valves, outlet manifolds, vault boxes and provision of flexible hose.
R1	Low	Fault-Rupture Slope-Stability	Haut du Cap	Reservoir Site Evaluation – Based on Section 7.1, three possible reservoir sites are noted based on our reconnaissance activities. Complete reservoir site characterization studies are necessary in order to vet their suitability. Site R1 is initially the preferred location based on elevation, slope stability and elevation. Site R2 was noted during a rapid reconnaissance as having suitable elevation, however it is situated immediately east of a major landslide complex. If
R2	Low		Goyard	

Location ID	Hazard Level	Hazard Type	Location	Recommended Mitigation Strategies or Assessments
R3	Moderate		Vaudreuil	suitable, site R2 would provide a convenient location intermediate to Bel-Aire and Site R1. Site R3 was not specifically visited however OREPA Nord indicated the presence of a small existing reservoir which could be replaced with a larger reservoir to supply the southwestern-most zones of the system in Vaudreuil.
P1	Moderate	Liquefaction Fault-Rupture	Plain south of airport	Alternate Supply Pipe Alignment Evaluation- This corridor, or a second one further to the south provide potential alternate/secondary supply line alignments which provide redundancy and potentially traverse less averse terrain in terms of liquefaction, tsunami and flood risk. Geotechnical and geophysical investigation is needed in order to better constrain the liquefaction hazard along these corridors and plan the best alignment and support structure to cross the thrust fault near Riviere Haut-du-Cap in Haut-du-Cap. Recommend that a geological engineer or geotechnical engineer experienced in liquefaction hazard evaluation and design be retained to design and oversee the geotechnical investigation. Potential activities include borings using SPT sampling techniques and use of geophysical techniques to efficiently estimate the lateral continuity of potentially liquefiable layers and constrain the location of the thrust fault. Final pipeline design needs to incorporate the findings and recommendations of the geotechnical study. This corridor would likely be most feasible if an alternate well field is developed southwest of Balan.