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## Groundwater Quality Sustainability

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# Extended Abstracts

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## INTRODUCTION

In many of the Caribbean islands, groundwater has been developed as a necessity when no surface water supplies were available. Over the years numerous funding agencies have sponsored drilling programs, which have resulted in various degrees of success. The programs that were successful often occurred in those islands where laterally extensive limestone aquifers existed, and developing groundwater therefore was relatively easy. In other islands that had no significant limestone aquifers, shallow alluvial sediments along drainage courses were targeted. Until recently (2000), fractured bedrock aquifer or permeable unconsolidated volcanic deposits had not been targeted with any degree of success, nor were they considered as potential aquifers.

This paper reports on the sustainable development of fresh and brackish groundwater supplies in deep volcanic aquifers on three Caribbean islands utilizing an integrated multi-disciplinary exploration program. In the last 10 years over 20 million imperial gallons per day has been developed by the author and his teams on seven Caribbean islands using this approach. Past attempts at developing groundwater on the islands using minimal field exploration were marginal, leading the island water authorities to assume that only desalination could solve their water supply shortages. Case studies of the exploration results in Tobago, Antigua and Nevis will be presented (Figure 1). These islands are primarily volcanic in origin, highly vegetated, have sparse fresh outcrops and minimal sources of hydrological data. Therefore remote sensing, GIS integration, recharge analysis, geological mapping and extensive geophysical surveying was critical in evaluating each islands water resources.

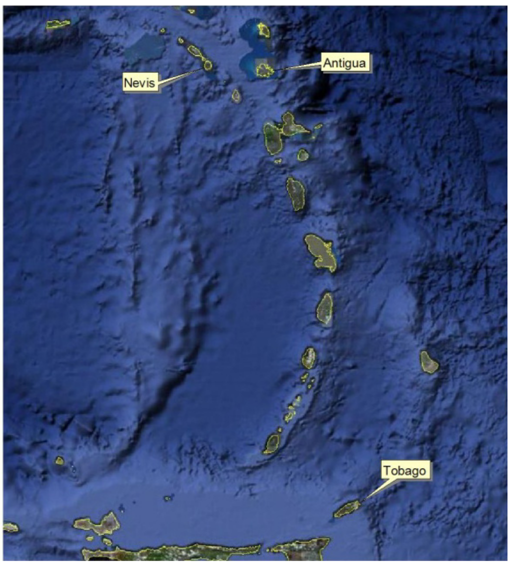


**Figure 1**. Location map.

## OVERVIEW OF THE INTEGRATED GROUNDWATER EXPLORATION PROGRAM

The technologies integrated recently in the successful development of groundwater supplies in the islands of the Caribbean include the use of imagery, ground surface testing and sub-surface investigations as summarised below:

- Geologic and hydrologic data acquisition and evaluation;
- Satellite imagery, aerial photographs and Digital Elevation Model (DEM) interpretation;
- Hydrological modelling to determine groundwater recharge;
- GIS integration of the data sets and various interpreted information;
- Field verification of implied geological features;
- Geophysical surveys such as resistivity, magnetic, electromagnetic and gravimetric;
- Test drilling using a dual rotary drilling rig that allows for accurate sampling of water quantity, water quality and rock type.

Expert integration of this data in addition to an in-depth understanding of the regional and local geology is the key to determining the presence of fractured bedrock and volcanoclastic aquifers, and adequate recharge into the aquifers.

**TOBAGO — 2000**

Tobago is the smaller of the twin island Republic of Trinidad and Tobago (300 square kilometres in area). The republic is the southern-most of the chain of Caribbean island countries of the Lesser Antilles. Tobago is composed of 100 million old volcanic and meta-sedimentary rocks originating in Central America and transported along the Caribbean plate boundary in the southern Lesser Antilles island arc which is a very different origin than the other islands of this arc. The island's geology consists of predominantly Mesozoic igneous and metamorphic rocks that form a southwest to northeast trending mountain range along the long axis of the island, and younger Cenozoic sedimentary deposits consisting of Pliocene conglomerates, Quaternary deposits of coralline limestone and alluvium in the south-western lowland area. Brittle fault systems caused by the plate boundary movement have transected the island, pervasively fracturing the Mesozoic belts.

Thirty years of prior groundwater development efforts performed by several consultants resulted in the development of three (3) alluvial wells producing 0.05 MGD to 0.10 MGD per well and a conclusion that the total groundwater potential was only 0.4 MGD.

**Results**

Average rainfall ranges from 2,800 mm on the main ridge to less than 1,400 mm in the south western lowlands. The island was divided into 1 km square sub-basins, called Groundwater Recharge Units (GRUs). Recharge was calculated by developing equations that related evapotranspiration and runoff to precipitation using several gauged watersheds. Using the equation Recharge = Precipitation – runoff – evapotranspiration, a recharge contour map of the entire island was developed. The recharge to each of these GRUs was calculated by overlaying the GRUs with the recharge contour map.

An evaluation of the published geological reports indicated that the most likely targets for large aquifers would be fracture and fault zones in the crystalline volcanic and sedimentary rocks enhanced by the tectonic activity rather than in rocks with primary permeability. Multi-basin Aquifer Systems (MBAS), three dimensional fractured bedrock aquifers crossing surface water divides, were delineated through an analysis of satellite, aerial photography and digital elevation shaded relief maps of the island in conjunction with the distribution of GRUs. Where implied fracture zones cross major watershed boundaries, the recharge to GRUs adjacent to these fractures are summed in order to estimate the recharge to the MBAS. Areas were selected for detailed investigation based on favorable fracture characteristics, accessibility to a drill rig, and recharge amounts. The MBAS were ground-truthed by the geological team. Those that showed evidence of major fracture permeability were selected for geophysical surveying.

The geophysical techniques that were selected to pinpoint drill sites in the selected favorable zones included those that are effective in delineating fracture zones such as electromagnetic, magnetic, micro-gravity and resistivity surveys. A Foremost Dual Rotary drilling rig was used so that the casing could be advanced to case off caving formations while obtaining accurate water and drill cutting samples. As a result of these surveys seven production wells were drilled in large fault and fracture systems and four million gallons per day of excellent quality groundwater (up to 0.8 migd per well) were developed.

**ANTIGUA 2002–2003**

Antigua is 280 km$^2$ in area. It has a relatively dry climate, with an average annual rainfall of 840 mm in the lowlands and 1270 mm in the higher elevations. It is the southernmost of the "Limestone Caribbes" and is considerably younger than Tobago (28 to 33 my) and is part of the eastern volcanically inactive island arc. Three major geological units form a relatively gentle monocline dipping to the northeast. The lowermost unit is a volcanic complex consisting of basaltic to andesitic lava flows, pyroclastic rocks and lahars (mudflows). The overlying unit, about 500 m thick, consists of conglomerates, sandstones and shales resulting from the erosion of the volcanic complex. The uppermost unit (Antigua Formation) is a 500-metre-thick limestone. However the volcanic units are highly weathered and have considerable less faulting and fracturing than Tobago because of the island distance from the active tectonics.

The exploration program was carried out in the volcanic portion of the island with a goal of developing 2.5 migd of fresh groundwater. This area had the greatest rainfall, and thus was most likely to have sufficient recharge into the volcanic rock sequence. Over a 50-year period, numerous foreign aid projects resulted in the drilling of more than 150 wells and the development of 1.5 migd of groundwater supplies. All of the projects either focused on the alluvium or the limestone, with limited or no geophysical surveying used to select well targets. No wells had been drilled in the fractured volcanic rocks.

**Results**

An integrated exploration program was applied in an effort to develop fresh water with a Total Dissolved Solids (TDS) concentration below 800 mg/l. Remote sensing using IKONOS satellite imagery, aerial photography and a digital elevation model were used to map potential fractured bedrock aquifers. Detailed geological mapping was conducted in order to identify areas favourable for geophysical surveying. Electromagnetic, magnetic and gravity surveys were conducted in to pinpoint drill sites in the volcanic terrane.

Over 20 wells were drilled into fractured bedrock aquifers with the most productive well, in an area of high rainfall, yielding about 250 igpm with a surprisingly high total dissolved solid (TDS) content of 1700 mg/l. Most of the other wells drilled also had high TDS concentrations between 1500 and 3000 mg/l. These very high TDS concentrations can be explained by the following factors: relatively low rainfall, high influx of salt from "dry fallout" due to the physiography of the island, soils and bedrock with a low permeability, and high groundwater evapotranspiration rate because of shallow groundwater tables.

While in a sense this project had a disappointing result in that large supplies of fresh groundwater do not apparently exist in the volcanic rock, it does appear that substantial supplies of brackish water can be developed. We estimate that between 2.0 and 4.0 migd of brackish water could be developed, representing an opportunity to substantially reduce desalination costs. Based on the results of this project and the identification of large supplies of brackish water, APUA is considering an aggressive exploration program to develop this brackish water in order to more cost-effectively meet a growing need for more water. Multiple groundwater sources sited at strategic points of demand would also buffer APUA customers against threats of hurricanes, droughts, oil spills and vandalism.

**NEVIS 2007–2010**

The island of Nevis is located in the northern region of the Lesser Antilles. Nevis is 93 km$^2$ in size and has a population of about 11,000. It is part of the volcanically active island arc and is the youngest of the three islands with the age of the volcanic rocks ranging from 4 million to only 100,000 years. The young age of the rocks dictates a completely different exploration approach than the other islands. Precipitation is similar to Tobago, ranging from 900 mm in the lowlands to 3000 mm on Nevis Peak. The island is mainly composed of loosely consolidated highly permeable reworked volcanic deposits which do not support a significant amount of fracturing. Consequently the major aquifers are expected to be primary volcanic formations such as buried alluvial channels and lava flows requiring geophysical techniques capable of penetrating to great depths.

**Results**

Even though the island is composed of several volcanic centres the youngest and highest centre, Nevis Peak, has the greatest impact on both the total quantity of rainfall, as well as the permeability of the aquifer materials. Because Nevis Peak is 900 metres (3000 feet) high, moist tropical air rises from sea level and condenses on the mountaintop. The intrusive rocks of the peak appear to be highly fractured and permeable.

Prior to the most recent volcanic events that occurred about 100,000 years ago erosion deeply dissected the flanks of the volcano creating deep valleys. During the last eruption these valleys were filled with highly permeable volcanic deposits and/or lava flows that have subequently been covered with recent permeable reworked volcanic deposits (mud and debris flows, landslides, etc.) leaving little surface evidence. These buried valley aquifers act like arteries that carry the bulk of the rainfall from the mountain as groundwater that discharges to the ocean. Since these aquifers are not obvious on the surface extensive geophysical surveying was required in order to identify them for drilling exploration targets.

The physical properties of subsurface volcanic deposits can be measured with various geophysical devices, however we found in previous projects that a resistivity method capable of providing a high-resolution resistivity profile from the surface to a depth of more than 400 meters is the Controlled Source Audio-frequency Magnetotelluric method (CSAMT). The resulting profiles were used to effectively delineate the buried volcanic deposits.

The Nevis groundwater exploration project has resulted in the development of approximately 1.5 migd of high quality groundwater from three production wells situated in proximity to the existing infrastructure of the Nevis water system. The program also resulted in the development of a hydrogeological map which will be used to develop additional groundwater resources in the future as the demand increases.

**CONCLUSIONS**

Failure to identify the geologic processes that result in productive aquifers has limited understanding of the groundwater potential of the Lesser Antilles. The three most important tasks in developing groundwater in the varied and complex environments of the Lesser Antilles are:

- Identification of the geological processes responsible for the development of aquifers so that a properly designed exploration program can be developed.
- Geophysical methods are selected based on their capability of measuring the physical properties defining the dimensions and groundwater potential of the conceptualized hydrogeology.
- Drilling methods that allow for the accurate sampling of water and formation materials must be selected so that the conceptual model is properly verified.

The results of these three projects have demonstrated that aquifers in the younger volcanic islands and the tectonically active older volcanic islands have excellent water quality, a very high recharge rate and substantial yields. Whereas the intermediate aged highly weathered volcanic islands in a tectonically quite area have brackish groundwater due to a combination of less recharge, a higher water table and a substantial influx of salt from dry fall out due to the geometry of the island. However in spite of this lower grade resource a substantial groundwater supply exists that can be more cost effectively desalinated than seawater.

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