Incorporating drought risk modelling as a planning tool for climate change adaptation measures in Saint Kitts and Nevis

Assessment of water resources of Saint Kitts and

FWR6614-RT006-R01-00

28 April 2022

Document information

Document permissions	Confidential - client
Project number	FWR6614
Project name	Incorporating drought risk modelling as a planning tool for climate change adaptation measures in Saint Kitts and Nevis
Report title	Assessment of water resources
Report number	RT006
Release number	01-00
Report date	28 April 2022
Client	Climate Technology Centre & Network (CTCN)
Client representative	Ramiro Salinas
Project manager	Gina Tsarouchi
Project director	Nigel Walmsley

Document history

Date	Release	Prepared	Approved	Authorised	Notes
28 Apr 2022	01-00	GMT	ABL	NW	

Document authorisation

Prepared	Approved	Authorised
Gina Tsarouchi	Andrew Ball	Nigel Walmsley

Contents

Tables

Figures

1 Introduction

1.1 Project summary

In an effort to address the impacts of climate change and climate variability in a sustainable way, access to critical information within the water sector is vital. Drought prediction models can identify areas most susceptible to water supply variability and shortages, and therefore facilitate early action to manage risks. In doing so, this will increase resilience in the water sector to improve agricultural use of water resources and therefore ensure food security and water usage including from the domestic sector and the tourism sector in Saint Kitts and Nevis. The overall objective is to incorporate drought risks modelling as a planning tool for climate change adaptation measures in Saint Kitts and Nevis. The main outputs include:

- Map stakeholders and establish a stakeholder working group;
- Assess drought risk and water resources in Saint Kitts and in Nevis;
- Benchmark, design and implement a drought prediction model in Saint Kitts and in Nevis;
- Train administrators and users of Saint Kitts and Nevis to the drought prediction model.

The Project outcomes respond directly to SDG 13 ‘Taking early action to combat climate change and its impacts’ by providing a system that will support planning and decision-making for the sustainable management and conservation of water resources in Saint Kitts and Nevis. The Project will also contribute to SDG 1 (End poverty), SDG 2 (Food security) and SDG 6 (Availability and sustainable management of water) as the drought prediction model will improve agricultural and use of water resources, improve food security and increase the income of rural communities.

1.2 About this report

The purpose of this report is to assess the water resources of Saint Kitts and Nevis with focus on groundwater resources. This includes a review of previous work and an assessment of key risks to water resources, such as saline intrusion in vulnerable coastal aquifers. While the development of a water balance for each aquifer was originally envisioned as part of this output, lack of data and in-depth knowledge of individual aquifers on the islands make this very difficult. However, an overall water balance has been completed for both islands and is described in Output 2.3.

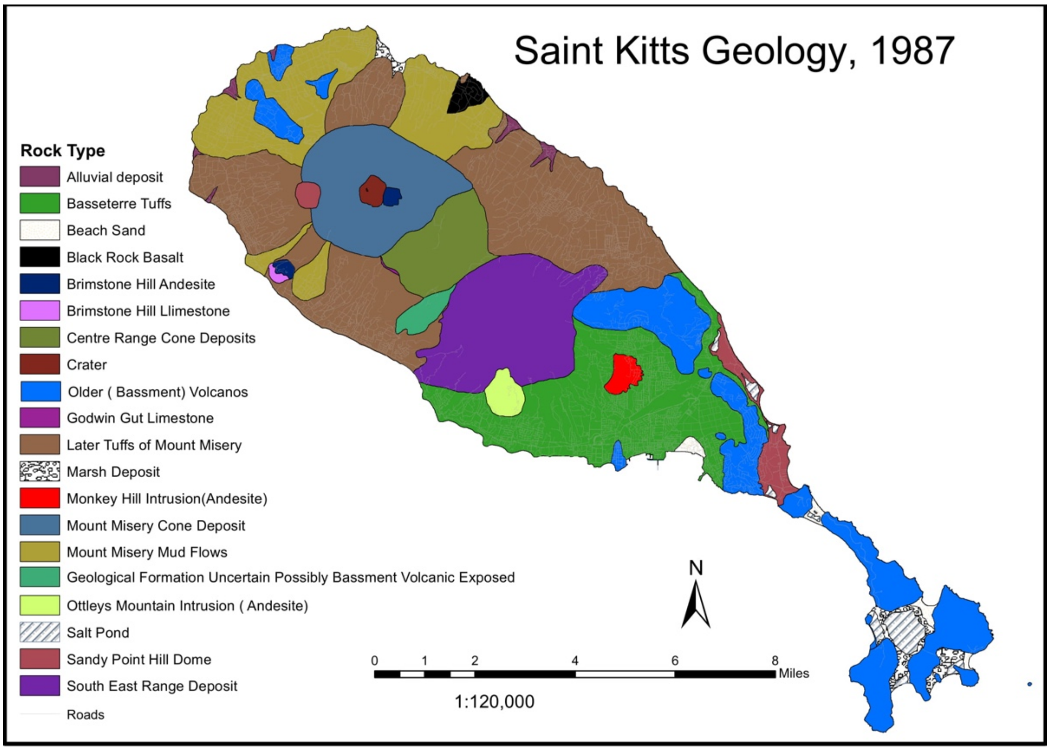
2 Water Resources of Saint Kitts and Nevis

2.1 Geology

A comprehensive study of the geology and soils of St. Kitts and Nevis was undertaken by Lang and Carroll in 1966 with subsequent studies by Martin-Kaye (1969), Hutton and Nuckholds (1978) and Baker (1985). These are summarized in detail in the Terrestrial Ecological Inventory for St. Kitts and Nevis, Compendium Report, Part I by Lindsay and Cooper (2020). The following is a brief synopsis of these studies.

The island of St. Kitts is composed almost exclusively of volcanic rocks of andesite or dacite mineralogy (Figure 2.1). Its geology is like that of other volcanic islands in the Lesser Antillean archipelago. The islands are the summits of a submerged mountain range that forms the eastern boundary of what is known as the Caribbean Tectonic Plate. The entire island archipelago is geologically young, having begun to form probably less than 50 million years ago, during the Miocene era. St. Kitts had since undergone numerous and considerable changes in elevation but is now relatively stable. Newer volcanics rest on a basement of older rocks, now only exposed where the newer deposits have been denuded. Evidence of older volcanic basement rocks can be seen on the face of the Southeast Peninsula and its extension to the Morne, Conaree and Canada Hills. These volcanics are generally coarse agglomerate and intrusive andesites with subsidiary tuffs. More recent volcanic centers along the island's central spine, Middle range and Mount Olivees range appear similar in age. Mt. Liamuiga, the most northerly volcano has a youth appearance and was active in recent (geologic) time. The main part of St. Kitts has a mountain range that runs northwest through the center of the island. The high mountain slopes are densely vegetated by rainforest, while the foothills gently slope from the base of the mountain range to the coast. In contrast, the topography and vegetation of the Southern Peninsula is dramatically different. Here, numerous low, round hills are separated by flat, low-lying areas and salt ponds.

Nevis is a volcanic island that began its formation in mid-Pliocene times (approximately 3.45 million years ago). However, the island comprises several discrete eruptive centers that range in age from mid-Pliocene to Pleistocene, which are summarized in detail by Hoag (2018) and shown in Figure 2.2. Generally, the geology of Nevis can be subdivided into four informal units: Volcanic of the eruptive centers, volcanogenic rocks – pyroclastic and lahars, fluviatile and lacustrine deposits and raised beaches.



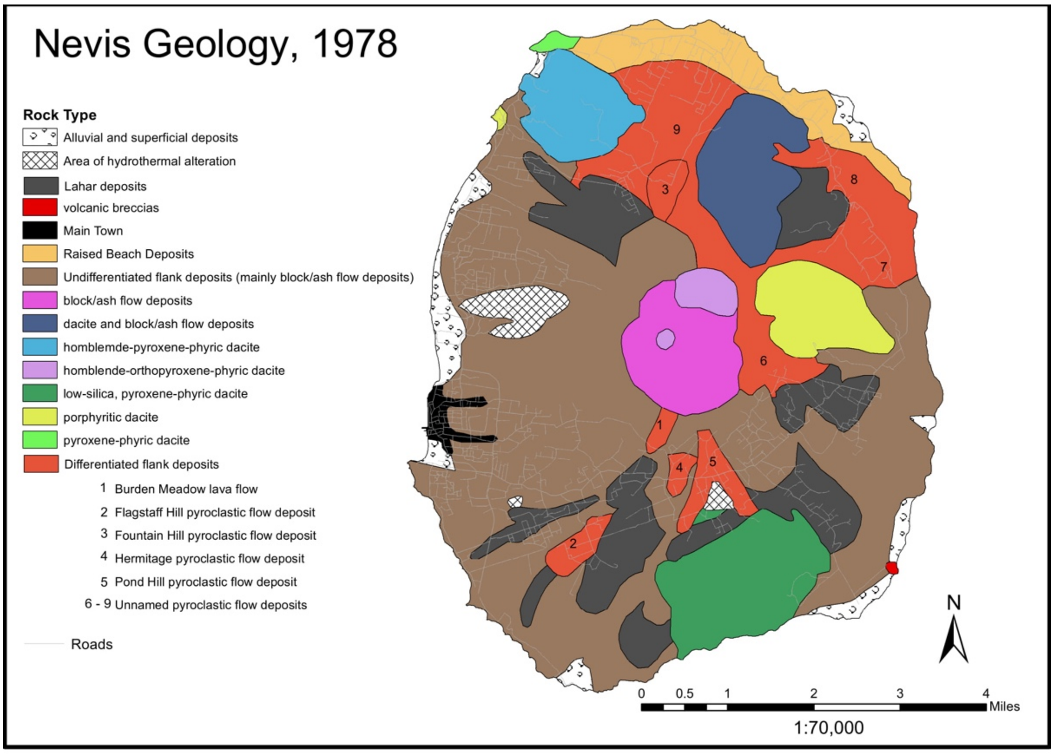
Sources:
Martin-Kaye and Baker, 1987

WGS 1984 UTM Zone 20N

September 9nd, 2017

Nigel Bardoe
PROJECT: Conserving Biodiversity and Reducing Habitat Degradation in Protected Areas and their Areas of Influence

Figure 2.1: Geological map of St. Kitts



Sources:
Hutton & Nockolds, 1978

WGS 1984 UTM Zone 20N

September 9th, 2017

Nigel Bardoe
PROJECT: Conserving Biodiversity and Reducing Habitat Degradation in Protected Areas and their Areas of Influence

Figure 2.2: Geological map of Nevis

2.2 Soils

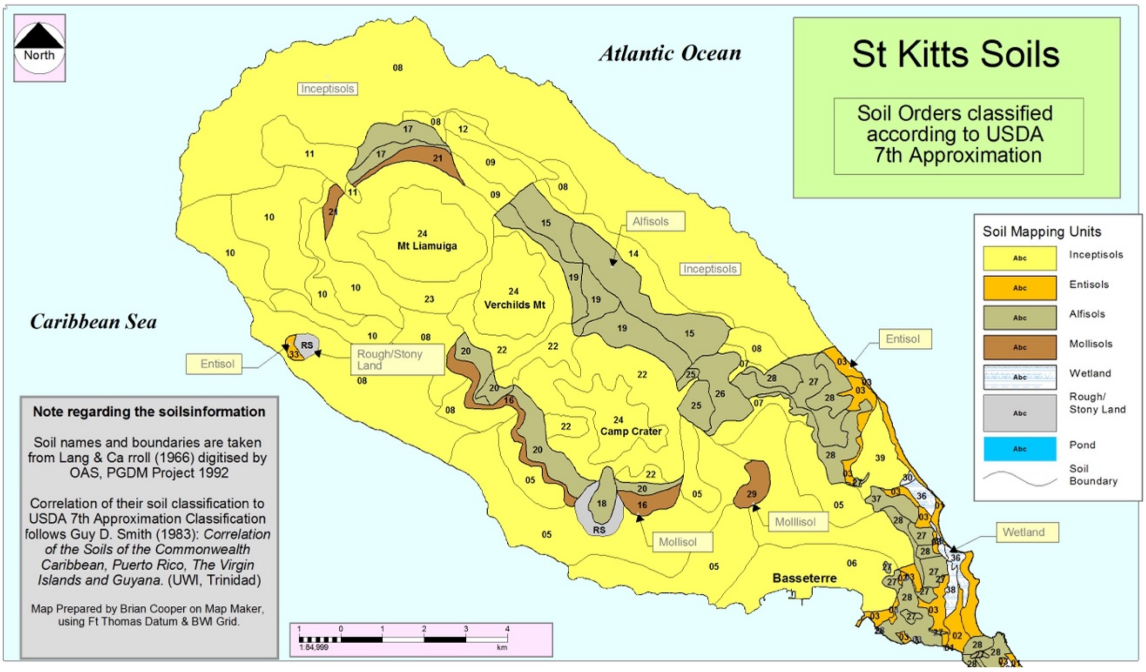
Lindsay and Cooper (2020) provide a detailed review of the soils. The soil descriptions given by Lang and Carroll (1966) are no longer commonly used and have been reclassified using the USDA Soil Taxonomy classification by Smith (1983), summarized by Lindsay and Cooper (2020) and shown in Figure 2.3 and Figure 2.4. In the USDA Soil Taxonomy classification there are 6 levels. These are Order, Sub-Order, Great Group, Sub-Group, Family and Series. In St. Kitts and Nevis, five of the 12 Orders are currently represented (as described in Table 2.1), but it is very likely that additional Orders will be recognised if the necessary information is collected especially at upper elevations in the Central Forest Reserve and Nevis Peak.

In comparing the soils of both islands, it is important to note that although Nevis lies a few kilometres to the south east of St. Kitts, and the geological origins and ages are quite similar, the soils that have developed are significantly different (Lindsay and Cooper, 2020). Nevis has a much greater area of heavier textured soils, some of which have developed a clay layer sufficiently compact as to restrict root penetration, thus reducing the natural productivity of the soil and groundwater recharge whereas in St. Kitts sandy and loamy textured soils predominate especially at below 300 m above sea level (asl), while clays and silty clays are much less common.

Table 2.1: USDA Soil Taxonomy Orders found on Saint Kitts and Nevis (Lindsay and Cooper, 2020)

Order	Description
Entisol	Soils that lack well-developed horizons. Commonly found on recent deposits such as loose river and beach sediments of sand and clay, or of volcanic ash. Some types have an A horizon (top soil) lying directly on top of bedrock.
Inceptisol	Young soils which have some subsurface horizon formation indicated by colour changes or in soil texture. Fertility depends on parent material (most common in St. Kitts).

Order	Description
Alfisol	Mostly found in semiarid to humid areas and under hardwood tree cover. They are quite fertile and show significant development of a clay horizon and often colour changes due to accumulation of aluminium or iron.
Mollisol	Are soft, deep, dark-coloured, fertile soils formed in grasslands and some hardwood forests with thick A horizons (top soil). Nutrient levels are good and pH is usually >7. Clay content high, but stays workable and crumbles on drying (most common in Nevis).
Vertisol	Deep, heavy clay soils, which shrink and swell with changing moisture levels, leading to deep cracks in dry periods exhibits significant cracking on drying. Heavy clays.
Andisol (not yet differentiated)	Soils developed on weathered volcanic ash, fertile, deep and well drained. Wetter soils (>60” of rainfall) often bind phosphorous, making it unavailable to plants.



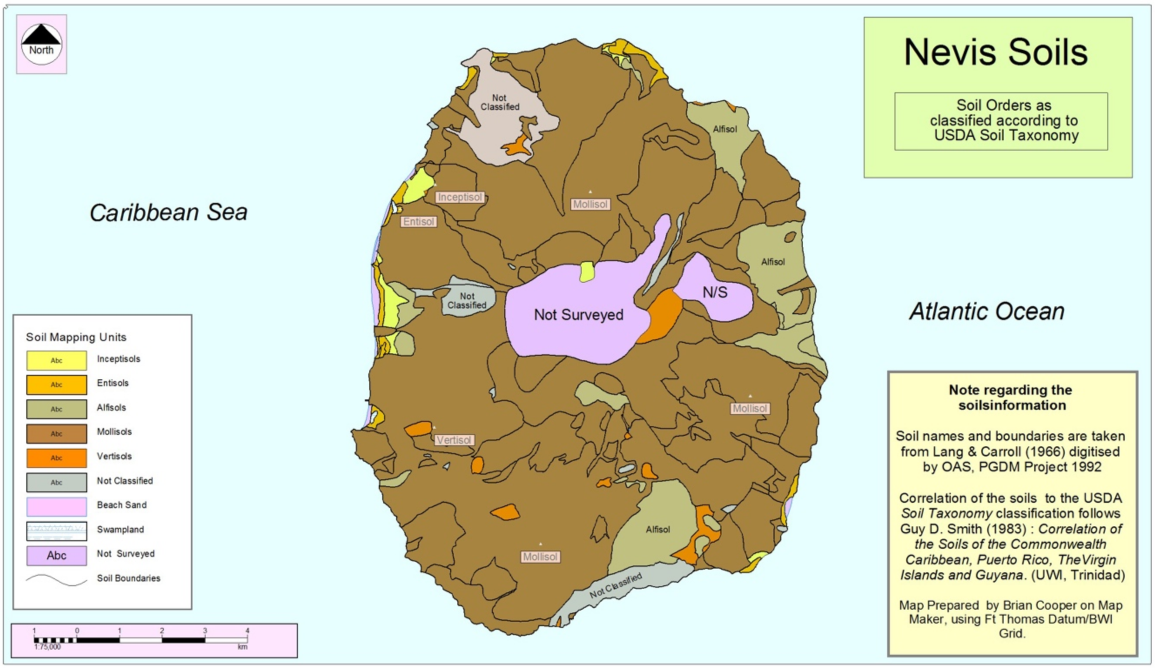
Note regarding the soilsinformation

Soil names and boundaries are taken from Lang & Ca rroll (1966) digitised by OAS, PGDM Project 1992

Correlation of their soil classification to USDA 7th Approximation Classification follows Guy D. Smith (1983): *Correlation of the Soils of the Commonwealth Caribbean, Puerto Rico, The Virgin Islands and Guyana*. (UWI, Trinidad)

Map Prepared by Brian Cooper on Map Maker, using Ft Thomas Datum & BWI Grid.

Figure 2.3: Soils map of St. Kitts



Note regarding the soilsinformation

Soil names and boundaries are taken from Lang & Carroll (1966) digitised by OAS, PGDM Project 1992

Correlation of the soils to the USDA *Soil Taxonomy* classification follows Guy D. Smith (1983) : *Correlation of the Soils of the Commonwealth Caribbean, Puerto Rico, TheVirgin Islands and Guyana*. (UWI, Trinidad)

Map Prepared by Brian Cooper on Map Maker, using Ft Thomas Datum/BWI Grid.

Figure 2.4: Soils map of Nevis

2.3 Watersheds and Drainage

In terms of topography, both islands are, geologically speaking, very young and the steep slopes, created by the erupting volcanoes, have had little time to be eroded to lower, more gently sloping topography (Lindsay and Cooper, 2020).

In St. Kitts, water drains in a radial pattern from the central mountain range to the ocean, interrupted only by the relatively minor volcanic cones at Brimstone Hill, Ottley's Mountain, Sandy Point Hill and Monkey Hill. There are seven major drainage basins (Williams, 2010) and 48 watercourses (Lindsay and Cooper, 2020) as shown in Figure 2.5. Most of the water channels have headwaters between 500-700 m asl are deep and steep sided and are usually dry along all or most of their stretches. Locally, these channels are named ghauts. Only the relatively large Wingfield and Cayon rivers flow almost to the sea for some of the wettest part of the year although less so since the drought of 2015. There are no stream gauges installed to measure the intermittent flow of the ghauts in St. Kitts.

Water also drains in a radial pattern form Nevis Peak to the ocean through 10 major drainage basins and is interrupted only by the smaller volcanic cones of Hurricane, Saddle and Round Hills. These basins comprise ephemeral ghauts with some of the largest being Camps River and Barns Ghaut. In some basins, water is channeled from over 400 m asl through relatively straight ghauts with steep narrow sides. All the major ghauts rise from within the Nevis Peak attesting to its importance to the water resources of Nevis (Lindsay and Cooper, 2020) as shown in Figure 2.6. Almost all the ghauts are ephemeral except the Bath Stream, which flows year-round to the sea from springs less than 1.6 km inland. Bath Stream does have a stream gauge installed and managed by the Nevis Disaster Management Department. Most of the other ghauts flow intermittently, about three to four times annually after heavy rainfall but less so since the major drought of 2015.

Importantly, runoff only occurs when there is abundant precipitation during a short period of time, such that the rate of precipitation exceeds the rate at which it can infiltrate the soil, or when there is an extended period of rain that results in a surplus after saturating the soil zone. The lack of runoff is due to the very permeable nature of the volcanic soils resulting in significant groundwater recharge and limited surface water flow (Hoag, 2011).

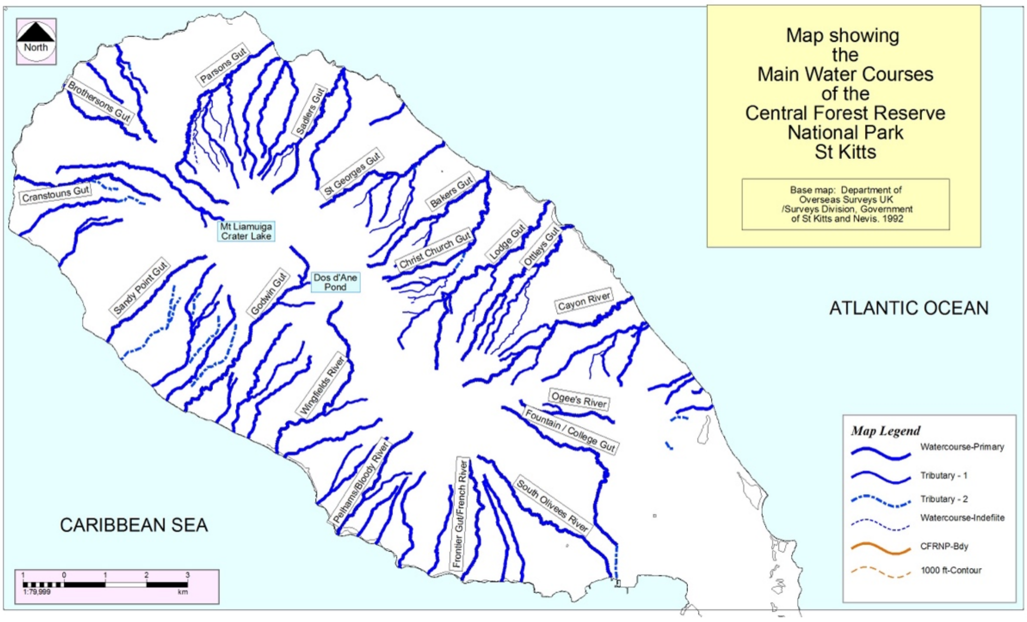


Figure 2.5: Watercourses of St. Kitts

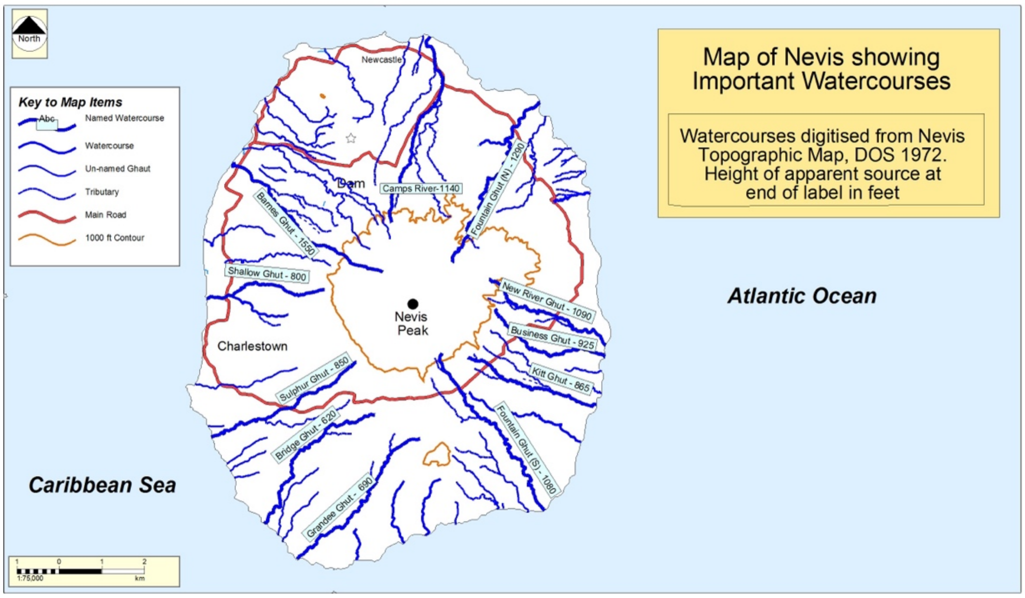


Figure 2.6: Watercourses of Nevis

2.4 Hydrogeology

2.4.1 St Kitts

Generally, most of St. Kitts is fringed by a coastal unconfined aquifer generally between 0.8 to 3.2 km inland and ground elevation from about 15 to 100 m above mean sea level. In this range, static water level is found to vary from about 0.6 to 6 m asl. However, the localized geology varies considerably and hence it is possible to find variation in transmissivity of several orders of magnitude within this zone (Williams, 2010 and USACE, 2004).

The most thoroughly studied aquifer in St. Kitts is the Basseterre Valley Aquifer (BVA). Christmas (1977) produced the first detailed hydrogeological analysis of the Basseterre Valley unconfined coastal aquifer system. The report provided an appraisal of available groundwater resources, determined characteristics of the aquifer to guide the development and management of the resource, and estimated a safe yield of the aquifer. Results were based largely on limited drilling logs and cuttings (rotary coring method), water table maps, pumping tests, water quality sampling, and groundwater level fluctuations. Christmas (1977) calculated an estimated safe yield for the aquifer of 2.5 million imperial gallons per day (MGD). Later, Ker, Priestman & Associates (KPA) (1988) conducted an exploratory drilling project on St. Kitts for the purposes of locating groundwater sources, to design and construct production wells to meet potable water demand, and to determine if further drilling would be required to locate additional sources of significant groundwater. They estimated a safe yield of about 3 MGD for the BVA. Williams (1999) conducted a re-appraisal of the BVA and assessed the hydrological conditions from 1977 to 1999 and concurred with the estimate made by Christmas (1977).

In 2009, Ocean Earth Technologies (OET) further studied the BVA using geophysical mapping, video logs and water quality monitoring. The geologic units of the aquifer were described as follows: Unit I is a high resistivity surficial unit of dry sands, clayey sands, and volcanic rock detritus with an average thickness of 4 meters (13 feet). Unit II is an intermixed sand, clay, and rock detritus, exhibiting lower resistivity than Unit I. The lower resistivity signature of Unit II is due to the saturation with freshwater. Unit III is the high resistivity strata beginning at an elevation of approximately 0 meters relative to mean sea level. This unit is interpreted to represent gravels, coarse sands, and boulder rocks, and is the water storage unit for the aquifer system with an average thickness of 30 meters (98 feet). The lower part of Unit III exhibits markedly lower resistivity material that represents the saltwater saturated part of the aquifer and marks the fresh/salt water interface across the mapped area.

OET (2009) also noted various deficiencies in well construction and highlighted the lack of data from the upper watershed area for full characterization of aquifer characteristics to determine the safe sustainable yield. They noted the need to better understand aquifer hydrologic parameters of transmissivity, storage, porosity, water level elevation, gradient and fluctuation, groundwater recharge, surface runoff, evapotranspiration, geology and aquifer units.

After an extended drought in 2015 and documented saltwater intrusion in the main wellfield of the BVA, OET was contracted to conduct further geophysical surveys in the BVA north of the airport, and at Shadwell and Beacon Heights (both northwest of the current location of the main wellfield). Results from the location north of the airport confirm a relatively flat unconfined water table susceptible to saltwater intrusion. They also documented some geologic features (impermeable intrusive dikes) which they believed could greatly limit groundwater storage volume. Investigation north and west of the current wellfield indicated similar narrow valley formations but groundwater storage units appeared to be at higher elevations which reduces the potential for saltwater intrusion (Nettles, 2021). OET recommended further exploration and drilling in this area.

Importantly, there has been no in-depth study of the potential for groundwater at higher elevations and in other locations outside of Basseterre similarly to what has been investigated and exploited in Nevis which is described next.

2.4.2 Nevis

The hydrogeology of Nevis has been summarized by Hoag (2018) as follows:

"Nevis Peak, which is responsible for the greatest impact on both the total quantity of rainfall as well as permeability of the aquifer materials. At almost 1000 m in elevation, moist tropical air rises from sea level and condenses on the mountaintop thereby significantly increasing precipitation in the higher elevations particularly on the western side. The intrusive rocks of the peak appear to be highly fractured and permeable. Perhaps the most important geological event influencing the availability of high yield bedrock wells in this complex aquifer system was the erosion and deep dissection of the mountain prior to the most recent volcanic event. The most recent volcanic eruption filled these deep valleys with highly permeable volcanic sediments and lava flows that have in turn been covered with very recent permeable reworked volcanic deposits (mud and debris flows, landslides, etc). These buried valleys are like "arteries" in the human body and carry the bulk of the recharge from the mountain to the overlying apron aquifer and to the ocean. They are not obvious from the surface and extensive geophysical surveying is required to identify them. Additionally, the recent reworked volcanic deposits from Nevis Peak are unweathered and loosely consolidated thereby forming a relatively thin volcanically derived "apron" aquifer. The low water levels in wells within this aquifer indicate that these shallow volcanic deposits are extremely permeable allowing for a significant amount of available precipitation to recharge into the groundwater system."

According to Hoag (2018), the aquifers in Nevis can be subdivided into five separate types with many of the more productive aquifers being a combination of two to three. Figure 2.7 shows the major volcanic aquifers of Nevis. These aquifers include lava flows, intrusive plutons, intrusive dikes, contacts between volcanic centers, buried channels and thin apron aquifer (as described above).

In 2006, the Nevis Island Administration signed an agreement with Bedrock Exploration and Development LLC (BEAD) for groundwater exploration. A programme of exploration utilizing several tools such as GIS, remote sensing data and geophysical surveys and drilling of test and production wells was conducted between 2006-2011. As a result, two deep wells (Maddens and Fothergills) produce approximately 0.6 MGD of fresh water. A third production well was also drilled at the same time but was not fully commissioned due to high levels of iron and manganese. This well at Hamilton Estate Reservoir is now fully in service and producing about 0.3 MGD after a treatment system was installed and started up in 2020. Also, additional work in 2018 helped to identify several more sites for future exploration.

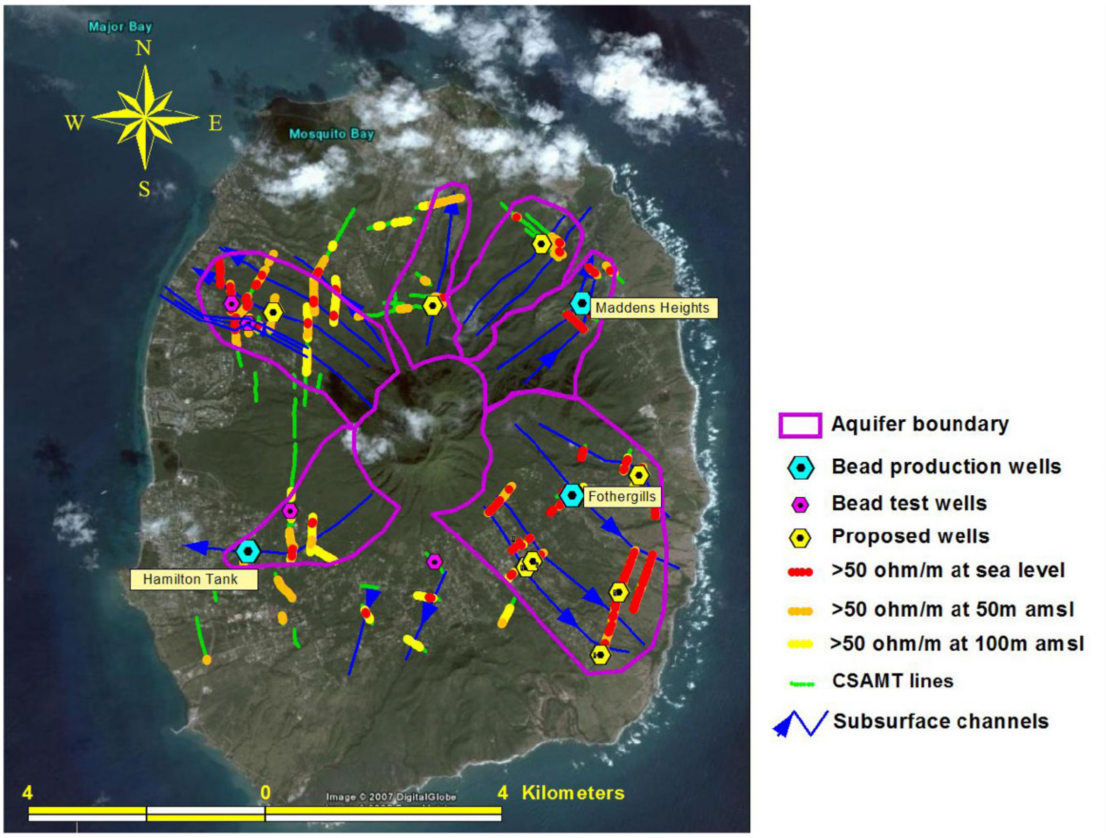


Figure 2.7: Major volcanic aquifers of Nevis (Hoag, 2018)

2.5 Water production and consumption

The hydrogeology of St. Kitts and Nevis clearly highlights the relationship between rainfall and freshwater resources on the islands. A discussion and analysis of precipitation is included in Output 2.3. Potable water is retrieved from either surface sources (springs) or groundwater (wells). In 2019, in St. Kitts, 70% (3.37 MGD) of the water was derived from groundwater and the remaining 30% (1.49 MGD) was from springs. In Nevis, 99% (1.44 MGD) of water was derived from groundwater and remaining 1% (0.16 MGD) from springs.

Surface water is tapped into six intake areas in St. Kitts and three in Nevis. On St. Kitts these water intake areas are at Wingfield, Franklands, Stonefort, Lodge, Phillips and Greenhill. From 2010-2014, these springs produced on average a total of 3.2 MGD but since the major drought of 2015, the average production between 2015-2020 has dropped to less than 2 MGD. On Nevis the intake areas are at Nevis Peak Source (Stoney Hill) (30 gpm), Camps Spring (40 gpm) and Maddens (14 gpm). Tables 2.2 and 2.3 list wells by name and capacity for both islands. Figure 2.8 and Figure 2.9 show the location of wells and surface water intakes.

In terms of water consumption by sector, in St. Kitts, about 60% of water supplies are consumed by the domestic sector, while the government, tourism and commercial sectors each use between 10 to 15% of the island's water resources. It is estimated that less than 5% of the supply goes to the agricultural sector. In Nevis, 52% goes to the domestic sector, 31% to government buildings and installations, while hotels and the commercial sector use about 8% each. As such, it is estimated that less than 1% of the supply goes to the agricultural sector. In recent times, after the closure of the sugar industry in the Federation, there has been a major focus on diversifying the agricultural sector. One of the main barriers to this is the availability of water for irrigation especially during the dry season. It is clear additional water resources would have to be developed and water demand control measures fully implemented to be able to supply sufficient water to this sector. Enhancing the ability of stakeholders to understand drought risks more fully will also greatly aid in management of water resources especially as the impacts of climate change worsen.

More in-depth analysis of consumption patterns is provided by Cole Engineering (2016) for Nevis and Daniel and Daniel Engineering (2013) for St. Kitts. Also, section 2 in Output 2.4 discusses the challenges faced by both utilities to continue to meet increasing demands despite less rainfall and drought conditions in recent times.

Table 2.2: List of wells in St. Kitts

Well	Well Capacity (igpm)
1-41	310
Shadwell 1	345
1-47	210
Ponds I	325
Ponds II	400
Taylor’s	270
Conaree	45
Golden Rock (R.L.B.)	50
La Guerite	36
Lodge I	60
Lodge II	65
Mansion	150
Tabernacle	85
Profit	50
St. Paul’s I	40
St. Paul’s II	50
Orton’s	50
Sir Gilles	250
Godwin’s	120
Stonefort	150
Wash Ghaut	25
Grange	150
Ponds 5	200
White Gate	150
Wingfield	75
Trinity	100
West Farm	40
Mattingley	25
Parsons	25

Table 2.3: List of wells in Nevis

Well	Well Capacity (igpm)
Maddens #1	80
Maddens #2	40
Maddens #3	55
Butlers #1	55
Butlers #2	45
Maddens Heights	245
CSS	40
Hospital	40
Gov’t Road	45
Stoney Grove	33
Zion	50
Padlock #1	80
Padlock #2	90
Padlock #3	80
Fothergills	250
Hamilton Estate	230

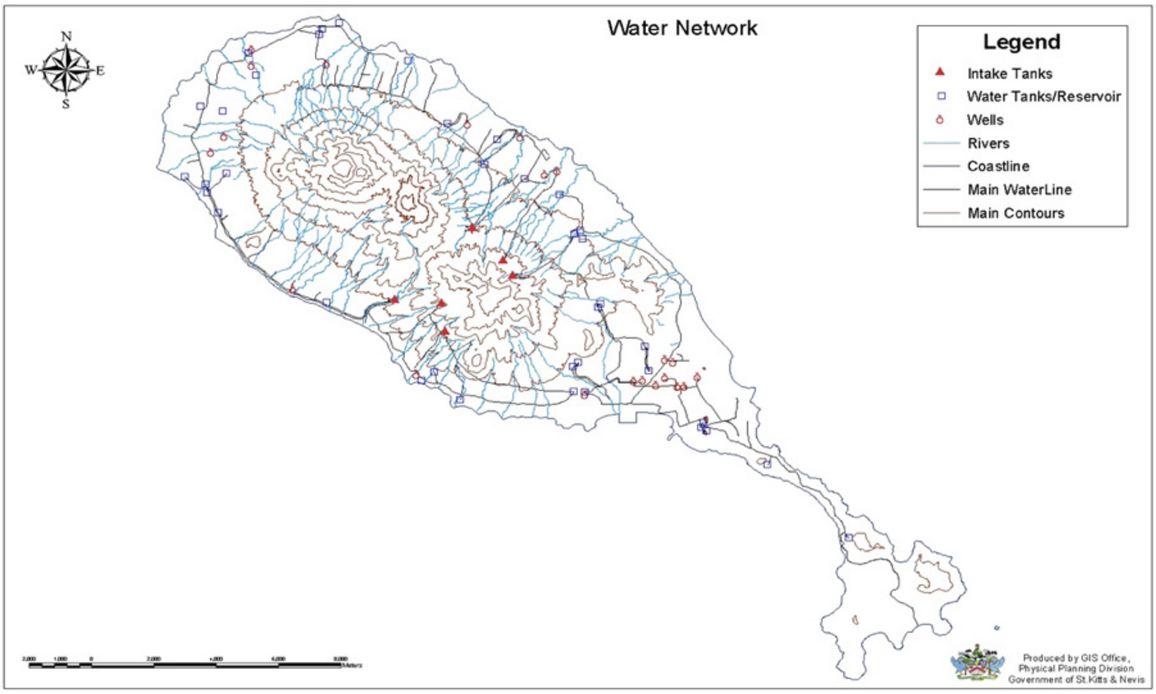


Figure 2.8: Map of water supply system in St. Kitts

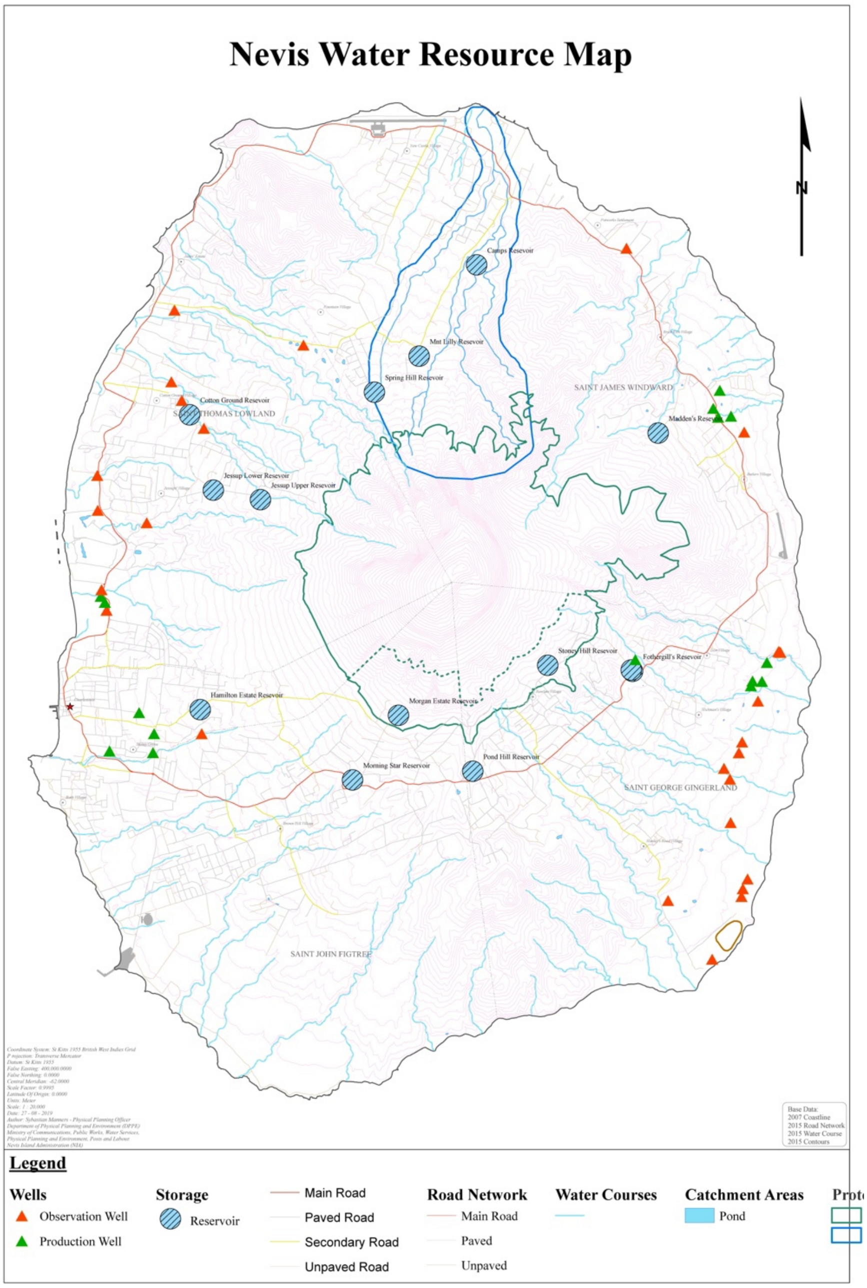


Figure 2.9: Map of water supply system in Nevis

3 Assessment of key risks to water resources

OET (2009) summarized the threats to the groundwater resources of the BVA but these threats are the same for all of the water resources in Saint Kitts and Nevis. In terms of water quantity, threats to recharge areas from improper land usage and insufficient development planning, decreasing precipitation and protracted periods of drought are major challenges. In terms of water quality, improper waste disposal practices, agricultural pollution (pesticides, fertilizers, and soil erosion), sewage and wastewater from onsite treatment systems which are no longer suitable for the more densely populated areas of Basseterre and Charlestown, saline intrusion due to drought conditions and / or sea level rise. Compounding these systemic vulnerabilities are very serious resource management issues including inadequate management of water resources arising from outdated or missing legislative mechanisms to protect the resources to support a more effective administrative framework, insufficient resources for data collection and monitoring of infrastructure and insufficient initiatives and controls for water conservation measures.

4 Concluding remarks

Freshwater availability in St. Kitts and Nevis is threatened by frequent drought conditions (especially since 2009) coupled with increasing water demand. Water supply challenges will continue to grow considering a growing population, greater socio-economic development, the impacts of climate change and the continued need for increased sanitisation and hygiene because of the novel coronavirus (SAS-CoV-2). This report highlighted the geology, soils, watersheds, and hydrogeology of both islands and gave an overall impression of the freshwater resources currently available for the country. Together with the assessment of drought risks (Output 2.1), water balance (Output 2.3) and water conservation measures (Output 2.4) as well as the Water Utility Adaptation Plan of 2021 (HR Wallingford, 2021), the path forward for more effective water resources management under drought conditions and climate change is clear. Output 3 will begin the development of the drought risk modelling tool.   Ultimately, it is anticipated that accurate prediction of drought with sufficient lead time will be able to support adaptation planning and decision making by providing valuable information on how much water is likely to be available to help in the management of water sources and supplies. In doing so, it will also help various sectoral interests by:

- Supporting water-use directives for the domestic and commercial sectors ahead of time so as to avoid or reduce water rationing and cuts which reduce sanitation and hygiene in the home; and business disruptions, especially in the tourism sector;
- Aiding agricultural planning and thereby reduce losses in agricultural production, leading to improvements in food security; and,
- Supporting planning in the health sector to mitigate potentially life-threatening impacts from compromised sanitation, hygiene and safety.

5 References

Baker, P.E. (1985). Volcanic hazards on St Kitts and Montserrat. Jour. Geol. Soc. Vol 142; p.279-295.

Christmas, J. (1977). Hydrogeology of an Unconfined Coastal Aquifer System, Basseterre Valley, St. Kitts. PhD Thesis. Geology Department, University of the West Indies, Jamaica, October 1977.

Cole Engineering (2016). Strategic Framework for Water Resources Management in Nevis. Prepared for the NIA / NWD. 2016.

Daniel and Daniel Engineering Ltd. (2013). Water Conservation Plan for St. Kitts. Prepared under the OECS / USAID RRACC Project for the SKWSD. 2013.

Hoag, R. (2011). Estimation of Groundwater Recharge on Nevis. Paper presented at the Caribbean Water and Wastewater Annual Conference. 2011.

Hoag, R. (2018). Hydrogeological Report and Maps for the Nevis Groundwater Project. October 2018.

HR Wallingford (2021) Vulnerability Assessment and Water Utility Adaptation Plans. St. Kitts and Nevis – Water Sector Adaptation Plan. Caribbean Community Climate Change Centre / EU GCCA+ Enhancing Climate Resilience in CARIFORUM Countries Programme. August 2021.

Hutton, C. & Nocholds, S.R. (1978). The petrology of Nevis, Leeward islands, West Indies. Overseas geology and mineral resources no. 52:32.

Ker, Priestman & Associates Ltd. (1988). St. Kitts-Nevis Exploratory Drilling, Project NO. 866-11044.

Final Hydrology Report Volume 1 – St. Kitts. Victoria, British Columbia, April 1988.

Lang, D. M. & Carroll, D.M. (1966). Soil and Land-Use Surveys, No. 16, St. Kitts and Nevis.

The Regional Research Centre, ICTA, Trinidad.

Lindsay, K. & Cooper, B. (2020). Terrestrial Ecological Inventory for St. Kitts and Nevis, Full Compendium of Result, Part 1. Prepared for the SKNDOE under the project "Conserving Biodiversity and Reducing Habitat Degradation in Protected Areas and Their Areas of Influence, St. Kitts and Nevis". February 2020.

Martin-Kaye, P.H.A.(1969). A summary of the geology of the Lesser Antilles. Overseas Geology and Mineral Resources 10: 172-207.

Nettles, S. (2021). Sea Level Rise Wellfield Protection Procedures. Paper presented at the Caribbean Water and Wastewater Annual Conference. 2021.

Ocean Earth Technologies (2009). Hydrogeologic Evaluation of the Basseterre Valley Watershed, St. Kitts. Volume 1, Section 1. Prepared for the SKWSD under the GEF-IWCAM project. September 2009.

Smith, G.D. (1983). Soil and Land Use Surveys No 27: Correlation of the Soils of the Commonwealth Caribbean, Puerto Rico, The Virgin Islands and Guyana. Dept Soil Science, Faculty of Agriculture, University of the West Indies, Trinidad.

U.S Army Corps of Engineers (2004). Water Resources Assessment of Dominica, Antigua, Barbuda and St. Kitts and Nevis. December 2004.

Williams, C. (1999). A Re-Appraisal of Basseterre Valley Aquifer, St. Kitts (1978-1999). Master's Thesis.

University College London, 1999.

Williams, C. (2010). St. Kitts and Nevis Water Resources. July 2010.

HR Wallingford
Working with water

HR Wallingford is an independent engineering and environmental hydraulics organisation. We deliver practical solutions to the complex water-related challenges faced by our international clients. A dynamic research programme underpins all that we do and keeps us at the leading edge. Our unique mix of know-how, assets and facilities includes state of the art physical modelling laboratories, a full range of numerical modelling tools and, above all, enthusiastic people with world-renowned skills and expertise.

HR Wallingford Ltd, Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom
tel +44 (0)1491 835381, email info@hrwallingford.com
www.hrwallingford.com