ESMP ACTION 8: RIVER HYDROLOGY, BIODIVERSITY AND WATER USE ASSESSMENT (ECO FLOW)

For the project
Climate Resilient Water Sector in Grenada
(G-CREWS)

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List of abbreviations

BMUV	German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
CANARI	Caribbean Natural Resources Institute
DO	Dissolved oxygen
ECOFLOWS	Environmental flows
GCF	Green Climate Fund
G-CREWS	Climate-Resilient Water Sector in Grenada
GIS	Geographical Information System
GoG	Government of Grenada
IPCC	Inter-governmental Panel on Climate Change
NAWASA	National Water and Sewerage Authority
NGO	Non-governmental Organization

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0. EXECUTIVE SUMMARY

Freshwater systems worldwide are under increasing pressure from anthropogenic activities, including both consumptive uses (e.g., water extraction for agriculture, industry, and domestic supply) and non-consumptive uses (e.g., hydroelectric regulation). Growing societal demand for water has significantly altered natural flow regimes, disrupting the physical, chemical, and ecological processes that underpin river ecosystems. These hydrological modifications are now recognized as major drivers of habitat degradation and biodiversity loss. Concurrently, there is a rising recognition of the ecological, cultural, and social importance of maintaining healthy riverine systems. In this context of multiple, often competing water uses, establishing sustainable environmental flow (ecoflow) guidelines is essential to mitigate the risks associated with altered flow regimes (Linnansaari et al., 2012). For Grenada, the development of a nationally coordinated ecoflow framework would address this urgent need. The hydrologic regime plays a fundamental role in shaping riverine ecosystems. All components of flow—including high flows (floods), medium flows, and low flows—contribute to ecological integrity (Acreman & Dunbar, 2004). However, human interventions such as channelization, abstraction, and dam construction act as hydromorphological pressures that alter natural flow patterns and degrade physical and chemical habitat characteristics. Environmental flows are vital not only to sustain aquatic ecosystems but also to support the human livelihoods that depend on them (Arthington et al., 2018). These flows can be secured through in-stream flow protections or by implementing regulated releases from reservoirs. Recognizing and managing environmental flow needs is critical to preventing ecological degradation, particularly in contexts where over-abstraction remains one of the most significant threats to freshwater systems.

Ecoflows estimation methods are categorized into:

- Hydrological
- Hydraulic rating
- Habitat simulation
- Holistic

Among hydrological methods, the Flow Duration Curve (FDC) and the Montana Method (Tennant, 1976) remain among the most commonly applied. The FDC approach is based on flow exceedance probabilities, while the Tennant method assigns ecological values to fixed percentages of mean flow. Hydrologically based methodologies continue to be widely adopted internationally, largely due to their simplicity, low cost, and reliance on existing flow datasets—whether real or simulated—which eliminates the need for extensive field campaigns (Linnansaari et al., 2012).

Amid growing global imperatives to restore and safeguard the ecological integrity of riverine systems and their associated wetlands, the role of these ecosystems in sustaining biodiversity and human well-being is increasingly recognized. It is now well established that anthropogenic modifications to natural flow regimes—such as those resulting from water abstraction or dam regulation—can cause substantial changes to ecosystem structure and function.

In this context, river basin managers are tasked with defining environmental flow regimes that maintain or enhance ecological conditions, and with assessing the ecological consequences of deviations from natural flow patterns. However, the inherent complexity of riverine ecosystems, coupled with the variability of biophysical and socio-cultural settings, means there is no universally applicable flow threshold for defining environmental water requirements. The key challenge for scientists lies in equipping water managers and policy-makers with robust, evidence-based guidance that aligns with ecological objectives and accommodates socially acceptable trade-offs.

Over the past decades, a diverse range of methods has emerged to support this effort—many embedded within broader, integrative decision-support frameworks. No single methodology can be considered universally superior; each presents context-dependent strengths and limitations in terms of hydrological conditions, spatial and temporal resolution, data availability, and ecological relevance. Continued refinement of these methods is warranted, particularly through research that addresses cross-cutting challenges such as integrating expert judgment into flow-setting processes. Advancing methodological approaches in this manner will likely lead to meaningful improvements in the development and implementation of environmental flow standards.

In the case of Grenada, the development of hydrologically based ecoflow methodologies requires consideration of local hydrological patterns, climate, topography, and land use. This report presents initial findings and outlines practical steps and recommendations for establishing context-specific methodologies to support sustainable water management and river ecosystem protection across the island.

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1. INTRODUCTION

1.1. G-CREWS PROJECT

Water is a scarce resource in Grenada, and the impacts of climate change are already compounding this challenge. Rising average temperatures and increasingly erratic rainfall patterns have begun to intensify water scarcity across the island. Frequent heavy rainfall events, in particular, lead to elevated turbidity in raw water sources, resulting in more frequent water supply interruptions. The primary objective of the G-CREWS (Grenada Climate-Resilient Water Sector Project) is to enhance the systemic resilience of Grenada's water sector to climate change. To achieve this, the project promotes a comprehensive transformation of the sector at multiple levels—representing a nationwide 'paradigm shift' in Grenada's approach to resilience. This paradigm shift engages citizens and businesses as responsible water users, while positioning the public sector as a key provider of potable water and essential infrastructure. Through improved governance, regulatory frameworks, economic incentives, and public awareness campaigns, the project aims to foster meaningful behaviour change.

The G-CREWS project is structured around the following five components:

- Climate-Resilient Water Governance
- Climate-Resilient Water Users
- Climate-Resilient Water Supply Systems
- Additional Contributions of the Water Sector to Grenada's climate goals
- Regional learning and replication

Jointly financed by the Green Climate Fund (GCF), the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) under its International Climate Initiative (IKI), and the Government of Grenada. Over 6 years, the Government of Grenada, the Grenada Development Bank and the National Water and Sewerage Authority (NAWASA) in partnership with the German Development Corporation (GIZ) implements the project's five components. The project has a total budget of 45.297 Million Euros (Approximately $130 million XCD). All citizens of Grenada, including the agricultural and commercial sectors, are expected to benefit from improved water supplies, especially during times of drought and after extreme weather events.

1.2. INTRODUCTION TO ECOLOGICAL FLOW ESTIMATIONS

The determination of ecological flows follows different methods in different countries. Some definitions of the ecological flow presented are:

- The minimum ecological flow in a river is the minimum amount of water that must flow through a river to maintain its ecological health.
- The quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (2007 Brisbane Declaration). The Brisbane Declaration on Freshwater Ecosystems was adopted in 2007 at the International River symposium and International Environmental Flows Conference in Brisbane, Australia.

- Dyson et al. (2003) in the IUCN guide on environmental flows define the concept as the water regime provided within a river, wetland, or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated.
- The 4th International Ecohydraulics Symposium (2002) defined environmental flows as the water that is left in a river system, or released into it, to manage the health of the channel, banks, wetland, floodplains, or estuary.
- Hirji and Davis (2009) describe environmental flows as "the quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems which provide goods and services to people".
- Arthington and Pusey (2003) define the objective of environmental flows as maintaining or partially restoring important characteristics of the natural flow regime (i.e. the quantity, frequency, timing and duration of flow events, rates of change and predictability/variability) required to maintain or restore the biophysical com-ponents and ecological processes of instream and groundwater systems, flood-plains, and downstream receiving waters.

Many rivers in the basin have physical modifications (e.g., dams, weirs, hydromorphological alterations), which may qualify them as modified waterbodies. Method selection depends on available resources, data, and constraints. While this study uses preliminary hydrological methods, future efforts should incorporate holistic methodologies for effective and sustainable river basin planning and also biological data as macroinvertebrates and fish composition and the information related with the habitat's selection and how this habitat simulation method. The habitat simulation methods combine the hydrological and hydraulic methods to determine ecological flows by quantifying the relationship between the hydraulic conditions required by the target species and habitat (Liu et al., 2017).

	HYDROLOGICAL ENVIRONMENTAL FLOW METHODS	HYDRAULIC RATING ENVIRONMENTAL FLOW METHODS	HABITAT-BASED ENVIRONMENTAL FLOW METHODS	HOLISTIC ENVIRONMENTAL FLOW METHODS (COMBINES COMPONENTS OF OTHER EFAS)
TIME REQUIREMENTS & LEVEL OF DETAIL FOR ASSESSMENTS:	0 → 3 MONTHS	0 → 6 MONTHS	6 → 12 MONTHS	12 → 36 MONTHS
1. Desktop	Modelled data.	Unusual – modelled.	Limited data used.	Limited data used.
2. Intermediate (usually with 1 site visit)	Modelled/real data.	Limited real data.	Real data for few components only.	Real data for few components only.
3. Comprehensive (usually with 2 site visit)	Real long term data.	Real data.	Data for all Components.	Data for all Components.
DATA REQUIREMENTS:				
1. Hydrological data	Required	Required	Required	Required
2. Hydraulic data	NA	Required	Required	Required
3. Habitat data	NA	NA	Required	Required
4. Water quality	NA	NA	Useful	Required
5. Water resource use scenarios	NA	NA	NA	Required
6. Ecological requirements	NA	NA	Partial	Required
Fish			Common	Common
Invertebrate			Common	Common
Riparian Vegetation			Uncommon	Common
Other				Unusual
7. Social data	Unusual	Unusual	Unusual	Common
8. Economic data	Unusual	Unusual	Unusual	Useful

Figure 1: Advantages and disadvantages of the environmental flow assessment categories (extracted from Nile Eflows Technical manual adapted from Reitberger and McCartney, 2011)

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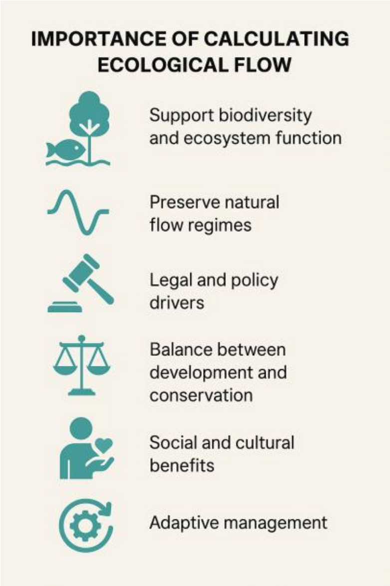
The importance of studying the ecological flow in the rivers.



- **Support Biodiversity and Ecosystem Function:** Environmental flows are essential for maintaining aquatic and riparian ecosystems, which depend on specific natural flow regimes for critical ecological processes like spawning, migration, nutrient cycling, and habitat maintenance.
- **Preserve Natural Flow Regimes:** The concept is based on the understanding that altered natural flow regimes are among the most significant threats to river ecosystems. Maintaining some semblance of the natural flow is often necessary to avoid degradation of ecological integrity**.**
- **Legal and Policy Drivers:** Increasingly, legislation and water policies **require the setting of environmental flows** to ensure rivers meet minimum ecological standards (e.g. Water Framework Directive in Europe).
- **Balance Between Development and Conservation:** Calculating e-flows enables **informed trade-offs** between economic uses (e.g. hydropower, irrigation, urban supply) and ecological sustainability. It is a tool for **integrated river basin management**.
- **Social and Cultural Benefits:** Healthy River ecosystems supported by appropriate flows contribute to **livelihoods (fisheries, agriculture)**, **recreation**, and **spiritual values** of local communities.
- **Foundation for River Restoration:** In many degraded systems, determining the appropriate environmental flow is a **first step in designing restoration strategies**, especially in catchments impacted by dams or water abstraction.
- **Adaptive Management:** Setting environmental flows promotes **adaptive water management**, where flow prescriptions can evolve based on monitoring and new ecological insights.

1.3. ABSTRACT OF THE LIMNOLOGIST ASSIGNMENT

Grenada's freshwater systems — including rivers, springs, and aquifers — are vital for domestic water supply, agriculture, potential hydropower and biodiversity. This assessment addresses water quality in line with biological, hydro-morphological, and physico-chemical parameters, with a focus on identifying risks and environmental safeguards for flood protection infrastructure.

The ecological flow assessment in the extended to all the Grenada watersheds focuses on the dry and wet seasons. Appropriate hydrological regimes are essential to reach the good status of the river basin. This approach recognizes the seasonal variability that characterizes tropical river systems and acknowledges the distinct ecological functions and water demands associated with each period. During the dry season, maintaining minimum flow levels is essential to support critical aquatic habitats, ensure water quality, and sustain baseflow-dependent species. In contrast, wet season flows contribute to the natural variability necessary for sediment transport, floodplain connectivity, and the life cycles of many aquatic and riparian organisms. Appropriate hydrological regimes, including the magnitude, timing, duration, frequency, and rate of change of flows, are fundamental to achieving and maintaining the good ecological status of river basins. These regimes support the structure and functioning of freshwater ecosystems, enable the provision of ecosystem services (such as water purification and biodiversity support), and enhance the resilience of the river system to climate change and anthropogenic pressures.

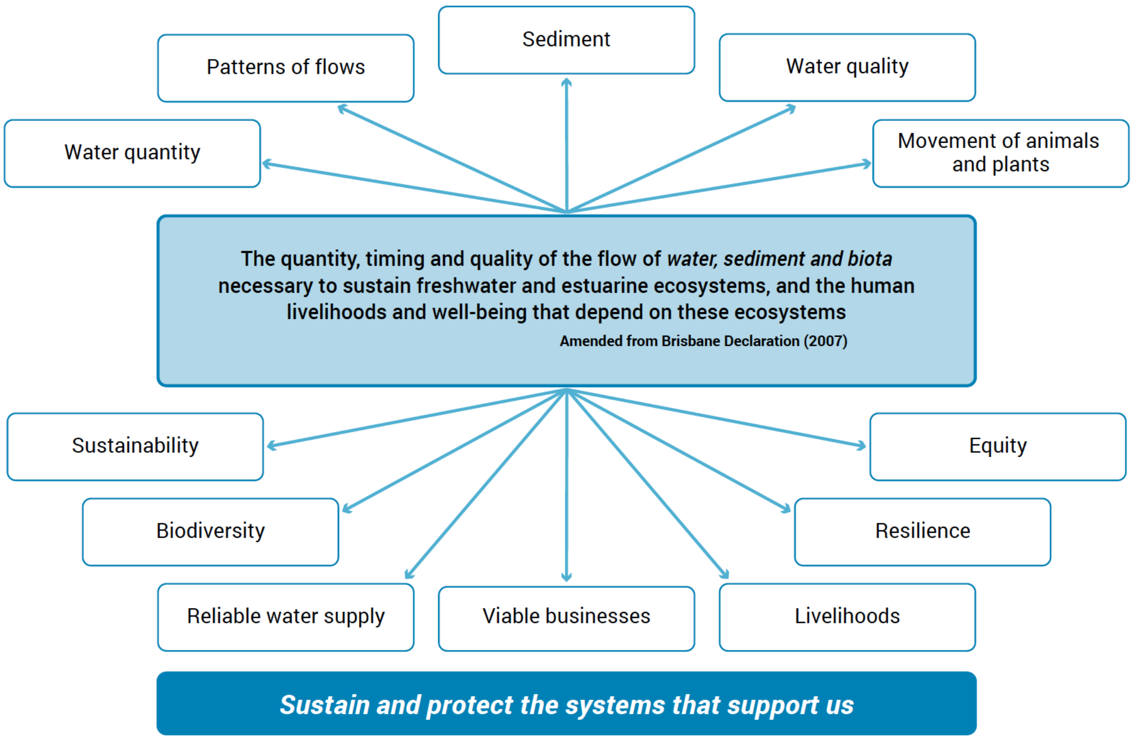


Figure 2: Importance of environmental flow (extracted from UNEP-Nairobi Convention/WIOMSA (2020))

The environmental flow approach proposed for Grenada includes the following aspects based on the Tharme classification (Tharme, 2003).

Hydrological method: requires long-term time series of measured or estimated streamflow under natural conditions. Examples: Tennannt method, Tessmand method, RVA. This method constitutes a valid approach for setting an E-Flow regime when biological and hydrological data are limited.

Hydraulic and Habitat simulation: is a flow dependent ecological data relationship between the hydrailic characteristics of the river stecht and the dataset of the chosen target species. Examples: Wetted Perimeter method, IFIM, PHABSIM. The need to have flow-dependent ecological data constitutes a limitation of the HD_Ms for which they are generally used on a local scale. HB_Ms are species-specific and need to be recalibrated when they are applied to a different region.

Holistic is a combination of hydrological, hydraulic and expert knowledge. ELOHA is one example. H_Ms are expert panel approaches that include multidisciplinary experts and stakeholders.

Combined is a hydrological, habitat-discharge and holistic elements. ·3H-EMC (hydrological, hydrodynamic and habitat modelling with the use of the Environmental Management Classes (EMCs)).

For complementing this information it is need to clarify and define the „EcoClassification" which is the term used for Ecological Classification and refers to the determination and categorisation of the Present Ecological State (PES; health or integrity) of various biophysical attributes of rivers compared to the natural or close to natural reference condition. The purpose of EcoClassification is to gain insights into the causes and sources of the deviation of the PES of biophysical attributes from the reference condition. This provides the information needed to derive desirable and attainable future ecological objectives for the river. The EcoClassification process also supports a scenario-based approach where a range of ecological endpoints have to be considered.

Present Ecological States are determined for driver and response components. The term Ecological when describing the present state of the Drivers can strictly only be used in terms of the EcoClassification process. Therefore the present state categories of geomorphology and fish are both described using the term PES.

The PES of the river is expressed in terms of various components. That is, drivers (physico-chemical, geomorphology, hydrology) and biological responses (fish, riparian vegetation and aquatic invertebrates), as well as an integrated state, the EcoStatus.

Ecological Category Definition A comparison of the present biophysical conditions to the natural reference conditions. Description: The ecological category is used to define and type the ecological condition of a river in terms of the deviation of biophysical components from the natural reference condition. This is done through an assessment of the system drivers (physico-chemical, geomorphology, hydrology) that provide the habitat template for biota and the response of native biotic groups (fish, riparian vegetation and aquatic macro-invertebrates) to this template, as well as the response of native biota to introduced biota.

A holistic, evidence-based approach is necessary to preserve Grenada's freshwater ecosystems amid development pressures. All infrastructure projects related with water regulation, water abstraction, river modifications (lateral barriers, disconnection between areas, etc), water retention (dams, hydroelectrical stations, etc) should be screened for hydrological and ecological impacts, and mitigation plans must be enforceable and backed by continuous monitoring.

2. STUDY AREA

2.1. LOCATION

Grenada is a tri-island state, located at longitude 61º4'W and latitude 12º4'N. It is situated 145 km north of Trinidad and Tobago and is the most southerly of the Windward Islands. The total area of the country is 340 km2. Grenada, which is 34 km long and 19 km wide, accounts for 89 percent of the area, and Carriacou and Petit Martinique account for 10 percent and 1 percent respectively. Grenada is mostly volcanic in origin, of steep rugged topography, with a main mountain chain running almost north-south in two main sections. The island is politically divided into six parishes, all of them on the island of Grenada (Saint Andrew, Saint David, Saint George, Saint John, Saint Mark and Saint Patrick), and 1 dependency (Carriacou and Petite Martinique together). The capital is Saint George's.

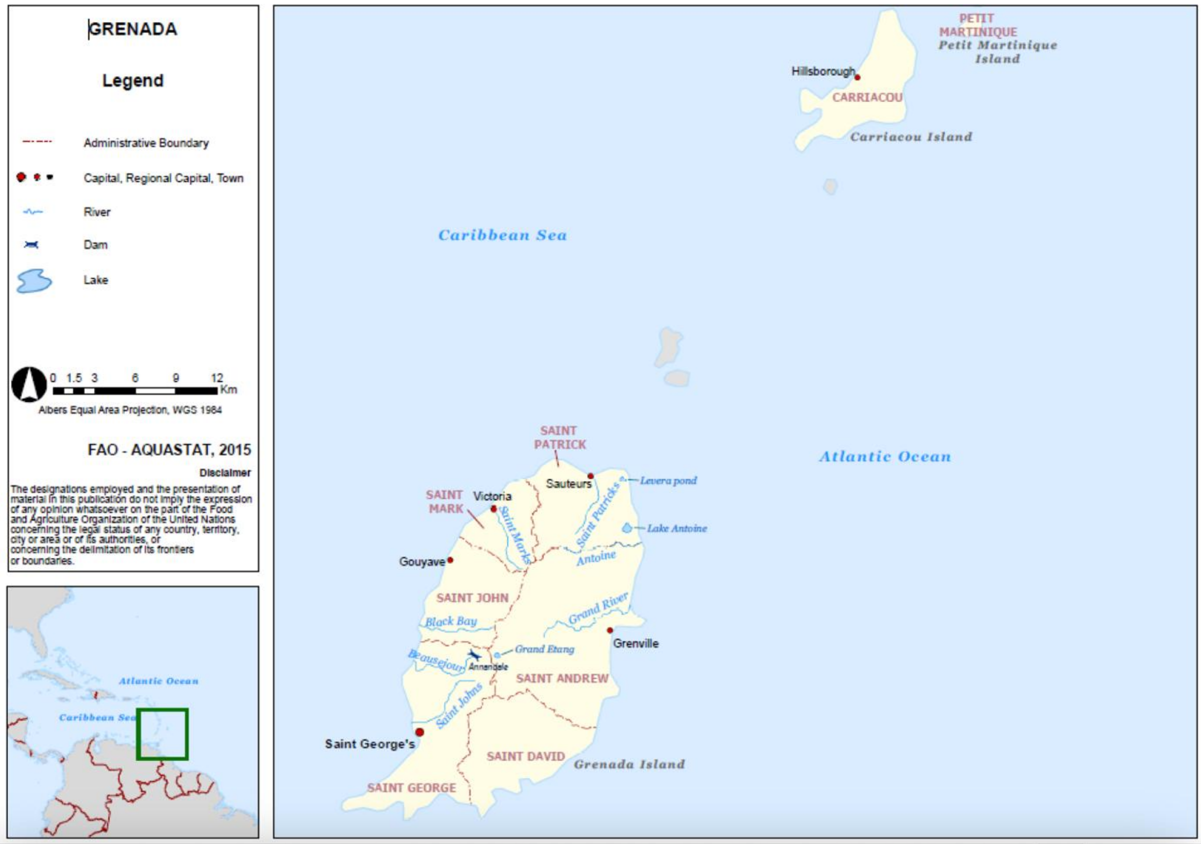


Figure 3: Map of Grenada (extracted from FAO, 2015)

The Draft Land Development Policy of the Ministry of Agriculture (1995) classifies 74.9 percent of the total land mass, or 25 500 ha, as being suitable for agriculture. In 2012, the total physical cultivated area was estimated at 10 000 ha, of which 70 percent (7 000 ha) consisted of permanent crops and 30 percent (3 000 ha) of temporary crops. Permanent meadows and pasture cover 1 000 ha, which brings to total agricultural area to 11 000 ha (FAO, 2015) Grenada experiences its wet season from June through December. The island's mountainous interior creates an orographic effect, leading to uneven rainfall distribution. Areas at higher elevations receive significantly more rain, with annual averages in the interior reaching about 4,000 mm. In contrast, the coastal regions typically get between 1,000 mm and 1,500 mm of rainfall (CEHI, 2007). The northern and southern tips of the island are the driest, making them the most arid parts of Grenada. Meanwhile, the smaller islands of Carriacou and Petite Martinique receive less rainfall overall—around 1,000 mm annually—due to their limited size and lower elevation (CEHI, 2007).

Rainfall on mainland Grenada feeds surface streams and replenishes underground aquifers. The island is divided into 71 watersheds, each containing a network of permanent rivers (CEHI, 2007). The largest of these is the Great River watershed, which covers about 15% of mainland Grenada's land area. Most surface water originates in the central high-rainfall zones and flows outward toward the coasts in a distinct radial pattern (Environmental Solutions Ltd., 2015). Additionally, lakes have formed in the craters of extinct volcanoes—Grand Etang being the largest, followed by Lake Antoine and Levera Pond (Government of Grenada, 2011c). Thanks to its numerous rain-fed streams and rivers, mainland Grenada is rich in surface freshwater resources, which are the island's main source of drinking water.

The climate can be classified as semi-tropical with a marked dry season from January to May and a wet season running from June to December. Spatial variations in annual rainfall range from about 1,000 mm near the coast to more than 4 500 mm in the central mountains, with an average totalling 2,350 mm.

2.2. WATER RESOURCES

Water resources originate mainly from a system of permanent streams and rivers but there is some groundwater available from the limestone areas along the northwest coast. Most of the surface water originates from the high rainfall areas in the central mountain ranges of Grenada island. Overall, there are 71 river basins on the island, of which the eight largest are: Grand River (4 574 ha), Beausejour (3 793 ha), Pearls (1 500 ha), Saint Patricks (1 253 ha), Bailes Bacolet (1 233 ha), Antoine (1 102 ha), Saint Johns (1 208 ha) and Saint Marks (835 ha). All major rivers have perennial flows, though these are significantly reduced during the dry season.

Rainwater harvesting was used widely in earlier times, but it has declined with the improvement of public water supply. However, in some remote high elevation areas, where the public water supply is inaccessible, rainwater harvesting is often the main source of potable water. Rainwater harvesting ponds are used in livestock production and, in a few cases, for the provision of water for intensive vegetable production (UNDESA, 2012).

In 2014, total produced municipal wastewater in Grenada was estimated at 11.4 million m3. Grenada has a number of rivers and small streams flowing from the high rugged interior peaks towards the sea. Three crater lakes, the Grand Etang lake in the centre of the island, Lake Antoine and the Levera lake in the north, along with the rivers constitute the main freshwater resource base for human consumption and agriculture. Grenada has 71 distinct watersheds of which the largest watershed, the Great River catchment comprises 159 sq. km or about ½ of the area of Grenada (Land Use Division, 1997).

There are 8 major watersheds on Carriacou and none in Petit Martinique. Carriacou and Petit Martinique have no permanent streams or springs. Water supply in Carriacou and Petit Martinique depends not only but mainly on the harvesting of rainwater in cisterns, while water for agriculture and livestock comes mainly from the withdrawal of groundwater and surface water stored in ponds. Given the increasing demand for water particularly in the urban south of Grenada as a result of construction and investment in the tourism sector, the provision of adequate water supply has become very important particularly in the dry season when there is maximum usage and at the same time reduced stream flow. As a result, the Grand Etang Lake is used as a source in the dry season as well as bore holes located in the south and south east of Grenada. There is also a full time borehole facility in Carriacou.

2.3. SELECTED STATIONS FOR THE ENVIRONMENTAL FLOW ANALYSIS

During the review of the data provided by NAWASA and in order to get field information and to visit some of the locations, a group of stations where selected to check the flow in the upper part of the basin and also in the downstream part to compare the streamflow changes in the same day and then comparing with the precipitation rate in the rain gauge stations.

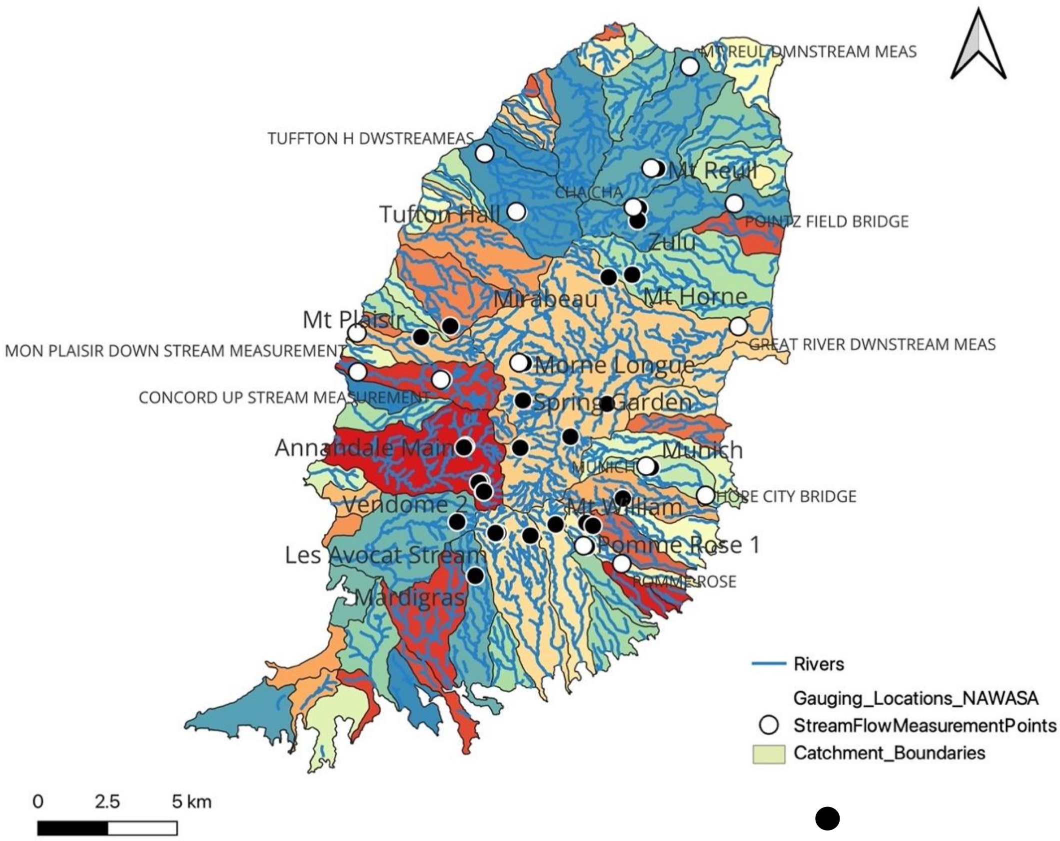


Figure 4: Map of Grenada.

The map of the figure 4 includes the locations of the rivers, stream flow measurements (white) taken during the assignment, and the gauging locations in black.

Table 1: List of the selected rivers and locations for taking the streamflow measure and the field visits.

River	Station names
Black Bay	Concord

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River	Station names
Black Bay	Black Bay Bridge (Mouth)
Grand Roy	Mt. Plaisir
Grand Roy	Grand Roy (Mouth)
St Marks	Tufton Hall
St Marks	Diamond Bridge (Mouth)
St Patricks	Mt. Reuil
St Patricks	La Fortune Bridge (Mouth)
Antoine	Cha
Antoine	Poyntzfield Bridge (Mouth)
Great	Morne Longue
Great	Paradise Bridge (Mouth)
Little river of Grand Bacolet	Munich
Little river of Grand Bacolet	Hope Estate Bridge (Mouth)
La Tante	Apres Tout
La Tante	Pomme Rose Bridge (Mouth)

The definition of the criteria for selection of sampling sites/locations is an important aspect of the environmental flow assessment for rivers. Sites along the river are for bringing together the ecological (hydrological, sedimentological, hydraulic, chemical and biological) information and predictions of change and/or environmental flows recommendations.

The number of sampling sites is dictated by finances, but also depends on the geomorphological variability of the river system, the location of developments such as dams or cities, social uses of different parts of the river, and more. A general aim is to cover the whole of the river study area through sampling sites that can represent the different sets of conditions prevailing in the basin.

In general, it is recommended to make measurements of the flow of the river every 5 to 10 km in relatively homogeneous river stretches. In case the river is smaller or it is needed a more detailed study, the measures can be More frequent (every 2–5 km) when there are significant changes in land use, tributaries, or human pressures or there are morphological or ecological transitions.

In the cases of larger-scale planning (e.g., regional water management plans): measurements every 10–20 km may be sufficient.

The criteria for selecting sampling sites include:

- Representation and habitat diversity
- Availability of hydrological data at the required resolution
- Location and levels of impact of developments or management interventions and access and safety

3. DATA DESCRIPTION

3.1. DATA NEEDED FOR AN ENVIRONMENTAL FLOW ANALYSIS

Environmental flow assessments are based on long-term hydrological and sediment time-series data sets, knowledge of potential biological data (species distribution and habitat preferences), whether recorded, modelled or estimated, against which ecosystem changes linked to flow changes can be assessed. These kinds of data sets cannot be created specifically for environmental flow assessments, which are relatively short-term activities but developed in several seasons, and should be an integral part of routine data collection for management of river systems.

Systems with inconsistent natural flow regimes will need to use longer data sets for evaluation. For instance, if a river natural flow regime was about the same year on year, every year, then meaningful patterns and summary statistics could be discerned using a short record, as there would be little variation to account for, and the record would need only to be long enough to capture the main phases in the life cycles of indicator organisms (e.g. 5-6 years). For perennial and seasonal rivers with a fair to high predictability, the standard recommended minimum length of hydrological record for use in an environmental flow assessment is 20 years, with 50-60 years cited as preferable (King and Brown, 2009a). For these rivers, ecologically-relevant hydrological data are usually summarized per year or per season. For ephemeral or intermittent rivers with unpredictable periods of flow that are better summarized over decades rather than years, longer periods of evaluation may be needed.

Land topography, land use/cover (LUC), and soil data are the fundamentals to extract the basic characteristics of a watershed (e.g., basin area and river length) and the initial information for the parameters of a hydrological model. The soil characteristics can be extracted from the Harmonized World Soil Database (Nachtergaele et al., 2012), the use of soil can be extracted from the Climate Change Initiative Land Cover (CCI-LC) product produced by the European Space Agency (ESA). The third important spatial data is the topographic information (elevation) of the study area. As a support, it can be used the digital elevation model (DEM) of NASA’s Shuttle Radar Topography Mission (SRTM) to generate physical characteristics of the streamflow lines, basin elevation, and basin area.

4. HYDROLOGY

4.1. PRECIPITATION DATA

Precipitation data is especially important when no direct streamflow measurements are available and streamflow must be estimated through hydrological modelling.

Historical precipitation time series

- Temporal resolution: Daily data is ideal; monthly data can be used if daily is not available
- Duration: At least 10 years, ideally 20–30 years to capture interannual variability
- Units: mm/day or mm/month
- Sources: National meteorological agencies or global datasets (National Meteorological Service)

Adequate spatial coverage

- Use data from multiple stations if the catchment is large or has varying climatic conditions
- Ensure that stations are representative of the catchment in terms of altitude, orientation, and climate.
- For distributed models (e.g., QSWAT+), spatially-distributed precipitation data (e.g., gridded raster) is necessary

Data Quality and Consistency

- Ensure data completeness and consistency, as gaps in the data can significantly affect hydrological calculations
- Precipitation data should be checked for errors and missing values before use

Application of Precipitation Data in Hydrological Methods

- When streamflow data is available: Precipitation data can be used to contextualize natural flow regimes, but it is not essential
- When streamflow data is not available:
  - Precipitation data is used to simulate streamflow through rainfall-runoff models (e.g., HEC-HMS, QSWAT+, HBV)
  - Once streamflow is estimated, hydrological methods (e.g., Q95, Tennant, Flow Duration Curve) are applied to calculate environmental flows

4.2. Discharge data

Depending on whether observed streamflow data is available, different types of input are needed. Additionally, geographic and climatic data are essential when estimating flow through hydrological modelling.

If observed streamflow data is available:

- Time series of streamflow (m^3/s), preferably daily or monthly
- Minimum duration: 10 years; ideally 20–30 years
- Used for calculating flow percentiles (e.g., Q95, Q50), analysing natural flow regimes (e.g., IHA), and determining ecological low/high flow periods

If no streamflow data is available:

- Discharge must be estimated using rainfall-runoff models. There are some limitations with the collection of data in field (for example, at the Concord discharge measuring point, it is only possible to measure the discharge up to a certain water level. If the discharge is higher than this, there is a high risk of the employee being carried away by the water. This results in a systematic error, as large discharges are not measured.)
- Requires precipitation data and physical parameters of the catchment

Table 2*: List of the selected rivers and locations for taking the streamflow measure and the field visits*

Data Type	Purpose	Format or Source
Observed Streamflow	Apply hydrological methods directly	Time series (m^3/s)
Precipitation	Input for rainfall-runoff modelling	Time series (mm/day)
DEM	Watershed delineation and slope	GeoTIFF
Land Cover	Estimate runoff and infiltration	Vector or raster
Soil Type	Model infiltration/storage	Raster or shapefile
Meteorological Stations	Model calibration/validation	Point shapefile

4.3. GIS data

Table 3: List of the selected rivers and locations for taking the streamflow measure and the field visits

Layer	Description	Typical Source
DEM (Digital Elevation Model)	Used for watershed delineation and drainage extraction.	SRTM, ALOS, Copernicus
Land Use / Land Cover	Classifies surface cover (e.g., forest, agriculture, urban).	CORINE, Copernicus, ESA WorldCover
Soil Type	Soil texture and hydrological properties (e.g., clay, sand).	FAO SoilGrids, HWSD
River Network	Existing or extracted river paths.	Local shapefiles or derived from DEM
Hydro-meteorological Stations	Locations and attributes of measurement stations.	National databases, shapefiles

These datasets are essential for catchment modelling and flow estimation:

4.4. OTHER USEFUL DATA

- Catchment area (km^2): Derived from DEM or official sources
- Average catchment elevation: Used to characterize climate
- Evapotranspiration (optional): For water balance models
- Runoff coefficients: For empirical flow estimations
- Additional climate data (optional): Temperature, humidity, wind, radiation (for comprehensive models)

5. METHODOLOGY

5.1. Proposal of an environmental flow calculation in Grenada

The ideal approach for determining environmental flows in Grenada is the holistic approach, which integrates hydrological, ecological, social, and geomorphological components to provide a comprehensive understanding of flow needs. However, the selection of a methodology must reflect the intended use of the eflow estimates, as well as practical considerations such as data availability, time, and resources. Environmental flow assessment methods vary significantly in terms of cost, complexity, and duration. For national-scale planning purposes, such as preliminary estimates to inform water balances across multiple catchments, a simple hydrological method, like the one applied in this report, is considered appropriate. This approach allows for rapid, consistent evaluations in data-scarce contexts and provides a foundation for future, more detailed studies. In contrast, when eflows are needed for environmentally sensitive or ecologically important sites, or where they will be used to define operational rules for dam releases or other infrastructure, a more comprehensive, site-specific method (hydraulic, habitat-based, or holistic approaches) may be required. It is therefore essential to present these considerations clearly, and to justify the use of a rapid, hydrological method in this case. The approach adopted here serves the purpose of a first-order assessment to support strategic water resource planning and to identify where more detailed studies may be warranted in the future. That method that includes the following aspects:

Biological Characteristics

- Biological assessment for macroinvertebrate communities.
- Biological assessment for fish populations.

Hydro-Morphological Characteristics: Assessment should include changes to riverbeds, banks, and floodplains from channelization or infrastructure.

- River connectivity (longitudinal and lateral)
- Flow variability and flashiness
- Sediment transport dynamics

Physico-Chemical Characteristics

- Monitoring parameters: temperature, pH, DO, conductivity, nitrates, phosphates, turbidity.
- Evaluate impacts of upstream agricultural runoff, point-source streamflows, and changes in land use (e.g., changes in the use of land, landslides, deforestation).

Ecological flow (e-flow) should be assessed using methods like:

- Flow Duration Curve (FDC): Based on percentiles of historical flow data (e.g., Q95 for low flows, Q50 for median flow).

- Tennant Method: Allocates a percentage of the mean annual flow (MAF) to define ecological flow classes. It can be done in dry season and another in wet season, in a separate way.
- Indicators of Hydrologic Alteration (IHA): Analyses 33 parameters of natural flow regime (magnitude, timing, duration, frequency, rate of change).
- Range of Variability Approach (RVA): Compares altered and natural flow conditions using IHA parameters.
- Site-specific habitat flow assessments: quantify how well a project meets design criteria for habitat enhancement at specific flows.
- There are other approaches such as the Building Block Methodology (BBM), globally the most widely used, and DRIFT, a comprehensive method (Tharme, 2003).

Under the definition of the environmental flow, the key Pressures on Ecosystems in Grenada have to be studied:

Agriculture

- Pesticide and fertilizer runoff leading to eutrophication.
- Livestock access to streams causing sediment and nutrient loading.

Infrastructure & Flood Control

- Flood walls, channelization, and culverts that might cause:
  - Disruption of sediment regimes
  - Habitat loss (e.g., spawning grounds)
  - Downstream erosion or sediment starvation

Protected Areas

- Information related with protected areas and cover:
  - **Grand Etang Forest Reserve**
  - **Annandale watershed**
  - Coastal fringe wetlands and mangroves

Ensure the Stakeholder Involvement (paragraph 1.3 ABSTRACT OF THE LIMNOLOGIST ASSIGMENT). Stakeholder participation is a critical component of effective environmental flow (eflow) assessments. Involving stakeholders as water users, local communities, environmental authorities, and infrastructure operators helps to ensure that the assessment reflects local priorities, values, and trade-offs. Stakeholders play an important role in:

- Setting Resource Quality Objectives (RQOs): These define the desired ecological condition of a river system and are often linked to legal, policy, or conservation targets.
- Determining the Recommended Ecological Category (REC): Through a participatory process, stakeholders evaluate the current ecological status (PES) and agree on an achievable and acceptable target condition (REC), balancing ecological protection with social and economic needs.
- Evaluating Trade-offs: Where water demands exceed supply, stakeholders are engaged in discussions to negotiate trade-offs between competing uses (e.g.,

irrigation, hydropower, ecosystem needs) in order to support equitable and sustainable decision-making.

This collaborative process not only enhances transparency and legitimacy, but also increases the likelihood of long-term implementation of eflow recommendations. In future, as eflow implementation progresses in Grenada, formal mechanisms for stakeholder engagement and co-management will be essential for achieving and maintaining the recommended ecological conditions in each basin.

6. RESULTS

6.1. PRECIPITATION RECORDS

There are different typologies of stations: stations with meteorological information and stations where NAWASA technicians take regularly measurements of the water discharge.

NAWASA carries out a daily collection of hydrological data through the acquisition of the meteorological data (table 4) through the collection directly from the station.

Table 4: List of the gauge stations in Grenada monitored by NAWASA.

Stations	Latitude (N)	Longitude (W)
Les Avocat (WTP)	12.0661	-61.7008
Mirabeau (WTP)	12.13867	-61.65921
Annandale (WTP)	12.088627	-61.71424
Concord (WTP)	12.117396	-61.721029
Vendome (WTP)	12.080384	-61.714727
Petit Etang (WTP)	12.061538	-61.685243
Peggy's Whim (WTP)	12.1726	-61.6477
Mamma Cannes (WTP)	12.074356	-61.65201
Mt.Plaisir (WTP)	12.129049	-61.731387
Mardigras (WTP)	12.055006	-61.712855
Pomme Rose (WTP)	12.065806	-61.665534
Tufton Hall (WTP)	12.176039	-61.696163
Mt Reuil (WTP)	12.189714	-61.646902
Mt Horne (WTP)	12.142601	-61.64226
Brandon Hall (WTP)	12.11417	-61.647214
Spring Garden (WTP)	12.111325	-61.6905
Chemin II	12.0219	-61.7222
Grand Etang (LAKE)	12.0958	-61.6969
Dougaldston (WTP)	12.153997	-61.72761
Munich (WTP)	12.085918	-61.646676
Bon Accord (WTP)	12.0716677	-61.7170933
Plaisance (WTP)	12.0997634	-61.6525383
Radix (WTP)	12.062561	-61.723346

Stations	Latitude (N)	Longitude (W)
Guapo	12.1030646	-61.6631223
Blaize (TANK)	12.1594	-61.6483
Carriacou (WTP)	12.488185	-61.453899
Clozier (Tank)	12.142362	-61.694137
Petit Martinique	12.5242	-61.3839
Mt Hartman		
Bacolet III	12.0306	-61.6903
Black Forest (forestry)	12.082575	-61.702677
Kublal	12.165327	-61.661512

Mr. Mtumda De Gale from the Water resource technician from Planning and Development Department in NAWASA prepared the following archives with hydrological information that was used for this report and the related analysis:

- Daily Rainfall (NAWASA).xls
- Discharge (NAWASA).xls
- Monthly Rainfall Total (NAWASA).xls
- Ecoflow locations.xls file with the streamflow measurements for the stations for the Ecological flow approach

Regarding the Rainfall analysis of the stations, there are 32-gauge stations, however not for all the stations there is a complete list of data. In the following table, there is a list with the names of the stations and the periods since when there are available rainfall data till the 19.03.2025. The table 5 presents with the dates since they have available data and the percentage of available data.

Table 5: List of the gauge stations in Grenada monitored by NAWASA.

Rainfall stations	Start Date	End Date	Available Data (%)
Tufton Hall (WTP)	01.06.2014	31.01.2025	52.93
Mt.Plaisir (WTP)	01.06.2013	31.01.2025	57.89
Concord (WTP)	01.05.2014	31.01.2025	53.35
Blaize (TANK)	16.01.2017	31.01.2025	39.90
Mamma Cannes (WTP)	01.06.2013	31.01.2025	57.89
Les Avocat (WTP)	01.03.2005	31.01.2025	98.82
Pomme Rose (WTP)	01.06.2013	31.01.2025	57.89
Mardigras (WTP)	01.05.2013	31.01.2025	58.31
Vendome (WTP)	01.05.2013	31.01.2025	58.31
Annandale (WTP)	01.01.2012	31.01.2025	64.91
Peggy’s Whim (WTP)	01.04.2014	31.01.2025	53.76
Petit Etang (WTP)	01.05.2014	31.01.2025	53.35
Grand Etang (LAKE)	01.01.2021	31.01.2025	20.26
Dougaldston (WTP)	01.01.2013	02.03.2024	55.39
Mt Reuil (WTP)	01.03.2015	31.01.2025	49.23

Rainfall stations	Start Date	End Date	Available Data (%)
Mirabeau (WTP)	01.01.2008	31.01.2025	84.75
Mt Horne (WTP)	15.01.2016	31.01.2025	44.88
Petit Martinique	08.12.2017	27.06.2024	32.51
Carriacou (WTP)	08.12.2017	30.06.2024	32.55
Spring Garden (WTP)	01.01.2018	31.01.2025	35.14
Bon Accord (WTP)	01.02.2022	31.01.2025	14.88
Radix (WTP)	01.01.2022	31.01.2025	15.30
Brandon Hall (WTP)	01.11.2015	31.01.2025	45.90
Munich (WTP)	01.11.2021	31.01.2025	16.13
Plaisance (WTP)	01.04.2022	31.01.2025	14.08
Guapo	03.08.2022	31.01.2025	12.40
Black Forest (forestry)	20.10.2014	31.01.2019	21.25
Kublal	31.10.2014	31.12.2016	10.77
Clozier (Tank)	01.02.2015	31.01.2025	49.61
Mt Hartman	01.06.2013	30.06.2015	10.32
Chemin II	22.01.2020	31.03.2024	20.79
Bacolet III	01.09.2023	31.03.2024	2.89

The earliest precipitation records in the dataset begin in March 2005 at Les Avocat (WTP), followed by January 2008 at Mirabeau (WTP). Most other stations began recording around 2012–2013, such as:

- Annandale (WTP) – Jan 2012
- Dougaldston (WTP) – Jan 2013
- Pomme Rose (WTP), Mt.Plaisir (WTP) – Jun 2013

Table 6: List of the gauge stations with the most complete rainfall records.

Station	Rainfall_Records (number)
Les Avocat (WTP)	5185
Mirabeau (WTP)	4905
Annandale (WTP)	4242
Concord (WTP)	3517
Vendome (WTP)	3500
Petit Etang (WTP)	3298
Peggy's Whim (WTP)	3252
Mamma Cannes (WTP)	3246

At country level, with the data from the gauge stations it is possible to determine that the rainfall in Grenada is very much influenced by orography. The catchment area of the upper Great River is one of the areas with highest rainfall. In the following graphics it is represented the average precipitation for each month (January-December) at country level (figure 4) and for each of the gauge stations (figure 5).

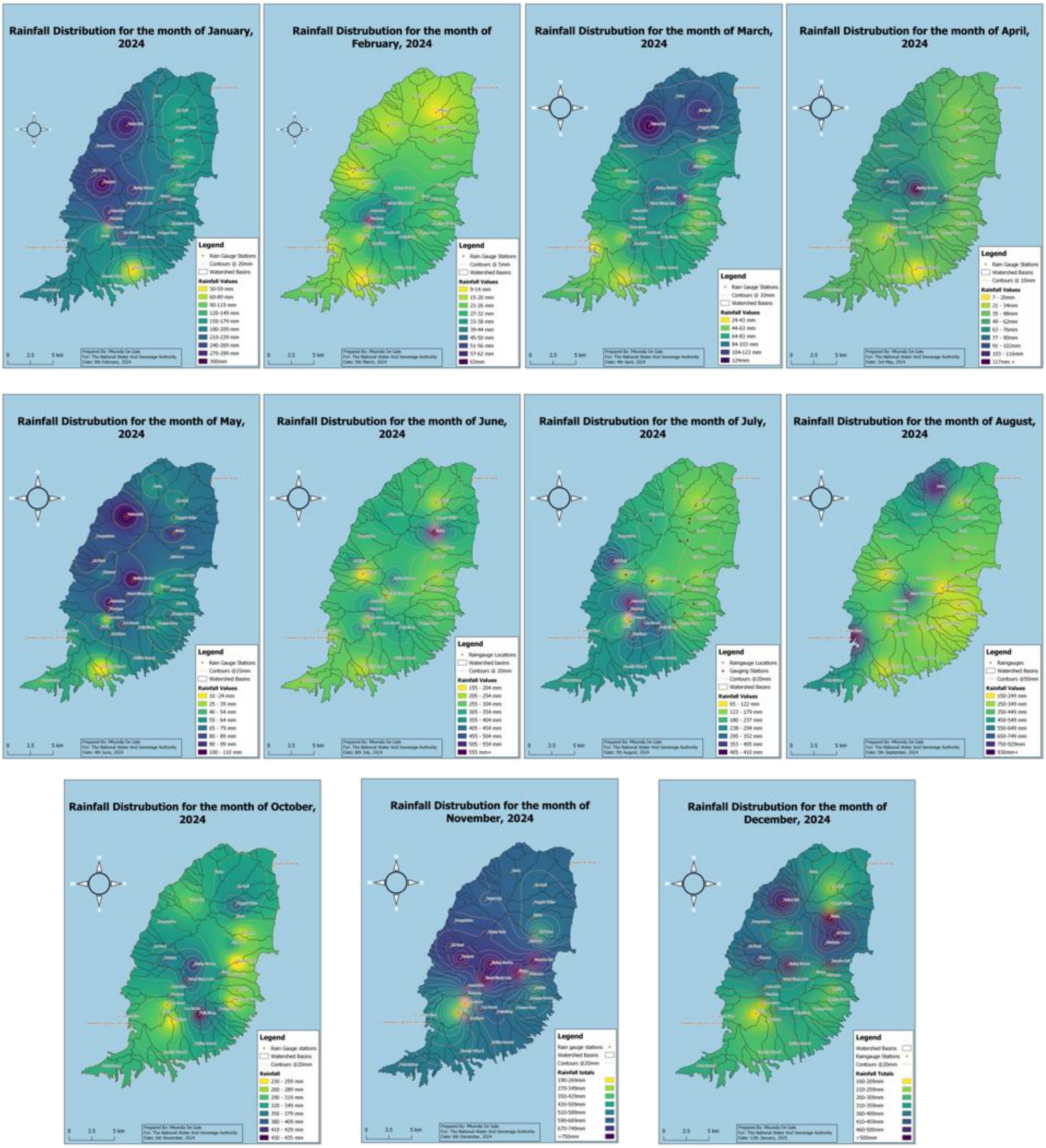
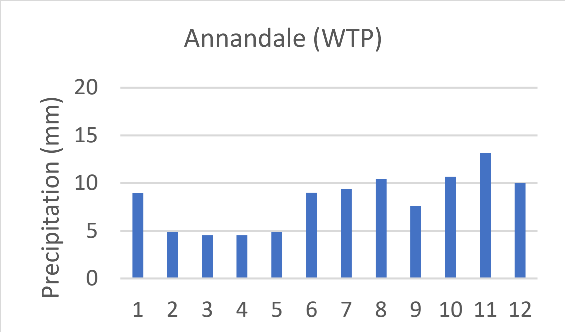
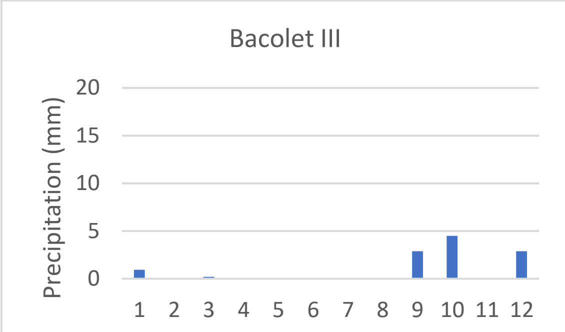
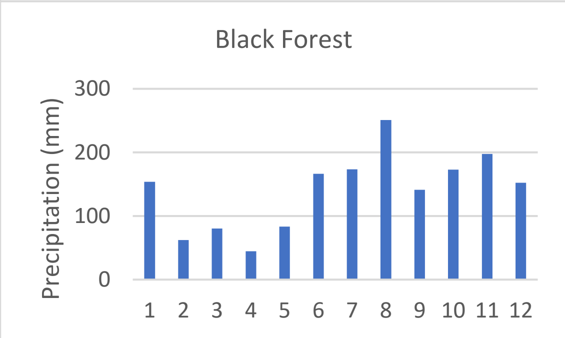
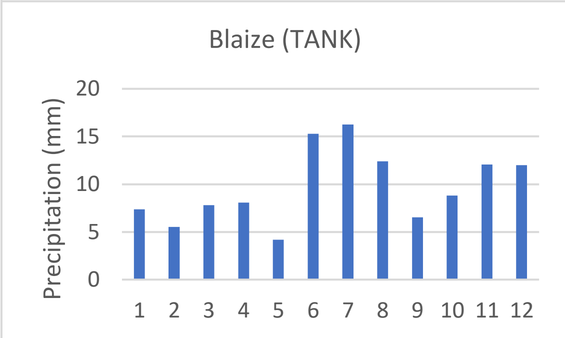


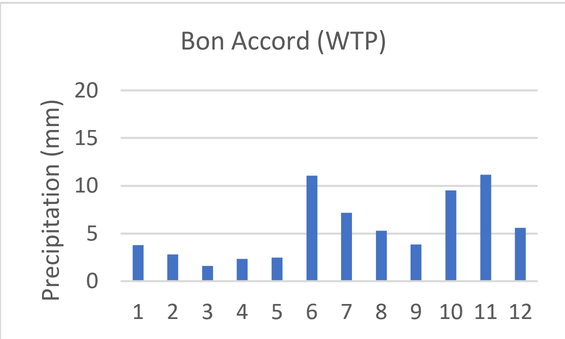
Figure 5: Monthly precipitation from the period January -December 2024.

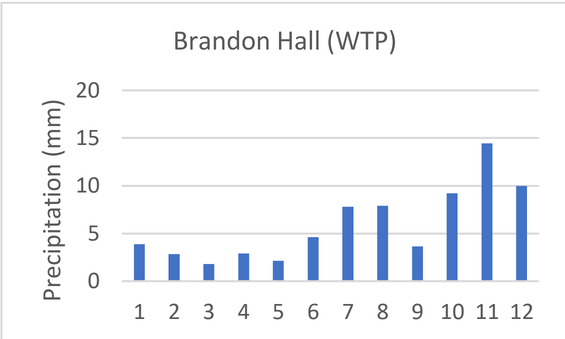

Annandale (WTP)
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

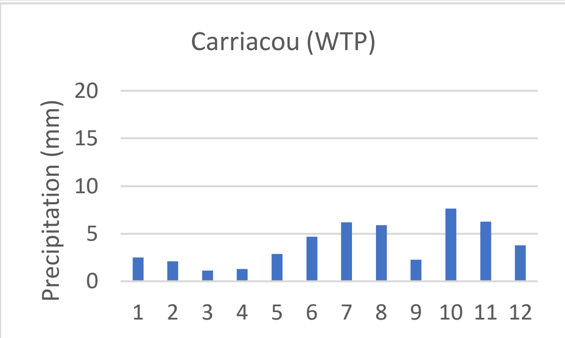

Bacolet III
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

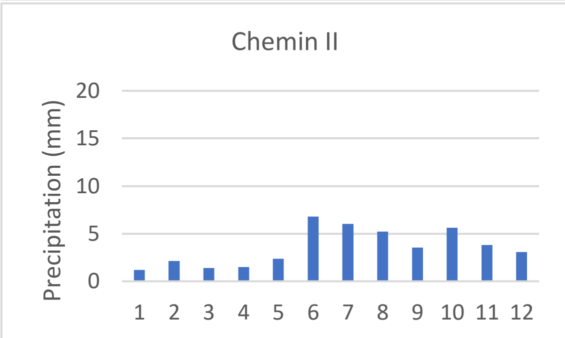

Black Forest
Precipitation (mm)
0 100 200 300
1 2 3 4 5 6 7 8 9 10 11 12

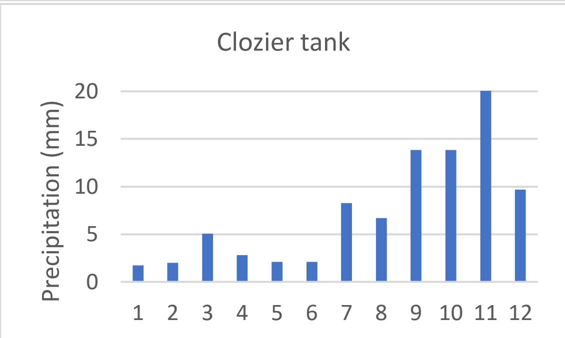

Blaize (TANK)
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

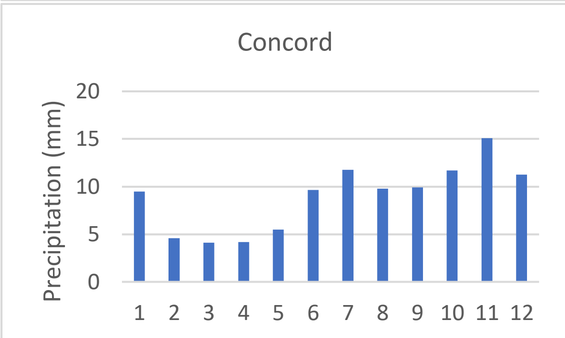

Bon Accord (WTP)
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

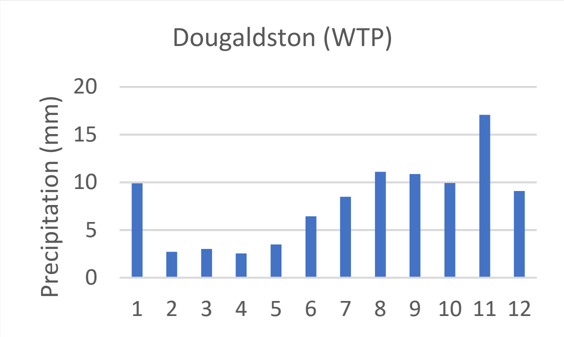

Brandon Hall (WTP)
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

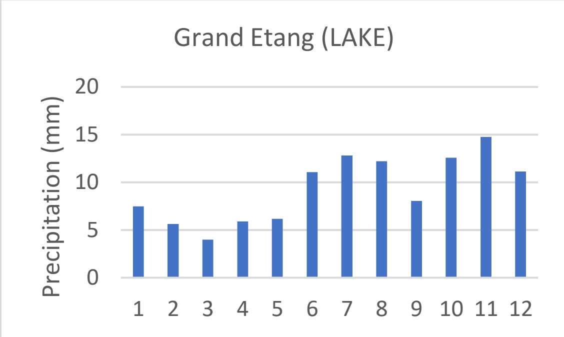

Carriacou (WTP)
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

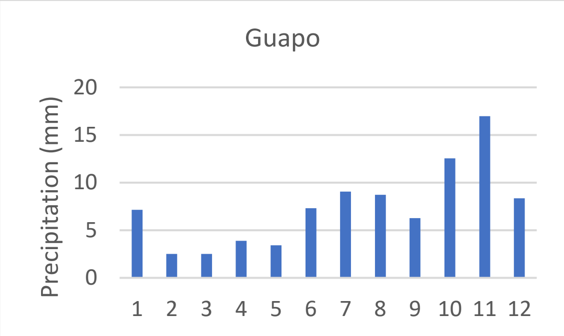

Chemin II
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

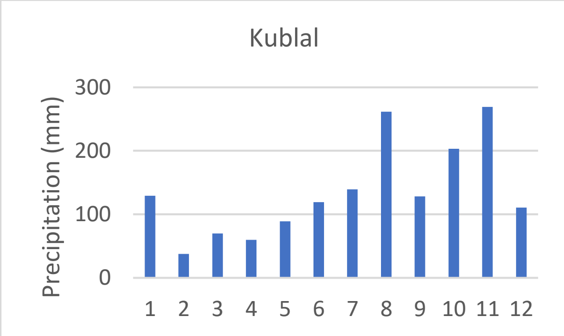

Clozier tank
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

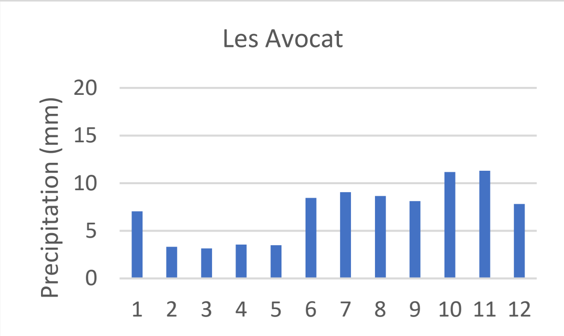

Concord
Precipitation (mm)
0 5 10 15 20
1 2 3 4 5 6 7 8 9 10 11 12

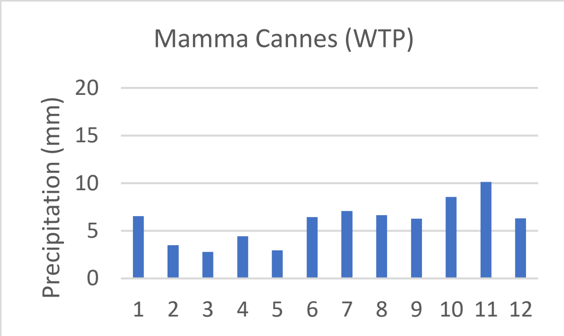

Dougaldston (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

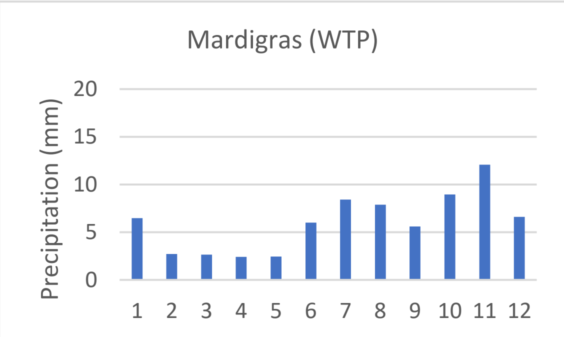

Grand Etang (LAKE)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

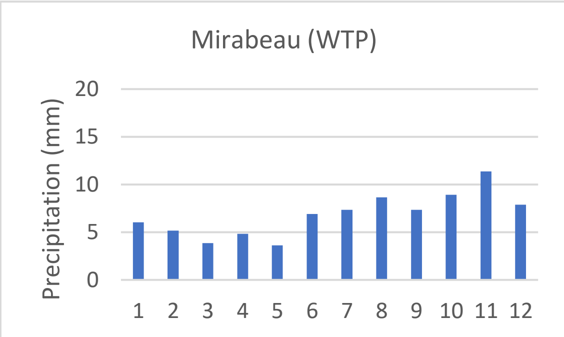

Guapo
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

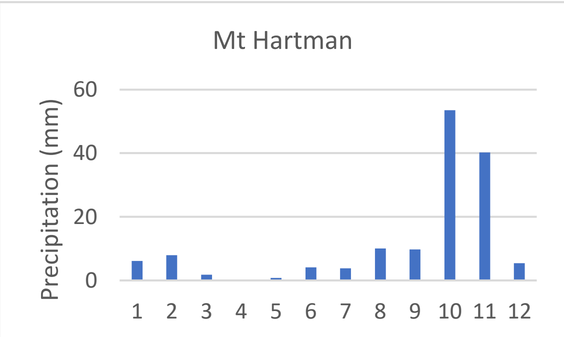

Kublal
Precipitation (mm)
300
200
100
0
1 2 3 4 5 6 7 8 9 10 11 12

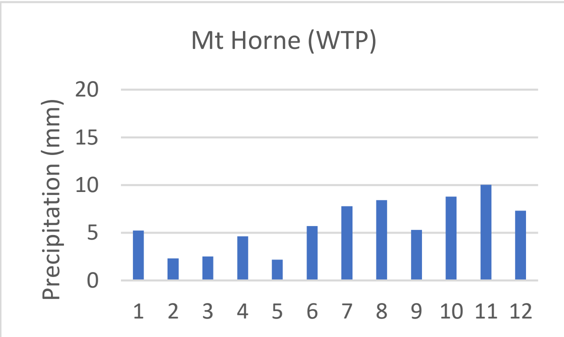

Les Avocat
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

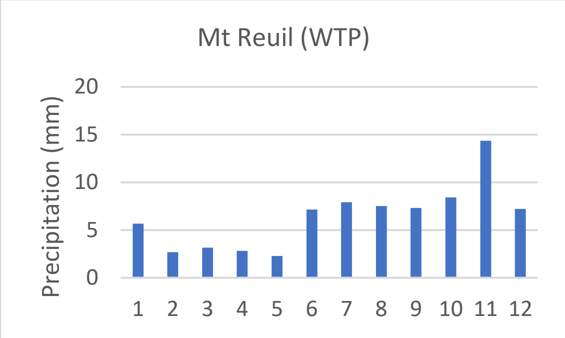

Mamma Cannes (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

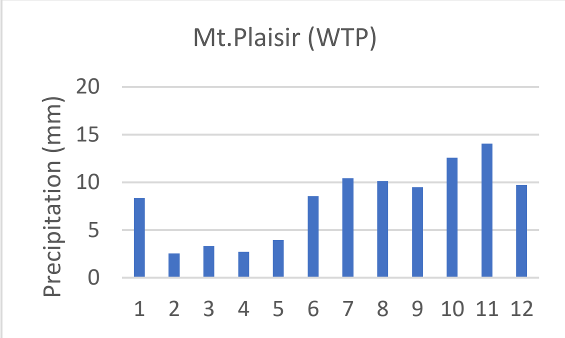

Mardigras (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

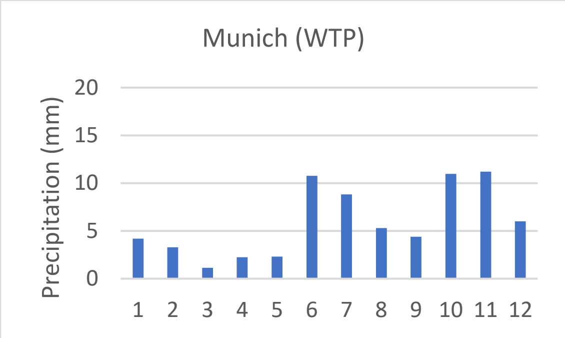

Mirabeau (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

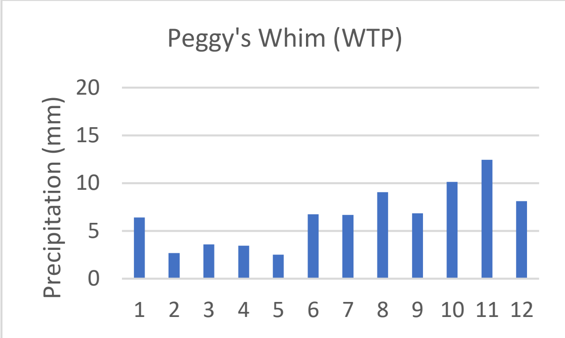

Mt Hartman
Precipitation (mm)
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12

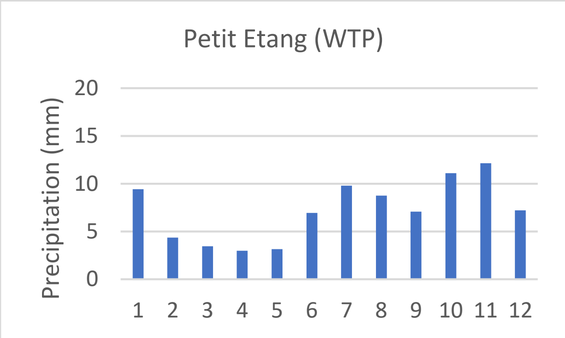

Mt Horne (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

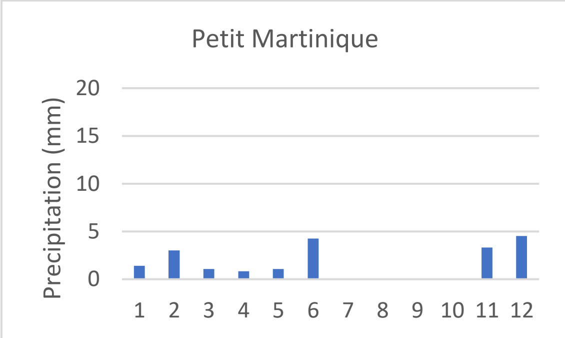

Mt Reuil (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

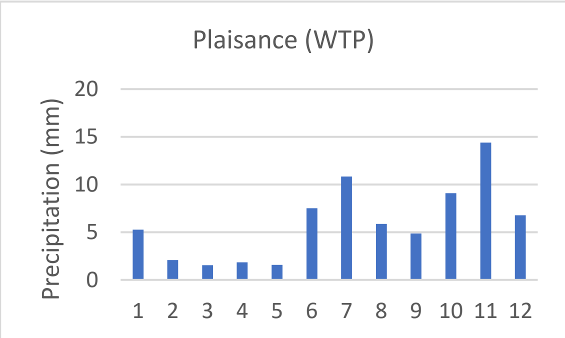

Mt.Plaisir (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

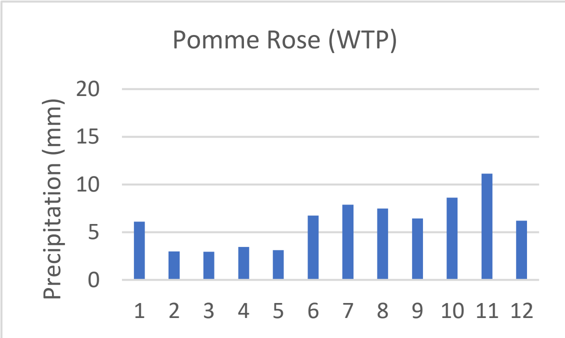

Munich (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12


Peggy's Whim (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12


Petit Etang (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12


Petit Martinique
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12


Plaisance (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12


Pomme Rose (WTP)
Precipitation (mm)
20
15
10
5
0
1 2 3 4 5 6 7 8 9 10 11 12

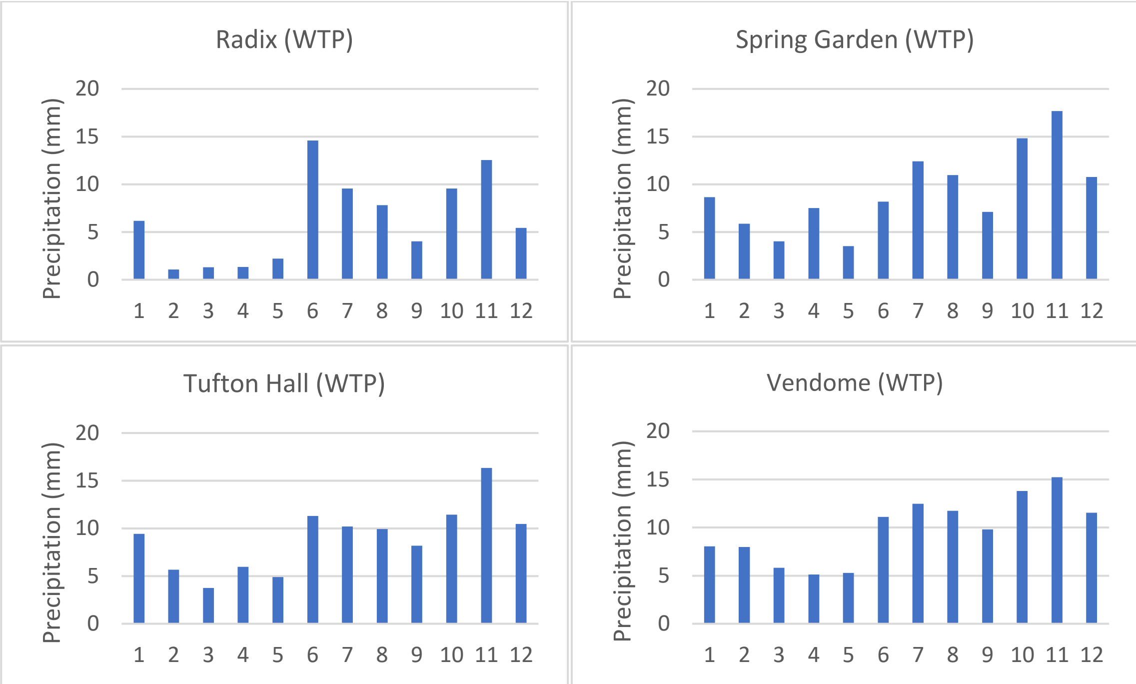


Figure 6: Monthly precipitation from the period January -December for each of the gauge stations operating in Grenada.

Some stations like Les Avocat (WTP) have 70% of data filled, others, such as Vendome (WTP), are around 45%. The stations with low completeness should be not used in hydrological analyses. In the following chart it is represented the average monthly precipitation for the six stations with the most complete data.

It is possible to analyse a possible similarity between the gauge stations. In the following figures it is presented the view of all the stations and the variability of stations where there are 3 possible clusters.

The cluster 0 represents a group with long rivers and rivers with high flow, the cluster 1 represents a group of small rivers and finally cluster 2 represents rivers from the other two islands (Cariacou and Petit Martinique). The rivers belonging to each of the groups has similar characteristics and maybe it is possible to elaborate a similar ecoflow approach.

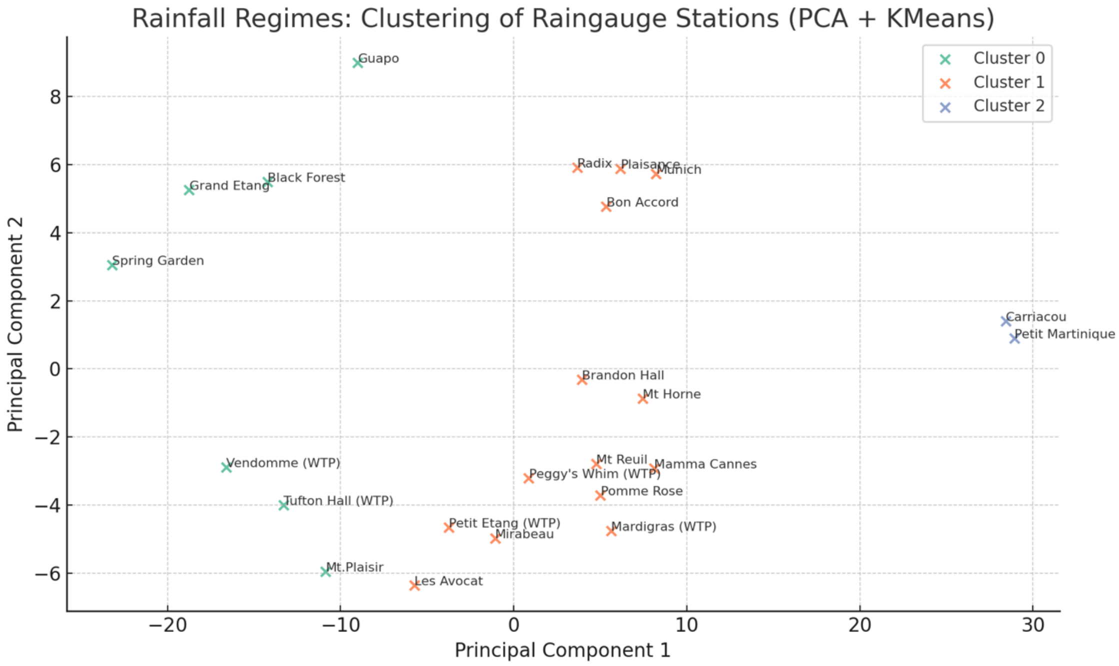


Figure 7: Rainfall regimes for the gauge stations: clustering principal component analysis and K-means.

In the following chart, all the stations and the annual streamflow and its variability are represented.

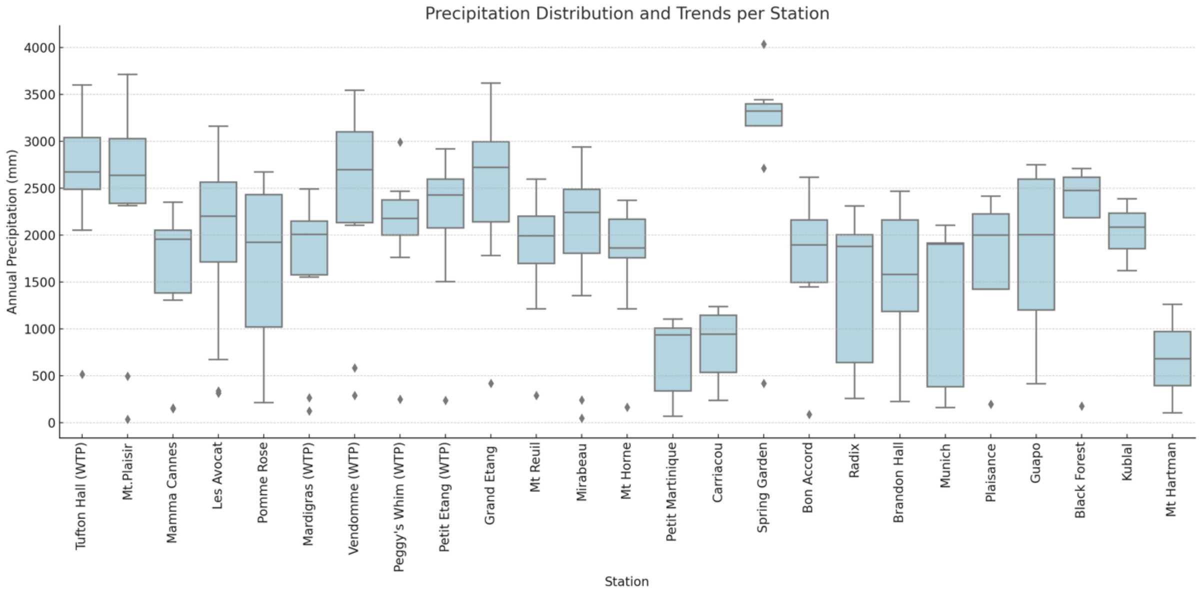


Figure 8 Annual precipitation distribution and trends per gauge station.

There is a huge variability between the gauge stations regarding the precipitation even for some of the events with picks of 600 mm as maximum values.

After reviewing the documents and information available that was provided by NAWASA, the selection of the most interesting rivers to visit was done.

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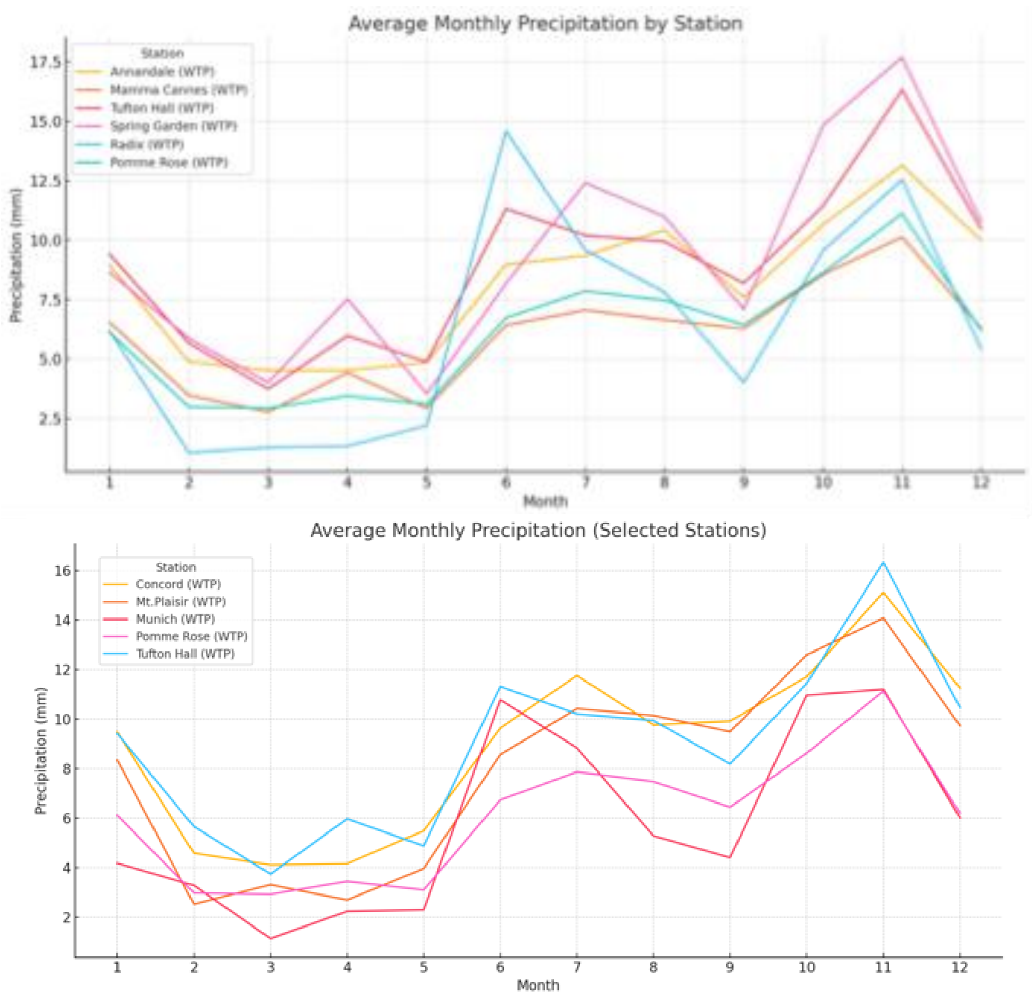

Figure 9: Two graphics that represents the average monthly precipitation for the stations with the longest records (up) and the graphic of the monthly precipitation for the five stations (down) that were sampling sited under this assignment during March-April 2025 .

On the upper part, the chart shows average monthly precipitation by the stations with longest track record on the island, and below, the chart shows average monthly precipitation for the five stations that were sampling sited under this assignment during March-April 2025 and where we had measured the discharge data, with the most complete data (Concord, Mt Plaisir, Munich, Pomme Rose and Tufton Hall) with the most complete series of precipitation data.

The selected rivers present hydrological stations (with precipitation data) nearby then. The selection of the places was done taking into account that are rivers representing different areas of the country (West, North, East and South-East) with certain basin area and with at least one gauge station and historical streamflow measures and also rivers where there is a routine of measuring the streamflow in the upper part of the basin (upstream the tanks or the dams).

Table 7: List of the selected rivers and locations for taking the streamflow measure and the field visits during the works done in March-April 2025 under the limnologist assignment.

River	Locations	Gauge station name	X Coord	Y Coord	Approx. Elevation (m)
Black Bay River	Upper part of waterfall	Concord	-61.71811	12.11707	320
Black Bay River	Mouth	Black Bay Bridge (Mouth)	-61.74553	12.11965	23
Grand Roy River	1 close to the Mt Plaisir gauge station	Mt. Plaisir			
Grand Roy River	Mouth	Grand Roy (Mouth)	-61.7458	12.13249	2
St Marks river	Upper part downstream Tufton Hall	Tufton Hall	-61.69323	12.17254	190
St Marks river	Mouth	Diamond Bridge (Mouth)	-61.70364	12.19171	15
St Patricks river	Upper part downstream Mt Reuil	Mt Reuil	-61.64867	12.18687	10
St Patricks river	Mouth	La Fortune Bridge (Mouth)	-61.63601	12.22031	141
Antoine river	Chacha and Zulu downstream	Cha	-61.65455	12.17395	267
Antoine river	Mouth	Poyntzfield Bridge (Mouth)	-61.62127	12.17515	38
Great River	Upper part	Morne Longue	-61.69231	12.12269	405
Great River	Mouth	Paradise Bridge (Mouth)	-61.61995	12.13462	7
Little river of Grand Bacolet	Upper part downstream Munich	Munich	-61.65034	12.0885	274
Little river of Grand Bacolet	Mouth	Hope Estate Bridge (Mouth)	-61.6308	12.07886	9
La Tante river	Upper part downstream Apres Tout	Apres Tout	-61.67102	12.0623	346
La Tante river	Mouth	Pomme Rose Bridge (Mouth)	-61.65839	12.05637	122

Using this information, it is possible to analyse the information available and develop a simple first hydrological environmental flow approach.

6.2. Discharge Records

On a routine basis, NAWASA collects streamflow data prior to entering the dam on a monthly basis; however, data collection was not carried out every month or each year.

In the following table there is a list of the locations where the streamflow measurements take place.

Table 8: List of the streamflow river stations.

Name of the discharge station	Longitude	Latitude	Elevation (m)
Adelphi (Parked)	-61.676008	12.100231	352.79303
Adelphi station	-61.67688	12.098377	320.133606
Spring Garden Parked	-61.691026	12.111369	408.974396
Spring Garden Dam	-61.692204	12.110388	412.722565
Spring Garden station	-61.692583	12.110368	414.260315
Morne Longue station and parked	-61.6923	12.122697	412.852051
Mt Granby station	-61.716487	12.134893	334.603607
Mt Plaisir parked	-61.727065	12.130726	216.925812
Mt Granby parked	-61.716524	12.134856	335.013275
Mt Plaisir dam	-61.726652	12.130902	205.567383
Mt Plaisir station	-61.726114	12.131302	214.022354
Brandon Hall parked	-61.664516	12.112222	261.507263
Brandon Hall Dam	-61.66548	12.109859	272.384705
Munich Dam	-61.650253	12.088129	282.472412
Munich Station	-61.650296	12.088208	281.667267
Brandon Hall station	-61.664757	12.109246	276.407471
Munich parked	-61.647705	12.088053	262.934631
Tufton Hall Dam	-61.694493	12.172473	160.294739
Tufton Hall Station	-61.694371	12.172335	159.7314
Mt Reuil station	-61.648293	12.186852	164.903839
Mt Reuil parked	-61.646789	12.187687	155.863556
Mt Reuil dam	-61.648243	12.186968	164.64711
Vendome parked	-61.70703029	12.08165658	318.14917
Vendome 1 dam	-61.70648951	12.08322056	344.894897
Vendome 1 station	-61.70635851	12.08340373	346.783112
Vendome 2 station	-61.707107	12.083214	339.024719
SULAY DAM	-61.70556608	12.08037455	372.576904
Vendome 3	-61.70550556	12.08020309	392.958984
Vendome 4	-61.70537462	12.08023367	381.17926
"ANNANDALE1 station"	-61.711455	12.095275	263.133301
ANNANDALE 2 station	-61.711967	12.094833	261.837646
Bon Accord station	-61.7142	12.070304	274.811188
BORN ACCORD DAM	-61.71428	12.07035	274.477966
Bon Accord Parked	-61.71486144	12.0706342	(no data)
Annadale Dam	-61.71162213	12.0947446	(no data)
Les Avocat parked	-61.700702	12.06615	349.386139
Les Avocat 2 station	-61.700641	12.066578	350.904816
Les Avocat 1 station	-61.701565	12.06666	348.417908
Les Avocat Dam	-61.701093	12.066023	350.205109

In this paragraph it is described the annual flow statistics and timing analysis.

Table 9: List of the main streamflow river stations with mean and variance (m^3/day)

Station	Mean Flow (m^3/day)	Variance (m^3/day)^2
Adelphi	17377.23	1.12E+08
Annandale Main	7462.944	11548858
Annandale Stream	3315.024	5899759
Apres Toute	58.45326	936.3509
Black Forest	1780.249	
Blin-eff	916.9216	809335.8
Bon Accord	390.9379	626700.1
Brandon Hall	1240.148	774538.9
Cha	3836.493	7442410
Clozier	1096.475	583121.2
Clozier Overflow	81.78416	170.8494
Concord	11062.31	34233177
Concord Downstream	11706	36622599
Cuba	1694.29	10511058
De Dig 1	734.3505	219553.1
De Dig 2	1105.033	555500.3
Digopeace	65.4637	
Ellen	1814.232	19702497
Golden Falls	4703.657	765923.1
Grand Etang Lake	1704.616	3445185
Great River	14897.09	1.81E+08
Guapo	105.9239	
Les Avocat Main	1619.505	9988034
Les Avocat Stream	1260.628	4978922
Mamma Cannes	3090.921	7399048
Mardigras	855.2211	998984.1
Mirabeau	3975.809	3687267
Morne Longue	1624.921	2426773
Mt Felix	762.5066	10028.08
Mt Granby	1320.08	743372.4
Mt Horne	2610.669	994826.5
Mt Plaisir	5974.34	19645617
Mt Reuil	6243.475	7898431
Mt William	1004.215	1158286
Munich	647.3201	296285.9
Petit Etang	1102.479	1212069
Plaisance	172.4205	2424.943

Station	Mean Flow (m³/day)	Variance (m³/day)²
Plesance	1997.445	2926035
Pomme Rose 1	640.542	237374.3
Pomme Rose 2	454.4975	346817.8
Radix	228.9792	113637.5
Ravine Fig	464.897	20773.33
Spring Garden	1516.062	989198.7
Tufton Hall	7866.503	38958400
Tufton Hall stream	1189.467	6049461
Vendome 1	1895.12	2632937
Vendome 2	2230.064	5502860
Vendome 3	1283.42	835247.2
Vendome 4	1293.608	738554
Walker	6236.038	2081584
Westerhall	1004.857	333260.2
Zulu	2295.193	1271737

This table presents the mean and variance of annual maximum and minimum flows (in m³/day) for the selected stations.

In the following chart, it is represented all the stations and the annual streamflow and its variability.

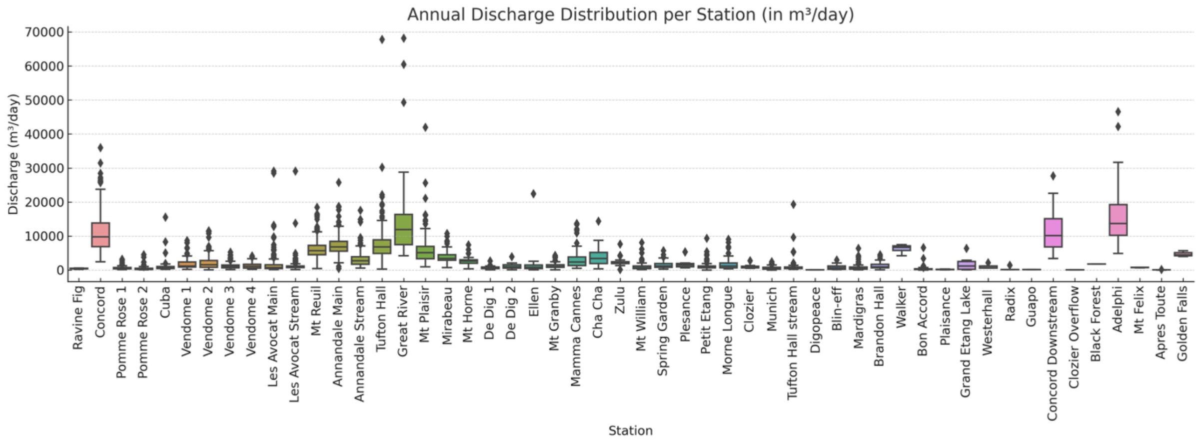

Figure 10: Annual streamflow distribution and trends per location in each river (m³/day).

The figure below shows the distribution of months when the annual maximum flows in all the rivers in Grenada occur. The histograms are showing when the **annual maximum and minimum flows** tend to occur:

- **Maximum flows** are most frequent in **December, January, and February**, suggesting a seasonal flood pattern, possibly linked to rainy season peaks or storm events.

- **Minimum flows** peak in **May and June**, indicating typical low-flow periods, potentially due to drier weather or increased evapotranspiration before the main rainy season.

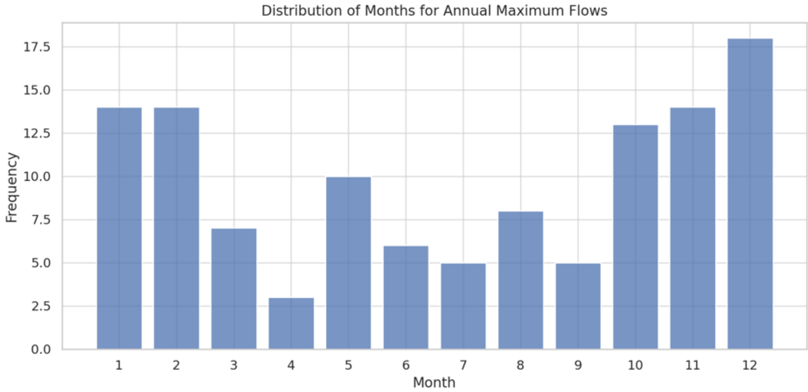

Figure 11: Distribution of months for annual maximum flows (m³/day).

Each bar shows the number of years where the peak streamflow (flood) occurred in that specific month, across all selected stations (with available data).

- Most **annual floods** happen in **November**, **December, January, and February**.
- These months are likely associated with:
    - The **rainy season** or intense storm events.
    - Hydrological response to **seasonal rainfall patterns**.

The figure below shows the distribution of months when the annual minimum flows occur.

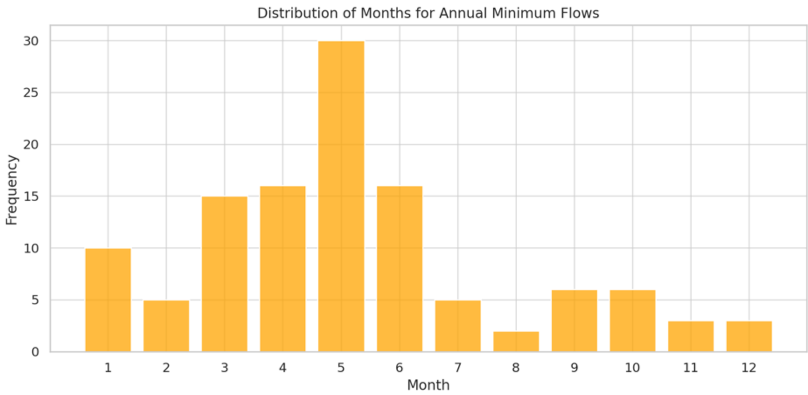

Figure 12: Distribution of months for annual minimum flows (m³/day).

Each bar shows how many times the **lowest flow (dry period)** occurred in each month over the years.

- Minimum flows are most frequent in **May and June**.
- These are likely the **driest months**, or times with:
    - Reduced rainfall.
    - Higher evapotranspiration (hot, sunny weather).
- Understanding low-flow periods is important for:

- **Water availability** (for people, agriculture).
- **Ecological flows** (e.g. maintaining aquatic habitat).
- **Pollution control**, as lower flows reduce dilution capacity.

In the following graphics the monthly average stream streamflow patterns for Concord, Mt. Reuil, Munich, Tufton Hall, Mt Plaisir and Pomme Rose are presented. This presents the monthly average stream streamflow patterns for selected stations in m³/day.

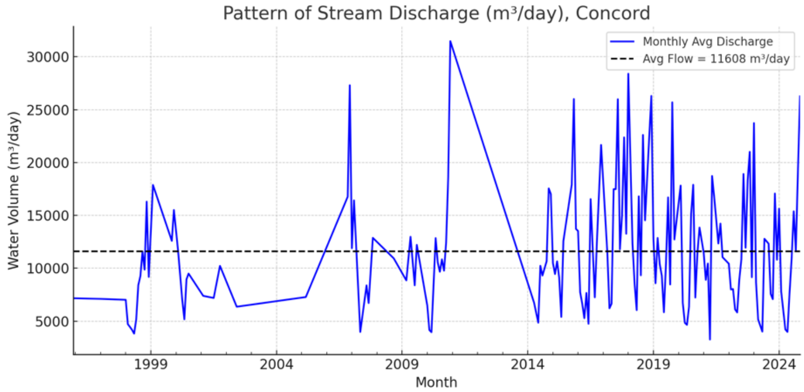

Figure 13: Monthly average streamflow for Concord (m³/day).

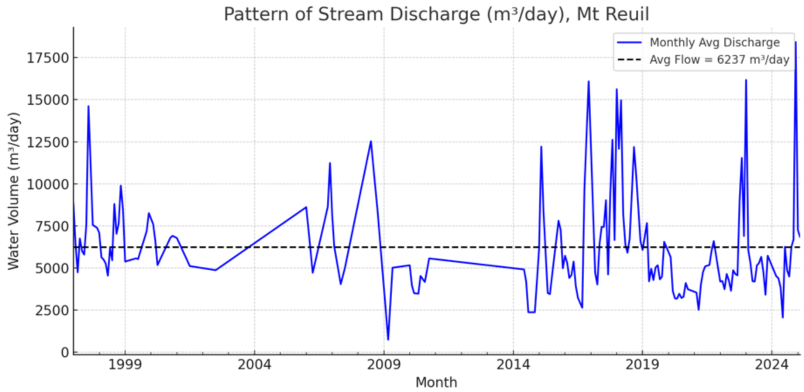

Figure 14: Monthly average streamflow for Mt Reuil (m³/day).

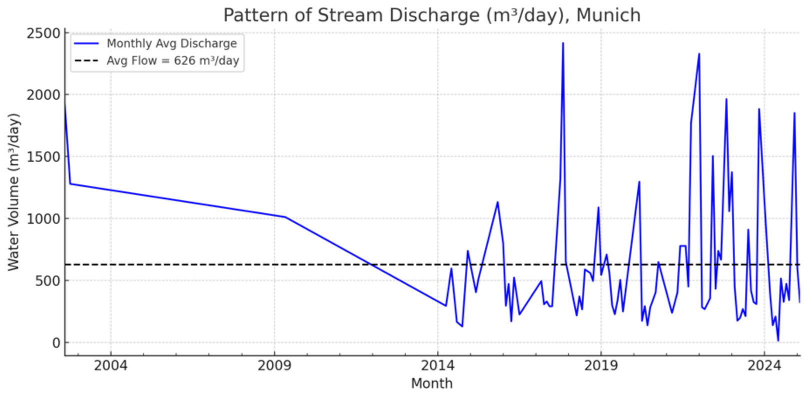

Figure 15: Monthly average streamflow for Munich (m³/day).

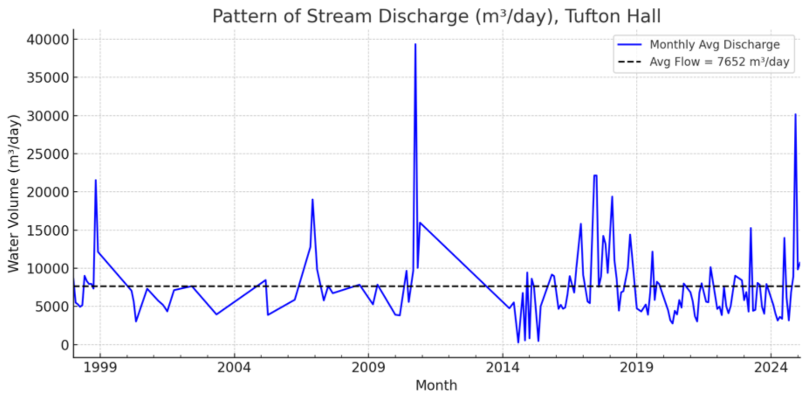

Figure 16: Monthly average streamflow for Tufton Hall (m³/day).

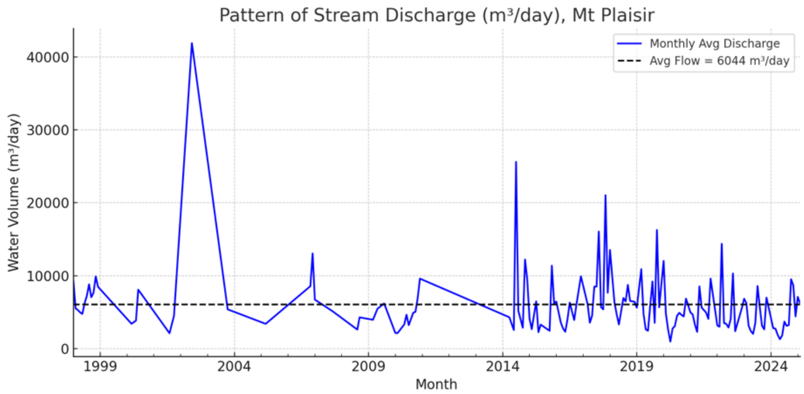

Figure 17: Monthly average streamflow for Mt Plaisir (m³/day).

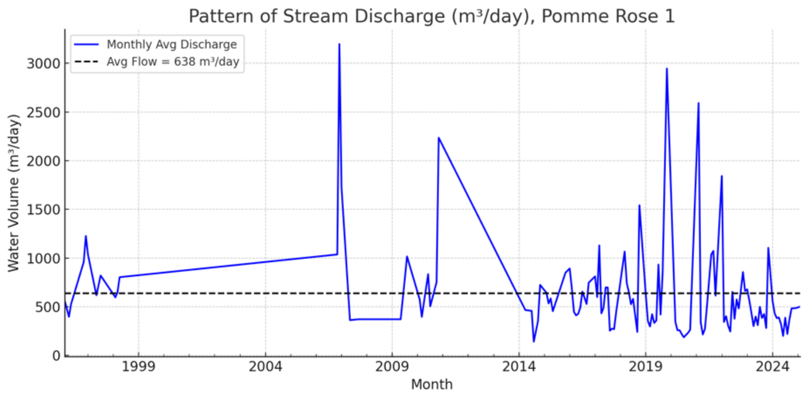

Figure 18: Monthly average streamflow for Pomme Rose 1 (m³/day).

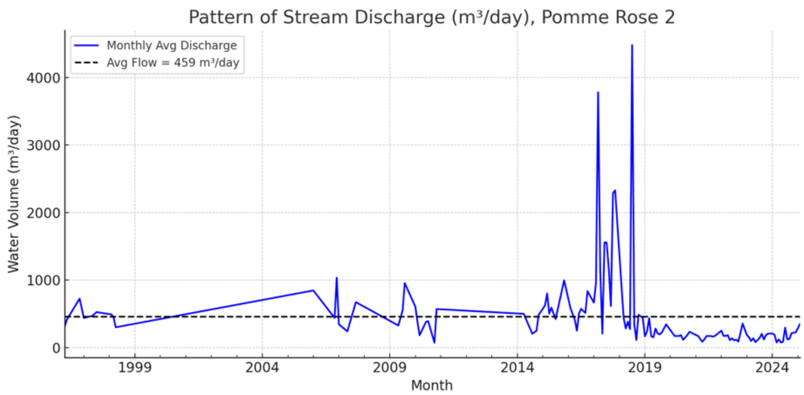

Figure 19: Monthly average streamflow for Pomme Rose 2 (m³/day).

6.3. GIS ANALYSIS

The spatial analysis was carried out with QGIS using the GIS layers produced by NAWASA.

6.4. FIRST APPROACH TO AN ENVIRONMENTAL FLOW CALCULATION IN GRENADA WITH HYDROLOGICAL METHODS : IN BLACK BAY RIVER USING THE INFORMATION AVAILABLE FOR CONCORD STATION

According to the data available in the country, it is not possible to deliver a full environmental flow calculation at holistic level. However, it is possible to deliver a hydrological calculation and presenting the methodological approach using the available data related with precipitation and streamflow measurements in Grenada. In parallel, it is possible to define the available techniques for carrying on the hydrological estimations and also the recommendations for improving the collection of data, how to acquire new data and the process of creating holistic environmental flow calculations in the future and the need to add more automatic stations.

The proposed methodology for the first approach on environmental flow calculation for Grenada is based on their special conditions of the two seasons, the uses of water that are quite natural, there are not big factories, industry, hydropower stations or mining activities in the country that might influence the water abstraction and the water uses.

Accordingly, streamflow data collected by NAWASA over the period 1995 to 2025 was analysed to better understand the natural flow regime within rivers mentioned. One of the locations, the gauge station Concord, in Black Bay River, was selected to implement this example of one environmental flow approach.

It is important to point out some of the limitations of the dataset, which can affect the interpretation of the results. Streamflow data was not continuous over the period under study. Typically NAWASA collected streamflow data prior to entering the dam on a monthly basis; however, data collection was not carried out every month or each year. This resulted in no or limited observation points for various months and years (e.g. data for six years were missing and only nine streamflow data points were available for the month of September over the 26 years). In rare instances, more than one observation point was available for a few months; however, this was not a consistent pattern. This limited calculation of key hydrological indicators, such as the 7Q10 (lowest 7-day average over 10 years).

Table 10: List of the streamflow river stations prior to entering the dam in Grenada monitored by NAWASA selected for the study.

River	Station names
Black Bay River	Concord
Black Bay River	Black Bay Bridge (Mouth)
Grand Roy River	Mt. Plaisir
Grand Roy River	Grand Roy (Mouth)
St Marks river	Tufton Hall
St Marks river	Diamond Bridge (Mouth)

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River	Station names
St Patricks river	Mt Reuil
St Patricks river	La Fortune Bridge (Mouth)
Antoine river	Cha Cha
Antoine river	Poyntzfield Bridge (Mouth)
Great River	Morne Longue
Great River	Paradise Bridge (Mouth)
Little river of Grand Bacolet	Munich
Little river of Grand Bacolet	Hope Estate Bridge (Mouth)
La Tante river	Apres Tout
La Tante river	Pomme Rose Bridge (Mouth)

In the following example in Concord, it is presented the analysis of the volume and percentage of water abstracted from the recorded discharge observations (upstream-downstream), and the estimated environmental flow downstream, during the reference period 1995, 1997–2002, 2005–2010, 2014–2025. This is important to establish ecological baselines of abstraction and environmental flow for Grenada rivers, and inform decisions of future increased abstractions in the rivers.

Following a previous study on Concord area and other studies, as Seven Sisters Project, the focus was placed on determining the annual, monthly and daily average patterns, including deviations from established seasonal means and periods of low flows. Data observation points for all available months, were used to inform the analysis.

In the following paragraph, it is presented the Concord station analysis of data for the Black Bay River.

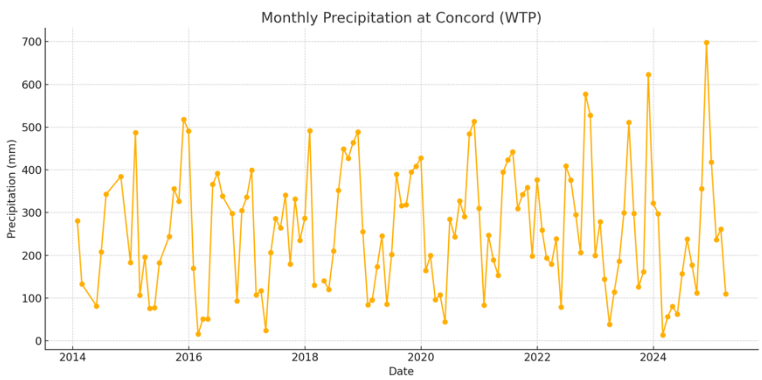

Figure 20: Precipitation data in mm at Concord (WTP) since 2014-2025.

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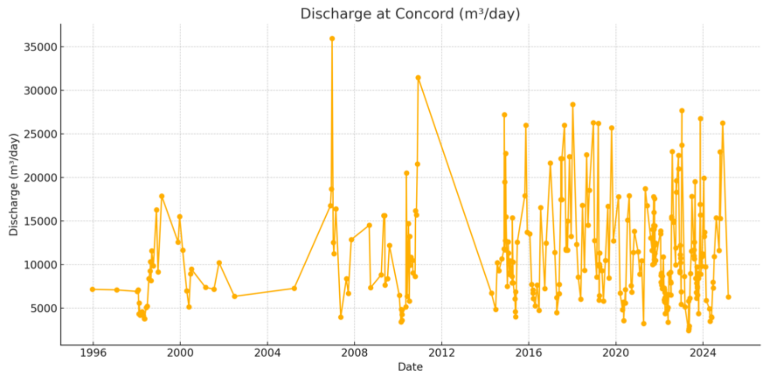


Figure 21: Streamflow data in m^3/day at Concord (WTP) since 2014-2025.

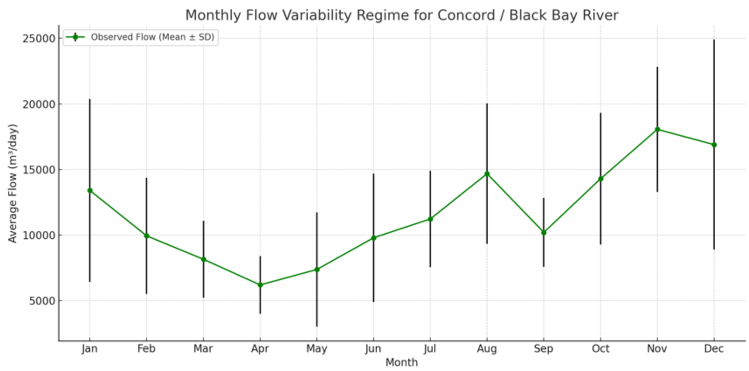


Figure 22: Annual monthly flow variability (mean and standard deviation of the streamflow) regime for Concord (WTP) with data from 2014-2025.

The streamflow patterns for all streamflow data collected at the Concord River prior to entering the dam over the period 2014 to 2025. More than half of the observation points (57.9%) were less than the annual daily average streamflow of 11,096 m3. These low to below average streamflow points were typically characteristic of the dry season and/or drought conditions. To better understand the seasonal patterns of streamflow in the Concord River, the dataset was disaggregated, and the wet and dry season patterns were analysed. All streamflow datapoints during the period January to June and July to December across the entire 11-year data series were used.

During the visits in March 2025, data of the discharge in the upper part of the stream was measured and also the same day, data from the discharge at mouth of the river.

After analysing the difference between the upper and the lower part of the river, it was found that there is an increase in the values of streamflow of 8% in one day. That means that there are other sources of water are not evaluated under the streamflow subbasin analysis (other tributaries, ground water springs, etc) and also there is no water abstraction information at basin level. That information would be interesting in order to know how much water is flowing in the basin and the needs of water for comparing the results of the environmental flow proposal with the uses in the basin.

Figure 23: Location of the area of study with the two locations upper part (left picture) and mouth of the river (left picture).

6.4.1. ADAPTATIVE E-FLOW METHOD

Using the hydrological approach for the idea of environmental flow proposal, adaptative e-Flow was calculated with a reduction applied to unmodified flow sequences on 40% for the wet season months and 30% on dry season months based on Tennant method (Tennant 1976).

- Excellent: 40% of mean monthly flow (WET SEASON)
- Good: 30% of mean monthly flow (DRY SEASON)
- Fair: 20% of mean monthly flow
- Poor/Minimum: 10% of mean monthly flow
- Severe Degradation: 0% of mean monthly flow

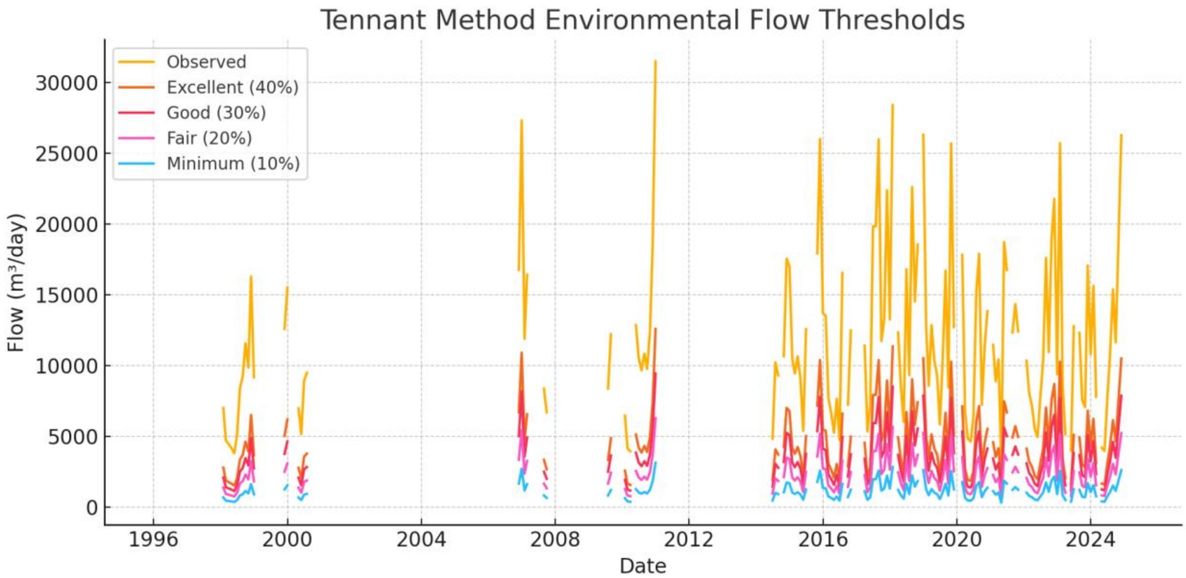


Figure 24: Tennant method calculated for Black Bay River: Years included in the calculation: 1995, 1997–2002, 2005–2010, 2014–2025.

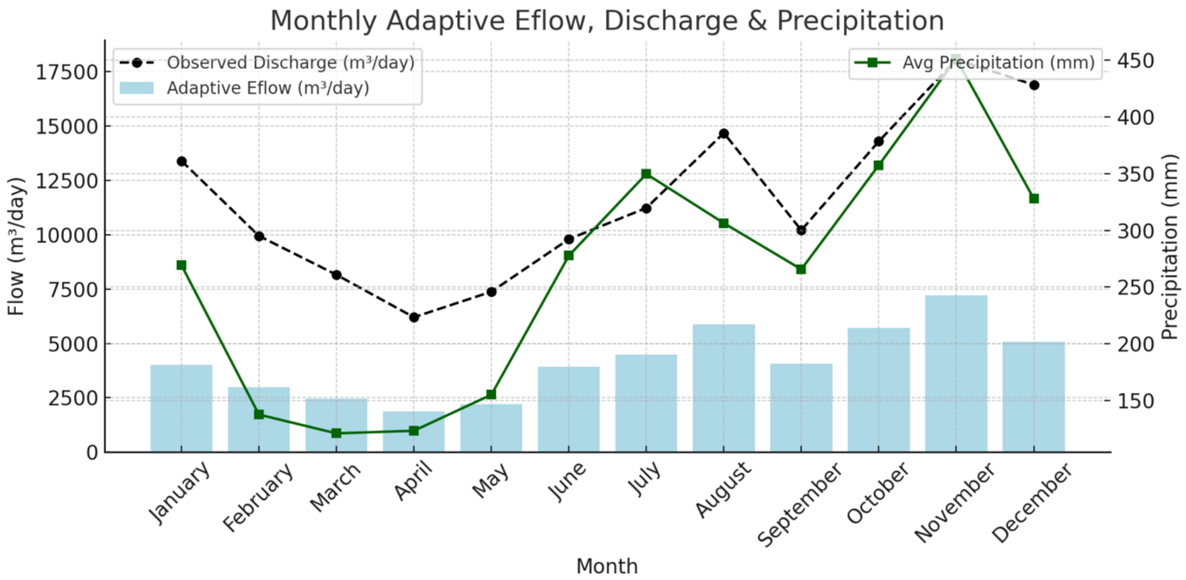


Figure 25: Adaptation of Tennant method, calculated for Black Bay River.

In the figure 25 it is presented the adaptation of Tennant method for Black Bay river applying a 40% of reduction for wet season and a 30% of reduction for dry season. The graphic represents the period of years included in the calculation: 1995, 1997–2002, 2005–2010, 2014–2025.

6.4.1. Kleynhans 1996 e-Flow Method

To calculate environmental flow (e-flow) using the Kleynhans (1996) method, which was adopted in the Nairobi Convention and incorporated into frameworks like BBM and DRIFT, typically it is used a percentage of mean annual runoff (MAR), often guided by the ecological management class (EMC).

It is needed to choose EMC (Ecological Management Class), which defines what % of MAR to allocate. According to Kleynhans (1996) and adaptations used in BBM/DRIFT, e-flow is assigned based on Ecological Management Class (EMC) (table 11).

Table 111: Kleynhans (1996) Method.

EMC	Description	% of MAR for E-flow
A	Natural	30–40%
B	Good	20–30%
C	Moderate	15–20%
D	Poor	10–15%
E/F	Seriously modified / critically	5–10%

According to the %MAR it is presented in the following figure 26 the estimation for the minimum and maximum e-flow for Concord river.

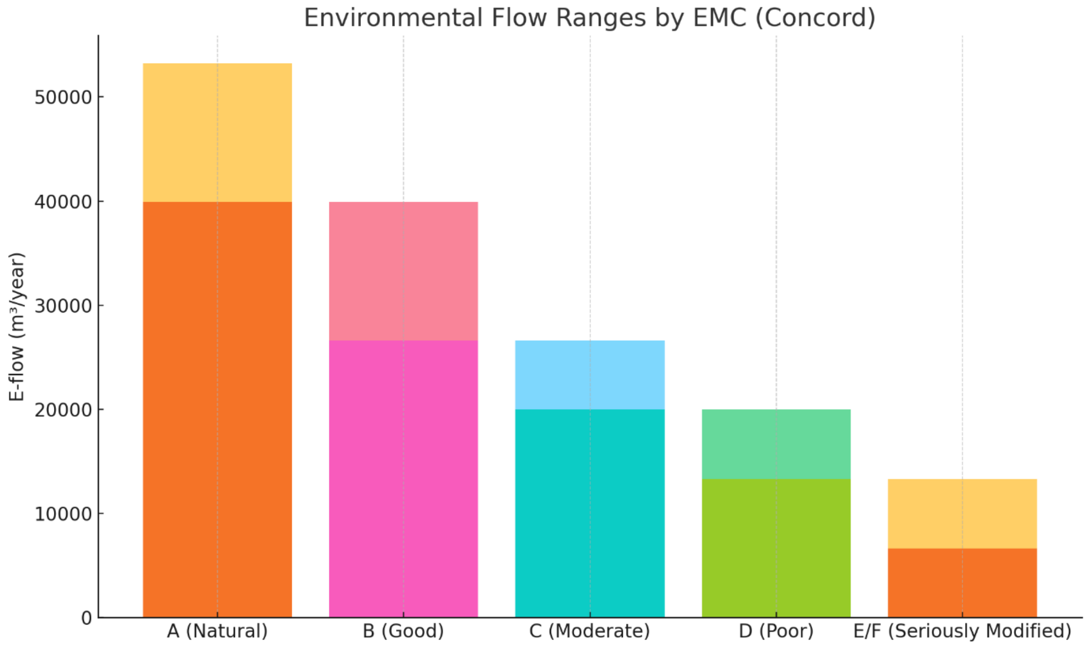
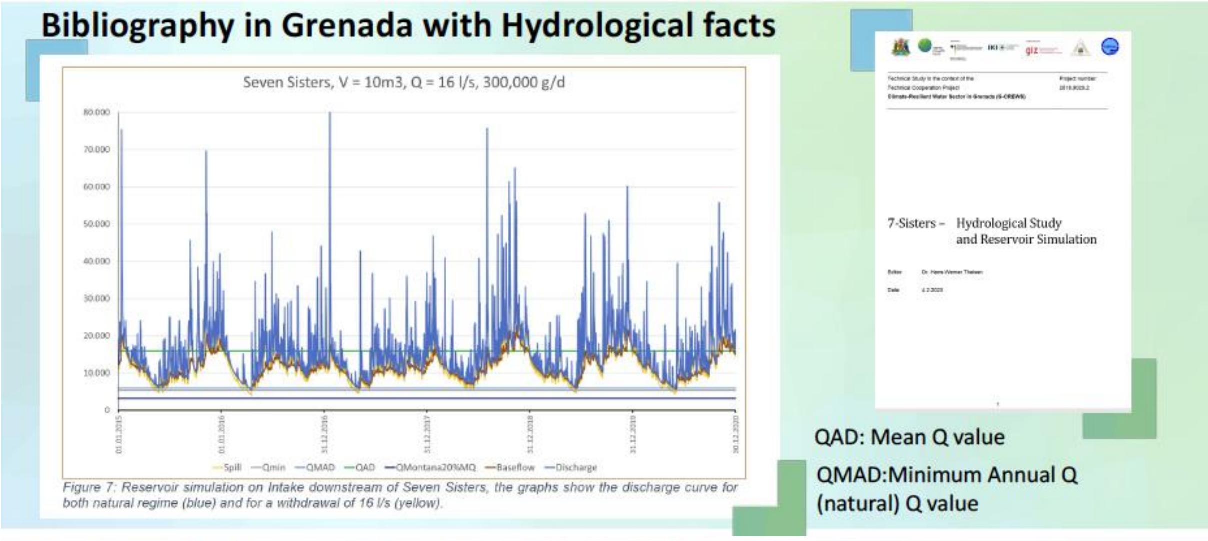


Figure 26: Ecological Management Class (Kleynhans 1996 method), calculated for Black Bay River.

6.5. RESULTS IN OTHER REPORTS

Previous reports

- An Assessment of the Economic Impact of Climate Change on the Water Sector in Grenada
- Grenada Water Sector Review
- Report on EISA Revised Final Environmental Social and Impact Assessment for Southern St. George's Water Supply Expansion and Wastewater Improvement Project GRE 31526 (2021)
- A hydrological study and reservoir simulation of the LA & PE system was undertaken in 2023 by the GIZ. The study was based on rainfall data for the last six years. The analysis also considered the effects of some dry years with a recurrence of one in 10 to 15 years based on rainfall data for the last 50 years (Theisen, 2023). south-eastern block is therefore necessary.



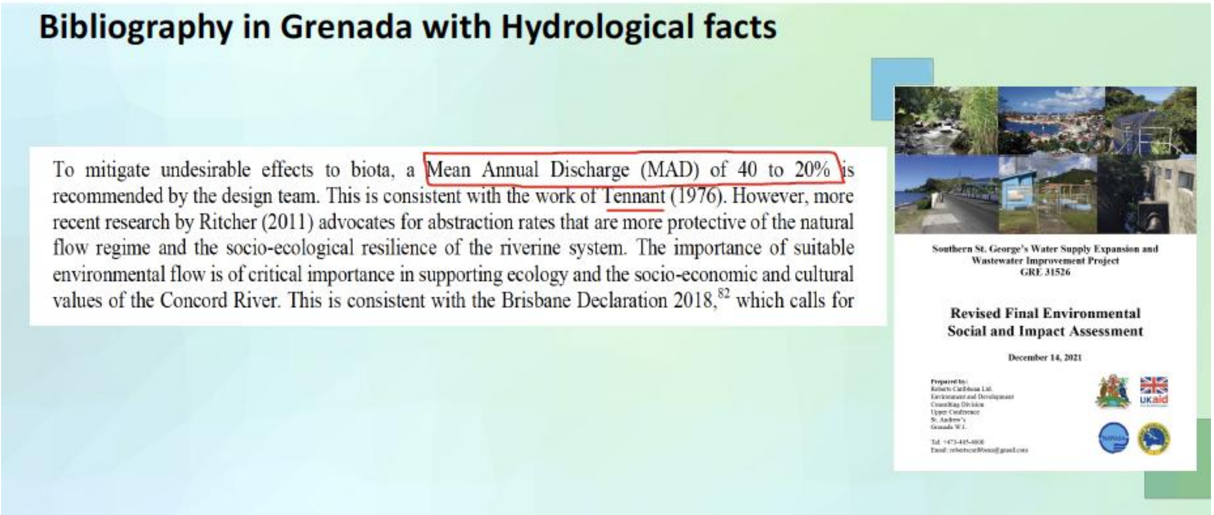


Figure 27*:* References of other projects in Grenada where they were addressing the hydrological analysis and environmental flow calculations.

7. DISCUSSION

Reliable and continuous hydrological data series are a key for conducting robust environmental flow assessments. Complete time series enable the characterization of natural flow regimes, the detection of hydrological alterations, and the definition of environmental flows that sustain the ecological integrity of riverine systems. The temporal resolution and consistency of these data are critical for identifying long-term trends, quantifying the effects of land use changes, water abstraction, and climate variability, and for supporting sound, science-based water management decisions. In the absence of high-quality hydrological records, the accuracy and credibility of environmental assessments are significantly compromised, potentially leading to suboptimal or unsustainable management outcomes.

Unless there is a great technical knowledge in NAWASA and there is a long list of meteorological locations and a routine where the discharges are measured in many locations distributed around the whole country, this is not enough. After the review and analysis of the available data, many gaps on the time series were found. In parallel, the climate variability and change are an overarching influence that has impacted Grenada water resources in the past and is an important driver to be considered in future water use planning and policy. Precipitation and river flow are projected to decrease in all regions of the island, exacerbating the current water management of this limited resource (Taylor et al., 2016).

For all these reasons it is important to configure in the near future an environmental flow approach that includes hydraulic and biological aspects as mentioned in figure 1 and allows to evaluate the water needed at basin level during the dry season in order to manage the consumptions and the balance of water.

Also, it is necessary to take into consideration the following interactions:

- In dry seasons, baseflows are critical for ecosystem survival — heavily influenced by forested areas.
- In wet seasons, peak flows may be dominated by agriculture-induced quick runoff.
- Dry season e-flow is critical for aquatic survival — focus on baseflow protection.
- Wet season should accommodate high-flow pulses to support ecological functions (e.g., sediment transport, spawning cues).

In this report, a preliminary hydrological analysis of the available information was conducted. However, there is a critical need for more extensive data collection and multidisciplinary research in order to establish robust, sampling site-specific, and seasonally-adapted environmental flow regimes for each basin.

First, hydraulic data, such as water depth, flow velocity, and wetted area under different streamflow conditions are essential for understanding habitat availability and for applying habitat simulation models (e.g., IFIM, PHABSIM). These parameters directly influence the suitability of conditions for aquatic organisms and help link hydrological metrics with ecological needs.

Second, targeted biological assessments are needed, especially for key bioindicators such as benthic macroinvertebrates and native fish species. These organisms respond sensitively to changes in natural flow regimes and provide crucial insights into the ecological health of freshwater systems. Their presence, abundance, and community composition can guide the development of environmental flows that not only maintain, but enhance, ecosystem functioning.

Lastly, efforts should focus on studying the most representative river basins across the country. Prioritizing these areas will enable the development of reference models and ecological flow benchmarks that can be adapted to other basins with similar hydrological and ecological characteristics. This approach would also allow for the efficient allocation of resources while ensuring scientific rigor and ecological relevance in flow management strategies.

In summary, advancing environmental flow assessments requires an integrated approach that combines hydrological, hydraulic, and biological data across a representative set of river basins. Only through such efforts, sustainable water management decisions can be made that truly reflect the ecological diversity and variability of the country's freshwater systems.

8. RECOMMENDATION NEXT STEPS FOR PREPARING AN ECOLOGICAL FLOW IN GRENADA USING BIOLOGICAL ELEMENTS

The following recommendations are in line to improve the objectives of the G-CREWS project creating a climate resilient water sector in Grenada through increased freshwater availability and demand reduction measures. In order to improve the knowledge of the hydrological data available, resources and the best use of them it is important to go through a planification process taking into account the needs and the available resources to make the use of water more sustainable in a climate change context.

8.1. SHORT TERM IMPROVEMENT

Data Collection and Monitoring

- Establish and continue routine collection of meteorological data (precipitation and temperature) and continue streamflow measurements at all main river stations.
- Expand the network of monitoring stations in key tributaries (e.g., Great River and others).
- Begin annual hydrological analysis: baseflow index, peak flows, zero-flow days, seasonal patterns.
- Install low-cost staff gauges or pressure sensors near ecologically sensitive zones.
- Ensure real-time, automated monitoring equipment is installed at strategic upstream and downstream points (e.g., above and below dams).
- Improve coordination among agencies to compile precipitation, temperature, and streamflow data into a unified, accessible national database.

8.2. MID-TERM RECOMMENDATIONS (3-5 YEARS)

Biological and Ecological Assessment

- Start routine biological sampling using macroinvertebrate-based indices (e.g., IBMA).
- Inventory key aquatic biodiversity (fish, macroinvertebrates, endemic species).
- Identify critical flow periods (e.g., dry season low flows, wet season flushing flows).

Institutional and Community Engagement

- Provide initial training for WRMU, NAWASA, and NGOs on ecoflow monitoring and data collection.
- Engage local stakeholders, including farmers and community water committees, in early planning efforts.

Holistic Environmental Flow Studies

- Launch integrated assessments combining hydrology, hydraulics, biology, water quality, sediment transport, and river connectivity.
- Conduct studies to assess hydromorphological alterations and their impacts on habitat structure.

- Design long-term research programs to assess ecological and socio-economic impacts of abstraction and modified flows, e.g., in Black Bay/Concord River.

Hydrological and Modelling Tools

- Develop rainfall-runoff models specific to Grenada's wet/dry seasons.
- Apply SWAT and other hydrological tools to simulate flow variability and sediment dynamics.
- Begin modelling of non-point source pollution and sediment yield.

Database and Information Systems

- Finalize and maintain a centralized national water information system.
- Integrate hydrological, meteorological, biological, and socio-economic data.
- Begin developing water balances for priority watersheds.

Policy and Institutional Development

- Start integrating environmental flow requirements into water abstraction permits and Environmental Impact Assessments (EIAs).
- Reassess existing flow thresholds based on new data and observed ecological responses.
- Support local authorities with resources and training to coordinate ecoflow implementation and monitoring.

8.3. LONG TERM RECOMMENDATIONS (MORE THAN 5 YEARS)

Climate-Resilient Planning and Adaptation

- Use hydroclimatic scenarios (e.g., downscaled IPCC projections and Grenada's NAP) to adapt flow thresholds to future rainfall and temperature changes.
- Plan for reduced baseflows and more intense flood events.
- Develop adaptive management frameworks that revise flow thresholds every 3–5 years.

Ecological Flow Framework

- Establish a national ecoflow monitoring program, combining:
  - Continuous hydrological monitoring
  - Biological indicators (macroinvertebrates, fish)
  - Sediment and water quality data
- Apply IHA (Indicators of Hydrologic Alteration) in catchments with long-term data.
- Propose seasonally-adjusted natural flow regimes:
  - Dry season minimum baseflows
  - Wet season flushing flows (sediment transport, channel maintenance)
  - Ecological pulses (algae control, migration cues)

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Habitat-Specific Thresholds

- Identify and protect critical ecological zones:
  - Fish spawning and migration corridors
  - Benthic macroinvertebrate habitats
  - Riparian vegetation zones
- Use HEC-RAS, QGIS, and field data to simulate flow-depth-velocity relationships and set hydraulic thresholds.
- Validate these with community knowledge and local expert input.

Integration into National Planning

- Incorporate ecoflow considerations into:
  - Watershed management plans
  - Water infrastructure design
  - National adaptation and conservation strategies
- Promote multi-sectoral planning to reduce conflicts among domestic use, agriculture, tourism, and ecosystem needs.

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