UNIVERSITY OF SOUTHAMPTON

FACULY OF SOCIAL AND HUMAN SCIENCES, September 2017

GEOGRAPHY AND ENVIRONMENT

EVALUATING CURRENT WATER MANAGEMENT STRATEGIES AND SUITABILITY FOR CLIMATE ADAPTATION IN JAMAICA

By DANELLIA AITCHESON

28880188

DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS IN SUSTAINABILITY (REMOTE SENSING AND GIS).

STATEMENT OF ORIGINALITY

Except for those parts in which it is explicitly stated to the contrary, this thesis is my own work. It has not been submitted for any degree at this or any other academic or professional institution.

I agree that the thesis may be made available for reading and photocopying at the discretion of the Head of the Geography and Environment. Permission for anyone other than the author to reproduce or photocopy any part of the thesis must be obtained from the Head of School who will give his/her permission for such reproduction only to an extent which he/she considers to be fair and reasonable.

Signed...

Candidate's name: ………………………………(Block Capitals)

ACKNOWLEDGEMENT

I would like to thank God for allowing me this opportunity and for providing me with the most supportive family. I would like to extend thanks to my supervisors for their support on this research. Special thanks to Professor Justin Sheffield for his guidance and Dr. Andrew Phillips for his technical assistance. I would like to extend thanks to the National Spatial Data Management Division of Jamaica, Professor Michael Taylor and his staff at the Climate Studies Group Mona for relevant spatial data. I would also like to express my gratitude to Mr. Herbert Thomas from the Water Resources Authority who was constantly assisting me throughout this study and assisting me in contacting several government Ministries. Lastly, I would like to thank a past colleague of mine, Mr Owen Evelyn for his support and encouragement.

ABSTRACT

The objective of this paper is to evaluate the current water management strategies and suitability in Jamaica for climate change adaptation. To undertake this evaluation an analysis on the impacts of climate change projections on Jamaica's Water sector using RCP 4.5 and 8.5 scenarios for downscaled Regional Climate Model was undertaken for near-term and far-term scenarios. It was evident that climatology was directly related to the hydrologic cycle and any change in precipitation and temperature will affect mean annual runoff and streamflow in watershed management units (Wang and Hejazi, 2011). Several scenarios of climate change projections were incorporated with a water scarcity indicator to produce water scarcity index maps. Despite evaluating climate change projections in isolation or interlinked with projected socio-economic withdrawals, it was evident that if socio-economic withdrawals do not exacerbate, changes in climate will still result in reduction in water availability. However, higher levels of scarcity is associated with scenarios of both socio-economic withdrawals and climate change. Hence, the need for adaptive management of water resources is necessary to cope with future reductions in water availability. The use of Integrated Water Resources Management is the toolkit that is recommended for achieving proper water management. Although already implemented in Jamaica, gaps exist between stakeholders which hinders efficiency.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EVALUATIING CURRENT WATER MANAGEMENT STRATEGIES AND SUITABILITY FOR CLIMATE ADAPTATION IN JAMAICA

Danellia Aitcheson

1.0 CHAPTER ONE: INTRODUCTION

Water is a vital resource for human survival, health, and economic well-being worldwide. A nation's environmental stability and quality of life is dependent on the resource. A country without adequate supplies of water can experience significant social and economic consequences (Ministry of water, 1999; Vorosmarty, 2000).

Available freshwater resources globally are being threatened by climate change and worsens with additional pressures from anthropogenic changes which include rapid growing demands, land use change and urbanization (Vorosmarty, 2000). Even with global withdrawals not exceeding available water resources, it is estimated that over 2 million people currently live in areas that experience high water scarcity (Oki, 2006). This can be related to the uneven spatial distribution of water resources and changes in the hydrologic cycle as a result of its sensitivity to climatology (Wang and Hejazi, 2011). It is therefore critical for understanding behavioral patterns in climate variables to inform future changes in climate. However, it is very complex to accurately account for water scarcity as a result of challenges in accurately measuring water supply and even more difficult for determining demands. Regardless of the difficulties, water scarcity indices have been developed to undertake assessment in order to assist in improving water management (Cashman, 2014). There are many water scarcity indices. However, for sustainable management of water resources, the best practice involves an index that accounts for environmental flow requirements (Amarasignhe, 2003).
Future freshwater resources are also challenging to assess as a result of the challenges in predicting future changes in demand, use, climatology and impacts on supply at varying

locations. However, with the onset of climate change, models have been developed to predict future changes. Global Climate Models projects that sea level will rise up to 0.58 metres by 2090, there will be variability in rainfall patterns, a general reduction in precipitation by 2039 and increasing temperature trends are projected for the Caribbean (and Jamaica) (IPCC, 2008; Richards, 2008; PIOJ, 2014).

The impacts are already evident as a result of hydro meteorological hazards that have resulted in damage and losses estimated at J$113 billion (PIOJ, 2014). There has been longer droughts, variability in seasonal rainfall and groundwater quality of basins within close proximity of the coast have already been impacted by sea water intrusion resulting in loss of 100 million cubic metres of groundwater (CSGM, 2012).

The impact of climate change will directly result in reduction of water availability and negatively impact quality of life. As a result of Jamaica's geographic location, the island is vulnerable and sensitive to any change in climate. This is largely due to the importance of water to the socio-economic development and sustainability of the country (NRCA and PIOJ, 1995).The country relies heavily on water for mining, irrigation and tourism. Agriculture contributed 6.8% to gross domestic product (GDP) in 2012 (NRCA and PIOJ, 1995). With agricultural crops in Jamaica being mainly rain fed, food security is dependent on the resource. Tourism is one of the country's largest earner of foreign exchange which requires requisite standard of water for activities. It is pertinent that adaptive management is undertaken to build resilience against water scarcity. This can be achieved through water resource assessments (Oki, 2006).

Recognizing the key role of water in sustainable development, UN-Water proposal emphasizes the importance of water security focusing on universal access to safe drinking water, sanitation, water use efficiency, wastewater treatment, water-related disasters and integrated resources water management-based approach for water resources management (UNESCO-IHP, 2014).

Motivation for Research

Jamaica's temperature has shown a warming trend of 0.20 – 0.31 °C per decade which has resulted in warmer days and nights (ODPEM, 2015). The country has also experienced hydrological and climatological events that have resulted in JMD$118.67 billion in losses

(ODPEM, 2015). These events have significantly affected water resources supply, distribution and quality across Jamaica. This is expected to continue with the impacts of climate change. Living in a small island developing state such as Jamaica, where livelihood and lifestyle is directly dependent on yearly climatic cycles, it is incumbent that I undertake this study to become sensitized on the impacts of climate change on water resources and the adaptation strategies for the future. Over the last decade, Geographic Information System (GIS) has been widely used among organizations in Jamaica. The Water Resources Authority has developed a web database containing hydrological data for the country. However, even with the increase in the availability of spatial data, the organization has not incorporated the data with climate change projections to update the existing Water Resources Development MasterPlan of Jamaica. As a result of water resources being threatened, I aim to use this platform to assess spatial variability of the country's water resources, identify critical watershed management units that will be most affected by projections of climate change and to evaluate current adaptation strategies for water management in the context of a sustainable approach.

1.1 Specific aims and objectives:

1. To determine available fresh water supply in Jamaica.
2. To identify water scarce areas in Jamaica.
3. To use near-term and far-term climate change projections to analyze spatial variability in water supply, quality and water scarcity.
4. To evaluate water management strategies and suitability for climate change adaptation.

1.2 Study Area

Jamaica is an island in the Caribbean Sea located at latitude 18°15'N and longitude 77°20'W. The island's total land area is approximately 10, 991 km^2. Jamaica is estimated to be 230 km long and 80 km in width. The topography consists of a mountainous interior with its highest peak being the Blue Mountains at 2256 metres above sea level (Richards, 2008). The mountains are surrounded by coastal plains on the north and south coast. However, there are plains that exist in the interior of the islands and are associated with fertile soil that is prime for agriculture (Richards, 2008). The geology of the island varies across three rock types. They include sedimentary, metamorphic and igneous rocks. However, about 70% of Jamaica is limestone and extends the length of the country (Environment and Disaster Management Unit of the Ministry of Local Government, 2011). There are over 120 rivers and the central mountain range acts as a divide from which the drainage system flow north and south. There are 10 hydrologic basins that are further subdivided into 26 watershed management units (WRA, 2005). In Jamaica, surface water boundaries are defined by the topographic highs. However, in the karstic limestone areas of the country the boundaries may not always be precisely defined due to difficulties in determining groundwater flow directions (WRA, 2005).

Jamaica has a tropical maritime climate. The island's temperature is consistent at 27. 40 degrees Celsius all year with few fluctuations when experiencing frontal systems. Jamaica mean annual rainfall is approximately 2135 mm and is characterized by a distinct wet and dry season. May to June and September to November are the wettest months while December to March marks the driest months (Richards, 2008).

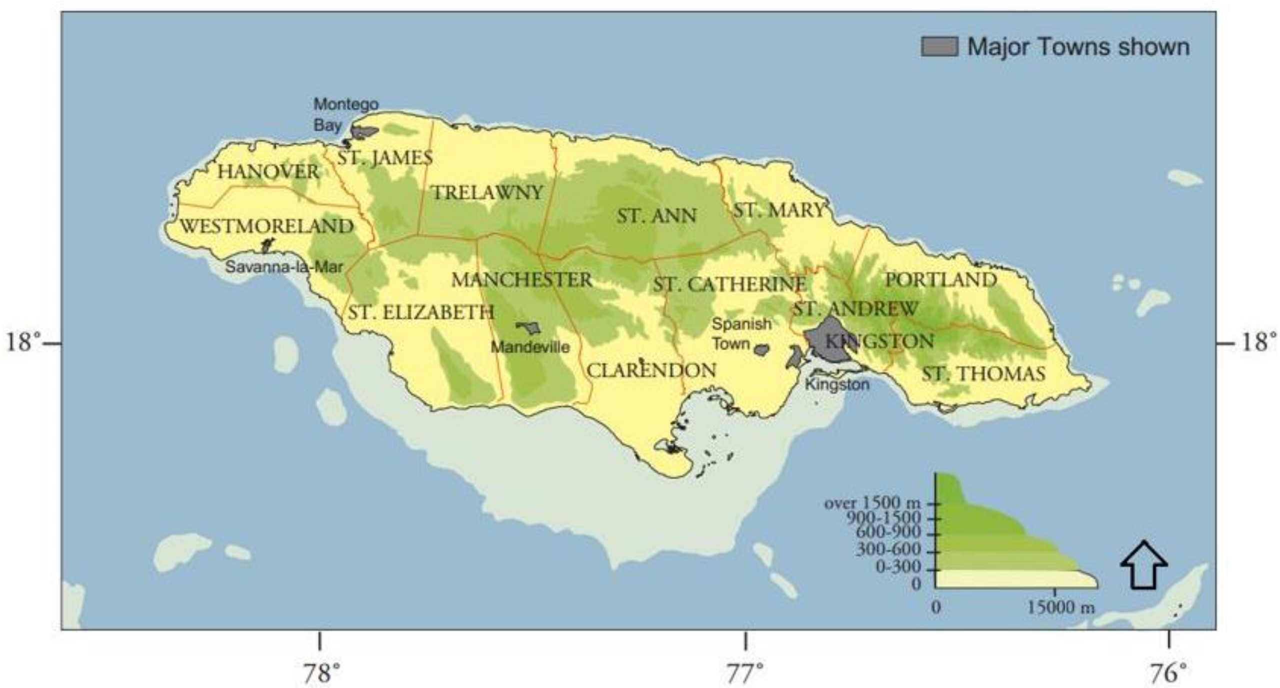


Figure 1.0: Map of study area (ODPEM, 2012).

2.0 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The literature review is structured by subtopics and explores the objectives of the research. Firstly, the term water availability and methods of deriving hydrological variables for long-term water budget are explored. The term water scarcity is then explored through various indicators paramount in determining areas that are vulnerable to water scarcity. Factors influencing water scarcity, along with in depth literature on climate change projections and implemented management strategies for coping with water scarcity are evaluated from a sustainable perspective. Literature incorporates research from regions and countries of similar geographic locations, socio-economic background and climatic conditions due to limited local publications of the topic in Jamaica.

2.2 Water Supply

Water supply refers to the amount of water available for use (Dessai and Hulme, 2007) and can be assessed through water budgeting. According to Milly (1994) availability of water includes both surface and groundwater which varies spatially and temporally. Therefore, it is crucial for assessing both surface and groundwater when determining the status of the water sector. This is usually obtained by modelling hydrological variables. Accurate water budgeting is necessary due to vulnerability of the natural resource and its importance to maintaining human society. Hence, water resources assessments are essential tools used to ensure there is sufficient water for sustaining life (Oki, 2006; UNESCO-IHP, 2014). A water balance model is most frequently used for determining long-term water budget that is necessary for understanding past climatology in order to understand and inform future predictions of the hydrological cycle (Vorosmarty, 2000; Allen and Ingram, 2017). Water availability can be determined from a range of parameters that are associated with a water balance equation. However, there are currently many different water balance models, which can assess water supply monthly, yearly and over a long term period when future climate change projections will be taken into consideration. These equations include Thornthwaite and Mather that was developed for undertaking monthly water balance models, which were recognized as most useful over wide range of soil and vegetation (Galvíncio, Moura and Sousa, 2008). Another equation suitable for monthly water budget was developed by Gleick (1987). However, this was derived to specifically support climate impact assessment and highlight benefits of using water balance type models in such capacity. A similar model was later developed by Galvíncio and Sousa at Epitácio Pessoa river basin, in Brazil and responded well to the impact of climate, vegetation, and topography of land use for runoff (Galvíncio, Moura and Sousa, 2008). It was observed that runoff had great impact on other hydrological variables such as streamflow and moisture that infiltrated the soil (Gleick, 1987). A Similar study undertaken on Epitácio Pessoa watershed in Brazil concluded that spatial variability correlates with runoff variability. However, soil depth can influence the amount of runoff available and is categorized as the most influential component in the water balance equation (Galvíncio, Moura and Sousa, 2008). On the other hand Oki (2006) determines water availability by net precipitation less evapotranspiration over land. This simple approach includes evapotranspiration flow (green water) and from water bodies (blue water) without taking soil storage as a component. However, it is argued that in order to make critical projections of water availability, freshwater storage is pertinent to adequately evaluate water availability (Taylor, 2009) and failure to incorporate storage will result in underestimates of water availability. Therefore, to determine water availability, a water balance model incorporating precipitation minus the demand (potential evapotranspiration) and water storage in the soil is recommended.

2.3 Water balance model parameters

The hydrologic cycle consists of several variables which are interlinked and are necessary for determining runoff. However, evapotranspiration (ET) is a very important component that needs to be determined despite the water balance equation used. ET is the greatest parameter after rainfall in the hydrologic cycle and is essential for determining soil water content, surface runoff, field irrigation, water balance studies and recharge of groundwater (Amarakoon, Chen and McLean, 2000). ET consists of a mixture of evaporation from soil and plant surfaces and transpiration from leaves (Harmsen et al., 2010). Minimal work have been undertaken on evapotranspiration in the tropics as actual evapotranspiration is very expensive and difficult to measure directly. Hence, the derivations of methods are frequently used for estimating ET. However, all methods that are available were developed in temperate climates and may not be applicable in some regions to accurately estimate ET (Amarakoon, Chen and McLean, 2000).

2.3.1 Estimating Evapotranspiration

There are several methods for estimating ET. However, selection of technique is highly dependent on the availability of data that is required to generate potential evapotranspiration (PET), which is later used to derive the actual evapotranspiration (ET). A frequently used method for calculating ET is a modified version of Pennman-Monteith. This method is seen as one of the most preferred, due to high sensitivity to small errors in surface temperatures (Harmsen et al., 2010). In addition, the Pennman-Motheith is observed as superior to other methods as it has been validated worldwide under diverse conditions and was specifically developed for the use of remote sensed data (Sheffield, Wood and Munoz-Arriola, 2010; Farg et al., 2012). This was justified by a study undertaken in Mexico using downscaled remote sensing data. The study demonstrated that Pennman-Monteith is the best approach for calculating evapotranspiration over the area (Sheffield, Wood and Munoz-Arriola, 2010).

2.3.2 Penman-Monteith

$$ET = \frac{\Delta R_{net} + \left(\frac{\rho c_p VPD}{r_a}\right)}{\Delta + \gamma\left(1 + \frac{r_s}{r_a} r\right)},$$

where $\Delta(Pa\ k^{-1})$ is the slope of the vapor pressure, R_{net} is the net radiation (Wm^{-2}), ρ is the density of air ($kg\ m^{-3}$), Cρ is the specific heat of air ($J\ kg^{-1}\ K^{-1}$), VPD is the vapor pressure deficit (Pa),r_a and r_s are the aerodynamic and canopy resistances ($s\ m^{-1}$), respectively.

$$PE = \frac{\Delta R_{net}}{\Delta + \gamma} + \frac{\gamma}{\Delta + \gamma} \frac{6.43(1 + 0.536u)VPD}{\lambda}$$

$$ET_{rc} = \frac{\Delta R_{net}}{\Delta + \gamma^*} + \frac{\gamma}{\Delta + \gamma^*} \frac{900uVPD}{T_a + 275}, \text{ where}$$

$$\gamma^* = \gamma(1 + 0.33u).$$

Where PE is potential evapotranspiration and ET_{rc} is reference crop evapotranspiration. u is the wind speed (ms^{-1}), γ is the latent heat of vaporization ($J\ kg^{-1}$). It is defined that the rate of evapotranspiration from an idealized grass crop of height 0.12 m, an albedo of 0.23, surface resistance of 69 $^{m-1}$ and T_a is air temperature.

On the other hand a more simplified method of the Pennman method is Priestly- Taylor equation.

$$ET_0 = \alpha \cdot \frac{\Delta \cdot (R_n - G)}{(\Delta + \gamma)}$$

α=constant 1.26 G= soil heat flux density (MJ m^{-2} day^{-1}) γ =psychrometric constant (KPa $^{o}C^{-1}$), R_n = net radiation (MJ m^{-2} day^{-1}).

It was observed that different PET models gave significantly different PET estimates. This was evident in a research for estimating PET of two forested watersheds in Southern Appalachians. The uncorrected Hamon and FAO PET methods were used and demonstrated underestimates of forest PET (L. Y. Rao et al., 2011) while Priestley-Taylor equation gave the most reasonable estimates of forest PET for both watersheds (L. Y. Rao et al., 2011). However, this method still poses a challenge in areas where data is unavailable.

An even simpler approach is the Hargreaves-samani method. This method uses less parameters and estimates are as good as the Pennman method (Harmsen et al., 2010). In addition, this simple method is recommended for estimating reference evapotranspiration considering limited climatological data (Samani, 2000). The use of temperature and solar radiation are the two essential parameters. The use of a simple equation that requires minimum parameters is beneficial in instances where there is limited data. However, this may increase uncertainties and reduce reliability in results.

2.3.2 Hargreaves-samani

$ET_o = 0.0135\ R_s\ (T + 17.8)$

Where R_s=solar radiation, T = mean air temperature.

This simple method was undertaken in Puerto Rico for estimating daily evapotranspiration of five crops and showed similar result with Pennman equation (Harmsen et al., 2010). Actual evapotranspiration was then estimated using equation:

$ET = K_c ET_0$ Where K_c= evapotranspiration crop coefficient

The Water Resources Authority (WRA) derived evapotranspiration by using Pan Evaporation. An average annual evapotranspiration was estimated using the empirical formula ET= E (Pan)*K_p*K_c, where E (Pan) is the mean annual evaporation and K_p is Pan coefficient. The results were flavourable when compared to values of Caribbean areas in close proximity (WRA, 2005). However, according to McVicar et al (2007) E(pan) is influenced by location, type of pan and climatic factors. This pose challenges for determining pan evaporation as pan stores and releases water different from crops.

On the other hand, K_c is a result of averaged crop processes and effects of evapotranspiration from soil (Allen et al., 1998.). Crop coefficient is crop and location dependent. The values mainly depend on the structure of canopies using vegetation indices through remote sensed data, which provides indirect estimates of crop coefficient (Farg et al., 2012). The use of Normalised Difference Vegetation Index (NDVI) and soil adjusted vegetation index (DAVI) have been used and tested to determine crop coefficient at large and small scales (Farg et al., 2012). Similarly, a simple linear regression was developed (K_{cNDVI}=1.457 NDVI- 0.1725) to demonstrate the relationship between NDVI and K_c from Moderate resolution satellite data and flux data measured from different crops respectively (Kamble, Irmak and Hubbard, 2013). Determining K_c values are also very time consuming and expensive. It is even more difficult for developing countries. Therefore, a standard approach of obtaining values from literature is sometimes more applicable. There is also tabulated crop coefficient values provided by FAO 56 study (Ministry of Agriculture Rural Physical Planning Division, 1989). However, a problem arises due to K_c values in the table being derived for specific locations and even bigger issue if a local crop is not listed in the literature. Associating a similar crop and applying an estimate would enhance the potential of errors. A study undertaken over the Nile Delta of Egypt demonstrated that tabulated values from FAO using five crop coefficient values were not applicable and this is an issue for other parts of the world (Farg et al., 2012).

2.4 Water scarcity

Water scarcity can be determined once water availability is determined and water withdrawals are assessed. Water scarcity has various definitions based on different perspectives which are dependent on geographic location and schemes used to assess freshwater resources. However, the simplest definition is the shortage in the availability of freshwater with respect to demand

(Taylor, 2009). Water scarcity has become a widespread issue despite the fact that water circulates in a hydrological cycle. It has been observed that more than 2 billion people in the world live in high water stressed areas. This issue of water scarcity has frequently being linked with challenges in food security, proper health and poverty, especially in developing countries (Oki, 2006; Eduke, 2009). Water scarcity is influenced by uneven distribution of renewable freshwater resources both spatially and temporally and the rate of recycling by climate system that determines how much water is available (US Army Corps, 2001; Oki, 2006). Similarly (Lawrence, Meigh and Sullivan, 2002) demonstrated that reliability or variability of the resource affects availability. In addition, this study concluded that water quality was also a significant factor influencing the availability of the resource. There can be available water to meet demands but if the adequate supplies is not of good quality it will not be available for consumption which pose great challenges for human society. Therefore, water security can be attained through having access to safe water for drinking and cooking, for irrigating crops or non-agricultural use (Lawrence, Meigh and Sullivan, 2002).

2.4.1 Water Scarcity Indicators

Water Scarcity Indicators are frequently used to determine the impact of water withdrawals on an area. However, there are complexities in assessing water scarcity attributed to difficulties in accurately accounting for renewable water supply, and annual demand. It was identified in literature where water demand was replaced by water withdrawals due to uncertainties that exist in determining demands (Brown and Matlock, 2011). Water stress can be quantitatively determined through several indices. A water scarcity index higher than 0.4 is considered to be highly water stressed (Oki, 2006, Taylor, 2009). Although this is a threshold, this shouldn't be held concrete as sufficient water may be available but cannot be used by humans, which creates a deficit in the water sector. On the other hand, water stress can be evaluated through policies or even scientific conclusions. However, it has been observed that freshwater scarcity has been frequently assessed as a function of water resources availability and population demands, which is expressed as annual per capita water. This index incorporates renewable water supply, and annual demand for water at the national scale (Ekue, 2009; Brown and Matlock, 2011). Therefore, water use would have been assigned by sectors such as agricultural, industrial, and domestic. This is a ratio that is expressed as a percentage of the amount of water drawn from the source divided by the total availability of the source.

In recent years, environmental flow requirements of river basins have been included as a sector (Amarasinghe, 2003) and a water stress Indicator (WSI) was developed to include this parameter. The total water availability is represented by mean annual runoff (MAR) and estimated environmental water requirements (EWR). The index highlights areas that are overexploited (current water use is withdrawing from EWR). This occurs when environmentally water scarce basin is $0.6 \leq WSI < 1$, ranging from severely to slightly exploit. Severity occurs when 0 to 40% of the exploitable water is available in a basin before EWR, between $0.3 \leq WSI < 0.6$ the basin is moderately exploited (40% to 70% of the utilizable water is still available in a basin before EWR are in conflict with other uses) and $WSI < 0.3$ when slightly exploited (Lawrence, Meigh and Sullivan, 2002).This research showed that when global water resources included EWR more basins show greater water stress when compared to results of other water scarcity indices (Lawrence, Meigh and Sullivan, 2002). The index of Local Relative water use and reuse is closely related to WSI indicator with the exemption of EWR. However, it is based on the sum of water withdrawals from Domestic (D), Industrial (I) and agricultural (A) sectors, which are derived by dividing water use cell by the sum of the local discharge (Q), while water reuse index takes into consideration the total water use for cell divided by the sum of local discharge (Lawrence, Meigh and Sullivan, 2002). This simply means that information can be generated at small scale.

Equation: $\frac{DIA}{Q}$

Conversely there is an index that is based on per capita usage known as Falkenmark. It is widely used to calculate water stress as a fraction of the total annual runoff available for human use (Rijsberman, 2006). In this case, water stress is categorized as no stress (> 1700m^3), stress (1000-1700 m^3), scarcity (500-1000 m^3) and absolute scarcity (<500 m^3). However, it can be argued that it doesn’t explain water scarcity but is often used because of minimal data requirement. Both Falkenmark and Gleick have both developed 1000 m^3 per capita per year as a benchmark accepted by the World Bank for determining scarcity (Taylor, 2009, Brown and Matlock, 2011). This takes into consideration individual use and allows for differentiating between climate and anthropogenic induced water scarcity. However, it does not provide adequate information at scales smaller than national scales (Brown and Matlock, 2011). In addition, Brown and Matlock (2011) determined scarcity through basic human water requirement. This measure of water availability to meet human uses is estimated at a total of 50 litres per person per day. India's total renewable water resource per person in 1995 was 2011 m^3. However, total renewable water resources per person of India excluding the Brahmaputra river basin is only 1500 m^3. From the water supply perspective this level of per capita water resources indicates that some parts of the country are experiencing some form of water stress. India's water demand at present is dominated by irrigation needs and is the primary reason of spatial inequalities of irrigation withdrawals (Amarasinghe, 2003).

The International Water Management Institute (IWMI) used a similar water scarcity assessment by conducting an analysis that includes renewable freshwater resources available for human requirements taking into account existing water infrastructure. "Physically water scarce" is an aspect that must be evaluated (Lawrence, Meigh and Sullivan, 2002; Rijsberman, 2006). Indicators of physical water scarcity include: severe environmental degradation, diminishing groundwater, and water allocations that has a bias in the different sectors. Countries having adequate renewable resources with less than 25% of water withdrawn from rivers made available for human purposes, and is hampered by old water infrastructure are considered "economically water scarce"(Lawrence, Meigh and Sullivan, 2002).

2.4.2 Water Resources and GIS

The use of GIS is practical for undertaking water scarcity as it highlights the threats and practices that are affecting water resources quality, availability and demonstrates spatial patterns. An analysis of Nigeria's water sector was undertaken due to current gaps in water management public health and threats to the environment (Merem et al., 2017). This included the use of several defined criteria in GIS. These included geospatial data of Population growth, demand and ageing infrastructure for highlighting geographic diffusion of water pollution sources and locations. Similarly, GIS using multi-criteria decision analysis (MDCA) was successfully applied for use in sustainability, water policy disputes, wastewater management, groundwater and desalination in Korea on the Nakdong River basin (Choi, Kim and Lee, 2012). This incorporated scenarios of future estimates modelling water balances. This was extremely beneficial as the use of MCDA provide alternatives and trade-offs through different information to stakeholders (Choi, Kim and Lee, 2012). The use of GIS was also recommended by Calizaya et al (2010) for integrated water resources management as results allowed water resources managers to efficiently account for ecological, social and economic criteria.

Considering that understanding the problem of water scarcity can only be addressed if the distribution of water is understood, GIS is applicable for determining spatial distribution of availability. This can be undertaken through hydrological modelling using Arc Hydro tools in GIS (Li, 2014). It provides a simple framework for estimating hydrological variables based on digital elevation model (DEM) of the terrain (Demuth, 2006). In addition, water flow and water quality models can be derived (Maidment, 2002). The application of estimating hydrologic variables in North eastern Puerto Rico, provided reliable results when simulated streams were compared to map stream network. However, the accuracy is highly dependent on the stream threshold set and quality of DEM. Hence reconditioning of the DEM is recommended for accuracy (Li, 2014).

2.5 Factors affecting water scarcity

2.5.1 Pollution

Water quality is an increasing concern that affects water shortages and is expected to result in problems for some of the world's largest companies. A survey concluded that declining water quality, increases in water prices, fines and litigation relating to pollution incidents is expected to accelerate (Gössling et al., 2012). It is projected that water resources will decline in many regions because of the pollution of water bodies and ground water source (Gössling et al., 2012). Examining at a local context, Jamaica generally has good water quality. However, degradation of quality over the years is attributed to saline intrusion and problems with pollution from bauxite mining as well as from improper sewerage disposal (Cashman, 2014; CSGM, 2012). In addition to these factors, pollution through governance and infrastructure contribute to pollution (Mejia, 2014). In a case study conducted on the Liguanea aquifer in the Kingston Jamaica, contamination of groundwater makes the resource unusable and requires expensive treatment if used (Cashman, 2014). Water demand is among the highest in Kingston and the implications of polluted aquifer puts pressure on an already water stressed area, especially during dry periods.

2.5.2 Population and Urbanization

Distribution of population, urbanization and rising standards of living are three impacting drivers which affect water security (UN, 2012, Cashman, 2014,). These factors were also identified in a case study by Merem et al (2017). On the other hand, Mejia (2014) associated urbanization and poor governance as the two main driving forces while Taylor (2009) conclude that population growth and climate change has shaped the relationship between availability and demand all over the world. The distribution of the population and density relative to availability is important to assess. In a case where there is water surplus for population but poor governance, water may not be accessible due to lack of planned and implemented infrastructure to deliver water especially in areas that are a product of urban sprawl.

Caribbean countries are associated with population growth rates of 1% per year or less. The rate of urbanization is also increasing, with 65% of the region's population living in urban areas. It can be noted that most urbanization has taken place around the coast or within 2km of the coast (Cashman, 2014). Similarly, urbanization and population growth are widespread in Nigeria, with urban areas in 2015 accounting for 60% of the population (Merem et al., 2017), which is twice the population of 1990. Lagos its largest city, has water deficit of approximately 300 million gallons per day which is attributed to a high population annual growth rate (Merem et al., 2017). The result of high population growth spirals into the changes of land use, especially areas that are deforested to accommodate population growth (Ekwue, 2009) which in turn have significant impacts on watersheds that regulate water quality and quantity.

2.5.3 Irrigation

Agriculture is responsible for 70% withdrawal of global water and with the growing population it is anticipated that this will increase in order to fill the demand of the increase in food production for the population (Ekwue, 2009; Gössling et al., 2012; UN, 2012). Crop can either be irrigated or rainfed. Irrigated crop production requires great volumes of water which is limited in some Caribbean islands due to inadequate capture and storage in reservoirs, groundwater aquifers and surface reservoirs (Ekwue, 2009). Water scarcity is exacerbated in densely populated arid areas of Central and West Asia, and North Africa that capture and use water for mainly food production (Rijsberman, 2006). However, in other parts of the world including the Caribbean, water that is captured and stored is for domestic and industrial uses and not irrigation. Caribbean islands reserve water for public water supply (Ekwue, 2009). Hence, Caribbean islands face great challenges in meeting irrigation demands during dry season (Ekwue, 2009; Gössling et al., 2012).This can be seen in Jamaica, where irrigation for agriculture is the largest water consuming activity with a demand of 33% in 2005 and is projected to increase in demand to 39% by 2025 (WRA, 2005). In order to overcome water challenges and scarcity improved irrigation methods are required.

2.5.4 Economic development

Tourism is a large consumers of water with visitors consuming up to three times as much as the local population (Cashman, 2014). Although studies undertaken by (Gössling et al., 2012) disagrees with this as results demonstrated that international tourism usually accounts for less than 1% of national water use. However, it is suggested that national scale discussions of water security should not be overlooked (Gössling et al., 2012). Therefore, islands that expect high tourist arrivals and currently water stressed are at a higher chance of increased water scarcity. Water supply is expected to be a constraining factor for economic activity and serious health concern (UNEP, 2008). Although the industrial sector only uses about 20% of global freshwater, industrial water use is rising and industries will increasingly be competing for limited water resources with growing urban and agricultural water demands (UN, 2012). Current unsustainable patterns of development and production are resulting in overexploitation of aquifers, watersheds and environmental degradation.

2.5.5 Climate change impact on freshwater resources

According to the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, vulnerable Caribbean islands are likely to experience accelerated water stress as a result of climate change (Mejia, 2014). Some of the changes expected include sea level rise between 5 to 10 mm per year, rise in temperature, changes in rainfall pattern, increase hurricane activities and intensified extreme rainfall events that will affect infrastructure and in turn result in economically water scarce areas (Lawrence, Meigh and Sullivan, 2002; Cashman, 2014).

Climate change can be defined as changes in global mean surface-air temperature that are caused by increased atmospheric concentrations of greenhouse gases relative to post-industrial revolution (Loáiciga, 2003). It is a major future trend that is accompanied by uncertainties that affect both water supply and demand. The hydrological cycle is sensitive to any changes which will affect supply and variability which in turn will affect reliability of water supply (Kiefer et al., 2013). Hence, accelerated climate changes is expected to also increase demands. Therefore the climate components, groundwater levels, water quality and runoff should be examined spatially (Loáiciga, 2003).

Climate varies spatially based on elevation and size of land mass. Temperatures are strongly correlated with elevation and varies along coastal areas between 32 °C to 24 °C. However, based on increasing elevation, temperatures can drop to 10 °C (Cashman, 2014). Throughout the Caribbean region there is a dry season and a wet summer season that influences seasonal supply of water (CSGM, 2012). Precipitation also varies between islands on the windward and leeward side. Hence it is practical to conclude that water resources vary spatially due to climate, geology and topography (Cashman, 2014).

Climate modelling projects greater warming for northwest Caribbean than in the eastern Caribbean islands during the summer. On the other hand, annual precipitation is projected to lessen between 10%–30% by 2080, especially during the wet season (Cashman, 2014). This significant reduction in wet season rainfall across the Caribbean will put a strain on water resources quantity and quality. If climate change results in hotter and drier weather in the future, demand for water will increase (Kiefer et al., 2013). This is particularly disastrous in countries that already have gaps between water supply and demand. Trinidad has had a water supply deficit since 2000, Jamaica is projected to experience deficits in supplies to areas of important economic activity by 2015 (Cashman, 2014), Antigua and Barbuda are dependent on desalination to meet their demands for water, and Barbados is currently using 100% of its available water resources (Cashman, 2014).

Water quality is also vulnerable to climate change. It is predicted that there will be an increase in category 4 and 5 hurricanes that is already impacting water infrastructure through resource availability. Increase landslides from intense rainfall will compromise storage reservoir integrity, damage pipelines and boreholes from sediments and debris (UNEP, 2008, Cashman, 2014).

Sediments, debris and pesticides from farmlands washed down during heavy showers will require more treatment for water to be consumptive (Mejia, 2014).

The Bahamas, Barbados and Jamaica rely heavily on groundwater resources. In Barbados, 90% of the supply is from groundwater and 84% in Jamaica (Cashman, 2014). Groundwater storage and recharge mechanisms are affected by in intra-seasonal rainfall. Although water is abundant in the Caribbean, 49.3% of stream flow takes place between August and October and only 7.3% from February to April (Mejia, 2014). However, prolonged periods of low rainfall, over exploited abstraction levels have resulted in saline intrusion of coastal aquifers (UNEP, 2008).

2.6 Climate Change projections

Climate prediction is a forecast of future climate system which includes both forced and internal parameters. This is made possible through climate projections, which is a model that forecast the future using a scenario of future external forcing (Campbell et al., 2010; Stephenson et al., 2014). Hence, the importance of climate models as tools for understanding quantitative estimates for future change (CSGM, 2012). These models have become increasingly important, especially over the Caribbean as a result of SIDS being most vulnerable to climate change. This has resulted in many international organizations promoting significant reduction in greenhouse gases to limit temperature rises to less than 2^{o}C by the end of the century. Types of models that contain and relate weather and climate indicators to water use, are therefore relevant for evaluating the potential effects of climate change (Kiefer et al., 2013).

The Special Report on Emissions Scenarios (SRES) scenarios are representations of future emissions of greenhouse gases based on assumptions of demographics, socio–economic development and technological changes (Campbell et al., 2010). For the IPCC fifth Assessment Report a set of four scenarios known as the Representative Concentration Pathways (RCPs) were defined replacing the SRES. The RCPs are defined by their total radiative forcing for 2100 with respect to 1750 .The RCPs are RCP2.6, which is a mitigation scenario leading to a very low forcing level, RCP4.5 and RCP6 are two stabilization scenarios and the last is RCP8.5. This scenario represents very high greenhouse gas emissions due to business as usual with no mitigations (IPCC, 2013). When these new scenarios are compared to the SRES, values are generally lower as the SRES did not take into account air quality legislation and other mitigations (IPCC, 2013).

IPCC projections are used for Global Climate models (GCM), which have very low resolution and are not detailed enough to be applicable for smaller regions or a country. Hence, for more accurate and detailed projections models are downscaled (Environmental Solutions Limited, 2009). These models for the region derived projections through the application of different scenarios relative to a bench mark of historic data and was compared with those from historic climate simulations (Loáiciga, 2003). In addition to this methods for assessing climate change, the use of historical climate time series with climate scaling factors have been used. This can be undertaken by multiplying a historical time series by the corresponding scaling factor for precipitation and difference for temperature using delta change (Hay, Wilby and Leavesley, 2000; Loáiciga, 2003). Although GCM may not be accurately estimated, internal consistency provides adequate estimates. It can also be argued that climate change forcing may change greatly from historical pattern. Therefore it is more plausible to undertake near term assessment.

2.6.1 Rainfall

The general climate of the Caribbean has bimodal seasonal rainfall patterns. This results into two dry and wet seasons with rainfall pattern occurring early (April-July) and late (August-November) (Environmental Solutions Limited, 2009; ODPEM, 2012). Jamaica's location with respect to tropical storm paths, surges along the coastline, geology and topography have great impact on rainfall runoff, streamflow and basin flooding. Jamaica's rainfall pattern is impacted by North Atlantic high pressure, sea surface temperature, easterly waves and trade winds (Environmental Solutions Limited, 2009). On the other hand, it is said that Rainfall and sea level are influenced by ENSO also known as El Nino or Southern Oscillation (Lal, Harasawa and Takahashi, 2002). From studies undertaken in Jamaica it can be observed that most rainfall occurs in the parish of Portland and early rainfall peaks occur in May or June and in October for the late season over the island while the dry seasons are November-April (Campbell et al., 2010; CSGM, 2012). Although there is no statistically significant trend in Jamaica's mean rainfall due to the inter-annual variability of rainfall pattern. This then poses a problem for the island when climate changes may introduce more variability.

GCM project that there will be increase and also decrease with the latter being more by 2100(Campbell et al., 2010). However, by the middle of the century there will be significant changes in precipitation which will range from -44% to +18% by 2050s and -55% to +18% in the wet season (June-November) with inter-annual variability. It is also expected that there will be drier dry periods (Environmental Solutions Limited, 2009; CSGM, 2012).

Providing Regional Climates for Impact Studies (PRECIS) projection demonstrated moderate reduction in rainfall in March to May and June to August with only -14% change in annual rainfall. However, this was quite different for the Hadley Centre Coupled Climate Model version 3 (HadCM3) where there was a significant reduction in rainfall of -41% in the wet season, with September to November drying out the most over the entire island (Lal, Harasawa and Takahashi, 2002). It is predicted that during the 2020s with A1 scenario it will be wetter but almost all stations decrease precipitation by 2050s and 2080s using A2 and B2 scenario (Environmental Solutions Limited, 2009). This model projections are in agreement with GCM projections. The Hadley Centre regional climate model simulates both rainfall and temperature very well by capturing the bimodality of rainfall and temperatures across the Caribbean. Although represented reasonably well there are some underestimations of rainfall amounts over the northern Caribbean and overestimation of temperatures (Campbell et al., 2010). Conversely, studies undertaken by the Environmental Solutions Limited (2009) shows that decrease in precipitation will begin by 2030s. Although rainfall is projected to decline there will be an increase in rainfall intensity. It was observed that heavy rainfall events have already been increasing in the last quarter century in Cuba (Lal, Harasawa and Takahashi, 2002; Stephenson et al., 2014).

2.6.2 Temperature

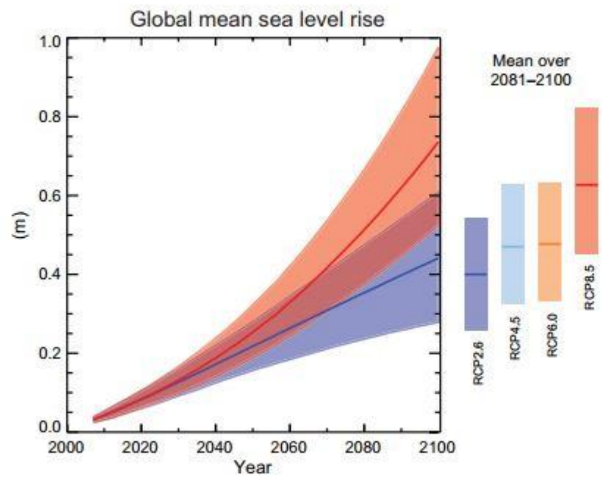
The PRECIS model shows that the peak in Caribbean temperatures occurs in August–September, meanwhile South Caribbean have warmer temperatures in in November- April. The larger Caribbean islands such as Cuba, Jamaica and Hispaniola, expect the greatest warming (Campbell et al., 2010). According to the projections of the GCM there will be a 2-3^{o}C increase in temperature by 2080s for Jamaica, showing that it warms faster in southern parishes and having greatest warming during the months of June-August. Although all the downscaled regional models also shows a warming trend during the said months (Campbell et al., 2010) the temperature is projected to be higher (2.9°C-3.4°C) by 2080's. Even though all models agree with the increase in temperature it must be noted that the increase will be dependent on the scenarios. The Caribbean has already started to experience statistically significant trend of warming, especially during the summer period (Stephenson et al., 2014). This increase in temperature is expected to increase evaporation, which impacts runoff that will be available.

RCPs	Projected Temp °C
RCP2.6	0.3 - 1.7
RCP4.5	1.1 - 2.6
RCP6	1.4 -3.1
RCP8.5	2.6 - 4.8

Table 1: CMIP5 simulations for 2081- 2100 (IPCC, 2013).

2.6.3 Sea level Rise

Sea level is strongly positively correlated to increase severity of hurricanes. Projections have been estimated at a maximum of 1.4 m with increase in potential storm surges elevations (MEGJC, 2017). There has been regional projections for sea level but much attention has not being given to these projections due to greater level of uncertainties that are associated with local simulations compared to global projections (Bates et al., 2008).



Source (IPCC, 2013)

Figure 2.0: Projections of global mean sea level rise over the 21st century relative to 1986–2005.

The increase in sea level is expected to negatively impact water quality. Ground water aquifers, especially those close to the coast will be contaminated through saline intrusion. Treating brackish water will have to be undertaken before consumptive use.

2.7 Defining adaptation and Suitability

All SIDS have acknowledged the need for adaptation actions and finances to build resilience for climate change as countries in the developing world are most exposed to the worst impacts and are least capable of dealing with the risks (Bates et al., 2008). This conclusion was based on scenario impact research of climate change, which saw the urgency for sustainable adaptation options. The Intergovernmental Panel on Climate Change (2001) defines adaptation as “An adjustment in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects or impacts” (Dessai and Hulme, 2007). Adaptations are governed by regulatory structures, property rights and rules in society to meet set goals and are undertaken through actions of stakeholders. As a result of the uncertainties that exist in the potential climate impacts in the water sector, resilience through adaptation cannot be dealt with in isolation (Neil Adger, Arnell and Tompkins, 2005; Dessai and Hulme, 2007; Bates et al., 2008). Adaptation goals can be met by building adaptive capacity and implementing adaptation decisions (Neil Adger, Arnell and Tompkins, 2005). Building adaptive capacity will require integration of the three arms of sustainable development through effective communication to ensure adaptation does not increase vulnerability to climate change stress. However, the challenge exist in obtaining adaptation at national scale that aligns with international agreement and meeting sustainable development goals. This requires research on collective action for decision making, funding to develop national adaptation plans, policy, and analogue approach which includes detailed case studies of past or present response to climate variability in regions with similar climate conditions. These existing coping strategies may then be built on or new innovations with technologies may be introduced (Adger et al., 2003).

Scales of adaptation should also be considered and are important at different levels based on technologies, regulatory systems and knowledge of future climate (Neil Adger, Arnell and Tompkins, 2005). However, appropriateness, which refers to suitability must be considered (Biswas, 2008). Where adaptation is needed, success is dependent on how actions meet criteria of set goals and suitability.

2.8. Water Management for Climate Adaptation

The main objectives of water management is to improve standard and quality of life of people, reduce poverty regionally and ensure equitable income distribution and environmental conservation (Biswas, 2008). However, with the current pressures of climate change on the water sector adaptive water management strategies are require and some steps towards adaptive management have been undertaken. In 2010, a consortium for Common Water Framework for the Community was held to facilitate the assessment of national water resources, identify priority issues, build up capacity, and update water legislation to assist member states with developing and implementing their plans (Global Water Partnership, 2014). Similarly, another meeting with the UN Framework Convention on Climate Change focused on adaptation to climate change through management. However, policy was the primary focus (Adger et al., 2003) while Global Water Partnership (2014) focused on Integrated Water Resources Management (IWRM).

2.8.1 Policy and Institutional roles

In many countries there is a commitment to adaptation, regardless of scenarios and Jamaica is no different. The Jamaica 2030 National development plan outlines the national vision for the country by 2030 through national goals, of which the water sector policy will aid. Strategies to conserve natural environment and its water resources, in the face of the global challenge of climate change are outlined (MEGJC, 2014). Policies provide a set of guidelines for institutions and Jamaica's water sector has undergone immense organizational change when a draft water policy was created. The policy was adopted in 2000 and revised in 2004(Global Water Partnership, 2014). The water sector policy focuses on the IWRM approach, climate change initiatives, activities to ensure that Jamaica's water resources are effectively managed for social, economic and environmental well-being now and in the future.This requires the input of entities that are regulators, service providers with policy and activities. The National Water Commission (NWC) is the service provider of pipped water supply and piped sewage in all major towns, National Environment and Planning Agency (NEPA) is responsible for coordinating IWRM committees (MEGJC, 2017) while Water Resources Authority (WRA) is responsible for management, protection and allocation of Jamaica's water resources (Wra.gov.jm, 2017).

2.8.2 Integrated water Resources Management (IWRM)

At the World Summit for Sustainable Development in 2002 IWRM was identified at the international level as the framework that should be utilized to manage water sector. This is seen as a cross-sectoral integration process to specific geographic, historical, cultural, social and economic conditions. The only drawback identified is that IWRM is a political process and will require solving conflict of interests at many different levels (Global Water Partnership, 2014). IWRM is seen as a toolkit for providing guidance and advice to decision makers and water managers on how to access impacts of climate change on water quality and quantity in order to implement suitable strategies. Implementation in Jamaica through environmental management and best practices in small hotels for efficiency in water use and to protect both coastal and freshwater resources. This was successful as 41.4 million imperial gallons, energy and chemical use were reduced making Jamaica a leader is sustainable tourism (Suchorski, 2007). Although IWRM is becoming increasingly popular, according to Biswas (2008) it is not a new management instrument and results of its application in a real world to improve policy, programmes and projects have not always been as successful. It was not a universal solution in the past and is believed that it will not be for the future either. However, if there is likely success of IWRM it will be at small scale (Biswas, 2008).

3.0 CHAPTER THREE: METHODOLOGY

3.1 Introduction

This research utilized mixed methodology of quantitative and qualitative approaches to enhance reliability, as this framework frequently results in superior research (Johnson and Onwuegbuzie, 2004). The predominant methodology employed for this research involved the use of GIS software for spatial analysis. This chapter provides an overview of the application of GIS for undertaking a water balance equation using mean annual inputs based on 30 years of historic data. The water balance parameters were first derived using temperature, solar radiation and crop coefficient data for evapotranspiration which was incorporated with preprocessed precipitation data. This resulted in depth of mean annual run-off that consisted of streamflow over land and ground water infiltrated into the soil. To illustrate spatio-temporal distribution of freshwater, Arc Hydro tools were used. Arc Hydro is based on digital elevation model (DEM) and was interlinked with observed streamflow to estimate the component of groundwater recharge. Water scarcity index for watershed management units were developed using historic socioeconomic withdrawals, environmental flow demands and mean annual run-off from the water balance equation. The same approach was applied for projected water scarcity using near-term socioeconomic and RCPs 4.5 and 8.5 for near term and end of the century climate change projections for downscaled Hadley Centre Global Environment Model (HADGEM). The results will identify areas ranging from very low to extreme water stress in the future and will be used to evaluate water management strategies and suitability for adaptation in hotspots. Data collection and statistical analysis followed.

3.2 Data collection

This research used both secondary and primary data. Secondary data were obtained from several sources (see appendix A). This was used to inform spatial and statistical analysis. Other secondary data include Government documents, Water Resources Authority publications and published literature. Spatial analysis was undertaken to visualise the distribution of water supply in Jamaica and water management units' water scarcity levels.

3.3 Spatial Analysis for Water balance

A thirty year period (1970- 2000) of high spatial resolution ($1km^2$) average monthly rainfall, solar radiation and mean air temperature global datasets were obtained from WorldClim (2017). The use of global data reanalyzed for hydrological applications have been frequently used and proven to give satisfactory results (Daggupati et al., 2017). Observed rainfall and temperature data were also provided by Met office of Jamaica but as a result of immense missing data at rain gauge stations and no record of temperatures before 1992, this data was only used for identifying trends (see figure 3.0). As a result of the variability associated with rainfall in Jamaica, the period of available data determined the data used to model long- term water budget. It was relevant to model sustained long-term climate behaviour of the past in order to inform future predictions and improve uncertainties (Allen and Ingram, 2017). ArcMap 10.5 (ESRI, 2017) was used to extract data for Jamaica and to undertake spatial analysis.

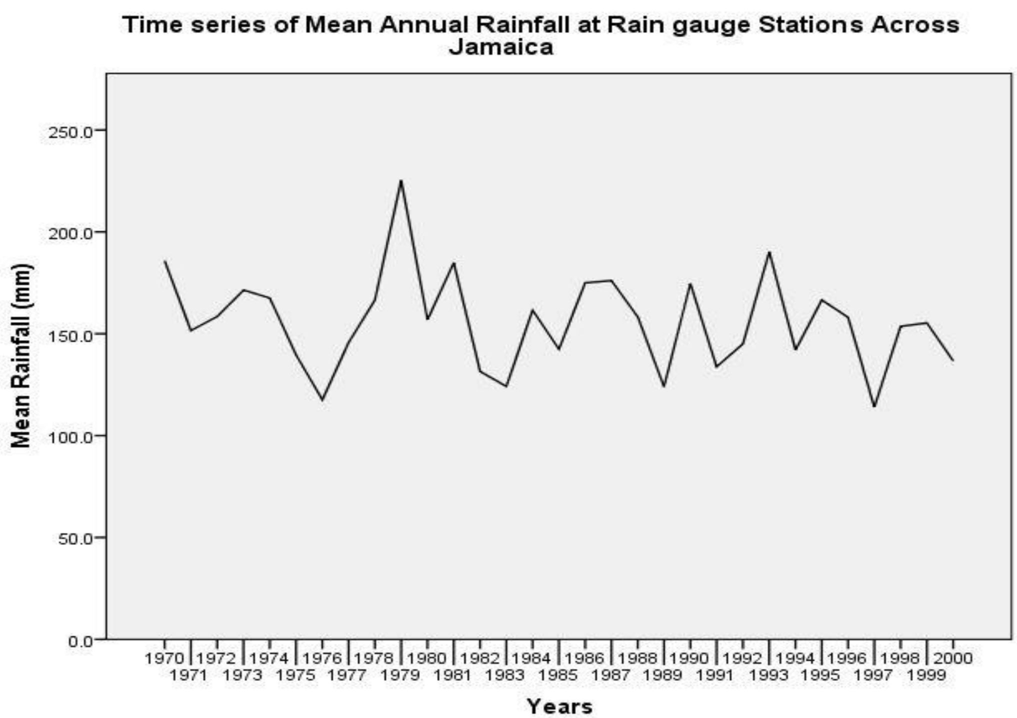


Figure 3.0: Observed rainfall data from 1970 – 2000.

In ArcMap 10.5, extracted precipitation, solar radiation and mean air temperature data for the 12 months of the year were used to create mean annual layers using raster calculator. Preprocessed layers were then used to generate parameters in the water balance equation:

Precipitation – Evapotranspiration = Streamflow + groundwater recharge (1)

To determine evapotranspiration, potential evapotranspiration was first derived using Hagreaves-samani method. This equation was most applicable due to limited data requirement while giving equally superior results as the recommended Pennman –Montieth method that requires more data. This showed superior results when undertaken in Puerto Rico (Harmsen et al., 2010). An island of similar geographic location, topography and climatic conditions as Jamaica. Potential evapotranspiration (PET) was determined using equation (2):

PET = 0.0135 R_s (T +17.8), where R_s= average annual solar radiation (J/m^2), T = average annual mean air temperature (^oC).

Actual evapotranspiration (ET) parameter was then derived using results of PET in equation (3):

ET= K_c * PET, where (K_c) is Crop coefficient.

A K_c of 0.8 was used in a Pan Approach for estimating evapotranspiration in Jamaica, which provided satisfactory results (WRA, 2005). Pan method was not applicable for this research due to inaccessibility of data and the challenges in understanding how pan stores and releases water. However, the 0.8 value previously used was adopted in equation 3 for estimating ET. Applying a single value as crop coefficient is not usually ideal as K_c differs by seasons and crop water use based on crop type (McKenney and Rosenberg, 1993). Using a single value of 0.8 may introduce some errors, overestimating and underestimating in some areas. Using rater calculator, result from equation 3 was substituted into equation 1 to generate spatial representation of mean annual runoff.

3.3.1 Arc Hydro for hydrological Variables

Mean annual runoff also referred to as effective rainfall consists of streamflow and groundwater recharge (WRA, 2005). To show spatial distribution of freshwater, Arc Hydro tool which utilizes DEM to simulate watershed catchments and streamflow (Maidment, 2002) was used. A Similar approach to Demuth (2006) was applied. This simple framework for estimating hydrological variables was most plausible considering limited time and data availability. The workflow can be seen in figure 3.

Jamaica's DEM and observed mean annual streamflow for period 1970- 2000 from stream gauging stations located near the outlet of rivers were incorporated. The pre-processing of the terrain using Fill and Dem reconditioning was undertaken to ensure consistency in elevation and between input stream networks and delineated stream networks. The process also required a threshold for stream definition that was set to 500 cells. This threshold was selected to account for most of the flow accumulation and aimed to derive the highest resolution stream network. The batch points created using streamflow data were adjusted using snap pour point to ensure points were sufficiently close to a drainage line in order to undertake batch watershed delineation upstream the stream gauge. This resulted in delineated watersheds for each stream gauge and was used to convert stream flow into depths within each catchment.

Arc Hydro estimates surface water variables using topography, with ideal landscape having well-defined drainage network and absence of influent streams. Landscape that is forested, of higher elevation and minimal anthropogenic changes tend to produce accurate results (Maidment, 2002). Jamaica's geology differs across the island and influences the landscape and drainage patterns (ODPEM, 2012). Northwest and central Jamaica is influenced by karstic features of the cockpit country and result in several streams disappearing underground. In these areas, Arc Hydro is unable to accurately estimate hydrological variables. Therefore, in WMUs of discontinued, insufficient streamflow observations and Karstic features, the tool was not used. Zonal statistics tool was then used to evaluate between depths of streamflow and previously estimated depths of mean annual runoff within each watershed. The ground water recharge was not derived due to complex geology in many watersheds where groundwater is difficult to separate from streamflow and require site visits.

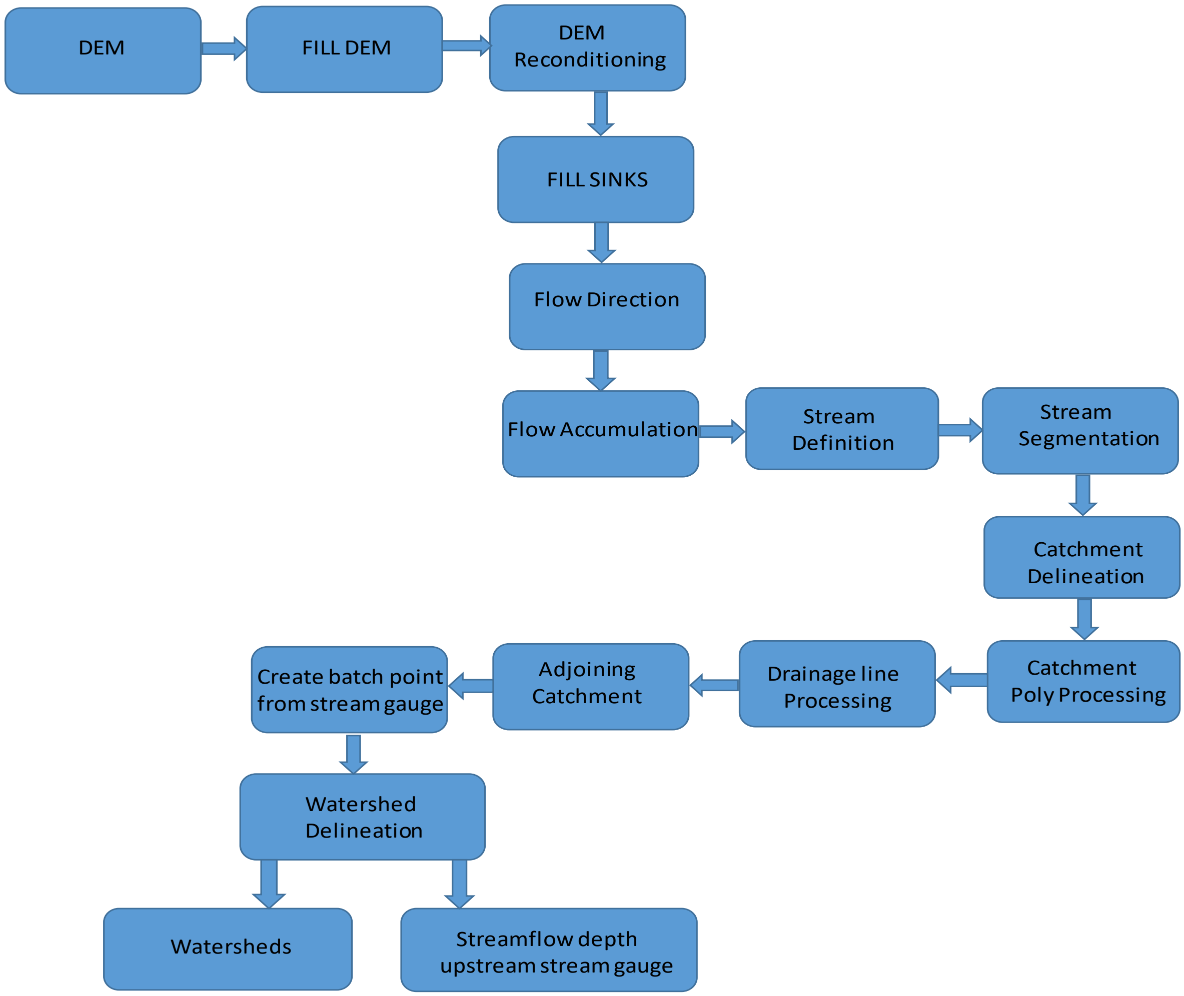


Figure 4: Workflow for determining hydrological variables using Arc Hydro tool.

3.4. Spatial Analysis for Water Scarcity

In this study water scarcity is defined as the excess of water withdrawals over available supply (Lawrence, Meigh and Sullivan 2002; Smakhtin et al 2004). This research focused on the impacts of physical climate change and withdrawal by sectors on water supply by 2030s (2028-2038). Physical climate changes for 2080s were also assessed. However, more focus was placed on 2030s to evaluate Jamaica's 2030 Vision for the Water Sector based on results. In addition, it is more plausible to focus on near-term due to uncertainties associated with physical climate and climate models.

A water scarcity indicator (WSI) was used to derive current and projected water scarcity index. This assessment is critical for adaptation, which can be achieved through water management. The current water scarcity indicator is first derived using similar approach to (Smakhtin et al 2004).

$$WSI = \frac{Withdrawals}{MAR-EWR}$$

The water scarcity indicator considers domestic, industrial, agricultural withdrawals and environmental flow requirements as a proportion of water supply (Lawrence, Meigh and Sullivan 2002; Smakhtin et al 2004). Food and Agriculture Organization of the United Nations (FAO) has indicated that environmental water reserve (EWR) should be accounted for in order to achieve sustainable development goal monitoring. Hence, this approach was used instead of traditional methods. To ensure available and sustainable management of water and sanitation for all (Johnston 2015) EWR was accounted for.

3.4.1 Data preprocessing and analysis for Current Water Scarcity Index

Mean annual run-off (MAR) data generated from the water balance equation was used to represent the water available in Jamaica. MAR was adjusted in areas where ET exceeded precipitation. The con tool was utilized to eliminate values less than zero which may have occurred due to errors in deriving MAR through empirical equations. MAR was also used to estimate environmental flows. EWR can be represented as a portion of long term MAR (Smakhtin et al 2004). WRA (2005) indicated that environmental flow demands fall within ranges 20-60% of annual flow. However, 39 percent was allocated in 2005 as a national estimate by the WRA of Jamaica. The national estimate was used due to unavailability of EWR data for each WMUs. Agricultural withdrawal was estimated using irrigation data, population density for domestic withdrawal and the country's GDP for industrial withdrawal were used as proxies (Fan et al., 2016) for socio-economic withdrawals. Population density data was rasterized using conversion tools while irrigation was converted using the fishnet tool in order to accurately represent average irrigation per unit area within each WMU. Both datasets were rasterized and resampled to the same spatial resolution as the other raster datasets ($1km^2$).

Water scarcity assessment used weighted sum multi-criteria evaluation approach to determine the status of water quantity in terms of a water scarcity index. This included total withdrawal by sectors and mean annual runoff ranked into five categories using analytical hierarchy process (Hill et al., 2005). The categories 1 to 5 were used to represent very low to extreme water scarcity. Datasets of population density, irrigation, GDP, EWR and MAR were reclassified into five classes using natural breaks (Jenks). This was used to group similar values in the data to optimise differences between each class (Esri, 2017). A MCDA of Reclassified withdrawals was conducted. In spatial analyst the weighted sum tool was used to derive total withdrawals. The weights assigned were reflective of FAO (2017) water withdrawals estimates and estimates of water demands by sector from (WRA, 2005). Weights assigned for each withdrawal sector can be seen in figure 5. The Water Scarcity index values 0 to 5 represented WMUs of no scarcity to extreme water scarcity. The model used for undertaking WSI can be seen in figure 6.

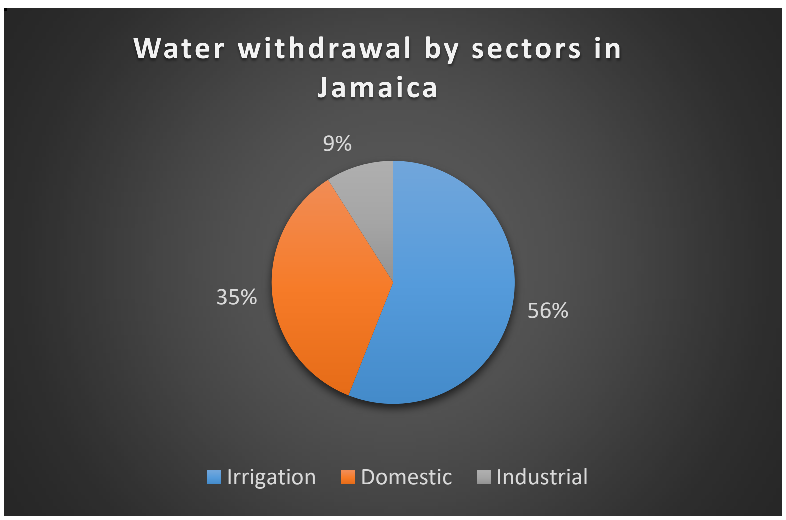


Figure 5: Weights assigned for WSI

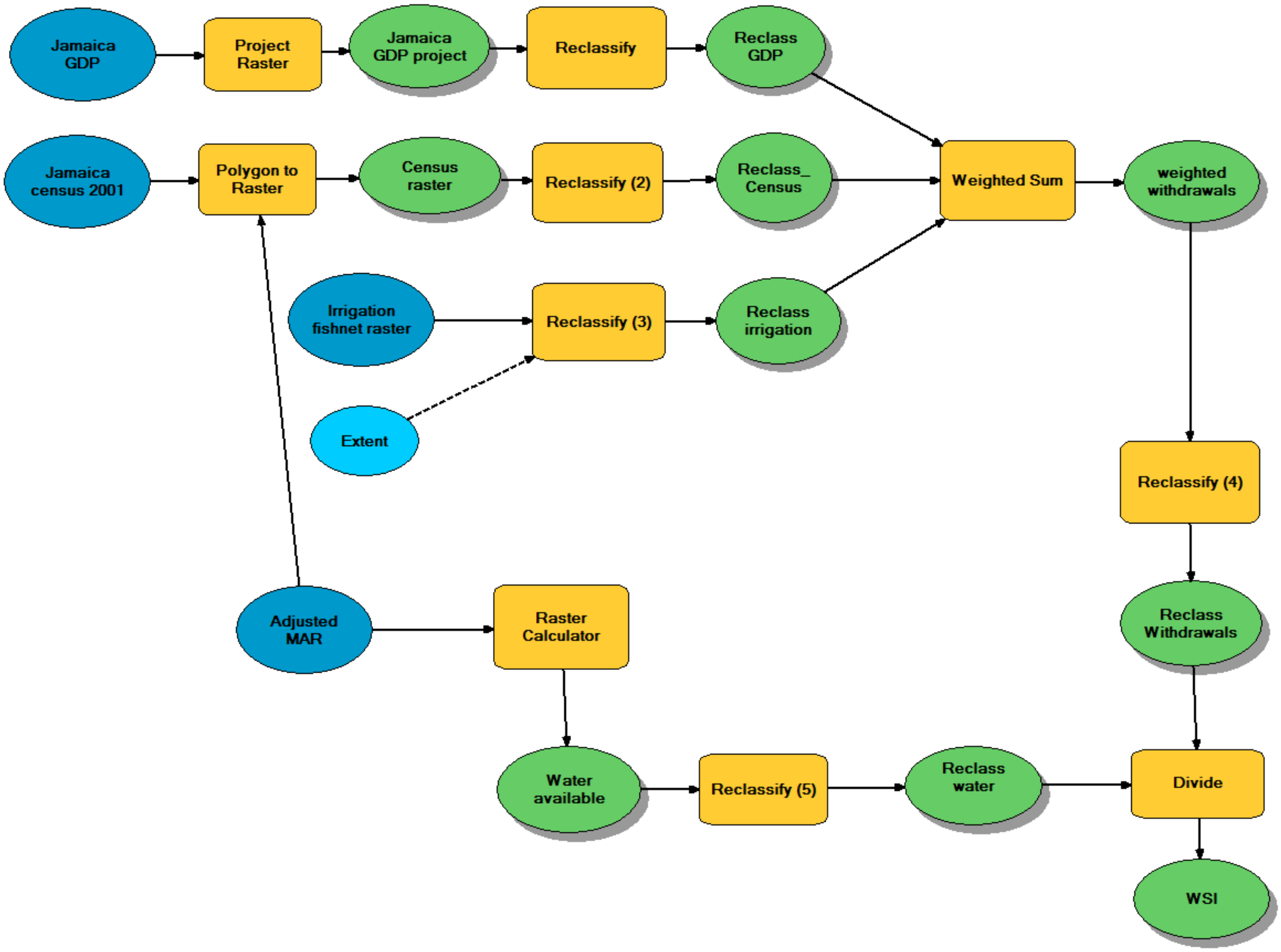


Figure 6: Water scarcity indicator model

3.4.2 Data preprocessing and analysis for future Water Scarcity Index

To develop a water scarcity index for the future the same approach by (Smakhtin et al 2004) was used. The current withdrawals by sector and water available were replaced with future projections. As a result of limited downscaled GCM models for the new RCP scenarios of climate variables for Jamaica, only one model was evaluated. The model from figure 3.3 was utilized, incorporating projected withdrawal by sectors for 2030 using estimates from FAO (2017), PIOJ (2017) and physical climate changes obtained from Climate Studies Group Mona (CSGM) relative to baseline 1970- 1999. The monthly physical climate changes in NetCDF format downscaled with 12 grids over Jamaica. These were converted to mean annual raster datasets using spatial analyst tools to show the spatial distribution of the future changes over the island (see figure 3.4).

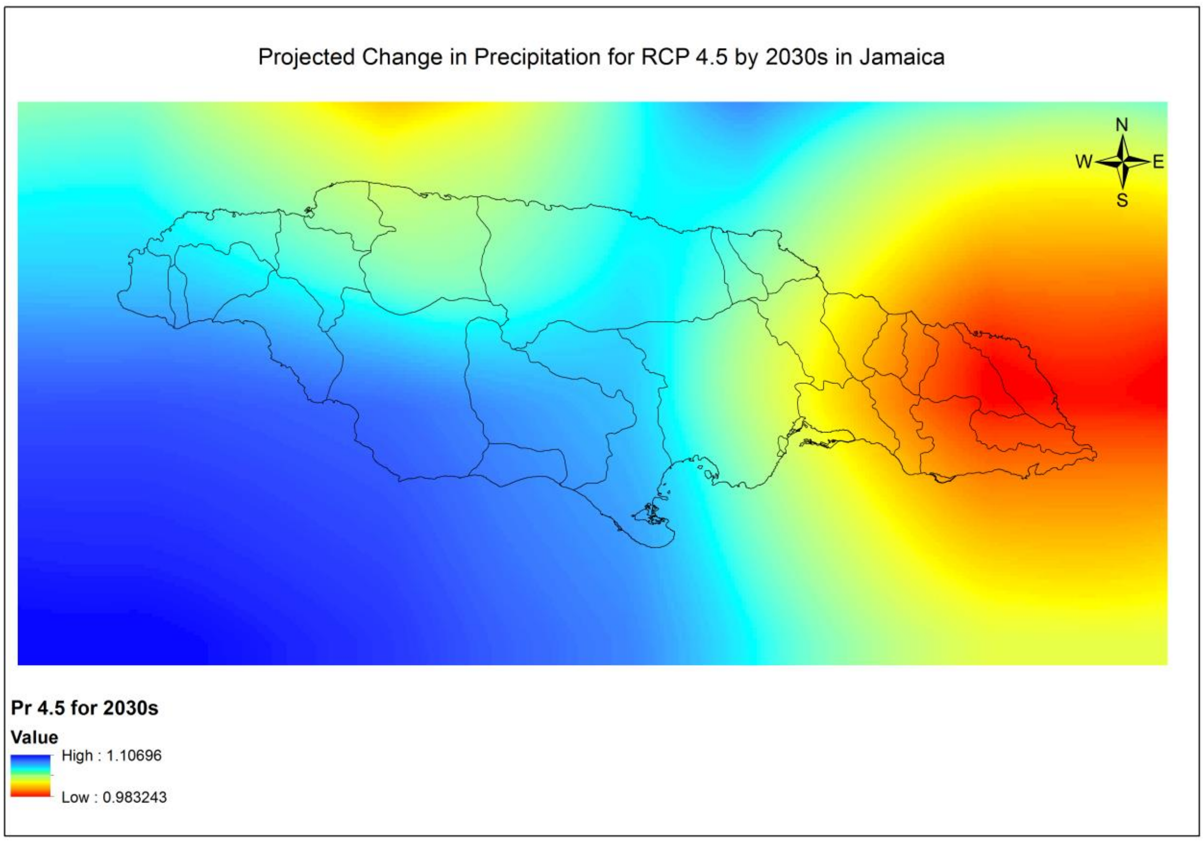


Figure 7: Climate change for precipitation

The climate change projections of precipitation and mean air temperature for RCP scenarios 4.5 and 8.5 from downscaled HADGEM were raw values with no bias corrections. Therefore, in order to determine the physical climate change impacts on mean annual runoff, the delta change method similar to (Hay, Wilby and Leavesley, 2000) was used for each scenario. Equations:

Bias correction = Future simulated mean temperature – Historic mean temperature baseline

This computes reliable differences between current and future HADGEM simulations to derive relative values instead of absolute (Hay, Wilby and Leavesley, 2000). Changes for temperature were added to observed time series 1970 – 2000.

Projected mean temperature = Bias correction + Observed temperature baseline

For precipitation bias corrections were added as a percentage. Equations:

$$\text{Precipitation bias correction} = \frac{\text{Future precipitation}}{\text{Simulated precipitation baseline}}$$

Projected precipitation = Observed precipitation * bias correction

The results were incorporated into the water balance equation (1) to derive future freshwater supply for specific time slices. For future withdrawal by sectors, the difference was applied as a percentage to the current withdrawals. For Jamaica, by 2030 the population will increase by approximately 10%, irrigation will increase by 14% for developing countries (FAO.org, 2002) and industrial by approximately 9% PIOJ (2017). Equations:

$$\text{Projected change} = \frac{\text{Future withdrawal}}{\text{Observed withdrawals}}$$

Projected withdrawals = Observed *Projected change

Both withdrawals by sectors and water available were reclassified adopting previous classifications 1 to 5. The final map outputs were classified based on index value (see table 3.1)

Index Value	Classification
0	No water Scarcity
1	Very Low Water Scarcity
2	Low Water Scarcity
3	Moderate Water Scarcity
4	High Water Scarcity
5	Extreme Water Scarcity

Table 2: Classification of water scarcity index.

As a result of uncertainties associated with future hydrology impacted by climate change and projected withdrawal by sectors, Fant et al (2016) conducted several scenarios. Similar approach was undertaken, where physical climate changes were isolated as if only these variables changed for 2030s and 2080s. In addition, scenarios including both future withdrawals and physical climate were also undertaken for 2030s (see figure 8).

To facilitate adaptation, water management strategies and suitability will be evaluated in context of hotspots in WMUs derived from WSI. WMUs important for tourism, agriculture and high population density having moderate to extreme scarcity index were assessed. The precautionary principle of environmental management informed the decision of assessing affected wmus. This principle requires action to be taken to prevent irreversible damages (Rogers, Sinden and De Lacy, 1997). As a result of limited time, assessing more complex aspects of water scarcity such as distribution and demand are beyond the scope of this research.

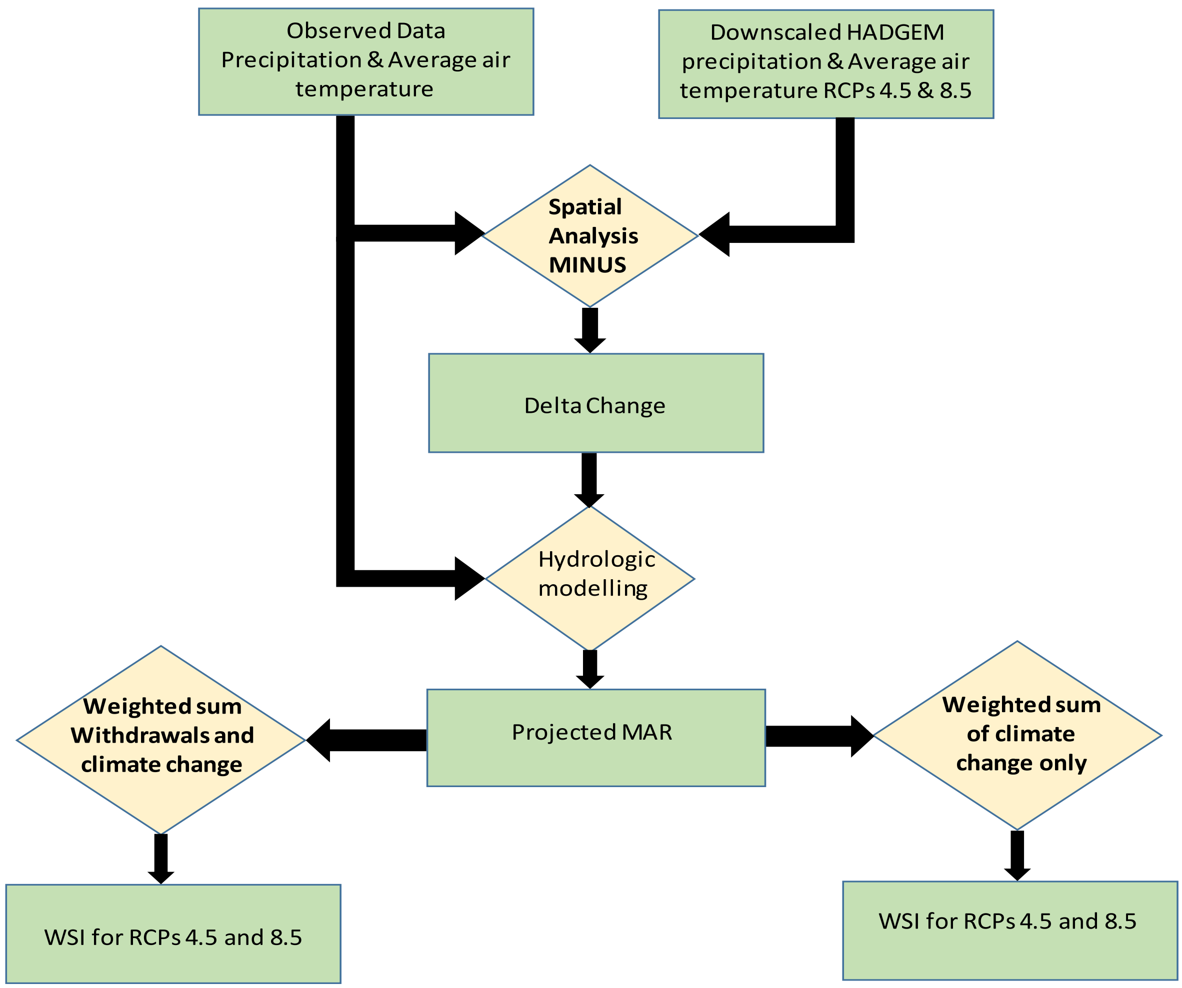


Figure 8: Workflow for future WSI.

3.5 Interview

Primary data was collected through a semi-structured interview with a key stakeholder; the Water Resources Authority (WRA) of Jamaica. WRA is the primary organization responsible for management, protection and controlled allocation of Jamaica's water resources (Ministry of Economic Growth and Job Creation, 2017). There are other key stakeholders such as the National Water Commission, which is responsible for potable water distribution to households and piped sewerage services in major towns (Ministry of Economic Growth and Job Creation, 2017). However, as a result of the research being more focused on water supply, it was critical that WRA insights on water supply and management were captured.

The interviewee was selected based on first-hand knowledge and expertise in relation to the aims and objectives of the research. As a result of undertaking a study at such a large scale and outside of Jamaica, the researcher was limited from having a larger sample size. These factors along with time constraint prevented contributions from residents within moderate to high water scarce WMUs to be included. This would have been ideal to capture perpectives and individual experiences from a range of key stakeholders. Therefore, to close the gap due to lack of varying perspectives, there was a need to select participant based on the wealth of information regarding national water status. A snowballing approach was employed and the Managing Director of the WRA was contacted. Snowballing process involves having a particpant recommend individuals who could participate in a study (Galleta, 2012). In this case, a potential participant recommended the interviewee.The participant was invited to a telephone interview. It is recommended that for semi-structured interviews the greater the participants the more rigorous the research would be and suggested to interview participants until there is satuaration of data (Galvin,2015). However, using one participant who has been working in the WRA from 1972 was sufficient.

A semi-structured approach was taken due to the complexities and different aspects that can be explored in relation to water supply and water scarcity. This approach allowed for the researcher to ask specific questions informed by theory while giving the interviewee the opportunity to explore issues that the researcher would not have been aware of. It is adequately structured to address aims and objectives while allowing participant to include new perspective to the study (Galleta, 2012). A questionnaire would have limited the depth of information on water resources that varies spatially and influenced by varying factors. According to Galvin (2015), more rigour is attained when using unstructured interviews.

3.5.1 Interview protocol

An Ethics and Research Governance online (ERGO) application was completed and approved for the interview to be conducted (ERGO ID 29582).

A Semi-structured interview took place using Skype as the medium. The purpose of the research was first established and appreciation expressed for participation. The interview started with general questions relating to the interviewees tenure and background at the WRA. Questions that were more specific and theoretically based followed. Commencing with grounded data provide the context for the interviewer to explore the participant's knowledge of the topic (Galleta, 2012). Responses were written throughout the interview. As a result of conducting only one interview, recording responses and undertaking grounded theory was not applicable. A detailed summary followed the interview and was analysed through thematic coding (see appendix B). Themes are patterns found in data collected which helps in interpreting qualitative information of open ended responses (Boyatzis, 1998). Themes that emerged from the interview were assessed through grouping codes and data was used to support literature.

Interview Questions:

1. How long have you been working with the Water Resources Authority?
2. What is the role of the Water Resources authority?
3. How has data collection for water inventory been over the last 10 years?
4. What is the status of ground water and surface water in the country?
5. Has there been any challenges in accounting for fresh water available in the country? If yes explain.
6. How will climate change projections affect water supply in the future?
7. Are there currently any water stressed basins in Jamaica? If yes what are factors influencing this?
8. Does the WRA work closely with any stakeholders?
9. What are the plans of the WRA to combat the issues the water sector will face in the future?

3.6 Statistical Analysis

IBM SPSS software (IBM, Excel 2013 and ArcMap 10.5 was used to undertake statistical analysis to highlight trends in historical data and statistical significant differences. One-way Anova and Turkey post hoc test were undertaken in SPSS to determine statistical significant differences between variables (Statistics.laerd.com, 2017).

4.0 CHAPTER FOUR: RESULTS

4.1 Introduction

This section aims to analyse the spatial variability in long-term mean annual Runoff and streamflow across watershed management units in Jamaica. This is vital for assessing critical hydrological variables in the future. The impact of climate change on the water budget is assessed and incorporated with socio-economic withdrawals to determine water stress status of watershed management across Jamaica. This is necessary for informing water management strategies for climate change adaptation for WMUs at moderate to high risk of water scarcity. The WMUs that are most critical to the country's sustainable development will be assessed by scenarios.

4.2. Spatial variability of Hydrological variables

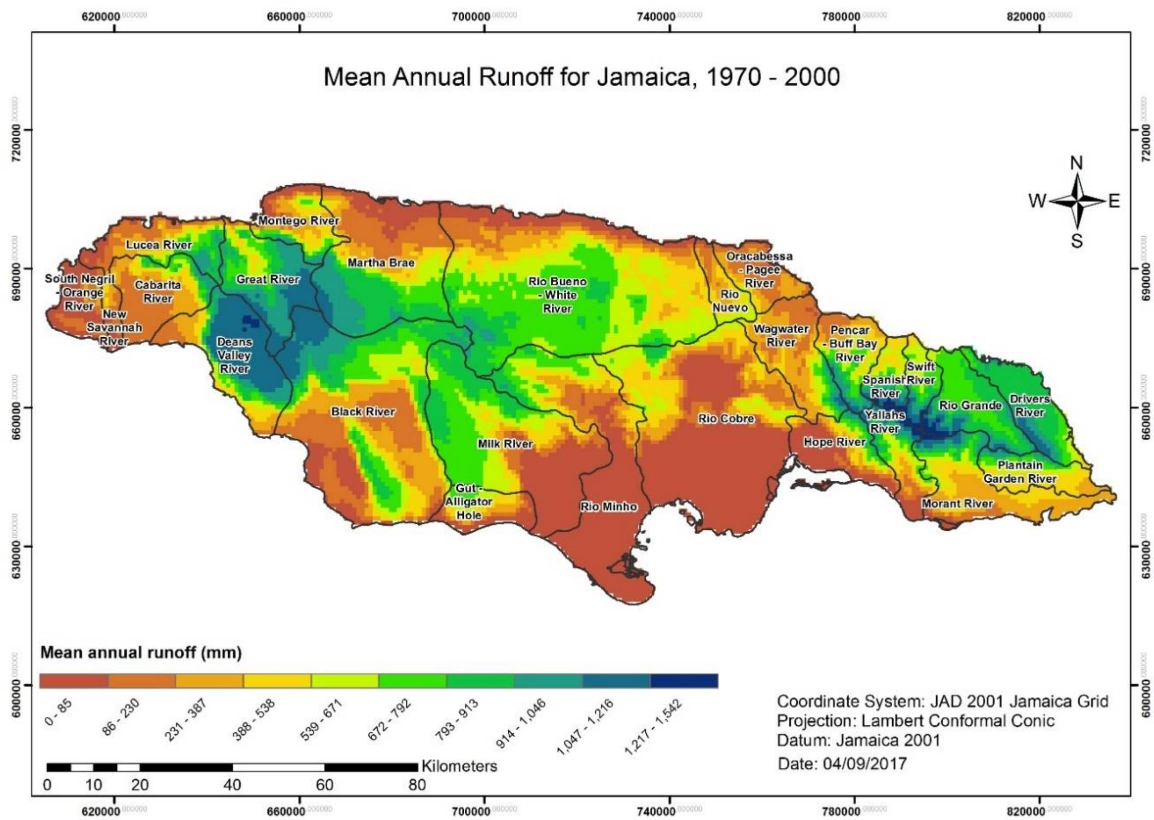


Figure 9: Long term mean annual runoff for twenty six watershed management units in Jamaica.

Long term Precipitation – Long term estimated evapotranspiration was used to derive MAR for Jamaica as shown in figure 9. The map shows spatial distribution of MAR for each watershed management unit. It can be observed that MAR is lowest in the southern Watershed Management units and ranges between 0 and 85 mm. The majority of Hope River, Rio Minho, Rio Cobre and Milk River are dominated by low MAR. The interior of the island receives moderate to high MAR particularly the central and eastern watershed management units. It can be observed that Rio Grande, Swift River and Spanish River in the east have the maximum MAR of 1542 mm. Figure 6 demonstrates variability across and within catchments. This variability can be a result of intensity, duration and spatial distribution of precipitation across Jamaica, which is in the form of rainfall. The windward side of the Blue Mountain consists of the eastern water management units which historically receive the most rainfall (CSGM, 2012) while less precipitation is associated with the leeward side of the Blue Mountains that consists of Hope River, Rio Minho, and Rio Cobre. The spatial variation in mean temperatures can also result in MAR variability, as temperature is directly related to evapotranspiration. Areas of lower elevation and along the coastal areas are expected to have higher temperatures than in the mountainous interior of the island. The type of vegetation in watershed management units can also contribute to the variations in MAR. This impacts evapotranspiration which vary according to crop water use. Solar radiation was included as a parameter for estimating PET. Jamaica receives an average of 1825 kWH/m^2 per year of direct solar radiation of which the south receives the majority of higher radiation (CSGM, 2012). In watershed management units where evapotranspiration is greater than precipitation MAR is 0 mm.

4.2.1 Streamflow spatial distribution

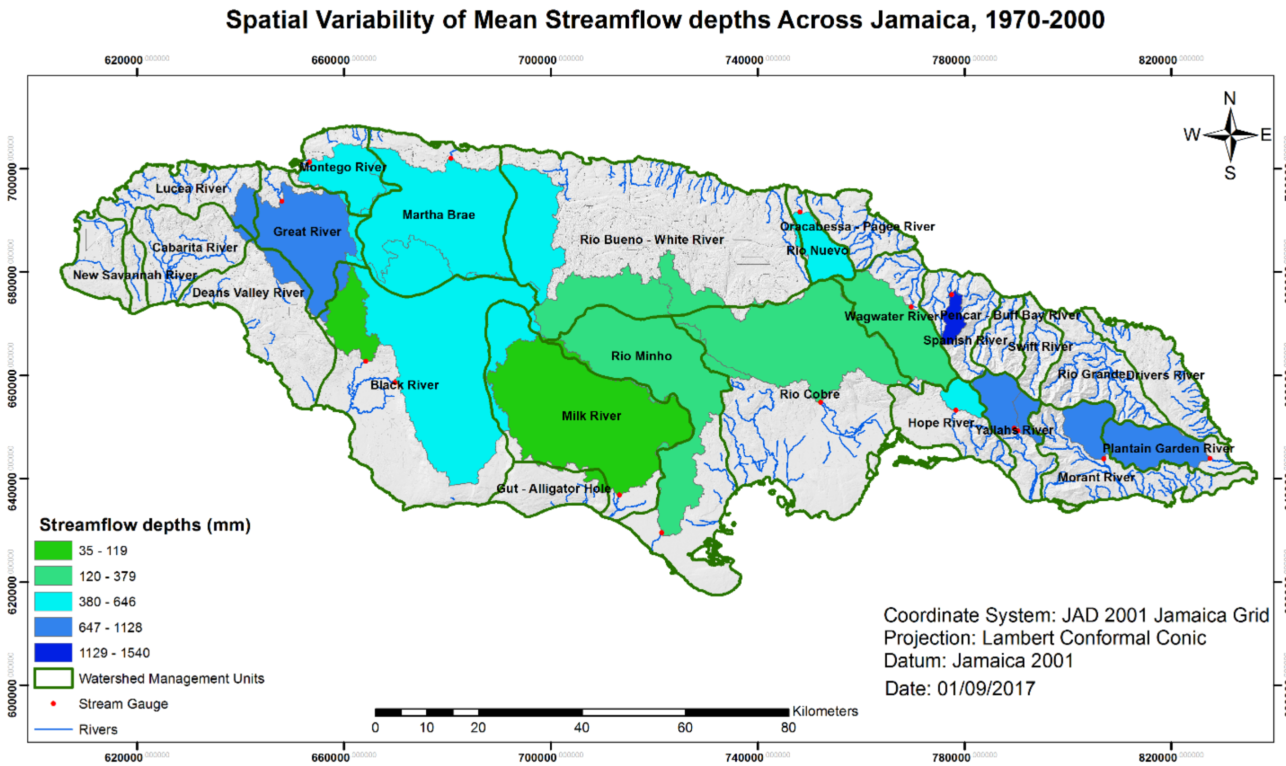


Figure 10: Spatial distribution of long term streamflow depths in Jamaica.

It can be observed in figure 10 that only 13 of 26 watershed management units were assessed for streamflow depths. This is a result of the complexity of the islands' topography and lack of data in some catchments to undertake a long term streamflow assessment. From figure 10 it can be seen that streamflow depths are generally lower in larger catchments in the south. The Milk River watershed management unit has the lowest depth, 35 mm. However, this is the opposite for smaller watershed management units in the east that consists of up to 1540 mm in streamflow depths. The maximum streamflow depth can be associated with the Pencar catchment. Large watershed management units of lower streamflow depths are located south of Jamaica, where less precipitation occurs. Hence, less volume of water would be available for draining into streams. It is evident that the topography across Jamaica varies based on the characteristics of the stream network in figure 10. It can be observed that eastern watershed management units have well defined and denser stream networks than anywhere else in the country. With denser stream networks, more rivers and streams can merge with other streams and result in increasing streamflow depths in the drainage systems. From figure 10, larger watershed management units predominantly have very few streams, of which many disappear underground. Therefore, resulting in lower streamflow depths in these areas. The amount of streamflow depths measured can also be related to the location of the stream gauges. Human impacts upstream the location of where streamflow are observed can result in reduced flows and volumes being measured. Withdrawals upstream and developments upstream the stream gauge can result in reduced streamflow and even diversions of runoff into other rivers that are not measured. The later can cause significant underestimation in streamflow depths at observed stream gauges in catchments.

4.2.2 Streamflow vs MAR

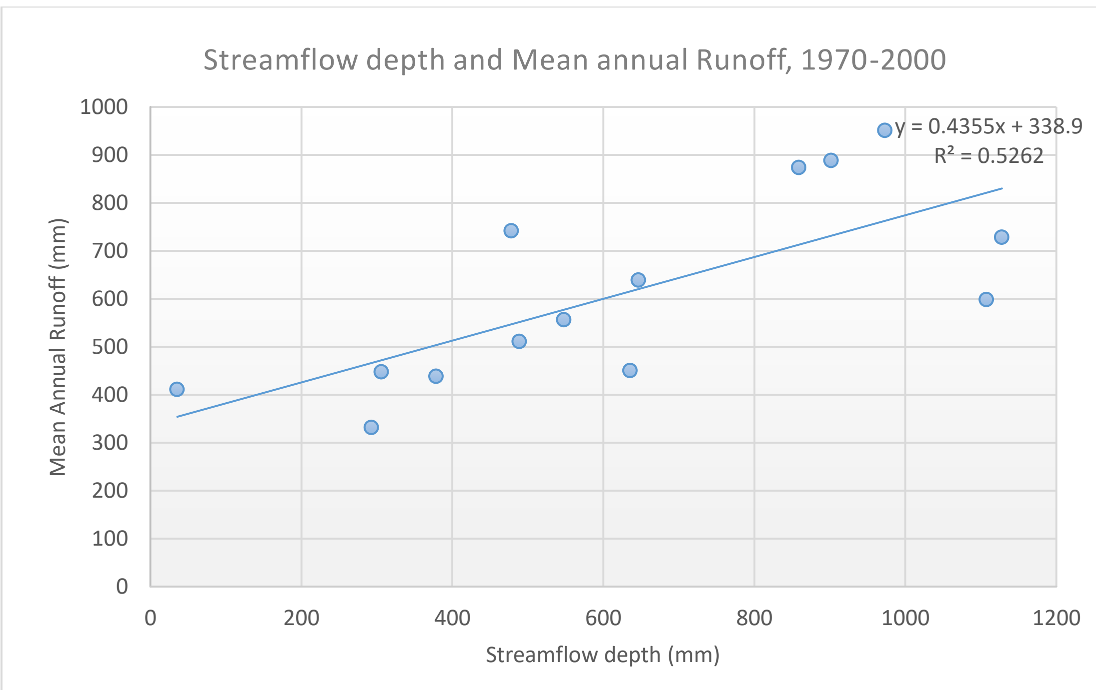


Figure 11: Shows the relationship between long term streamflow depths and MAR.

Figure 11 represents measured streamflow depths for the areas upstream stream gauges in the watershed management units seen in figure 11 and long term MAR for the same area in each catchment. It can be observed from figure 11 that there is moderate positive correlation (R^2= 0.53) between the streamflow depths and MAR. Therefore, streamflow depths is related to the volume of water running off the catchments into the streams. The general trend shows that as catchments streamflow depths increase the MAR also increases. However, there are both overestimation and underestimation of MAR within some catchments. This could have resulted from MAR being simulated using empirical equations that required some assumptions. As a result of the limited spatial data, the equation used to derive PET was not the most superior approach. In addition, the lack of crop coefficients data that varies by crops across the island had to be estimated. As a result of the uncertainties in estimating the ET components, there were overestimation in some catchments and underestimation in others. Hence, the MAR would also overestimate and underestimate in some watershed management units.

4.3. Climate Change Projections

	Climate variable		
RCP Scenarios	***Temperature***	***Precipitation***	**Time slice**
RCP 4.5	*+1.3*	-4% to 11%	2030s
RCP 8.5	*+1.5 to +1.6*	-4% to 3%	2030s
RCP 4.5	*+2.3 to +2.6*	-16% to -8%	2030s
RCP 8.5	*+3.7 to +4.5*	-39% to -17%	2030s

Table 3: RCPs 4.5 and 8.5 for downscaled HADGEM model for Jamaica.

Temperatures will increase for both scenarios irrespective of time. However, for 2030s a difference of 0.3^{o}C will occur between RCP 4.5 and RCP 8.5. A greater increase is expected for RCP 8.5 and even more warming by 2080s. Precipitation will increase and decrease respective of scenario by 2030s, ranging from minimum of 4% reduction to a maximum increase of 11% However, significant decrease is expected for all scenarios by 2080s with a maximum of 39% precipitation reduction.

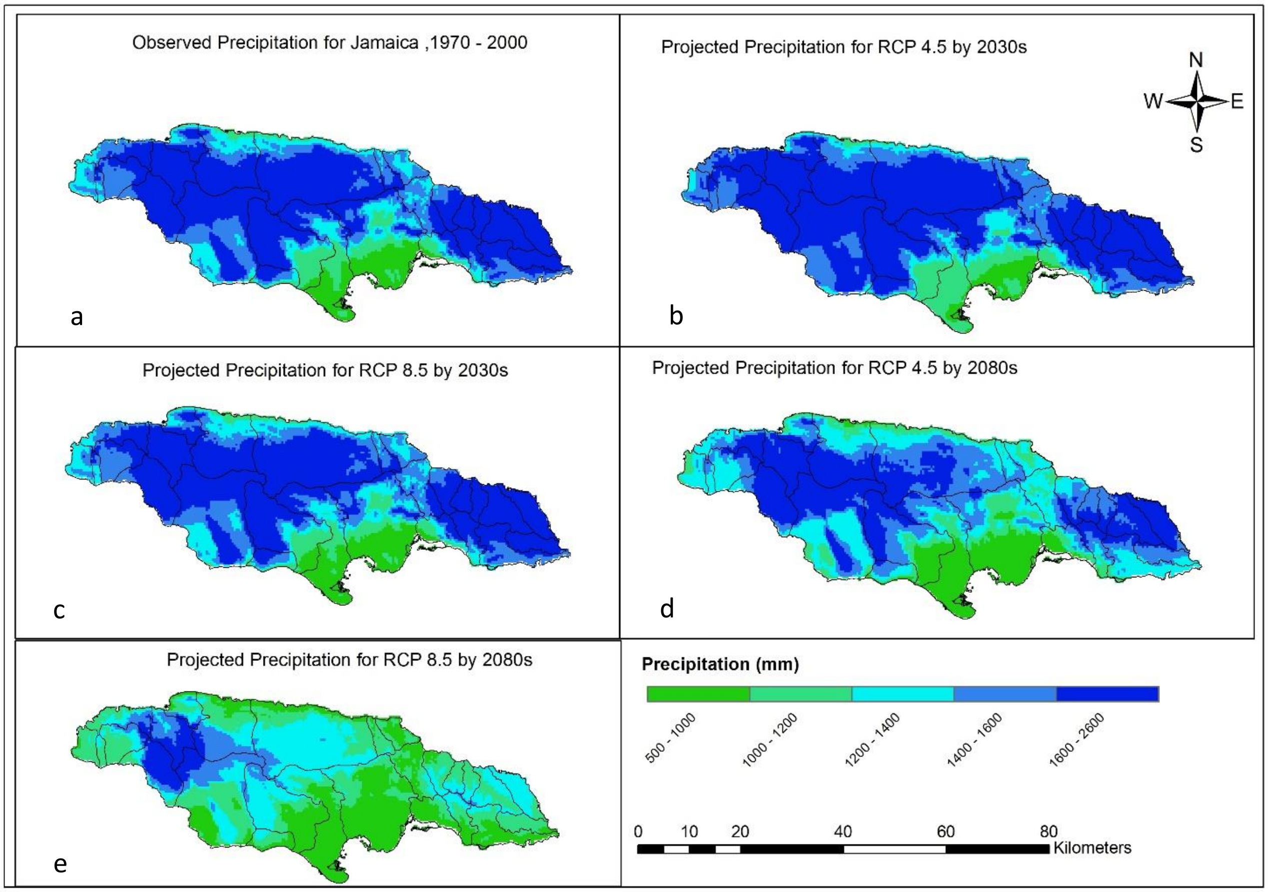


Figure 12: Long term precipitation and future precipitation for Jamaica.

Figure 12 represents the spatial distribution of historic precipitation and precipitation for the future based on scenarios and time slices. It can be identified that precipitation varies spatially and is expected to vary with climate changes despite the scenario between 500mm -2600mm. There will be both increase and decrease with the impact of climate change with most significant changes occurring by 2080s. From long term observed precipitation (a) it can be identified that Jamaica' highest precipitation is associated with watershed management units on the eastern side of the island. This is a result of relief rainfall that occurs in the mountainous interior (see appendix A) of Jamaica. Warm air is forced up the mountains, cools as it rises and condenses. Clouds are then formed and precipitation occurs. As the clouds move over the mountains there is less rainfall as the air becomes drier (ODPEM, 2012). The interior of the central catchments also receive high precipitation with over 1600 mm annually. However, the opposite can be observed for the majority of the southern watershed management units. It is evident that these catchments will experience the lowest precipitation, ranging from 500 to 1000 mm. From (b) projected precipitation for scenario RCP 4.5 by 2030s shows a general increase of approximately 200 mm in annual rainfall across Jamaica. This is predominantly in the south western watershed management units (see appendix B) and will be distributed along the coast and interior of the island. From (c) precipitation for RCP 8.5 by 2030s will start to show slight decrease (see appendix B) across Jamaica when compared with long term observed annual precipitation. The interior of the southern catchments Milk River and Black River will mostly be affected. From (d) and (e) significant rainfall reduction can be observed across all WMUs for RCPs 4.5 and 8.5 by the end of the century. From (d), up to more than 400 mm of rainfall reduction is expected in the eastern catchments as a result of significantly low rainfall (see appendix B). From scenario (e) it is expected to worsen and rainfall will be further reduced.

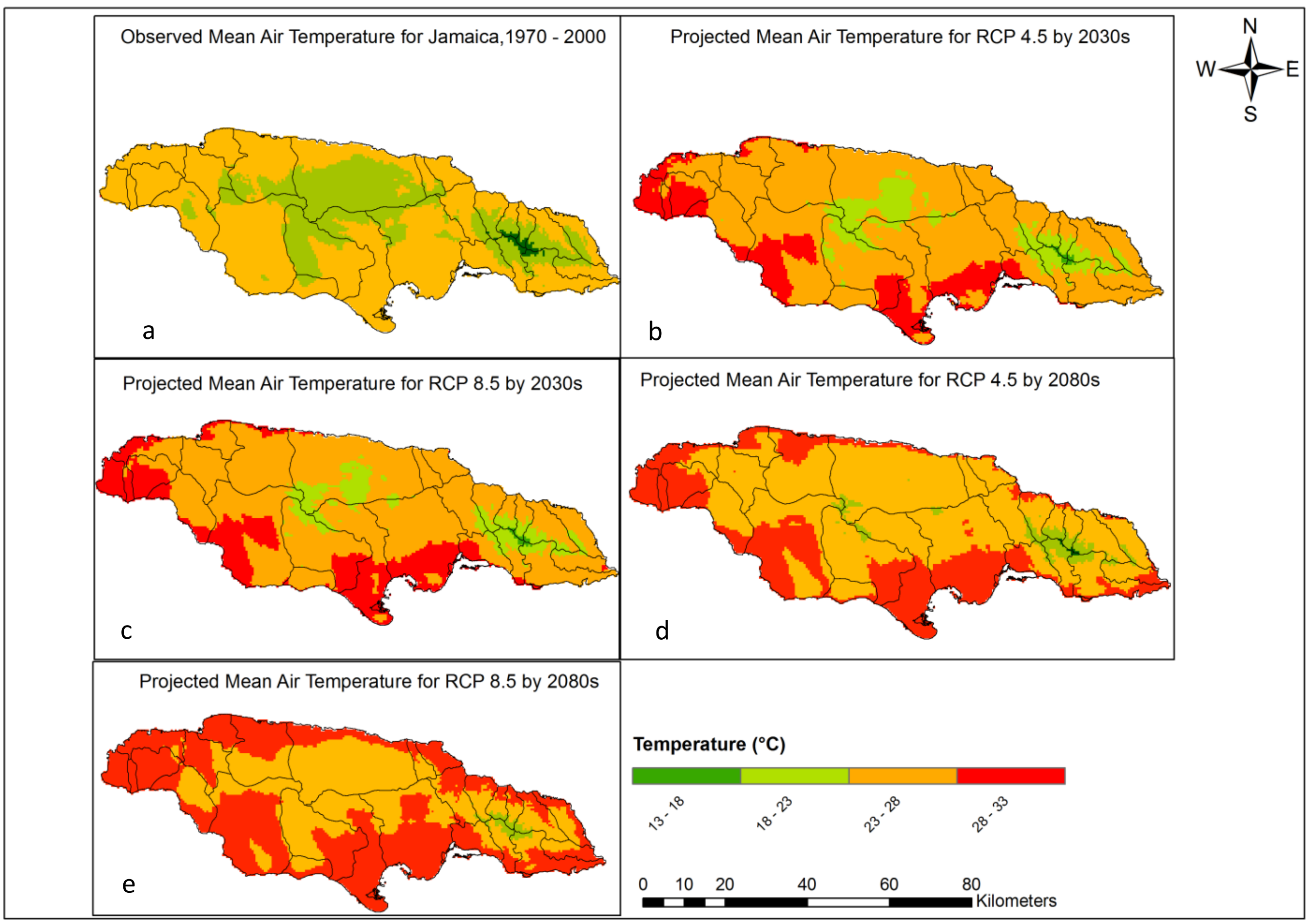


Figure 13: Shows long term observed mean temperature and future temperature for Jamaica.

Figure 13 (a) represents the mean temperature of Jamaica. Almost all watershed management units experience the same mean temperature. This ranges from 23°C to 28 °C with the mountainous interior of the eastern and central experiencing minimum temperatures that range from 13°C - 18°C. Temperatures are strongly correlated to elevation. High elevation areas in Jamaica are associate with lower temperatures and low elevation areas along the coast temperatures are higher (Cashman, 2014). For all scenarios and time slices in figure 13 Jamaica will be experiencing higher temperatures predominantly south west of Jamaica. From (b) temperatures will increase on the northwest and the south side of the island up to 1.3°C. Warming is even higher in 12 (c) for these regions with greater changes in temperature especially along the north coast of Jamaica (see appendix B). The change is expected to increase up to 2.6 °C. By the end of the century it is expected that the areas of higher elevation inland will also be impacted. From (d) and (e) it can be observed that minimum temperatures will range from 18°C -23°C. By the end of the century maximum temperature is expected to be 33°C.

4.3.1 Difference in MAR

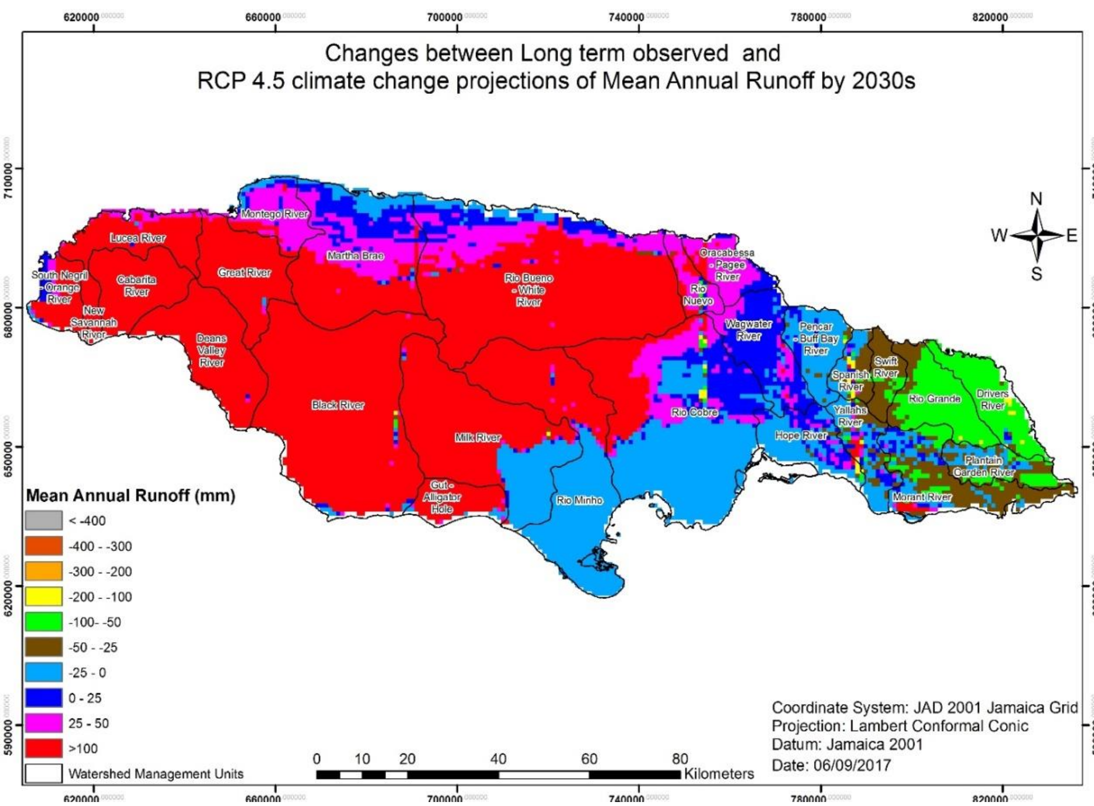


Figure 14: Shows the difference between Future MAR for RCP 4.5 by 2030s and long term MAR.

From figure 14 it can be seen that the eastern watershed management units will experience the greatest reduction in MAR. This is attributed to these areas experiencing the most increase in temperature and the least amount of rainfall (see appendix B). These watershed management units show most changes as a result of historically being dominated by high precipitation and lower temperatures. Although precipitation remains the highest, the increase in temperature will increase evapotranspiration and reduce MAR. It can be identified that the changes even in the same catchments vary. Potential evapotranspiration vary by changes in altitude, radiation, albedo of exposure and steepness of slope (Gurtz, Baltensweiler and Lang, 1999). These factors can influence the variation of MAR in the same catchment. The runoff reduction vary in these areas can also be a result of topography. A reduction between 50 mm to 200 mm of MAR is expected. The Southern catchments were not greatly impacted as these areas already had extremely low annual run off due to higher temperatures and lower precipitation. The remaining 2/3 of the island will have an increase in runoff of up to 100 mm. From the map, artefacts can be seen in the data after undertaking spatial analysis. This could be a result of the data preparation process for WorldClim climatology data that was used. In areas where this is evident those pixels will be ignored due uncertainties that exist in the pixel representation.

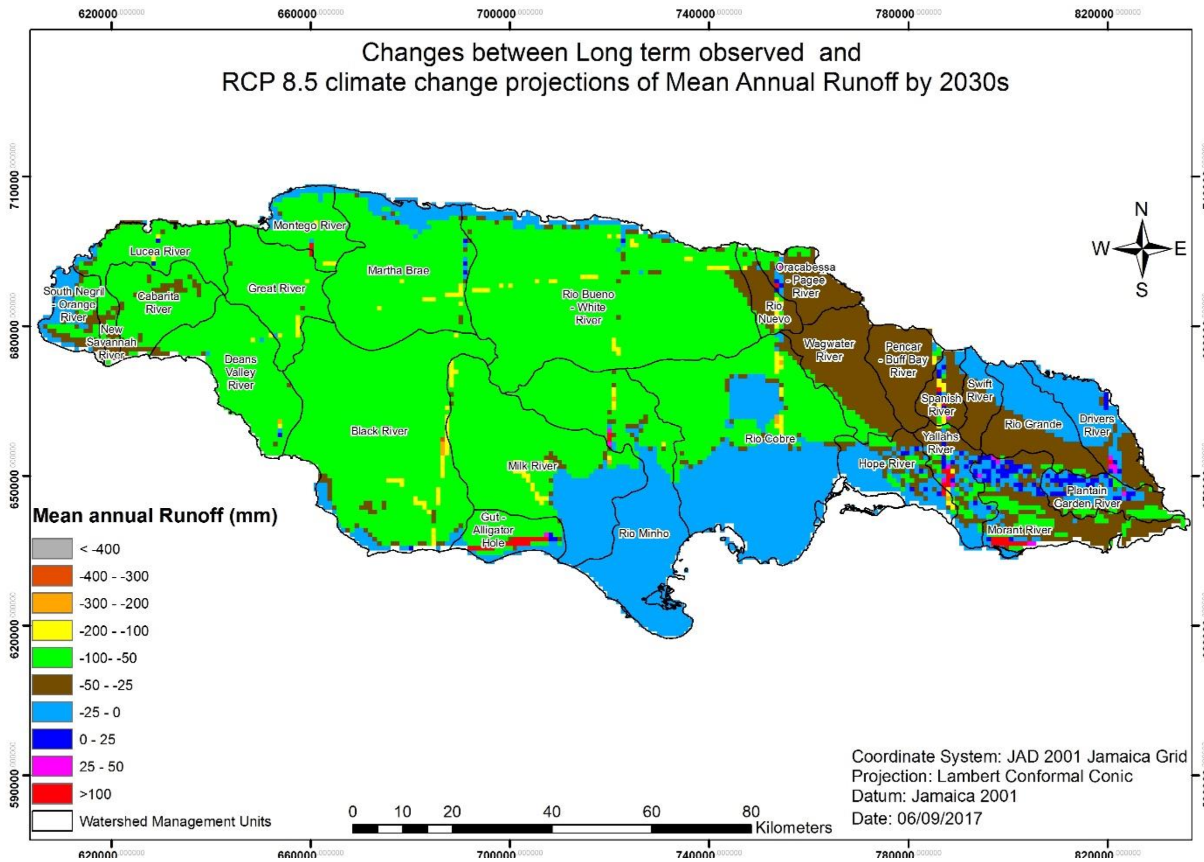


Figure 15: Shows the difference between Future MAR for RCP 8.5 by 2030s and long term MAR.

From figure 15 it can be observed that MAR will experience greater reduction than RCP 4.5 scenario for the same time slice. The reduction of MAR will be seen in the majority of central watershed management units. A reduction of up to 100 mm can is expected in these areas. This worsens for Gut Alligator Hole catchment. As a result of very low precipitation that will dominate this catchment up to 370 mm of reduced MAR is expected.

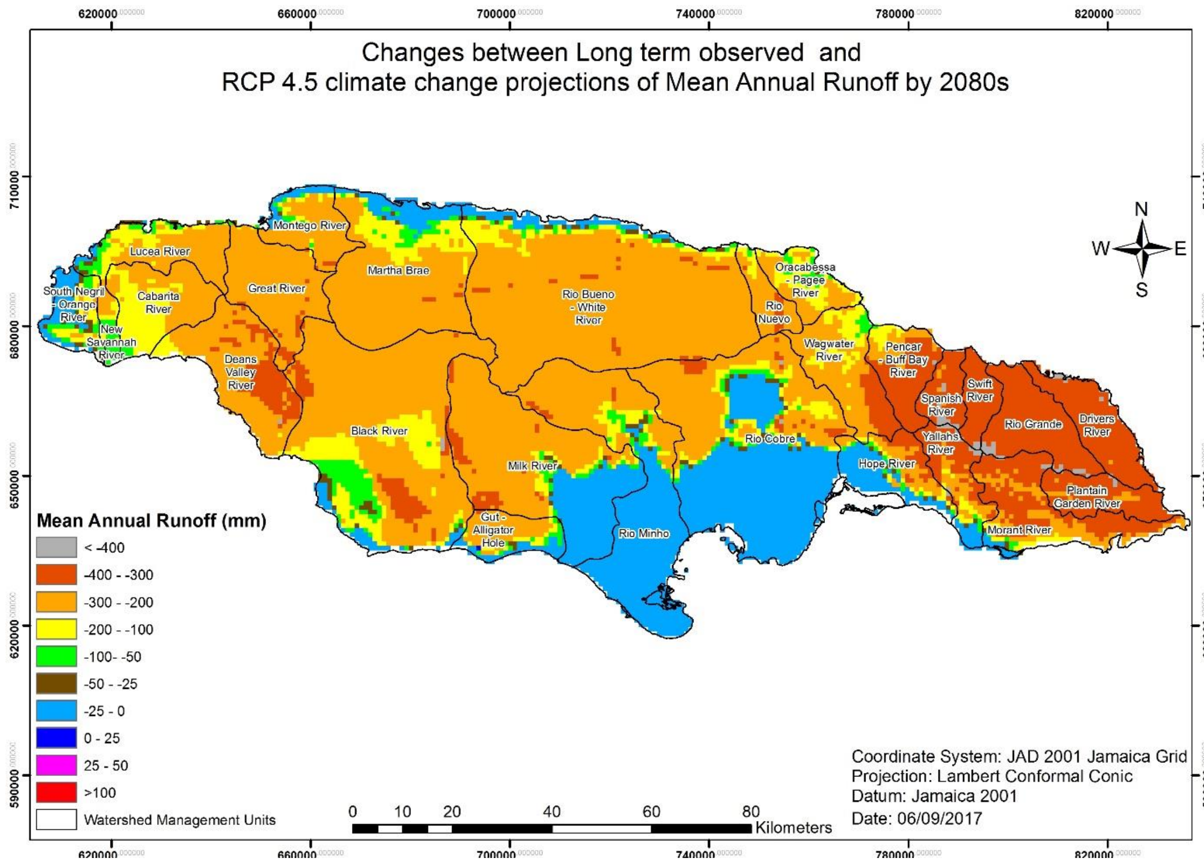


Figure 16: Shows the difference between Future MAR for RCP 4.5 by 2080s and long term MAR.

Figure 16 map shows that there will be no positive change in MAR. Therefore, no increase in MAR is expected over the island. However, significant reduction of MAR will be evident. This is attributed to the significant reduction of rainfall and increase of temperatures in predominantly high runoff in eastern and central parishes. A 200 mm -400 mm reduction in MAR can be expected. The Southern catchments will continue to experience lesser runoff than others. However, due to no significant change is water available the MAR in figure 16 would not reflect great difference.

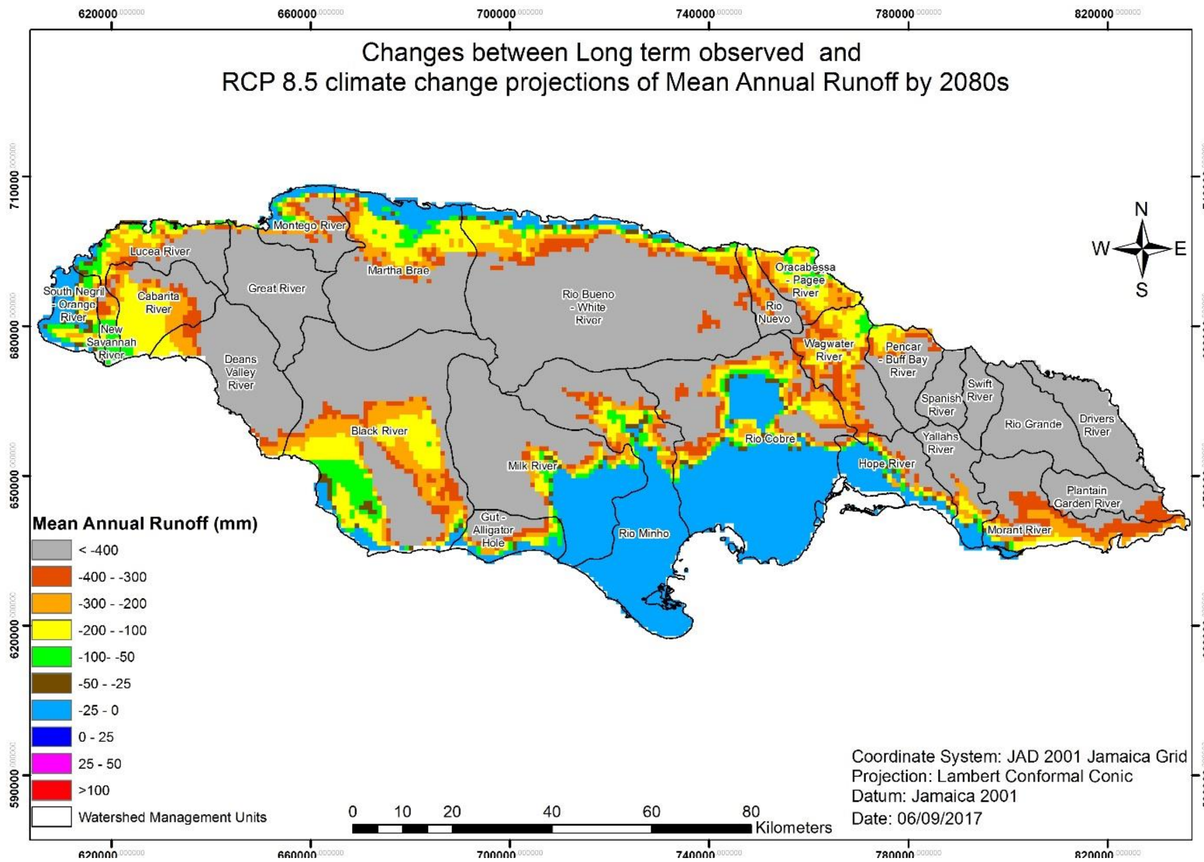


Figure 17: Shows the difference between Future MAR for RCP 8.5 by 2080s and long term MAR.

From figure 17, Jamaica's MAR will significantly reduce is all watershed management units. This is expected as there is significant reduction in precipitation and significant increase in temperatures for RCP 8.5 by the end of the century (see appendix B). This will result in the majority of catchments experiencing a reduction of more than 400 mm of MAR. All catchments will be impacted but the change is greatest in areas that historically have high precipitation.

4.4. Water Scarcity Index

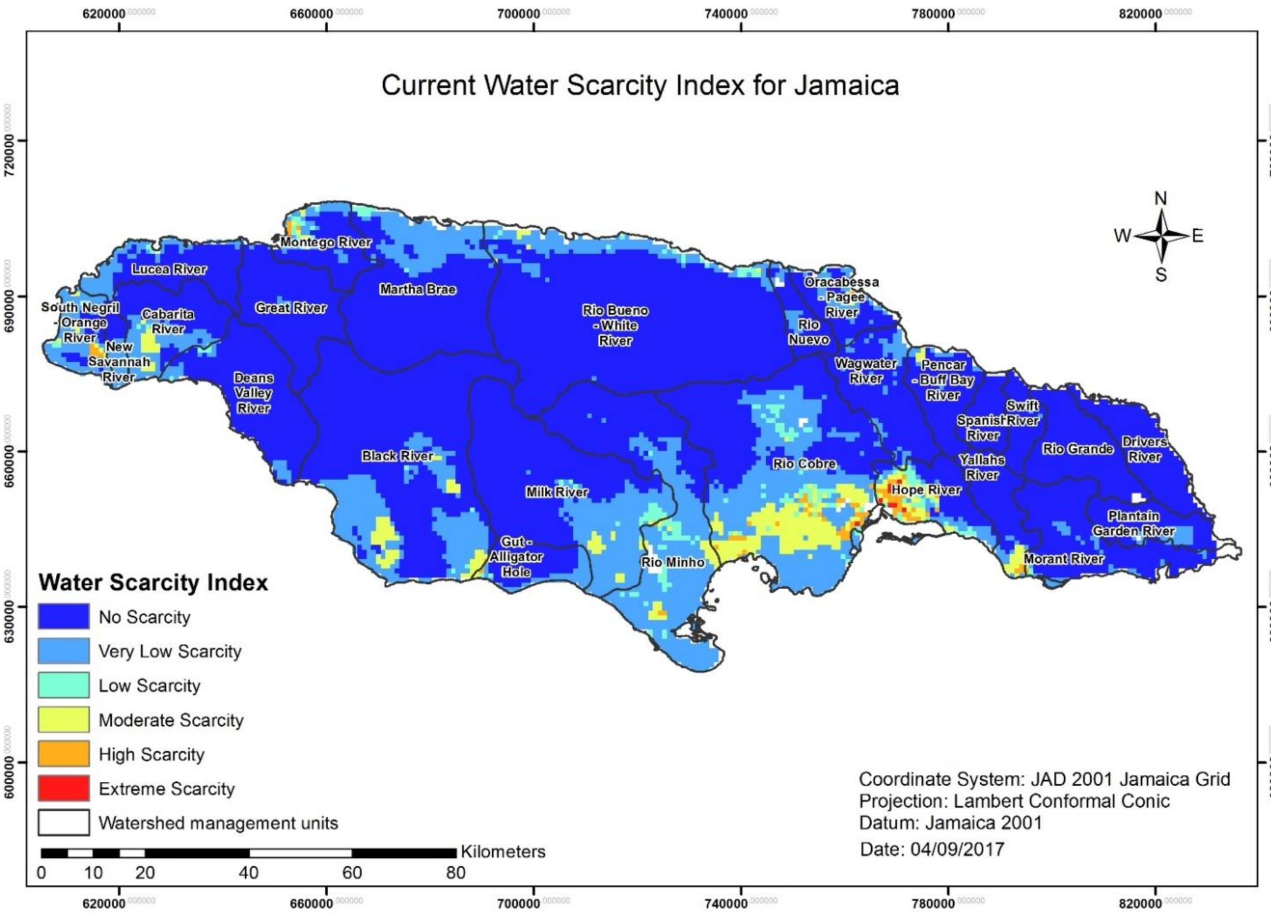


Figure 18: Present water stress indicator index in Jamaica.

Figure 18 represents a coarse resolution spatial distribution of water scarcity by watershed management units across Jamaica. It can be observed from the map that majority of Jamaica ranges from no scarcity to very low water scarcity. However, there are watershed management units that are currently experiencing moderate to extreme water scarcity. This is evident in some of the southern catchments, more specifically affecting the majority of the Hope River and Rio Cobre watershed management units. This could be a result of withdrawals exceeding supply in sections of these catchments. In figure 19, it can be observed that the Hope River catchment is experiencing the highest level of water scarcity, with approximately 12% of the catchment associated with high to extreme water scarcity. This can be attributed to extremely high withdrawal levels coupled with historically low precipitation that is associated with southern watershed management units. On the other hand, catchments of no scarcity to low scarcity signify less water withdrawals and greater water supply.

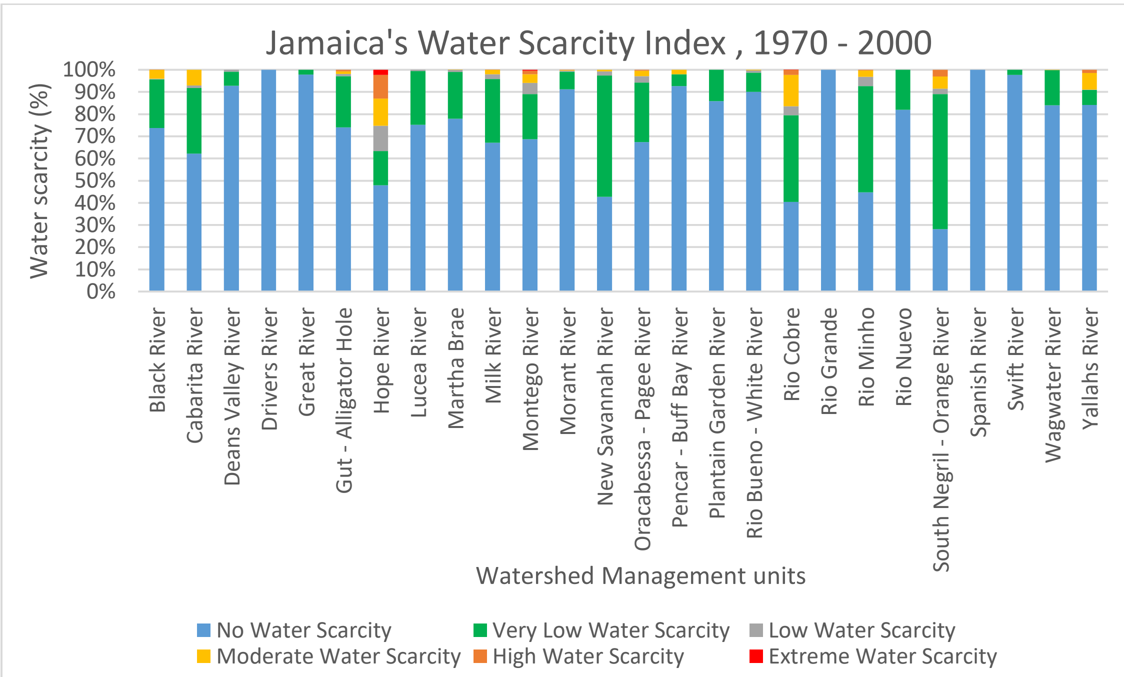


Figure 19: Water scarcity as a percentage of Watershed Management units.

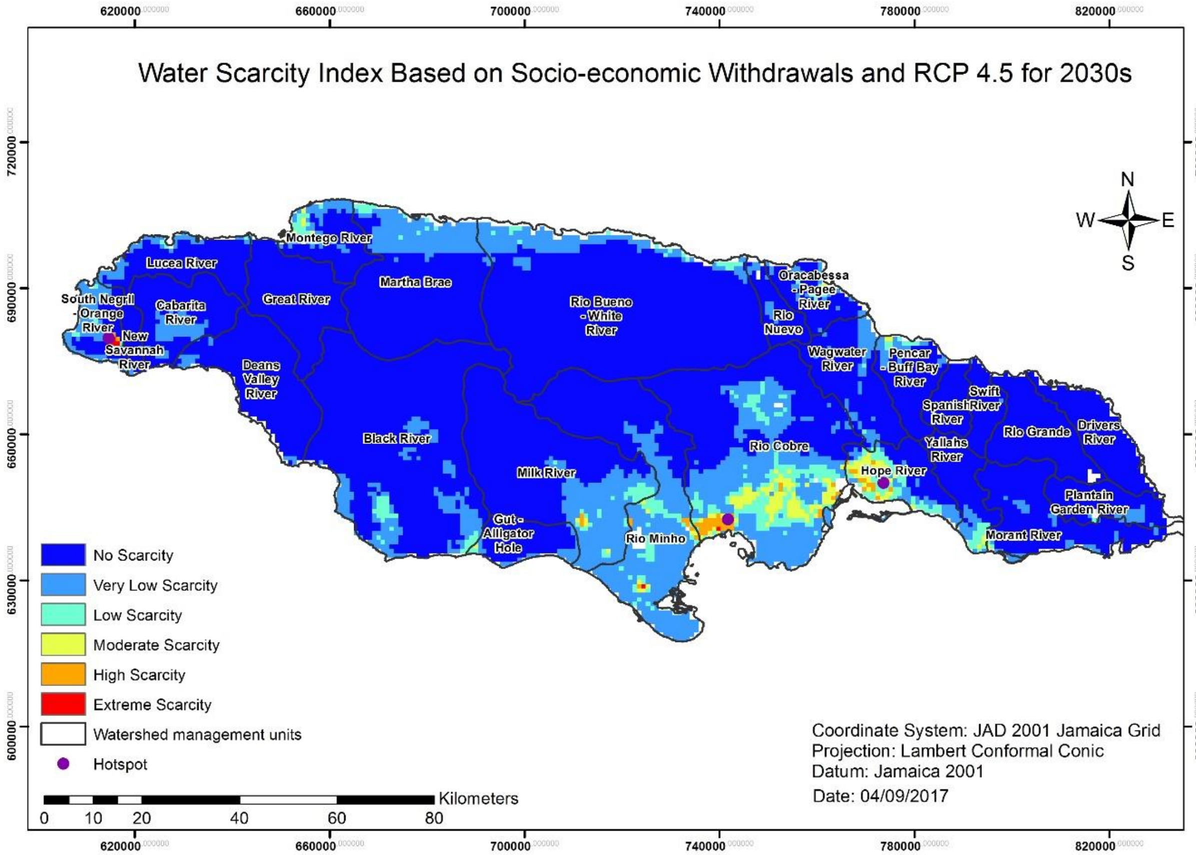


Figure 20: Water stress indicator index for RCP 4.5 scenario and socio-economic changes by 2030s

Figure 20 represents a spatial distribution of water scarcity by 2030s based on RCP 4.5 scenario and projected agricultural, industrial and domestic withdrawals for Jamaica by 2030. It can be observed that catchments that were experiencing high to extreme water scarcity will remain water scarce or worsen. It can be observed that Rio Cobre, Rio Minho and South Negril catchments will experience an increase in water scarcity while the Hope River and Morant River will still experience water scarcity but is expected to subside in areas of extremely high to moderate scarcity. This can result from the expected variability in precipitation across some catchments. The South Negril, Rio Cobre and Hope River important catchments for the country's economic development and were highlighted as a result of their vulnerability to future change.

From figure 21, it can be identified that sections of the Morant River will reduce to 17% of the catchment having low to moderate scarcity. However, this is not the case for South Negril catchment where 3% will experience extreme water scarcity. This could result from the increase in withdrawals for irrigation and industry that exceed the minimal increase in water supply.

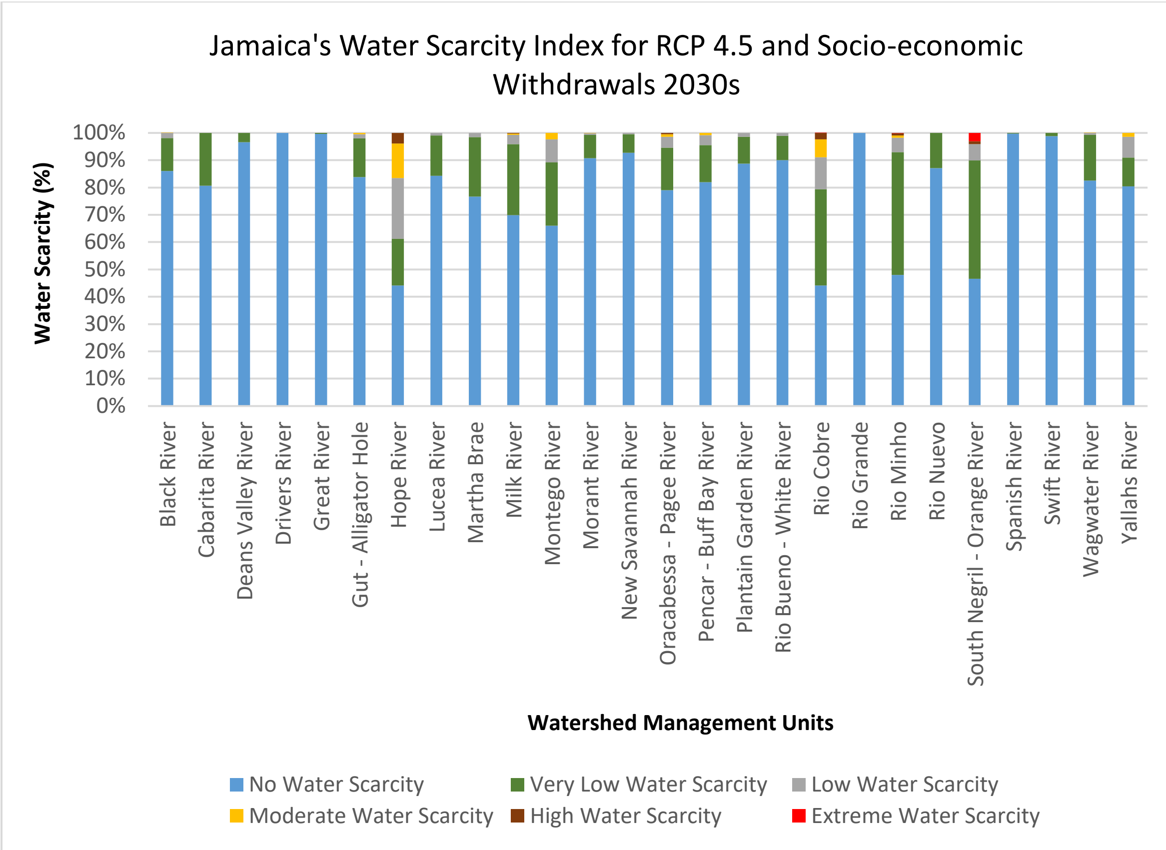


Figure 21: Water scarcity as a percentage of Watershed Management units

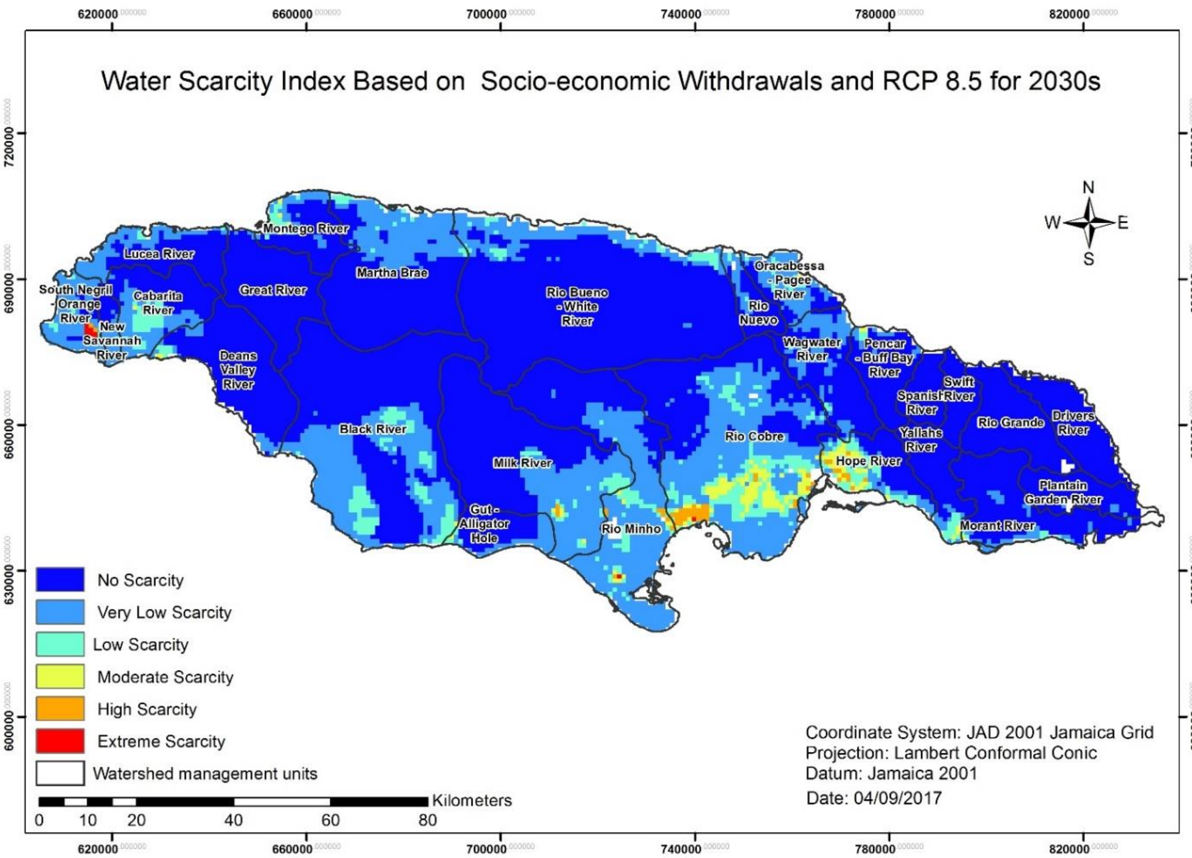


Figure 22: Water stress indicator index for RCP 8.5 scenario and socio-economic changes by 2030s.

From figure 22, it can be observed that water scarcity levels will have greater increase in areas of moderate to high water scarcity than is expected for RCP 4.5 scenario. With increase withdrawals expected in already moderate to extremely high water scarce catchments, an increase in water scarcity can be expected. From figure 23, approximately 3 % of the Rio Cobre and 5% of South Negril will experience high to extreme water scarcity. Due to less precipitation for scenario RCP 8.5 than RCP 4.5, the supply in these catchments may not meet the demands for 2030. However, majority of eastern and central catchments will remain stable with no water scarcity to low scarcity expected. This can result from negligible increase in withdrawals (see appendix C).

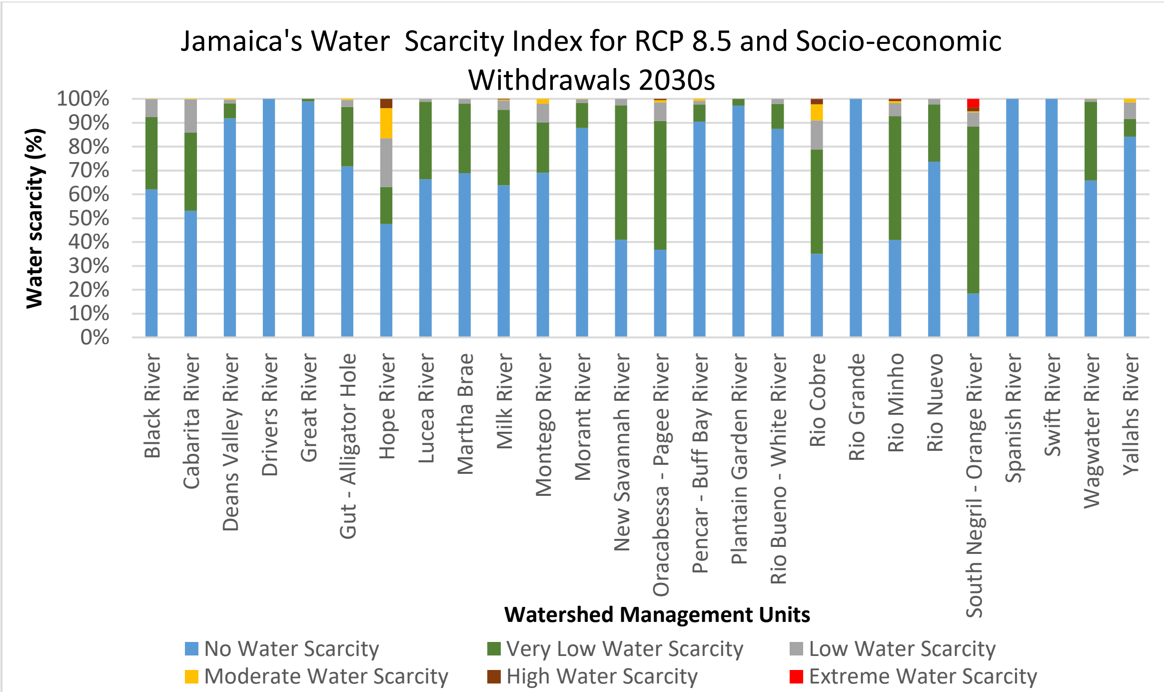


Figure 23: Water scarcity as a percentage of Watershed Management units.

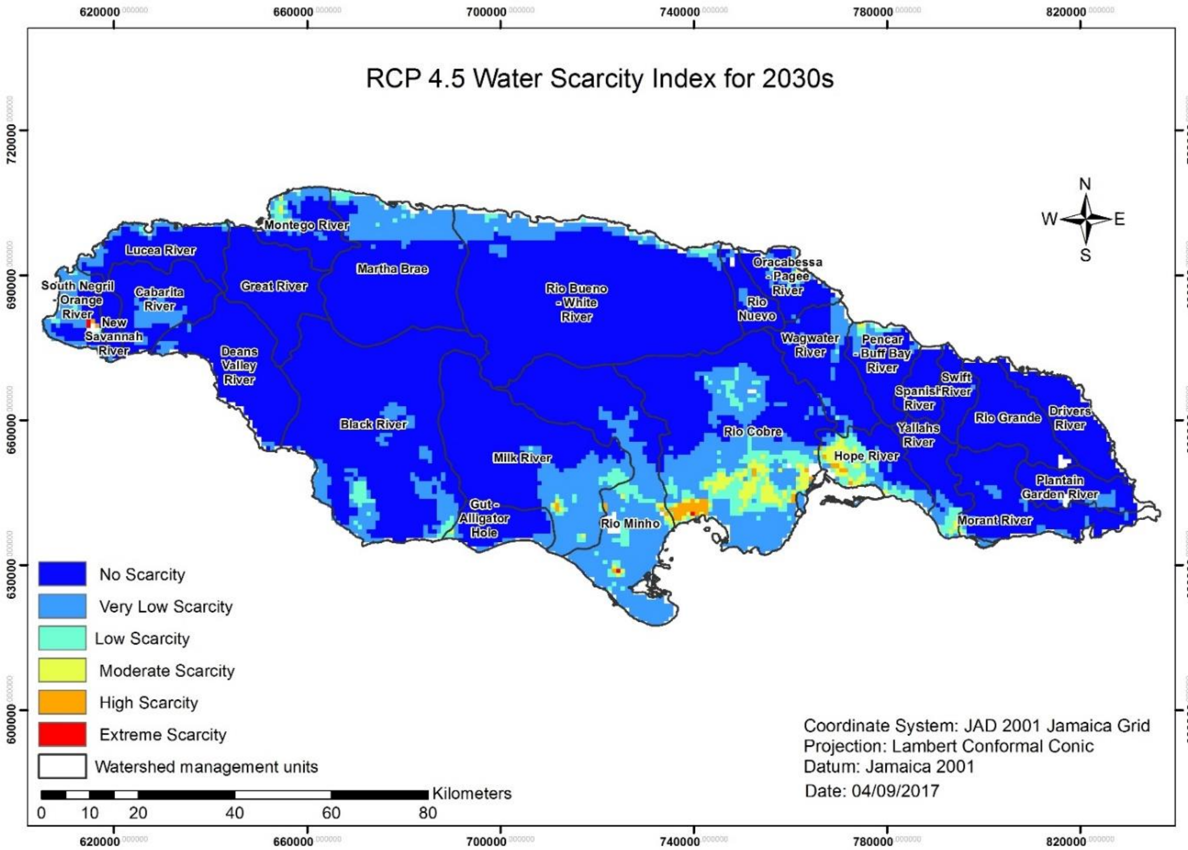


Figure 24: Water stress indicator index for RCP 4.5 scenario by 2030s.

Figure 24 represents water stress by watershed management units for 2030s based on only physical climate changes. It can be observed that even in instances where there is no increase in withdrawals physical climate changes will result in the increase in moderate to extreme water scarcity for southern catchments and South Negril. Figure 25 shows that although there will be an increase of water stress in Rio Cobre, Hope River, Rio Minhno and South Negril catchments, less areas within catchments will be impacted by water stress once withdrawals do not increase by 2030s. In figure 26, for RCP 8.5 scenario there will be a greater increase water stress within watersheds than RCP 4.5 for Rio Cobre, Hope River, Rio Minhno and South Negril catchments. Although there will be an increase in precipitation, distribution will vary. In areas of negligible increase in precipitation and higher temperatures associated with RCP 8.5, catchments can expect greater increase of areas of water stress than with RCP 4.5

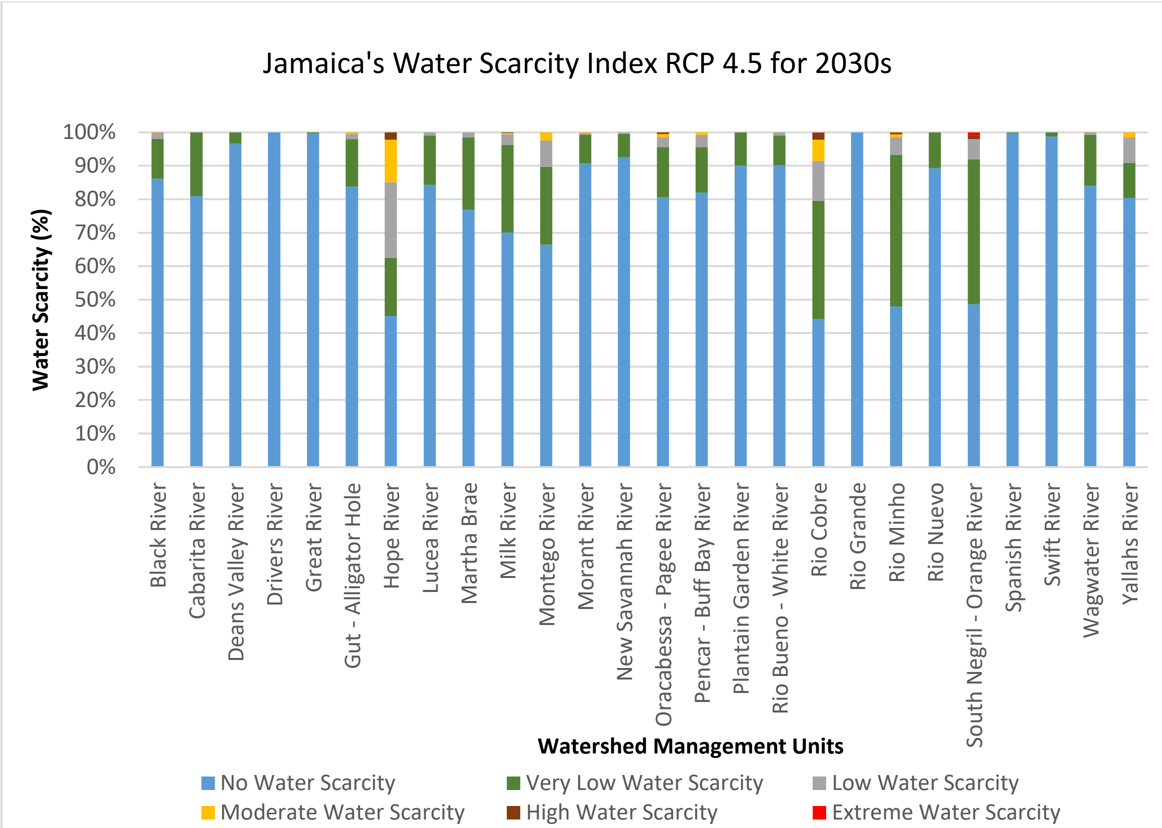


Figure 25: Water scarcity as a percentage of Watershed Management units for RCP 4.5 by 2030s.

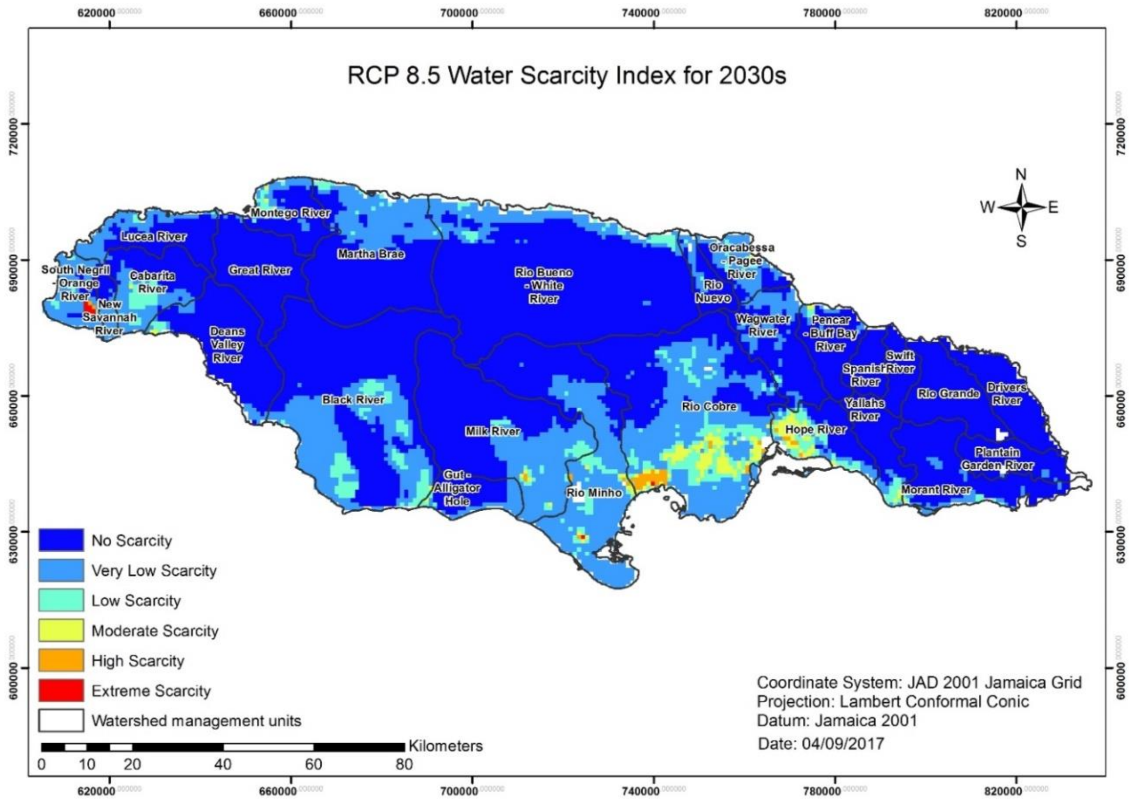


Figure 26: Water stress indicator index for RCP 8.5 scenario by 2030s

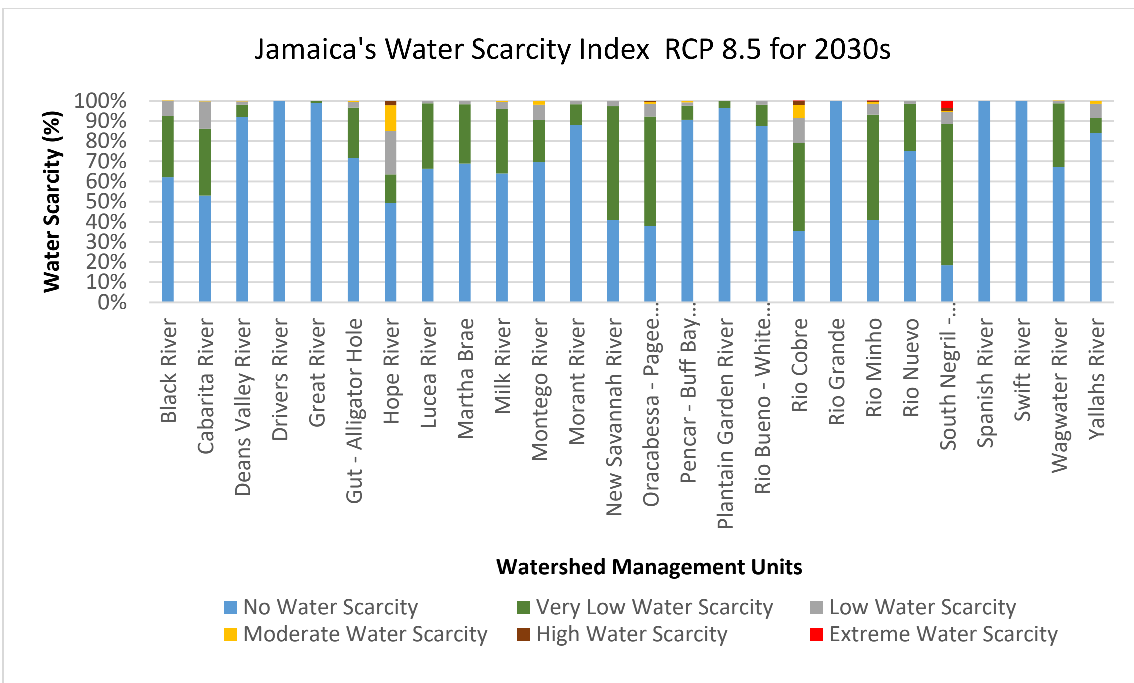


Figure 27: Water scarcity as a percentage of Watershed Management units for RCP 8.5 by 2030s.

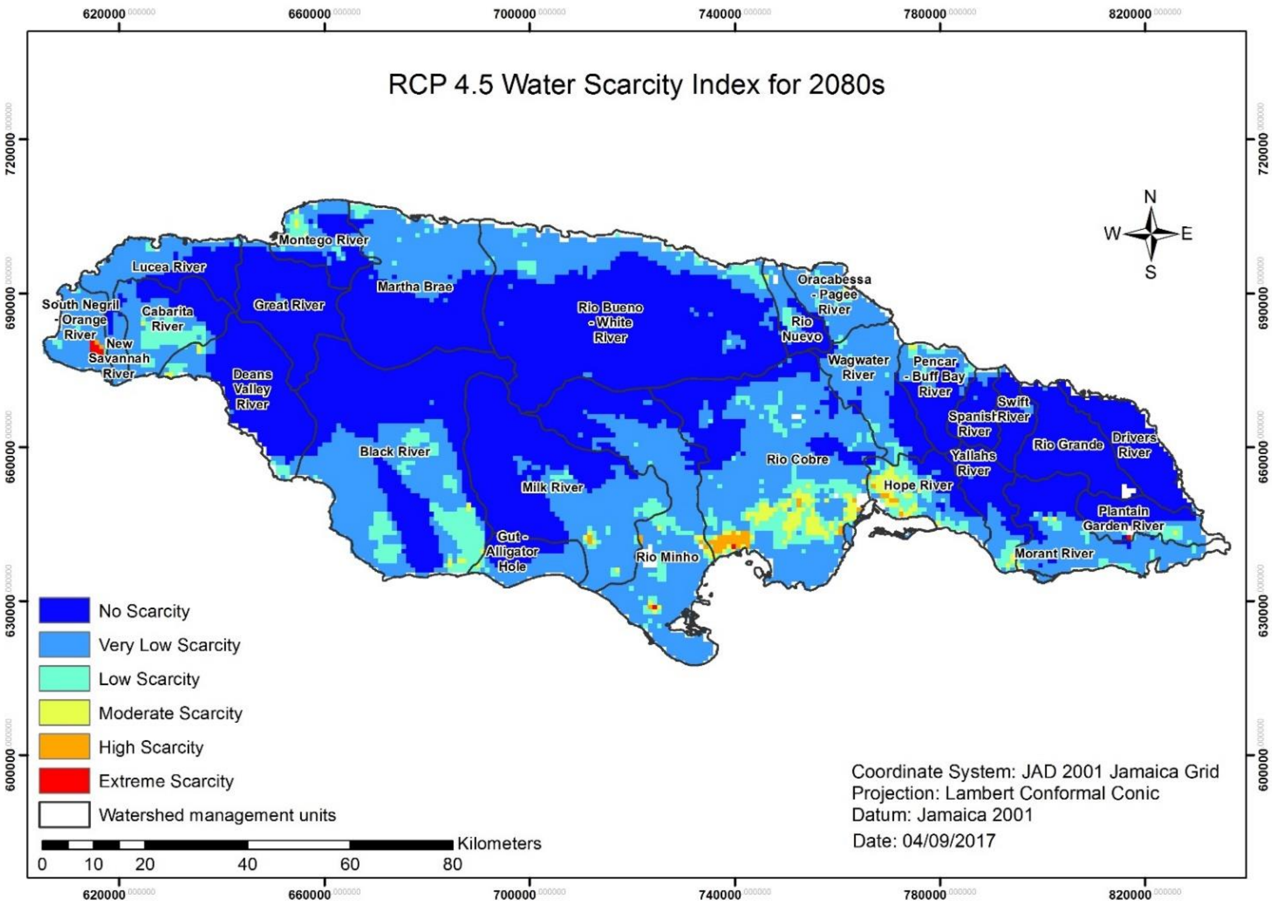


Figure 28: Water stress indicator index for RCP 4.5 scenario by 2080s

From figure 28, it can be observed that by 2080s all watershed management units would have a level of water stress. The eastern and northern catchments that were predominantly no water scarcity areas will experience very low to moderate scarcity while the already water scarce catchments in the south will become high to extreme water scarce. Although the withdrawals were assumed to remain stable with no increase the impacts of physical climate change will be evident. From figure 29 it can be seen where approximately 36% of Plantain Garden that was predominantly a “no scarcity” catchment will become water scarce, with approximately 1 % of extreme water scarcity expected. From figure 30, it can be observed that RCP 8.5 will have the greatest impact on water supply across Jamaica by the 2080s. This will result in the majority of the catchments ranging from low water scarcity to moderate. This can be directly associated with the decrease in precipitation and increase in temperature over the whole island. From figure 31 catchments in western and eastern Jamaica will experience extreme scarcity. Specifically, South Negril and Plantain Garden will experience 3.6% and 1.5% respectively. This can be a result of these catchments receiving the least rainfall, the highest temperatures or both.

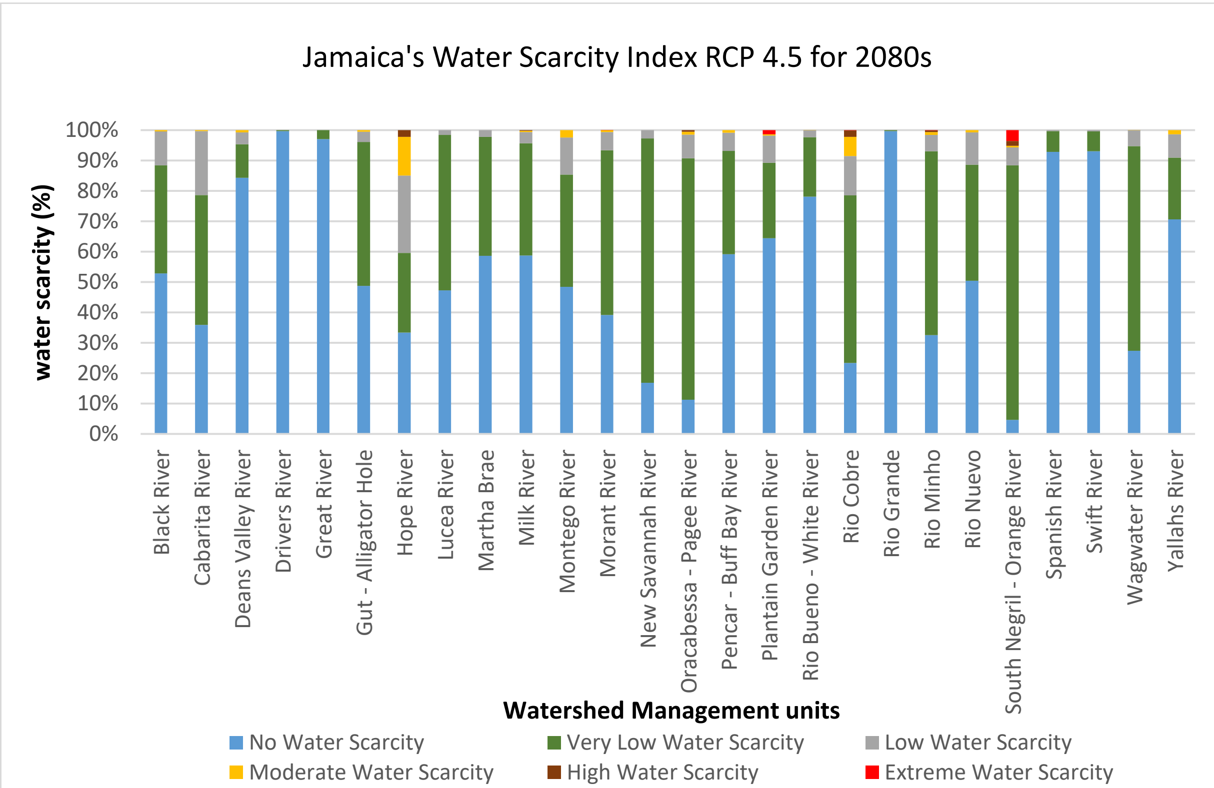


Figure 29: Water scarcity as a percentage of Watershed Management units for RCP 4.5 by 2080s.

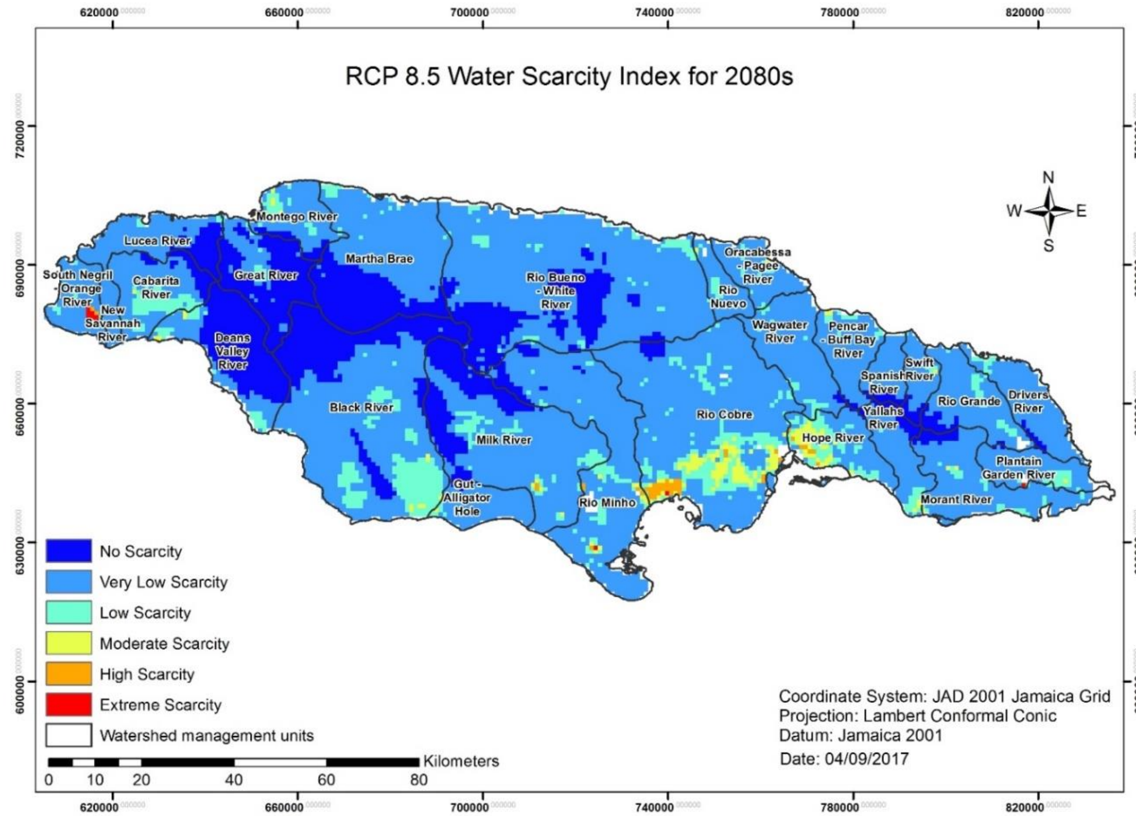


Figure 30: Water stress indicator index for RCP 8.5 scenario by 2080s

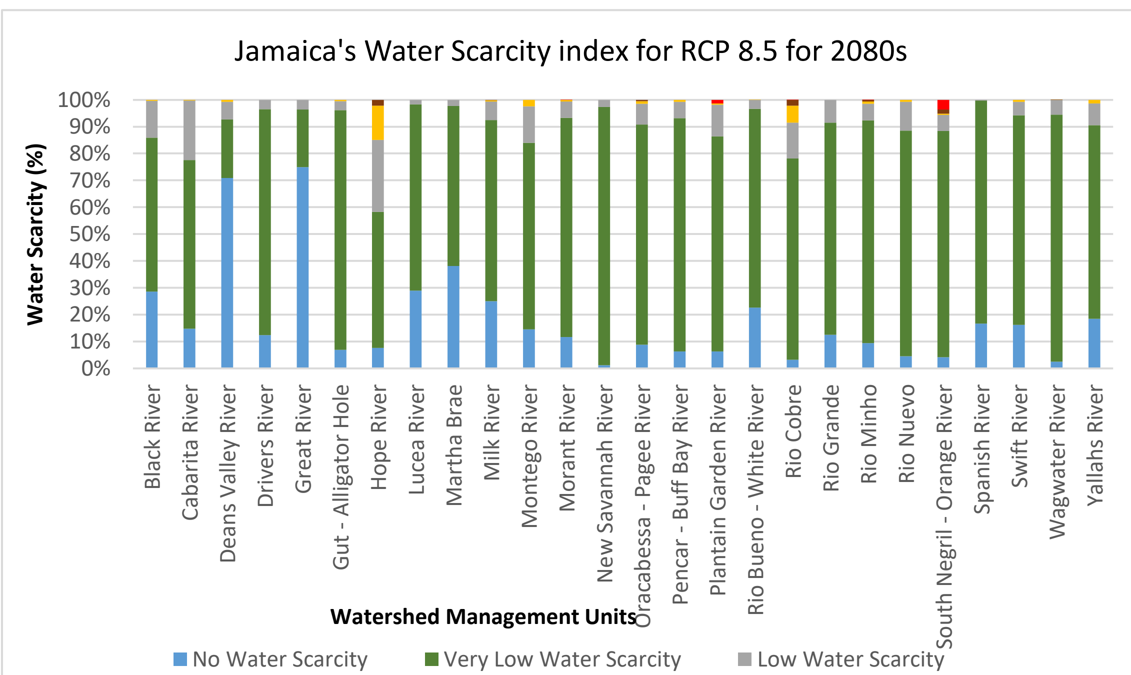


Figure 31: Water scarcity as a percentage of Watershed Management units.

4.5. Hotspot scenarios

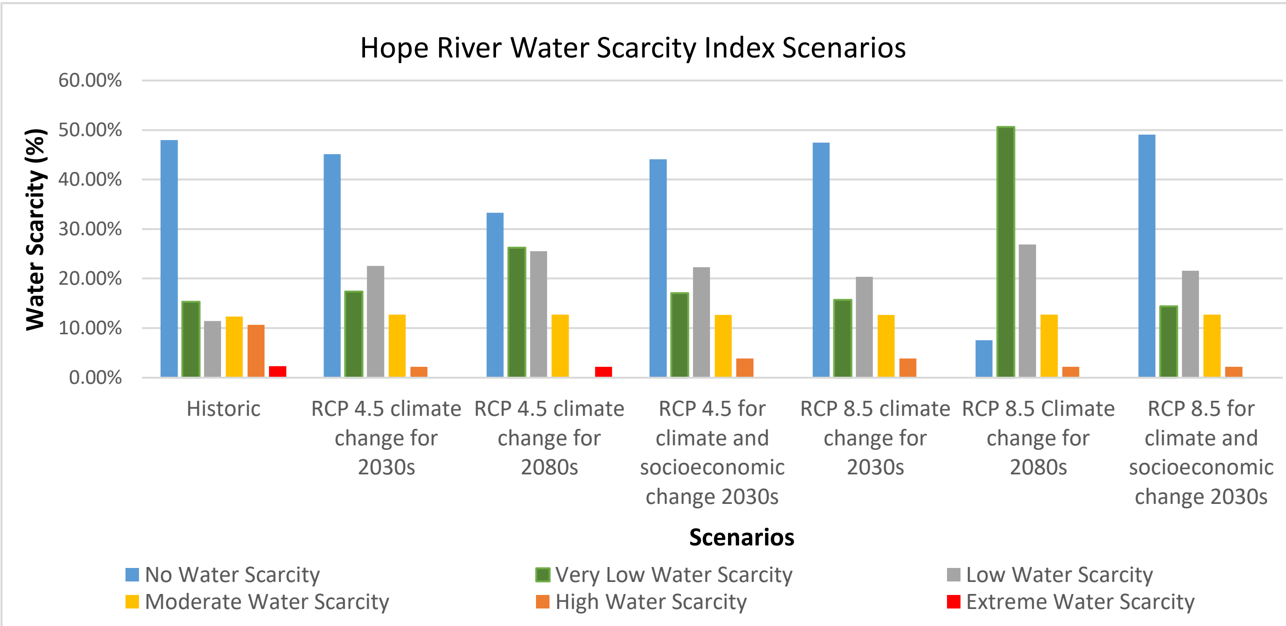


Figure 32: Percentage of water scarcity in Hope River by scenarios.

From figure 32 it can be observed that Hope River historically shows approximately 53% of water stress in which approximately 12 % of the catchment ranges from high to extreme water scarcity. For all scenarios for 2030s figure 32 shows that the catchment will not experience any extreme water scarcity with reductions in water stressed areas for all RCP 4.5 scenario and an increase for scenarios 8.5 in 2030s. However, it can be identified that areas of historically no water scarcity will experience some level of water stress. This can be attributed to uneven distribution and intensity of precipitation spatially within the catchment and the increase of withdrawals in areas that will increase in water supply. It can also be identified that by 2080s majority of the catchment will be water scarce even without any increase in socio-economic withdrawals. For RCP 4.5 67% of the catchment will be water stressed of which 2% will have extreme water scarcity. This will worsen for RCP 8.5 where it can be seen that 93% will be water stressed. This can be associated with the significant reduction in precipitation and highest increase in temperature for RCP 8.5 by 2080s.

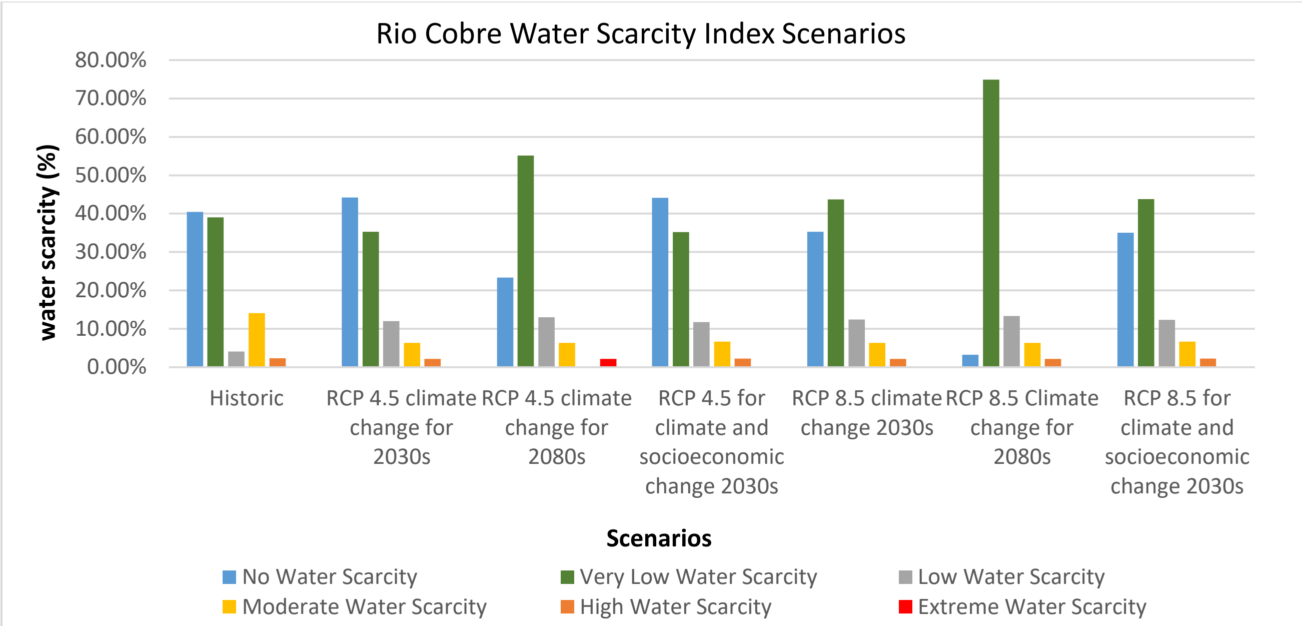


Figure 33: Percentage of water scarcity in Rio Cobre by scenarios.

From figure 33 Rio Cobre historically shows approximately 60% of water stress that is mainly associated with very low water scarcity. By 2030s for RCP 4.5 for both physical climate change and socio-economic withdrawals areas of water scarcity will shift to become areas of no water scarcity. This is not the case for RCP 8.5 scenarios by 2030s. Sections of no scarcity in the catchment will reduce by approximately 5% but areas that were moderately scarce will become areas of low water scarcity. However, it can also be noted that there will be negligibly greater areas experiencing water stress from physical climate change and increase socio-economic withdrawals than the scenario with only change in physical climate by 2030s for RCP 4.5 and RCP 8.5. By the 2080s the catchment will experience significant water stress. For RCP 4.5 by 2080s, the catchment will have some areas of extreme scarcity but approximately 23% will have no scarcity. For RCP 8.5 majority of the catchment will range from very low scarcity to high scarcity with only 3% of the catchment is expected to have no water stress.

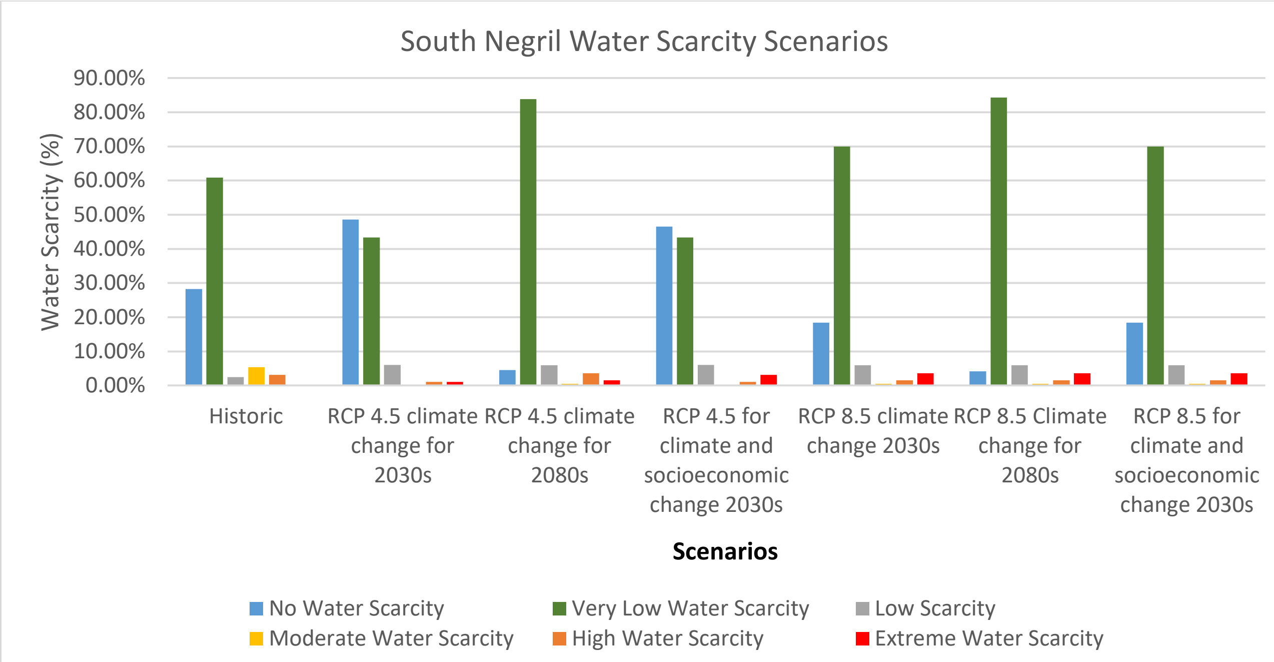


Figure 34: Percentage of water scarcity in South Negril by scenarios.

It can be observed from figure 34 that 82% of South Negril catchment is historically water stressed. However, majority of the stressed areas are associated with very low water scarcity. It can be observed that by 2030s all scenarios show that the catchment will have sections o extreme water scarcity. This is predominantly 4% of the catchment for RCP 8.5 scenarios. Figure 34 demonstrates that RCP 8.5 scenarios of projected socio-economic withdrawals and physical climate change will have the same impact on the catchment even if there were no changes in withdrawals by 2030. By the end of the century RCP 8.5 will result in 96% of the catchment ranging from very low to extreme water scarcity. For RCP 4.5 water scarcity will not be as significant as RCP 8.5. Approximately 46% of the catchment will not experience any water stress. Scenarios for RCP 8.5 by 2030s demonstrated significant water stress for the catchment which means that in the event withdrawals for RCP 8.5 by 2080s were included there will be more water stressed areas.

5.0 CHAPTER FIVE: DISCUSSION

5.1 Water availability

According to Oki (2006) water is a key resource needed for sustaining life and it is paramount to account for its availability. This is usually undertaken using water balance models (Vorosmarty, 2000). However, there are many challenges and uncertainties in undertaking a water budget to determine present and future supply. Rainfall is the main source of freshwater supply in Jamaica and spatial distribution of the available resources was undertaken using long-term water balance equation, Precipitation less evapotranspiration to derive mean annual runoff (see figure 9). From figure 9 and appendix F it can be observed that approximately 63% of rainfall becomes mean annual runoff and varies spatially. It can be seen where the highest run-off is associated with the interior of eastern WMUs while the lowest MAR is distributed along the coastlines of the southern WMUs. This can be attributed to elevation. According to a study undertaken by Pike (2006) 63% of rainfall was MAR and that both rainfall and runoff were dependent on elevation. This study agrees with figure 9 as the eastern WMUs are associated with the highest elevations (see appendix D) and consists of the Country's highest peak, the Blue Mountains. This is also the country's highest rainfall region and receives an annual average rainfall of 5080mm – 6200mm (ODPEM, 2012). The south coast which is relatively flat is the rain shadow region and receives less rainfall than any other areas (Richard, 2008; ODPEM, 2012).Therefore, WMUs of higher elevations and high precipitation are expected to have high MAR. Potential evapotranspiration was also a key component that relates to MAR. It is considered the second most important component of the hydrological cycle (Amarakoon, Chen and Mclean, 2000). This was simulated using Hargreaves- samani approach which incorporated mean air temperature and solar radiation. The spatial variation in PET is also directly related to elevation and was observed that higher altitudes result in lower potential evapotranspiration due to lower air temperatures associated with high elevation areas (Gurtz, Baltensweiler and Lang, 1999). As a result of lower temperatures there would be lower evaporative demand in vegetation. In addition, evapotranspiration can also be linked with albedo of exposure from solar radiation (A. and P.-A., 2013; Gurtz, Baltensweiler and Lang, 1999). Solar radiation increases with elevation. In Jamaica the far eastern tip receives the highest solar radiation while the south receives the majority of higher solar radiation (CSGM, 2012). However, the south is dominated by significant anthropogenic impacts and vegetation cover would be limited in comparison to the mountainous WMUs in the east. Hence, evapotranspiration would be higher for southern WMUs. Therefore, catchments that receive high precipitation and lower evaporation with increased altitude and low albedo exposure are dominated with higher MAR than WMUS that are along the coastline and south of Jamaica.

5.1.1 Streamflow variability

The simulated MAR was evaluated against measured streamflow (see figure 11). The streamflow within a basin is directly related to runoff as a result of streamflow being a component of MAR. It can be observed that there is a moderate positive correlation of 52% between the two. As streamflow increases MAR also increases. This agrees with (Gleick, 1987) that observed that any alterations in MAR will directly impact streamflow. It is evident that streamflow varies spatially (see figure 10).This can be attributed to topography and MAR as seen in figure 9. Since MAR and streamflow are directly related the eastern catchment of higher MAR can be associated with strong precipitation which will result in higher streamflow in eastern WMUs than other catchments. Streamflow is dependent on rainfall intensity and seasonality (ODPEM, 2012). It can be observed in figure 11 that residuals exist. There are overestimation and underestimation of MAR in some WMUs. The variability of soil depth for storage is the most important control of runoff variability and availability (Galvincio, moura and sousa, 2008). However, the methodology undertaken to derive simulated MAR did not take into consideration soil storage. According to Taylor (2006) deriving MAR without soil storage could result in underestimations. However, for the measured streamflow, infiltration into the soil from MAR would have occurred therefore simulated MAR could have overestimations when evaluated against streamflow. In Jamaica, measured streamflow itself could either be overestimated or underestimated as a result of the complex geology. According to Patrick:

“Because of the complexities and variability in the geology it is difficult to model and measure streamflow in WMUs especially the ones fed by groundwater usually in the dry season.

Streamflow can either be overestimated or underestimated. It requires going into the field to measure base flow”.

In deriving MAR assumptions were made for crop coefficient which assumes crop water demand did not vary across WMUs and could have resulted in both overestimation and underestimations. This was evident in smaller catchments in the east and larger catchments in central Jamaica. As a result of Jamaica’s geology and terrain variability it is difficult to model MAR. Mountainous catchments that are highly dependent on climate variables and topography will result in higher errors than in low elevation areas when modelled (Gurtz, Baltensweiler and Lang, 1999).Therefore, greater errors could be associated with mountainous WMUs. According to Pike (2006) discharge is also based on drainage area. However, the larger WMUs have less streamflow (see figure 10). Climate and anthropogenic induce changes in hydrology can directly impact streamflow (Wang and Hejazi, 2011). In Jamaica, floodplains frequently exist in the middle and lower courses of the river due to the location of low elevation (ODPEM, 2012) which is prime land for agriculture. Human activities in the flat areas of the southern basin can result in huge abstractions and water diversions resulting in low flow being measured.

5.2 Climate changes

Climate change can result in shifts in temperatures and precipitation, which has direct impact on water resources (Wang and Hejazi, 2011). Climate change causes alterations in precipitation and temperature (see table 3). From downscaled HADGEM for Jamaica it can be observed that there will be increase warming from 1.3ºC to 1.6ºC by 2030s. However, this trend continues to the end of the century with an expected increase of up to 4.5ºC with business as usually scenario. This is not the case for precipitation. Both increase and decrease in precipitation is expected for 2030s between 4% reduction to 11% increase. By 2080s significant reduction in precipitation is expected irrespective of scenario. Results are similar to (Environmental Solutions Limited, 2009; CGSM, 2012) that shows agreement with GCM models with decrease commencing by 2030s and worsen by the end of the century by 41%. The changes in precipitation and temperature will vary spatially (see figures 12 and 13). The shift is rainfall from eastern to south western watershed management units is expected for 12 (b). This is expected to increase approximately 200 mm in annual rainfall in these catchments. However, this differs for 12(c) where precipitation will decrease across all WMUs except the north eastern catchments. Further reduction is observed in

12 (d) where reduction in rainfall will dominate the eastern WMU and worsen in 12 (e). However for temperature 13 (b) northern WMUs will experience the greatest change while in 13 (c) eastern will be affected most by increased temperatures. The warming trend continues and by 2080s the entire country would experience warming with a maximum temperature of 33ºC. According to (CSGM, 2012) Jamaica will experience increased temperature with greater warming of up to 3.4ºC. The difference between maximum temperatures can be associated with the use of different downscaled models and scenarios. RCPs scenarios have replaced SRES and are expected to generate lower values as SRES did not account for any mitigations (IPCC, 2013). However, RCP resulted in higher values. This is a result of using the HADGEM model. According to Campbell et al (2010) HADGEM represents rainfall and temperatures across the Caribbean well but underestimates rainfall and over estimates temperature in the northern Caribbean.

5.2.1 Impacted Watershed Management Units

According to McKenney and Rosenberg (1993) runoff response to climate change is linked to the sensitivity of PET and ET to changes. The decrease in precipitation (see figure 12) and increase PET and ET with increase temperatures (see figure 13) will negatively affect spatial variability of MAR (see figure 14-17). The southern catchments of Jamaica historically has the lowest MAR while the eastern are associated with the highest MAR. With south west warming due to climate change the southern catchments are expected to have less MAR for all scenarios. However, the change in MAR would not be significant due to already limited freshwater supply in southern catchments (see figures 14-17). This agrees with (McKenney and Rosenberg, 1993). However, the greatest impact on MAR will occur in the eastern WMUs as early as 2030s for all scenarios with RCP 8.5 resulting in greater rainfall reduction (see figure 14 and 15). As a result of runoff being more sensitive to changes in precipitation than temperature (McKenney and Rosenberg, 1993) a reduction exceeding 400 mm of MAR is expected in catchment of high MAR (eastern and central catchments) by 2080s.

5.3 Water Scarcity

The way of life, activities and economy of Jamaica is heavily dependent on rainfall as the source of freshwater supply. As a result the country's sensitivity to any changes in climate, a reduction of the resource would accelerated water demand (Kiefer et al., 2013) which can result in water stressed WMUs. A long term water scarcity index of Jamaica was simulated to represent spatial and temporal variability based on water withdrawals of irrigation, domestic and industry from water available. This include the consideration of environmental flow reserves (see figure 18). This justifies Wang and Hejazi (2011) study that both climate and anthropogenic changes affect hydrology. Figure 18 demonstrated that majority of Jamaica is not water stress. However, the southern WMUs excluding Driver's river have moderate to extreme water scarcity. Water scarcity index higher than 0.4 in a catchment are considered to be highly water stressed (Oki, 2006; Taylor, 2009). However, for this study due to lack of spatial data for water withdrawals across WMUs a relative index from 1-5 was used, where higher that 4 was equivalent to higher than established threshold of 0.4.

According to Patrick:

"Jamaica is not water stressed as we use less than 50% of the available water. The problem is that where the demand is along the south coast is where there is low water supply".

To determine projected water scarcity, climate change projections and projected withdrawals for 2030s were used. As a result of the variations seen in precipitation, the uncertainties in climate change RCPs and climate model, different scenarios were undertaken of water scarcity index (see figure 19-31). This consisted of isolating the effects of socioeconomic growth from the effects of climate change in order to identify the primary drivers of stress on water resources .It is evident that in 2030s water scarcity decreases in some portions of the southern catchments but an increases in South Negril from RCP 4.5. This is attributed to the expected drying in the western and eastern parishes. However, this worsens with RCP 8.5 scenarios. This is attributed to the shift in spatial distribution of rainfall. It was observed that that water needs related to socioeconomic changes will increase considerably in the future, often overshadowing the effect of climate change on levels of water stress. This agrees with (Fant et al., 2016). However, for 8.5

despite scenario, it shows that with climate change alone water stress will also increase. By 2080s even with climate change alone water scarcity will be exacerbated and even more so for scenario RCP 8.5. However, for analysis of the same RCPs used the scenario of expected increase in human withdrawals is slightly greater and will exacerbate water scarcity.

Similar to (Door, 2005; Fant et al., 2016) scenarios were undertaken to quantify the contributions of climate change and anthropogenic changes on water scarcity.

In the absence of independent adaptation or societal response, a much larger portion of the region's population will live in water-stressed regions in the near future (Fant et al., 2016)

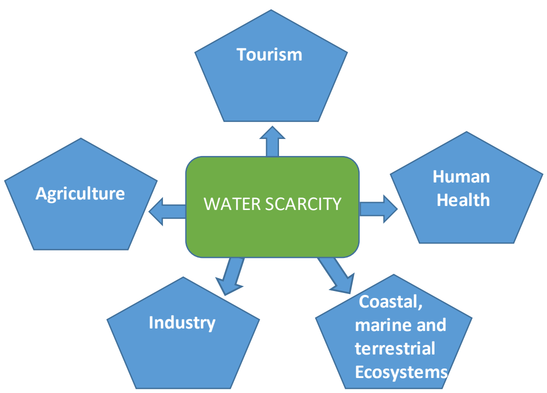


Figure 35: Water Scarcity projected impacts.

5.3.1 Hotspots for Adaptive Management

Hope River

The Hope River consist of the capital of Jamaica, Kingston and is one of the largest metropolitan area in the Caribbean. The WMU is home to 22.2% of Jamaica's population (Richard, 2008), resulting in high population density. Approximately 53% of this WMU is historically water stressed (see figure 32) and shows increase and decrease based on scenarios by 2030s. Although there is expected increase in supply for RCP 4.5 for 2030s, it is negligible and will require proper management. For RCP 8.5 for 2030s approximately 56% of the WMU will experience water stress of different severity. This is a result of limited uneven distribution of freshwater supply and the increase withdrawals that is associated with population growth, commercial and industrial activities that dominate the catchment. The population stood at 651,879 in 2001 (NWC, 2012) and an expected 10% population growth by 2030 for Jamaica (FAO, 2017) interlinked with increase temperatures will result in greater water demands and use. According to (Nwcjamaica.com, 2017) the average household uses 3000 to 5000 gallons monthly. However, hotter days will result in frequent showers and greater amounts of water for consumption. In addition, the increase in industrial activities and manufacturing production will increase pressures on already limited MAR. Currently the WMU has 17.5 million gallons per day supply deficit and is expected to increase by 2030 to 18.9 million gallons per day supply deficit (NWC, 2012).

South Negril- Orange River

Travel and tourism contributed 7.3 % of Jamaica's total GDP in 2006 (Richard, 2008) and is the main livelihood in South Negril WMU. This catchment in western Jamaica consists of the resort community, Negril. As a result of drying in the western WMU, freshwater supply is expected to reduce commencing 2030s. Tourism is a major water withdrawal sector, consumption of water by visitors tend to be three times as much as the local population (Cashman, 2014). The tourist community shows a general increase in water stressed areas based on climate changes and exacerbates with expected increase of socio-economic withdrawals (see figure 34) and variability in rainfall that characterizes the catchment (ODPEM, 2012). In addition, water withdrawals associated with farming of banana and sugar cane in rural Jamaica and results in immense withdrawal from the South Negril River. Sugar cane accounts for 70% of total irrigated lands (MEGJC, 2017) and is expected to increase by 2030 (see Appendix c).

Rio Cobre

Approximately 65% of the Rio Cobre will experience very low water scarcity to high water scarcity for "business as usual" scenarios by 2030s (see figure 33) and worsens to extreme water scarcity by 2080s. The catchment is associated primarily with agricultural activities as a result of fertile soil attributed with southern WMUs in Jamaica. Water stress in the catchment will increase regardless of physical climate change in isolation or climate change interlinked with increased socio-economic water withdrawal (see figure 33). The catchment is even more vulnerable as a result of significant degradation of the watershed due to deforestation (MEGJC 2017). The reduction is water availability in catchment of already limited water and degraded watershed is an indication of water stress. With increase population of Jamaica by 14% by 2030 (see appendix J) significant increase in irrigation demand and availability for increase food production is anticipated (Bates et al., 2008). The increase in water stress will have further implications on livelihoods with farming being the predominant activity in rural areas (Selvaraju et al., 2013).

5.4 Adaptive Management for climate change

Jamaica's current and future water demands are greatest in the southern WMUs due to highly irrigated areas, urban centres and majority of industries being located in southern Jamaica. This poses a problem as a result of available water resources being located on the north of the island (MEGJC, 2017). Changing climate patterns require adaptation or the change in precipitation and temperature will impact food security, tourism, mining, manufacturing industries and urban areas in Jamaica. Undertaking several scenarios for a water scarcity index aided in identifying geographic location of WMUs that are at risk of being water stressed in the future (see figure 20). The Hope River, Rio Cobre and South Negril are important contributors for economic growth and require evaluation of water management strategies and suitability to inform climate response ability and build resilience. According to Bates et al (2008) adaptation actions are necessary to build resilience and are usually directed by regulatory structures to obtain set goals (Neil Adger, Arnell and Tompkins, 2005). Adaptation actions to achieve and maintain resilience requires adjustments in individuals, governments and through collective action, working as groups (Tompkins and Adger, 2004).This agrees with Jamaica's 2004 Water sector Policy strategies and Action Plan that governs the country's water resources and aligns with Vision 2030 Jamaica National Development Plan. The Plan was designed to aid Jamaica in obtaining developed country status by 2030. The current key principles include universal access, financial self-sufficiency, private sector participation in service delivery and a strong commitment to Integrated Water Resources Management (MEGJC, 2017). The use of Integrated Water Resources Management (IWRM) approach is implemented for efficient, equitable and sustainable management of the country's water.

This tool box consists of three fundamental elements that include:

1) Enabling environment
2) Institutional Roles
3) Management Instruments

The government of Jamaica has established the enabling environment through synchronizing policies and legislation. This consists of the Vision 2030 Jamaica-National Development Plan along with the Water Sector Policy revision. The institutional framework for water resources management aligns with the goal of IWRM in which land and water management agencies are currently under the same ministry. This supports the requirement of cross-sectoral integration of agencies and organization (Global Water Partnership, 2014).

5.4.1 Current Water Management strategies Urban Area

The Kingston metropolitan area located within the Hope River WMU and is already experiencing water deficit. This is expected to worsen by 2030s if suitable adaptive management is not implemented. As a result of the geology in this catchment, ground water is negligible and cannot feed surface streams during dry periods. As a result, Mona and Hermitage Reservoirs were established for water storage to meet the growing demands in the urban area. However, the metropolitan area still experience water shortages during dry seasons primarily due to incapacitated infrastructure (NWC, 2012). The supply network in the urban area is mainly from the 1960s and associated with severe internal corrosion .Currently, due to limited water supply, abstraction of water from the neighboring parishes of St. Catherine and St. Thomas is undertaken, yet marginally meets demands (NWC, 2012). Karsts features and alluvial aquifers in northern and central St. Catherine can be identified as the most appropriate areas for abstracting groundwater (NWC, 2011). However, from undertaking several scenarios for water scarcity index in the context of climate change it was identified that the southern WMUs are located within the rain shadow region of the country and is expected to experience decrease in precipitation. St. Catherine is located within the Rio Cobre WMU and is dominated by water stress ranging from very low to high water scarcity. Hence, supplying the Kingston metropolitan area with water from vulnerable catchment with limited water supply will increase the risk of extreme water scarcity in the Rio Cobre. Adaptation to climate change requires conceptualization of sustainable development in order for effective response to build resilience (Tompkins and Adger, 2004). Based on climate change projections, transporting water from an area of low availability is not suitable as water stress may be exacerbated.

5.4.2 Current water management strategies for Agriculture

Currently, local communities in South St. Elizabeth have established strategies of adaptation without outside interventions. This has been possible through planting quick crops, drought resistant crops, reducing production in the dry periods, the use of plastic storage tanks, drip irrigation and trucking of water (Selvaraju et al., 2013). Evapotranspiration of crops play a major role in MAR and with reducing precipitation it is necessary to plant crops that require less water and are drought resistant.

A watershed management committee was also formed consisting of None-governmental organizations, Private and Public Sectors for planning, implementing and monitoring projects and programmes. This initiative interlinks land use and water which is supportive of cross-sectoral integration required for successful IWRM (Global Water Partnership, 2014). This agrees with Selvaraju et al (2013) that an integrated approach is necessary for climate change adaptation. The local watershed management committee is supported by the National irrigation Commission and Water Users Associations to manage water and farmers groups under the Eastern Jamaica Agricultural support project (MEGJC, 2017). This is critical as watersheds play an important role in MAR, streamflow and quality. Community involvement through co-management has proven to be a means of reducing vulnerability and build resilience to climate change. As a result of expected drying occurring on the east and west this initiative is suitable. However, this programme should be implemented in South Negril agricultural communities where extreme scarcity is expected as early as 2030s irrespective of scenario. An extension of the initiative is applicable for Rio Cobre where precipitation will be low and possibly impacting groundwater recharge. The integration between stakeholders can also be identified between WRA and National Environmental Planning Agency (NEPA). According to Patrick:

“The WRA works closely with NEPA that has to approve disposal of waste before water can be abstracted, even if someone has abstracting license”.

Strengths of the Water Sector for Climate change	Weaknesses
• Cross-sectional integration between stakeholders. These include National .Irrigation Commission and community members. NEPA and WRA. • Collective Action at community scale. • Established Web base • Adjusting agricultural crops to drought resistant crops. • Policy and legislative Framework synchronized for adapting to climate change is implemented. • Monitoring of water resources. • Draft Water Supply Plans.	• Lack of amendment of NWC Act (1980) and Irrigation Amendment Act. • Lack Prioritized to respond to the growing threat of climate • Storage of water supply is inadequate. • Poor infrastructure due to lack of finances. • Non-revenue water is high at 65%. • The WRAC is a requirement of the Water Resources Act (1995) committee to advise the minister on policy on management, conservation and water use. This is currently non-active. The Master Plan and water quality control of Jamaica should be amended. • Irrigation methods are not best practices. • Freshwater shortage due to unevenly spatial distribution of rainfall.

Table 4: Summary of current water management strategies

6.0. CHAPTER SIX: LIMITATIONS

The lack of spatial data has been a major limitation to this study. This resulted in immense assumptions for undertaking a long term water budget of Jamaica which is pertinent for understanding past and future trends associated with climate change in order to better cope with impacts. Although a simplistic approach for deriving the long term water budget was undertaken using Arc Hydro tools, spatial variability of hydrological variables across some WMUs were restricted by the complexities of Jamaica's geology that is characterized by karstic limestone (ODPEM, 2012). Modelling based on DEM in Arc Hydro tools was not adequate to accurately model spatial distribution of hydrological variables as the tool is very dependent on landscape for optimum and accurate results (Maidment, 2002). Due to methodological failure associated with the model for surface water component in complex topography, the model was not further utilized to estimate groundwater recharge component. Therefore, this resulted in inaccuracies of water availability, in which both surface and groundwater must be assessed (Milly, 1994). As a result of alluvial aquifers providing 84% of freshwater resources (MJCEG, 2017) accurate water inventory is necessary due to the potential impacts of reduced precipitation resulting in major reduction in groundwater recharge (Cashman, 2014). This will therefore influence any water scarcity assessment and agrees Taylor (2009) that it will be challenging to calculate water scarcity.

This study focused on downscaled GCM projections of future rainfall and temperature of Jamaica using only one model. Although this model agrees with most models predicting a general decrease in precipitation and even more immense by the end of the century, projected temperature change was overestimated. Climate change output deviations provide further uncertainties in projections and could be addressed by undertaking assessment using several models as seen in the Intergovernmental Panel on Climate change reports. However, due to limited data available on downscaled GCM for the new RCPs for Jamaica, only the HADGEM was evaluated.

Jamaica rainfall pattern shows large inter-annual variability and decadal variability (see figure 36 and 37) which results in no significant trend due to fluctuations in El Niño events (ODPEM, 2012). However, the climate is bimodal and is characterized by the island's wet and dry seasons (ESL, 2009; CSGM, 2012; ODPEM, 2012). As a result the agricultural sector planting and reaping seasons are dependent on distinct wet and dry season. The overall decrease in annual rainfall was strongly related to JJA (early wet season) and SON (late wet season) of rainfall (MEGJ, 2014) and requires intra-annual analysis of water availability. According to Taylor (2009), intra-annual approach is identified as a new approach in measuring water scarcity that will play a key role in developing freshwater storage.

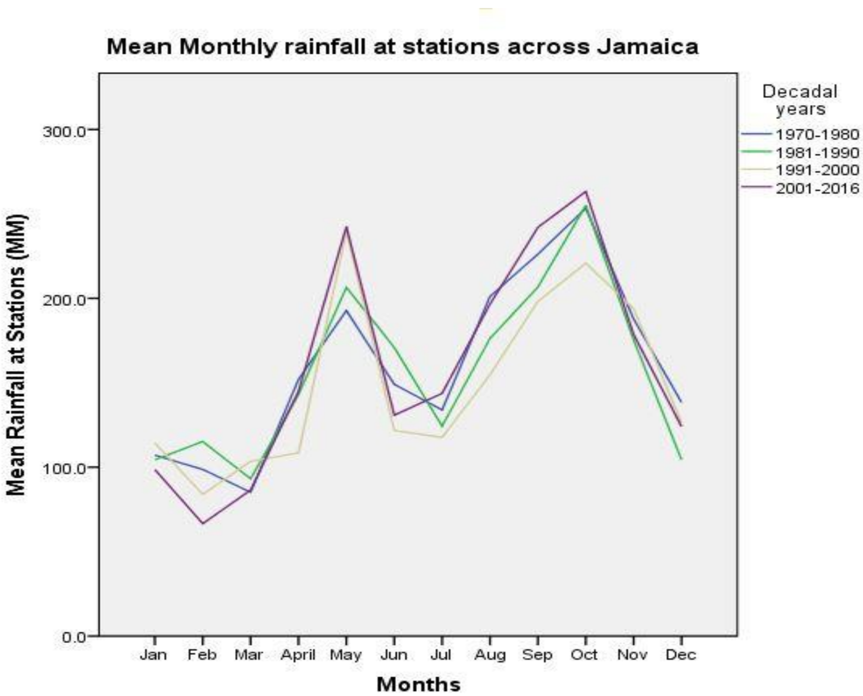


Figure 36: Decadal variability of rainfall across Jamaica.

A warming trend of surface air temperature is evident and projected mean surface air temperatures will increase most rapidly over Jamaica in June, July and August (Campbell et al., 2010) which is also the months associated with decrease precipitation. Assessing seasonal variability in temperatures is also necessary for efficient climate change adaptation. However, due to lack of long- term data availability and time constraint, it was beyond the scope of this research.

Anova table:

Mean Rainfall	*Mean Rainfall*	*Mean difference*
1970-1980	1981-1990	4.310
		(2.310)
1970-1980	1991-2000	11.390*
		(2.370)
1970-1980	2001-2016	0.710
		(2.140)
1981-1990	1970-1980	-4.310
		(2.470)
1981-1990	1991-2000	7.070*
		(2.450)
1981-1990	2001-2016	-3.600
		(2.190)
1991-2000	1970-1980	-11.390*
		(2.380)
1991-2000	1981-1990	-7.070
		(2.450)
1991-2000	2001-2016	-10.680*
		(2.090)
2001-2016	1970-1980	-0.710
		(2.110)
2001-2016	1981-1990	-3.610
		(2.190)
2001-2016	1991-2000	10.680*
		(2.100)
F Statistics	10.56*	

Note: This model provides standard errors which are in parentheses
* Significance at the .05 level

Figure 37: Regression

Water availability for this research did not account for water quality as a component. However, this is an integral aspect that impacts the availability of the resource. According to Lawrencence, Meigh and Sullivan (2002) there can be surplus of water to meet demands but is not available for use if supplies are of poor quality. In Jamaica, the quality of water is projected to deteriorate with climate change and additional pressure from growing socio-economic withdrawals.

Increased mean global sea levels have risen by 0.17 ± 0.05 m over the 20th century is projected to increase to 0.59m by 2100 with respect to 1980-1999 levels (CSGM, 2012). This is expected to have significant effect on groundwater quality in Jamaica on coastal aquifers that are major source for water. This is expected to worsen with the projected severity of increase rainfall intensity, frequency and magnitude in hurricanes that are accompanied by flood waters and high storm surges causing pollution, saline intrusion and damage to water infrastructure (CSGM, 2012; Stephenet al., 2014; Cashman, 2014; Mejia, 2014).

Socio-economic data for undertaking water scarcity index were not readily available and required use of proxies for withdrawals by sector. This resulted in coarse spatial data being used to undertake water scarcity analysis that requires high resolution spatial data. Data conversion of vector to raster is a process that is accompanied by errors (Liao, Bai and Bai, 2012). Hence, resulting in low accuracy and coarse resolution.

7.0. CHAPTER SEVEN: CONCLUSION AND RECOMMENDATION

The hydrological cycle is directly linked to climatology and is very sensitive to climate changes. The results of this study demonstrates that there will be a general decrease in water availability in the future and is therefore necessary to undertake hydrological modelling to determine long-term water budget that is pertinent for understanding the spatial distribution of water supply in order to assess climate change impacts and inform climate change adaptive management of the finite and vulnerable resource.

Freshwater supply variability in Jamaica is dependent on geographic location, climate variables, the geology and topography which all play an important role in water available in WMUs. This study demonstrated that assessing water availability is challenging due to the complexities in the geology of Jamaica and cannot be independently assessed by hydrological modelling. This will result in overestimations or underestimations in some WMUs characterized by karstic limestone features, which make it challenging to separate surface water from groundwater. As a result, in field assessment is required for improved water inventory in these catchments. MAR is directly related to precipitation and follows the same spatial distribution pattern over the island. Therefore, where precipitation is strongest in the eastern WMUs, freshwater supply is also greatest while southern WMUs receive low mean annual rainfall and are associated with limited water supply. This is however problematic, as most of the country’s economic activities and largest urban areas are located in the south and is expected to exacerbate with future climate change.

From analyzing climate change projections for 2030s and 2080s it was observed that there will be a general decrease in precipitation mostly in the eastern and western WMUs and increase temperatures all across Jamaica, with greater warming in the South. This will reduce freshwater availability and increase socio-economic withdrawals as early as 2030s. However, decrease is MAR is dependent on climate change scenarios and time slices. It was evident that greater reduction in freshwater supply was associated with “business as usual scenarios” by the end of the century resulting in significant impact on the South Negril, Hope River and Rio Cobre WMUs. This is attributed to increasing high withdrawal of water for the highly populated urban centre of Kingston, for agriculture and tourism, coupled with reduction of already limited MAR.

Assessment also revealed that even if there were no additional withdrawal of water in the future MAR will reduce just by the impacts of physical climate changes. However, scenarios coupled with projected socio-economic withdrawals demonstrate slightly higher percentage of catchments being water stressed.

In conclusion, despite scenarios and time periods water supply will reduce in the future and will have adverse impacts on livelihoods, health and ecosystems. Therefore, water management strategies and suitability for climate adaptation in the water sector in pertinent. The government of Jamaica has adopted the internationally recommended management approach of implementing Integrated Water Resources Management. This has initiated the synchronization of policies and legislative frameworks, stakeholder involvement and water supply plans. However, there are gaps that can be identified. Hotspot analysis in the context of climate change have not been undertaken to determine suitability of water supply strategies and a need for prioritization of already water stressed and degraded catchments. There are issues in activating collective action committees, funding of water management plans, lack of policy amendments which hinder integration between stakeholders and reduces the efficiency of Integrated Water Resources Management.

Recommendations:

1. Water management plans proposed should prioritize on degraded WMUs to prevent possible irreversible effects on water resources. Integration between WRA and withdrawal sectors in WMUs is required. This is encouraged for the South Negril catchment where tourism and agriculture govern livelihoods.
2. An update of the existing National Water Resources Master Plan is necessary to incorporate the impacts of climate change on the water sector.
3. The amendment of policies to allow for successful IWRM. Through IWRM a Water Resources (WRAC) Advisory Committee is a requirement of the Water Resources Act (1995) and should be led by the director of the WRA to advise the minister in policy, management, conservation and water use (MEGJC, 2017). However, currently the WRA does not have the authority to interact at ministerial level and the WRAC has remained inactive due to the existing regulatory framework.

4. Water management systems for adaptation should include all stakeholders. Currently, stakeholders involved are businesses and society groups. However, the involvement of citizens within the local community should be involved in decision making due to their first-hand knowledge of the issues faced. Therefore, a bottom up approach is necessary. This agrees with (Tompkins and Adger, 2004) that shows that community based resource management have successfully improved resilience in Trinidad and Tobago.
5. Educating local individuals to build capacity is necessary for water resources management. This should be extended to the Tourism sector as conservation of water is necessary. Studies show that approximately 30% of water in homes can be reduced with conservation actions (NwcJamaica.com, 2017).
6. Development of spatial data for sharing between ministries and other stakeholders is necessary. Other Ministries need to develop a web database similar to WRA to enable access to information that can assist in decision making.
7. Rain water harvesting- Approximately 15% of Jamaicans use rain water harvesting (MEGJC, 2017). Rainwater harvesting at the household level should be implemented in the Hope River WMU due to its low start-up cost for storage, low rainfall associated with the catchment and suitable for the catchment due to negligible dependency on groundwater in this catchment. Therefore, harvesting would not affect the rate of ground water recharge.
8. Irrigation –Planting drought tolerant crops coupled with assigned irrigation hours is encouraged especially in the Rio Cobre catchment. This includes irrigation in early mornings or late evenings to decrease evapotranspiration.
9. SUDS (sustainable drainage system) – According to Taylor (2009) disregarding water storage will prevent adaptation to water scarcity. As a result of projected increased rainfall intensity and floods associated with high magnitude hurricane the implementation of SUDS is suitable. SUDS prevent increase in flooding, increased pressure on freshwater due to climate change and provides benefit of landscape irrigation through storage (Shuttleworth et al., 2017). Green SUDS for combined benefits of dealing with storm water and providing water for irrigation in a cost effective way.

8.0 REFERENCES

A., M. and P.-A., C. (2013). Influence of Vegetation Cover on Regional Evapotranspiration in Semi-Arid Watersheds in Northwest China. *Evapotranspiration - An Overview*.

Adger, W., Huq, S., Brown, K., Conway, D. and Hulme, M. (2003). Adaptation to climate change in the developing world. *Progress in Development Studies*, 3(3), pp. 179-195.

Allen, M. and Ingram, W. (2017). *Constraints on future changes in climate and the hydrologic cycle.*

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). FAO Irrigation and drainage paper No. 56. *Rome: Food and Agriculture Organization of the United Nations*, *56*(97), pp.156.

Amarakoon, D., Chen, A. and McLean, P. (2000). Estimating daytime latent heat flux and evapotranspiration in Jamaica. *Agricultural and Forest Meteorology*, 102(2-3), pp.113-124.

Amarasinghe, U. (2003). Spatial variation in water supply and demand across the river basins of India. *Sri Lanka: International Water Management Institute*..

Bates, B., Kundzewicz, Z., Wu, S. and Palutikof, J. (2008). Climate change and water. Technical paper of the intergovernmental panel on climate change. *Geneva: IPCC Secretariat*, pp.210.

Biswas, A. (2008). *Integrated water resources management: Is it working? International Journal of Water Resources Development, 24(1), pp.5-22.*

Boyatzis, R. (1998). *Thematic analysis*. Thousand Oaks, CA: Sage Publications.

Brown, A. and Matlock, M. (2011). *A review of water scarcity indices and methodologies*. Arkansas: University of Arkansas The Sustainability Consortium, pp.1-15.

Calizaya, A., Meixner, O., Bengtsson, L. and Berndtsson, R. (2010). Multi-criteria decision analysis (MCDA) for integrated water resources Management (IWRM) in the Lake Poopo Basin, Bolivia. *Water Resources Management*, 24(10), pp.2267-2289.

Campbell, J., Taylor, M., Stephenson, T., Watson, R. and Whyte, F. (2010). Future climate of the Caribbean from a regional climate model. *International Journal of Climatology*, 31(12), pp.1866-1878.

Cashman, A. (2014). Water security and services in the Caribbean. *Water*, 6(5), pp.1187-1203.

Choi, S., Kim, J. and Lee, D. (2012). Decision of the water shortage mitigation policy using multi-criteria decision analysis. *KSCE Journal of Civil Engineering*, 16(2), pp.247-253.

Climate Studies Group, Mona (CSGM) (2012). *State of the Jamaican climate 2012: Information for resilience building (Full report)*. Kingston: Climate Studies Group, Mona (CSGM).

Daggupati, P., Srinivasan, R., Ahmadi, M. and Verma, D. (2017). Spatial and temporal patterns of precipitation and stream flow variations in Tigris-Euphrates river basin. *Environmental Monitoring and Assessment*, 189(2).

Demuth, S. (2006). *Climate variability and change - hydrological impacts*. Wallingford: The International Association of Hydrological Sciences.

Dessai, S. and Hulme, M. (2007). Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the east of England. *Global Environmental Change*, 17(1), pp.59-72.

Dore, M. (2005). Climate change and changes in global precipitation patterns: What do we know? *Environment International*, 31(8), pp.1167-1181.

Ekwue, E. (2010). Management of water demand in the Caribbean region: Current practices and future needs. *The West Indian Journal of Engineering*, 32(1-2), pp.28-35.

Environment and Disaster Management Unit of the Ministry of Local Government (2011). *The second national communication of Jamaica to the United Nations Framework Convention on Climate Change*. The Government of Jamaica.

Environmental Solutions Limited (2009). *Development of a national water sector adaptation strategy to address climate change in Jamaica*. Kingston: Environmental Solutions Limited, pp.6-16.

Fant, C., Schlosser, C., Gao, X., Strzepek, K. and Reilly, J. (2016). Projections of water stress based on an ensemble of socioeconomic growth and climate change scenarios: A case study in Asia. *PLoS One*, 11(3), pp.e0150633.

Fao.org. (2002). FAO: World agriculture 2030: Main findings. [online] Available at: http://www.fao.org/english/newsroom/news/2002/7833-en.html [Accessed 20 Aug. 2017].

Fao.org. (n.d.). *Chapter 6 - ETc - Single crop coefficient (Kc)*. [online] Available at: http://www.fao.org/docrep/X0490E/x0490e0b.htm [Accessed 4 Jul. 2017].

Farg, E., Arafat, S., Abd El-Wahed, M. and EL-Gindy, A. (2012). Estimation of evapotranspiration ETc and crop coefficient Kc of wheat, in south Nile Delta of Egypt using integrated FAO-56 approach and remote sensing data. *The Egyptian Journal of Remote Sensing and Space Science*, 15(1), pp.83-89.

Fick, S.E. and R.J. Hijmans, 2017. WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology.*

Galletta, A. (2012). *Mastering the semi-structured interview and beyond: From research design to analysis and publication (Qualitative studies in Psychology)*. New York University Press.

Galvin, R. (2015). How many interviews are enough? *Do qualitative interviews in building energy consumption research produce reliable knowledge?* Journal of Building Engineering, 1, pp.2-12.

Galvíncio, J., Moura, M. and Sousa, F. (2008). Water balance model to predict climate change impacts in the watershed Epitácio Pessoa dam– Paraíba River - Brazil. In: *13th World Water Congress*. Campina Grande, pp.1-12.

Gleick, P. (1987). The development and testing of a water balance model for climate impact assessment: Modeling the Sacramento Basin. *Water Resources Research*, 23(6), pp.1049-1061.

Global Water Partnership (2014). Technical focus paper integrated water resources management in the Caribbean: The challenges facing small island developing states. *Global Water Partnership.*

Gössling, S., Peeters, P., Hall, C., Ceron, J., Dubois, G., Lehmann, L. and Scott, D. (2012). Tourism and water use: supply, demand, and security. An international review. *Tourism Management*, 33(1), pp.1-15.

Gurtz, J., Baltensweiler, A. and Lang, H. (1999). Spatially distributed hydrotope-based modelling of evapotranspiration and runoff in mountainous basins. *Hydrological Processes*, 13(17), pp.2751-2768.

Harmsen, E., Mecikalski, J., Mercado, A. and Cruz, P. (2010). Estimating evapotranspiration in the Caribbean region using satellite remote sensing. In: *AWRA 2010 Summer Specialty Conference*. San Juan: AWRA.

Hay, L., Wilby, R. and Leavesley, G. (2000). A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. *JAWRA Journal of the American Water Resources Association*, 36(2), pp.387-397.

Hill, M., Braaten, R., Veitch, S., Lees, B. and Sharma, S. (2005). Multi-criteria decision analysis in spatial decision support: the ASSESS analytic hierarchy process and the role of quantitative methods and spatially explicit analysis. *Environmental Modelling & Software*, 20(7), pp.955-976.

IPCC (2013). *Climate change 2013 The Physical Science Basis. Working group I contribution to the fifth assessment report of the intergovernmental panel on climate change.* New York: Cambridge University Press.

Johnson, R. and Onwuegbuzie, A. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Researcher*, 33(7), pp.14-26.

Johnston, R. (2015). *Monitoring the Water SDG An emerging framework*. Swiss Water Partnership. Swiss Water Partnership

Kamble, B., Irmak, A. and Hubbard, K. (2013). Estimating crop coefficients using remote sensing-based vegetation index. *Remote Sensing*, 5(4), pp.1588-1602.

Kiefer, J., Clayton, J., Dziegielewski, B. and Henderson, J. (2013). *Changes in water use under regional climate change scenarios*. Water Research Foundation.

L. Y. Rao, G. Sun, C. R. Ford and J. M. Vose (2011). Modeling potential evapotranspiration of two forested watersheds in the southern Appalachians. *Transactions of the ASABE*, 54(6), pp.2067-2078.

Lal, M., Harasawa, H. and Takahashi, K. (2002). Future climate change and its impacts over small island states. *Climate Research*, 19, pp.179-192.

Lawrence, P., Meigh, J. and Sullivan, C. (2002). *The water poverty index: an international comparison*. KERP. Staffordshire: The Keele Economics Department, pp.4-13.

Li, Z. (2014). Watershed modeling using arc hydro based on DEMs: a case study in Jackpine watershed. *Environmental Systems Research*, 3(1), pp.11.

Liao, S., Bai, Z. and Bai, Y. (2012). Errors prediction for vector-to-raster conversion based on map load and cell size. *Chinese Geographical Science*, 22(6), pp.695-704.

Loáiciga, H. (2003). Climate change and ground water. *Annals of the Association of American Geographers*, 93(1), pp.30-41.

Maidment, D. (2002). Arc Hydro GIS for Water Resources vol 1. [ebook] RedLands: ESRI. Available at: https://books.google.co.uk/books?hl=en&lr=&id=07vH7Sf0v6MC&oi=fnd&pg=PP7&dq=ArcHydro+tools+for+stremflow+data&ots=ajJwvCbflx&sig=OED3XDpP7aRsZElDBCMhHvSdTis#v=onepage&q=ArcHydro%20tools%20for%20stremflow%20data&f=false [Accessed 5 Aug. 2017].

Martin, A., and Charles, P.-A. (2013). Influence of vegetation cover on regional evapotranspiration in semi-arid watersheds in Northwest China. *Evapotranspiration - An Overview*.

McKenney, M. and Rosenberg, N. (1993). Sensitivity of some potential evapotranspiration estimation methods to climate change. *Agricultural and Forest Meteorology*, 64(1-2), pp.81-110.

Mckenzie,, R., Chunda, C., Rademeyer, J. and Wegelin, W. (2007). Integration of demand side management and supply side management. *In: SANCHIAS Conference*. WRP Consulting Engineers (Pty) Ltd.

McVicar, T., Van Niel, T., Li, L., Hutchinson, M., Mu, X. and Liu, Z. (2007). Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology*, 338(3-4), pp.196-220.

Mejia, A. (2014). *Water scarcity in Latin America and the Caribbean myths and reality*. pp.3-16.

Merem, E., Twumasi, Y., Wesley, J., Isokpehi, P., Shenge, M., Fageir, S., Crisler, M., Romorno, C., Hines, A., Hirse, G., Ochai, S., Leggett, S. and Nwagboso, E. (2017). Analyzing water management issues using GIS: The case of Nigeria. *Geosciences*, 7(1), pp.20-46.

Milly, P. (1994). Climate, soil water storage, and the average annual water balance. *Water Resources Research*, 30(7), pp.2143-2156.

Ministry of Agriculture Rural Physical Planning Division (1989). *A computerized procedure for rating the land quality adequacy of water supply to annual crops under rainfed conditions*. Kingston: Ministry of Agriculture Rural Physical Planning Division Soil Survey Project, pp.4-7.

Ministry of Economic Growth and Job Creation (2014). *Biennial Update Report of Jamaica, Covering GHG Emissions for 2006- 2012.*

Ministry of Economic Growth and Job Creation (2017). *Draft National Water Sector Policy and Implementation Plan 2017*. Kingston: Ministry of Economic Growth and Job Creation.

Ministry of Water (1999). *Jamaica Water Sector Policy Paper*. Ministry of Water.

National Water Commission (2011). *Water Supply Plans St. Catherine*. [online] Kingston: National Water Commission. Available at: http://www.nwcjamaica.com/uploads/Advertisements/PPLan%20-%20PDF/Draft%20St.%20Catherine%20WS%20PPlan%20-%20October%2012%202011.pdf [Accessed 15 Sep. 2017].

National Water Commission (2012). *Kingston and St. Andrew Water Supply Plans-Draft*. [online] National Water Commission. Available at: http://www.nwcjamaica.com/uploads/Advertisements/PPLan%20-%20PDF/Draft%20KSA%20WS%20PPLan%20-%20October%2012%202011.pdf [Accessed 18 Sep. 2017].

Natural Resources Conservation Authority and Planning Institute of Jamaica (1995). *Jamaica National Environmental Action Plan*. Kingston: Natural Resources Conservation Authority and Planning Institute of Jamaica.

Nwcjamaica.com. (2017). *National Water Commission | Jamaica*. [online] Available at: http://www.nwcjamaica.com/Conservation [Accessed 18 Sep. 2017].

Neil Adger, W., Arnell, N. and Tompkins, E. (2005). Successful adaptation to climate change across scales. *Global Environmental Change*, 15(2), pp.77-86.

ODPEM (2012). *Country Document for Disaster Risk Reduction: Jamaica*. [online] ODPEM. Available at: http://dipecholactools.org/jamaica/4-national-context/4-1-physical-environment/ [Accessed 6 Sep. 2017].

ODPEM (2015). *Draft Negril Climate Risk Atlas*. [online] Kingston: ODPEM. Available at: http://www.odpem.org.jm/Portals/0/Mitigation_Preparedness/GIS/Chap%201-2%20Negril%20Draft%20Risk%20Atlas.pdf [Accessed 6 Sep. 2017].

Oki, T. (2006). Global hydrological cycles and world water resources. *Science*, 313(5790), pp.1068-1072.

Pike, A. (2006). Application of digital terrain analysis to estimate hydrological variables in the Luquillo Mountains of Puerto Rico. In: *Fifth FRIEND World Conference*. [online] Philedelphia: IAHS, pp.81-85. Available at: http://iahs.info/uploads/dms/13640.18-81-85-78-308-Pike.pdf [Accessed 12 Sep. 2017].

Planning Institute of Jamaica (2014). *Investment project 1 strategic programme for climate resilience*. Kingston: Environmental Solutions Ltd., pp.10-12.

Richards, A. (2008). *Development Trends in Jamaica's Coastal Areas and the Implications for Climate Change*. Planning Institute of Jamaica.

Rijsberman, F. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management*, 80(1-3), pp.5-22.

Rogers, M., Sinden, J. and De Lacy, T. (1997). The precautionary principle for environmental management: A defensive-expenditure application. *Journal of Environmental Management*, 51(4), pp.343-360.

Samani, Z. (2000). Estimating solar radiation and evapotranspiration using minimum climatological data. *Journal of Irrigation and Drainage Engineering*, 126(4), pp.265-267.

Selvaraju, R., Trapido, P., Santos, N., Lacasa, M. and Hayman, A. (2013). *Climate Change and Agriculture in Jamaica*. [online] Rome: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/018/i3417e/i3417e.pdf [Accessed 18 Sep. 2017].

Sheffield, J., Wood, E. and Munoz-Arriola, F. (2010). Long-term regional estimates of evapotranspiration for Mexico based on downscaled ISCCP Data. *Journal of Hydrometeorology*, 11(2), pp.253-275.

Shuttleworth, A., Nnadi, E., Mbanaso, F., Coupe, S., Voeten, J. and Newman, A. (2017). Applications of SuDS Techniques in Harvesting Stormwater for Landscape Irrigation Purposes: Issues and Considerations. *Current Perspective on Irrigation and Drainage*. [online] Available at: https://www.intechopen.com/books/current-perspective-on-irrigation-and-drainage/applications-of-suds-techniques-in-harvesting-stormwater-for-landscape-irrigation-purposes-issues-an [Accessed 15 Sep. 2017].

Smakhtin, V., Revenga, C., Doll, P., Tharme, R., Nackoney, J. and Kura, Y. (2004). *Taking into account environmental water requirement in global-scale water resources assessments*. IWMI.

Statistics.laerd.com. (2017*). One-way ANOVA in SPSS Statistics - Step-by-step procedure including testing of assumptions*. [online] Available at: https://statistics.laerd.com/spss-tutorials/one-way-anova-using-spss-statistics.php [Accessed 22 Aug. 2017].

Stephenson, T., Vincent, L., Allen, T., Van Meerbeeck, C., McLean, N., Peterson, T., Taylor, M., Aaron-Morrison, A., Auguste, T., Bernard, D., Boekhoudt, J., Blenman, R., Braithwaite, G., Brown, G., Butler, M., Cumberbatch, C., Etienne-Leblanc, S., Lake, D., Martin, D., McDonald, J., Ozoria Zaruela, M., Porter, A., Santana Ramirez, M., Tamar, G., Roberts, B., Sallons Mitro, S., Shaw, A., Spence, J., Winter, A. and Trotman, A. (2014). Changes in extreme temperature and precipitation in the Caribbean region, 1961-2010. *International Journal of Climatology*.

Suchorski, A., 2007. A summary of integrated water resources management (IWRM) and its potential in the Caribbean.

Taylor, R. (2009). Rethinking water scarcity: The role of storage. *Eos, Transactions American Geophysical Union*, 90(28), pp.237.

The National Report on Integrating the Management of Watersheds and Coastal Areas In Jamaica. (2001). Natural Resources Conservation Authority.

Tompkins, E. and Adger, W. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society*, 9(2).

UNEP (2012). *Integrated Water Resources Management Planning Approach for Small Island Developing States*. [online] UNEP. Available at: http://www.unep.org/nairobiconvention/sites/unep.org.nairobiconvention/files/integrated_water_resources_management.pdf [Accessed 8 Sep. 2017].

UNESCO-IHP (2014). *Water in the post-2015 Development Agenda and Sustainable Development Goals Discussion paper*. [online] Paris: UNESCO-IHP. Available at: http://unesdoc.unesco.org/images/0022/002281/228120e.pdf [Accessed 8 Sep. 2017].

United Nations (1992). *United nations framework convention on climate change*. United Nations, pp.7.

United Nations (2012). *Water and a green economy in Latin America and the Caribbean*. Santiago: United Nations.

United Nation Environment Programme (2008). *Climate change in the Caribbean and the challenge of adaptation*. Panama: United Nation Environment Programme.

US Army Corps (2001).W*ater resources assessment of Jamaica*. US Army Corps of Engineers Mobile District & Topographic Engineering Center.

Vorosmarty, C. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. *Science*, 289(5477), pp.284-288.

Wang, D. and Hejazi, M. (2011). Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. *Water Resources Research*, 47(10).

Water Resources Authority (1990). *The Water Resources Development Master Plan of Jamaica*. Kingston: Water Resources Authority.

Water Resources Authority (2005). *A National Water resources master plan for Jamaica, 2nd Draft*. Kingston: Water Resources Authority.

Wra.gov.jm. (2017). *Water Resources Authority*. [online] Available at: http://www.wra.gov.jm/ [Accessed 26 Jul. 2017].

9.0 APPENDIX

Appendix A

Dataset	Data Type	Source
Irrigation	Vector	National Spatial Data Management Division
Population density	Vector	National Spatial Data Management Division
Gross domestic product (GDP)	Raster	Global Risk Data Platform
Streamflow	Vector	Water Resources Authority Jamaica
Rivers	Vector	Water Resources Authority Jamaica
Rainfall	Excel	Meteorological Service Jamaica
Minimum Temperature	Excel	Meteorological Service Jamaica
Maximum Temperature	Excel	Meteorological Service Jamaica
Average Temperature	Raster 30 seconds	Worldclim
Precipitation	Raster 30 seconds	Worldclim
Solar radiation	Raster 30 seconds	Worldclim
Watershed Management units	Vector	Water Resources Authority Jamaica
Digital Elevation Model (DEM)	Raster	National Spatial Data Management Division
Hydrologic Basins	Vector	Water Resources Authority Jamaica
HADGEM RCP 4.5 and 8.5 Precipitation rate 2030 & 2080	NetCDF	Climate Studies Group Mona Department of Physics
HADGEM RCP 4.5 and 8.5 Mean 2m temperature 230 & 2080	NetCDF	Climate Studies Group Mona Department of Physics

Appendix B

Participant	Responses	Themes
Managing Director WRA Jamaica Patrick	The participant has been working at the WRA since 1972. He spoke of the fairly well data collection for water inventory across the island. He also assured that Jamaica is not water scarce and is currently using less than 50% of the total water resources. Approximately 50% of the resources is ground water and the other 50% is surface water. However, groundwater is mostly used and it is in in the western 2/3 of the country. The participant also stated that there was sufficient water to meet demands but the issue is that where the demand is along the southside that is where there is less supply. This has resulted in a few stressed hydrological basins. where there are no well defined drainage network. In some catchments the flows measured is a combination of ground water recharge and surface flow. During dry season these catchments become ground waterfed. He spoke of the need for infield experience for water inventory as a model cannot truly represent some catchments.	Water Availability
	There are anthropogenic challenges that exist. Managing the waste from Bauxite mudlake and managing the waste from the Rum Industry to prevent pollution of groundwater. There are also challenges for sewage in urban areas. There are mainly old infrastructure which cause leaks and groundwater contamination. He also stated that significant amount of water does not reach consumer due to leaks from old infrastructure, stolen water along the way and unpaid. Only 40% of the water sent into the system is paid for.	Challenges
	The participant was aware of the implications of climate change. The variations in rainfall patterns will have mpact on farmers who plan agricultural activities based on the dry and wet season. This variation could also mean longer periods of droughts. This will also affect the amount of water that can be stored. With the increase in temperatures there will be increase evapotranspiration by plants and demand from sectors will increase. When it is hot people will shower more often.	Climate changes
	The use of IWRM approach is being implemented and the WRA works closely with organizations such a National Environmental Planning Agency (NEPA) who has to approve how waste the is generated from abstraction will be dismissed. They also work closely with National Works Agency (NAW) to provide flood plain maps and WRA also collaborates with Disaster planning agencies and international stakeholders to provide a web database.	Stakeholders

Appendix C

UNIVERSITY OF
Southampton

CONSENT FORM

Study title: Evaluating water management strategies and suitability for climate change adaptation for Jamaica.

Researcher name: Danellia Aitcheson
ERGO number:29582

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (date: 21/7/2017) and have had the opportunity to ask questions about the study.	✓
I agree to take part in this research project and agree for my data to be used for the purpose of this study.	✓
I understand my participation is voluntary and I may withdraw two weeks after the interview for any reason without my rights being affected.	✓

Name of participant (print name)……Mr. Herbert Thomas

Signature of participant……………………………………………………………………

Date……………………………………………2014 – 08 – 10……………………

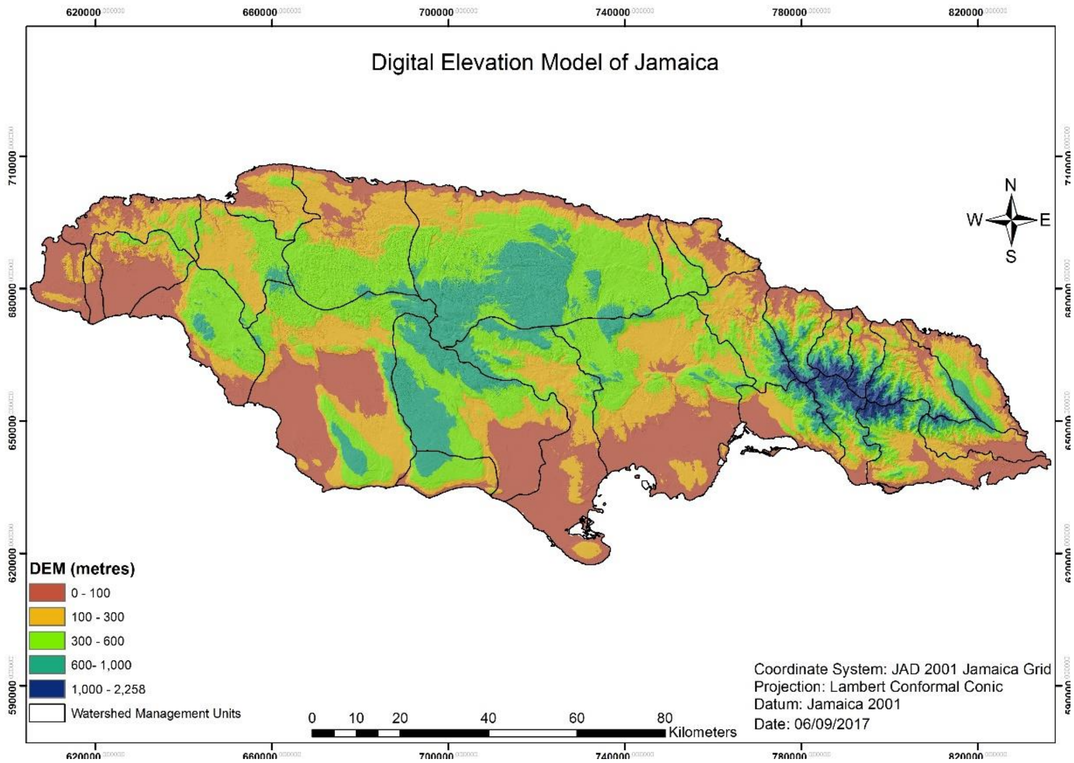
Name of researcher (print name) Danelllia Aitcheson

Signature of researcher ……………………………………………………………………

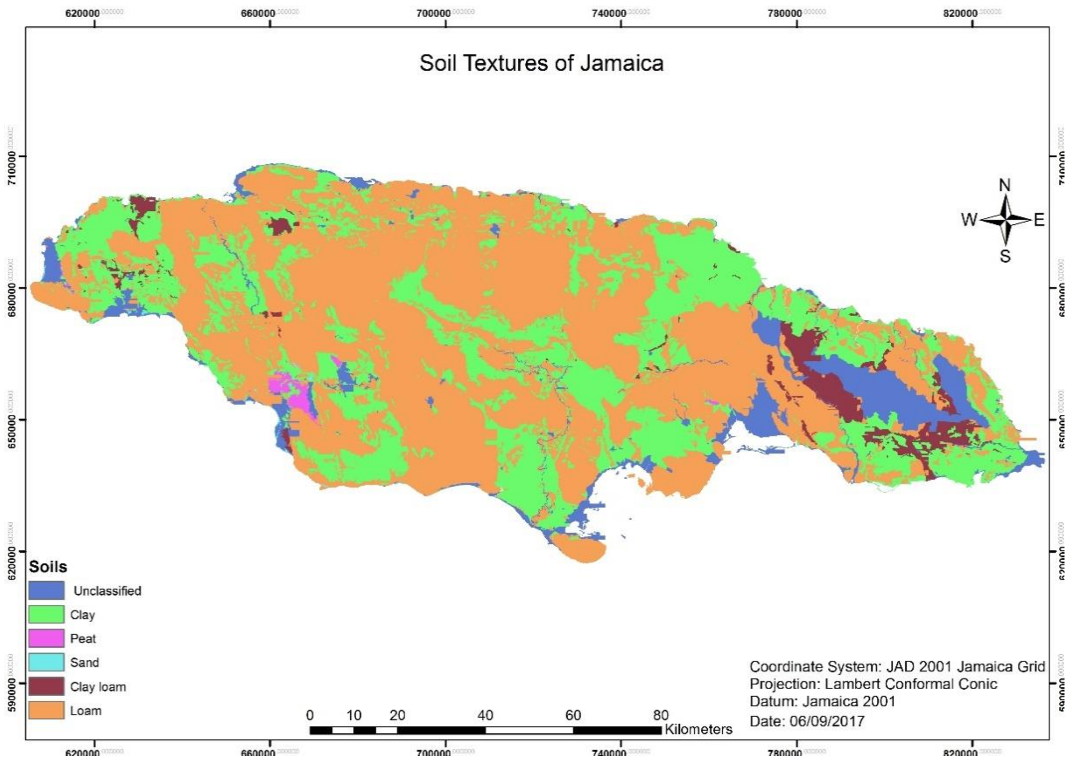
Date……………………………………………………………………………………………

[21/7/2017] [Ergo number: 29582]

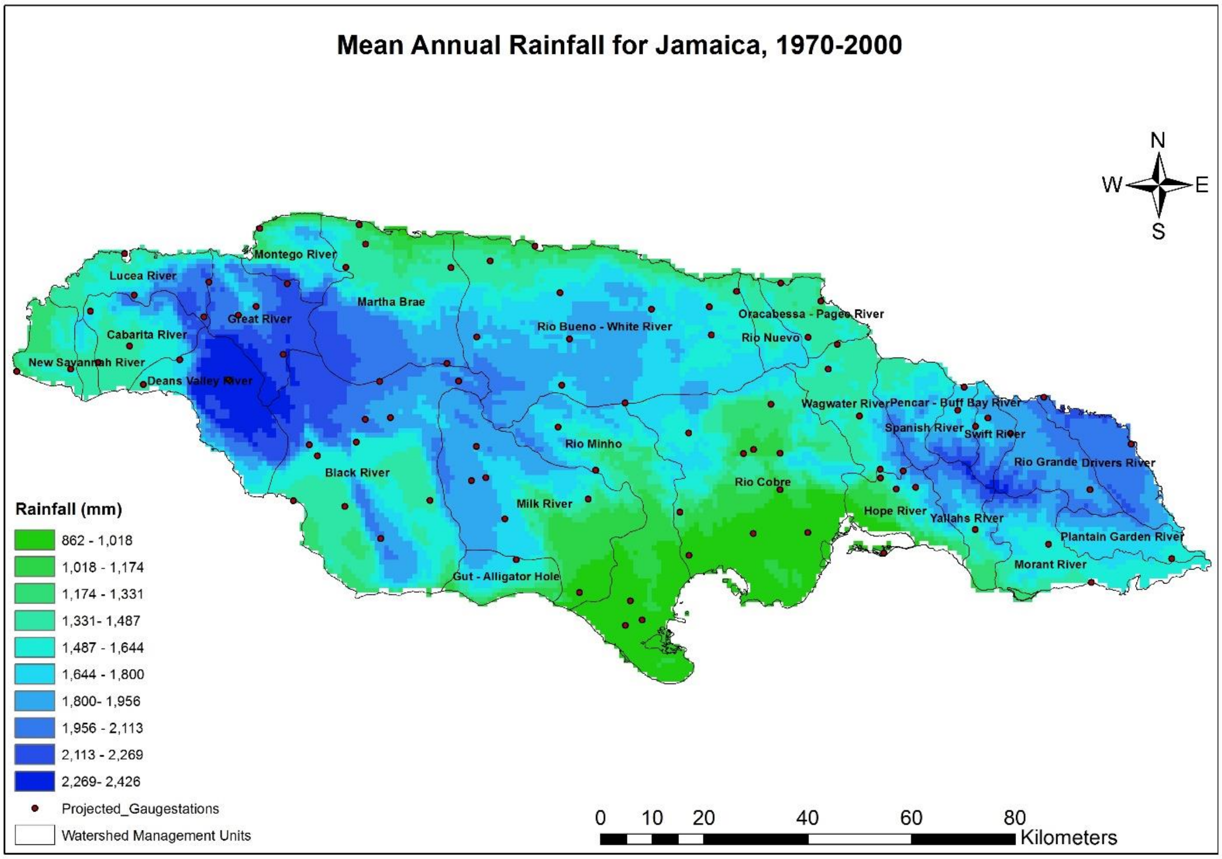
Appendix D



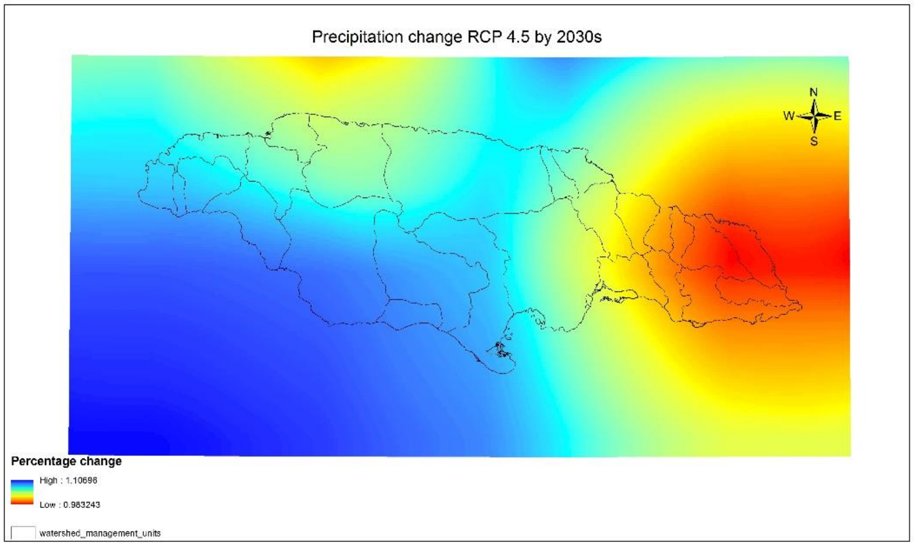
Appendix E

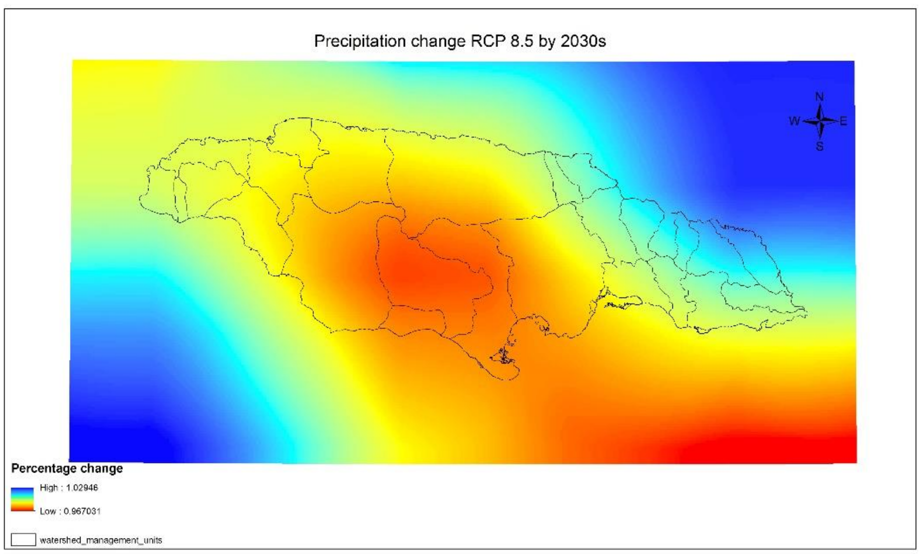


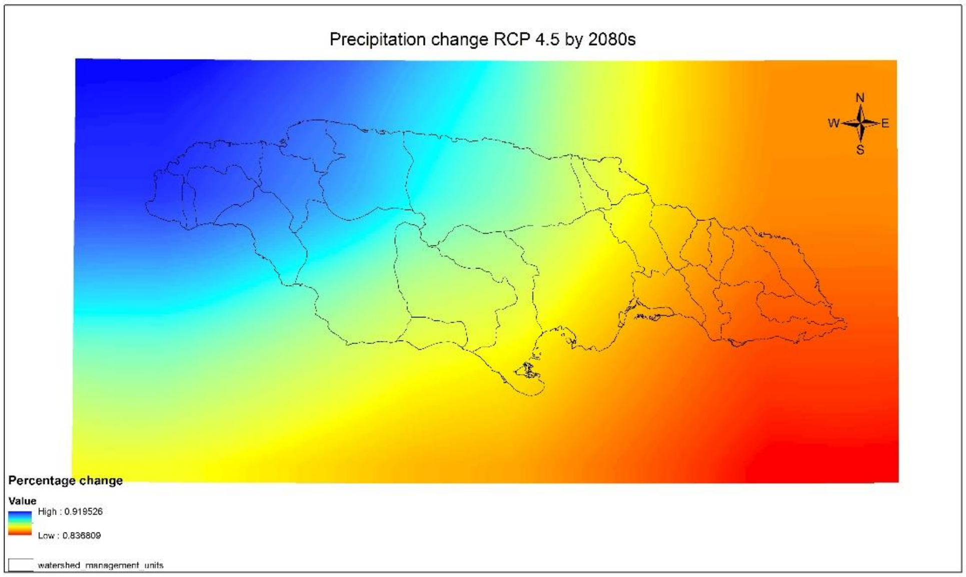
Appendix F

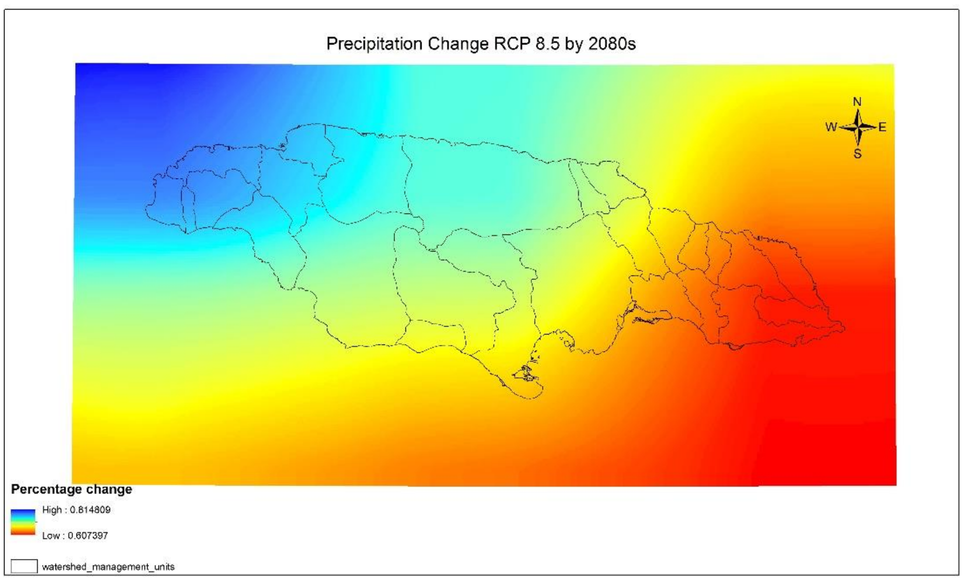

Mean Annual Rainfall for Jamaica, 1970-2000
N
W
E
S
Montego River
Lucea River
Martha Brae
Great River
Cabarita River
New Savannah River
Deans Valley River
Rio Bueno - White River
Oracabessa - Pagee River
Rio Nuevo
Wagwater River
Pencar - Buff Bay River
Spanish River
Swift River
Rio Grande Drivers River
Rio Minho
Black River
Rio Cobre
Milk River
Hope River
Yallahs River
Plantain Garden River
Morant River
Gut - Alligator Hole
Rainfall (mm)
862 - 1,018
1,018 - 1,174
1,174 - 1,331
1,331- 1,487
1,487 - 1,644
1,644 - 1,800
1,800- 1,956
1,956 - 2,113
2,113 - 2,269
2,269- 2,426
Projected_Gaugestations
Watershed Management Units
0 10 20 40 60 80
Kilometers

Appendix G

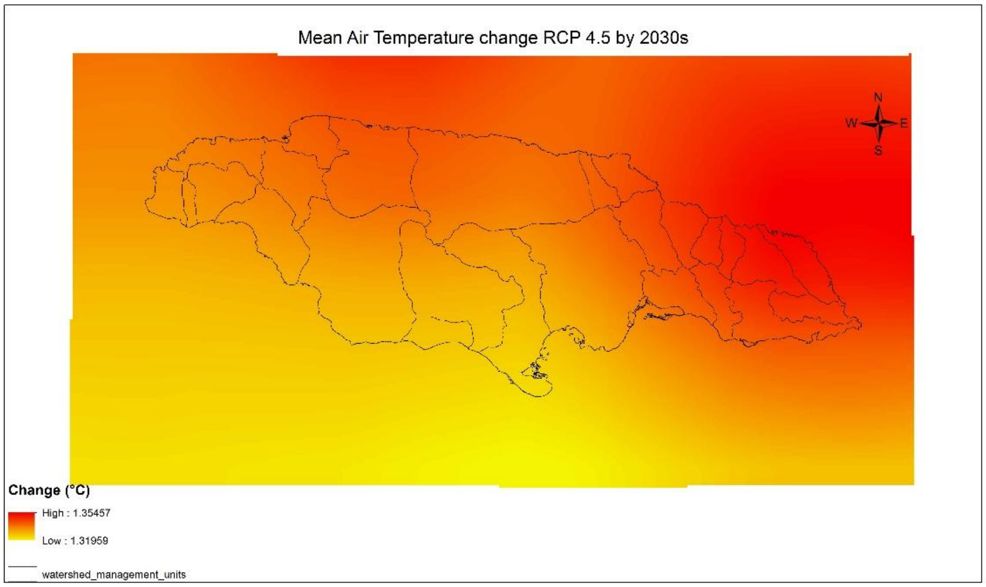

Precipitation change RCP 4.5 by 2030s
N
W
E
S
Percentage change
High : 1.10696
Low : 0.983243
watershed_management_units

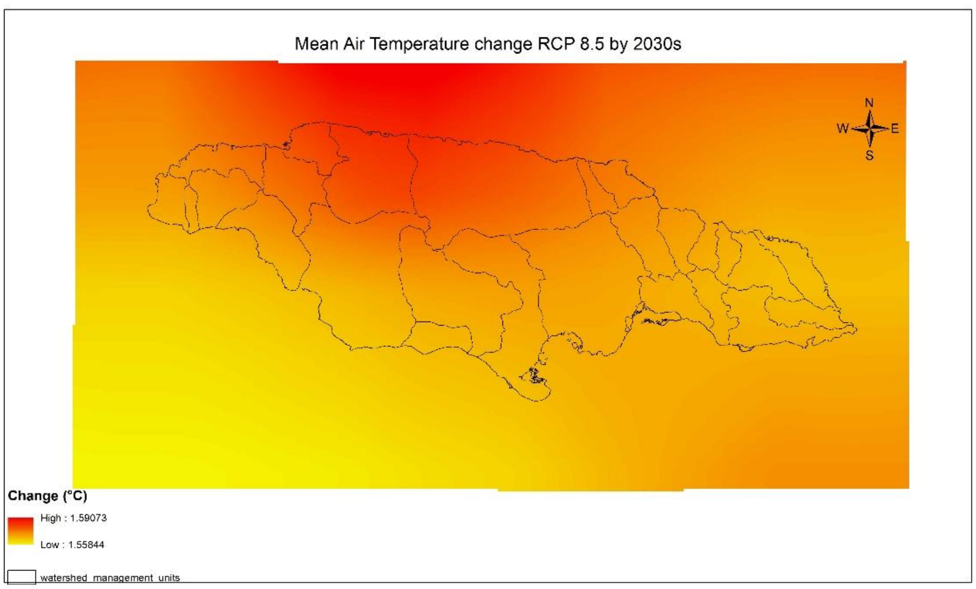

Precipitation change RCP 8.5 by 2030s
N
W
E
S
Percentage change
High : 1.02946
Low : 0.967031
watershed_management_units

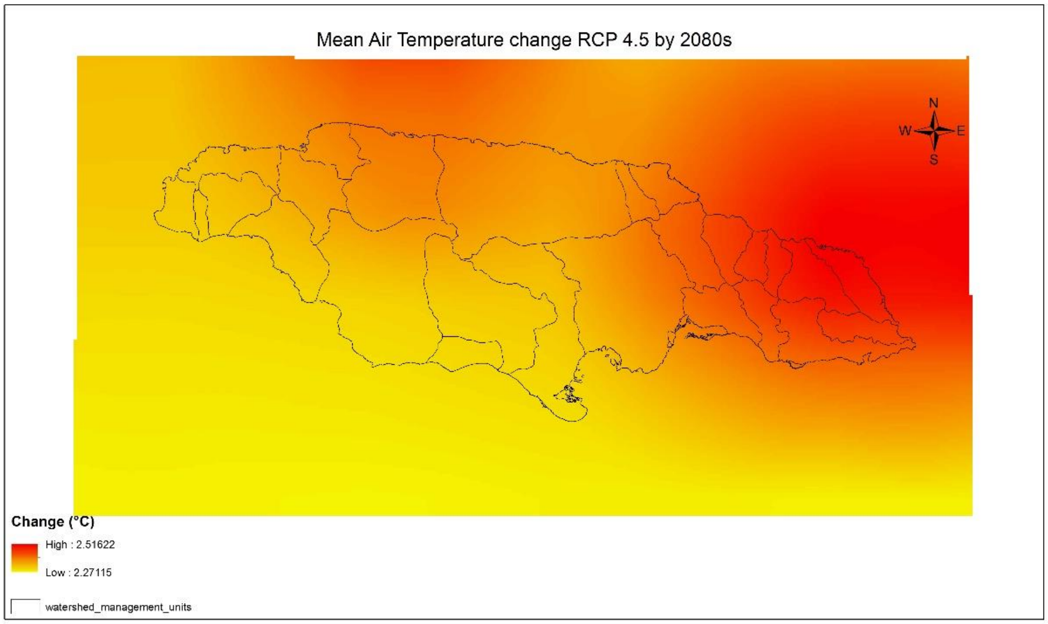

Precipitation change RCP 4.5 by 2080s
N
W
E
S
Percentage change
Value
High : 0.919526
Low : 0.836809
watershed_management_units

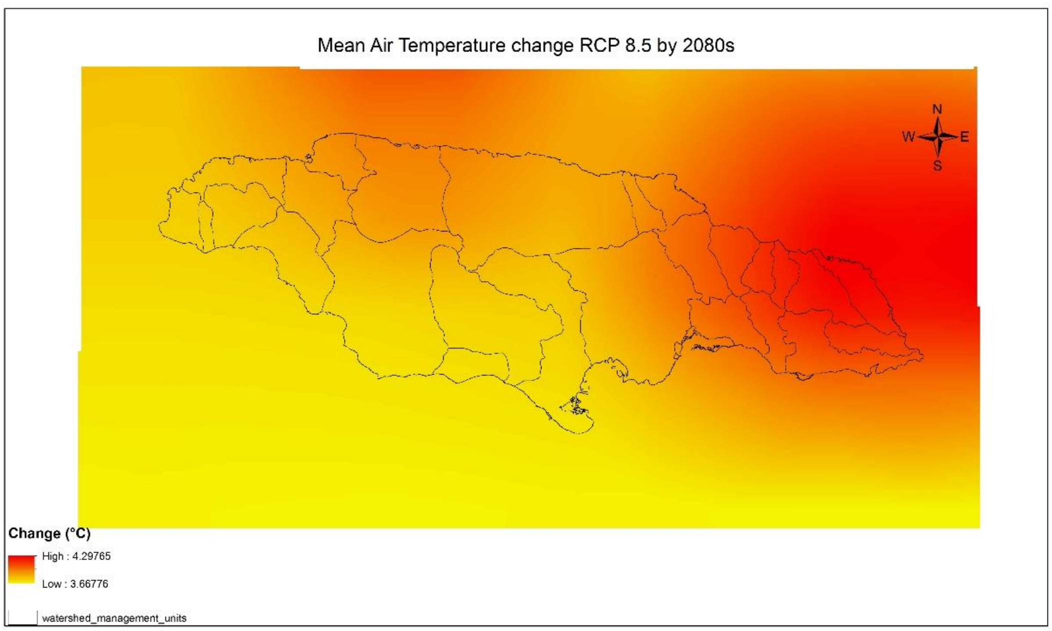

Precipitation Change RCP 8.5 by 2080s
N
W
E
S
Percentage change
High : 0.814809
Low : 0.607397
watershed_management_units

Appendix H

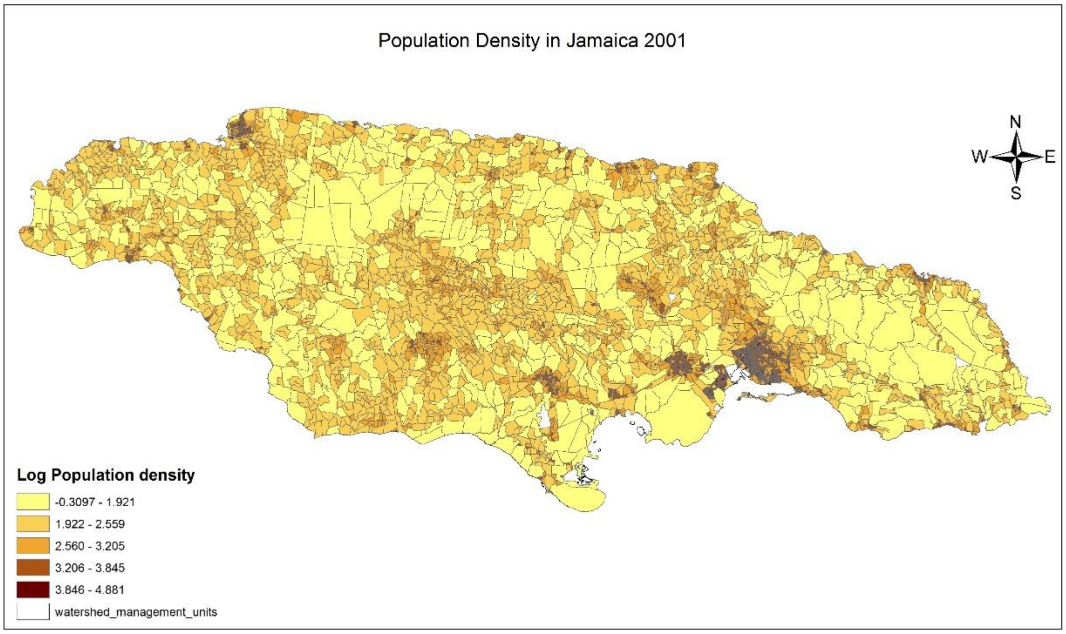

Mean Air Temperature change RCP 4.5 by 2030s
N
W
E
S
Change (°C)
High : 1.35457
Low : 1.31959
watershed_management_units


Mean Air Temperature change RCP 8.5 by 2030s
N
W
E
S
Change (°C)
High : 1.59073
Low : 1.55844
watershed_management_units

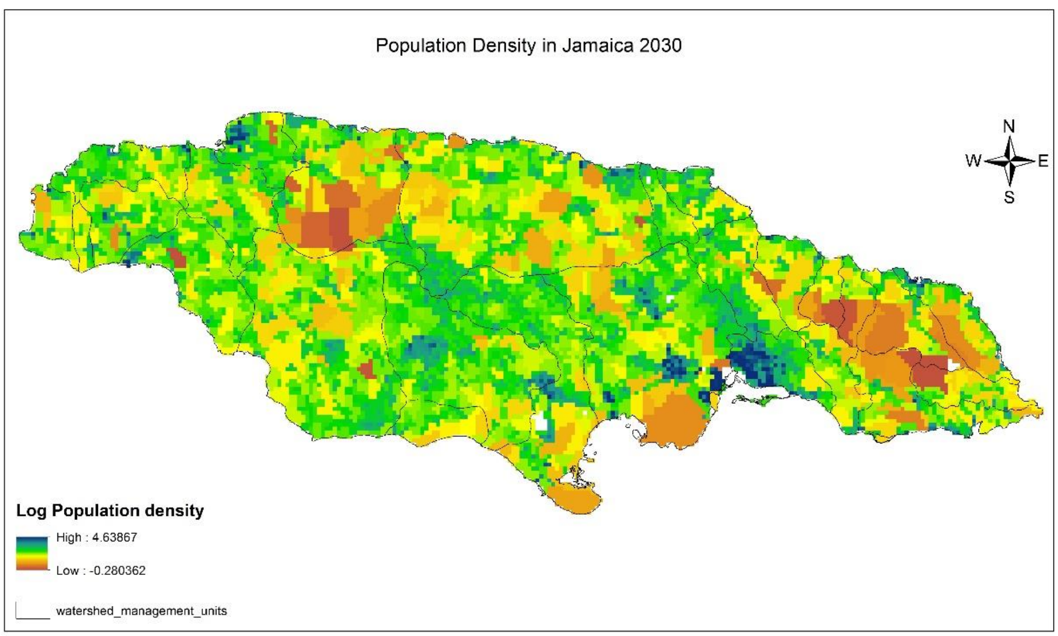

Mean Air Temperature change RCP 4.5 by 2080s
N
W
E
S
Change (°C)
High : 2.51622
Low : 2.27115
watershed_management_units


Mean Air Temperature change RCP 8.5 by 2080s
N
W
E
S
Change (°C)
High : 4.29765
Low : 3.66776
watershed_management_units

Appendix I

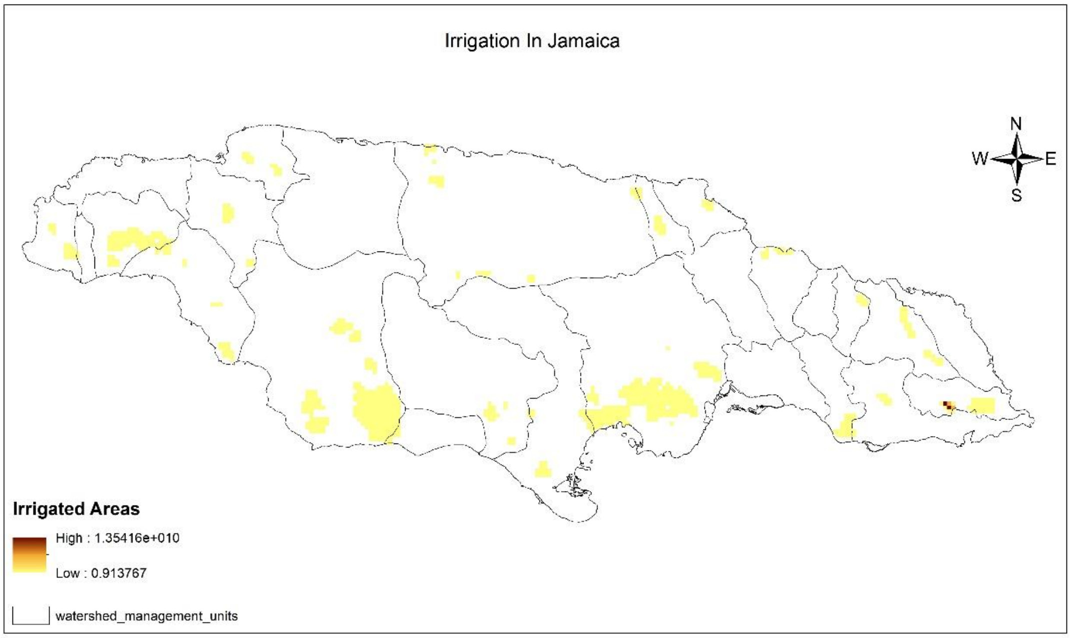


Population Density in Jamaica 2001
N
W
E
S
Log Population density
-0.3097 - 1.921
1.922 - 2.559
2.560 - 3.205
3.206 - 3.845
3.846 - 4.881
watershed_management_units

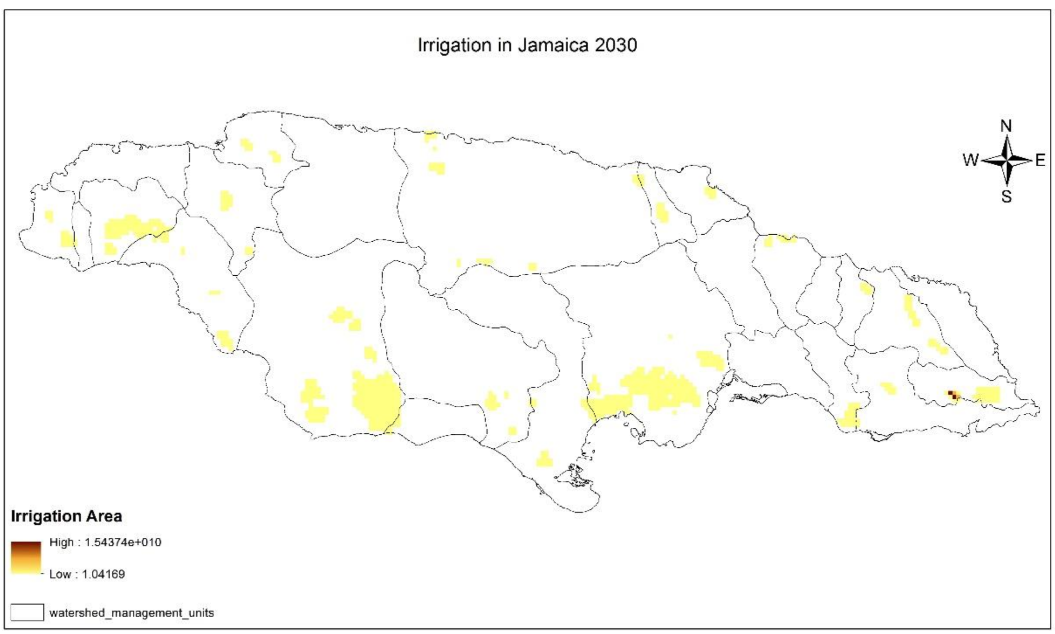


Population Density in Jamaica 2030
N
W
E
S
Log Population density
High : 4.63867
Low : -0.280362
watershed_management_units

Appendix J

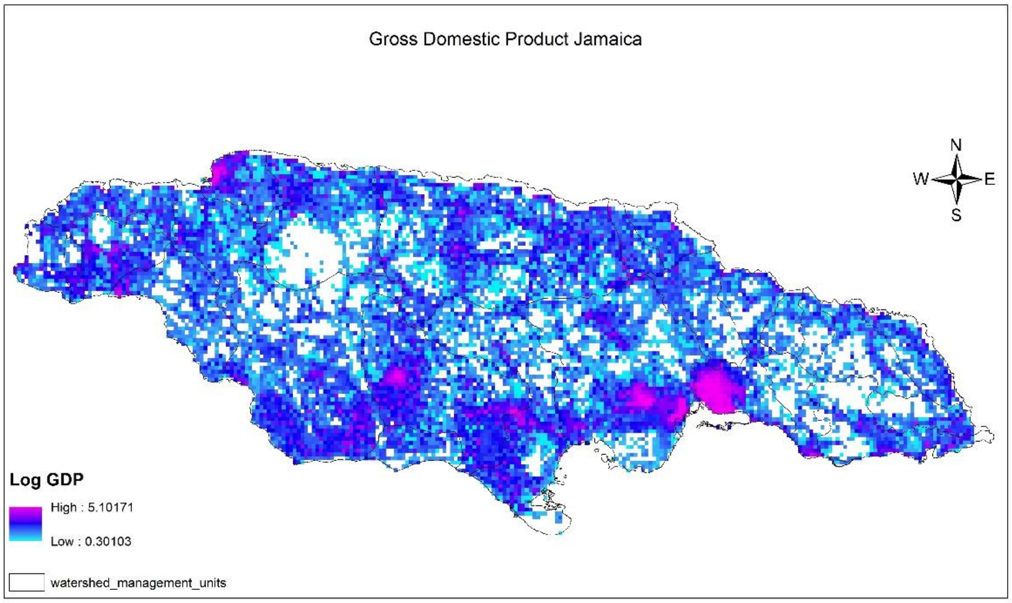


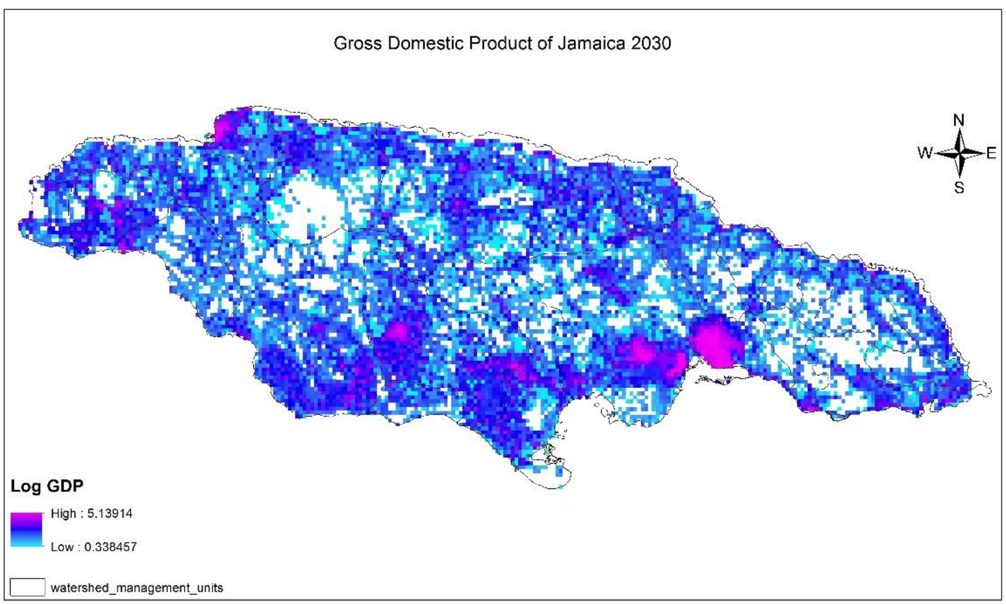
Irrigation In Jamaica
N
W
E
S
Irrigated Areas
High : 1.35416e+010
Low : 0.913767
watershed_management_units



Irrigation in Jamaica 2030
N
W
E
S
Irrigation Area
High : 1.54374e+010
Low : 1.04169
watershed_management_units

Appendix K


Gross Domestic Product Jamaica
N
W
E
S
Log GDP
High : 5.10171
Low : 0.30103
watershed_management_units


Gross Domestic Product of Jamaica 2030
N
W
E
S
Log GDP
High : 5.13914
Low : 0.338457
watershed_management_units