Solutions to long-term water supply–demand balance challenges: Decision making under uncertainty in the Marquis catchment

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Abstract

This study has quantified water scarcity for the Marquis watershed and Hill 20 water supply system in Saint Lucia, including the development of practical metrics to help water sector planners objectively quantify risks and support long term planning for a more resilient water sector.

The study developed a 60-year time series of daily rainfall and potential evapotranspiration (PET) and used this to drive a hydrological Probability Distributed Model (PDM) to derive flow time series for the Marquis watershed and sources serving the Hill 20 water treatment plant. A simple metric was developed to represent periods of water scarcity for the run-of-river sources where flows dropped below design demand. The impact of changing demand, climate change and potential interventions to alleviate water scarcity were then investigated to better understand system behaviour.

The study showed that the PDM hydrological model provided a good representation of observed flows in the catchment, lending confidence to the findings. Drought events were identified in the record, with the most significant being the 1974/1975 drought in which the model indicates demand exceeded supply for around 140 days per year for both years. Climate change projections were included in the hydrological modelling, and resulted in substantial reductions in flow rates of around 40% for the 2050s, and higher for the 2080s, although considerable uncertainty exists in the projections. The effects of introducing a reservoir into the system were modelled, and demonstrate benefits in increasing performance through drought episodes, as do interventions to reduce leakage and demand.

The performance metric (or variants of it) could be used as the basis for long term planning, either using a least cost approach to achieving a predefined level of performance, or by trading gains in performance against the investment cost of achieving it.

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1. Introduction

Saint Lucia, like many Caribbean Small Island Developing States (SIDS), faces issues of water scarcity. Public water supply is sourced from surface water sources via intakes on rivers and streams. The two main abstractors are agricultural users, who typically have their own abstractions, and the Water and Sewerage Company Inc. (WASCO), which is the Island's only water utility company. The Water Resource Management Agency (WRMA) is responsible for the overall sustainable management of the water resources. WASCO supplies water to the general public, public authorities, businesses, industry, tourism, ships and bottling companies. WASCO abstracts water at 36 intake locations and operates the John Compton Dam in the Roseau Watershed.

Surface water sources, especially run-of-river sources are highly susceptible to droughts particularly during the dry season (December-May). This results in low flows, limits water abstraction, and often coincides with the peak tourism season where there is an increase in water demand for touristic as well as agricultural users. Figure 1 below shows low flows in the Marquis catchment occur from April to July, lagging behind the low rainfall months of January to April.

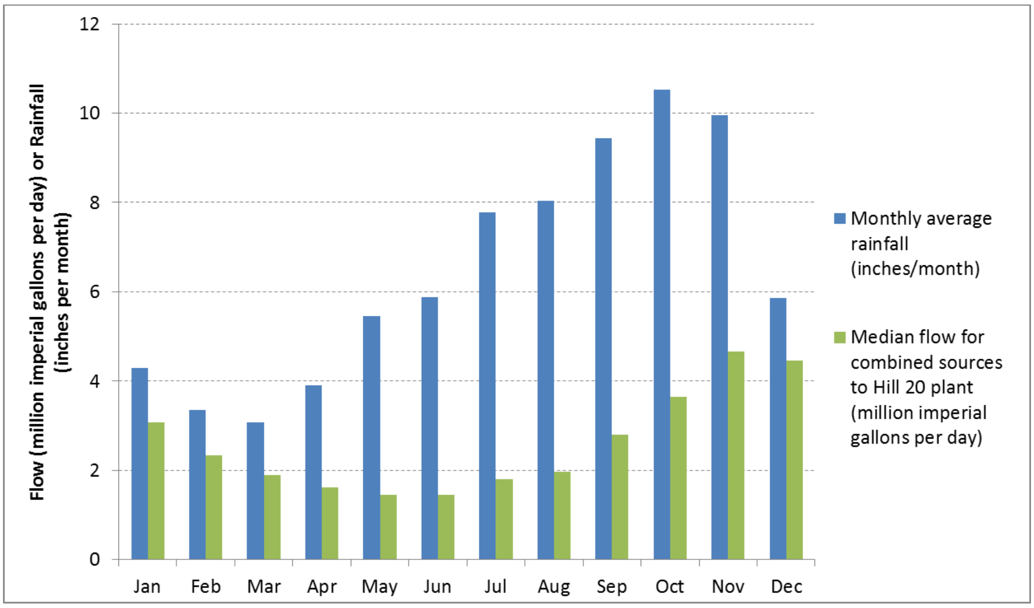

Figure 1: Monthly average rainfall and flow for the Marquis catchment (1958-2018)

Saint Lucia experiences droughts and consequential impacts on water supplies. The drought of 2001 led to strict water rationing and it was reported that even at the significantly reduced rate of abstraction, the reserves in the Roseau reservoir would not last more than one month for supply to the north of Saint Lucia (Government of Saint Lucia, 2010). Within the month, however, there were rainfall events that alleviated the situation. Following this event, drought susceptibility mapping and a drought management plan (Government of Saint Lucia, 2009) were put in place by the Government of Saint Lucia. The drought of late 2009 into 2010 activated the drought management plan measures and the water-related emergency component of the Water and Sewerage Act of 2008, where the indiscriminate use of water was banned.

Climate change presents an additional challenge to planners and managers as it is likely to exacerbate existing hazards. Broad trends for the Caribbean based on climate model projections suggest a future climate of warmer temperatures and reduced rainfall. Although not the subject of this study, water scarcity in Saint Lucia also arises as a result of storm related damage to infrastructure and high turbidity in source waters, and therefore, the potential for increased storminess exacerbates this risk. This study provides a quantitative assessment of the risks posed by climate change on water scarcity and evaluates options to address these.

1.1. Scope and purpose of the study

While the issues of water scarcity in Saint Lucia are well known, quantification of scarcity and of performance of water supply systems is challenged by a lack of data and limited resources to undertake both data collection and analysis.

This study has quantified water scarcity for the Marquis Watershed and Hill 20 water supply system in Saint Lucia, using practical metrics to help water sector planners objectively quantify risks and support long term planning for a more resilient water sector. This has included the following:

- Development of long time series (1958 to present day) for meteorological variables
- Calibration of hydrological model for the Marquis watershed
- Analysis of inflows to Hill 20 treatment plant and development of performance metrics
- Generation of climate change projections for the Marquis watershed and analysis of impacts on flows and water system performance
- Exploring solutions for alleviating water scarcity

1.2. Stakeholders involved

This study has been undertaken by HR Wallingford in collaboration with the Water Resources Management Agency (WRMA) and the Water and Sewerage Company Inc. (WASCO) of Saint Lucia. HR Wallingford is a UK based non-profit distributing consultancy and research organisation, and undertook this study using internal research funding.

2. Case study catchment and water supply system

2.1. Marquis Watershed

The Marquis watershed is located in the north-eastern portion of the island and encompasses an area of 31 km² between the latitudes of 13°57'39.396" and 14°2'8.597" North and longitude of 60°53'24.095" and 60°57'37.557" West. The Castries Waterworks Forest Reserve form the upper extent and source of the Marquis Watershed, while other blocks of forest reserves that exist in the lower regions are composed primarily of dry scrub vegetation (Cox, 1997) .The river flows in a predominantly northerly direction towards the Atlantic Ocean. Tropical dry forest characterizes the lower portion of its valley, while the upper part is tropical moist forest. Priority biodiversity areas within this watershed are ranked as being high (GoSL, 1991). This watershed is classified as one of the seven major river basins on island for water supply. Its topography is reflected in its long history of geological erosion which is seen in its valley; expansive, flat, mature, filled with alluvium and highly suitable for intensive agricultural purposes (GoSL, 1991).

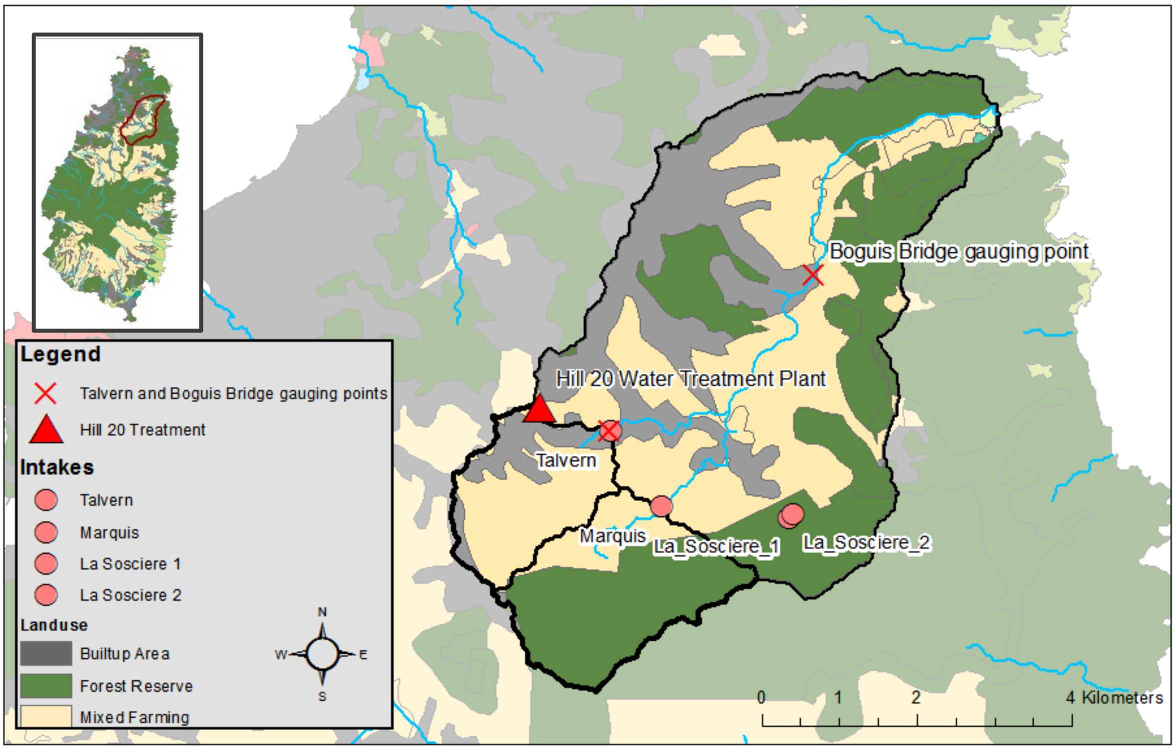

Figure 2: Map of Marquis watershed, data provided by WRMA, WASCO and accessed from the CHARIM Geonode (CHARIM, 2019) (the specified intakes are primarily for domestic and commercial potable water production and supply)

2.2. Agriculture

Intensive farming dominates in the lower plains while the slopes are predominantly mixed farming with semi evergreen seasonal forest. According to Cox, (1997) over 60% of the Marquis watershed was under extensive Agriculture, which has been facilitated by its network of agricultural roads and relatively gentle slopes. Traditionally, intercropping of bananas and mangos has occurred among coconut production along lower sloping regions towards the coast (Cox, 1997). The production of vegetables and root crops are also prevalent in the watershed.

The primary source of water in the basin is surface water. This is sustained by precipitation of 2000 mm to 2700 mm recorded annually in some areas. Ground water abstraction is not very significant and does not serve as an alternate source of water for farming or residential purposes. This means that irrigation depends mainly on rainfall and pumping from the river and its tributaries. The Water and Sewerage Company Inc. (WASCO) supplements irrigation activities to a few farmers by providing abstracted raw water from its main line.

2.3. Water Supply System

The Hill 20 water supply system is located within the catchment (in Cacoa Girard) and is one of four major water supply systems on the island. The treatment plant has a capacity to treat 0.8 MG/day. Peak production occurs in the dry season around December to March, and is around 10% higher than the annual average. Intake facilities include gravity sources such as La Sorcière (La Sorcière intakes 1 and 2), the eastern branch of the Marquis River (Marquis intake) and the Talvern Intake on the Babonneau tributary. These sources all feed into the Hill 20 Treatment Plant which in turn supplies potable water to residents in the watershed and beyond.

Due to a lack of natural storage (ponds, lakes, reservoirs), supply is dependent on rainfall intensities throughout the year. In the dry season, with a reduction of water available at the intakes and the pressures on the demand side, water allocation schedules are used to respond to shortages. Glass fused steel and concrete tanks offer a level of storage, and buffers some communities against water shortages, however, this is limited in duration. The Hill 20 Treatment Plant supplies potable water to 5 main tanks ranging in storage capacity of 100,000 to 150,000 gallons, totalling 550,000 gallons, which is less than one day of system production. The population served by the system is 11,100 based on the 2010 census of population in settlements served by the Hill 20 system.

2.4. Water Quality

The watershed is vulnerable to contamination that leads to poor water quality. Only 2% of national domestic wastewater is treated and most households and pig farms rely on septic tank systems for treatment (Draft National Policy on Wastewater Management 2017). Agricultural activities contribute fertilizers and pesticides through runoff into waterways, and through inadequate practices, allow for sediment transport into watercourses. It should be noted 2 of the 4 main intakes (for domestic and commercial potable water production and supply) in the watershed are located in unprotected areas where mixed farming and other anthropogenic activities occur (See Figure 2).

According to the GFA Consulting group (2017), water quality in St. Lucia is affected by direct human activities on the land and also from the consequences of rainfall on the land. As seen in Figure 2, except for Talvern, the previously mentioned intakes are located away from human settlements and in the upper reaches of the catchment. However, agricultural activities remain a concern within the vicinity of the Talvern and Marquis intakes which are on unprotected agricultural lands. It should be noted that WASCO has a quality assurance and control system in place to monitor treated water quality that is in keeping with World Health Organisation (WHO) standards, however possible environmental impacts to raw water from sedimentation and other contaminants remain a concern.

2.5. Future trends in development

As part of Saint Lucia's national vision plans, the Marquis watershed forms part of the North-East quadrant zone for development. The natural flora and fauna has been highlighted for potential eco-tourism and expansion of activities such as zip lining and ATV tours. Also, with tentative plans in a neighbouring watershed to develop an eco-park with lodging as part of a sustainable tourism development initiative, this will have implications for future water supply demand from the Marquis watershed.

With the current level of development, including zones identified by Government for residential areas, a plan has been designed to convert the commercial area along the Marquis watershed into a town. This would be a catalyst for rapid growth and greater demand for water.

3. Method

The method has been divided into phases (see Figure 3) which flow from the input variables through hydrological modelling to analysis system performance, sensitivity testing for demand and climate change, and finally exploring potential solutions to alleviate scarcity.

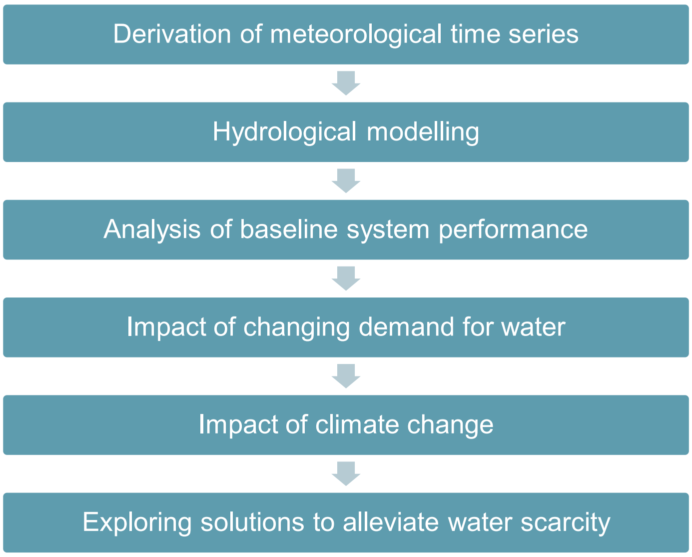

Figure 3: Methodological process

3.1. Derivation of meteorological time series

Continuous rainfall and PET series were generated from April 1958 to August 2018 using gauges representative of the Marquis catchment. For rainfall, gauges were used in Marquis, Monchy, Mabouya, Union and Barre De L'Isle. Marquis was used in preference and infilled with the other gauges based on proximity to the site to generate a continuous record (see Figure 4). Infill gauges were scaled according to the ratio of the monthly rainfall to the Marquis gauge to remove systematic bias as far as practicable. PET was generated from the Union Agro-met station, hindcast back to 1958 using a repeating monthly PET pattern based on the data available.

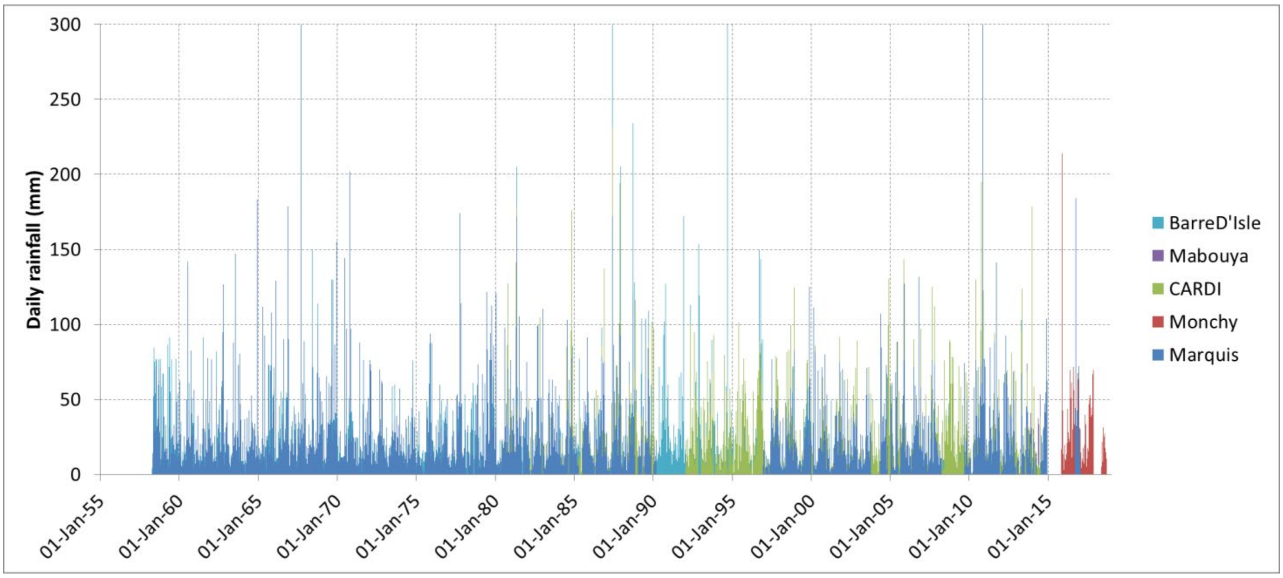

Figure 4: Composite rainfall time series showing rain gauges used in different periods of the record

3.2. Hydrological modelling

The rainfall and PET series were used as inputs to a hydrological model, known as Kestrel (developed by HR Wallingford) which is based on the Probability Distributed Model (PDM) a general conceptual rainfall-runoff model (Moore, 2007) which has been employed in many forms to suit different modelling objectives (e.g. Bell et al., 2007; Reynard et al., 2010; UKWIR, 2007).

All forms of PDM include a ‘mass-balance’ probability distributed soil moisture accounting component, with resulting direct runoff and recharge routed via ‘slow’ and ‘fast’ pathways to the basin outlet. A Pareto distribution is typically used (and has been used in this study) to describe the distribution of the storage capacity across a catchment, with the distribution shape altered to reflect different proportions of deep or shallow stores. If the storage capacity at a point is exceeded, direct runoff occurs, otherwise water remains in storage with losses to evaporation and via recharge to the groundwater store. Both the direct runoff and the recharge component use a storage element to represent surface storage (‘fast’) and groundwater storage (‘slow’) and also act as a delay in the system to represent different catchment characteristics. The catchment river flow output combines the discharges from the surface and groundwater stores (see Moore, 2007, for a detailed description, including the process equations, of the PDM model structure). Figure 5 provides an overview of the PDM model structure.

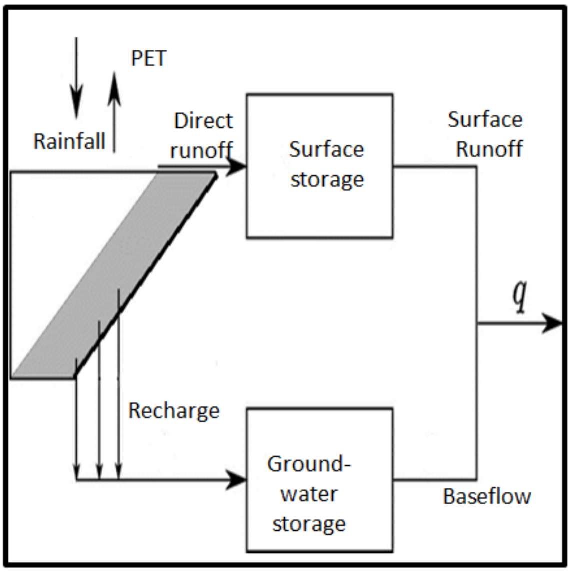

Figure 5: The PDM conceptual model structure
(adapted from Moore, 2007)

Hydrological models were developed at three locations, the WASCO intakes on the Talvern and Marquis catchments, and Marquis at the Boguis Bridge. The Boguis Bridge model was developed purely for calibration purposes, as there is no water intake at this location. In addition, a model was developed for the Sorcière springs which are abstracted by WASCO and feed the Hill 20 system by gravity.

Table 1: Catchments for which hydrological models have been developed.

Catchment name	Total catchment area (km^2)	Built up area (km^2)	Agriculture (km^2)	Forest (km^2)
Talvern river at WASCO intake	3.2	0.9	2.3	0.0
Marquis river at WASCO intake	4.6	0.0	1.1	3.5
Marquis river at Boguis Bridge (note this location is not a WASCO intake, modelled only for calibration purposes)	22.9	5.5	9.4	8
La Sorcière springs	0.7	0.0.	0.0	0.7

The models for the WASCO intake at Talvern and Boguis Bridge at Marquis were calibrated against spot flow gauging records, and the same parameter values were used for the WASCO intake at Marquis and Sorcière springs for which no gauging data were available. The model fit at Talvern and Boguis Bridge was considered to be good when taking into consideration the small size of the catchment and potential spatial variability in the rainfall series. The model represents periods of low flow effectively, and the lowest gauged record in July 2015 appears to be lower than the metered flow from the Talvern intake into the Hill 20 treatment plant, indicating that gauged flow may have been lower than true flow at that time.

A significant challenge with calibration is the use of water for agricultural purposes in the catchment. Farmers abstract water directly from the river upstream of the intake at Talvern, and the raw water main from the intake at Marquis has a few connections to farms before it reaches the Hill 20 plant. No data on the abstraction volumes were available for this study and therefore it is not possible to quantify how much available water is being used for agriculture prior to WASCO's abstractions. However, given that the Talvern observed gaugings will incorporate any upstream abstractions, this may be implicitly incorporated in the hydrological model.

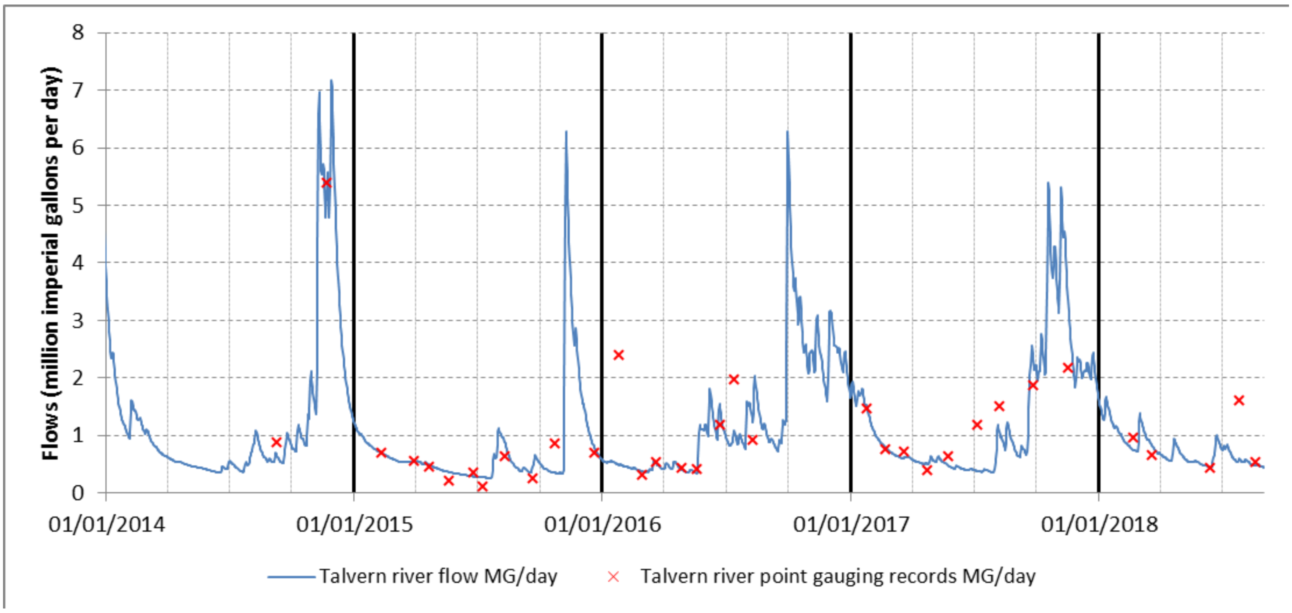

Figure 6: Observed and modelled flows for Talvern at the WASCO intake

3.3. Analysis of baseline system performance

Once the hydrological models for the four sources was completed, this was then compared with the Hill 20 water supply system production rates, both design and historical to assess the performance of the system. Figure 7 shows the modelled flow rate in the combined sources feeding the Hill 20 treatment plant, including the long term (1958-2018) 50th and 95th percentile monthly flow rates, the Hill 20 plant inflow rate for the period 2013 to 2018, and the Hill 20 plant design production rate of 0.8 MG/day. This graph shows the relatively severe drought experienced in 2015/16 in which unusually low flows in the second half of 2015 and into the first half of 2016 appear to depress inflows to the Hill 20 plant. Combined inflow rates dip below the Hill 20 design capacity in both 2015 and 2016.

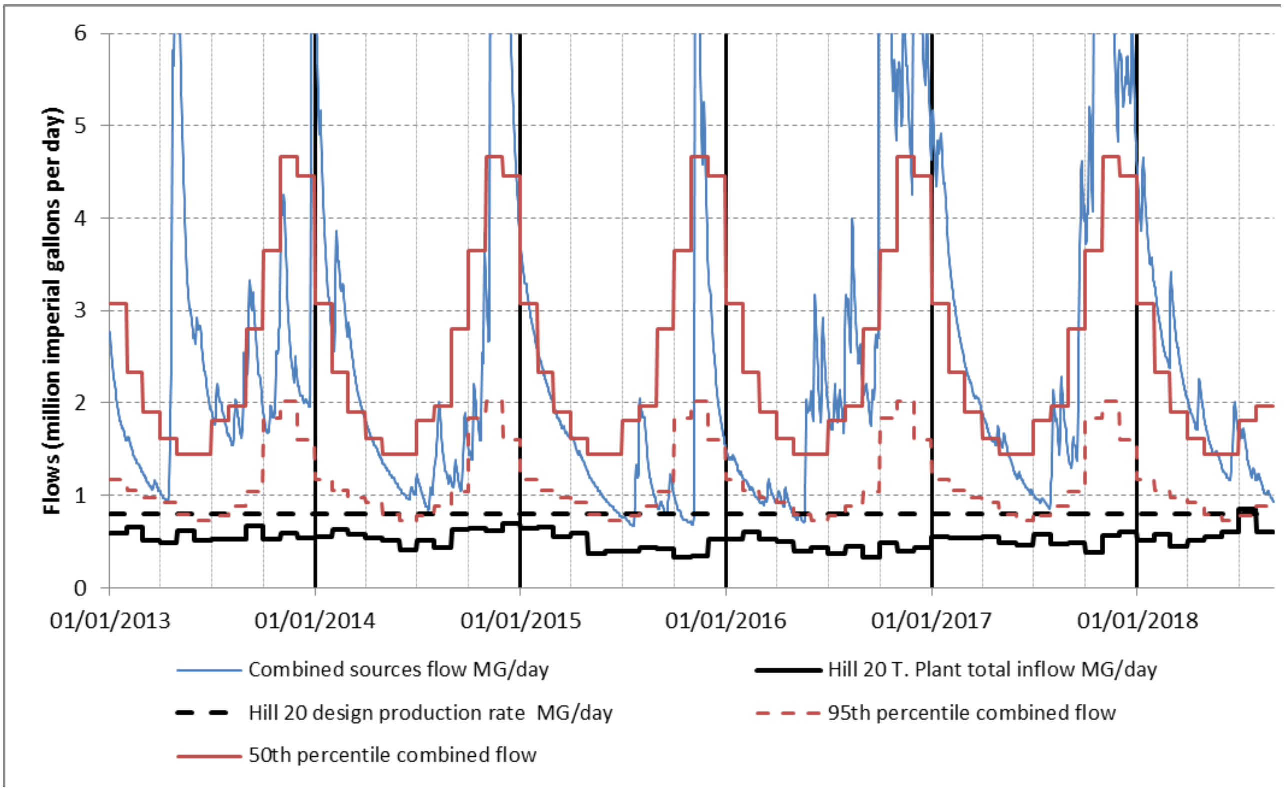

Figure 7: Modelled flow rate in the combined sources feeding the Hill 20 treatment plant (including the long term 50th and 95th percentile monthly flow rates), and the Hill 20 plant production rate for the period 2013 to 2018.

The long term rainfall and PET records developed in this study allowed the modelling of inflows to the Hill 20 system back to 1958. This long term record provides greater confidence in the assessment of severe droughts. The number of days per year where the combined modelled inflow to the treatment plant was below the design production rate was used as a simple performance metric to identify droughts which would likely affect the water supply in the system under present day demand. This has been plotted in Figure 8, and indicates that 1974 – 1975 is the most severe drought on record, resulting in around 140 days per year where flows are below design production rate. The drought periods correlate well with other sources of historical drought information (e.g. Herrera & Ault, 2017). The use of long time series to drive hydrological models has in this case identified a severe drought event, which would have been missed if using more recent records for system design. Although severe droughts have occurred in the relatively recent past, none have been of the same magnitude as the 1974 – 1975 event (shown in Figure 9).

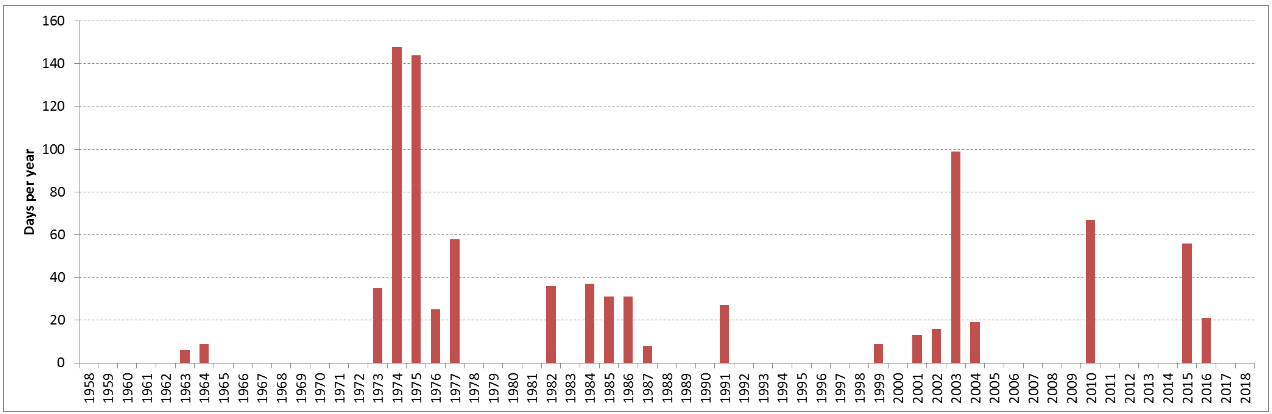

Figure 8: Number days per year in which modelled combined flow rates for sources is below design production rate of 0.8 MG/day

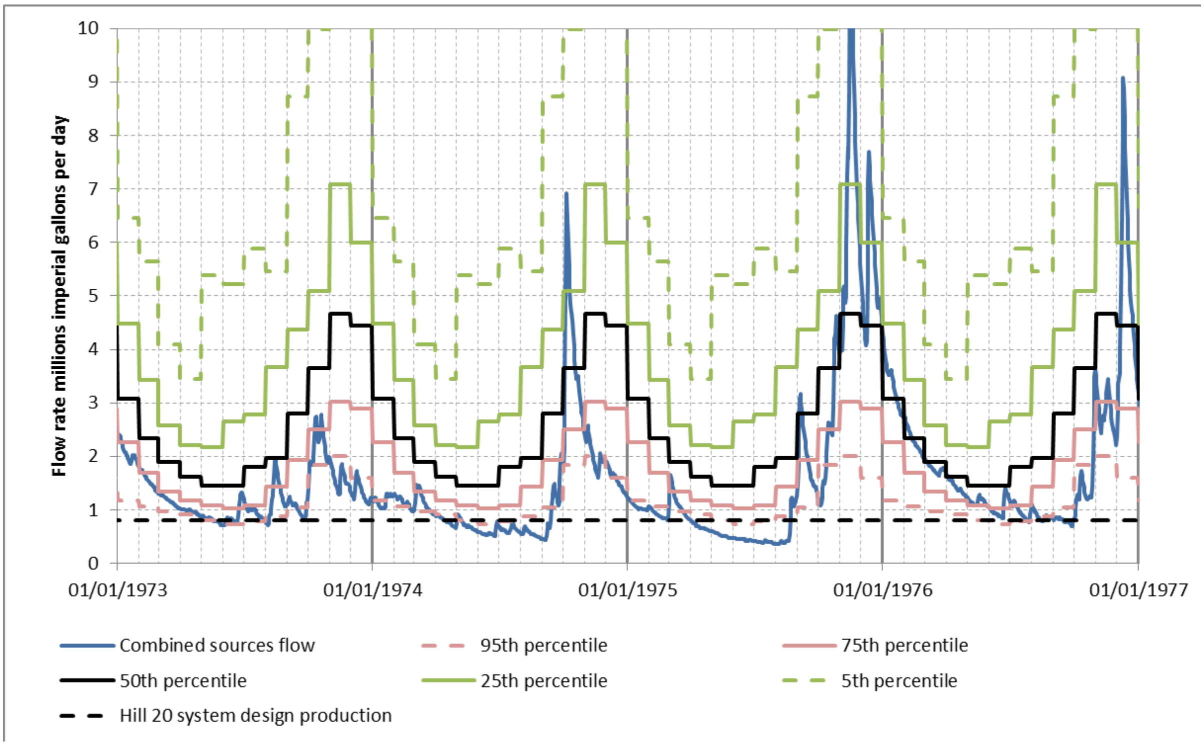

Figure 9: Flow rate for the combined sources to Hill 20 plant showing percentile flows and Hill 20 design production rate for the most severe drought on record 1974/75

3.4. Impact of changing demand for water

The impact of changing demand for water on the performance metric has been assessed for two scenarios in addition to the base scenario of 0.8 MGD.

- Firstly, a scenario has been developed for an increase in population of 10%, based on central estimate UN-DESA population projections for Saint Lucia for 2035 (UN DESA, 2019). It has been assumed that a 10% population increase will result in 10% water demand increase (demand of 0.88 MGD), however, this does not account for changes in consumption patterns which may alter per capita consumption, or for short duration peaks in demand.
- Secondly, a 20% increase in demand has been used as an upper estimate representing substantial development in the area served by the Hill 20 supply system (demand of 0.96 MGD).

These scenarios are considered indicative and no likelihood associated with these has been assigned. Figure 10 shows the number of days per year the system demand exceeds supply for the baseline and +10% and +20% scenarios. It indicates that for the most severe droughts on record there are relatively small increases in additional days (for example 1974, 1975, 2003). Whereas during minor droughts, events are significantly exacerbated, and new drought events are introduced in years where previously no deficit occurred (for example 1994).

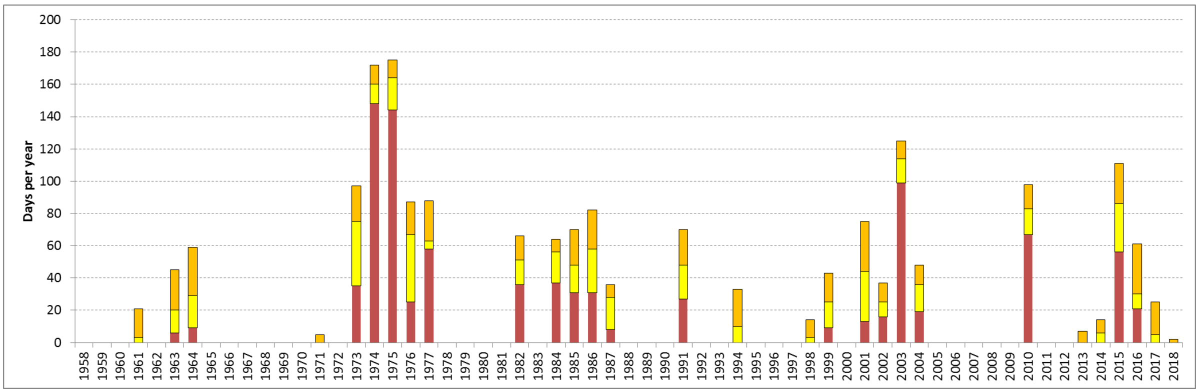

Figure 10: Number of days per year in which modelled combined flow rates for sources is below design production rate of 0.8 MG/day, and additional days for rates scenarios of 10% and 20% increase in demand (0.88 and 0.96 MGD).

3.5. Impact of climate change

Regional Climate Model (RCM) data for Saint Lucia were obtained from the Caribbean Community Climate Change Centre (CCCCC) and used to adjust the historical time series by monthly average factors of change for rainfall and PET to produce series representative of future epochs centred on the 2050s and 2080s. These were then used as inputs to the hydrological model to produce flow series representative of these future periods. The RCM data consisted of seven RCM simulations (referred to as *aenwh* to *echam5* in Figure 11) driven by the IPCC SRES (2000) emission scenario A1B (medium emissions), and three RCM simulations driven by the more recent Representative Concentration Pathway (RCP) RCP2.6, RCP4.5 and RCP8.5, each representing a progressively higher greenhouse gas emissions trajectory. Figure 11 shows these change factors from the climate projections for the 2050s in terms of rainfall, PET and river flows.

Although considerable uncertainty exists in the projections there appears to be a strong drying and warming trend, which together result in dramatic reductions in monthly average flow for the Marquis catchment of around 40% in the dry season in the 2050s. In the 2080s these reductions are even more pronounced, being 50-70% lower relative to the baseline period of 1970-2000.

The impact of climate change on the water supply system performance metric has been assessed summarised in Figure 12. This indicates that by the 2050s, the 15 days shortage experienced on average could become around 50, and by the 2080s many projections are in excess of 100. This study has not made an assessment in the confidence associated with these RCMs, and this should be an area of further investigation given the dramatic changes in water resources which they imply.

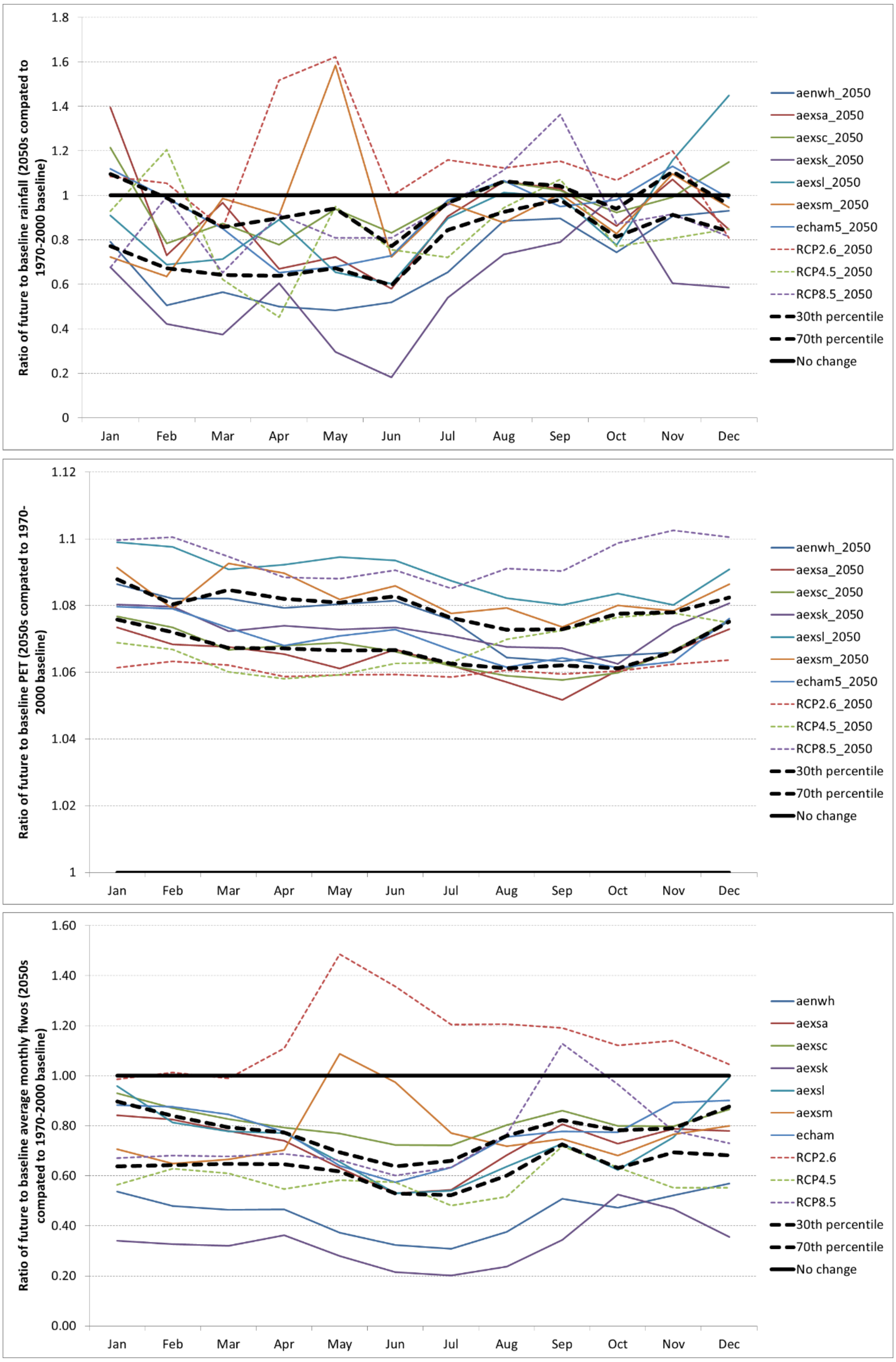

Figure 11: Changes in average rainfall (top), PET (centre) and river flow combined sources to Hill 20 (bottom) for the 2050s based on SRES and RCP driven climate models

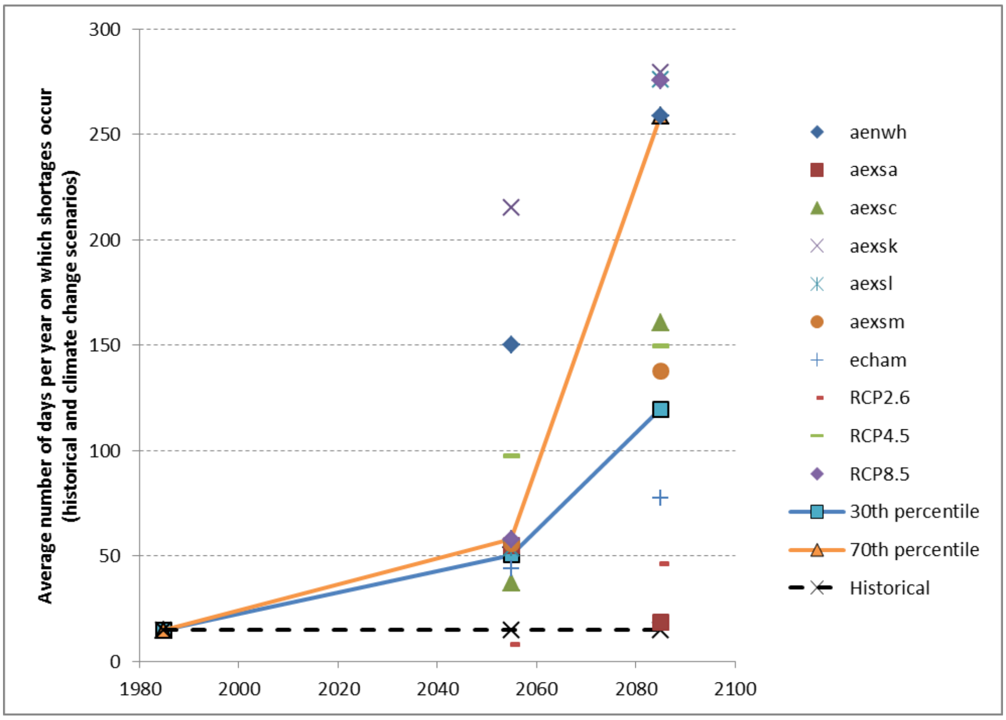

Figure 12: Average number of days per year on demand exceeds supply for historical baseline and climate change scenarios

3.6. Exploring potential solutions to alleviate water scarcity

Water shortage may be alleviated by both supply side and demand side options. Supply side options might include commissioning new sources, transferring water from other areas, constructing reservoirs or desalination plants. Demand side options include measures to reduce leakage or customer water usage such as retrofitting appliances and plumbing fixtures. The mix of supply and demand side options appropriate will depend on feasibility, effectiveness, cost and water user preferences amongst other factors. This paper does not seek to examine these factors in detail, instead illustrating the effects of a single supply side option (a raw water supply reservoir) and demand side option (reducing leakage). It is stressed that the feasibility and costs associated with these options have not been examined, and they are presented as illustrative solutions on which the performance metric has been applied. In the context of the Marquis watershed it is also worth noting that reducing agricultural water abstraction during drought periods would likely alleviate water shortages, for example by constructing agricultural water storage or rainwater harvesting systems.

A raw water storage reservoir has been modelled for volumes ranging from 5 to 60 million gallons total. The reservoir has been assumed to accept inflows from the four sources feeding the Hill 20 treatment plant. Figure 13 shows the performance of the reservoir in alleviating water shortage for varying levels of demand. The performance metric has been averaged over the 1958 – 2018 period to give the number of days per year on average where demand exceeds supply. The baseline demand of 0.8 MG / day scenario shows that a reservoir of 5 MG reduces the number of expected days per year from 15 to 5 days, the benefits of additional storage then tail off.

Two scenarios of leakage reduction have been included in the model, which are equivalent to water production reduction of 15% (0.68 MG/ day) and 30% (0.56 MG/day). These are based on an assumption that Non-Revenue Water in Saint Lucia is around 50% of production, being made of up of real losses of 39% and apparent losses of 11%, and that 15% and 30% reduction in production is feasible The 15% reduction in production through leakage control with no reservoir reduces the average number of days where demand exceeds supply from 15 to around 6, similar in effect to a 5 MG raw water storage reservoir, but with the co-benefit of reduced pumping and O&M costs compared to the maintenance of a new reservoir. Finally, a 10% increase in production has been modelled to highlight the negative effects on system performance, with the number of days exceeding 20 per year on average.

It should also be noted that reservoir evaporation and any requirement for environmental flow releases have not been included in this assessment, and would negatively impact the performance of a reservoir.

The impacts of climate change on reservoir performance have also been assessed. Figure 14 shows how the performance metric is affected by climate change assuming no reservoir, a reservoir of 10 MG and a reservoir of 50 MG for a demand of 0.8 MG/day. This shows that a reservoir would reduce incidence of water supply shortage under climate change but as projections become more severe, the proportional benefits of the reservoir reduce.

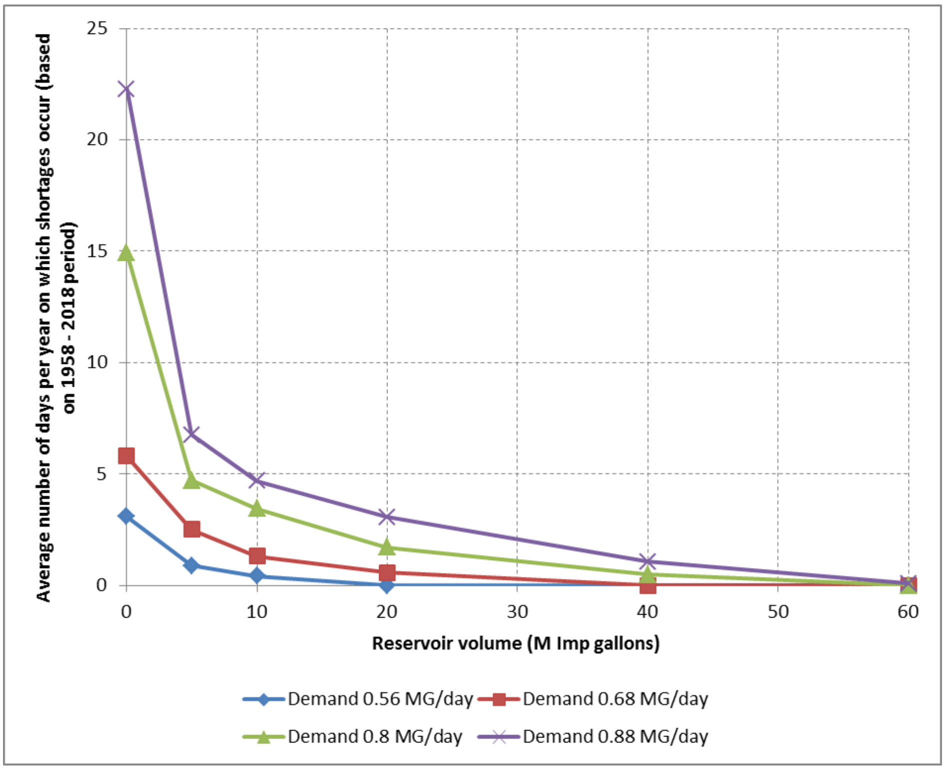

Figure 13: Average number of days per year where demand exceeds supply under scenarios of raw water reservoir and demand.

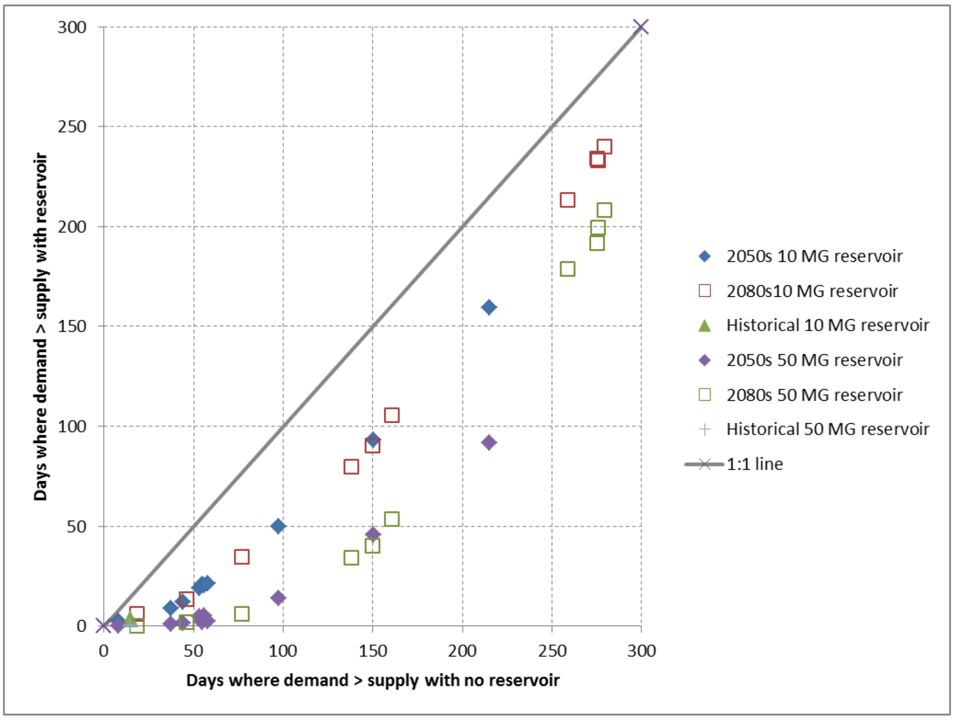

Figure 14: Average number of days per year where demand exceeds supply with and without a 10MG and 50MG reservoir for historical, 2050s and 2080s climate change

4. Key conclusions and recommendations

This case study has provided an illustrative example of the use of hydrological modelling and the definition of practical performance metrics to make an objective assessment of the resilience of the water supplies in the Marquis catchment serving the Hill 20 water supply system. It demonstrates the value of using long time series to explore a relatively (60 years) long record of droughts in the catchment, and could be replicated across the island and more broadly across the region for run of river water supply systems.

The study has shown that the PDM model appears to provide a good fit against observed data and that the simulation of long time series is possible using composite records. Further, continuous flow gauging especially during low flows would provide additional confidence to the modelling. More detailed information on agricultural water abstractions in the catchment is a key pre-requisite to reliable hydrological modelling, in order to provide a naturalised observed flow data set against which to calibrate a hydrological model. The variability of rainfall with elevation in Saint Lucia does mean that careful comparison of gauges is required when infilling records. A comprehensive inventory of all rainfall records, including any paper records, would be beneficial as the starting point to develop long time series rainfall for several key sites across the island.

A simple system performance metric has been used to identify periods of likely water shortage. This metric (or variants of it) could be used as the basis for long term planning, either using a least cost approach to achieving a predefined level of performance, or by trading gains in performance against the investment cost of achieving it.

The study has a number of limitations in its representation of water resources and supplies. For example, demand has been assumed to be a fixed daily rate, and makes no allowance for peak periods of demand. Environmental flows, and drought management interventions such as demand management have also not been included, and these may go some way to alleviate water scarcity issues. These could be included in a more advanced future study to further explore how demand and supply interact over time.

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