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Abstract

The long-term sustainability of proposed or existing hydropower schemes strongly depends on the availability of water resources. Under climate change, long-term water resource availability in the Caribbean is highly uncertain. This study presents an approach for assessing future climate impacts on regional hydropower potential premised on the use of hydrological models and projections from the latest generation of climate models. When the methodology is applied to the Afobaka hydropower scheme in Suriname, the results indicate significant changes in both water resources availability and hydropower potential with increasing global temperatures. A decrease of approximately 40% is projected by the end of the century for global temperature increase in the range of 1.5°C above pre-industrial levels. Under a “business as usual” greenhouse gas emissions pathway, which would lead to global temperatures significantly above 1.5 °C, the impact is more severe, with a projected decrease of up to 80% (65 Mega Watt) of the firm power capacity (80 Mega Watt) by the end of the century.

Keywords: Hydropower; Climate change; Climate modeling; Statistical downscaling; CMIP5; Suriname

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1. Introduction

The energy sector in Suriname is reliant on hydropower generation. Extreme climate events in the last decade have, however, significantly impacted water resources and hydropower capacity in Suriname. For example, during the drought of 2004-2005, there was a need for additional thermal generation (Diesel and Heavy Fuel Oil) to supply sufficient energy to industries and households due to the decrease in hydropower generation from the Afobaka hydropower scheme (Nurmohamed et al. 2007). The Afobaka hydropower scheme contributes approximately 40% of Suriname's power demand, with a firm power output of 80 MW average on a daily basis (Van Els 2012). Similarly, drought conditions in 2009, and 2012-2014, resulted in the power utility of Suriname drawing 25 up to 40 % (20 up to 30 MW) less from the Afobaka hydropower scheme.

In addition to droughts of higher frequency and greater intensity, there is also the potential for increased occurrence of extreme rainfall and flooding in the Caribbean under climate change (Taylor et al. 2017). This is also a concern for the Suriname energy sector considering the potential impact on dam safety and integrity (Berga 2013). There is, therefore, a need for modeling studies that project future climates and their effect on water resources in Suriname. A few such studies exist. For example, Nurmohamed and Donk (2017) showed that for the north-west of Suriname, the annual rainfall is expected to decrease by the end of the century due to prolonged and more intense droughts, resulting in declining water resources in general. The study used projections from, both, a regional climate model (RCM) run under Special Report on Emission Scenarios (SRES) greenhouse gas (GHG) emission scenarios (IPCC 2000), and Global Climate Models (GCMs) from the World Climate Research Programme's Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012) run using Representative Concentration Pathways (RCPs) (IPCC 2013). In another study, Nurmohamed et al. (2007) undertook sensitivity analysis of water balance components under temperature and precipitation change for the Upper-Suriname river basin. The study used GCM projections and hypothetical scenarios of increased global mean surface temperatures (GMSTs) in the range of 2°C to 4°C, combined with decreasing precipitation in the range of -10% to -50%. The results showed significant decreases in river discharge for, both, the GCM scenarios (approximately 35%) and for the hypothetical scenarios (up to 87.5%). Both studies suggest that there will be significant reductions in water resources under climate change, with negative impact on the hydropower sector.

A number of studies (e.g. Nurmohamed et al. (2007); Taye et al. 2011; Ntegeka et al. 2014) use hydrological models driven by output from climate models for assessing the potential impacts of climate change on water resources. We adopt this approach in this study, which assesses the potential impact of future climate change on water resources availability, and hydropower potential in Suriname, with particular focus on the existing Afobaka hydropower scheme. Donk et al. (2013) followed a similar approach for a planned hydropower scheme in the west of Suriname (i.e. the Kabalebo river basin project), projecting a decline (10 to 15% or 30 to 40 MW) in the estimated firm power capacity (290 MW) towards the end of the century. Their results, however, were based only on one SRES emission scenario and one RCM. For this study, we use results from the latest generation of climate models. An ensemble of 32 GCMs run under the CMIP5 project for 4 RCPs (RCP2.6, 4.5, 6.0 and 8.5) are used,

allowing for a broad spectrum of future climate possibilities and a better understanding of the range of possible future climate impacts and associated uncertainties. The results for the hydrological impact assessments are also compared to those from the study by [Nurmohamed et al. \(2007\)](#) (see section 4), allowing for a comparison of the relative impact of using two very distinct hydrological modeling approaches.

The main goal of this study is to consider the significance of limiting GMST increase to 1.5 °C above pre-industrial levels by the end of the century. There has been a strong push by developing country states with respect to this global target ([Benjamin and Thomas 2016](#)), resulting in its acknowledgement in the Paris Agreement ([UNFCCC 2015](#)). A comparison is made of water resources and hydropower potential at the end of the century, using climate output from climate models run under (I) a mitigation oriented development pathway, which keeps global temperature rise within the 1.5°C range above pre-industrial periods, and (II) a “business as usual” development pathway, which results in GMST rise significantly above 1.5°C. Section 2 presents a detailed outline of the methodology applied. Section 3 presents the results and section 4 the discussion.

2. Material and methods

2.1 Study area and historical data

This study considers the existing Afobaka hydropower scheme in Suriname. The water resources of the reservoir (the van Blommenstein Lake, or Afobaka Lake) of the Afobaka hydropower scheme are supplied by the Upper-Suriname river basin (7750 km²)(Fig. 1). Historical (observed) data for the study area were obtained for the period 1975-1983, representing 9 consecutive years of available (continuous) observations, including minimum, mean and maximum temperatures (respectively T_{min} , T_{mean} and T_{max}), potential evapotranspiration (ET_o) by pan observations, precipitation (P) from five rain gauges and discharge (Q) measurements at the basin outlet. Fig. 1 depicts the locations of the hydro-meteorological stations. Only 9 years of data are available due to the abrupt stoppage of records during social instability in the early and mid-1980's. Although this is a limiting factor, especially for climate change impact investigations, an attempt is made to address this by utilizing methods that reasonably compensate for limited observed data. This is explained further in section 2.3.3.

Fig 1

Map of the lake and river basin upstream of the Afobaka hydropower station (Afobaka dam) in Suriname; Suriname is situated between 1.5°-6° N and 54°-58° W; The locations of the meteorological and hydrometric stations used in this study are also shown (Source: CELOS-NARENA)

2.2 Hydrological modeling

The hydrology of the basin supplying the reservoir of the Afobaka hydropower scheme was simulated by means of a lumped conceptual model, the VHM model ([Willems 2014a](#); [Willems 2014b](#)). Different modeling strategies have been developed and applied to hydrological problems e.g. the lumped conceptual, semi-distributed and distributed modeling approaches, and there have been a number of studies comparing the various modeling approaches ([e.g. Clarke 2008a](#); [Clarke 2008b](#); [Reed et al. 2004](#);

Refsgaard and Knudsen 1996; Refsgaard 1997; Smith et al. 2004). However, no study resulted in an objective categorization of such models based on the application and performance. Common problems faced by rainfall-runoff modelers are data limitation, model over-parameterization and related problems of parameter identifiability and uncertainty. As Willems (2014a; 2014b) discusses, depending on the application, possible solutions to overcome these problems include the use of parsimonious conceptual models, avoiding the use of a fixed pre-defined model conceptualization, and applying a “top-down” or “downward” method, allowing the model structure to be adjusted or inferred from available data and field evidence. Given the objective of this research, whereas model performance at basin outlet is of main importance, we adopted a lumped conceptual approach.

The VHM approach has been widely applied to different catchments over the world (e.g. Taye et al. 2011; Ntegeka et al. 2014; Willems 2014a; Willems 2014b). It utilizes a top-down procedure that starts from a generalized model structure framework, as shown in Fig. S1 (in Supplementary Information (SI)), which is adjusted in a case-specific parsimonious way. The model structure is built in a transparent, step-wise (data mining based) way, rather than a fixed pre-defined way. Separate parts of the model structure (sub-models) are identified and calibrated (step-wise) based on multiple and non-commensurable information derived from Q series by means of a number of sequential time series processing tasks (Willems 2014a, Willems 2014b). The flexibility of the VHM approach in defining the detailed model structure is a virtue that fits with parsimony. The input time series are P and ET_o averaged over the basin area, where averaging considers a weighted average, of for example P depths, for available stations using the Thiessen method (Han and Bray 2006). Thus, the model is built after partitioning the observed Q into quick, inter and slow sub-flows, considering quick and slow flow events. The time series of quick and slow sub-flows are used to determine hydrograph characteristics and event specific fractions of the rainfall input and sub-flows and total flows. These are in turn used to identify and calibrate the rainfall-runoff relationships, thus considering sub-model components. The identified sub-models are combined with reservoir models (e.g. linear reservoir theory: Chow et al. 1988). The first and most important sub-model to be identified and calibrated in the VHM approach is the soil moisture storage model, which for this study is identified from the data as a linear relationship:

$$f_u = c_1 - c_2 \frac{u}{u_{max}} [1]$$

where: u is the soil water depth, u_{max} is the maximum soil water capacity, c_1 and c_2 are model coefficients, and f_u is the rainfall fraction to soil water storage. The soil moisture storage volume is depleted by the actual evapotranspiration, ET_a , which is a fraction of ET_o (the potential evapotranspiration) and is given by:

$$ET_a = ET_o, (u \geq u_{evap}) [2]$$

$$ET_a = \frac{u}{u_{evap}} ET_o, (u \leq u_{evap}) [3]$$

where: u_{evap} is the threshold value for u , above which the evapotranspiration happens at the potential rate. The overland flow and inter flow fractions of precipitation, $f_{i,o}$, are analysed using the relationship:

$$f_{i,o} = \exp \left(\left(c_1 + c_2 \frac{u}{u_{max}} \right) + (c_3 + c_4 \ln r) \right) [4]$$

where: r is the antecedent rainfall and c_1 , c_2 , c_3 and c_4 are model coefficients. For the final flow routing, the recession constants k of the defined linear reservoirs, per flow component (inferred from the discharge series processing tasks), are defined as k_{of} , k_{if} and k_{sf} for the overland, inter and slow sub-flows. The calibration procedure is consistent with the methods described by Willems (2009), also covering the evaluation of extremes during the model calibration, next to the cumulative runoff volumes and overall model performance statistics.

The Nash-Sutcliffe Efficiency ($rNSE$) is used as a measure of the model performance:

$$rNSE = 1 - \frac{\sum_{i=1}^N \left(\frac{s_i - o_i}{\bar{o}} \right)^2}{\sum_{i=1}^N \left(\frac{o_i - \bar{o}}{\bar{o}} \right)^2} [5]$$

where N is the total number of daily values in the observed and simulated Q series, s_i the simulated Q , o_i the observed Q , and $\bar{o}$ the average of the o_i values. A $rNSE$ value equal to 1 indicates perfect agreement between the simulated and observed series. It is noted that the step-wise model structure identification approach does not necessarily lead to higher accuracy than the traditional approaches when evaluated using common statistical criteria like the $rNSE$. Willems (2014b) showed this by comparing the VHM approach to different approaches for the construction and calibration of lumped conceptual rainfall-runoff models for two case studies with unrelated meteorological and hydrological characteristics located in two regions, Belgium and Kenya. However, while such criteria evaluate the overall performance, they do not necessarily reflect the model performance for high and low flow extremes, and sub-models or sub-flows. Explicit evaluation of (sub) model results for peak and/or low flow extremes and changes in these extremes provides a better basis for impact investigations on such hydrological extremes, especially for climate change impact investigations Willems (2014b).

Finally, the calibrated VHM model is used for the impact assessments on Q , and hence on water resources availability and hydropower potential, by simulating the hydrological response of the modeled basin, using different plausible (climate change) scenarios of P and ET_o as input. An important requirement is that the existing hydrological data should be sufficient for calibration. An equally important assumption is that drastic changes in land use scenarios are not likely to occur in the study area, which is indeed the case for the Upper-Suriname river basin.

2.3 Future climate projections

2.3.1 Climate models

Initially we used the output of 32 General Circulation Models (GCMs) run under the CMIP5 project (Table 1). The use of a large model ensemble is important to account for the uncertainty associated with the range of possible future climates (i.e. greenhouse gas scenario uncertainty), the climate modeling

and parametrization (i.e. climate model uncertainty) and the internal variability of the climate system (i.e. stochastic uncertainty). The CMIP5 project brought together a coordinated set of climate model simulations from climate modeling centres around the world (Taylor et al. 2012) and allowed for an assessment of each model's relative strengths and weaknesses, as well as a quantification of the range of projections across the contributing models. Given the amount of data involved with working with 32 models and the aim of the study to assess changes for 1.5 °C versus higher global warming, we selected a smaller ensemble of models, which is representative of the full range of change of the original (full) ensemble. The process to limit the ensemble size is outlined in section 2.3.4.

2.3.2 Scenarios and future climate projections

The Representative Concentration Pathways (RCPs) are scenarios that explicitly explore the impact of climate policies (Van Vuuren et al. 2011a; Van Vuuren et al. 2011b; IPCC 2013). They allow researchers to explore the long-term consequences of present decisions (including the role of mitigation and adaptation) while taking account of the inertia in both the socio-economic and physical system (Moss et al. 2011). Initially we considered 4 RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). RCPs are defined by their total radiative forcing expressed in Watts per square meter, pathway and level by 2100 (Meinshausen et al. 2010). Not all RCP simulations were available for the 32 GCMs considered, resulting in 84 model runs, based on the available GCM-RCP combinations (Table 1).

We extracted model data for P , T_{min} , T_{mean} and T_{max} , for a baseline period (1960-1990) and for the end of the century (2070-2100). Projected ET_o was derived from model data using three different simple empirical methods. There are numerous methods to estimate ET_o based on meteorological data. However, because of the limited number of GCM runs providing all meteorological inputs for the more complex ET_o methods, it is simple empirical equations that relate ET_o to an easily measured process variable (e.g. T), and which do not consider the effect of advective variables, which are used in this study. Hosseinzadehtalaei et al. (2016), however, show that the changes projected by these simple approaches may differ substantially from those by the more complex (standard) methods and that the differences add uncertainty to derived climate change signals and future water balance projections. The use of three different empirical methods - one temperature based (Schendel) and two radiation based (Makkink and Jensen-Haise) - were used to account for the uncertainty. The methods used are:

- The Schendel method given by (Hosseinzadehtalaei et al. (2016)):

$$ET_o = 16 \frac{T_a}{RH} [6]$$

where: ET_o is the reference evapotranspiration (mm day^{-1}), T_a the mean air temperature ($^{\circ}\text{C}$), and RH the relative humidity (%).

- The Jensen-Haise method given by (Hosseinzadehtalaei et al. (2016)):

$$ET_o = \frac{C_T(T_a - T_x) \times R_s}{\lambda} [7]$$

where: λ is the latent heat of vaporization (cal gr^{-1}), R_s the solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), C_T a temperature constant equal to 0.025, and $T_x = -3$ when T_a is in $^{\circ}\text{C}$. These coefficients are considered to be constant for a given area.

- The Makkink method given by (Hosseinzadehtalaei et al. (2016)):

$$ET_o = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{\lambda} - 0.12 \quad [8]$$

where: R_s is the solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), γ the psychrometric constant ($\text{KPa } ^{\circ}\text{C}^{-1}$), Δ the slope of the saturation vapor pressure-temperature curve, and λ the latent heat of vaporization (MJ kg^{-1}). The meteorological parameters RH , R_s and Δ in the described methods are derived as function of T (Smith 1992; Raes 2012).

2.3.3 Statistical downscaling

To assess local scale impact, the coarse scale outputs from the GCMs (resolution of 50 km^2) were further downscaled statistically applying a quantile perturbation method (Willems and Vrac 2011; Ntegeka et al. 2014; Tabari et al. 2015). This approach provides projections consistent with the frequency of occurrence of intensities for the climatic variables of interest, considering daily or sub-daily (hourly) time series. The ranked intensities of the baseline (model projections for 1960-1990) are compared to the ranked intensities of the future model projections (2070-2100), thereby comparing quantiles (values of the same rank) based on their empirical return period (or associated exceedance probability) for each specific month. The ratio between future and baseline intensities is a unit-less value:

$$\varphi(p) = \frac{Q_f(p)}{Q_c(p)} \quad [9]$$

where φ is the perturbation factor, and $Q_f(p)$ and $Q_c(p)$ are respectively the future and current quantiles for the climatic variable of interest, both associated with the exceedance probability p . The derived perturbation factors are then consistently used to perturb historical (observed) series. Each intensity, ranked according to the associated exceedance probability, p , is therefore perturbed with a unique factor. In this way, historical time series are perturbed, for each climate model run, to obtain the future climate projections. It is noted that for observed series with less than 30 years of data (for example this study), the perturbations can be a bit less accurate, given that these are a function of the exceedance probabilities of the daily ranked intensities. In that case, the use of monthly change factors (i.e. considering an average of the perturbation factors derived for each specific month) is optional. This is referred to as the “delta change method”, generally applied for meteorological parameters with relatively less variability, such as T and ET_o , compared to P with greater variability in the intensities. For this study, although only 9 years of observed series were available, we used exceedance probability specific perturbation factors for the P series, to enhance accuracy. The methods applied here, supported by the Climate Perturbation Tool, are described comprehensively by Ntegeka et al. (2014).

2.3.4 Selection of an optimal ensemble

For the selection of the final (reduced) ensemble of climate model runs, used for the impact assessments, we initially evaluated all model runs based on the range of change factors they produce, following the quantile perturbation procedure. Model runs were removed if their change factors were outlying in the full range of change factors. We evaluated the latter per RCP and per month. Following a boxplot approach, outliers were detected based on the inter quartile range (IQR) of the monthly change factors (Dawson 2011). Based on the first quartile (Q1) and the third quartile (Q3), which constitute the IQR ($Q3 - Q1$) (e.g. as shown in Fig. 2), inner and outer fences were defined. The inner fences were at $Q1 - 1.5 \text{ IQR}$ and $Q3 + 1.5 \text{ IQR}$, while the outer fences were at $Q1 - 3 \text{ IQR}$ and $Q3 + 3 \text{ IQR}$. Data outside the inner fences, but inside the outer fences, were considered mild outliers. Data outside the outer fences were considered extreme outliers.

Following the assessment of change factors, we retained only the model runs based on RCPs 2.6, 4.5 and 8.5. As stated previously, the context of this study is an examination of water resources for a world where the GMST anomaly with respect to pre-industrial times is around 1.5°C , compared to higher global temperature increases. According to the IPCC, RCP2.6 is associated with a mean likely GMST anomaly of 1.6°C (range of 0.9°C to 2.3°C) by 2081-2100 (IPCC 2013) and is therefore taken as the scenario most likely to produce change closest to 1.5°C . RCP2.6 represents a strong mitigation oriented pathway where greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially over time (Van Vuuren et al. 2011b). It is a “peak-and-decline” scenario, i.e. its radiative forcing level first reaches a value of around 3.1 W/m^2 by mid-century, and declines to 2.6 W/m^2 towards 2100. RCP8.5, on the other hand, is associated with a mean likely GMST anomaly of 3.7°C (range of 3.2°C to 5.4°C) by 2081-2100 (IPCC 2013). RCP8.5 is characterized by increasing greenhouse gas emissions leading to high concentration levels by the end of the century. It is considered a “business as usual” oriented emission pathway. RCP4.5 has been chosen as an intermediate emission pathway which corresponds to a mean likely GMST anomaly of 2.4°C (range of 1.7°C to 3.2°C) by 2081-2100 (IPCC 2013) with respect to pre-industrial times.

Finally, the analysis of change factors further allows for the identification of redundant projections (models with more or less the same outcomes). This in turn provides a strong basis for the selection of an optimal sub-set or optimal ensemble of climate model projections that is representative of the original (full) ensemble. The selection of such a sub-set is particularly important when the model ensemble is large as otherwise the impact study becomes challenging, taking into account the resources required for each impact model run (McSweeney et al. 2016). The optimal ensemble of climate model projections was defined by selecting a number of non-redundant model projections, based on the RCPs 2.6, 4.5 and 8.5, aiming for a, as small as possible, sub-set which span the full range of the original model projections most effectively, excluding the outliers. The aim is that the boxplots (especially the IQRs) of the optimal ensemble and the original ensemble should match closely.

2.4 Hydropower potential

The hydropower potential assessments were done based on the principles presented by Bulu (2017). The theoretical potential power is given by:

$$P_H = H \times Q \times 9.8[10]$$

where P_H is the power potential in kilo Watts (kW), or Mega Watts (MW), Q is the specific discharge on which the P_H calculations are based, and H is referred to as the “Head”, which is the difference in elevation at the specific location of consideration, in this case at the dam site of the Afobaka hydropower scheme. Typically, specific discharges are considered to characterize the hydropower potential of a specific facility, e.g. the 50%, 95% and 100% duration percentiles (Bulu 2017), derived from the 10 to 30 years average flow duration curve (FDC) for a specific site (refer to Fig. S4 for example). For this study, Q for the 50% duration percentile has been considered, which is an important parameter for the annual average power capacity and a good measure for the firm capacity rating of a hydropower facility. The Afobaka hydropower scheme is currently rated at 80 MW, at a nominal H of 54 m, based on the current hydrological conditions. This corresponds with the observed (historical) Q for the 50% duration percentile, i.e. 144.7 m³/s.

3. Results

3.1 Calibration and validation of the applied hydrological model

The $rNSE$ for the model performance for calibration (period 1975-1979) and validation (period 1980-1983) are respectively 0.56 and 0.71. Values for the $rNSE$ suggest that the model is reasonably representative of the observed data and therefore suitable for hydrological simulations for the basin of consideration. Fig. S2 presents the complementing water balance discrepancy (WBD), a graphical goodness-of-fit statistic, for a more objective validation of the model performance (Willems 2009). The WBD is considered, given the importance of cumulative Q in terms of water resources availability, hence hydropower potential.

3.2 Optimal ensemble selection

Given the context of this study, we used the mean daily temperature, T_{mean} , as the basis for the selection of the optimal model ensemble. Fig. 2 shows line plots representing the mean monthly change in T_{mean} with respect to the model baseline, for each available simulation (i.e. all GCM-RCP combinations) and for the end of the century (2070-2100). The corresponding range of change per month for the original (full) ensemble is also shown for reference as black boxplots. The resulting optimal ensemble of model runs, then, would be one that most effectively spans the full range of changes (by all model runs) represented by the black boxplots.

Table 2 presents the optimal ensemble, consisting of 15 model runs - 5 runs for each RCP considered (RCP2.6, 4.5 and 8.5). In Fig. 2, the model runs included in the optimal ensemble are highlighted in green,

blue and yellow for RCP2.6, RCP4.5 and RCP8.5 respectively. The corresponding range of change for T_{mean} , per month, for the optimal ensemble of model projections is shown as red boxplots. There is a general coincidence of the red and black boxplots suggesting that the optimal ensemble reasonably captures the range of projections of the original (full) ensemble.

We used the optimal ensemble to examine changes in the other meteorological variables necessary for the hydrological simulations and further impact assessments. The results for ET_o and P are presented in Fig. S3 (top and below respectively). The results for ET_o are based on the 3 methods previously noted in section 2. It is apparent, considering the IQRs of the boxplots, that the Schendel and Jensen-Haise methods are in close agreement, but deviate from the Makkink method results. Nevertheless, the impact assessments are further done based on ET_o derived by all 3 methods, allowing for a sensitivity analysis.

Fig 2

Range of change for Mean Temperature, per month, for the optimal ensemble of model projections (red boxplot) that most effectively spans the full range of change of all model projections (black boxplot) for the end of century (2070-2100); Each model simulation (over all models and Representative Concentration Pathways) is represented as a line plot; The model runs of the optimal ensemble are highlighted in green, blue and yellow, respectively for the Representative Concentration Pathway 2.6, 4.5 and 8.5; Change is with respect to the 1960-1990 model baseline

3.3 Hydrological impact assessments

Fig. S4 is an example of FDCs determined using each simulation of the optimal ensemble. It depicts the relative changes in Q and duration, per scenario and for the Jensen-Haise ET_o method. Fig. S4 also shows the FDC based on historical observations. The intercomparison of the results for the impact on Q , for the three different ET_o methods (Fig. S5), reveals that the relative effect on Q , per ET_o method, is minor. Therefore, further impact assessments have been done consistently based on Q for the Jensen-Haise ET_o method. Fig. 3 presents the results per RCP.

Fig 3

Comparison of Discharge values for specific duration percentiles, per Representative Concentration Pathway, for the end of century (2070-2100); Values are derived from the resulting Flow Duration Curves for all model runs of the optimal ensemble, considering the Jensen-Haise method for Evapotranspiration; The green, blue and red boxplots respectively represent the results for Representative Concentration Pathway 2.6, 4.5 and 8.5; The black/dashed reference lines represent the historical (observed) Discharge values

3.4 Impact on the hydropower potential

The impact on the hydropower potential is evaluated based on Eq. [10], considering the Q projections for the 50% duration percentile, for the Jensen-Haise ET_o method. The annual average power is determined (i.e. the guaranteed firm capacity per scenario run). The nominal value for H at the dam site of the Afobaka hydropower scheme is used in the calculations assuming that under normal conditions

for operation, H should be in the design range, i.e. 54 m. For example, the historical (observed) Q for the 50% duration percentile is equal to 144.7 m³/s, and the associated power potential, based on Eq. [10], equals 76.6 MW at nominal H . This is in accordance with the current capacity rating of 80 MW, i.e. the current firm power, on daily basis, under the current climatic conditions. The results per scenario run are presented in Fig. 4, presenting a tabular overview of the projected change per scenario (model and specific RCP), compared to the historical (observed) conditions. The range of change for P_H , per RCP, is also presented by the boxplots in Fig. 4. The IQR for RCP2.6 is from 43 % to -40 %, moving towards more negative changes for RCP4.5 (from 4 % to -53 %) and RCP8.5 (from -41 % to -82 %).

Fig 4

Range of change for Hydropower Potential for the end of century (2070-2100); The Inter Quartile Ranges of the boxplots depict the range of change per Representative Concentration Pathway

4 Discussion

4.1 Projected changes in climate by 2100

The model runs of the optimal ensemble showed a clear distinction in the projected mean temperature increase in the Afobaka region for each RCP (Fig. 2). Highest (lowest) temperature changes with respect to the present day baseline occur for RCP8.5 (RCP2.6), which is consistent with the increasing trend in the projections of future GMST ranges towards the end of the century, with higher RCP (IPCC 2013). That is, there are distinct changes at the regional level in response to future emission scenarios and for progressively higher global warming targets.

The corresponding future projections for ET_o and P respectively indicate increasing and decreasing rates with respect to the present day baseline. This is apparent in the monthly boxplot IQRs shown in Fig. S3, with changes up to +20% for ET_o and -80% for P . The monthly rainfall distribution throughout the year in Suriname is mainly governed by the Inter Tropical Convergence Zone (ITCZ), alternately causing wet and dry seasons. The short (Dec-Jan) and the long (May-Aug) wet seasons account for about 75 % of the annual rainfall. The projected decreases for P and increases for ET_o are across all seasons (wet and dry), indicating declining water resources, overall, towards the end of the century. The projected decrease for P is also significant for the long wet season. This season contributes the most to water resources in general, further strengthening the idea that there will be a higher probability for declining water resources towards the end of the century.

4.2 Impact on water resources availability and hydropower potential

The results (Fig. 3) reveal significant changes in the rainfall-runoff flows, Q , especially for the extremes, by the end of the century. Recall that these results are for Q based on the Jensen-Haise ET_o method. It was shown previously that the relative impact on Q per ET_o method was minor. The extreme high flows (Q projections for the 1% duration percentile) could potentially increase by a factor of 3 for RCP2.6. The tendency for an increase is generally noted in the boxplot IQRs for the 1% duration percentile for all RCPs. There is also a higher probability for increasing high flows (Q projections for the 5% and 10%

duration percentiles) for RCP2.6, however, projections for the 50% and the 95% duration percentiles indicate, more or less, an equal range for increases and decreases for Q . For RCPs 4.5 and 8.5, i.e. for higher GMST increase above 1.5°C, the associated boxplot IQRs suggest an overall general tendency for decreasing Q , projected with higher probability (greater confidence). This is especially the case for the high (“business as usual”) greenhouse gas concentration pathway (RCP8.5), which corresponds to a likely global temperature rise of greater than 3°C by the end of the century.

The strong increase projected for the extreme high flows in general, notwithstanding that the probability of occurrence is low (1% duration percentile), suggests a strong increase in flood hazards, which would be a source of concern with respect to dam safety and integrity in the future. However, the predominant climatic factor of concern would be the occurrence of (extreme and prolonged) droughts, which could potentially occur with greater intensity and frequency as GMST increases above 1.5°C above pre-industrial values. The Q projections for the greater flow duration percentiles for successively higher RCPs, especially the 50% and the 95% duration percentiles (the latter being associated with dry recession periods/ dry seasons), suggest a great potential for decreasing water resources availability in the future.

The impact of further increasing GMST becomes even more apparent in the assessment of hydropower potential, using the Q projections for the 50% duration percentile (Fig. 4). There is a, more or less, equal range for increases and decreases projected for P_H under RCP2.6. However, there is greater confidence (relative higher probability) of projected decrease, as the first quartile range (Q1: red) relative to the third quartile range (Q3: blue) indicates that more weight (greater data density) is given to decrease. For RCP4.5, further decrease in P_H is projected. Although there is uncertainty involved, decrease is projected with much greater confidence (much higher probability), given that the majority of the data is situated below the zero line. For RCP8.5, decrease is projected with even greater confidence (even higher probability), given that the majority of the data is situated well below the zero line, but also because of the significantly smaller IQR range (much greater data density). It becomes apparent that with further GMST increase above 1.5 °C, the uncertainty aspect becomes less relevant in terms of the probability for increase or decrease. It is rather the range of decrease and associated impact which becomes more important with further increasing GMST.

It is noted that the results presented are based on the consideration of only one hydrological model, the VHM model. Nevertheless, there is consistency with the results of similar studies done for Suriname using other models. For example, in the study done for the Upper-Suriname river basin by [Nurmohamed et al. \(2007\)](#), using a fully distributed physically based hydrological model (WETSPA), the projected maximum decrease in discharge was 87.5 %. This is of the same order of magnitude as projected by this study. From Fig. 4, there is a maximum decrease of 83 % projected for Q 50%, for RCP8.5 (recall that Q 50% is the annual average discharge associated with firm power capacity). The hypothetical climate change scenarios used by [Nurmohamed et al. \(2007\)](#) (i.e. increased GMST in the range of 2 °C to 4 °C, combined with decreasing precipitation in the range of -10% to -50%) are generally in agreement with the RCP4.5 and 8.5 scenarios considered for this study (see the projections of T and P in Figs. 2 and S3). [Nurmohamed et al. \(2007\)](#) obtained a $rNSE$ of 0.55 and 0.78 respectively for calibration and validation,

indicating comparably equal model performance to the VHM model in this study. Although it is recognized that different models could be used for the impact assessments, it is again noted that a major advantage of the VHM approach over other modeling approaches (considering the parsimonious, transparent and step-wise procedure), is the explicit evaluation of (sub)model results for peak and/or low flow extremes and changes in these extremes.

When the potential impact of climate change on hydropower potential is considered from a global perspective, it can be concluded that it may not change significantly (less than 1%) (Hamududu and Killingtveit 2012). However, regional increases or decreases could be quite large (Hamududu and Killingtveit 2012). Van Vliet et al. (2016) focused on global vulnerability of hydropower production to climate change and found that, while overall increases in river flow are expected in many regions, most existing hydropower plants are located in areas where river flow is expected to decline, resulting in an overall loss of global hydropower capacity. The impact of seasonality related to a specific location is also important. For example, Boehlert et al. (2016) showed, for the contiguous United States, that due to generally increasing river flow under higher emissions scenarios, climate change tends to increase overall hydropower potential. However, during low flow months, the potential tends to fall with increasing emissions, threatening the estimated firm (low flow) energy from hydropower. Kopytkovskiy et al. (2015) focused on the upper Colorado river basin and showed a decline in precipitation at low elevations and an increase at high elevations, although precipitation declined during the summer months at all elevations. Using a business as usual scenario, they projected an overall decrease in annual river flow, which was attributed to a reduction in precipitation and increasing temperature trends. However, this was not consistent during the winter months, which showed an increase in precipitation at high elevations and a modest temperature increase, resulting in an increase in river flow. They further showed that the response of reservoir levels to climate change varied basin-wide due to variability in precipitation, evapotranspiration, and river flow. Their study (Kopytkovskiy et al. 2015), therefore, shows that climate change impacts are both seasonal and site specific. Finally, another aspect of importance is water budgeting, i.e. giving consideration to multipurpose projects and water resources demand management. Raje and Mujumdar (2010) studied the overall performance of reservoirs in India for multiple purposes including irrigation, flood-control, and hydropower production. They showed that, due to increased irrigation needs, hydropower generation would fall below current levels under all climate scenarios considered in their study. Regional impact investigations and site specific impact assessments, e.g. as in our study, are very important, because, as also seen from the other studies considered, climate change impacts strongly depend on region specific factors (even at the basin level).

5 Conclusions

We used hydrological modeling, incorporating the latest generation of climate model results, to assess the impact of climate change on the hydropower potential of the Afobaka hydropower scheme in Suriname. The use of 3 different greenhouse gas concentration pathways, i.e. RCP2.6, 4.5 and 8.5, facilitated an assessment of the potential future climate impacts within the context of a 1.5°C versus higher global mean surface temperature increase, towards the end of the current century. The selected optimal ensemble of climate model runs revealed a clear distinction, dependent on RCP, in projected

temperature increase in the Afobaka region at the end of the century. Mean monthly temperature anomalies with respect to a present day model baseline were smallest for RCP2.6 and largest for RCP8.5.

The ensemble climate model runs showed that potential changes in the occurrence of extreme droughts, and decreasing water resources availability in general, are factors of concern in the future, potentially having an enormous negative impact on the hydropower potential of the Afobaka hydropower scheme. Extreme drought and decreased water resources availability projections generally characterize the RCP8.5 based climate model runs. In comparison, the RCP2.6 based projections generally indicate less extreme impacts (particularly with respect to droughts, and the associated impact on hydropower potential). The RCP4.5 based projections illustrate the cascading effect of further increasing temperature, with a clear tendency towards less available water resources. A potential decrease in hydropower potential, relative to historical observations, of up to approximately 40% is projected towards the end of the century for mean global surface warming in the range of 1.5 °C (RCP2.6). This increases to approximately -50% for mean global surface warming slightly above 2.0 °C (RCP4.5), and to approximately -80% for mean global surface warming above 3.0 °C (RCP8.5).

There are clear indications that a “business as usual” greenhouse gas emission pathway will have severe impacts on the hydropower sector in Suriname. Although there is potential for other renewable resources such as wind and solar, no assessment has been done considering to what extent these can contribute in a significant way to the energy mix of Suriname, i.e. to offset future changes in hydropower potential and to keep fossil fuel based power generation to a minimum. There would need to be policy and legislative reforms to regulate the energy sector, e.g. steering households towards more self-sufficiency using domestic solar power. It is also very important to take into consideration that wind and solar are intermittent resources, which do not guarantee firm power output and therefore introduce technical limitations associated with grid stability. This study points to an urgent need for a range of actions needed in the Caribbean energy sector (e.g. policy through technological advancements) to ensure future energy security in the face of global warming.

Suriname is committed to the Paris agreement and is determined to further increase renewable energy contribution in its energy mix, both, as its contribution to mitigating climate change, and to ensure energy security by steering away from fossil fuels. The contribution of hydropower to the energy mix in Suriname and by extension to the country’s economic development is significant. It will continue to grow due to other major hydropower projects planned for the future. In that light, the impact of increasing global temperatures will likely result in enormous negative socio-economic impacts. Therefore, in view of the potential impacts on hydropower potential and energy production, it seems clear that a 1.5°C global temperature increase limit by the end of the century, as put forward by the small island developing states, should not be considered as too ambitious a goal.

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Table1

CMIP5 climate model runs

Climate model/(Modelling centre)	RCP	Number of available runs
ACCESS1-0_r1i1p1/(CSIRO-BOM)	8.5	1
bcc-csm1-1-m_r1i1p1/(BCC)	4.5; 6.0; 8.5	3
BNU-ESM_r1i1p1/(GCESS)	4.5	1
CanESM2_r1i1p1/ (CCCMA)	2.6; 4.5; 8.5	3
CanESM2_r2i1p1/ (CCCMA)	2.6; 4.5; 8.5	3
CanESM2_r4i1p1/ (CCCMA)	2.6; 4.5; 8.5	3
CanESM2_r5i1p1/ (CCCMA)	2.6; 4.5; 8.5	3
CMCC-CESM_r1i1p1/ (CMCC)	8.5	1
CMCC-CMS_r1i1p1 / (CMCC)	4.5; 8.5	2
CNRM-CM5_r1i1p1/ (CNRM-CERFACS)	2.6; 4.5; 8.5	3
CSIRO-Mk3-6-0_r10i1p1/ (CSIRO-QCCCE)	4.5; 8.5	2
EC-EARTH_r12i1p1/ (EC-EARTH)	4.5	1
GFDL-ESM2G_r1i1p1/ (NOAA GFDL)	2.6; 4.5; 6.0; 8.5	4
GFDL-ESM2M_r1i1p1/ (NOAA GFDL)	4.5; 6.0; 8.5	3
GISS-E2-R_r6i1p1/ (NASA GISS)	4.5	1
GISS-E2-R_r6i1p3/ (NASA GISS)	4.5	1
HadGEM2-AO_r1i1p1/ (NIMR/KMA)	4.5; 6.0; 8.5	3
HadGEM2-ES_r1i1p1/ (MOHC, additional realizations by INPE)	2.6	1
inmcm4_r1i1p1/ (INM)	4.5; 8.5	2
IPSL-CM5A-LR_r1i1p1/(IPSL)	2.6; 4.5; 6.0; 8.5	4
IPSL-CM5A-LR_r2i1p1 / (IPSL)	2.6; 4.5; 8.5	3
IPSL-CM5A-LR_r3i1p1/(IPSL)	2.6; 4.5; 8.5	3
IPSL-CM5A-MR_r1i1p1/(IPSL)	2.6; 4.5; 6.0; 8.5	4
IPSL-CM5B-LR_r1i1p1/(IPSL)	4.5;8.5	2
MIROC-ESM-CHEM_r1i1p1/ (MIROC)	2.6; 4.5; 6.0; 8.5	4
MIROC-ESM_r1i1p1 / (MIROC)	2.6; 4.5; 6.0; 8.5	4
MIROC5_r1i1p1 / (MIROC)	2.6; 6.0; 8.5	3
MIROC5_r2i1p1 / (MIROC)	4.5; 6.0; 8.5	3
MIROC5_r3i1p1/ (MIROC)	4.5; 6.0; 8.5	3
MPI-ESM-LR_r1i1p1/ (MPI-M)	2.6; 4.5; 8.5	3
MPI-ESM-MR_r1i1p1/(MPI-M)	2.6; 4.5; 8.5	3
MRI-CGCM3_r1i1p1/ (MRI)	2.6; 4.5; 6.0; 8.5	4
Total model runs		84

Table2

Optimal ensemble of climate model runs

Climate model	RCP
ACCESS1-0_r1i1p1	8.5
CanESM2_r2i1p1	2.6
CanESM2_r1i1p1	4.5
CanESM2_r5i1p1	4.5
CanESM2_r5i1p1	8.5
CMCC-CMS_r1i1p1	8.5
GFDL-ESM2G_r1i1p1	2.6
GFDL-ESM2M_r1i1p1	4.5
HadGEM2-AO_r1i1p1	8.5
HadGEM2-ES_r1i1p1	2.6
inmcm4_r1i1p1	8.5
IPSL-CM5A-LR_r3i1p1	4.5
MIROC-ESM-CHEM_r1i1p1	2.6
MIROC-ESM-CHEM_r1i1p1	4.5
MPI-ESM-LR_r1i1p1	2.6

Fig 1

Fig 2

Fig 3

Model run		Q per duration percentile [m^3/s]				
Model	RCP	1%	5%	10%	50%	95%
ACCESS1-0_r1i1p1	8.5	450.4	257.2	173.1	26.5	2.0
CanESM2_r5i1p1	8.5	504.7	326.8	261.8	42.4	7.3
CMCC-CMS_r1i1p1	8.5	734.8	267.1	168.7	24.3	1.4
HadGEM2-AO_r1i1p1	8.5	3473.5	1812.4	1267.9	84.9	6.1
inmcm4_r1i1p1	8.5	1413.5	747.6	608.5	172.4	35.6
CanESM2_r1i1p1	4.5	772.0	470.2	382.5	62.1	8.8
CanESM2_r5i1p1	4.5	797.9	420.3	328.7	67.3	11.1
GFDL-ESM2M_r1i1p1	4.5	1369.3	756.8	607.5	151.1	28.9
IPSL-CM5A-LR_r3i1p1	4.5	1197.4	574.9	395.7	108.7	25.1
MIROC-ESM-CHEM_r1i1p1	4.5	1863.1	948.3	718.8	162.4	25.8
CanESM2_r2i1p1	2.6	1003.7	597.7	486.3	87.5	13.0
GFDL-ESM2G_r1i1p1	2.6	2487.1	1405.9	1035.5	207.0	27.9
HadGEM2-ES_r1i1p1	2.6	1222.8	828.3	634.3	114.2	23.2
MIROC-ESM-CHEM_r1i1p1	2.6	3298.7	2180.9	1732.6	551.6	89.8
MPI-ESM-LR_r1i1p1	2.6	515.1	283.5	207.0	52.1	8.8
OBSERVED	---	1007.5	649.8	511.8	144.7	20.5

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