



Hydrological modeling to assess water resources resilience towards climate change impacts in Tacloban, Philippines

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Received: 15 June 2017 / Accepted: 15 January 2018 / Published online: 13 February 2018

Abstract

Tacloban, Philippines, the city most devastated by typhoon Haiyan in 2013, faces severe water supply constraints, particularly on the relocation sites that are expected to accommodate 40% of Tacloban's population by 2018. This region's hydrological system was modeled using QSWAT to evaluate the impacts of climate change, namely, rising temperatures and variation of rainfall patterns, on three rivers (Binahaan, Pongso, and Cabayugan). These rivers are the potential sources of water for the two supply solutions currently being considered. Thus, it is essential to assess their resilience as sources of water. Two climate scenarios were generated for 2020 and 2050 using the Change Factor (CF) method, and the system response was compared to the baseline data (1979–2010).

Results show that, regardless of the chosen supply solution, for certain time periods (most severely for the quarter of March to May), the percentage of days in which the river flows were insufficient to meet the proposed water catchment flows was significant (reaching up to 25%). Outputs also suggest that Binahaan River, where the current water catchment is located, may fail in providing sufficient water to the region for future scenarios. However, it should be noted that Pongso and Cabayugan Rivers in northern Leyte can represent a resilient water source to supply the new resettlement areas.

Keywords: Climate change adaptation · hydrological modeling · QSWAT · resilience · typhoon haiyan · water resources management

DOI: <https://doi.org/10.18783/cddj.v003.i01.a02>

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Introduction

Climate change (CC) has recently become a matter of the utmost importance in water studies, as it is capable of altering water availability worldwide due to variation of rainfall patterns. The potential impacts include the changes in timing and magnitude of surface runoff, stream discharge, evaporation, and flood events (Neupane & Kumar, 2015). Several studies have demonstrated that even small perturbations in the frequency and/or quantity of precipitation can have significant impacts in terms of watershed runoff (Minville, et al., 2008).

However, coupling hydrological and climate studies is a relatively young discipline (Teutsschbein, 2013). CC impact studies on hydrological systems faced the obstacle of the Global Circulation Models (GCMs), which were used to simulate future climate scenarios but did not provide sufficiently detailed outputs. This obstacle was surpassed only with the use of dynamic downscaling tools, namely, Regional Climate Models (RCMs), even though some bias correction is still recommended when using directly RCM outputs on hydrological studies (Fowler & Kislby, 2007).

The concept of resilience, initially coined for an ecological context, has conquered prominence in CC discussions, particularly those regarding adaptation. In brief, the resilience of a system can be defined, for a certain system, as the “ability to reduce both the magnitude and the duration of the deviation from the equilibrium stadium” (Proag, 2014). Likewise, in the context of disaster resilience, Klein, Nicholls, and Thomalla (2003) claim that the concept of resilience sits under the broader concept of “adaptive capacity” as one of the numerous factors capable of influencing it. Hence, resilience appears as an idea with direct application potential, especially when moving from disaster recovery (as for this particular case study) towards hazards prediction, or disaster prevention and preparedness (Klein et al., 2003).

Resilience indicators for water resources focus mostly on water scarcity or quality degradation issues. Possible indicators for water scarcity are average precipitation, average river discharge, and average soil moisture or groundwater level—these are examples of components that can be accurately studied through hydrological modeling, facilitating the benchmarking of various scenarios and the development of a sensitivity analysis to better understand the weight of each variable. The sensitivity of a system to water scarcity is therefore determined by the influence of the stress factor (e.g., CC): for example, in some basins, a reduction of rainfall can result in a reduction in water availability, whilst in other basins, it can have only a negligible impact on stream flow. Other possible indicators are the changes in water demand for future scenarios, comparatively to a reference period (and the possible disaggregation by water users and sectors); the loss of industrial and agricultural production (or jobs), income, and livelihoods; desertification; and land degradation (Elis, 2014).

Case Study Presentation

The Republic of the Philippines is one of the most vulnerable territories to CC, given its geographic location in the Tropical Pacific, archipelagic formation, and population distribution. In recent years, this country was ranked highest in the world in terms of vulnerability to tropical cyclone (TC) occurrence and third in terms of people exposed to seasonal events (Climate Change Commission, 2012). The Philippines has already experienced noticeable adverse effects in recent years, with the observed changes in its climate in most recent times having never been seen in the past 140 years. Climate trends evaluated for the 1951–2009 period (using reference data from 1971 to 2000) revealed an increase in the annual mean temperature by 0.65°C, with an increase of 0.36°C and 0.1°C in terms of maximum and minimum temperatures, respectively. The trends of rainfall (extreme rainfall intensity and frequency) are not so clear, with very little spatial coherence, varying between islands and regions (increasing in some, while decreasing in others). These climate simulations were obtained by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) using the project Providing Regional Climates for Impact Studies (PRECIS), an RCM developed by the UK Met Office Hadley Center for Climate Prediction and Research, considering boundary data from the ECHAM4 and HadCM3Q0 Global Climate Models. For this downscaling, three emission scenarios were assumed: A2 (high range), A1B (medium range), and B2 (low range) (PAGASA, 2011).

Although there is still no sound evidence of an overall nationwide increase in the frequency of TCs, for the Visayas region, TCs seem to have increased from 1971 to 2000, as compared with previous periods. Moreover, a slightly superior number of extreme cyclones have been observed (from the typhoon category, with winds above 150 km/h (PAGASA, 2011)). These observations are partially sustained by the work of Cinco et al. (2016), stating that, for the period of 1951–2013, there have actually been fewer typhoons reaching the country, but there is an increase in the frequency of the most extreme ones.

The city of Tacloban is located at the northeastern coast of Leyte island, Visayas region, Philippines, between the San Juanico Strait and the island's highlands—Sta. Helena and Naga-Naga mountain ranges—that reach above 450 m of altitude (Wernstedt & Spencer, 1967). To most authors, the climate in this region resembles a Type II climate, with no dry season and a period of relatively more intense rainfall from November to February. From the analysis of local climatological patterns for the period of 1987–2006, Tacloban's annual average rainfall totaled 2600 mm. The Philippines coincides with the typhoon belt, with circa 20 storms crossing the country per year and the strongest ones being registered from July to October (Gultiano, et al., 2003). However, on November 8, 2013, super typhoon Haiyan, the strongest registered so far to ever make landfall, roared ashore over Tacloban, causing catastrophic destruction and over 6000 casualties (NDRRMC, 2014), with its outrageous proportions being often linked to CC causes. Being one of the major cities hit by the 6-m tsunami-like storm surge, Tacloban soon became the focus of world media attention and international relief operations.

To the present day, the city is undergoing major relocation efforts towards north that will create new residential, institutional, and commercial areas on a supposedly storm-surge-safer zone. Leyte Metro Water District (LMWD), the local water utility, is responsible for supplying Tacloban City and the seven surrounding municipalities of Dagami, Palo, Pastrana, Sta. Fe, Tabontabon, Tanauan, and Tolosa. Despite only 25% of the city's households being actually connected to this utility, "due to political disputes, LMWD does not intend to increase their service area within the City of Tacloban" (United States Agency for International Development [USAID], 2015). However, a proposal to expand the city's network has been submitted, which relies mostly on the Binahaan River catchment, towards the northern relocation areas. Until the submission of this article, this resettlement area that will accommodate 40% of Tacloban's population in 2018, was still lacking a solid water supply solution and other proposals were being evaluated—some advanced by the local government unit (LGU) of Tacloban.

As a consequence, relocated families are fleeing back to the city, rebuilding their homes in markedly dangerous flood-prone areas, as Santos, Toda, Orduña, Santos, and Ferrão, (2016) have foreseen. The impacts of this typhoon also affected the region's vegetation (Carlos, et al., 2016) and water resources (Tolentino, et al., 2016).

Therefore, the goal of this research is to quantify the impacts of CC on the hydrological system on which Tacloban relies for water supply purposes. A closer look was given to the three waterways currently considered for water extraction: the already explored Binahaan River and the Pongso and Cabayugan Rivers, pointed out by the USAID as possible water sources to supply the new resettlement areas. Furthermore, this work is expected to contribute to the enforcement of the role of hydrological models in CC impact studies—specifically in developing countries where data collection is scarcer—and to support the resilience-enhancing practices on local water resources management.

Materials and Methods

Hydrological Modeling with QSWAT

In order to replicate Tacloban's surrounding water lines behavior under CC impacts, a QGIS-based version of the Soil and Water Assessment Tool (SWAT) was used. This is a widely used hydrological model from the US Department of Agriculture, i.e., QSWAT. Since it has the nature of a continuous-time model (not as adequate to simulate single-event but rather long-term changes), SWAT enables users to address gradual environmental problems—being increasingly used for CC contexts all over the globe. For instance, the model is capable of simulating the impacts of temperature changes and soil water deficit on vegetation growth and erosive response, besides the effects of global CCs on hydrological balance and, therefore, on the processes that determine surface and base flow generation (Serpa et al., 2015).

QSWAT interface presents a three-step configuration to be followed by the user in order to prepare the SWAT simulation (Dile, et al., 2016), followed by a fourth step for output analysis. Step 1: Delineate Watershed, where the user selects the elevation map grid to be used and can optionally burn an existing stream network and a predefined watershed. In this step also, the threshold for creating subbasins is set, either by area or number of cells. Step 2: Create Hydrological Response Units (HRUs), where the user sets the conditions to delineate HRUs. The HRUs are smaller partitions of the subbasins, which share a unique land use, soil, and slope; therefore, in this step, both land use and soil maps are required, together with their respective look-up tables that should be previously prepared if the user is not using the default ones. Step 3: Edit Inputs and Run SWAT, where the input tables containing climatic data are provided by the user. Step 4: Visualize, in which, to analyze the simulation outputs, the user may choose from static data, animation, or plotting. For more details on QSWAT functioning, setup and outputs visualization options, refer to the work of Dile et al. (2016).

Data Sources

QSWAT requires both maps and table data as inputs. In Step 1 of the setup, the watersheds are delineated based on elevation layers and a stream network. The Digital Elevation Model (DEM) raster file was obtained from Earth Explorer, a database from the US Geological Survey. The 30-m resolution grid was then clipped to show only Tacloban City and its surroundings (this allowed faster simulations; hence, the model had a smaller area to process). As for the streams shapefile, it was obtained from the online database DIVA-GIS and again clipped to show only the interest area. After a few attempts, it was determined that a threshold of 50 km² for delineating watersheds was adequate to match the created stream network, providing sufficient detail for the objectives of the study.

Land use and soil maps were required in Step 2 for the creation of HRUs. The land-use layer was downloaded from the WaterBase database, a service provided by the United Nations University with the aim of advancing the practice of Integrated Water Resources Management in developing countries, while the soil map used was one from the Food and Agriculture Organization (FAO) of the UN. Only clipping and reprojecting operations were then necessary to have these maps ready for the simulation. The standard land use and soil lookup tables used, compatible with the maps from this database, were by default included on QSWAT.

Climate variables for QSWAT simulations (introduced as table data) provide the moisture and energy inputs that affect the water balance and determine the relative importance of its various components. Tacloban City weather station is installed 2.71 m above the sea level in the peninsula that hosts the city airport (11°12'32.21"N, 125°01'29.92"E) and is managed by PAGASA. Daily data records from this

station were collected for the following variables, according to the model requirements: precipitation (in millimeters), temperature (min and max, in degree Celsius), relative humidity (in percentage) and wind speed (in meters per second). These series corresponded to the period of January 1, 1979, to December 31, 2010. The solar radiation series was extracted from the Global Weather database; hence, these records were not available for Tacloban. This database hosts data for any given location, which are already displayed in a compatible format. The “stations” on this database, however, do not correspond to real stations but to points of a matrix of a weather generating model. The point 1111250 was chosen as being closest to Tacloban’s PAGASA station (only 16 km apart and with an elevation of 4 m). It was assumed that using solar radiation data from a different station would not have significant impacts on the modeling outputs, considering the proximity of the stations, similar elevation, and no relevant orographic occurrences between them. Moreover, from all the climatic variables, solar radiation is believed to be the one with the lowest expected spatial variability and not as influenced by local factors. Finally, the Weather Generator Tables (WGEN for the different scenarios) were created according to the model description of Neitsch, Arnold, Kinity, and Williams (2011; for further detail on the creation of these tables, refer to these authors’ work).

It should be noted that QSWAT uses the SCS-CN method to estimate superficial runoff, balancing for each hydrological unit its soil characteristics, which loses some accuracy when applied to larger basins. However, the lack of spatially distributed rainfall data for the study area did not allow the use of other methods that could enhance the accuracy of this impact study.

Statistical Validation of Precipitation Series

The rainfall records registered by a meteorological station are statistically defined as random variables (assuming that rainfall events are independent from each other), thus being only useful if validated through a statistical analysis. If a sufficiently long series of rainfall records is available, one can determine which probability distribution function is closer to the empirical distribution of the data. One of the main advantages of adjusting such function is that it further allows extrapolating values with a return period larger than the one of the analyzed sample (with a comfortable confidence degree, usually around $1-\alpha=0.95$). The normal distribution (or Gaussian Law) is reportedly adjusted to annual average records, while the Gumbel Law is used to describe the distribution of extreme data (Lencastre & Franco, 2006).

The quality of fit of these adjustments was analyzed recurring to analytical methods such as the Chi-squared and the Kolmogorov–Smirnov tests. For more detail on these statistical procedures, refer to the work of Lencastre and Franco (2006).

Scenarios and CC

CC can be simulated with SWAT by manually manipulating the climatic daily data series and then running the model using them as input data to assess changes in the hydrological system (Neitsch et al., 2011). This method is frequently defined in specialized literature as the CF method. In essence, this method modifies the observed historical time series by affecting it with the projected differences between future and current climates, computed by climate models, either GCMs or RCMs (Chen, et al., 2011). These perturbation factors are computed on a monthly basis, for each future time period (Equations 1 and 2; Minville et al., 2008). With regards to generating future temperature daily series ($T_{fut,d}$), the CF method involves adjusting the observed daily records ($T_{obs,d}$) by adding the difference in monthly averages ($\bar{T}_{fut,m}$ and $\bar{T}_{obs,m}$) predicted by the climate model between the future horizon and the reference period.

$$T_{fut,d} = T_{obs,d} + (\bar{T}_{fut,m} - \bar{T}_{obs,m}) \quad (1)$$

As pointed out by Chen et al. (2011) and Minville (2008), for the precipitation series, the adjusted precipitation on the horizon period ($P_{fut,d}$) is obtained by affecting daily observed records ($P_{obs,d}$) by the precipitation ratio between monthly averages ($\bar{P}_{fut,m}$ and $\bar{P}_{obs,m}$).

$$P_{fut,d} = P_{obs,d} \times (\bar{P}_{fut,m} \div \bar{P}_{obs,m}) \quad (2)$$

Despite being frequently used to strategic-scale assessments of hydrological impacts of CC, this method is not without problems: statistically, the baseline and scaled series are different in their means, maxima, and minima, but all the other properties of the data remain unchanged (such as range and variability). Thus, the CF method application to the precipitation series does not affect the number of rainy days—meaning that the temporal sequence of wet and dry days remains unchanged, limiting the method’s efficiency in circumstances of persistent droughts, for example, which are important in impacts assessment. Furthermore, the procedure fails by admitting that the spatial pattern of the present climate remains unchanged (Diaz-Nieto & Wilby, 2005). Nonetheless, assuming that it should not be used to make projections of precipitation on a daily basis as the temporal structure of the series remains constant, the CF method is still largely used in quantifying the impacts of CC on hydrology, and its application is enforced when equivalent observational and GCM/RCM data exist for comparison purposes.

CC scenarios for this modeling exercise were created consistently with PAGASA’s official projections for Leyte, as summarized on Table 1. These climate trends were obtained via the UK Met Hadley Center RCM data

Table 1. Seasonal temperature increases (°C) and rainfall variation.

	Temperature Projections			Rainfall Projections		
	Baseline (°C)	2020 (°C)	2050 (°C)	Baseline (mm)	2020 (%)	2050 (%)
DJF	24.6	+0.9	+1.8	689.5	+3.0	+9.4
MAM	27.8	+1.2	+2.3	342	-8.9	-18.9
JJA	28	+1.1	+2.2	568.7	+9.5	+19.6
SON	27.7	+1.0	+1.9	725.5	+7.4	+19.5

(from the project Providing Regional Climates for Impacts Studies or PRECIS). This downscaling to the Filipino territory was performed using a grid resolution of 25 km, considering a baseline period from 1971 to 2000. For Leyte, rainfall is expected to increase in all seasons except from March to May, and for the same period, temperature increases are expected to be the highest (PAGASA, 2011).

Taking the Tacloban's weather station data series (for precipitation and maximum and minimum temperatures), the daily records were affected by these variations to obtain two new series for projected CC scenarios of 2020 and 2050, which are designated as CC2020 and CC2050, respectively. For the remaining climatic variables (relative humidity, wind speed, and solar radiation), the same records as the original series were used due to lack of projections for future scenarios.

Modeling Calibration and Validation

The calibration and, if possible, the validation of any modeling exercise outputs are essential steps to assure that the chosen model is accurately describing the real system. Thus, both calibration and validation are often processed by comparing obtained data with real empiric observations.

The QSWAT modeling results for Tacloban were calibrated using a series of observed monthly average flow gauge records for the Sapiniton Gauging Station, from 1985 to 2003, available on the referred USAID report (hence, there were no flow measurements available for Binahaan, Pongso, and Cabayugan Rivers). This gauging station (refer to Figure 1 for its location) corresponded to a drainage area of 204 km². Although relatively smaller (with only 147 km²), for calibration purposes, subbasin 3 was considered as correspondent. To assess the similarity of observed and obtained results, simple correlation functions were applied.

Resilience Analysis

Quantitative indicators of water supply are limited by the premise that there is either sufficient or insufficient water to suppress a certain demand. The modeling output daily flows, from the three rivers relevant to the considered supply solutions, were the subjects of a resilience analysis.

This analysis comprised the referred modeling scenarios: baseline (1980–2010), CC2020 (2007–2036), and CC2050 (2037–2065).

As a resilience indicator, the number of days in which the river flows were lower than the proposed water withdrawal was determined, expressed in a percentage of total days and discretized into four quarters to assess possible seasonal variations of water availability (Equation 3).

$$\% \text{ of days} = \frac{N_r \text{ days where flow} < \text{threshold on trimester}}{\text{Total } N_r \text{ days of trimester}} \quad (3)$$

In accordance with the supply constraints that Tacloban faces and the supply proposals currently considered, two supply solutions were evaluated:

- the “business-as-usual” scenario, in which LMWD keeps extracting water from Binahaan River to supply the whole community (including Tacloban City and the seven supplied municipalities of Dagami, Palo, Pastrana, Sta. Fé, Tabontabon, Tanauan, and Tolosa) plus the Tacloban North resettlement areas, considering the existing withdrawal rate of 0.72 m³/s; and
- the USAID-proposed complementary solution of resorting to the northern Leyte rivers (with an extraction rate of 0.58 m³/s), i.e., Pongso and Cabayugan, to supply only the new resettlement areas, while the City of Tacloban and surrounding municipalities continue to receive water from the Binahaan River.

Results and Discussion

Data Series and Statistical Validation

Tacloban's station daily precipitation records for the baseline series were arranged to obtain the total annual and annual daily maximum series. The former was adjusted using a Gaussian distribution function, while the latter was adjusted using a Gumbel Law function. The quality of these adjustments was validated through the Kolmogorov–Smirnov and Qui-squared tests, the results of which are presented on Table 2.

Both the adjustment tests resulted in the positive for the two data arrangements. The daily precipitation series was considered robust and trustworthy to be used on the subsequent modeling exercise.

Hydrological Modeling with QSWAT

Twelve watersheds were delineated by QSWAT for the study area, using a threshold of 50 km². From these, the most relevant ones were the subbasins 1, 3, and 5, the first two corresponding to the NGO-proposed supply solution for Tacloban North (from Pongso and Cabayugan Rivers) and the third one to Binahaan River, where the current catchment is located.

The characteristics of these basins are summarized in Table 3.

Noticeably, for the three basins, the most common land-use occupation is cropland, mostly a mix of crops and woods, also with a small percentage of forest. This non-urban occupation of the watersheds can be beneficial in terms of watershed management and for the safeguard of the water quality from both point or diffuse pollution sources. As

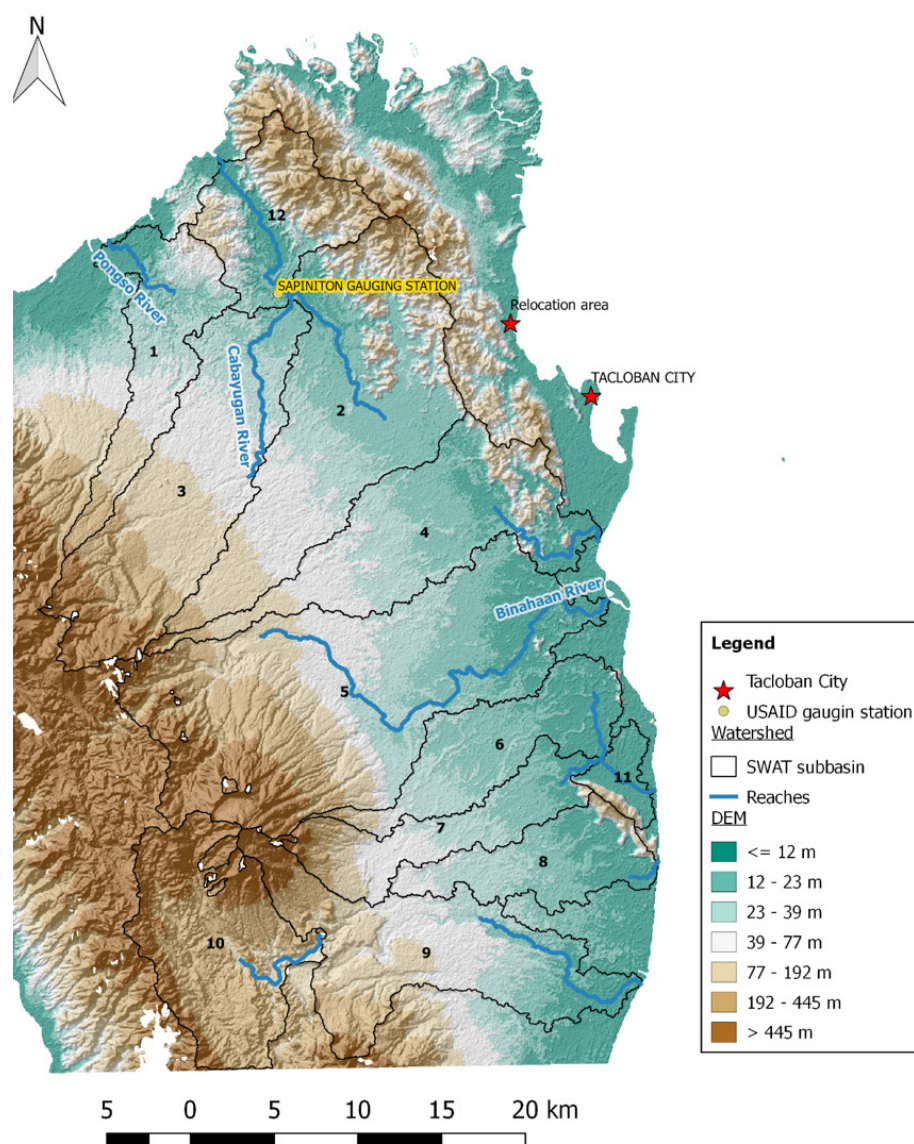


Figure 1. Delineated subbasins and rivers by QSWAT modeling.

Table 2. Statistical validation of precipitation series.

Data Series	Average	Std Dev	Adjusted Distribution Function	Kolmogorov-Smirnov Test Results	Qui-squared Test Results
Total Annual rainfall (mm)	2563.07 mm	576.22 mm	Gaussian	Accepted ($D_{\max_{\text{tab}}} = 0.169 > D_{\max_{\text{calc}}} = 0.127$)	Accepted ($\chi^2_{\text{tab}} = 11.07 > \chi^2_{\text{calc}} = 7.60$)
Daily maximum rainfall (mm)	129.07 mm	28.33 mm	Gumbel Law	Accepted ($D_{\max_{\text{tab}}} = 0.145 > D_{\max_{\text{calc}}} = 0.111$)	Accepted ($\chi^2_{\text{tab}} = 11.07 > \chi^2_{\text{calc}} = 8.40$)

Table 3. Selected subbasins characterization.

Subbasin #	Corresponding Waterway	Area (km ²)	Land-use Classes	Main Soil Classes**
1	Pongso River	70.6	89.33% CRWO 19.00% CRDY 6.97% CRIR 1.19% FOEB	55.75% Af14-3-c 39.77% Fo8-2ab 2.17% Jc4-2a
3	Cabayugan River	146.9	76.63% CRWO 15.32% CRIR 6.60% FOEB 1.45% CRDY	56.67% Fo8-2ab 42.75% Af14-3-c 0.58% Jc4-2a
5	Binahaan River	262.5	92.36% CRWO 4.97% FOEB 2.66% CRIR	55.69% Fo8-2ab 38.63% Af14-3-c 3.62% Jc4-2a

*Landuse classes: CRDY, dryland cropland and pasture; CRIR, irrigated cropland and pasture; CRWO, cropland/woodland mosaic; FOEB, evergreen broadleaf forest.

**Soil classes (FAO Classification): Af14-3-c, Ferric Acrisol (Hydrologic group C); Fo8-2ab, Ortic Ferrasol (Hydrologic group C); Jc4-2a, Calcaric Fluvisol (Hydrologic group D).

for the soil classes present on these watersheds, the hydrologic groups varied between C and D, the first corresponding to fine to very fine textured soils, with characteristically low permeability, and group D to clay soils with characteristically high-water tables and very low infiltration rates (Neitsch, 2011).

QSWAT includes SWAT-Check, a tool used to summarize results from simulations and to provide warnings that can help to improve results. The ratios between different water balance components, for instance, are vital to provide an easy understanding of the hydrological system studied (Dile, et al., 2016). Table 4 displays these ratios obtained for Tacloban's simulations.

Table 4. Hydrology Tab result from SWAT-Check.

Water Balance Ratios/Scenario	Baseline	CC2020	CC2050
Streamflow/Precipitation	0.59	0.60	0.62
Baseflow/Total Flow	0.41	0.40	0.39
Surface runoff/Total Flow	0.59	0.60	0.61
Percolation/Precipitation	0.23	0.23	0.23
Deep Recharge/Precipitation	0.01	0.01	0.01
Evapotranspiration/Precipitation	0.39	0.37	0.35

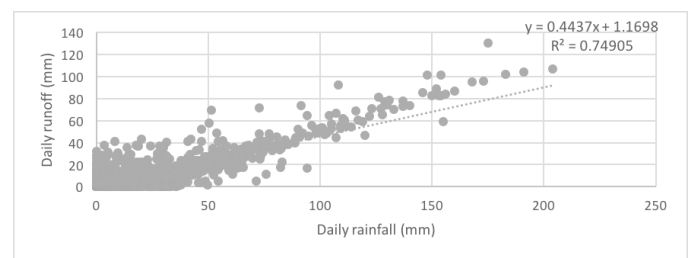
Surface runoff volume is computed in SWAT using a modification of the SCS curve number method, in which the curve number varies non-linearly with the moist content of the soil (near 0 as the soil approaches the wilting point and near 100 as it approaches saturation; Neitsch et al., 2011). The model returned an average curve number of 77.99, which is consistent with the obtained ratios. The clay-like texture of the majority of soils in the watersheds, for example, can be a factor in the appreciable Streamflow/Precipitation or Surface Runoff/Total

Flow ratios, as well as in the lower Percolation/Precipitation ratio. Some of the ratios tend to rise for CC scenario for 2020 and subsequently for 2050, which may be explained by the overall increase of rainfall. In turn, Evapotranspiration ratio tends to drop, despite the general temperature increases, possibly due to the rise of the amount of water that integrates the immediate runoff and thus does not reach evapotranspiration processes.

Modeling Calibration and Validation

The comparison between the flow series generated by QSWAT and the USAID measurements returned encouraging correlations. This was true for the monthly average series (in cubic meters per second), which returned a correlation of 0.899 and for the watershed runoff (in millimeters), determined for the two subbasins (obtaining a correlation of 0.830). The ratio obtained between the averages of these runoff series (167.2 and 132.9 mm for the USAID and QSWAT series, respectively) was of 0.79, which was consistent with the ratio between the two compared subbasins areas of 0.72. Intuitively, hence, the subbasin delineated by QSWAT was relatively smaller, so it should be the amount of superficial runoff generated to the same extent, which was verified.

Additionally, a regression analysis was performed between the daily rainfall and runoff series, obtaining again a high coefficient (of circa 0.8), as shown on Figure 2. This is indicative of a positive performance by QSWAT in simulating this hydrological system's behavior, which strengthens the importance of the role that hydrological modeling can play in CC impact studies.

**Figure 2.** Linear regression results between daily rainfall and runoff series.

Based on these satisfactory correlations, it was assumed that no further calibration measures were required and that the modeling results were valid and trustworthy.

Resilience Analysis

The resilience of Binahaan, Pongso, and Cabayugan Rivers as water sources for Tacloban was evaluated as, for a certain time period, the percentage of days in which the river flows did not meet the water extraction rates predefined for that river catchment. Table 5 summarizes the obtained results.

Table 5. Resilience of supply results: percentage of days below extraction rate.

	Water Extraction rate/Quarter	Binahaan River	Pongso + Cabayugan Rivers
		0.72 m ³ /s	0.58 m ³ /s
Baseline	DJF	0.7%	0.6%
	MAM	16.2%	16.8%
	JJA	20.3%	26.4%
	SON	1.3%	1.2%
	TOTAL	9.7%	11.3%
CC2020	DJF	0.7%	0.5%
	MAM	17.7%	18.1%
	JJA	16.7%	21.6%
	SON	0.8%	0.9%
	TOTAL	9.0%	10.4%
CC 2050	DJF	0.5%	0.3%
	MAM	19.3%	19.5%
	JJA	15.2%	20.2%
	SON	0.2%	0.4%
	TOTAL	8.9%	10.2%

For the supply solution based solely on Binahaan River, the baseline period of 9.7% days does not match the water extraction rate of 0.72 m³/s, with DJF and SON being the most favorable quarters (only 0.7% and 1.3% of days, respectively). However, for this 1980–2010 series, the MAM and JJA quarters evidence some water shortage probability, with 16.2% and 20.3% of days, respectively, with the river flow of Binahaan being insufficient.

Overall, i.e., on a yearly basis, nevertheless, this situation tends to evolve favorably due to the general increase of precipitation with CC, with the yearly number of supply gaps decreasing from 9.7% to 9.0% for the CC2020 scenario and to 8.9% for CC2050. However, the breakdown in quarters revealed that, for the MAM period, due to the PAGASA's forecasted decrease in rainfall, the availability of water actually worsens.

From these results, it becomes evident that Binahaan River, during the March to August period, cannot be considered a resilient water source. Therefore, considering an additional water catchment from the northern rivers to supply the Tacloban resettlement areas, as proposed by the development agency USAID, may be seen as a pertinent alternative. Assuming an extraction rate of 0.58 m³/s, a similar response to the one aforementioned for Binahaan River was observed: the yearly resilience of these rivers to be used as supply sources evolved from 11.3% of days not meeting the demand, for baseline data, to 10.4% for the CC2020 scenario and 10.2% for CC2050—results of the same order of magnitude as the ones obtained for the Binahaan River, assuming also a similar seasonal behavior. Once more, these rivers alone are not resilient water sources but both solutions could complement each other: Binahaan River supplying Tacloban City and neighboring municipalities, and a catchment up north to supply the resettlement areas.

Accordingly, either for Binahaan or Pongso and Cabayugan Rivers' as solutions, the significant percentage of days pointing to water scarcity for the MAM and JJA quarters was indicative of the necessity of a flow regulation infrastructure, such as a small dam, to ensure the region's water supply resilience. The pre-dimensioning of such structures as a function of the existing flow regimes is one possible future development of this work. Moreover, the evolution of water demand, as a consequence of demographic growth, or its variability within quarters, should be addressed. Likewise, considering land cover changes could be also interesting, hence, as demonstrated by Tolentino et al. (2016), after Haiyan, the reduction of forests on these watersheds conducted to a decrease of a third of the groundwater infiltration—thus increasing the potential runoff.

Conclusion

Tacloban's regional hydrological system was modeled using QSWAT to evaluate the impacts of CC and thus assess these water resources' resilience as supply sources. Results show that, regardless of the chosen supply solution, for certain time periods (most severely for the quarter of March to May), the percentage of days in which the river flows were insufficient to meet the proposed water catchment rates was significant. Outputs suggest that Binahaan River, where current water catchment is located, may fail in providing sufficient water to the region for future scenarios. However, it should be enhanced that Pongso and Cabayugan Rivers in northern Leyte can represent a complementary water source to supply the new resettlement areas. Moreover, it is likely that this development would also bring benefits to the quality of the supply in Tacloban City itself, as it eases the burden on the existing network by reducing the number of service connections. This is particularly pertinent if one considers the expected demographic growth for this region, as well as the long-term impacts of CC.

Further work should focus on the design and sizing of dams on the studied waterways, which are proven necessary by this study to increase the system resilience and assure water supply to the city of Tacloban and its surroundings—with a special relevance on the months of March, April, and May. Another interesting analysis would be the cross-over of the determined resilience indicator with the population's perception or the existing infrastructures resilience.

Bearing in mind the encouraging consistency between modeling outputs and field data, this work has reinforced the importance of the emerging role of hydrological modeling in CC impact studies. Hence, it is strongly recommended that the evaluation of the dependable flow of waterways should be used to support water districts decisions as well as local (or even national) water resources management policies.

Acknowledgements

The authors would like to thank the Portuguese Foundation of Science and Technology for the support of this research through the grant PD/BD/114299/2016, awarded in the context of the Doctoral Program in Climate Change and Sustainable Development Policies. Likewise, a word of appreciation should also be given to the Oscar M. Lopez Center's team, mainly to Rafaela Jane Delfino, Kristoffer Kendrick Co, and Carlos Tito Santos, who have greatly contributed to the accomplishment of this research.

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