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Hydrological Assessment for Watershed Health in a Headwater Sub-Basin of the Rio Grande de Arecibo, Puerto Rico

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Abstract

The Río Grande de Arecibo (RGA) Watershed is a crucial source of water for the residents of the Island of Puerto Rico, including those living in the San Juan metropolitan area that are supplied by the North Coast Super Aqueduct. It is also significant for forest conservation, with five state forests providing around 10% of the watershed's protected forest area. However, land cover changes in the region are putting the watershed's sustainability at risk, as is the case in many places worldwide. This study takes an integrated socioecological approach to examine environmental changes in a headwater sub-basin of the RGA Watershed over a 20-year period (2001-2021). Using the Soil and Water Assessment Tool (SWAT), we assessed the impact of land cover changes on water sustainability. Our findings indicated that the headwater sub-basin of the RGA showed a decrease in both Forest Land and Range Land and an increase in Urban Built-up Land cover 20 years later. The results from SWAT provided the information to establish a "less healthy" condition 20 years later, due to the increase in the surface runoff metric and a decrease in the lateral flow metric. The study provides a baseline for future socioecological watershed studies and sustainable management actions, and its novel approach, combining geospatial analysis with hydrological modeling, could be applied to other watersheds, particularly in the tropics, where such studies are scarce.

Keywords

Socioecological Assessment, SWAT, Land Cover, Sustainability

1. Introduction

There are several efforts toward the goal of "a better place for all" through the use of a conceptual framework of sustainable development, which is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Grober, 2017). However, as Becker (2014) stated, the first step in sustainable development should be to assess the current condition. To understand the current condition, we need to assess the past conditions that led to the actual status and, if necessary, re-focus on sustainable actions to improve watershed resilience (Miralles-Wilhelm et al., 2023). To address sustainability challenges effectively, it is widely recognized that a more comprehensive understanding of the human and social dimensions of science and technology is necessary (Veiga Ávila et al., 2019; Kern et al., 2019). For societies to attain sustainability, it is essential to acknowledge the relationship between nature and society, manifested through ecosystem services and the well-being of humans (Wang et al., 2021).

In order to promote human well-being, it is essential to emphasize water as vital to life. Water supports human activities such as industry, households, agriculture, transportation, and energy (Sadoff et al., 2015). Furthermore, water is recognized as the main driver through which climate change impacts ecosystems, society, and human well-being (United Nations Organization, 2015; Xian et al., 2022). Due to its critical role, water can be a limiting factor to achieving the United Nations Sustainable Development Goals (Ait-Kadi, 2015).

Water is a crucial factor in achieving sustainability, and in this context, watersheds play a vital role as natural units for managing water. Bunch et al. (2011) compare watersheds to the human body, where water acts as a "bloodstream", linking the man-made world with nature. This analogy highlights that the condition of a watershed provides insight into the condition of society, similar to how a blood test informs about the health of the human body. Therefore, the condition of the watershed serves as a reflection of society.

A watershed is also the landscape unit that longitudinally frames upstream and downstream process that regulates water quality, quantity, accessibility, and ecosystem services, all of them needed for human health and well-being (Bunch et al., 2011; Regan et al., 2019). Apart from being a hydrological system, a watershed also serves as the fundamental geographical unit that governs the ecosystem processes and services that are essential for human well-being (Bunch et al. 2011; Cao et al., 2022).

"Watershed Health" is a concept that can assist us in this pursuit of sustainability. Watershed Health is defined as "a measure of how well resources management can balance anthropogenic needs, ecological function, and integrity within watersheds" (Jones et al., 2002). The U.S. Environmental Protection Agency (EPA) launched the Healthy Watershed Protection Program (HWPP) as a response to the Clean Water Act in order to restore and maintain the integrity of the water of the United States of America. Under this Program, a healthy watershed is defined as "one in which natural land cover supports: dynamic hydrologic and geomorphologic processes within their natural range of variation; habitats of sufficient size and connectivity to support native aquatic and riparian species; and physical and chemical water quality conditions able to support healthy biological communities" (U.S. Environmental Protection Agency, 2018). The US EPA Healthy Watershed Program developed a Watershed Health Index comprising six essential parameters: landscape condition, aquatic habitat condition, geomorphological condition, water quality condition, biological condition, and hydrological condition.

The implementation of technology, the advancement in spatial analysis, and the development of hydrological models have made possible the assessment of watersheds as socioecological systems (Cabello et al., 2015). There are several approaches to assessing the health of a watershed through a socioecological approach coupled with spatial analysis and modeling tools. They all contribute to new ways of better understanding complex and interrelated watershed processes.

The use of remote sensing is an example of how a socioecological approach coupled with technology can help address the challenges associated with pursuing sustainability. One of the advantages of remote sensing is that it serves for ecological modeling over large areas, such as a watershed (Wu et al 2006). Integrating remote sensing analysis with Geographic Information System (GIS) makes large-scale spatial analysis possible at the watershed or sub-watershed levels.

The Soil and Water Assessment Tool (SWAT) is an example of a hydrological model that can help us to study watershed health (Ahn & Kim, 2017). SWAT is a widely used watershed-scale simulation tool that is computationally efficient and flexible (Gull & Shah, 2021). Consequently, under a socioecological approach, SWAT can link the social dimension with the natural system in a watershed by studying the impacts of land cover on the quantity and quality of the water.

The use of the Soil and Water Assessment Tool (SWAT) is a suitable hydrological model for tropical watersheds (Grey et al., 2014). Although SWAT is enabled to operate with limited data, its implementation in tropical watersheds has shown satisfactory results (Grey et al., 2014, Montecelos-Zamora et al., 2018, Nilawar et al., 2017).

In this study, we conducted a socioecological assessment of a headwater sub-basin from a vital water supply watershed in Puerto Rico. A hydrological sustainability assessment was conducted using the Hydrological Condition parameter described by the EPA Watershed Health Index. A landcover change analysis was initially performed and coupled with SWAT modeling to evaluate the land cover effects on water yield, surface runoff, lateral flow, soil water content, and percolation from 2001 to 2021. The coefficient of Determination (R2) was used to evaluate the model's fitness for selected Forest Land Cover and Urban or Built-up Land Cover outputs. The specific aims of this study were: 1) To assess the water sustainability of a headwater sub-basin in terms of accessibility; 2) To assess model predictability between several land covers and hydrological processes; 3) To provide more information about the applicability of implementing SWAT in tropical regions; 4) To set the basis for conducting further analysis toward watershed health and sustainability. This study could significantly contribute to the understanding hydrological behavior in tropical ecosystems, where studies are limited, and to provide the foundation for future watershed sustainability assessments.

2. Data and Methods

2.1. Study Area

The study was done in a headwater sub-basin in Puerto Rico at the Río Grande de Arecibo Watershed (Figure 1). The Río Grande de Arecibo watershed is located in the north-central region of Puerto Rico with an area of 665 km^2. Its headwaters are in the Central Mountain Range in Adjuntas and Jayuya. Its outlet is located in the coastal alluvial plains in Arecibo. The watershed represents a critical water source (0.45 Mm^3 per day) for the people and those leaving outside the watershed, in the metropolitan area, through the North Coast Super Aqueduct. The watershed is drained by two main rivers: the Río Grande de Arecibo and the Caonillas River. These two rivers have two main reservoirs, Dos Bocas and Caonillas.

Dos Bocas reservoir is located between the municipalities of Arecibo and Utuado. It was constructed in 1942 for water supply and to provide energy. It has a catchment area of 453 km^2 with an original capacity of 37.50 Mm^3 (Soler-López, 2012). The United States Geological Survey performed, in collaboration with the Puerto Rico Aqueduct and Sewer Authority, a bathymetric survey in which Dos Bocas reservoir showed a reduction of its storage capacity from 17.26 Mm^3 in 2005

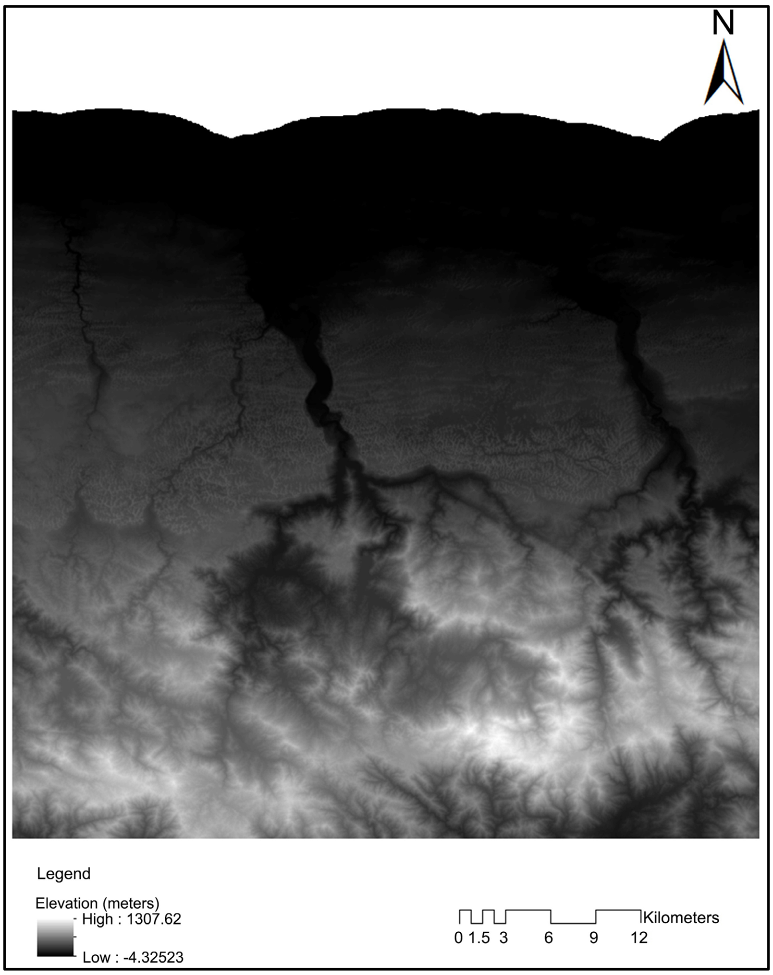

Figure 1. Map of Río Grande de Arecibo watershed.

to 16.6 Mm^3 in 2010. This represents a loss of 3%, or 104,000 m^3/yr. From 2005 to 2010, the sedimentation rate slightly decreased from 321,000 m^3/yr in 2005 to 305,000 m^3/yr in 2010. It is stated that assuming a constant sedimentation rate of 305,000 m^3/yr, the useful life of Dos Bocas reservoir will be until 2065 (Soler-López, 2012). The trophic status of the Dos Bocas reservoir is hypertrophic (Department of Natural and Environmental Resources of Puerto Rico, 2007).

This study focuses on a headwater sub-basin of the Río Grande de Arecibo Watershed that discharges into the Dos Bocas reservoir. This sub-basin was chosen due to the recognition that any changes in this area could have adverse effects on the water supply, water quality, and ecosystem integrity.

2.2. Headwater Sub-Basin Delineation

The Headwater Sub-basin of the Río Grande de Arecibo Watershed was delimited using Arc Map version 10.5 with the SWAT interface. A 10-meter resolution "Digital Elevation Model" (DEM) from the U.S. Geological Survey (USGS) published in 2020 was used for watershed delineation. The DEM was projected into UTM WGS 1984 19N and served as the basis in the hydrological model for calculating flow direction, flow accumulation, and to define the drainage network. Additionally, the USGS water monitoring station 50024950, depicted in Figure 2, was designated as the outlet for the headwater sub-basin.

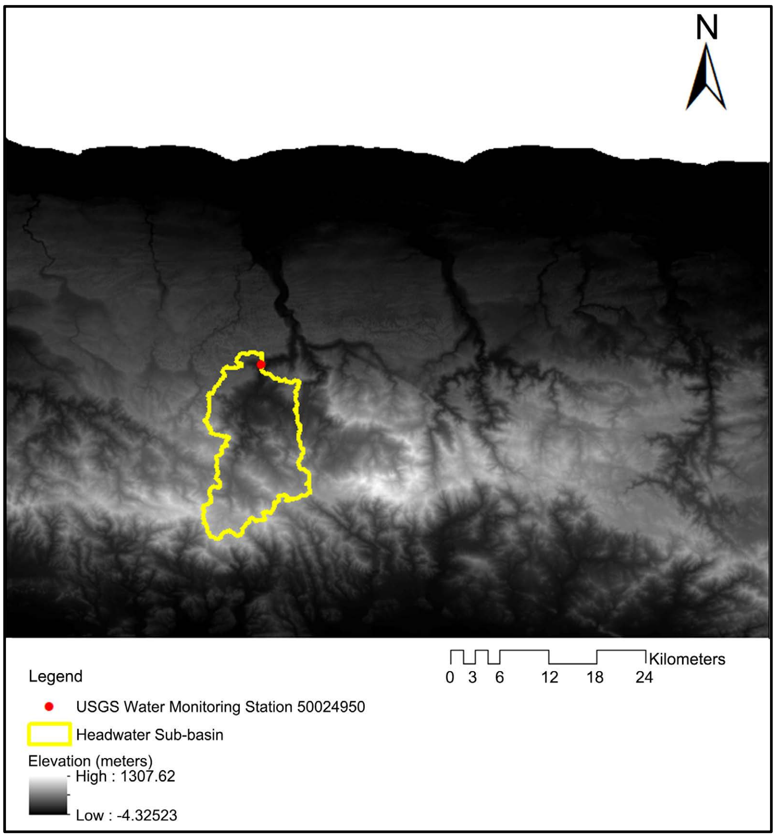

Figure 2. Map of the digital elevation model showing the headwater sub-basin. The red dot shows the location of the USGS water monitoring station 50024950.

2.3. 2001 and 2021 Land Covers

In this study, land cover was an important variable. The land cover serves as a reflection of the social system of the headwater. Therefore, it can serve as the bridge between the natural and social systems. This study used the USGS Anderson classification system at Level I as the land cover classification scheme. The Land Cover/Land Use (LCLUC) categories of the Anderson classification system at Level I used in this research are Agricultural Land, Barren Land, Forest Land, Urban or Built-up Land, Range Land, and Water (Anderson et al., 1976).

The National Land Cover Database Commonwealth of Puerto Rico Land Cover Layer (NLCD) was used for this study to assess past conditions in 2001. The land cover classes of the 2001 NLCD are: barren land, cultivated crops, deciduous forest, developed-high intensity, developed-low intensity, developed-medium intensity, developed, open space, emergent herbaceous wetlands, evergreen forest, hay/pasture, herbaceous, mixed forest, open water, shrub/scrub, and woody wetlands. These land covers were reclassified using ArcMap the Reclassify-Spatial Analysis method into the Anderson classification system at level 1. The description of the 2001 NLCD classes and their corresponding reclassification are shown in **Table 1**.

Table 1. 2001 NLCD classes and their corresponding reclassification (Multi-Resolution Land Characteristics Consortium, 2022).

2001 NLCD Classes with Description	Reclassified Land Cover Classes
Barren Land	Barren Land
Cultivated Crops	Agricultural Land
Deciduous Forest	Forest Land
Developed, High Intensity	Urban or Built-up Land
Developed, Low Intensity	Urban or Built-up Land
Developed, Medium Intensity	Urban or Built-up Land
Developed, Open Space	Urban or Built-up Land
Emergent Herbaceous Wetlands	Range Land
Evergreen Forest	Forest Land
Hay/Pasture	Range Land
Herbaceous	Range Land
Mixed Forest	Forest Land
Open Water	Water
Shrub/Scrub	Range Land
Woody Wetlands	Forest Land

An image classification procedure was conducted to identify land cover categories for the headwater sub-basin at the Río Grande de Arecibo Watershed for the year 2021. Landsat 8 Operational Land Imager (OLI) was used as the remote sensing images for this evaluation. Ancillary data, such as ground truth data, topographic maps, and Google Maps, were used for the classification. A supervised classification procedure was performed, using training sites for each class type proposed. Finally, an accuracy assessment of the classified image was performed by comparing it with ground truth data using 100 random accuracy assessment points and a confusion matrix.

2.4. Climate

The NOAA climatological stations were used to gather the precipitation and minimum and maximum temperature data. The average annual precipitation and minimum and maximum temperatures were calculated for 1996-2021. The average annual precipitation for 1996-2021 was 1848.8 mm for Adjuntas Station, 2082.8 mm for Arecibo Observatory station and 1981.3 mm for the Dos Bocas station. Dos Bocas Station showed the lowest annual precipitation, 1173.6 mm, and 1280.8 mm in 2014 and 2015, respectively, and this period correspond to the most recent drought that impacted Puerto Rico (Department of Natural and Environmental Resources of Puerto Rico, 2016).

Comparing precipitation data between stations showed a similar pattern for the 25 years. A similar pattern is evident between the three stations from 1996 to 2003 (**Figure 3**). In 2004, the Adjuntas station showed increased precipitation, but Dos Bocas station showed a minor increase, and Arecibo Observatory showed a decrease. Concerning the drought period of 2014 to 2015, the most drastic decline in precipitation was registered at the Dos Bocas station.

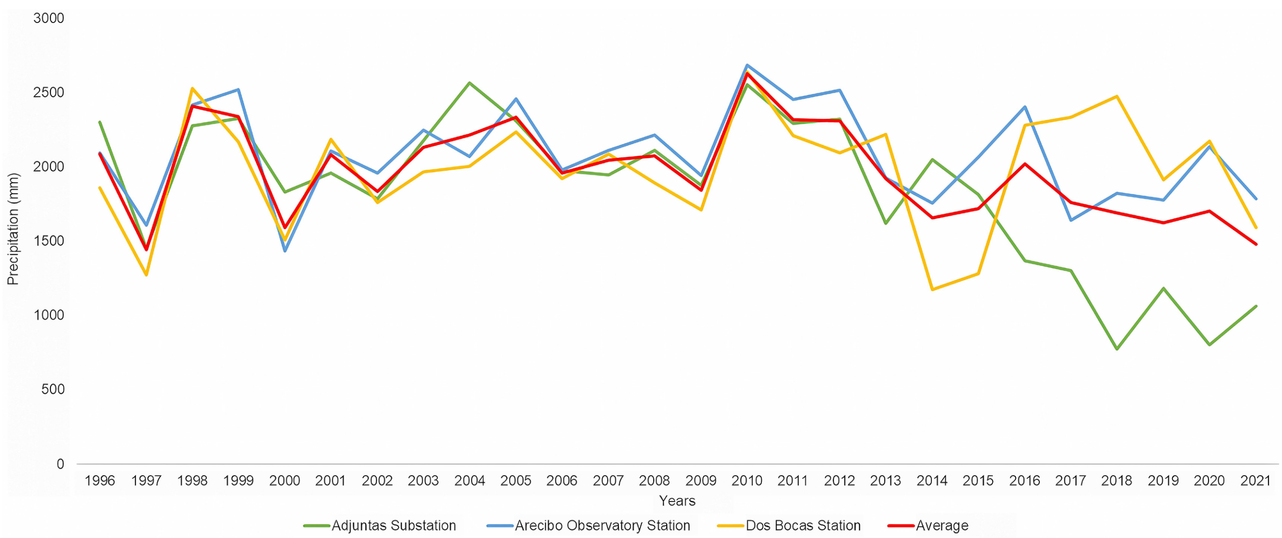

Figure 3. Annual average precipitation at NOAA stations.

Based on the climatologic data from the NOAA stations for 1996-2021 the annual average minimum temperature at the Adjuntas substation (RQC00660061) was 15.46˚C; at the Arecibo Observatory station (RQC00660426), it was 18.73˚C; at Dos Bocas station (RQC00663431), it was 20.14˚C. The annual average maximum temperatures for those three NOAA climatological stations were 28.06˚C at the Adjuntas substation (RQC00660061), 28.80˚C at Arecibo Observatory station (RQC00660426) and 30.72˚C at Dos Bocas station (RQC00663431).

The lowest annual average minimum temperature was at Adjuntas station (elevation 557.8 m amsl), due to its location in the mountain region and the highest annual average minimum temperature was located at Dos Bocas station (elevation 61 m amsl) (**Figure 4**). Dos Bocas station had the highest annual average maximum temperature (**Figure 5**). A comparison between stations showed climatic variability due to location, which is useful in terms of gathering representation for the further hydrological modeling process in this study.

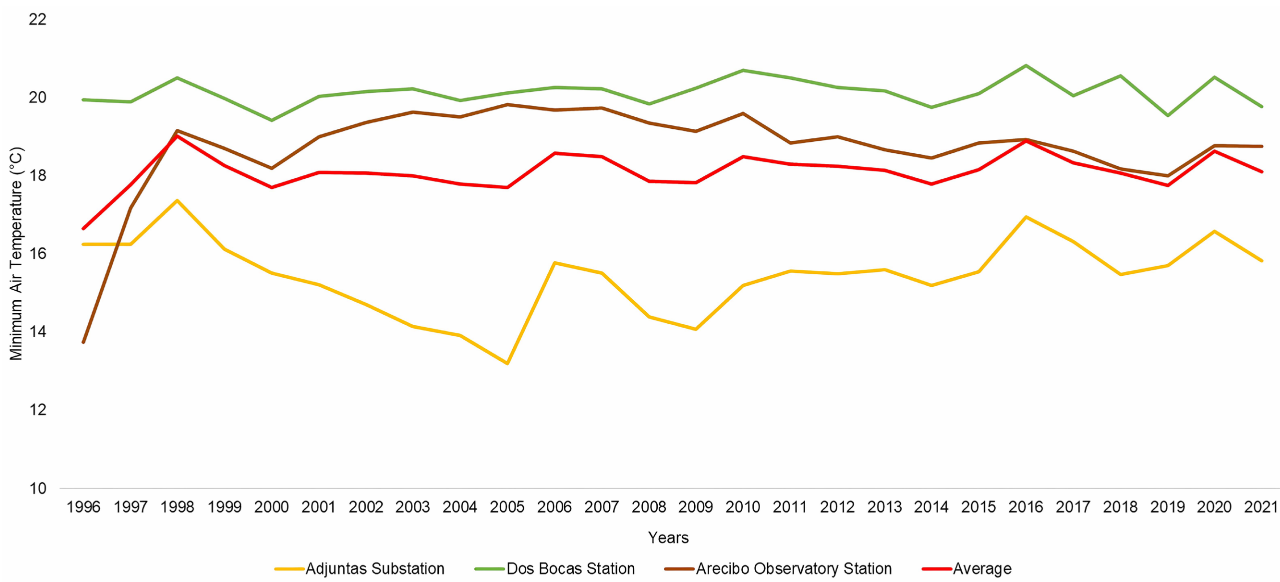

Figure 4. Annual average minimum air temperature at NOAA stations.

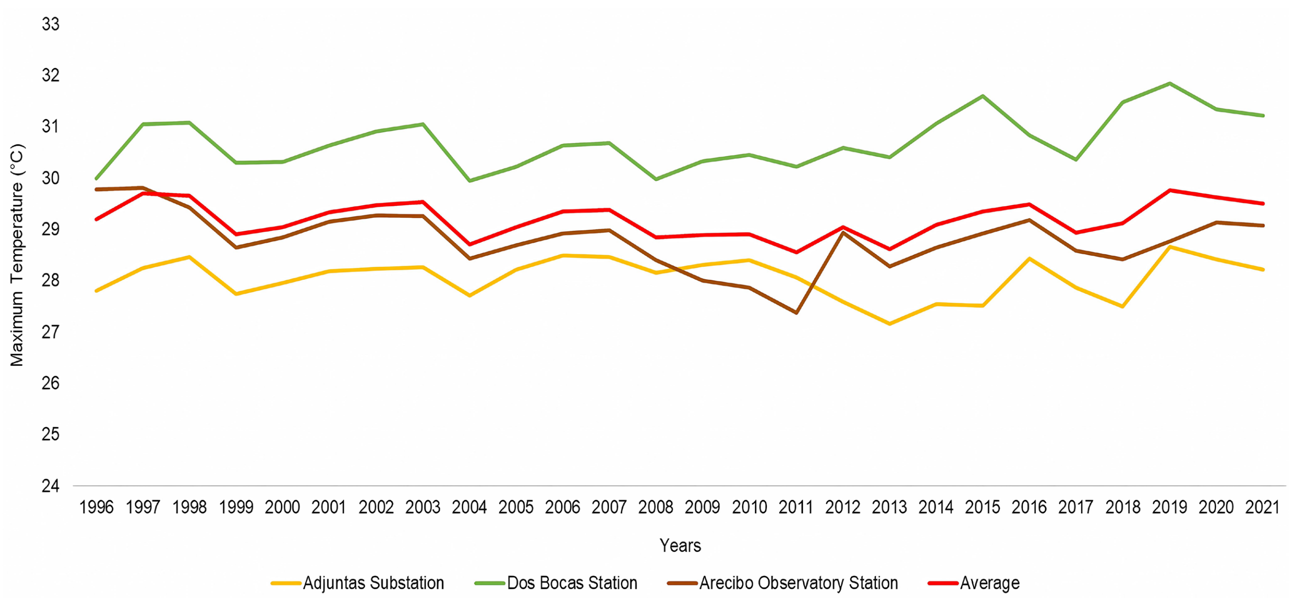

Figure 5. Annual average maximum air temperature at NOAA stations.

2.5. SWAT

2.5.1. SWAT Calibration and Validation

Overall, the period of the SWAT model simulation was from 1996-2022. This period included calibration (1996-2003), validation (2003-2007). We also conducted a global sensitivity analysis to identify the model parameters that are most relevant or sensitive to the model outputs. The sensitivity analysis was based on a multiple regression approach to quantify each parameter's sensitivity (Abbaspour et al., 2018).

The SWAT model was first calibrated for streamflow using data from January 1996 to June 2003 and validated from July 2003 to June 2007. The first three years were used to warm up the model. The calibration and validation procedures were performed using SWAT-Calibration and Uncertainty Procedure (SWAT-CUP) (Arnold et al., 2012b). The SUFI-2 algorithm in SWAT-CUP was used for the model calibration and validation procedures. The algorithm aims to estimate the uncertainty associated with hydrological model parameters and improve model predictions by iteratively adjusting these parameters.

In SUFI-2, all sources of parameter uncertainties are assigned to parameters. The uncertainty in the input parameters is described as uniform distributions. Meanwhile, model output uncertainty is quantified by the 95% prediction uncertainty (95PPU) determined at the 2.5% and 97.5% levels of the cumulative distribution of output variables obtained through Latin hypercube sampling.

The algorithm uses two indices, the *p*-factor and r-factor, to determine the goodness-of-fit and uncertainty of the model. The *p*-factor is the percentage of observed data bracketed by the 95% prediction uncertainty (95PPU), while the r-factor is the average thickness of the 95PPU band divided by the standard deviation of the observed data.

In an ideal situation where the simulation exactly matches the observed data, the *p*-factor tends to be 100%, and the r-factor tends to be 0. However, in real cases, errors from different sources make it impossible to achieve these values (Abbaspour, 2022). A wide r-factor can lead to a large *p*-factor, but SUFI-2 searches to bracket most of the measured data with the smallest possible uncertainty band (r-factor).

2.5.2. SWAT Procedure

Soil type (SSURGO), DEM (USGS), climate data (NOAA) and water quality (USGS) monitoring databases were used in this study for assessing the physical attributes of the Headwater Sub-basin.

The dataset and sources to run SWAT are shown in **Table 2**.

The SWAT outputs provided the metrics to conduct the hydrological assessment based on the Hydrological Component of the EPA Watershed Health Index, which are namely: Water Yield (WYLD) for the General Metric, Surface Runoff (SURQ) and Lateral Flow (LATQ) for the Surface Process Metric, Soil Water Content (SW) for the Soil Water Dynamics Metric; and Percolation (PERCOL) for the Groundwater Dynamics Metric (Table 3). The monitoring data for the Hydrological Condition using SWAT was streamflow ($m^3 \cdot s^{-1}$). The parameters chosen for the calibration procedure (Table 4) were recommended by Dr. Karim Abbaspour (Personal communication).

Table 2. Datasets used for SWAT Setup.

Datasets	Source
Headwater sub-basin delineation	As described
The SSURGO Soil types	USDA Natural Resources Conservation Services website (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). The original maps from soil survey manuscripts were recompiled to scales of 1:12,000 or 1:24,000 for digitizing into the SSURGO format
The reclassified 2001 NLCD	USGS was acquired through Multi-Resolution Land Characteristics (MRLC) Consortium website
The 2021 Land Cover	As described
Streamflow daily data from the USGS stations 50024950	USGS National Water Information System: Web Interface website (1996-2022) (https://waterdata.usgs.gov/nwis/rt)
Climatic data (Precipitation, Minimum and Maximum Temperature) from 1996 to 2022	National Oceanic and Atmospheric Administration website (https://www.ncei.noaa.gov/cdo-web/) of the following meteorological stations: Adjuntas Substation, RQC00660061; Arecibo Observatory, RQC00660426; Dos Bocas, RQC00663431

Table 3. General metrics for the hydrological sustainability assessment and their respective measurement technique selected with a description.

Process	Metric	Description
Surface process	Water Yield (mm)	The net amount of water that leaves the subbasin and contributes to streamflow in the reach
	Surface runoff (mm)	Surface runoff contribution to streamflow during time step
	Lateral Flow (mm)	Lateral flow contribution to streamflow
Soil water dynamics	Soil Water Content (mm)	Amount of water in the soil profile at the end of the time period
Groundwater dynamics	Percolation(mm)	Water that percolates past the root zone. There is potentially a lag between the time the water leaves the bottom of the root zone and reaches the shallow aquifer. Over a long period of time, this variable should equal groundwater percolation

Table 4. Parameters and ranges selected in the calibration-validation procedures in SWAT modelling.

Parameter Name	Definition (Arnold et al., 2012a)	File Extension	Method	Minimum	Maximum
CN2	Initial SCS runoff curve number for moisture condition II	.mgt	Relative	−0.7	−0.3
ALPHA_BF	Baseflow alpha factor	.gw	Replace	0.02	0.1
GW_DELAY	Groundwater delay times (days)	.gw	Replace	0	100
GWQMN	Threshold depth of wáter in the shallow aquifer required to return flow to occur (mmH_2O)	.gw	Replace	50	2000
SOL_AWC	Available wáter capacity of the soil layer (mmH_2O/mmsoil)	.sol	Relative	−0.5	0.5
SOL_K	Saturated hydraulic conductivity (mm/hr)	.sol	Relative	−0.7	0.7
SOL_BD	Moist bulk density (*Mg/m^3)	.sol	Relative	−0.7	0.7
ESCO	Soil evaporation compensation factor	.hru	Replace	0.7	1
EPCO	Plant uptake compensation factor	.hru	Replace	0.7	1
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mmH_2O)	.gw	Replace	50	2000
OV_N	Manning's "n" value for overland flow	.hru	Replace	0.01	0.5
GW_REVAP	Groundwater "revap" coefficient	.gw	Replace	0.02	0.1

2.5.3. Setting the Reference Condition and Assessing Hydrological Sustainability

The EPA Watershed Health Index (EPA WHI) comprises several primary components, including Landscape, Aquatic Habitat, Geomorphological, Water Quality, Biological, and Hydrological Conditions. In our study, we used the Hydrological Condition component of the EPA WHI to evaluate the sustainability of hydrological systems in the headwater sub-basin.

To construct this index, we compared the simulated data obtained from the current conditions of the study area with a reference condition that can be considered "healthy" or "pristine" due to the absence of any significant human impact. This reference condition serves as a benchmark against which the current conditions are evaluated to determine the degree of hydrological sustainability.

The Headwater Sub-basin with a total land cover as Forested Land was set as the reference condition. Thus, it was a hypothetical scenario of a pristine forest. This was operationalized by reclassifying the 2021 classified sub-basin image into Forested Land cover. After the reclassification, to gather the reference condition, the SWAT model was used to gather the outputs of hydrological metrics.

The outputs generated by SWAT and used as metrics were: WYLD, SURQ, LATQ, SW, PERC (Ahn & Kim, 2017) for 2001 and 2021. They were used to calculate a Hydrological Sustainability Assessment Index as follows:

- Water Sustainability Assessment metric (x): Simulated value (x) of the headwater sub-basin at current condition/Reference Condition for value x.

Data was normalized to develop the Index into scores from 0 to 1 for effective communication. The higher the score is, the "healthier" are the conditions for that metric. In this study, it was stated that the range of a "less healthy" condition is between 0 and 0.50 and the range for a "healthier" condition is those higher than 0.51. For this research, the attributes were not weighted. After the construction of the EPA WHI for the years 2001 and 2021, the changes were analyzed in a 20-year frame. The Coefficient of Determination is a measure of how useful a model is by measuring the percentage of variability of a value that can be explained by another independent variable. Therefore, the Coefficient of Determination was calculated to assess the availability of the model to predict the percentage of Forest and Urban or Built-up Land covers with respect to the hydrological metrics.

3. Results

3.1. 2001 and 2021 Land Cover

The original 2001 land cover categories for the headwater sub-basin were: Open Water; Developed, Open Space; Developed, Low Intensity; Developed, Medium Intensity; Developed, High Intensity; Barren Land; Evergreen Forest; Shrub/Scrub; Herbaceous; Hay/Pasture. The results from the 2001 reclassification procedures are shown in **Table 5** and visualized in **Figure 6**.

Forest Land cover is the major land cover type identified in the headwater sub-basin for 2001, with 70%. In 2001, no Agricultural Land cover was identified. Forest Land cover was concentrated around the headwater sub-basin south of the Garzas reservoir (**Figure 6**).

Not many Urban or Built-up Land areas were identified along the headwater sub-basin this year. Most of the Urban or Built-up Land covers are concentrated to the north and south of the headwater sub-basin corresponding to the urban center of the municipalities of Utuado and Adjuntas, respectively.

In 2021, land cover classification was identified as the six-land categories: Forest Land, Range Land, Urban or Built-up Land, Barren Land, Agricultural Land, and Water. The kappa statistic resulted in 0.74, which can be considered moderate to substantial in terms of strength of agreement. However, when verifying the

Table 5. Area (km^2) and percentage of land cover classification for the year 2001.

Land Cover	Area (km^2)	Percentage (%)
Forest Land	133.0	70.5
Range Land	45.5	24.1
Urban or Built-up Land	9.2	4.9
Barren Land	0.5	0.3
Agricultural Land	0.0	0.0
Water	0.4	0.2

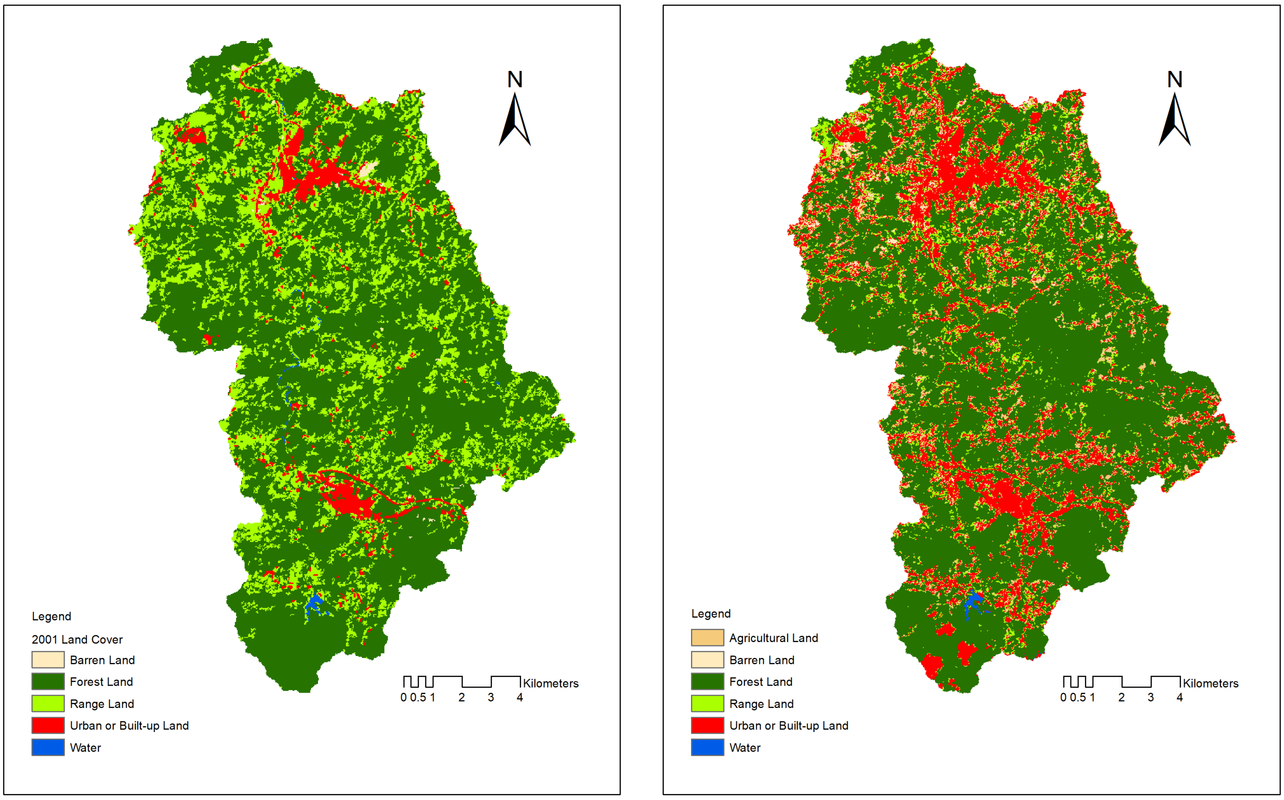

Figure 6. Land cover maps for the years 2001 (left) and 2021 (right) of the headwater sub-basin.

accuracy assessment points, some areas of conflict, such as classified agricultural land areas, are a forest with very close agricultural activities. Therefore, using other images with a better spectral resolution is suggested for the future.

For 2021, Forest Land cover remained the main land cover type identified in the headwater sub-basin. The Urban or Built-up Land cover spreads across the northern region of the headwater sub-basin and across its south-central section (Figure 6) and expands along the roads. The study site presented a small increment in Agriculture Land area (8.92 km^2; Table 6) from 2001 (Table 5).

The land cover changed along the headwater sub-basin over the 20-year time frame (2001 to 2021). A decrease of 4.4 km^2 in Forest Land cover was identified,

Table 6. Area (km^2) and percentage of land cover classification for 2021.

Land Cover	Area (km^2)	Percentage (%)
Forest Land	128.6	68.2
Range Land	16.8	8.9
Urban or Built-up Land	31.4	16.7
Barren Land	2.6	1.4
Agricultural Land	8.9	4.7
Water	0.27	0.1

which represents a reduction of about 2.3%. Range Land cover also decreased by 28.7 km^2, which represents a reduction of about 15.2%. Therefore, when combined, both land cover types showed a decrease of 33.1 km^2 over 20 years. On the other hand, the Urban or Built-up Land cover showed an increase of 22.2 km^2, which represents an increase of about 11.8%. The Barren Land cover also showed an increase of 2.1 km^2, representing an increase of about 1.1%. We noted that a broader Urban or Built-up Land cover in areas already Urban or Built-up Land cover in 2001 suggesting a concentric pattern of urban sprawl (**Figure 6**). In addition, a new Urban or Built-up Land cover area was observed in the southernmost part of the headwater sub-basin. It is important to note that for 2001, the study area showed no agricultural activity. However, the 2021 Agricultural Land cover increased to about 8.9 km^2. Therefore, a significant part of Forest and Range Land cover types were replaced by Urban or Built-up Land cover.

3.2. Hydrological Process—SWAT

3.2.1. Sensitivity Analysis, Calibration/Validation

The global sensitivity analysis was performed on twelve parameters. The global sensitivity analysis shows that the most sensitive parameters in decreasing order are: SOL_BD, SOL_K, CN2 and SOL_AWC (**Table 7**).

The flow output calibration statistics for 2001 resulted in acceptable values of *p*-factor = 0.7 and r-factor = 0.7. The flow validation statistics for 2001 showed a *p*-factor of 0.5 and an r-factor of 0.7 (**Figure 7**). The validation resulted in a lower *p*-factor than calibration, while the r-factor is smaller than calibration, indicating smaller uncertainty.

The model produced 31 Hydrologic Response Units (HRUs). The area of the headwater sub-basin was 188.65 km^2. The model output metrics were as follows: Water Yield of 885.35 mm; Surface Runoff of 65.11 mm; Lateral Flow of 572.12 mm; Soil Water Content of 443.07 mm; and Percolation of 249.37 mm. The model output revealed an excessive water yield.

The calibration of 2021 data also provides acceptable results with a *p*-factor = 0.6 and r-factor = 0.7. The validation for 2021 had a *p*-factor = 0.5 and r-factor = 0.6 (**Figure 8**).

The model output metrics were as follows: Water Yield of 680.74 mm; Surface Runoff of 96.25 mm; Lateral Flow of 361.17 mm; Soil Water Content of 409.44 mm; and Percolation of 217.11 mm. Like in 2001, the 2021 water balance revealed an excessive water yield.

3.2.2. Setting the Reference Condition

All the land covers produced for 2021 were reclassified by changing Urban Land, Barren Land, and Agricultural Land covers into Forest Land covers. The visualization of the reclassification to gather the reference condition is shown in **Figure 9**.

Table 7. Global sensitivity analysis results.

Parameter	T-Test	*P*-Value	Sensitivity Rank
SOL_BD	−20.5982	0.00	1
SOL_K	−11.2411	0.00	2
CN2	−9.4368	0.00	3
SOL_AWC	7.6361	0.00	4
GW_DELAY	4.4956	0.00	5
ALPHA_BF	−3.7448	0.00	6
ESCO	−3.4557	0.00	7
GWQMN	−2.4647	0.01	8
OV_N	1.7459	0.08	9
EPCO	−1.1470	0.25	10
REVAPMN	0.7818	0.43	11
GW_REVAP	0.1863	0.85	12

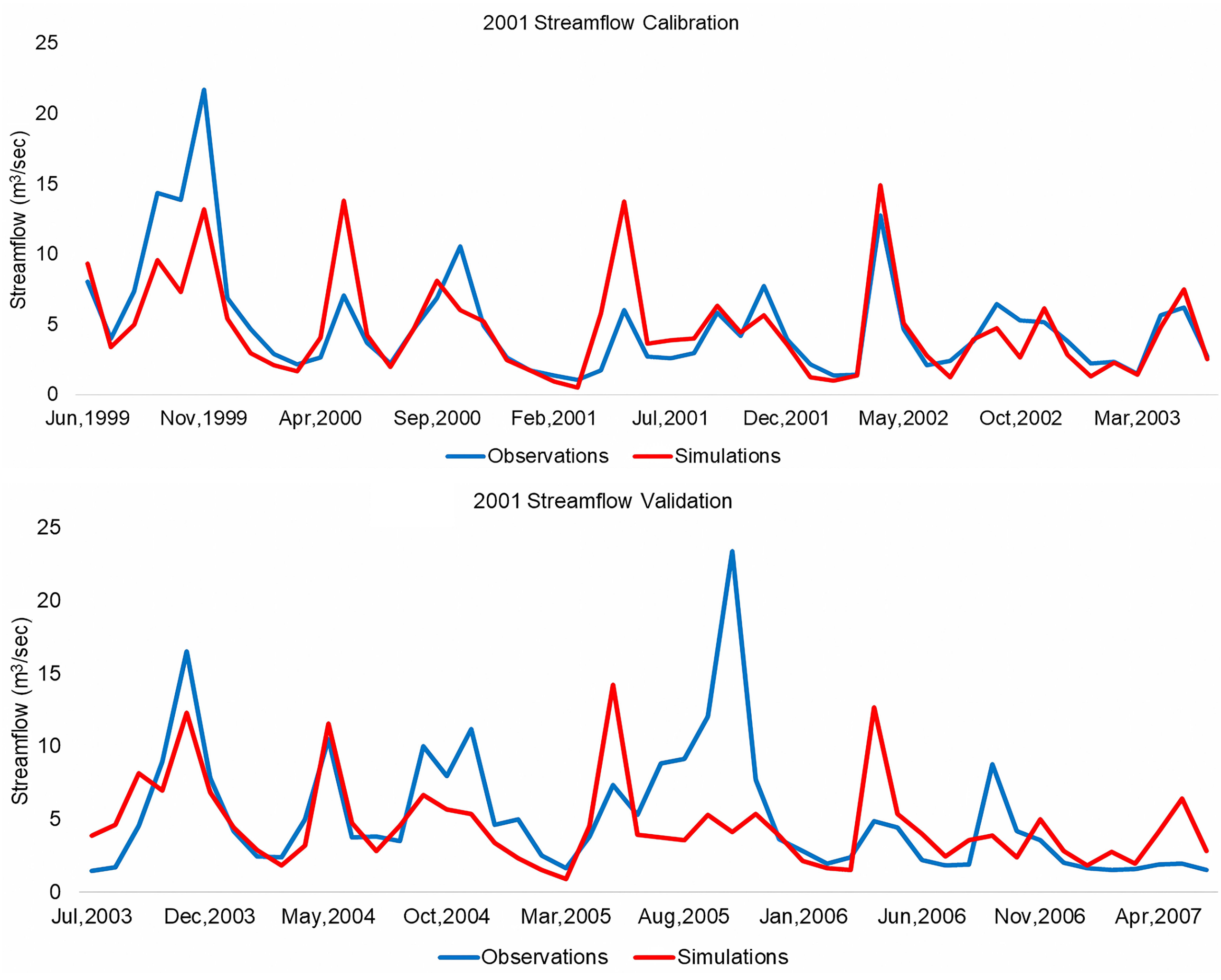

Figure 7. Observations versus simulations of streamflow for 2001 during calibration and validation procedures.

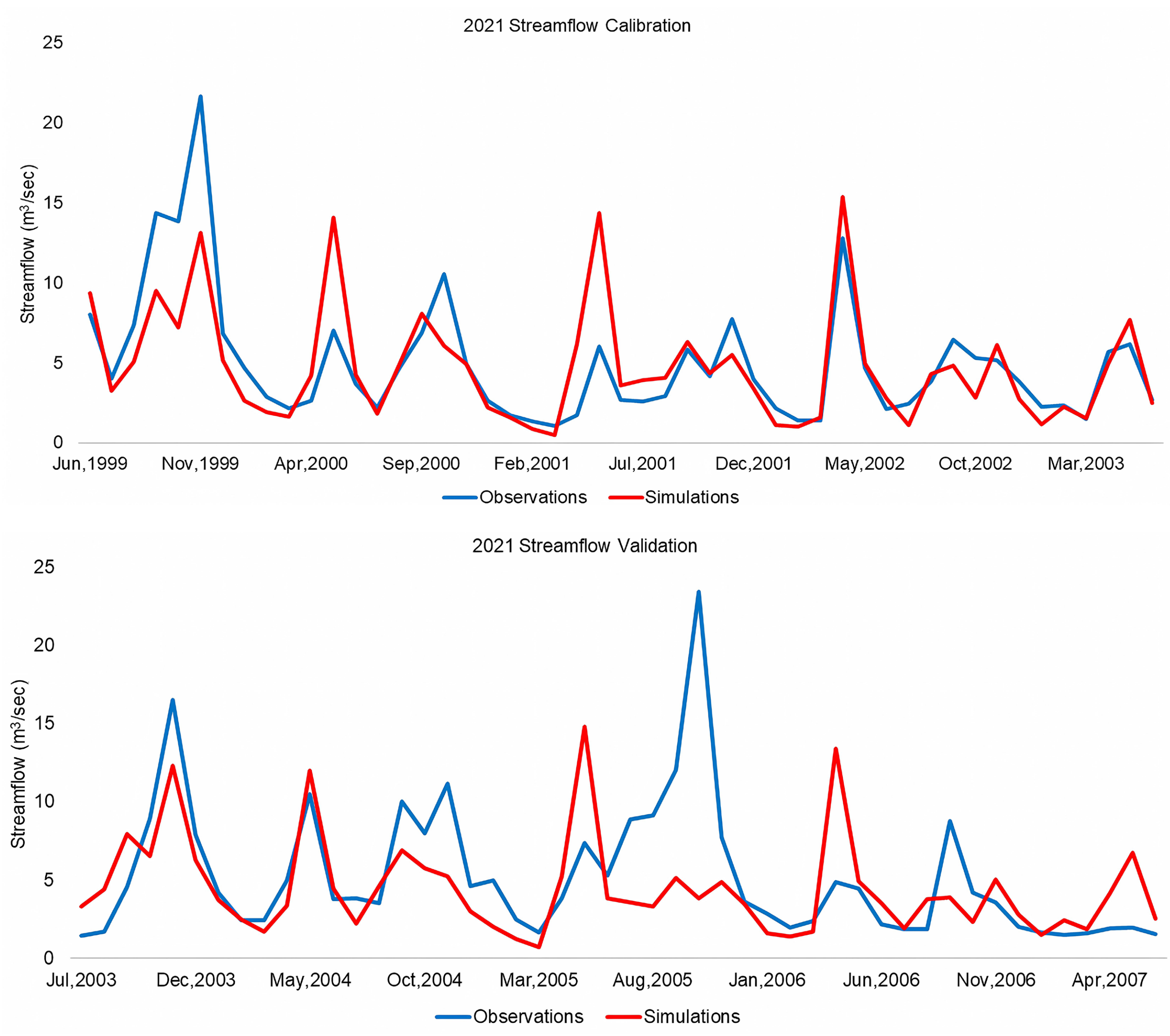

Figure 8. Observations versus simulations of streamflow for 2021 in calibration and validation procedures.

The model produced 16 HRUs. The outputs parameters metrics in 2001 were as follows: Water Yield of 109.98 mm; Surface Runoff of 80.11 mm; Lateral Flow of 628.91 mm; Soil Water Content of 239.67 mm; and Percolation of 336.71 mm. The model revealed an excessive water yield. The model output metrics in 2021 were as follows: Water Yield of 835.55 mm; Surface Runoff of 35.87 mm; Lateral Flow of 544.52 mm; Soil Water Content of 248.37 mm; and Percolation of 275.66 mm. The model also revealed an excessive water yield during 2021.

3.3. Calculations of Hydrological Sustainability

The Hydrological Sustainability Assessment is comprised of the following metrics: Water Yield, Surface Runoff, Lateral Flow, Soil Water Content and Percolation. The outputs of those metrics for 2001, 2021 and the reference condition for the years 2001 and 2021 are shown in Table 8.

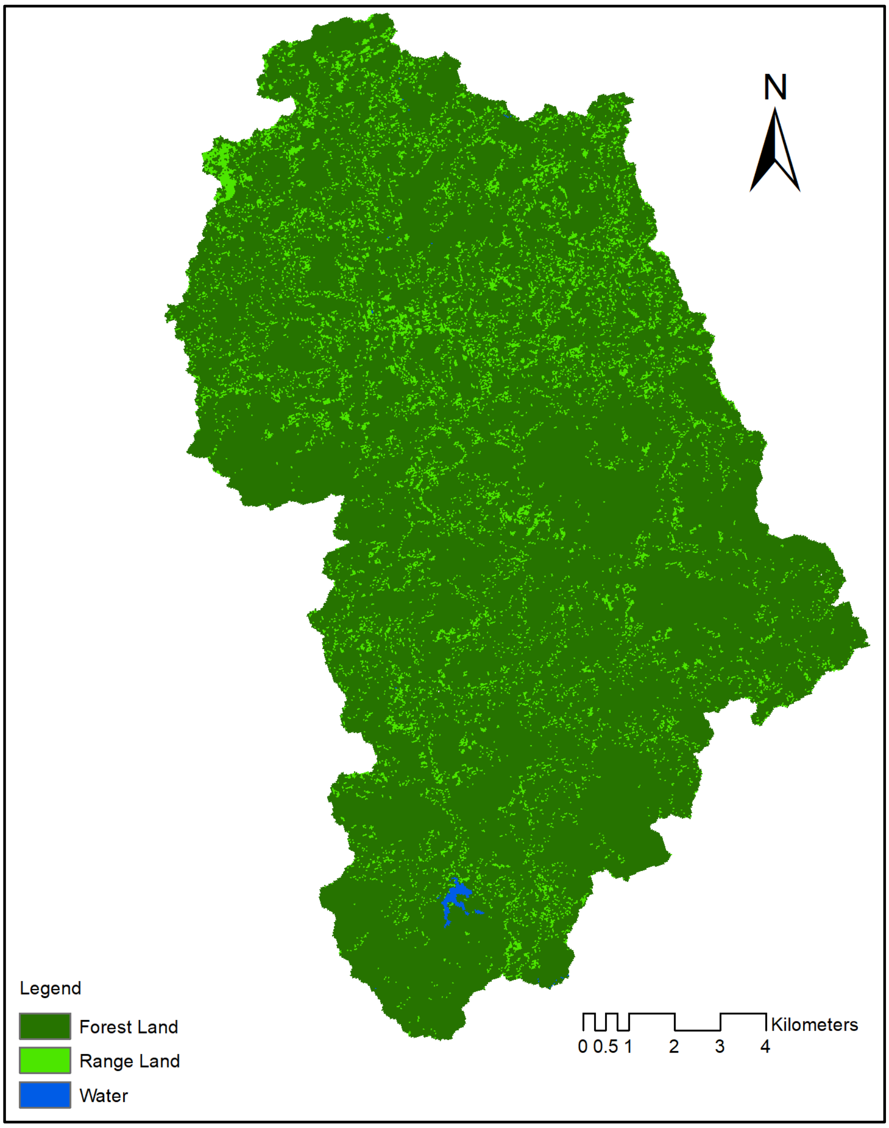

Figure 9. Map of the reference condition for SWAT modeling for the hydrological sustainability assessment.

Table 8. Hydrological values from the outputs of SWAT model for the years 2001, 2021 and the reference condition (2001 and 2021) for the headwater sub-basin.

Hydrological Metric	2001	2001	2021	2021
	Headwater Sub-basin 50024950	Reference Condition	Headwater Sub-basin 50024950	Reference Condition
Water Yield (WYLD) mm	885.3	1010.0	680.7	835.6
Surface Runoff (SURQ) mm (1/X)	65.11 0.015	80.11 0.012	96.25 0.010	35.87 0.028
Lateral Flow (LATQ)mm	572.1	628.9	361.2	544.5
Soil water content (SW) mm	443.1	239.7	409.4	248.4
Percolation (PERC) mm	249.4	336.7	217.1	275.7

Those outputs were used to calculate the hydrological metric as follows: simulated value/value from reference Condition (Table 9). In terms of Hydrological Sustainability Assessment, the head water sub-basin was healthy during the 20-year period, by being the index higher than 0.51. However, it got "less healthy" in 2021 due to a decrease on lateral flow and an increase on surface runoff.

From the ANOVA analysis (Table 8) of the Hydrological metrics for 2001 and 2021 it can be stated that there was not significant difference of water yield (p = 0.14), surface runoff (0.22), soil water content (0.86) and percolation (0.77) between 2001 and 2021. Lateral Flow was the only hydrological metric where a significant difference (0.000005) was observed between 2001 and 2021. From Table 10, it can be stated that lateral flow got "less healthy" in the 20-year period.

Table 9. Hydrological metric sub-index and results of ANOVA test for 2001 and 2021 of the headwater sub-basin.

Hydrological Metric	Sub-Index		ANOVA
	2001	2021	*P*-VALUE
Water Yield	0.88	0.81	0.14
Surface Runoff (1/X)	1.23	0.37	0.22
Lateral Flow	0.91	0.66	0.000005
Soil Water Content	1.85	1.65	0.86
Percolation	0.74	0.79	0.77

Table 10. Calculation of the hydrological sustainability assessment index for the headwater sub-basin. The sub index is the average of all normalized hydrological metrics.

Metrics	2001		2021	
	Normalized metric	Sub Index	Normalized metric	Sub Index
WYLD	0.88		0.81	
SURQ (1/X)	1.23		0.37	
LATQ	0.91	1.12	0.66	0.86
SW	1.85		1.65	
PERC	0.74		0.79	

The percentage of Forest and Urban or Built-up Land covers with respect to the hydrological metrics are shown in Table 11. How well the data fit the regression of model between % Land Cover and the outputs of hydrological metrics from SWAT is shown in Table 12. Apparently, the "goodness of fit" between the variables are: Well between Forest Land cover and soil water content and percolation; Well between Urban Land cover and lateral flow and water yield. Based on the "goodness of fit" and the results on Table 12 it can be stated that:

- The reference condition (2001 and 2021), with 91% forested areas, shows less soil water content, which can be due to high evapotranspiration from forest coverage and to a rapid infiltration rate due to root zone area.

- A similar soil water content between the land cover of 2001 and 2021.
- The reference condition (2001 and 2021) shows the highest percolation. This result can explain the lowest soil water content with highest forest land cover observed in the reference condition.
- The lowest percolation result and the lowest percentage of forest land cover was observed in 2021.
- The lowest lateral flow and the highest urban land cover was observed in 2021.

The percentage of Forest and Urban or Built-up Land covers concerning the hydrological metrics are shown in **Table 11**.

Table 11. Forest land and Urban or built-up land covers and hydrological metrics for 2001, 2021 and the reference condition.

Land Covers	Forest Land Cover (%)	Urban or Build-up cover (%)	WYLD	SURQ	LATQ	SW	PERC
2001 Land Cover	70.5	4.88	885.35	65.11	572.12	443.07	249.37
2001 Reference Condition	90.93	0	1009.98	80.11	628.91	239.67	336.71
2021 Land Cover	68.17	16.66	680.74	96.25	361.17	409.44	217.11
2021 Reference Condition	90.93	0	835.55	35.87	544.52	248.37	275.66

Table 12. R-squared between the % land cover and the hydrological metrics.

Land Covers	R^2				
	WYLD	SURQ	LATQ	SW	PERC
% Forest Land	1.0	0.1	0.6	0.9	0.5
% Urban or Built-up Land	0.6	0.7	1.0	0.3	0.0

4. Discussion

Using the watershed as the basis of sustainable development, we applied a socioecological approach using land cover change analysis and SWAT modelling to assess changes in the hydrological condition of a tropical headwater sub-basin. This approach is intended to evaluate changes in the spatial and temporal conditions over a 20-year time frame of a headwater sub-basin used for water supply.

The Land Cover change analysis gives us valuable information by converting qualitative data into numbers that can be interpreted and used for modeling purposes. From 2001 to 2021, we found reductions in Forest Land cover and Range Land cover of about 2.34% and 15.23%, respectively, representing a loss of about 33.12 km^2. Meanwhile, an increase in Urban or Built-up Land cover of about 11.78% was observed. Some of the increase in Urban or Built-up Land cover in 2021 occurred by expanding the existing urban areas in 2001 with new urban settlements, such as in the southernmost part of the headwater sub-basin. Based on the kappa statistics for the 2021 land cover classification, we recommend an image with better spectral resolution in future assessments. A suggestion for future application is to study the effect of spatial configuration as part of the integrative analysis.

According to the Hydrological Sustainability Assessment, the headwater sub-basin was "healthy" during the 20-year period (higher than 0.50) but became "less healthy" in 2021. By looking at the metrics that comprise this assessment, we can see a decrease in lateral flow and an increase on surface runoff. More urban or built-up land cover relates to less lateral flow. The evaluation of natural-based solution practices to increase permeability of the land in those urban or built-up areas is proposed. Conducting an assessment at a finer scale to identify those areas with potential to generate significant amount of surface runoff to reduce it is proposed. This information can then be used to establish a specific course of action.

The SWAT model was very useful to gather parameters that describe hydrological processes such as surface process, soil water dynamics and groundwater dynamics, which are difficult to obtain using other methods. Based on SWAT analysis, the water sustainability of the headwater sub-basin that discharges to Dos Bocas reservoir can be established as a "healthy" one. Therefore, it can be established that the greater the forest land cover, the greater the percolation, which also provides for the sustainability of groundwater. Consequently, the use of the SWAT in Puerto Rico and in other tropical areas is recommended. We suggest SWAT training be included in professional development plans for personnel in governmental agencies related to land-use planning and natural resources management.

Ahn & Kim (2017) proved the utility of SWAT to gather the parameters from the Water Quality Condition and Hydrological Condition of the EPA WHI in South Korea. In future study, I expect to use SWAT again to gather the data of metrics from the Water Quality condition of the EPA WHI. SWAT has been used extensively around the world because of the advantages it provides when studying ungagged watersheds. However, when conducting this research, I suggest using it first in gauged tropical basins to get better understanding of the model and be able to use it with confidence in tropical ungagged basins. That way, SWAT can be made accessible to disadvantaged regions, overcoming one of the challenges that we as scientists face, to provide accessible tools for everyone.

5. Conclusion

This study assessed the hydrological and land cover changes over a 20-year time frame at an important tropical headwater sub-basin used for water supply. This socioecological approach was conducted for two decades (2001-2021) in order to evaluate temporal changes over this period. It showed the decrease in forest land cover and the increase in the urban or built-up land cover over time.

The headwater sub-basin shows a "healthy" condition through time in terms of the hydrological assessment overall. Therefore, it can be rated as having good condition in terms of water availability that contributes to the Dos Bocas reservoir. When looking at detail at the index components, however, we see the impact of land cover changes when more urban land cover and less forest land cover results in less water yield, less lateral flow, less water content, less percolation, and more surface runoff. Therefore, more efforts should be taken toward conserving areas with already natural land cover and less impermeabilization of the soil.

From the ecological point of view, there is a clear need to study the watershed as an integrated unit. Using this study as a baseline, it is suggested to conduct future landscape level studies to assess the spatial configuration of the land cover and broaden the area of scope at the Río Grande de Arecibo Watershed to make a comparative analysis with other subbasins. In addition, this study provides insight into the advantage of using an integrative approach that can be applied to other tropical regions.

Using SWAT in watershed studies is useful in Puerto Rico, however there is a need to better understand the performance of the model and the calibration of parameters based on the heterogeneity of soils, diversity of vegetation and variability of the climate. Including Dr. Karim Abbaspour is recommended as part of any future research, not only because of his profound and broad knowledge of the subject matter, but also because he has proven to be an accessible and kind person.

The present study focuses only on one of the six components of the EPA WHI, the Hydrological Condition. Therefore, it will be conducted the EPA WHI coupled with an assessment of social vulnerability of the headwater sub-basin. The socioecological approach, using the watershed as the management unit, will serve us to propose specific courses of actions to the improvement of the integrity of the system, but also to the people living in it to promote a "better place for all".

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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