

A Socio-Ecological Approach to Determine Social Vulnerability in a Headwater Sub-Basin of the Río Grande de Arecibo Watershed, Puerto Rico

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Abstract

The Río Grande de Arecibo Watershed (RGAW) in Puerto Rico is a crucial source of water for residents in the north and for those living in the San Juan metropolitan area. RGAW is also essential for forest conservation, with its five State forests providing around 10% of the watershed's area. Land cover changes are causing risk to sustainability in the RGAW. In terms of sustainable development, there cannot be such without reducing social vulnerabilities. This study assessed changes in the social vulnerability of a Headwater Sub-basin of the RGAW over a 20-year period (2000-2020). The CDC Social Vulnerability Index was used to identify those socially vulnerable populations, which brings information about the social disparities occurring on the Headwater Sub-basin of RGAW. Nevertheless, the CDC Social Vulnerability Index presented limitations because some variables such as Minority Status and Housing Types and Transportation do not represent the realities of Puerto Rico. The study provides a baseline to conduct future socioecological watershed studies and sustainable management actions.

Keywords

Watershed, Sustainability, Social Vulnerability

1. Introduction

Water is a crucial factor in achieving sustainability; therefore, 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. Watersheds are the landscape unit that longitudinally frames upstream and downstream process that regulates water quality, quantity, accessibility, and ecosystem services, all of which are needed for human health and well-being (Bunch et al., 2011; Regan et al., 2019).

As stated by Becker (2014) the first step in sustainable development should be to assess the current situation. 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 (Avila et al., 2019; Kern, Rogge, & Howlett, 2019). Therefore, science and technology can contribute to identify and assess these needs by generating structured knowledge and embracing the natural and social sciences, in order to find solutions toward sustainable development (Komiyama & Takeuchi, 2006; Hazbavi, Sadeghi, Gholamalifard, & Davudirad, 2019). Komiyama & Takeuchi (2006) identified the need to construct indicators that integrate social and natural science disciplines with the intention to produce a structure of knowledge toward the identification of sustainability problems and solving them.

To progress toward sustainable development, the use of the concept of social vulnerabilities in a watershed is proposed. In the study of social vulnerability, it is important to assess the drivers that can contribute to it, such as the social determinants of health (SDOH). SDOH are conditions in the environment where people are born, live, and interact that affect a wide range of health, functioning and quality of life factors (United States Department of Health and Human Services, 2020). The need to apply a multidisciplinary approach in dealing with SDOH is recognized and such as establishing a knowledge structure framework from data to understand SDOH is proposed (United States Department of Health and Human Services, 2020). One of the tools that can help in building a knowledge structure framework to improve health status and the well-being of the people is the Center for Disease Control and Prevention Social Vulnerability Index (Center for Disease Control and Prevention, 2021). The Center for Disease Control and Prevention (CDC) in association with the National Center for Environmental Health, the Office of Terrorism Preparedness and Emergency Response and the Agency for Toxic Substances and Disease Registry developed a Social Vulnerability Index using 15 indicators based on census data (Agency for Toxic Substances and Disease Registry, 2020). The objective of this index consists in the identification of the locations where are the most vulnerable population.

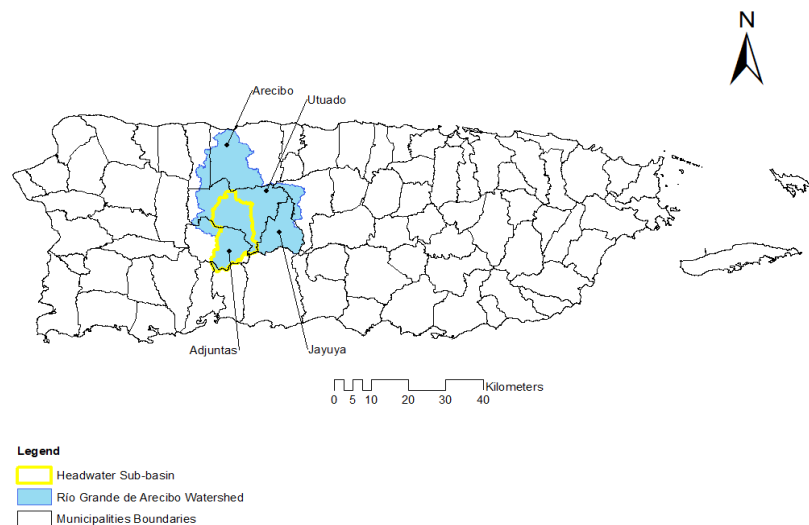
Of particular interest for this research is the lack of knowledge on the sustainability of the RGAW. The specific aims of this study are: 1) To assess and analyze both spatiotemporal changes in social vulnerability in a Headwater Sub-basin at the RGAW over a 20-year time frame; 2) To identify the most socially vulnerable locations in a Headwater Sub-basin of the RGAW using the CDC Social Vulnerability Index; 3) To assess the applicability of the CDC Social Vulnerability Index

in Puerto Rico. Some of the contributions to science and society expected from this research are: 1) Findings can be used as a baseline to develop and improve watershed management plans, particularly the headwater sub-basins of the RGAW; 2) Findings can be presented to the community organizations as a way to empower them; 3) To reinforce the use of social vulnerability as a metric in the management of watersheds.

2. Data and Methods

2.1. Study Area

The study was done in a Headwater Sub-basin at the RGAW (**Figure 1**). The RGAW have 665 km² drainage area, two main rivers and two reservoirs (Dos Bocas and Caonillas). This study focuses on the Headwater Sub-basin of the RGAW 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.



Note: Municipalities Boundaries shapefile downloaded from <https://gis.pr.gov/Pages/default.aspx>.

Figure 1. Map of Puerto Rico with Municipalities Boundary, Río Grande de Arecibo Watershed and Headwater Sub-Basin.

2.2. Headwater Sub-Basin Delineation

The Headwater Sub-basin of the RGAW 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.

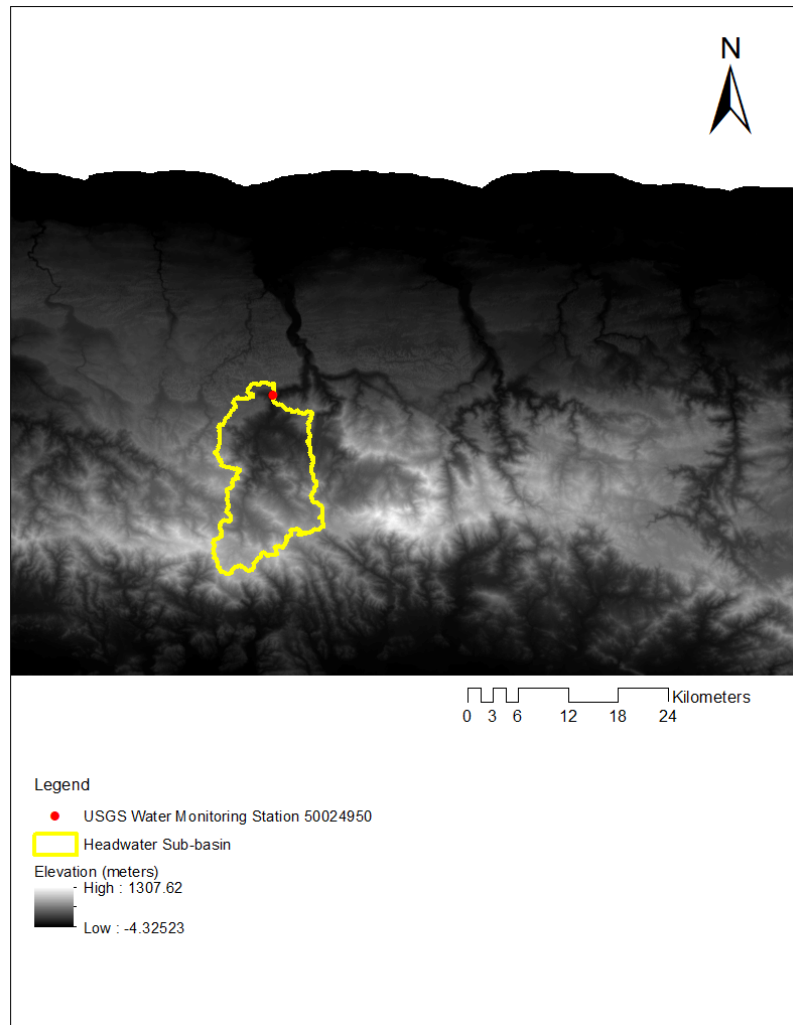


Figure 2. Map of the Digital Elevation Model showing the Headwater Sub-basin. The red dot shows the location of the USGS Water Monitoring Station 50024950.

2.3. CDC Social Vulnerability Index

The CDC Social Vulnerability Index (SVI) was used to identify the most vulnerable population residing in the Headwater Sub-basin. The variables considered in the construction of SVI are presented in **Table 1**.

The data for those variables are based on the 2000 Decennial Census and the 2020 American Community Survey (ACS). The demographic scale of the data for the CDC SVI was the census tracts. Census tract was used as a base unit because it is the smaller demographic unit that includes socioeconomic data from the census products.

For the construction of the CDC SVI, the following process was used: 1) The shapefile of the census tracts was downloaded (<https://gis.pr.gov/Pages/default.aspx>); 2) In Arc Map 10.5, the clip tool was used to gather the census tracts from the Headwater Sub-basin. Those census tracts with almost zero percentage of coverage were rejected for use on the research; 3)

All the data gathered from the ACS was downloaded from the official Census site (<https://data.census.gov/cedsci/advanced>); 4) For every census track, the percentile ranking for every variable was calculated for each Theme, then the percentiles were summed to obtain the percentile at Theme level; 5) An overall percentile rank for each census track was then calculated as the sum of the Theme's percentile rankings; 6) The Count or "Flag" was performed in order to identify social vulnerability in a particular variable or indicator by using the 90 percentile at Theme level, as well as the Overall Social Vulnerability. Therefore, a census track with 90 or higher percentile values were given a value of 1 to indicate high vulnerability and those census tracks below 90 percentiles were given a value of 0.

Table 1. Variables of the CDC social vulnerability index.

CDC SVI themes	Variables
Socioeconomic Status	% Below Poverty Level
	% Unemployment
	Per Capita Income
Household Composition & Disability	% Age 25 or Older with No High School Diploma
	% Age 65 or Older
	% Age 17 or Younger
	% Age 5 or Older with a Disability
Minority Status & Languages	% Single parent households with children under 18
	% Minority
Housing Type & Transportation	% Age 5 or Older Speaks English "Less than Well" or "Not at All"
	% Multi-structure-housing units with 10 or more units in structure
	% Housing units that are Mobile Houses
	Crowding-At Household level, more than 1 person per room.
	% Households with No vehicle available
	% Persons living in Group quarters

2.4. Census Tracks of Headwater Sub-Basin

After clipping (ArcMap 10.5) for the watershed boundaries, 18 census tracks in the Headwater Sub-basin were identified, as follows: Municipality of Adjuntas (9563, 9565, 9566, 9567, and 9568); Municipality of Guayanilla (7401.01); Municipality of Jayuya (9562); Municipality of Peñuelas (7301 and 7302); Municipality of Ponce (726); Municipality of Utuado (9569, 9570, 9571, 9572, 9573, 9574, 9575, and 9576). From those 18 census tracks those with almost zero percentage of coverage were excluded, which were basically the borders of the Headwater Sub-basin. The census tracks used in this research are visualized in **Figure 3**.

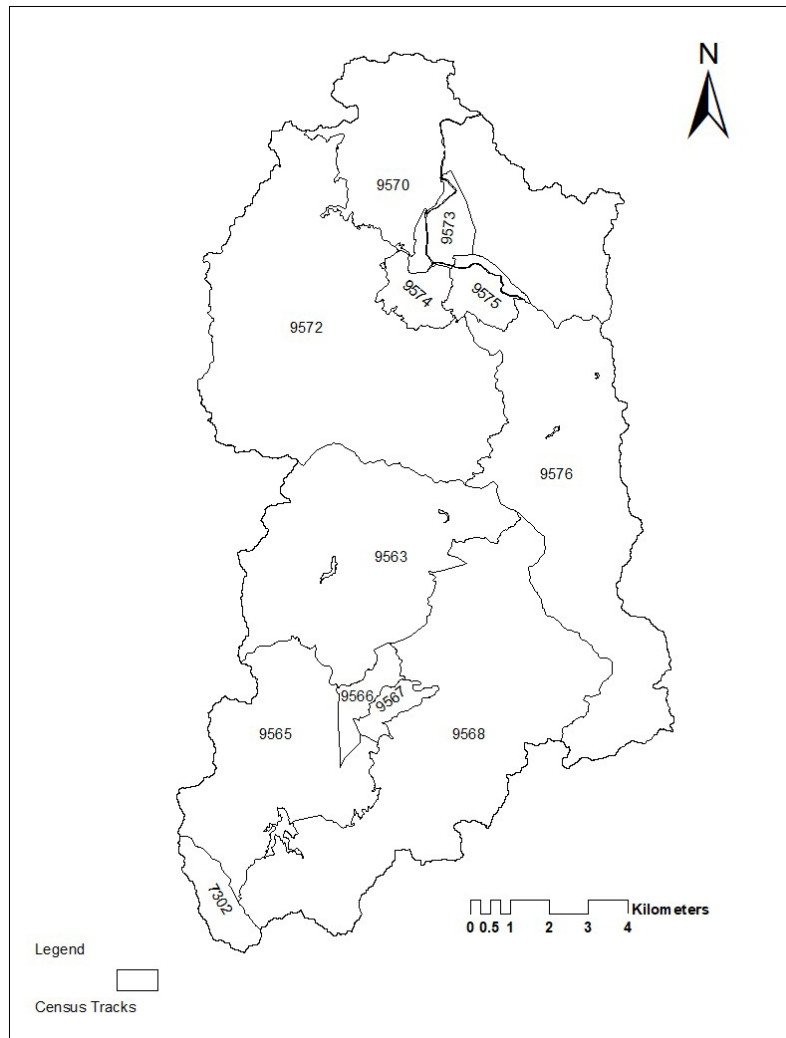


Figure 3. Map showing the selected census tracks in the headwater Sub-basin (Note: The census track boundaries shapefile downloaded from: <https://gis.pr.gov/descargaGeodatos/GeografiaCensal/Pages/default.aspx>).

3. Results

3.1. CDC Social Vulnerability Index

3.1.1. Overall CDC SVI for 2000

As seen in **Table 2** a high vulnerability of the Socioeconomic Status can be observed in the municipality of Adjuntas, census track 9565; high vulnerability of the Household Composition and Disability Theme can be observed in the municipality of Utuado, census track 9574; high vulnerability of the Minority Status and Language Theme can be observed in the municipality of Adjuntas, census track 9563; and high vulnerability of the Housing Type and Transportation Theme can be observed in the municipality of Utuado, census track 9574.

Figure 4 shows the more socially vulnerable tracks in the Headwater Sub-basin for the year 2000, which were in census tracks 9563 and 9565, both located in the municipality of Adjuntas, at the west region of the Headwater Sub-basin.

Table 2. Percentiles of themes for CDC SVI in the headwater sub-basin for Year 2000.

Census track	CDC SVI themes percentiles				Sum themes
	Socioeconomic status	Household composition & disability	Minority status & language	Housing type & transportation	
7302	0.09	0.45	0.45	0.55	1.55
9563	0.91	0.36	1.00	0.64	2.91
9565	1.00	0.91	0.82	0.36	3.09
9566	0.27	0.73	0.91	0.09	2.00
9567	0.36	0.64	0.55	0.18	1.72
9568	0.55	0.27	0.73	0.82	2.36
9570	0.18	0.00	0.18	0.18	0.54
9572	0.64	0.18	0.64	0.73	2.18
9573	0.00	0.55	0.18	0.45	1.18
9574	0.82	1.00	0.00	1.00	2.82
9575	0.64	0.82	0.09	0.91	2.45
9576	0.45	0.09	0.36	0.00	0.91

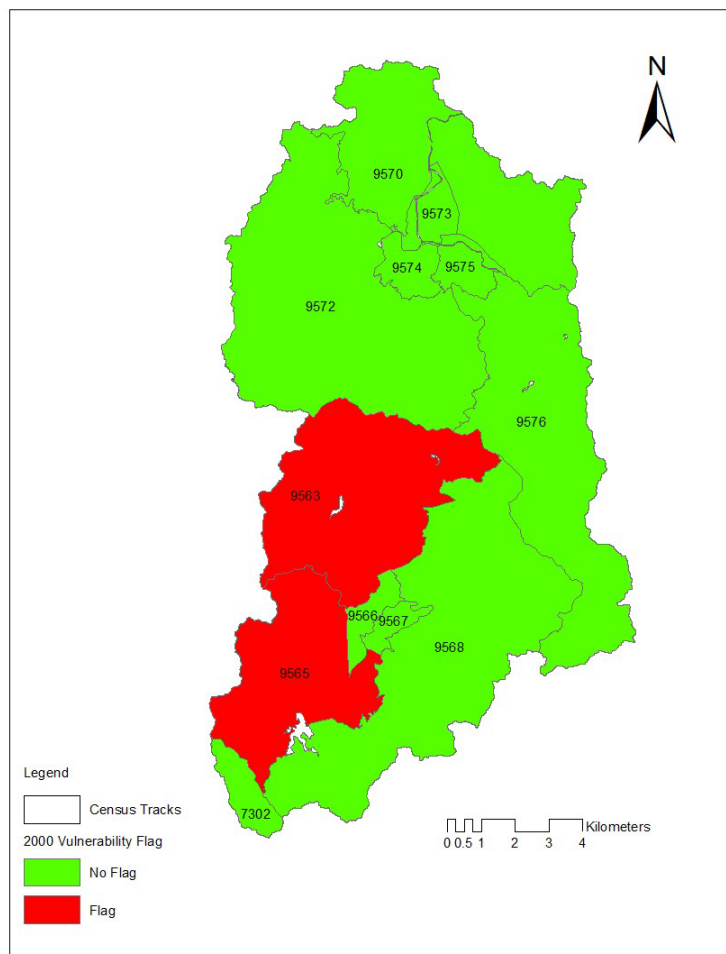


Figure 4. Map of the overall social vulnerability in the headwater sub-basin for the year 2000.

3.1.2. Overall CDC SVI for 2020

The data seen in **Table 3** shows that the highest vulnerability in Socioeconomic Status and Household Composition and Disability Themes can be found in the municipality of Utuado, census track 9574, in the mid-north region; the highest vulnerability in Minority Status and Language Theme in the municipality of Adjuntas, census track 9565, in southwest region; and the highest vulnerability in Housing Type and Transportation Theme in the municipality of Utuado, census track 9576, in the east region of the Headwater Sub-basin.

Table 3. Percentiles rank of the themes for CDC SVI in the headwater sub-basin for year 2020.

Census track	CDC SVI themes percentiles				Sum of themes
	Socioeconomic status	Household composition & disability	Minority status & language	Housing type & transportation status	
7302	0.00	0.27	0.18	0.36	0.82
9563	0.64	0.00	0.82	0.45	1.91
9565	0.91	0.64	1.00	0.09	2.64
9566	0.82	0.36	0.64	0.73	2.54
9567	0.55	0.82	0.09	0.82	2.27
9568	0.36	0.64	0.73	0.18	1.91
9570	0.45	0.18	0.36	0.00	1.00
9572	0.27	0.91	0.45	0.27	1.91
9573	0.09	0.45	0.00	0.64	1.18
9574	1.00	1.00	0.45	0.55	3.00
9575	0.73	0.55	0.91	0.82	3.00
9576	0.18	0.09	0.27	1.00	1.54

From the 90th percentile a social vulnerability flags were established in the municipality of Utuado, census tracks 9574 and 9575, in the mid-north region of the Headwater Sub-basin (**Figure 5**).

3.1.3. Spatial-Temporal Change Analysis of the CDC SVI

From 2000 to 2020 the total population in the Headwater Sub-basin decreased from 44,213 to 37,452, a reduction of 6,761 inhabitants in 20 years. In 2000, the census track with the highest population was located in the municipality of Utuado, particularly in the census track 9572 in northwest region. Twenty years later it was still on the municipality of Utuado, but located in the census track 9570, more toward the north of the Headwater Sub-basin.

1) Comparison between 2000 and 2020 Overall Social Vulnerability

A comparison between 2000 and 2020 overall social vulnerability index indicates a shift in the location of higher social vulnerability populations from the municipality of Adjuntas, particularly in the communities located in the census tracks 9563 and 9565, to the municipality of Utuado, particularly in the census

tracks 9574 and 9575. Therefore, the communities with the highest social vulnerability transitioned spatially from the mid-south-east region in 2000 to the mid-north region in 2020.

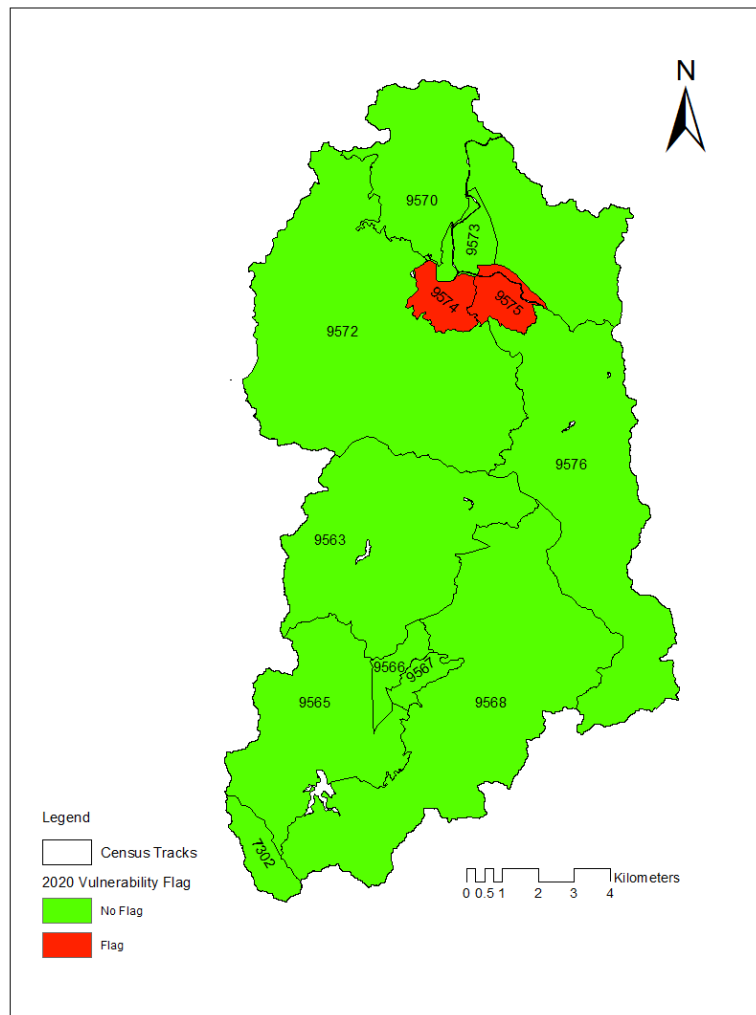


Figure 5. Map of the overall social vulnerability in the headwater Sub-basin for the year 2020.

2) Socioeconomic Status Theme

In 2000, the population with the lowest per capita income and the highest population below poverty level were located in the southwest region of the Headwater Sub-basin, in the municipality of Adjuntas, census track 9565; but by 2020 a shift in the geospatial distribution of these variables occurred, migrating from the southwest to the mid-north site of the subbasin. In 2020, the population with lowest income and highest level of poverty is located in the municipality of Utuado, census track 9574.

Also, the geospatial distribution of unemployed population changed during the 2000 to 2020 period. In 2000, the highest percentage of unemployed individuals was located in the municipality of Adjuntas, census track 9566, in the mid-south

region; and by 2020 it was located in the municipality of Utuado, census track 9574, in the mid-north region.

For the 20-year time frame, the highest percentage of population of age 25 or older without high school diploma was found in the municipality of Adjuntas, census track 9565, in the southwest region (Table 4).

Table 4. 2000 and 2020 socioeconomic data of the headwater sub-basin.

	2000											
Census Track	7302	9563	9565	9566	9567	9568	9570	9572	9573	9574	9575	9576
Per capita annual income	\$5,410.0	\$4,231.0	\$3,556.0	\$6,613.0	\$8,404.0	\$4,278.0	\$5,833.0	\$4,885.0	\$5,706.0	\$3,944.0	\$4,530.0	\$5,129.0
% Below Poverty	53.6	65.73	71.11	58.58	53.44	68.98	58.97	62.56	44.51	65.88	70.73	64.69
% Unemployment	5.6	12.0	11.7	13.0	12.5	10.0	7.9	11.5	10.2	11.0	10.8	10.7
% of population of age 25 or older without high school diploma	40.9	59.9	63.6	39.5	49.5	49.5	48.1	53.8	34.7	54.7	48.9	49.1
	2020											
Per capita annual income	\$10,930.0	\$7397,0	\$6291,0	\$5686,0	\$7930,0	\$7827,0	\$8534,0	\$8871,0	\$10,327,0	\$5102,0	\$6488,0	\$9110,0
% Below Poverty	39.38	61.75	70.7	76.72	61.35	62.1	50.49	55.29	44.23	81.43	69.72	36.3
% Unemployment	19.8	37.0	40.2	34.7	39.9	15.7	35.8	34.5	21.0	63.4	37.8	36.3
% of population of age 25 or older without high school diploma	18.82	34.42	52.12	35.72	21.2	26.77	27.41	30.13	18.01	38.61	27.35	24.27

In 2000, vulnerability flags were established in the municipality of Adjuntas, census tracks 9563 and 9565, in the south-west region. In 2020, vulnerability flags were still identified in the southwest site of the basin in the municipality of Adjuntas, and in the mid north site at the municipality of Utuado in the census track 9574. It is important to emphasize a decrease in social vulnerability in Adjuntas, as well as an identification of a new vulnerable location in the municipality of Utuado, census track 9574.

3) Household Composition and Disability Theme

In 2000, the highest elderly population was located in Adjuntas, census track 9567, in mid-south region; by 2020, it was located in Utuado, census track 9572, in the north-west region.

In 2000, the highest percentage of population of age 17 or younger was located in the municipality of Adjuntas, census track 9565, in the southwest region; by 2020, it was located in the municipality of Peñuelas, census track 7302, at the south region.

For the 20-year period, the highest percentage of population age 5 or younger with disabilities was located in the municipality of Utuado, census track 9574, at the mid-north region.

In 2000, the highest percentage of total single parents with children under 18 was located in the municipality of Adjuntas, census track 9565, in the southwest region; and in 2020, it was located in the municipality of Utuado, census track

9574, at the mid-north region (Table 5).

Table 5. 2000 and 2020 household composition and disability data of the headwater sub-basin.

2000												
Census Track	7302	9563	9565	9566	9567	9568	9570	9572	9573	9574	9575	9576
% 65 Year or more	6.01	9.12	9.24	9.37	18.05	8.60	11.21	11.23	11.11	12.12	15.07	11.58
% 17 Year or Less	33.15	34.38	34.77	31.85	28.1	31.26	29.94	30.28	28.17	33.96	30.9	31.3
% Age 5 or over with disability	24.43	25.29	32.69	25.75	19.27	29.91	24.14	27.73	30.98	34.16	29.31	23.4
% Total single parent with children under 18	12.6	9.82	21.14	12.38	18.89	11.24	11.22	5.66	12.09	17.3	15.4	6.25
2020												
% 65 Year or more	17.8	14.4	18	17.6	20.3	21.2	20.4	27.5	24.5	24.6	21.8	19.9
% 17 Year or Less	26.4	16.7	20.1	20.3	21.2	23.3	17.2	21.3	17.4	22.8	13.3	15.6
% Age 5 or over with disability	11.95	14.79	26.42	14.23	17.87	15.38	20.9	23.74	14.84	27.12	26.32	13.71
% Total single parent with children under 18	20.1	11.36	25.75	30.35	26.22	19.15	15.29	11.79	20.55	37.91	24.54	18.63

In 2000, it was established vulnerability flags in the municipality of Adjuntas, census track 9565, in the southwest region and in the municipality of Utuado, census track 9574, in the mid-north region. In 2020, the vulnerability flags were in the municipality of Utuado, census tracks 9572 and 9574, in the north-east region.

4) Minority Status and Language Theme

During the 20-year period more than 50% of the population age 5 or older speaks English “less than well” or “not at all”. Also, for the 20-year period, the highest percentage of population of age 5 or older that speaks English “less than well” or “not at all” was located in the municipality of Adjuntas, census track 9565, in the southwest region of the Headwater Sub-basin (Table 6).

Table 6. 2000 and 2020 minority status and language data of the headwater sub-basin.

2000												
Census Track	7302	9563	9565	9566	9567	9568	9570	9572	9573	9574	9575	9576
% Minority	99.35	99.85	99.63	99.81	99.36	99.51	99.27	99.4	99.27	99.1	99.2	99.34
% Age 5 or older speaks English “less than well” or “not at all”	69.31	63.11	71.23	51.9	56.47	68.42	69.18	69.52	69.79	70.56	60.6	58.16
2020												
% Minority	99.39	99.64	99.82	99.9	99.46	99.63	99.45	99.35	99.43	99.75	99.92	99.07
% Age 5 or older speaks English “less than well” or “not at all”	73.22	79.96	82.34	69.31	59.81	77.24	73.4	82.25	64.9	69.79	75.1	77.59

In 2000, vulnerability flags were established in the municipality of Adjuntas, census tracks 9563 and 9565, in the west region and in the municipality of Utuado, census track 9572, in the northwest region. In 2020, the vulnerability flags still were in the municipality of Adjuntas, census track 9565 at the southwest region and in the municipality of Utuado, but in census track 9575, in the mid-north region of the Headwater Sub-basin.

5) Housing Type and Transportation Theme

Within the 20-year time frame, the highest percentage of population living in multi-structure housing units with 10 or more units in structure was located in the municipality of Adjuntas, census track 9566, in the mid-south region. In 2000, the highest percentage of population living in housing units that are mobile houses was located in the municipality of Adjuntas, census track 9567, in the mid-south region; in 2020 it was located in the municipality of Utuado, census track 9576, in the east region. It is important to mention that these two variables, Housing & Transportation Theme, were present in few census tracks with small percentage of population under them.

In 2000, the highest percentage of population living in crowding-at household level (more than 1 person per room) was located in the municipality of Peñuelas, census track 7302, in the south region; and in 2020 it was located in the municipality of Utuado, census track 9576, in the east region.

Table 7. 2000 and 2020 housing type and transportation data of the headwater Sub-basin.

Census Track	2000											
	7302	9563	9565	9566	9567	9568	9570	9572	9573	9574	9575	9576
% Multi-structure-housing units with 10 or more units in structure	0	0	0	8.24	0	0	0	0	0	0	0	0
% Housing units that are mobile houses	0	0.5	0	0.5	1.3	0	0	0	0.5	0	0	0
% Crowding-at household level, more than 1 person per room	19.3	18.3	16.9	16.2	11.8	18.8	10.1	10.2	8	9.2	13.9	14.6
% Households with no vehicle available	32.2	32.4	24.8	46.2	33.2	27.3	29.4	49.4	32.8	47.5	34.2	30
% Persons living in group quarters	0	0	1.65	0	2.79	0.11	0.38	2.23	0.01	0.64	0.61	0.2
Census Track	2020											
	7302	9563	9565	9566	9567	9568	9570	9572	9573	9574	9575	9576
% Multi-structure-housing units with 10 or more units in structure	0	0	0	13.1	6.3	0	0	0	3.9	4.9	0	1.1
% Housing units that are mobile houses	0	0	0	0	0	0	0	0	0.6	0	1.2	1.7
% Crowding-at household level, more than 1 person per room	0.8	1.2	0	0.6	0	0	0	0	0	0	0	1.6
% Households with no vehicle available	9.5	13.6	16.8	26.9	22	11.8	15.2	12.7	17.7	35	43.1	9.3
% Persons living in group quarters	0.93	0.21	0	0	1.33	0.59	0	0.99	0.05	0.12	0.71	0.18

In 2000, the highest percentage of households with no vehicle available were

observed in the municipality of Utuado, census track 9572, in the northwest region. In 2020, it was still located in the municipality of Utuado, but in census track 9575, in the mid-north region.

For all the 20-year time frame the highest percentage of persons living in group quarters was located in the municipality of Adjuntas, census track 9567, in the mid-south region (**Table 7**).

In 2000, vulnerability flags were established in the municipality of Utuado, census track 9574 and 9575, in the mid-north region. In 2020, the vulnerability flags were in the municipality of Adjuntas, census track 9567, in the mid-south region and in the municipality of Utuado, census tracks 9575 and 9576, in the mid north-east region of the Headwater Sub-basin.

4. Discussion and Conclusion

Garcia J. et al. (2024) identified the migration trends of Puerto Ricans who moved to the United States between 2000 and 2022, noting that net outmigration began in 2003 and reached its peak in 2018. Possible drivers of this migration include the impacts of Hurricane María in 2017 and the seismic activity experienced in 2020 (United States Census Bureau, 2021). In 2020, however, net outmigration declined, likely due to the travel restrictions and broader disruptions associated with the COVID-19 pandemic (Focus Economics, 2026).

In broad terms, Puerto Rico has confronted several major economic challenges: the expiration of Section 936 tax incentives in 2006, which had supported the island's pharmaceutical and medical device manufacturing sectors; the accumulation of approximately \$70 billion in public debt by 2015, prompting the establishment of a fiscal control board in 2016; persistently high unemployment; and a labor force participation rate significantly lower than that of the mainland United States (United States Census Bureau, 2021).

The total population in the Headwater Sub-basin decreased from 44,213 to 37,452, a reduction of 6,761 individuals in 20 years. Studying changes in a 10-year frame instead of a 20-year one can help establish the possible causes for that reduction. However, the decrease in population can be due to the migration of residents to the United States, as previously stated.

This research responds to the need to identify those most vulnerable in a Headwater Sub-basin for a 20-year period. In order to achieve this, the CDC SVI was used.

This study found a significant shift in social vulnerability in RGAW. From Adjuntas in 2000, census tracks 9563 and 9565, to the municipality of Utuado, census tracks 9574 and 9575. Therefore, the communities with the highest social vulnerability transitioned spatially from the mid-south-west region in 2000 to the mid north region in 2020. Some data points are particularly noteworthy. The population of census tract 9574 in Utuado declined significantly over the past 20 years, dropping from 3,227 to 1,652 residents. In 2000, the highest levels of socioeconomic vulnerability were found in Adjuntas, specifically in census tracts 9536 and

9565. By 2020, census tract 9565 in Adjuntas continued to exhibit elevated vulnerability, but census tract 9563, which had been vulnerable in 2000, was replaced by census tract 9574 in Utuado.

These shifts highlight the importance of examining the internal components of the composite index rather than relying solely on overall scores. Although identifying the underlying causes of these changes falls outside the scope of this study, they present a valuable opportunity for future research.

In terms of socially vulnerable populations, the analysis showed that their geographic distribution shifted over the 20-year period. This underscores the dynamic nature of social vulnerability and the importance of monitoring changes over time. A more detailed examination of the variables that make up the CDC SVI can support the development of more targeted and effective courses of action at finer spatial scales.

Based on the CDC SVI findings for census tracts 9574, 9565, and 9572, several efforts are recommended. These include improving the quality of education; promoting job creation and access to decent employment; supporting single parents by expanding access to childcare, thereby enabling them to pursue higher education and stable jobs; implementing an adult high-school diploma (GED) program and an ESL conversational English program; and providing economic and social assistance to elderly residents.

The CDC SVI has limitations arising from its selected variables and aggregation method, which can cause socially vulnerable census tracts to be overlooked. For instance, census tract 9576 ranked as the most vulnerable in 2020 for the Housing Type and Transportation Theme, exhibiting the highest percentiles and the largest cumulative percentile score across that theme's variables. However, the "mobile homes" variable does not carry the same meaning in Puerto Rico as it does in the continental United States. On the Island, mobile homes are often used for recreational purposes rather than as primary residences. This mismatch can distort index results and their interpretation, particularly when assessing vulnerability within the Housing Type and Transportation Theme.

The variables that make up the Minority Status and Language Theme do not accurately reflect Puerto Rico's demographic reality. In the United States, the Hispanic population is classified as a minority. However, Puerto Rico was under Spanish colonial rule for nearly 400 years, and Spanish remains the island's primary language. After becoming a territory of the United States in 1898, the population continued to be predominantly Hispanic and Spanish-speaking. As a result, almost 100% of census tracts are categorized as "minority," not because they represent a small or marginalized demographic group, but because the indicator is based on criteria designed for the continental U.S. context. From Puerto Rico's perspective, being Hispanic does not constitute minority status, since the population is predominantly Hispanic. Therefore, this variable does not capture the island's true demographic characteristics.

Looking at the vulnerability flags results in detail, the variables "Minority and

Language” and “Housing Type and Transportation” could have helped give weight to census tract 9575 in the 2020 overall vulnerability.

In my view, the CDC SVI should not be interpreted solely at the Overall level. Census tracts with very low values across several variables can end up receiving more weight in the index than tracts with higher values concentrated in fewer variables. This dynamic can distort the identification of truly vulnerable areas. One could argue that this represents a methodological limitation that should be addressed in order to more confidently determine which populations are most socially vulnerable.

For this type of research, the use of the CDC SVI’s Socioeconomic and Household Composition and Disability themes is recommended. For the housing component, incorporating measures of physical vulnerability, such as those included in the EPA’s Watershed Vulnerability Index (United States Environmental Protection Agency, 2023), is advisable. Based on these considerations, the development of an adjusted social vulnerability index tailored to Puerto Rico is proposed for future studies. This recommendation aligns with the findings of Ipek Eroglu et al. (2020), who argue that adapting the SoVI to Puerto Rico’s specific context enables a more accurate understanding of local conditions and highlights the importance of analyzing social vulnerability at finer spatial scales.

The selection of variables should be grounded in a solid understanding of the country’s context and the characteristics of the population living within the watershed. For example, active involvement with community organizations in the Headwater Sub-basin highlighted the importance of including variables that capture residents who serve as family caregivers for bedridden individuals. Another social factor that merits consideration is the local crime rate. Additionally, using “no vehicle available” as a vulnerability indicator conflicts with sustainable development principles, since long-term sustainability goals emphasize the creation of efficient and accessible collective transportation systems in cities and communities.

In addition, it would be beneficial to consult other data available through the ACS to gain a more comprehensive understanding of the population living within the watershed. Certain groups that require special attention and support are not fully captured by the CDC SVI. Therefore, it is proposed that additional variables—such as adults aged 65 or older living alone and grandparents living with and caring for their own grandchildren under 18—be incorporated into a future Social Vulnerability Index for the Headwater Sub-Basin of the RGA.

Therefore, the selection of variables for a social vulnerability index applied at the watershed level—and aligned with sustainable development principles—should incorporate factors such as access to drinking water, runoff management, flood potential, exposure to environmental and public-health pollutants, food security (including the percentage of agricultural areas using good conservation practices), access to affordable and sustainable transportation, and the availability of green space, among others.

In conclusion, this research highlights the need to develop sustainable development indices that can better inform and support decision-making processes. The CDC SVI, while useful in other contexts, is not recommended for identifying vulnerable populations in Puerto Rico. Instead, the creation of Social Vulnerability Indices tailored to the island's specific social, cultural, and environmental realities is proposed, offering a more accurate and context-appropriate model for future applications.

Conflicts of Interest

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

References

- Agency for Toxic Substances and Disease Registry (2020). *CDC/ATSDR Social Vulnerability Index*. <https://www.atsdr.cdc.gov/place-health/php/svi/index.html>
- Avila, L. V., Beuron, T. A., Brandli, L. L., Damke, L. I., Pereira, R. S., & Klein, L. L. (2019). Barriers to Innovation and Sustainability in Universities: An International Comparison. *International Journal of Sustainability in Higher Education*, 20, 805-821. <https://doi.org/10.1108/IJSHE-02-2019-0067>
- Becker, P. (2014). Conceptual Frames for Risk, Resilience and Sustainable Development. In P. Becker (Ed.), *Sustainability Science* (pp. 123-148). Elsevier. <https://doi.org/10.1016/b978-0-444-62709-4.00005-1>
- Bunch, M. J., Morrison, K. E., Parkes, M. W., & Venema, H. D. (2011). Promoting Health and Well-Being by Managing for Social-Ecological Resilience: The Potential of Integrating Eco-Health and Water Resources Management Approaches. *Ecology and Society*, 16, 6. <https://doi.org/10.5751/es-03803-160106>
- Center for Disease Control and Prevention (2021). *Social Determinants of Health: Know What Affects Health*. <https://www.cdc.gov/socialdeterminants/data/index.htm>
- Focus Economics (2026). *Puerto Rico Economic Data & Projections*. <https://www.focus-economics.com/countries/puerto-rico/>
- Garcia, J., Palomino, L., & Venator-Santiago, C. R. (2024). *Migration Profile of Puerto Ricans at State Level, 2000-2022*. UCONN Puerto Rican Studies Initiative.
- Hazbavi, Z., Sadeghi, S. H., Gholamalifard, M., & Davudirad, A. A. (2019). Watershed Health Assessment Using the Pressure-State-Response (PSR) Framework. *Land Degradation & Development*, 31, 3-19. <https://doi.org/10.1002/ldr.3420>
- Ipek Eroglu, D., Pamukcu, D., Szczyrba, L., & Zhang, Y. (2020). Analyzing and Contextualizing Social Vulnerability to Natural Disasters in Puerto Rico. *17th ISCRAM Conference* (pp. 389-395).
- Kern, F., Rogge, K. S., & Howlett, M. (2019). Policy Mixes for Sustainability Transitions: New Approaches and Insights through Bridging Innovation and Policy Studies. *Research Policy*, 48, Article ID: 103832. <https://doi.org/10.1016/j.respol.2019.103832>
- Komiyama, H., & Takeuchi, K. (2006). Sustainability Science: Building a New Discipline. *Sustainability Science*, 1, 1-6. <https://doi.org/10.1007/s11625-006-0007-4>
- Regan, R. S., Juracek, K. E., Hay, L. E., Markstrom, S. L., Viger, R. J., Driscoll, J. M. et al. (2019). The U. S. Geological Survey National Hydrologic Model Infrastructure: Rationale, Description, and Application of a Watershed-Scale Model for the Conterminous United States. *Environmental Modelling & Software*, 111, 192-203.

<https://doi.org/10.1016/j.envsoft.2018.09.023>

United States Census Bureau (2021). *Net Outmigration from Puerto Rico Slows during Pandemic*. New Population Estimates Rely on Monthly Flight Data to Capture Puerto Rico's Migration Flows.

<https://www.census.gov/library/stories/2021/12/net-outmigration-from-puerto-rico-slows-during-pandemic.html>

United States Department of Health and Human Services (2020). *Social Determinants of Health*. Healthy People 2030.

<https://health.gov/healthypeople/objectives-and-data/social-determinants-health>