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DESIGNING WATER SYSTEMS FOR CLIMATE CHANGE: A CASE STUDY IN CUMAYASA, DOMINICAN REPUBLIC

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DESIGNING WATER SYSTEMS FOR CLIMATE CHANGE:

A CASE STUDY IN CUMAYASA, DOMINICAN REPUBLIC

BY

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Abstract

The purpose of this study was to design a climate-ready drinking water system for a newly constructed school in Cumayasa, Dominican Republic while developing components of a Community Climate Change Strategy (CCCS). The goal of the CCCS is to bridge the gap between macro-scale climate change science and drinking water system development at the community level.

In this proposed CCCS, “no-regrets” and “low-regrets” decision-making is applied to water system design for small, rural or peri-urban communities. The CCCS was designed to be used in all phases of a project’s lifecycle, with adaptation actions corresponding to each phase of the project process. This paper addresses the adaptation actions for the first three phases of the project process: project formation phase; assessment phase; and alternatives analysis phase.

The Dominican Republic is listed in the lowest third out of 100 countries based on the Vulnerability-Resilience Indicator Model (VRIM) and is vulnerable to climate change and extreme weather events. Therefore, Cumayasa was selected as a location to study the possible ways to prepare for and adapt to climate change and sea level rise.

The CCCS used inputs from the World Resources Institute’s AQUEDUCT Water Risk Atlas and summaries of climate change projections based on the Caribbean Community Climate Change Centre’s derivation from observed climate data sources and climate model projections using a General Circulation Model (GCM) ensemble of 15 models and the Regional Climate Model (RCM), *PRECIS,* to determine Climate Risk Assessment

Value Ratings (CRAVR) and ease of implementation scores. The CRAVR and ease of implementation inputs were used to build a location specific Climate Adaptation Matrix for Prioritization (CAMP). Adaptation solutions were categorized as high, medium, or low priority. The high priority design adaptations identified using the CCCS process were incorporated into the system design. An overview of the system design including the adaptations to climate change and sea level rise was provided.

Following the CCCS process, information for the Dominican Republic and Cumayasa region was applied to generate the CAMP. The results obtained from the CAMP showed eight high priority, five medium priority, and five low priority design adaptations. Due to factors such as financial and technical capacity, incorporating all potential design adaptations was not feasible. By understanding how current and future climate hazards affect the functionality of water technologies and impact water sources, water treatment technologies and water sources were prioritized and the best alternatives to improve Cumayasa's resilience to climate change were selected. All of the high priority design adaptations were related to flood risk. The high priority adaptations recommended in the CAMP for Cumayasa included: conducting field assessments to identify potential water supply contaminants and designing a robust treatment system; using an activated carbon filter to remove chemical contaminants; incorporating chlorine disinfection into the design; incorporating a 5-micron membrane filter to remove turbidity; ensuring proper maintenance and protection of the underground storage cistern; elevating the electric-powered pump to protect from flood events; and diversifying water sources (groundwater and rainwater).

This framework could be a valuable tool to help engineers and decision-makers prioritize climate change adaptation solutions for community-based water systems. By providing guidance on identifying current and future climate risks and vulnerabilities; mapping pathways between climate hazards (e.g., flood and drought), impacts, and design adaptations; and prioritizing appropriate solutions to select which adaptations should be incorporated in the design, adaptations can be incorporated into community-based water systems. The CCCS was designed for water systems in small, rural or peri-urban communities. Therefore, it can provide a sufficient level of detail for water system design at the community-level while remaining relatively concise. The CCCS could provide rural or peri-urban communities around the world with the capability of adapting water systems to climate change.

Acknowledgements

I would like to thank Vinka Craver, Ph.D., for advising this research and providing continued guidance throughout my Master of Science degree, and for being a great mentor. I would also like to thank Ali S. Akanda, Ph.D. for his continued guidance and advice throughout this research and participation in the project; Todd Guilfoos, Ph.D. for his support in developing community surveys for this project and participation on my thesis committee; and Soni Pradhanang, Ph.D. for her support as chair of my thesis committee.

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Preface

This research was initiated due to my passion for improving water quality and availability worldwide. After working on international water projects for several years across Africa and Latin America, the need for improved community-based design tools became apparent. Communities were driven to improve the resilience of their water systems to climate change and natural disasters. This research will aid my goal to help communities worldwide have sustainable and resilient water supplies. This thesis was conducted in manuscript format.

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Designing Water Systems for Climate Change:

A Case Study in Cumayasa, Dominican Republic

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1. Introduction

More than 748 million people worldwide lack improved water supply, however an additional 1.8 billion people do not have access to safe and reliable water (*Mellor et al.,* 2016). Small island developing States (SIDS) are particularly vulnerable to hydrometeorological, climate, and socioeconomic disturbances (*Farrell et al.,* 2010). Population growth and coastal urbanization, combined with limited land resources, geology, and unique topography further intensify these issues. Therefore, reducing vulnerability of SIDS is critical (*Farrell et al.,* 2010).

Flooding and drought associated with climate change, sea level rise, and hurricane activity impact water infrastructure causing water supply contamination, service outage, and damage to infrastructure. Hurricane Maria made landfall in Puerto Rico on September 20, 2017, causing major damage to infrastructure and severely limiting access to potable water (*Concepción-Acevedo et al*., 2018). In Haiti, the neighboring country to the Dominican Republic, a single natural disaster resulted in the destruction of water and sanitation infrastructures and subsequent impacts on public health lasting many years. Hydrometeorological disasters are the most frequently occurring disasters in the Caribbean (*Farrell et al*., 2010). If a severe storm or other natural disaster strikes hurricane-prone Dominican Republic, an entire water system could be destroyed. Without diversified water sources and robust infrastructure, communities in the Dominican Republic could be left without reliable water for months.

Sea level rise, warmer weather, and more frequent flooding are global climate change symptoms that are affecting the Dominican Republic, and it is prone to a variety of natural disasters including hurricanes, earthquakes, floods, and landslides (*USAID*, 2013). USAID/Dominican Republic has initiated a plan to integrate climate change information and increase adoption of adaptation measures in Santo Domingo and Santiago (the two most populous cities in the Dominican Republic), as well as the fast-growing coastal tourist towns of Samaná-Las Terrenas and Bayahibe. The goals of this initiative were to increase resilience of these communities to the impacts of climate change with a focus on water source protection and disaster risk reduction. The initiative aligns with the priorities of the Government of the Dominican Republic. The Dominican Republic's National Development Strategy emphasizes "a sustainable society that protects the environment and natural resources, and promotes climate change adaptation" as a high-level objective (*USAID*, 2013). Despite these objectives and efforts, the majority of communities throughout the country, especially those located in rural and periurban areas, were not reached. Climate change information generated at the Caribbean regional and national levels does not flow to local community governments outside large cities, and the climate data is often not appropriate or understandable (*USAID,* 2013). In addition, while water is a major focus of the strategy, details for community integration of climate data into water system design has not yet been provided. The proposed CCCS seeks to address this need to support small communities to incorporate climate change as a design parameter for their water infrastructure.

Climate change planning and adaptation strategies have been established for several large metropolitan areas in developed countries, and a range of cities have begun to modify water systems (*Revi et al.*, 2014). Notable adaptation efforts exist in the United States (*Rosenzweig et al.*, 2010), Australia (*Hamin and Gurran*, 2008 and *Revi et al.*, 2014), Canada (*Revi et al.*, 2014), and the United Kingdom (*Rosenzweig et al.*, 2010). However, small developing communities often lack the technical and economic resources needed to develop such plans. This study had the objective to develop a regional community climate change strategy (CCCS) that could provide an innovative approach to design water systems at a community level that not only considers economic feasibility and environmental impact, but also impacts of climate change. The CCCS compiles and applies region-specific climate and water data to a decision matrix to select the most appropriate water treatment technologies and water source for communities. The CCCS is innovative in that this type of design and decision-making has never before been applied to small developing communities. The CCCS will be essential for communities to make fact-based decisions regarding their water supply, switch their sources, and improve their adaptability to climate change.

In the CCCS, "no-regrets" and "low-regrets" decision-making is applied to water system design for small, rural or peri-urban communities. "No-regrets" and "low-regrets" options include robust designs for climate change uncertainty (*Global Water Partnership Caribbean (GWP-C) and Caribbean Community Climate Change Centre (CCCCC)*, 2014). "No-regret" strategies are those that would generate net social and/or economic benefits irrespective of whether or not climate change occurs (*Elliot et al*., 2011). "Low-regret" adaptation strategies are those where moderate levels of investment increase the capacity to cope with future climate risks (*Caribbean Community Climate Change Centre*, 2012). Adaptations that address resilience to extreme weather events, contamination of drinking water supplies, and water resource diversification and conservation will yield social, economic, and health benefits in almost any climate scenario (*Elliot et al.*, 2011). In the CCCS, adaptations were identified and prioritized by (1) understanding and scoring risk of climate variables by geographic location; (2) mapping pathways to identify potential adaptation solutions and ease of implementation (financial, resource, and technical capacity); and (3) including economic and impact parameters to prioritize potential adaptations through use of a matrix.

The Dominican Republic is one of the ten most vulnerable countries in the world to climate change (*United States Agency for International Development (USAID)*, 2013). As part of this study, a climate-ready potable water system was designed for a developing coastal community in the Dominican Republic with limited resources, unreliable access to electricity, and that is extremely vulnerable to the impacts of climate change. Throughout execution of the first phases of the project process (i.e., project formation, assessment, and alternatives analysis), sections of the CCCS were developed and applied.

The goals of the CCCS align with the Dominican Republic National Action Plan for Climate Change Adaptation, and parameters listed by the government of the Dominican Republic are considered in the decision-making process. The first priority for the Dominican Republic National Action Plan for Climate Change Adaptation is water resources. Some means of adaptation included in the plan are: increased storage capacity; water conservation and reuse; desalination; management of water-related risks; and collaboration with other sectors (*Secretaría de Estado de Medio Ambiente y Recursos Naturales (SEMARENA)*, 2008). Barriers to adaptation are categorized into financial, resource, and technical capacity (*SEMARENA*, 2008). Prioritizing adaptations and addressing these barriers in the CCCS can support community implementation of appropriate and sustainable climate-ready water systems.

2. Study Area

This case study was conducted in partnership with an elementary school located in Cumayasa, Dominican Republic. From 2011 to 2012, a drinking water treatment system, a water distribution system, and sanitation facilities were implemented at the existing elementary school in Cumayasa. Due to increased enrollment in the school, a new school is under construction to accommodate 1,200 students. In 2015, this project to design and implement a climate-ready potable water system at the newly constructed school was formed with our partner institution, Escuela Primaria Kilometro Diez de Cumayasa.

Cumayasa is a developing coastal community located in the Yuma region of the Dominican Republic (*Oficina Nacional de Estadística*, 2016), vulnerable to the impacts of climate change, sea level rise, and hurricanes. Cumayasa is a municipal district inside the province of La Romana (*Oficina Nacional de Estadística*, 2008). Its geographic coordinates are 18º 35' North latitude and 68º 58' West longitude (*Oficina Nacional de Estadística*, 2016). According to the 2010 National Population Census, the municipal district of Cumayasa had a population of 11,963 (*Oficina Nacional de Estadística*, 2016) and a population density of 758 people per square kilometer (*Oficina Nacional de Estadística*, 2016); however through discussions with local government officials in 2016 it was indicated that this number does not accurately account for the majority of children living in Cumayasa.

Approximately 1,565,000 inhabitants (37.4 percent) in the Dominican Republic lack access to reliable potable water (*USAID*, 2006), and the drinking water sector is vulnerable to the impacts of climate change (*Dominican Republic's Intended Nationally Determined Contribution (INDC-DR),* 2015). As climate change brings heavier rains and more prolonged dry spells, current deficiencies in water supply will be more evident (*USAID*, 2013). Reduced precipitation (*Caribbean Community Climate Change Centre*, 2012), increased flooding (*Farrell et al*., 2007), and seawater intrusion from sea level rise (*Karanjac,* 2005) will affect freshwater quality and availability. In addition, climate change is predicted to increase extreme events such as precipitation intensity, hurricanes (*Chu and Clark*, 1999), and droughts (*Farrell et al*., 2010) in the region. According to the Global Climate Risk Index developed by Germanwatch, the Dominican Republic ranked in the top 10 countries most affected by extreme weather events in 1992 to 2011 (*Harmeling and Eckstein*, 2012).

Coastal populations are particularly vulnerable to the impacts of global climate change. The Global Flood Map predicts that a one meter rise in sea level would flood almost 200,000 people in the Dominican Republic, not accounting for the 76 percent population growth expected to occur in coastal provinces between 2010 and 2020 (*USAID*, 2013). The municipal district of Cumayasa is a coastal community near the city of La Romana, Dominican Republic. Cumayasa's proximity to the ocean makes it vulnerable to the many effects of climate change, and a valuable location to study the possible ways to prepare for and adapt to those changes.

As of the 2010 National Population Census, 25.0 percent of households in the municipality received water supply from the public network at the household (*Oficina Nacional de Estadística*, 2016). Other sources of drinking water used throughout the Dominican Republic include community piping, wells, springs, rivers, streams, rainwater, truck tanked water, and bottled water. The public network in Cumayasa extracts groundwater from wells in the Caribbean Coastal Plain. Shown in Figure 1, the

Caribbean Coastal Plain, also known as the Planicie Costera Oriental, is the coastal area from the capital of Santo Domingo to the tourist areas of Bavaró and Punta Cana in the southeast of the Dominican Republic. The study location is marked with a star on the map.

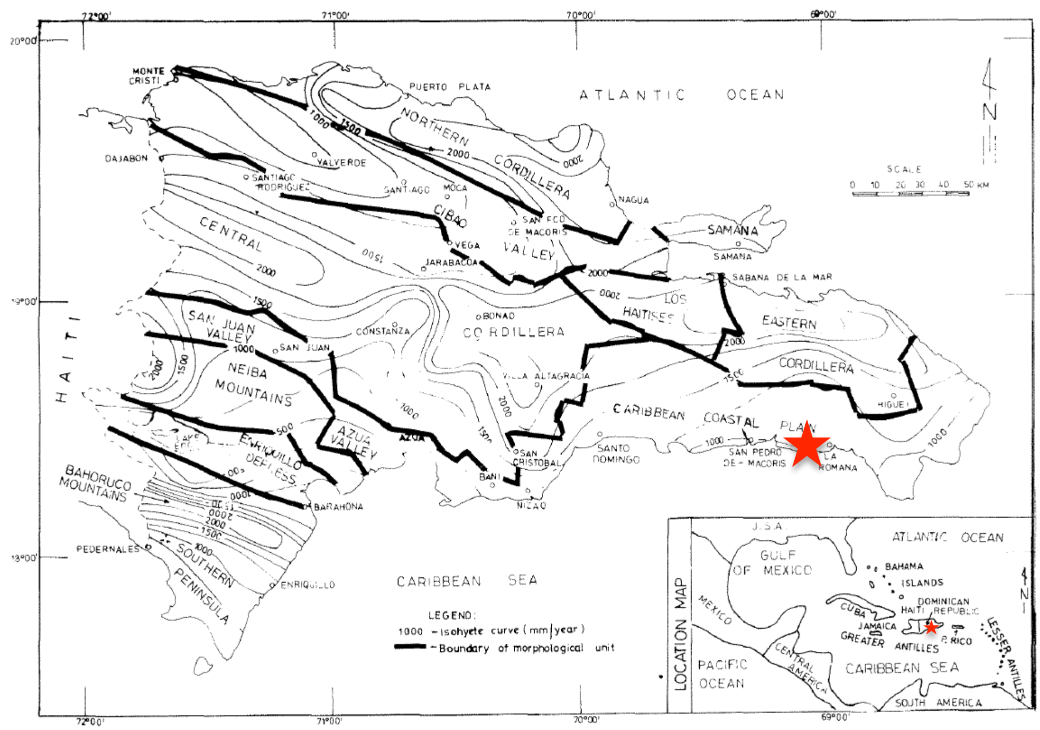

Figure 1 Regions of the Dominican Republic. The Caribbean Coastal Plain is the coastal area from Santo Domingo to Bavaró and Punta Cana in the southeast. The star on the map indicated Cumayasa's location. The location map in the lower right corner shows the Dominican Republic's location within the Caribbean Sea (Reference: Gilboa, 1980).

This region is rapidly growing and its resources are impacted by the demands of the tourism industry. Unplanned tourism development in several coastal communities has depleted underground aquifers and increased seawater intrusion, threatening the stability of the drinking water supply (*USAID*, 2013).

This region belongs to the regional quaternary reefal limestone aquifer (*Gilboa,* 1980). Due to urbanization and population growth in Cumayasa and La Romana, groundwater resources are vulnerable to over-extraction. Deteriorated water quality due to extensive pumping and sea water encroachment has been observed in the highly permeable aquifer near Cumayasa's neighboring city of San Pedro de Macoris (*Gilboa,* 1980). According to the Central Intelligence Agency World Factbook, 79 percent of the total population in the Dominican Republic is urban, with a 2.6 percent annual rate of change (*United States of America Central Intelligence Agency*, 2017). In addition, coastal development in the southern coastal plains where Cumayasa is located is rapidly increasing (*USAID*, 2013). The groundwater aquifer in this region is extremely vulnerable from seawater intrusion due to excessive abstraction and rising sea-levels, as well as contamination by sewage, the sugarcane industry, and tourism (*Karanjac,* 2005).

3. Methodology

The CCCS was designed to be used in all phases of a project's lifecycle. The steps in the project process were modeled after Engineers Without Borders-USA's International Project Process (*Knight*, 2014). Figure 2 shows the general CCCS approach; adaptation actions correspond to each phase of the project process.

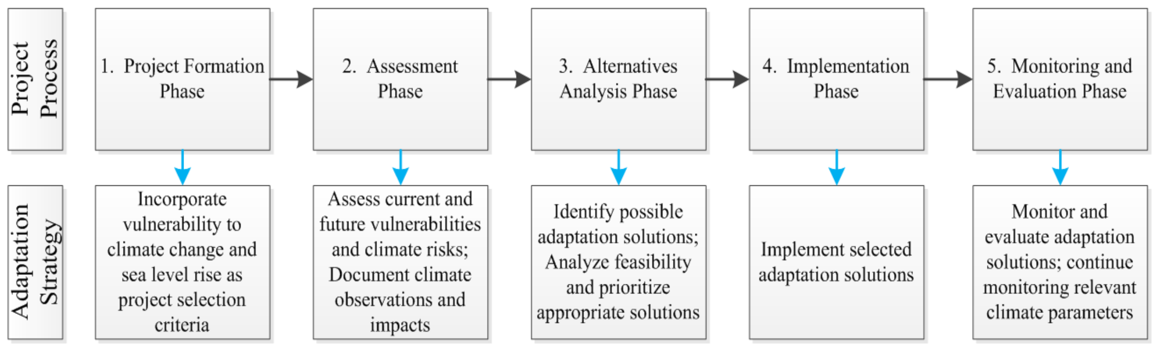

Figure 2 CCCS process for incorporating climate change adaptation solutions into water system designs.

This study focused on the adaptation actions for the first three phases of the project process: project formation phase; assessment phase; and alternatives analysis phase as shown in Figure 3. The implementation phase and monitoring and evaluation phase will be addressed in a follow-on study.

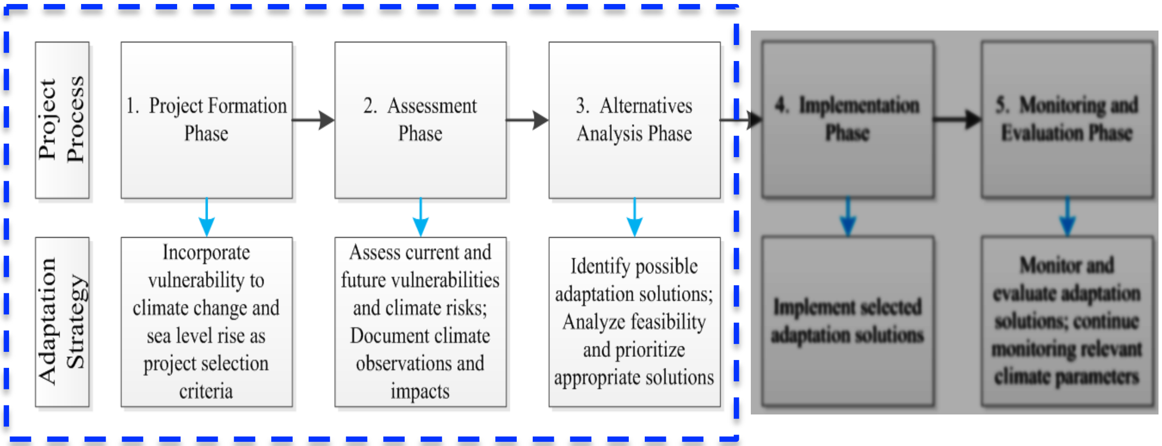

Figure 3 First three phases of the CCCS process. The dashed line demonstrates the boundaries of this study.

The CCCS helps engineers and decision-makers prioritize climate change adaptation solutions by inputting location specific values the into the Climate Adaptation Matrix for Prioritization (CAMP). The two CAMP inputs include the Climate Risk Assessment Value Ratings (CRAVR) and ease of implementation.

The CRAVR inputs were assigned for current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability based on information generated by the AQUEDUCT Water Risk Atlas. This information was summarized in the Current Climate Risks table, and numerical CRAVR values were assigned.

Ease of implementation was determined by mapping pathways between climate hazards (i.e., flood and drought), impacts, design adaptations, and ease of implementing the design adaptations. General Circulation Models (GCMs) and Regional Climate Models (RCMs) were used to identify climate change projections and the generally accepted direction of change for several variables. This data was then entered into the Future Climate Projections and Hazards Table. The generally accepted direction of change (or the climate effect), leads to climate hazards, such as flooding or drought. The pathways between climate hazards and impacts on water systems were mapped. Potential design adaptations were identified. For each potential design adaptation, an ease of implementation score was identified. Ease of implementation for each design adaptation was scored based on several community-specific criteria, such as financial and technical capacity, preferences, and reliance on external entities.

In the CAMP, the CRAVR inputs range from 1 (EXTREMELY HIGH risk hazard) to 5 (LOW risk hazard), and the ease of implementation inputs range from 1 (HIGH ease of implementation/easiest) to 3 (LOW ease of implementation/most difficult). The CAMP was populated with identification numbers for each design adaptation determined by inputting the CRAVR and ease of implementation values. Adaptation solutions in red were considered "high priority." Adaptation solutions in orange were considered "medium priority." Adaptation solutions in yellow were considered "low priority." High priority adaptation solutions were incorporated into the design. Medium and low priority adaptation solutions will be considered if financial and technical resources are available at later phases in the project.

3.1. Project Formation Phase

Different organizations (e.g., community-based, non-governmental, and governmental) have unique criteria for selecting locations for water projects. The CCCS provides basic, high-level guidance for including climate change and sea level rise vulnerability as a potential selection criteria. From a global perspective, vulnerability rankings of 100 countries were provided in Yohe et al. (2006). The table was divided into lowest, middle, and highest thirds based on the Vulnerability-Resilience Indicator Model (VRIM) estimates of vulnerability. The VRIM used the geometric mean of various measures of sensitivity and adaptive capacity to identify a vulnerability index. In addition, a series of maps showing the geographical distribution of combined national indices of exposure and sensitivity were provided (*Yohe et al*., 2006). Impacts and vulnerabilities to climate change vary by region. Regional impacts, sectoral vulnerabilities, and adaptive capacity for Africa, Asia, Latin America, and SIDS are summarized by the United Nations Framework Convention on Climate Change (*United Nations Framework Convention on Climate Change*).

The VRIM and United Nations Framework Convention on Climate Change were used to understand general climate-related vulnerabilities and impacts for the Caribbean. Summaries from the VRIM and United Nations Framework Convention on Climate Change were inputs for the CCCS and were used to understand general impacts and challenges facing different regions. This information was then applied as a criteria for project selection.

3.2. Assessment Phase

Using the CCCS, climate change adaptations were incorporated into the assessment phase of the water project by: (1) identifying current climate risks and vulnerabilities; (2) documenting community observations associated with climate events; and (3) identifying future climate risks and vulnerabilities.

3.2.1. Current Climate Risks

To identify the impacts of climate change and sea level rise on the available water sources and technologies, current risk was examined. The World Resources Institute's

AQUEDUCT Water Risk Atlas was used to analyze current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability based on geographic coordinates. Figure 4 shows an example of the AQUEDUCT Water Risk Atlas map for flood occurrence in the Dominican Republic.

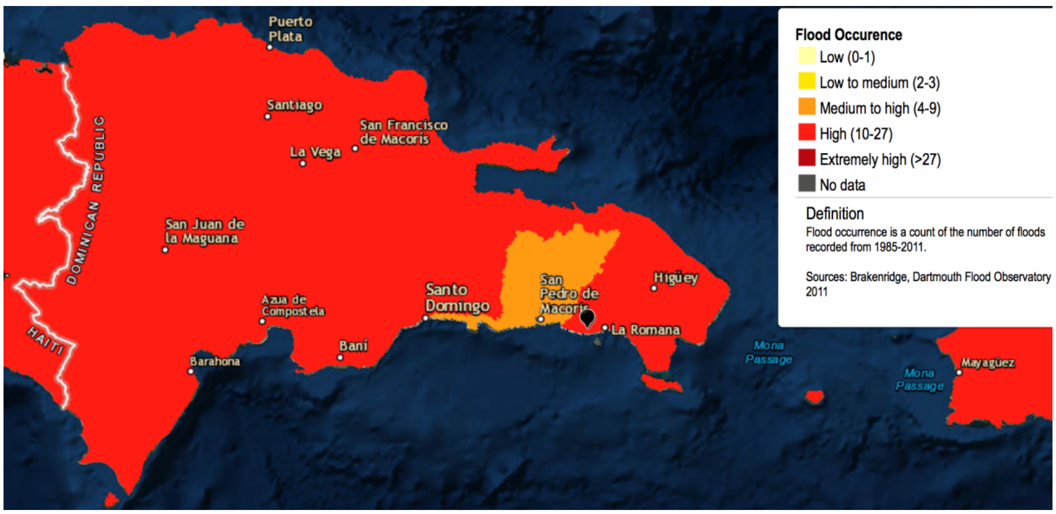

Figure 4 AQUEDUCT Water Risk Atlas map of the current flood risk in the Dominican Republic based on historical flood occurrence.

The AQUEDUCT Water Risk Atlas map was used to identify current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability for the project location. This information was used as an input to the Current Climate Risks table. Table 1 provides an example of the Current Climate Risks table without location-specific data. The boxed column demonstrates the location where AQUEDUCT Water Risk Atlas map data was entered. Definitions, data sources, and references for each variable were provided.

Table 1 Current Climate Risks Example Table

	Variable	Value for Cumayasa (CCCS Input)[1]	Definition	Data Source(s)	Reference
CURRENT CLIMATE RISKS	Flood		Number of recorded flood events from 1985-2011	Brakenridge, Dartmouth Flood Observatory, 2011	WRI Aqueduct, 2014
	Drought		Drought is defined as a continuous period where soil moisture remains below the 20th percentile, length is measured in months, and dryness is the number of percentage points below the 20th percentile.	Sheffield and Wood, 2007	WRI Aqueduct, 2014
	Baseline Water Stress		Baseline water stress is defined by ratio of total annual water withdrawals to total available annual renewable supply, accounting for upstream consumptive use	FAO AQUASTAT, 2008-2012; NASA GLDAS-2, 2012; Shiklomanov and Rodda, 2004; Flörke et al., 2012; Matsutomi et al., 2009	WRI Aqueduct, 2014
	Inter-annual Variability		Inter-annual variability is defined by a variation of in water supply from year-to-year	NASA GLDAS-2, 2012	WRI Aqueduct, 2014
	Seasonal Variability		Seasonal variability is defined by a variation in water supply between months of the year	NASA GLDAS-2, 2012	WRI Aqueduct, 2014

NOTES
1. Range of values include: low, low to medium, medium to high, high, and extremely high

Figure 5 demonstrates how the data obtained from the AQUEDUCT Water Risk Atlas map fits into the Current Climate Risks table.

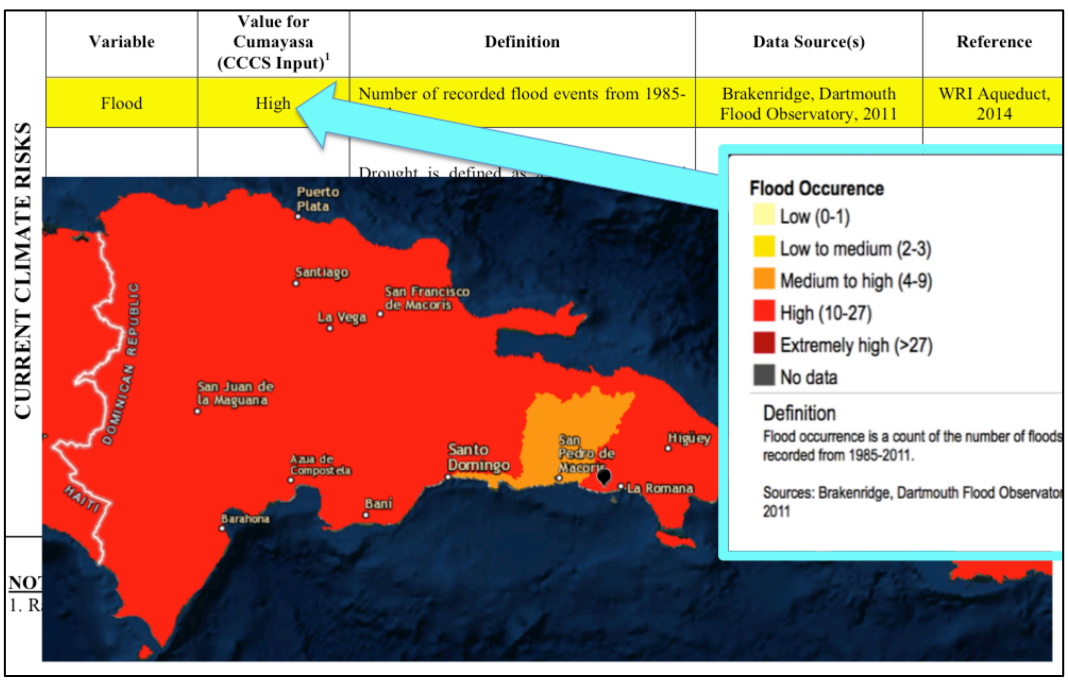

Figure 5 Example of entering AQUEDUCT Water Risk Atlas map data into the Current Climate Risks table.

In addition, a literature review of surrounding communities was conducted to provide a more holistic understanding of potential issues in the area. Understanding climate change patterns based on historical occurrences and current data was critical for applying "no-regret" and "low-regret" adaptation strategies to benefit current and potential future climate conditions. These climate risks were given CRAVR values (*See Table 6 in Section 3.3.1*), which were used for prioritizing adaptation solutions during the alternatives analysis phase of the project.

3.2.2. Climate Observations and Community Perceptions

During the assessment phase, community observations of recent and historical climate events were noted. Impacts on water infrastructure from extreme weather events were identified. An assessment to determine the impacts of recent extreme events (i.e., Hurricane Maria and Hurricane Irma) on water systems was conducted.

Surveys were conducted at sixty households in Cumayasa to understand the community's perception of climate change and water quality. Meetings were held with community leaders and project partners to discuss their awareness of climate change impacts and adaptation. This information was gathered to support dissemination of appropriate and understandable data, tools, and the CCCS education plan.

3.2.3. Future Climate Risks

Climate change and sea level rise will impact water resources at global, regional, and local levels. GCMs indicate changes in temperature, precipitation, severe storms (e.g., hurricanes), and sea level rise. GCM projections of future climate can indicate potential impacts on water resources and should be considered when planning for water infrastructure. Future climate projections were used to identify which climate hazards were relevant to the case study location, and which pathways needed to be mapped.

Regional hydrological and precipitation characteristics can dictate which water sources and technologies are most resilient to climate change and sea level rise for a specific location. Rainfall and climatic models can be used to determine which water technologies are most appropriate in different regions.

Climate change and weather variability will impact different water sources and technologies. Common water sources and technologies impacted across the world include springs, boreholes, dug wells, rainwater collection, treatment systems, piped distribution systems, and bottled water. Each poses unique challenges under changing climatic conditions. By understanding predicted climatic changes for each region and the challenges associated with different water technologies, appropriate solutions can be implemented now.

The CARIBSAVE Climate Change Risk Atlas (*Caribbean Community Climate Change Centre*, 2012) and reviewed literature were used to summarize climate change projections. The initial version of the CCCS focused on the Caribbean region, however other regions can later be integrated.

Climate variables considered for this study include sea level rise, precipitation, temperature, sea surface temperature (SST), and tropical storms and hurricanes. Climate change projections for each climate variable were examined and included in the Future Climate Projections and Hazards table. An unpopulated example of this table is provided in Table 2.

Table 2 Future Climate Projections and Hazards Example Table

	Climate Variable	Value for Cumayasa (CCCS Input)	Generally Accepted Direction of Change	Climate Hazard(s)	Data Source(s)
FUTURE CLIMATE PROJECTIONS	Global Mean Sea Level (GMSL) rise		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	21 Coupled Model Intercomparison Project phase 5 (CMIP5) Atmosphere–Ocean General Circulation Models (AOGCMs)[4]
	Precipitation		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	GCM; RCM projections driven by HadCM3[5]
	Mean Annual Temperature		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	GCM projections from a 15-model ensemble; RCM projections from ECHAM4 and HadCM3[5]
	SST		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	GCM projections[5]
	Tropical cyclones		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	Coupled Model Intercomparison Project Phase 3 (CMIP3) and CMIP5 multi-model ensembles[6]

<u>NOTES (*Pertains to Table 2*):</u>
1. For the period 2081-2100 compared to 1986-2005
2. By the 2080s
3. By the 2080s relative to the 1970 - 1999 mean
4. Reference: *Church et al*., 2013
5. Reference: *Caribbean Community Climate Change Centre*, 2012
6. Reference: *Chu and Clark*, 1999; *Lighthill et al.*, 1994; *Knutsen et al*., 2008; *Deo et al*., 2011; *Christensen et al.*, 2013; *Charles et al*., 2010

Summaries of climate change projections are based on the Caribbean Community Climate Change Centre's derivation from observed climate data sources and climate model projections using a GCM ensemble of 15 models and the RCM, *PRECIS,* as well as reviewed literature. RCM simulations from *PRECIS* are driven by models ECHAM4 and HadCM3 (*Caribbean Community Climate Change Centre*, 2012). The information obtained from these data sources were entered into the Future Climate Projections and Hazards Table for the project location, as shown in Table 3.

Table 3 Demonstration of Data Source Entry into Future Climate Projections and Hazards Table for Project Location

FUTURE CLIMATE PROJECTIONS	Climate Variable	Value for Cumayasa (CCCS Input)	Generally Accepted Direction of Change	Climate Hazard(s)	Data Source(s)
	Global Mean Sea Level (GMSL) rise		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	21 Coupled Model Intercomparison Project phase 5 (CMIP5) Atmosphere–Ocean General Circulation Models (AOGCMs)[4]
	Precipitation		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	GCM; RCM projections driven by HadCM3[5]
	Mean Annual Temperature		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	GCM projections from a 15-model ensemble; RCM projections from ECHAM4 and HadCM3[5]
	SST		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	GCM projections[5]
	Tropical cyclones		Increasing/ Decreasing/ No Change	Flooding and/or Drought and/or Seawater intrusion	Coupled Model Intercomparison Project Phase 3 (CMIP3) and CMIP5 multi-model ensembles[6]

Once the value for the project location is analyzed, the generally accepted direction of change is entered into the Future Climate Projections and Hazards Table as shown in Table 4.

Table 4 Example of Future Climate Projections for Project Location and Generally Accepted Direction of Change Being Entered into Future Climate Projections and Hazards Table

	Climate Variable	Value for Cumayasa (CCCS Input)	Generally Accepted Direction of Change	Climate Hazard(s)	Data Source(s)
FUTURE CLIMATE PROJECTIONS	Global Mean Sea Level (GMSL) rise	Projected GMSL rise for RCP2.6 is 0.26 to 0.55 m; RCP4.5 is 0.32 to 0.63 m; RCP6.0 is 0.33 to 0.63 m; and RCP8.5 is 0.45 to 0.82 m.[1] Observations from tidal gauges surrounding the Caribbean basin indicate that sea level rise trends in the Caribbean are relatively consistent with GMSL trends.[5]	Increasing	Flooding and Seawater intrusion	21 Coupled Model Intercomparison Project phase 5 (CMIP5) Atmosphere–Ocean General Circulation Models (AOGCMs)[4]
	Precipitation	GCM projections range from -42 to +7 mm per month (-69% to +19%) for low, medium high, and high emissions scenarios. RCM projections indicated large decreases in rainfall in March, April, May (MAM) (-24%); June, July, August (JJA) (-51%); and September, October, November (SON) (-40%); resulting in a large decrease in total annual rainfall (-27 mm or -30%) under a high emissions scenario.[2]	Decreasing	Drought	GCM; RCM projections driven by HadCM3[5]
	Mean Annual Temperature	GCM projections indicate that temperature in the Dominican Republic will increase by 0.9℃ to 3.0℃, ranging around 1 - 1.5℃ for any emissions scenario[3]. RCM projections indicate that temperature will increase 3.4℃ and 3.1℃ in mean annual temperatures in high emissions scenarios[2].	Increasing	Drought	GCM projections from a 15-model ensemble; RCM projections from ECHAM4 and HadCM3[5]
	SST	GCM projections indicate SSTs will increase between +0.7˚C and +2.7˚C across low, medium high, and high emissions scenarios, ranging around 1 - 1.5℃ for any emissions scenario[2].	Increasing	Flooding	GCM projections[5]
	Tropical cyclones	As the SST become warmer, certain tropical ocean basins may be faced with an increased number of and/or more intense tropical cyclones; Likely increase in both global mean tropical cyclone maximum wind speed and precipitation rates.	Increasing (intensity)	Flooding	Coupled Model Intercomparison Project Phase 3 (CMIP3) and CMIP5 multi-model ensembles[6]

This generally accepted direction of change (or the climate effect), leads to climate hazards, such as flooding, drought, or seawater intrusion. For example, "increasing" precipitation intensity associated with tropical cyclones will result in a flooding hazard. This is the last column to be populated in the Future Climate Projections and Hazards Table as shown in Table 5.

Table 5 Example of Climate Hazard(s) Being Entered into Future Climate Projections and Hazards Table

	Climate Variable	Value for Cumayasa (CCCS Input)	Generally Accepted Direction of Change	Climate Hazard(s)	Data Source(s)
FUTURE CLIMATE PROJECTIONS	Global Mean Sea Level (GMSL) rise	Projected GMSL rise for RCP2.6 is 0.26 to 0.55 m; RCP4.5 is 0.32 to 0.63 m; RCP6.0 is 0.33 to 0.63 m; and RCP8.5 is 0.45 to 0.82 m.[1] Observations from tidal gauges surrounding the Caribbean basin indicate that sea level rise trends in the Caribbean are relatively consistent with GMSL trends.[5]	Increasing	Flooding and Seawater intrusion	21 Coupled Model Intercomparison Project phase 5 (CMIP5) Atmosphere–Ocean General Circulation Models (AOGCMs)[4]
	Precipitation	GCM projections range from -42 to +7 mm per month (-69% to +19%) for low, medium high, and high emissions scenarios. RCM projections indicated large decreases in rainfall in March, April, May (MAM) (-24%); June, July, August (JJA) (-51%); and September, October, November (SON) (-40%); resulting in a large decrease in total annual rainfall (-27 mm or -30%) under a high emissions scenario.[2]	Decreasing	Drought	GCM; RCM projections driven by HadCM3[5]
	Mean Annual Temperature	GCM projections indicate that temperature in the Dominican Republic will increase by 0.9℃ to 3.0℃, ranging around 1 - 1.5℃ for any emissions scenario[3]. RCM projections indicate that temperature will increase 3.4℃ and 3.1℃ in mean annual temperatures in high emissions scenarios[2].	Increasing	Drought	GCM projections from a 15-model ensemble; RCM projections from ECHAM4 and HadCM3[5]
	SST	GCM projections indicate SSTs will increase between +0.7°C and +2.7°C across low, medium high, and high emissions scenarios, ranging around 1 - 1.5℃ for any emissions scenario[2].	Increasing	Flooding	GCM projections[5]
	Tropical cyclones	As the SST become warmer, certain tropical ocean basins may be faced with an increased number of and/or more intense tropical cyclones; Likely increase in both global mean tropical cyclone maximum wind speed and precipitation rates.	Increasing (intensity)	Flooding	Coupled Model Intercomparison Project Phase 3 (CMIP3) and CMIP5 multi-model ensembles[6]

3.3. Alternatives Analysis Phase

The alternatives analysis phase of the water project identified and compared potential solutions to determine the most appropriate design. Climate change adaptation was incorporated into this phase of the CCCS by: (1) rating climate risk; (2) mapping pathways between climate hazards (i.e., flood and drought), impacts, and design adaptations; and (3) prioritizing appropriate solutions to select which adaptations should be incorporated in the final design.

3.3.1. Rating Climate Risk

The CRAVR system was used to score risk of climate variables by geographic location. The AQUEDUCT Water Risk Atlas was used to assign risks of current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability based on geographic coordinates. A corresponding CRAVR index was assigned. As shown in Table 6, CRAVR 1 denotes EXTREMELY HIGH risk hazard; CRAVR 2 denotes HIGH risk hazard; CRAVR 3 denotes MEDIUM TO HIGH risk hazard; CRAVR 4 denotes LOW TO MEDIUM risk hazard; and CRAVR 5 denotes LOW risk hazard. While all identified risks should be considered when designing water systems in climate vulnerable locations, prioritizing the highest risks can help make "no-regret" or "low-regret" solutions affordable and maintainable for communities.

Table 6 Current Risk (Corresponding with AQUEDUCT Water Risk Atlas) and Assigned CRAVR

CURRENT RISK	CRAVR
EXTREMELY HIGH	1
HIGH	2
MEDIUM TO HIGH	3
LOW TO MEDIUM	4
LOW	5

Rankings from the CRAVR system are CCCS inputs, and help prioritize climate adaptations (*See Section 3.3.3*).

3.3.2. Mapping Pathways for Climate Hazards

To identify the most appropriate adaptations for community water systems, pathways between climate hazards (i.e., flood and drought), primary and secondary impacts, and design adaptations were mapped. In addition, ease of implementation for each design adaptation was included in the pathway. To design a climate-ready water system, "no-regret" and "low-regret" decision-making was applied. Therefore, community investment (e.g., financial and resource contributions) was considered in the "ease of implementation" category.

Climate change and sea level rise impacts, design adaptations, and ease of implementation were identified for the project location. Adaptation solutions were incorporated into designs to address these impacts. Multiple alternatives were available and appropriate for the community, therefore understanding the impacts and available adaptation solutions assisted in selecting the best alternatives.

Changes in temperature, precipitation, extreme weather events, water salinity, and storm surges due to climate change and sea level rise will impact water quality. Microbial, nutrient, and chemical contaminants can become mobilized due to precipitation events, extreme weather events, and storm surges. These microbes, nutrients, and chemicals may enter water sources, altering levels of contamination in pretreated water and impacting drinking water quality. In addition, changes to the survival, persistence, and reproduction of microbial agents due to changes in temperature and salinity also alter levels of contamination in pretreated water and impact drinking water quality (*Rose et al*., 2001). Water quality is affected by land use and water resource management and protection. Sources of contamination in water systems include urban and agricultural storm water runoff, industrial runoff and discharges, animal waste, human waste (sewage spills and discharges, boating wastes, untreated sewage), and other wastes.

Climate Hazards, Impacts, and Resilience of Water Systems

Climate hazards are the natural hazards associated with climate variables. Climate hazards driven by changes in sea level, precipitation, temperature, SST, and tropical storms and hurricanes are discussed; including flood, drought, and seawater intrusion. The "flood" category includes several types of flooding and flood-related events, including heavy precipitation, excessive runoff, coastal inundation, coastal erosion, storm surge flooding, sea level rise, and superstorm flooding (combination of two types of flooding events). The "drought" category addresses severe declines in precipitation (short-term), decreases in mean annual precipitation (long-term), and reduced aquifer recharge. Seawater intrusion is also discussed is the "drought" category since one major causal factor of seawater intrusion is reduced recharge.

The impacts of these climate hazards on water supplies and weaknesses of water systems are discussed. Resilience of available water supplies (i.e., groundwater and rainwater) to each climate hazard was identified. Resilience scores obtained from an expert assessment of the resilience of water technologies to climate extremes conducted by Luh et al., 2017 were used to determine the resilience of water technologies to climate-related hazards relative to other technologies.

Pathway Example

The pathways between climate hazards and impacts on water systems were mapped. Potential design adaptations were identified. For each potential design adaptation, an ease of implementation score was identified. An example of the pathway mapping is shown in Figure 6.

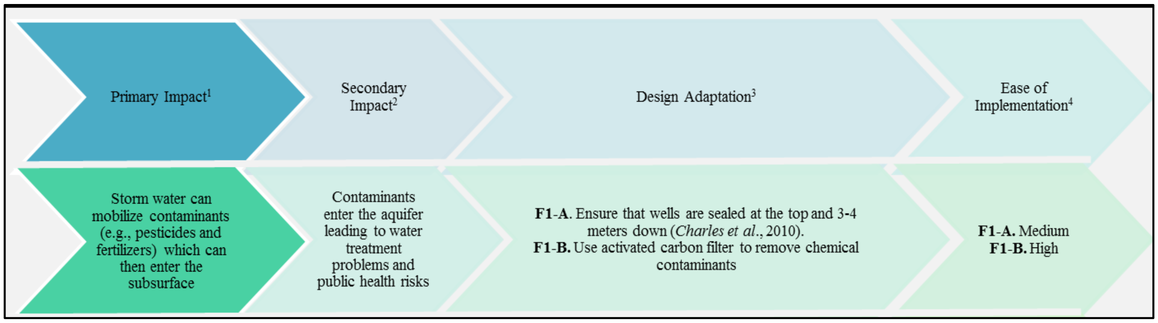

Figure 6 Example of pathway mapping. Impacts of the climate hazard on water system, potential design adaptations, and ease implementation is identified.

Primary impact is the immediate consequence of the combination of the hazard and vulnerability on the water system under consideration. Secondary impact is the result of the primary impact on another system, such as physical assets or the provision of water related services (*GWP-C and CCCCC*, 2014).

Applicable design adaptations were identified through literature review. Each design adaptation was assigned a unique identification number. "F" indicates the design adaptation corresponds with a flood-related hazard. "D" indicates the design adaptation corresponds with a drought-related hazard. Numbers were assigned for each impact. Letters were assigned to identify design adaptations associated with that impact.

Ease of implementation was scored high, medium, or low based on community-specific preferences and limitations. The method for performing this task included field assessments and discussions with stakeholders. Table 7 provides definitions for high, medium, and low ease of implementation scores.

Table 7 Ease of Implementation Ranking Definitions

Ease of implementation	Definition
HIGH	Can be implemented, operated, and maintained (both financially and technically) by stakeholders
MEDIUM	Municipal-level design adaptations (i.e., limited level of stakeholder influence on the municipal water infrastructure)
LOW	Design adaptations requiring large financial or technical support, or those under the cognizance of external entities

3.3.3. Prioritizing Adaptation Solutions

Adaptations were prioritized by inputting values from the CRAVR and ease of implementation into the CAMP, as demonstrated in Tables 8 and 9.

Table 8 Demonstration of Entering CRAVR into CAMP

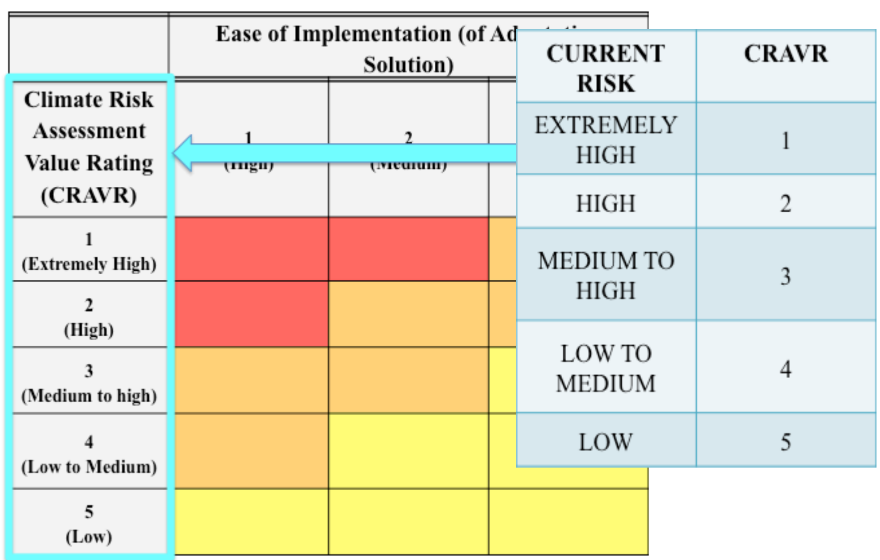

Table 9 Demonstration of Entering Ease of Implementation into CAMP

	Ease of Implementation (of Adaptation Solution)		
Climate Risk Assessment Value Rating (CRAVR)	1 (High)	2 (Medium)	3 (Low)
1 (Extremely High)			
2 (High)			
3 (Medium to			
4 (Low to Me			
5 (Low)			

Ease of implementation	Definition
HIGH	Can be implemented, operated, and maintained (both financially and technically) by stakeholders
MEDIUM	Municipal-level design adaptations (i.e., limited level of stakeholder influence on the municipal water infrastructure)
LOW	Design adaptations requiring large financial or technical support, or those under the cognizance of external entities

Adaptation solutions in red were considered "high priority." Adaptation solutions in orange were considered "medium priority." Adaptation solutions in yellow were considered "low priority." Table 10 demonstrates the CAMP structure populated with identification numbers for each design adaptation determined by inputting the CRAVR and ease of implementation values. High priority adaptation solutions were determined using the CAMP and are circled in Table 10.

Table 10 Example of CAMP Structure with High Priority Adaptation Solutions Circled

	Ease of Implementation (of Adaptation Solution)		
Climate Risk Assessment Value Rating (CRAVR)	**1 (High)**	**2 (Medium)**	**3 (Low)**
1 (Extremely High)			
2 (High)	F1-B F2-C F3-A F4-C F4-D F5-A F5-B F5-C	F1-A F2-A F2-B F4-A	F4-B
3 (Medium to high)			
4 (Low to Medium)			
5 (Low)	D1-A D2-B D3-A D3-B		D2-A

4. Applying the CCCS to Design a New Water System for Escuela Primaria Kilometro Diez de Cumayasa

4.1. Project Formation Phase

The project formation phase of this study was conducted from 2015-2016. The Dominican Republic is listed in the lowest third out of 100 countries based on the VRIM (*Yohe et al.,* 2006) and is quite vulnerable to climate change and extreme weather events. Therefore, Cumayasa was determined to be a valuable location to study the possible ways to prepare for and adapt to climate change and sea level rise.

4.2. Assessment Phase

The assessment phase of this study was conducted from 2016-2018. During this timeframe, three site assessments were conducted in Cumayasa. The assessment phase of this project included investigating water quality and quantity problems in Cumayasa through field tests, observations, discussions with community partners, community surveys, and identifying and discussing possible solutions and with the stakeholders.

Prior to conducting a thorough risk assessment on water sources and technologies, an assessment of available alternatives was conducted in the community. Available water sources, water access, distribution, storage technologies, and water treatment technologies were identified through community discussions, field observations, and using satellite imagery. Figure 7 identifies alternatives determined to be appropriate and supported by the stakeholders based on financial, resource, and technical capacity.

Water Sources	Water Access, Distribution, and Storage Technologies	Water Treatment Technologies
• Groundwater • Rainwater	• Borehole • Mechanical pumps • Piped distribution • Underground cistern • Elevated storage tank	• Membrane filtration • Block activated carbon filtration • Chlorine disinfection

Figure 7 Available and appropriate water sources and technologies for Cumayasa based on financial, resource, and technical capacity

4.2.1. Current Climate Risks

The AQUEDUCT Water Risk Atlas map was used to identify current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability for Cumayasa. Figure 8 shows the map for flood occurrence in the Dominican Republic. The majority of the country, including Cumayasa, has high flood occurrence.

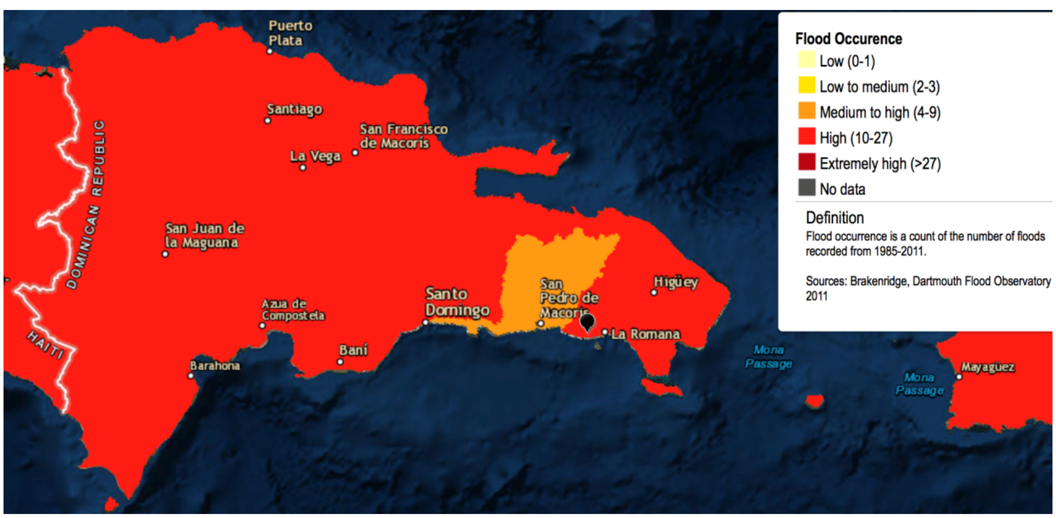

Figure 8 AQUEDUCT Water Risk Atlas map of the current flood risk in the Dominican Republic based on historical flood occurrence. Flood risk is high for Cumayasa.

Current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability for Cumayasa are provided in Table 11.

Table 11 Current Climate Risks for Cumayasa

	Variable	Value for Cumayasa (CCCS Input)[1]	Definition	Data Source(s)	Reference
CURRENT CLIMATE RISKS	Flood	High	High flood occurrence is defined by 10-27 recorded flood events from 1985-2011	Brakenridge, Dartmouth Flood Observatory, 2011	WRI Aqueduct, 2014
	Drought	Low	Drought is defined as a continuous period where soil moisture remains below the 20th percentile, length is measured in months, and dryness is the number of percentage points below the 20th percentile. Low drought severity estimates the average of the length times the dryness of droughts from 1901 to 2008 is less than 20 .	Sheffield and Wood, 2007	WRI Aqueduct, 2014
	Baseline Water Stress	Low to medium	Low to medium baseline water stress is defined by 10-20% ratio of total annual water withdrawals to total available annual renewable supply, accounting for upstream consumptive use	FAO AQUASTAT, 2008-2012; NASA GLDAS-2, 2012; Shiklomanov and Rodda, 2004; Flörke et al., 2012; Matsutomi et al., 2009	WRI Aqueduct, 2014
	Inter-annual Variab-ility	Medium to high	Medium to high inter-annual variability is defined by a variation of 0.5-0.75 in water supply from year-to-year	NASA GLDAS-2, 2012	WRI Aqueduct, 2014
	Seasonal Variab-ility	Low to medium	Low to medium seasonal variability is defined by a variation of 0.33-0.66 in water supply between months of the year	NASA GLDAS-2, 2012	WRI Aqueduct, 2014

NOTES (*Pertains to Table 11)*

1. Range of values include: low, low to medium, medium to high, high, and extremely high

A literature review of surrounding communities was conducted to provide a more holistic understanding of potential issues in the area. Seawater intrusion has already been detected in the quaternary reefal limestone aquifer in the Caribbean Coastal Plain (*Gilboa,* 1980). Dotted areas on the map in Figure 9 show the extension of seawater intrusion. Diagonal lines demonstrate karstic nature of the limestone aquifer.

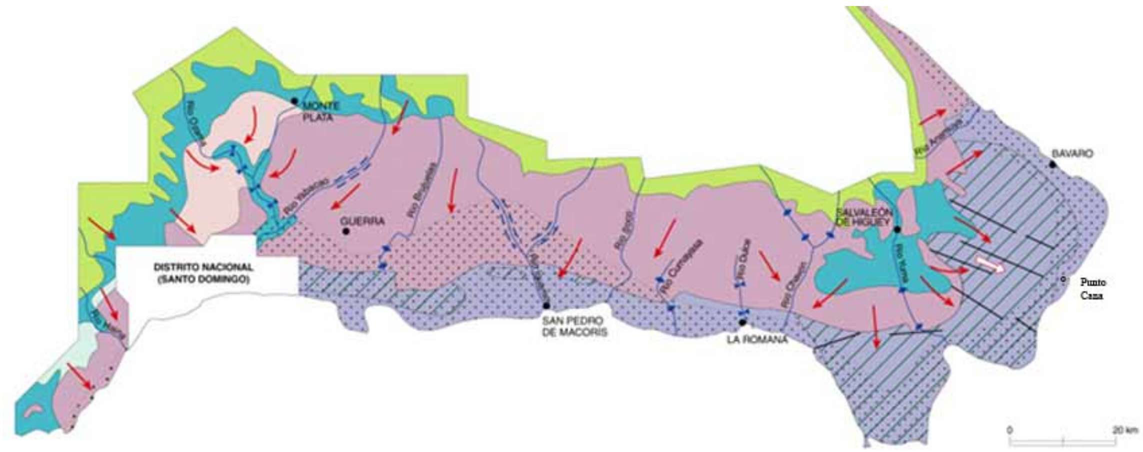

Figure 9 Hydrogeologic features of the Caribbean Coastal Plain. Dotted areas show the extension of seawater intrusion. Dashed lines identify the areas of intensive karstification. (Reference: *Gilboa,* 1980)

Deteriorated water quality due to extensive pumping and sea water encroachment has been observed in the highly permeable aquifer near San Pedro de Macoris (*Gilboa,* 1980). A large portion of drinking water in the Caribbean Coastal Plain is extracted from groundwater wells. The reefal limestone aquifer is recharged by rainfall, percolation from rivers and canals, and irrigation losses. The Caribbean Coastal Plain is a sandy area where rainwater soaks into the ground where it floats on top of seawater that rises and falls with the tide. This freshwater layer is becoming thinner as the water levels are declining from groundwater being overextracted, causing the aquifer to be more susceptible to seawater contamination as sea level rises. In addition, recharge rates are dependent on rainfall, and therefore the impacts of climate change on precipitation frequency and intensity make the aquifer even more vulnerable (*World Bank*, 2014).

4.2.2. Climate Observations and Community Perceptions

Observed climate impacts, such as hurricane-related flooding causing failure of electricity-powered water pumps, were taken into consideration when mapping pathways between climate hazards and impacts on water systems. Also during the assessment in Cumayasa, a few community members on private groundwater wells indicated "salty-tasting" water, indicating the need for further analysis and monitoring of groundwater in Cumayasa.

4.2.3. Future Climate Risks

For the Caribbean region, climate variables considered include sea level rise, precipitation, temperature, SST, and tropical storms and hurricanes. Broad trends for the Caribbean based on climate model projections include: warmer temperatures, reduced rainfall, increased storm intensity, and higher sea levels (*Global Water Partnership Caribbean (GWP-C and CCCCC*, 2014). In addition, inter-annual variability and hurricane occurrence in the Caribbean are strongly influenced by the El Niño Southern Oscillation (ENSO) (*McSweeney et al.*, 2010). A study by the World Bank states that if the sea continues to rise at the current rate, Santo Domingo, the capital of the Dominican Republic, will be one on the five cities most affected at a global level by climate change in 2050 (*World Bank*, 2014). Climate change projections for each climate variable were examined for the Dominican Republic and included in Table 12.

Table 12 Future Climate Projections and Associated Climate Hazards for Cumayasa

FUTURE CLIMATE PROJECTIONS	Climate Variable	Value for Cumayasa (CCCS Input)	Generally Accepted Direction of Change	Climate Hazard(s)	Data Source(s)
	Global Mean Sea Level (GMSL) rise	Projected GMSL rise for RCP2.6 is 0.26 to 0.55 m; RCP4.5 is 0.32 to 0.63 m; RCP6.0 is 0.33 to 0.63 m; and RCP8.5 is 0.45 to 0.82 m.[1] Observations from tidal gauges surrounding the Caribbean basin indicate that sea level rise trends in the Caribbean are relatively consistent with GMSL trends.[5]	Increasing	Flooding and Seawater intrusion	21 Coupled Model Intercomparison Project phase 5 (CMIP5) Atmosphere–Ocean General Circulation Models (AOGCMs)[4]
	Precipitation	GCM projections range from -42 to +7 mm per month (-69% to +19%) for low, medium high, and high emissions scenarios. RCM projections indicated large decreases in rainfall in March, April, May (MAM) (-24%); June, July, August (JJA) (-51%); and September, October, November (SON) (-40%); resulting in a large decrease in total annual rainfall (-27 mm or -30%) under a high emissions scenario.[2]	Decreasing	Drought	GCM; RCM projections driven by HadCM3[5]
	Mean Annual Temperature	GCM projections indicate that temperature in the Dominican Republic will increase by 0.9℃ to 3.0℃, ranging around 1 - 1.5℃ for any emissions scenario[3]. RCM projections indicate that temperature will increase 3.4℃ and 3.1℃ in mean annual temperatures in high emissions scenarios[2].	Increasing	Drought	GCM projections from a 15-model ensemble; RCM projections from ECHAM4 and HadCM3[5]
	Sea Surface Temperature	GCM projections indicate SSTs will increase between +0.7˚C and +2.7˚C across low, medium high, and high emissions scenarios, ranging around 1 - 1.5℃ for any emissions scenario[2].	Increasing	Flooding	GCM projections[5]
	Tropical cyclones	As the SST become warmer, certain tropical ocean basins may be faced with an increased number of and/or more intense tropical cyclones; Likely increase in both global mean tropical cyclone maximum wind speed and precipitation rates.	Increasing (intensity)	Flooding	Coupled Model Intercomparison Project Phase 3 (CMIP3) and CMIP5 multi-model ensembles[6]

NOTES (*Pertains to Table 12)*:

1. For the period 2081-2100 compared to 1986-2005
2. By the 2080s
3. By the 2080s relative to the 1970 - 1999 mean
4. Reference: *Church et al*., 2013
5. Reference: *Caribbean Community Climate Change Centre*, 2012
6. Reference: *Chu and Clark*, 1999; *Lighthill et al.*, 1994; *Knutsen et al*., 2008; *Deo et al*., 2011; *Christensen et al.*, 2013; *Charles et al*., 2010

4.3. Alternatives Analysis Phase

In the alternatives analysis phase of this project, adaptation solutions to reduce vulnerability of water resources and technologies were evaluated (*Mall et al*., 2006). Climate risk was rated, pathways between climate hazards, impacts, and design adaptations were mapped, and solutions were prioritized for inclusion in the system design.

4.3.1. Rating Climate Risk

The CRAVR system was used to score risk of climate variables for Cumayasa. The AQUEDUCT Water Risk Atlas was used to assign risks of current flood occurrence, drought severity, baseline water stress, and inter-annual and seasonal variability as shown in Table 13.

Table 13 CRAVR for Cumayasa, Dominican Republic

Climate Variable	Current Risk	CRAVR
Current flood occurrence	High	2
Drought severity	Low	5
Baseline water stress	Low to medium	4
Inter-annual variability	Medium to high	3
Seasonal variability	Low to medium	4

Rankings from the CRAVR system are CCCS inputs, and help prioritize climate adaptations (*See Section 4.3.3*).

4.3.2. Mapping Pathways for Climate Hazards

Climate Hazards, Impacts, and Resilience of Water Systems

The Dominican Republic is highly vulnerable to the impacts of climate change. The country is located on the island of Hispaniola in the Caribbean Sea, and is susceptible to hurricanes. Climate change will impact water quality and quantity through changes in sea level rise, precipitation, temperature, SST, and tropical storms and hurricanes. The climate hazards and impacts discussed in this study were selective based on relevance to the case study location.

Flood

Rising sea levels and changes in the intensity of precipitation events, storms, and hurricanes will impact flooding in the Dominican Republic. Intense rainfall associated with storms and hurricanes may result in increased surface water run-off leading to increased flooding. Field observations and numerical modeling studies have shown that increased rainfall intensity results in increased run-off. In addition, sea level rise may lead to flooding of lowlands (*Farrell et al.*, 2007). Storms, hurricanes, and high intensity precipitation may also cause erosion and sediment transport. Floods impact water infrastructure causing water supply contamination, service outage, and damage to infrastructure.

Flooding could result in the water quality degradation of the resource and damaged infrastructure. Storm water can mobilize contaminants (e.g., pesticides, fertilizers, wastes, sediments, nutrients, and pathogens), which can then enter the subsurface, thereby contaminating aquifers (*Farrell et al*., 2007) and underground cisterns, leading to water treatment problems and public health risks (*Global Water Partnership Caribbean (GWP-C and CCCCC,* 2014). Contamination may arise from floodwater entering well heads or underground cisterns, flood levels higher than well head walls, or physical damage to water treatment plants (*Charles et al*., 2010).

Erosion caused by more intense rainfall events and run-off will lead to an increase in suspended solids (turbidity). Increased turbidity can stress water treatment systems by increasing coagulant demand, fouling filters, and increasing the chlorine demand. In addition, waste contamination from both point sources (e.g., damaged wastewater systems and sewage treatment discharge pipes) and nonpoint sources (e.g., microbe-contaminated runoff from farmlands and untreated human waste) can contaminate water supply. Water supply lines can be inundated by floodwater mixed with waste and sewage. Nutrient contamination, higher water temperatures, and longer periods of low flow can promote algal blooms, increased bacteria and fungi content, and re-growth of coliform bacteria in the distribution system (*Charles et al*., 2010). Changes to the survival, persistence, and reproduction of microbial contaminants due to changes in temperature and salinity also alter levels of contamination in pretreated water and impact drinking water quality (*Rose et al*., 2001).

Long term sea level rise and coastal erosion also present a risk to water infrastructure (*GWP-C and CCCCC,* 2014). Physical force and debris from high-velocity flood events can damage water treatment systems and pumping stations. Increased ground movement and changes in groundwater can cause degradation of piping materials. During extreme events, water infrastructure can be washed away. Energy supply may be affected by extreme events damaging infrastructure, or by a lack of water available for power generation or cooling. Due to the reliance on energy for pumping, the impacts on energy infrastructure will also affect water treatment and distribution systems (*Charles et al*., 2010).

Utility managed, untreated, piped groundwater systems were assessed to have a resilience score of 8.4 and 6.1 to flooding and superstorm flooding, respectively. Depending on the proximity to the coast, superstorm flooding may also have a potential long-term salinization of groundwater. Due to its proximity to the coast, it is likely that Cumayasa's piped groundwater system is less resilient to flooding than the global standard provided by Luh et al., 2017. Rainwater systems were found to have a resilience score of 7.4 and 6.5 to flooding and superstorm flooding, respectively. In order for the rainwater system to stop functioning, physical damage to the storage tanks and catchment systems need to occur (*Luh et al.*, 2017).

Drought

Drought from reduced rainfall and higher temperatures is one of the most common climate hazards affecting the Caribbean (*Farrell et al*., 2010). Droughts can be classified into meteorological drought (low precipitation), hydrological drought (low water levels or flow), agricultural drought (low soil moisture), and environmental drought (a combination of the above) (*Charles et al*., 2010). Groundwater recharge is dependent on precipitation and surface run-off. Increased rainfall intensity is expected to lead to increased surface run-off thereby reducing infiltration and potential aquifer charge. In addition, urbanization is expected to further enhance surface runoff. A reduction in annual rainfall and more intense rainstorms resulting in reduced recharge could lead to falling groundwater levels and aquifer depletion. In addition, increasing temperature is expected to increase evapotranspiration rates and reduce soil moisture, thus reducing infiltration and aquifer recharge further (*Farrell et al.,* 2007).

In addition to water scarcity, a deterioration of water quality associated with drought is also expected. Decreased groundwater recharge, combined with overabstraction of groundwater and sea level rise, can result in aquifer salinization due to seawater intrusion. Reduced dilution of pollutants and wastes due to reduced groundwater mixing volumes causes increased pollutant concentrations (*Farrell et al.*, 2010). Drought conditions reduce the capacity for water services to supply sufficient quantity of water and cause a reliance on water trucking and bottled water. Water quality in piped water systems is vulnerable to reduced annual precipitation and drought. When piped distribution systems are empty and unpressurised due to intermittent operation, contaminants enter damaged pipes (*Charles et al*., 2010).

Utility managed, untreated, piped groundwater systems were assessed to have a resilience score of 7.9, 6.8, and 4.6 to drought, decreased precipitation, and seawater intrusion, respectively. However, the resilience is dependent on the aquifer and depth of the borehole. Due to the karstic nature of the reefal limestone aquifer and its location close to the coast, it is likely that Cumayasa's piped groundwater system is less resilient to drought, decreased precipitation, and seawater intrusion than the global standard provided by Luh et al., 2017. As rainwater harvesting is directly affected by quantity of rainfall, resilience scores for rainwater systems were found to be 1.7 and 1.9 to drought and decreased precipitation, respectively. During the wet season, rainwater systems regularly deliver water, but during the dry season rainwater systems are limited by storage capacity. However, since rainwater is not subject to impacts from sea level rise, rainwater harvesting was found to have the highest resilience of all technologies assessed to seawater intrusion with a score of 9.9 (*Luh et al.*, 2017).

Pathways for Cumayasa

The pathways demonstrated in Figures 10 and 11 are not comprehensive for all water systems. These pathways are specific to Cumayasa, however this methodology can be applied to all community-based water projects.

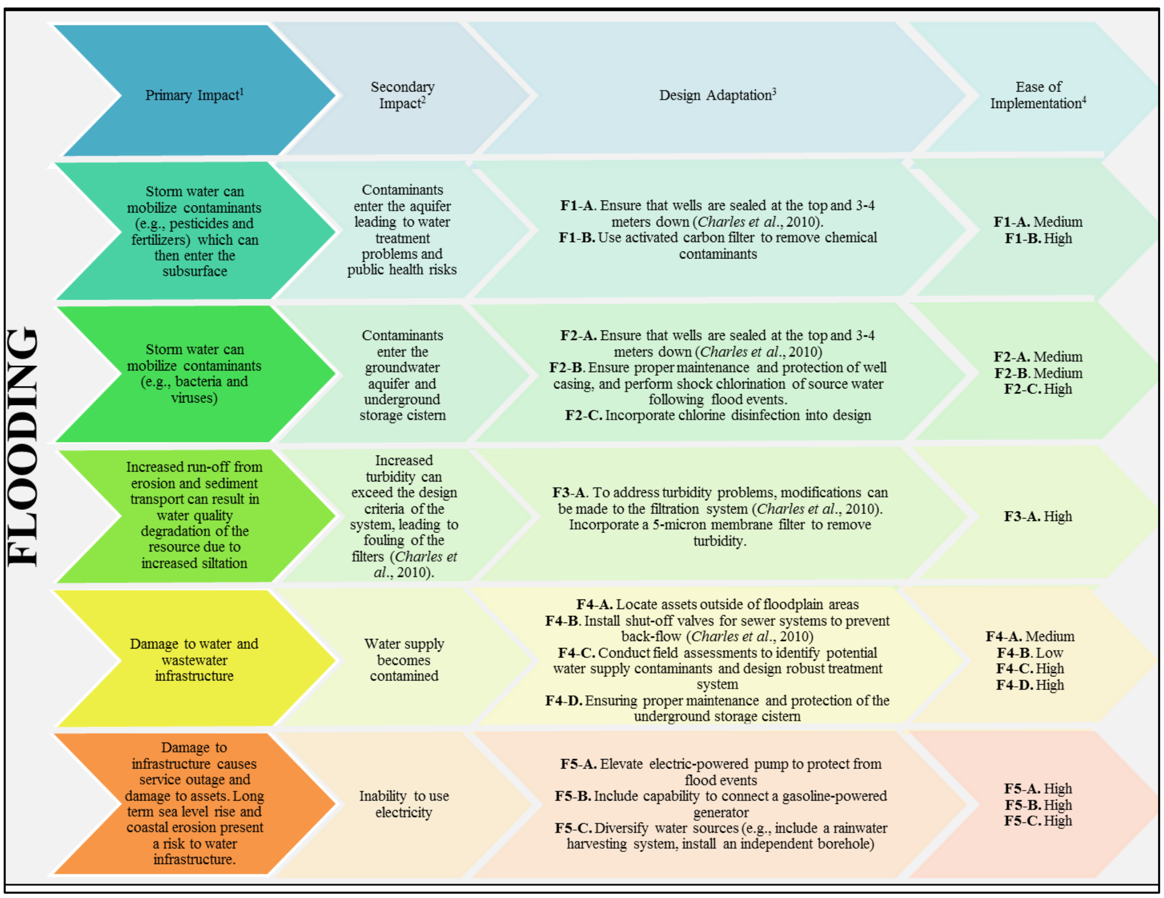

Figure 10 Flood-related impacts on water systems and potential design adaptations

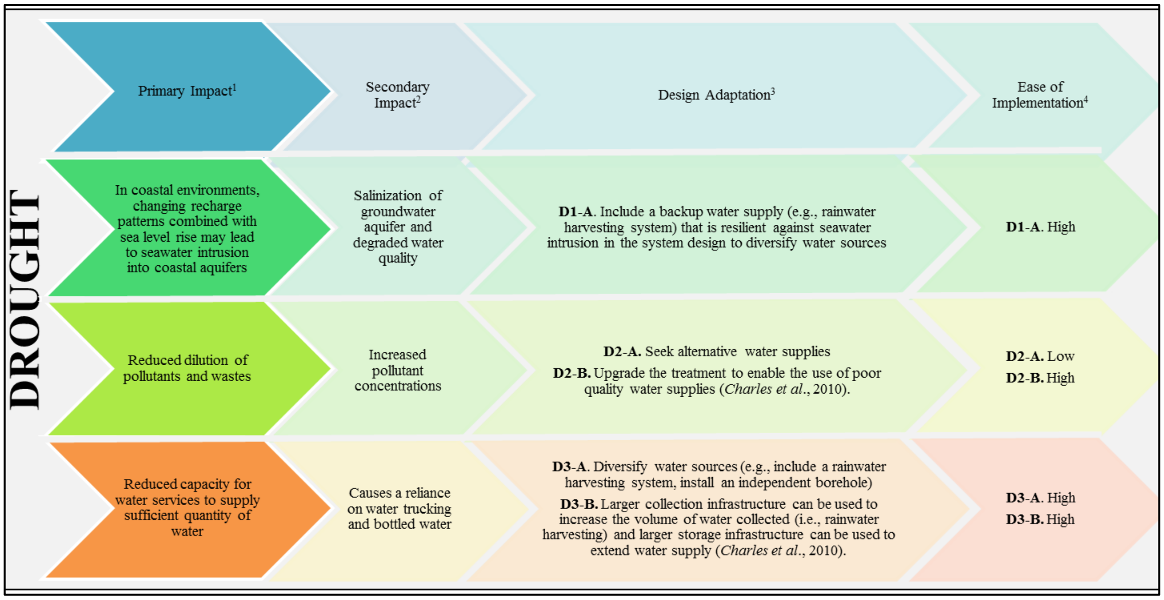

Figure 11 Drought-related impacts on water systems and potential design adaptations

NOTES (*Pertains to Figures 10 and 11*):

1. Primary impact is the immediate consequence of the combination of the hazard and vulnerability on the water system under consideration (*GWP-C and CCCCC*, 2014)
2. Secondary impact is the result of the primary impact on another system, such as physical assets or the provision of water related services (*GWP-C and CCCCC*, 2014)
3. Applicable design adaptations were identified through literature review. Each design adaptation is assigned a unique identification number. "F" indicates the design adaptation corresponds with a flood-related hazard. "D" indicates the design adaptation corresponds with a drought-related hazard. Numbers are assigned for each impact. Letters are assigned to identify design adaptations associated with that impact.
4. Ease of implementation was scored low, medium, or high based on community-specific preferences and limitations. The method for performing this task included field assessments and discussions with stakeholders. Design adaptations that can be implemented, operated, and maintained (both financially and technically) by stakeholders were scored "high" ease of implementation. Municipal-level design adaptations were ranked "medium" ease of implementation due to the limited level of stakeholder influence on the municipal water infrastructure. Design adaptations requiring large financial or technical support, or those under the cognizance of external entities were scored "low" ease of implementation.

4.3.3. Prioritizing Adaptation Solutions

Design adaptations were prioritized for Cumayasa by entering values from the CRAVR (Table 13) and the ease of implementation (Figures 10 and 11) into the CAMP, as shown in Table 14.

Table 14 CAMP for Cumayasa, Dominican Republic

	Ease of Implementation (of Adaptation Solution)		
Climate Risk Assessment Value Rating (CRAVR)	**1 (High)**	**2 (Medium)**	**3 (Low)**
1 (Extremely High)			
2 (High)	F1-B F4-D F2-C F5-A F3-A F5-B F4-C F5-C	F1-A F2-A F2-B F4-A	F4-B
3 (Medium to high)			
4 (Low to Medium)			
5 (Low)	D1-A D2-B D3-A D3-B		D2-A

High priority
Medium priority
Low priority
Pertains to Table 14

The following design adaptations were determined to have high priority in Cumayasa; therefore they were incorporated into the system design. If possible, design adaptations determined to have medium or low priority will be addressed following implementation of the primary water treatment system.

- **F1-B.** Use activated carbon filter to remove chemical contaminants
- **F2-C.** Incorporate chlorine disinfection into design

- **F3-A.** To address turbidity problems, modifications can be made to the filtration system (*Charles et al*., 2010). Incorporate a 5-micron membrane filter to remove turbidity
- **F4-C.** Conduct field assessments to identify potential water supply contaminants and design robust treatment system
- **F4-D.** Ensure proper maintenance and protection of the underground storage cistern
- **F5-A.** Elevate electric-powered pump to protect from flood events
- **F5-C.** Diversify water sources (e.g., include a rainwater harvesting system, install an independent borehole)

5. Recommendations and Conclusions

5.1. Climate-Ready Design Recommendations

The high priority design adaptations (i.e., F1-B, F2-C, F3-A, F4-C, F4-D, F5-A, F5-C) identified using the CCCS process were incorporated into the system design. If possible, design adaptations determined to have medium or low priority will be addressed following implementation of the primary water treatment system. A general system overview incorporating the high priority design adaptations is recommended below. Detailed system design and corresponding engineering drawings are not provided in this paper. Components discussed are not comprehensive and are discussed to provide a basic overview of the system design and its adaptations to climate change and sea level rise.

Field assessments in Cumayasa were conducted to ensure the proposed design is appropriate for the community. Water quality, available water sources, community capacity, and existing climate impacts were analyzed. Water quality parameters, such as Total Coliform bacteria, *E. coli*, nitrates, nitrites, pH, alkalinity, chlorine, and chlorine demand were analyzed in Cumayasa using portable laboratory equipment. Portable meters were used to analyze conductivity, temperature, and total dissolved solids (TDS) in-situ. Water samples were collected to test additional quality parameters, such as anions, cations, and heavy metals. In addition, locally available materials were identified to ensure operation, maintenance, repairs, and system overhaul can be conducted by the community. The proposed water treatment facility was requested by the community and the project is community-driven. The system design was developed in collaboration with the community partners.

The source of the proposed drinking water treatment system is an untreated, piped groundwater system managed by the municipality of Cumayasa with support from a water utility company. Groundwater is pumped from a borehole and distributed intermittently throughout the community. The proposed drinking water treatment system includes an underground cistern for water collection and storage at the project site.

Components of the proposed drinking water treatment system will be located inside of a secure pump house. An electric powered pump will be used to pump water from the cistern through a series of filters. The principal microorganisms of concern in water treatment are (1) *Giardia lamblia, Cryptosporidium parvum*, and other protozoa, (2) bacteria, and (3) viruses (*MWH's Water Treatment: Principles and Design,* 2012*)*. The first filter in the series is a 5 µm membrane filter. The 5 µm membrane filter will physically remove larger contaminants (5 µm or greater in diameter), such as sediments. The second and third filters in the serious are 1 µm membrane filters. Two 1 µm membrane filters are included in the design for redundancy. The 1 µm membrane filters will physically remove smaller contaminants (particles with a diameter of 1 to 5 µm). *Giardia lamblia* cysts are 11 to 15 µm in diameter and *C. parvum* oocysts are 3 to 5 µm in diameter (*MWH's Water Treatment: Principles and Design,* 2012*)*. Therefore, both are larger than the pore size ratings of the 1 µm membranes and should be completely rejected, as long as there are no integrity problems. The final filter in the series is an activated carbon block filter. The activated carbon block filter removes chemical contaminants. Following the filter series is a liquid chlorine dosing point for disinfection of remaining microbial contaminants. The treated water is then pumped into a 500-gallon elevated storage tank. Disinfection occurs in the tank. Following the required contact time for disinfection, treated water can be collected from a tap inside the pump house. Operational procedures and training will be provided to the community to ensure proper disinfection and regular water quality testing prior to consumption.

In addition to the main drinking water treatment system, a rainwater harvesting system will be located at the project site. An exiting roof structure and piped drainage will be utilized. Rainwater will be collected on the roof surface, and will fill a 500-gallon storage tank. A first flush system will remove initial runoff to reduce contaminants entering the tank. A tap will be located at the tank for water collection. The tank will be slightly elevated to provide sufficient pressure head to fill the underground cistern (feed supply for the drinking water treatment system). Normal operation of the rainwater harvesting system will be for non-potable uses (e.g., cleaning). However, the design will allow the rainwater harvesting system to gravity feed water into the drinking water treatment system during water shortages or emergencies.

5.2. Continued CCCS Development

The remaining sections of the CCCS will be developed concurrent with the execution of the remaining phases of the project process (i.e., implementation phase and monitoring and evaluation phase). Once all sections of the CCCS are complete, a comprehensive guide will be disseminated in Cumayasa and surrounding communities. Preliminary meetings with the Ministry of Education for the Dominican Republic were held to discuss potential design and implementation of climate-ready water systems for schools located in communities across the Dominican Republic.

Climate hazards such as floods and droughts impact water resources and technologies. Community-based water systems are especially vulnerable to the impacts from floods and droughts. This case study in the Dominican Republic used field research, literature review, and climate change projections to design a drinking water treatment system that is resilient to the impacts of climate change and sea level rise. Understanding how climate hazards affect the functionality of water technologies and impact water sources is essential for communities to make fact-based decisions regarding their water supply. Selecting the most appropriate water treatment technologies and water sources can improve a community's resilience to climate change.

Aggregating the data collected in this case study, future studies, and other region specific climate data a CCCS can be developed to help bridge the gap between macro-scale atmospheric science and resilient water system development for communities around the world. Recommendations for future research include: surveying communities vulnerable to climate change and sea level rise about their water supplies; documenting climate-related technology failures, source water issues, and existing solutions; creating a geographic map to identify trends in water source issues, technology failures modes, and water quality issues by region; using field data and outputs of appropriate models to determine water technologies most resilient to local conditions; and incorporating research findings from case studies, field observations, and laboratory testing into the CCCS documents and decision matrix. By developing a comprehensive understanding of climate change impacts on water technologies and water resources, communities around the world can improve their resilience to climate change.

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