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AGRICULTURAL WATER MANAGEMENT AND PUERTO RICO'S FOOD INSECURITY

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SPECIAL PUBLICATION I

2019-2020

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AGRICULTURAL WATER MANAGEMENT AND PUERTO RICO'S FOOD INSECURITY

Eric W. Harmsen and Rhea Howard Harmsen

Introduction

Water is precious. The Native American Water Protectors have declared, "Water is life". Efficient use of water has become a moral and ethical issue. Increasing global population, dwindling water supplies, degraded water quality, climate variability, and the various sectors competing for it, all affect the management of water resources. By far, the largest sector demanding water is agriculture. Seventy percent of all water withdrawals globally are used for agriculture (WBCSD, 2008).

In this paper, we will discuss various issues related to the management of water in Puerto Rico, considering historic, current and potential future conditions. Emphasis will be on agricultural water management, given that irrigated agriculture in Puerto Rico may dramatically expand in the future. Growth is imperative because of current food insecurity and because of the impending increase in dry areas anticipated by climate change. Our recent experience with a devastating natural disaster, Hurricane Maria, also requires water resources analysis. Recommendations are provided that may contribute to a new culture of dialogue that has emerged since Hurricane Maria, resonating with a wide range of stakeholders (e.g., educators, public policy administrators, resource managers and the individual citizen).

Agricultural water management should be addressed at the level of principle, because water is a vital commodity, intrinsically connected with our economy, food supply, health and security. The concept of principle is rooted in the United Nation's Universal Declaration on Human Rights. Article 1 of this document states: "All human beings are born free and equal in dignity and rights. They are endowed with reason and conscience and should act towards one another in a spirit of brotherhood." On the level of principle, this one Article alone suggests that an individual, commercial entity or government must not exploit or miss-use a resource in a manner that will harm their fellow-citizens, now or in the future.

Other fundamental principles that are universally accepted and which should inform discussions about resource management include:

- That agriculture is the foundation of society
- the need for economic and environmental sustainability
- the need for the healthy flow of international trade
- the need for elimination of extreme poverty
- the need for universal employment; and
- that future needs should be planned for and all stakeholders should be invited to the planning table.

Ideally, a healthy society should include at least these six principles in its policies and planning. They are so basic that they can be found in sacred religious texts. For example, "…regard should be had to the matter of agriculture...it is endowed with the first station."[1] "Man is organic with the world. His inner life molds the environment and is itself also deeply affected by it."[2] "The fundamental basis of the community is agriculture."[3] "Be anxiously concerned with the needs of the

[1] Tablets of Bahá'u'lláh Revealed after the Kitáb-i-Aqdas", Haifa: Bahá'í World Centre, 1982.
[2] Shoghi Effendi, Letter to an individual Bahá'í, through his secretary, 17 February 1933.
[3] Gleanings from the Writings of Bahá'u'lláh, US Bahá'í Publishing Trust, 1990. Page 213.

age ye live in, and center your deliberations on its exigencies and requirements."[4,5,6,7] "And the LORD will continually guide you, and satisfy your desire in scorched places, And give strength to your bones; And you will be like a watered garden, And like a spring of water whose waters do not fail.[8] These ethical or religious principles could be said to underlie concepts in the language of resource management such as integrated, robust, resilient, reflective and resourceful systems, sustainable development and risk mitigation (Resilient Puerto Rico Advisory Commission, 2018a).

How is Puerto Rico doing vis-à-vis these principles? Unfortunately, we must acknowledge that its agriculture is weak (over 80% of its food is imported), its trade costs are artificially inflated due to an outdated law (Jones Act), its unemployment rate is high (13%), 46% of its population is living below the poverty line, the sustainability of its energy and water infrastructure is in question (96.4% of Puerto Rico's energy use is from fossil fuel; WorldData.info, 2016), the stewardship of its resources would benefit from a more long-term vision, and planning for its future needs more cohesion. According to an Energy Sector Report (Resilient Puerto Rico Advisory Commission, 2018a), "The severity of the impacts (from Hurricane Maria) highlighted the Island's physical and natural infrastructure vulnerability to extreme weather events and the need to better prepare for future events. The hurricane also exposed structural socioeconomic weaknesses that existed prior to the

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[4] On the necessity for economic and environmental sustainability: "We cannot segregate the human heart from the environment outside us and say that once one of these is reformed everything will be improved. Man is organic with the world. His inner life molds the environment and is itself also deeply affected by it. The one acts upon the other and every abiding change in the life of man is the result of these mutual reactions." (Shoghi Effendi, Letter to an individual Bahá'í, through his secretary, 17 February 1933).

[5] On the necessity for the healthy flow of international trade: "…the policy of high and prohibitive tariffs, so injurious to the healthy flow of international trade and to the mechanism of international finance." (Shoghi Effendi, The world order of the Baha'u'llah. p 35). This principle is embedded within a larger principle, namely the oneness of humanity. "It is not for him to pride himself who loveth his own country, but rather for him who loveth the whole world. The earth is but one country, and mankind its citizens. (Gleanings from the Writings of Bahá'u'lláh, page 249).

[6] On elimination of extreme poverty: "There will be a readjustment in the economic conditions of mankind so that in the future there will not be the abnormally rich nor the abject poor." 'Abdu'l-Baha. The Promulgation of Universal Peace page 132.

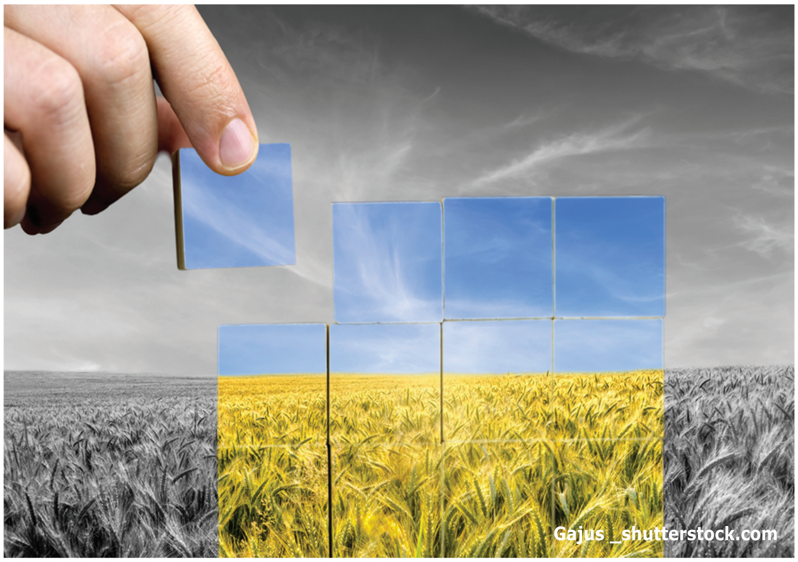
[7] On Universal employment: "It is made incumbent on every one of you to engage in some occupation, such as arts, trades, and the like. We have made this—your occupation—identical with the worship of God." (Bahá'u'lláh: Bahá'í World Faith, p. 195)

[8] Isaiah 58:11, Holy Bible, King James Version.

storms and that exacerbated their impacts, among them a contracting economy, a bankrupt public sector, declining jobs, high inequality, aging infrastructure, and continuous population loss." This combination of factors is not unique to Puerto Rico, many countries face similar ones. But it is in the context of this objective reading of our reality that we will examine the question of Puerto Rico's water situation.

Specific issues that will be discussed throughout this paper include:

1. Should Puerto Rico expand its agricultural production?
2. Is the current water infrastructure sufficient for that purpose or will it need to be expanded?
3. To what extent are public funds used to subsidize the water used for agriculture and how much might this increase in the future?
4. Does the water subsidy discourage sound water management practices by farmers?
5. How will climate change exacerbate water management problems in the island; and
6. What are some potential solutions for addressing agricultural water management in Puerto Rico?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Food Security

Currently, there is a convergence of bad conditions in Puerto Rico, as described above. Add to this, massive infrastructure destruction from Hurricane Maria. Puerto Rico has a $70 billion debt and recently the U.S. Government installed a fiscal control board to manage the crisis. Important statistics from the Puerto Rico Fact Sheet of the Government Development Bank for Puerto Rico (GDB, 2016) are as follows: Population: 3,598,357 (July 1, 2015 est.); Population growth rate: -0.6% (2015 est.); Gross Domestic Product (GDP): $103.7 billion (2014); GDP per capita: $28,850 (2014); Persons below poverty level: 46.2% (2014); Labor force: 1.1 million (2015); Unemployment rate: 13.0% (2015). Labor force by occupation: (2015) Services: 33.8%, Trade: 24.3%, Government: 20.1%, Manufacturing: 8.3%, Transportation and other public utilities4.5%, Construction and mining: 3.8%, Finance, insurance and real estate: 3.4% Agriculture: 1.7%. GDP by sector: Manufacturing: 47.6% Finance, insurance and real estate: 19.7% Services: 12.5% Trade: 7.7% Government: 7.6% Transportation and other public utilities: 2.9% Construction and Mining: 1.1% Agriculture: 0.8%. Food in Puerto Rico is 25.4% more expensive than the average cost of food in the U.S. (CB, 2016).

From an agricultural perspective, Puerto Rico is in a perilous situation, amounting to a food crisis, with more than 80% of its food imported (Santiago, 2012), with some estimates exceeding 90% since Hurricane Maria. This is not only significant from the standpoint of food security, but also economically, because Puerto Rico pays $8.5 billion each year for its food. If Puerto Rico could produce 90% of its food it would result in $3.5 billion, currently spent on imports (wholesale), staying in the local economy and producing 85,000 jobs (Santiago, 2012). Currently, agriculture makes up only 0.8% of the island's GDP, as compared with 35.9% in 1950 (Marxuach, 2012).

An obvious disadvantage of Puerto Rico's low agricultural production rate is that it has little control over its food supply. There is a growing sense of urgency to address this problem. With increasing uncertainty in the climate, the sense of insecurity will continue to grow. Most food imports to Puerto Rico come from the United States (approximately 70%, PR Planning Board, 2017). It is conceivable that if certain regions of the U.S. experience increased severe weather events, such as droughts, food supplies from traditional markets may become unavailable.

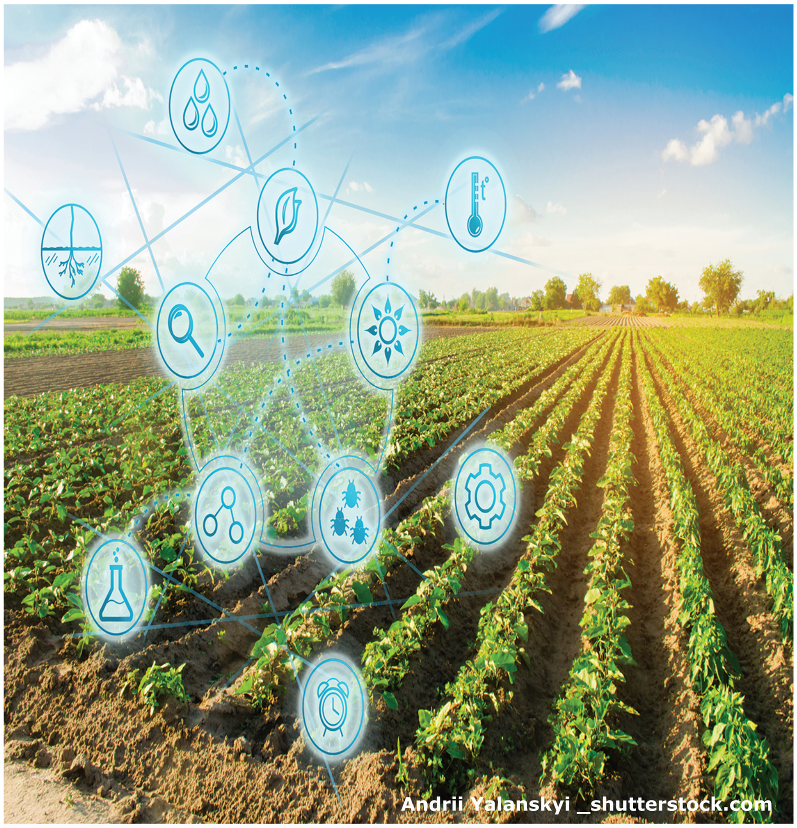
The answer to the question, "Should Puerto Rico expand its agriculture?" appears to be obvious. González Martinez (2008) has written: "…all countries should strive for full food security" and "the achievement of this goal must be the yearning of every society." Increasing agricultural production in Puerto Rico would seem to be a win-win, from both the food security and economic perspectives. But what happens if Puerto Rico grows its agriculture to 90%, and there is a devastating drought on the island? Does a Puerto Rico with 90% agricultural production lead to more food insecurity? It is important to examine whether we have a water capture infrastructure sufficiently robust to withstand demands associated with catastrophic drought events. If our food supply system shuts off due to an extreme weather event, can we obtain the food we need from other markets? What mix of locally grown food and imported food (e.g., 50:50 or 90:10) will provide the highest level of food security?

The healthy flow of international trade is needed to ensure Puerto Rico's food security. Concerted efforts must be made to free Puerto Rico from the current restrictions on its importation of food (Jones Act), which results in elevated food prices. Exemption from the Jones Act has already been granted to the U.S. Virgin Islands. Concerted, sustained appeals must be made to the Federal Courts and Congress, and beyond that, to the World Court, if the U.S. Government is unresponsive. The national security aspect of the Jones Act would not be adversely affected by exempting Puerto Rico. It appears that the reluctance to exempt Puerto Rico from the Jones Act is based solely on the fact that Puerto Rico is the largest off-shore market of any of the U.S. non-continental States or Territories.

Puerto Rico's Climate

The island of Puerto Rico has climate zones that vary from tropical rainforest (4,500 mm rainfall per year) to semi-arid dry forest (750 mm rainfall per year). There is a wet season from June to November and a dry season from December to April. Hurricanes and extreme weather events are common on the island. During Hurricane Maria, rainfall exceeded 37 inches in five municipalities in southeast Puerto Rico. Puerto Rico experienced severe droughts in 1923, 1930, 1947, 1957, 1964-1967, 1973-1976 and 1994-1997 (Colón, 2009). The most recent drought occurred during 2014-2016 (DRNA, 2016a).

Wet air carried by the Easterly Trade Wind moves from the east to the west of the island. Much of this wet air produces rainfall as it passes over central Puerto Rico's Cordillera Central, a mountain range that runs east to west through the middle of the island. The maximum elevation in Puerto Rico is 1,338 m at Cerro de Punta. The rain shadow effect results in a very dry southern and southwest coastal region. In the west, the sea breeze effect carries wet air from the Mona Channel eastward, converging with the Trade Wind and producing intense convective rainstorms almost every afternoon during the wet season (Jury et al., 2009).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Climate Change

In general, climate change in the Caribbean Region is expected to cause increasing air and sea surface temperatures, rising sea levels, increases in the magnitude and frequency of extreme weather events, increase in stream flow seasonal variability, increase in extended dry period probabilities, and greater risk of droughts and floods (IPCC, 2007). Extended dry periods and the potential for greater evaporation will have a negative impact on lake levels and will increase crop water requirements. Where groundwater resources are available, pumping will likely increase due to increasing demand and because groundwater may be needed to offset declining surface sources during the drier months (Harmsen et al., 2009a). Several climate change studies have concluded that rainfall will decrease in the region between now and the end of the century (e.g., Meehl et al., 2007; Biasutti et al., 2012; Campbell et al., 2011; and Cashman et al., 2010). Neelin et al. (2006) and Scatena (1998) have predicted increasingly severe droughts in the region in the future, while rainfall during the rainy season is expected to increase (Magrin et al., 2007, Jennings et al., 2014).

Kahlyani et al. (2015) studied the potential ecological and economic effects of climate change in Puerto Rico using output from 12 statistically downscaled global circulation models (GCMs). Overall, rainfall was predicted to decline in Puerto Rico through the end of the century. Greatly disturbing, were projections of near desertification in some regions and drastic disruption of rain forest regions. The projected decrease in annual precipitation was in the range of 130- to 1397-mm, depending on location and greenhouse gas (GHG) emission scenario considered. This result suggests that certain areas of the island that currently rely on rain-fed agriculture will likely require irrigation in the future.

Temperature is also projected to rise in Puerto Rico in the future (Jennings et al., 2014; Bueno et al., 2008, PRCCC, 2013), which will increase evapotranspiration and crop water requirements. Harmsen et al. (2009a) studied the seasonal climate change impacts on evapotranspiration, precipitation deficit and crop yield at Adjuntas, Mayaguez and Lajas, Puerto Rico. The analysis considered three GHG emission scenarios using the Department of Energy (DOE)/National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM) (Washington et al., 2000). Results from the analysis indicated that the rainy season will become wetter (by 121 to 321 mm) and the dry season will become drier (by -27 to -77 mm) between 2000 and 2090. Additional rainfall during the rainy season will likely lead to increased soil erosion and a loss of soil fertility, and cause more sediment to enter the island's reservoirs, leading to a further reduction in storage capacity. The authors suggested that the additional water could be saved during the wet months to offset increased irrigation requirements during the dry months. However, this may not be feasible unless the capacity of the reservoir network is increased. A positive finding from the study was the increase in annual aquifer recharge, because most recharge occurs during the wet season, which is anticipated to become wetter.

Sea level rise can be expected to reduce the arable land near the coasts, and could further reduce the island's agriculture production, resulting in increased agricultural imports. Sea level rise intensifies induced saltwater intrusion produced by groundwater pumping in coastal aquifers. Increasing chloride concentrations have been observed in groundwater in coastal areas of Puerto Rico, especially in the south coast aquifer (Gould et al., 2018).

Another factor that will influence Puerto Rico's food supply is the anticipated change in the nutrient content of food due to climate change (related to increased CO_2 concentrations). Rice grown under conditions of elevated atmospheric CO_2 have exhibited decreased concentrations of iron and zinc, which are important for human nutrition (Meyers et al., 2014). Ziska et al., (1997) found that grain protein content decreased under conditions of elevated CO_2 and temperature. A study of barley, rice, wheat, soy bean and potato showed reductions in protein content on the order of 10 to 15%, except for soy bean, which was less than 2% (Taub et al., 2007). Nitrogen levels are generally reduced under elevated CO_2 levels. (Cotrufo et al., 1998). These results are important, because humans and animals will need to eat more food to receive their minimum nutritional requirement.

It is generally understood that elevated atmospheric CO_2 will produce higher crop yields (Taub, 2010). However, the benefit of elevated CO_2 may be cancelled when accompanied by elevated air temperatures (Hatfield and Prueger, 2015). Furthermore, weeds may similarly benefit from the elevated CO_2, competing for limited soil water and nutrients (Poorter and Navis, 2003).

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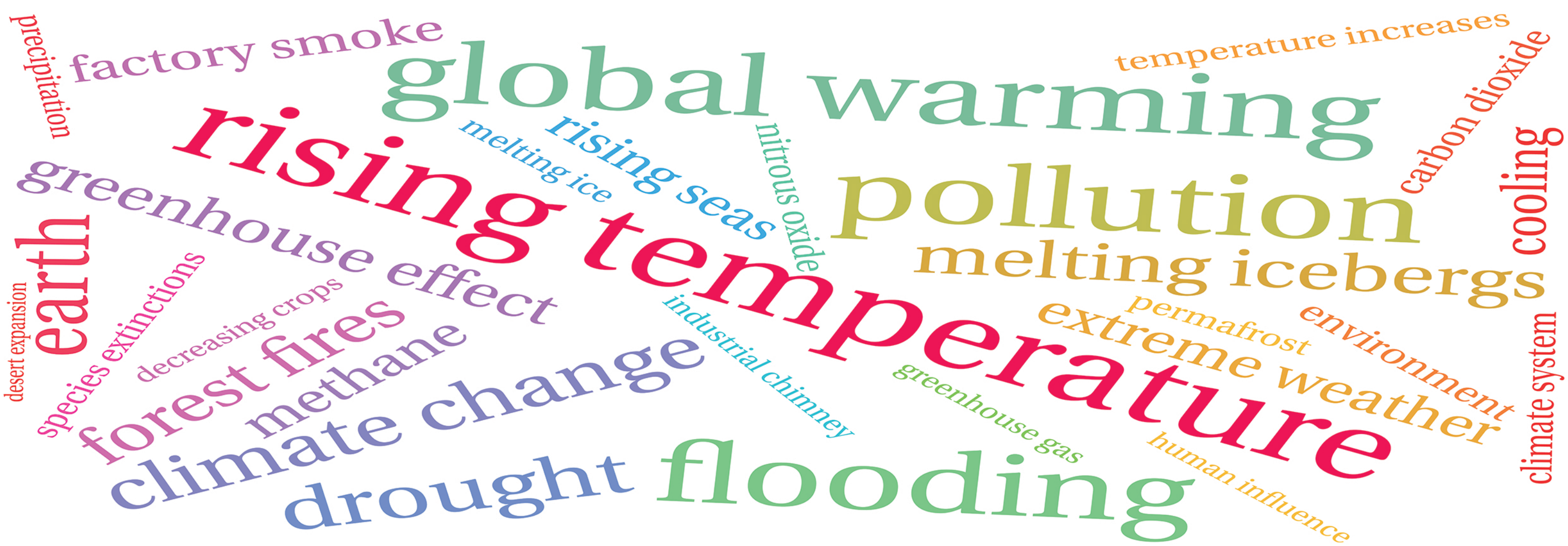

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Natural Disasters

Recent natural disasters experienced by Puerto Rico included the Drought of 2014-2016 and the two hurricanes, Irma and Maria in September of 2018. The impact of these natural disasters, occurring in swift succession, and superimposed onto a failing economy, is difficult to convey. As a Small Island Developing State (SID), Puerto Rico is especially vulnerable to natural disasters. Briguglio (1993) has asserted that nine out of ten most vulnerable countries were SIDs, owing to their export dependence, insularity and remoteness and being prone to natural disasters. Under climate change conditions we can expect "natural" disasters to increase in the future.

It is obvious that recovery from natural disasters is expensive, sometimes exceeding a country's GNP (e.g., Hurricane Mitch, 1998 in Honduras; Clay and Benson, 2005). But how do natural disasters affect mid- to long-term economic growth? The literature is mixed in terms of providing a direct correlation between natural disasters and economic growth. Klomp and Valckx (2014) reported that natural disasters have the most significant adverse effect on the economies of developing countries. Whereas a study performed by Cavallo et al. (2013) revealed that natural disasters had no direct effect on economic growth. Shabnam (2014) reported that the extant literature is inconclusive on this question. In some cases, after a natural disaster, positive growth has been observed, while in other cases a negative effect was observed. As an example,,after the 1998 floods in Bangladesh, cereal production was projected to decline 10-11%. However, with an aggressive planning adjustment (rapid expansion of much lower-risk dry season irrigated rice), cereal production actually rose by 5.6% the following year. This example illustrates a case where the agricultural sector benefitted as a result of the natural disaster.

To minimize the tremendous cost of recovery from natural disasters, mainstreaming risk analysis has been promoted by development agencies such as the Inter-American Development Bank, United Nations Development Program and World Bank (Clay and Benson, 2005). According to the Overseas Development Institute, between the 1950s and 1990s, insurers reported that the cost of natural disasters globally increased 15-fold. The goal of mainstreaming risk analysis is to assign risk and costs associated with potential natural disasters in the planning of the country's development. Financial resources are then allocated in order to achieve sustainable development. An example of mainstreaming risk analysis related to Puerto Rico's agricultural water resources with an increase in local food production from 20% to 50% is presented in subsequent section (Preliminary Estimates of Future Water Requirements).

As mentioned, Puerto Rico experienced severe drought from 2014 to 2016. The greatest impact from the drought occurred in the eastern half of the island. Many of the island's water supply reservoirs dropped to levels not seen since the devastating drought of 1994. In response to the smaller drought of 2014, the Government established the Puerto Rico Technical Scientific Drought Committee (Comité Técnico Científico de Sequia de Puerto Rico), whose task is to provide short and long-term recommendations to the Governor of Puerto Rico and Agency Secretaries, with the goal of improving the island's response to extreme drought events. Participants on the Committee included numerous Federal and Commonwealth agencies, as well as the University of Puerto Rico. During 2015, the Committee met weekly to discuss ways the drought was impacting the island, and to develop recommendations for managing the island's water resources. Data evaluated included rainfall amounts, regional weather forecasts, drought classifications by the U.S. Drought Monitor, water supply lake levels, groundwater levels, stream flows, stream and lake biological health, forest fires, agricultural damage, soil moisture, and a variety of hydro-climate indicators. The Technical Scientific Drought Committee developed recommendations for better managing droughts in the future (DRNA, 2016a). Resolving problems related to drought is a puzzle with many moving parts and it can be said that serious consultation and dialogue is needed to devise the necessary solutions. The mere creation of such a think tank and consultative space is a very significant advance. Another example of systematic water management planning in the island is the Plan Integral de Recursos de Agua de Puerto Rico (Integrated Plan of Puerto Rico's Water Resources) (DRNA, 2016b). The plan evaluated projections for "base" and "potential" water requirements for various regions of the island through 2030. An analysis resulted in a recommendation for the development of a drought management plan for the southeast region of the island.

Agricultural Water Management in Puerto Rico

Macro-Scale

During the first half of the 20th Century, Puerto Rico's main agricultural crop was sugar cane (Maio et al., 2012), followed by tobacco (Gage, 1939). Surface irrigation was provided in the Southern Coast Irrigation District (Juana Díaz and Guayama) starting in 1914, the Isabela Irrigation District starting in 1928, and the Lajas Valley Irrigation District starting in 1955. Figure 1 shows the locations of the irrigation districts.

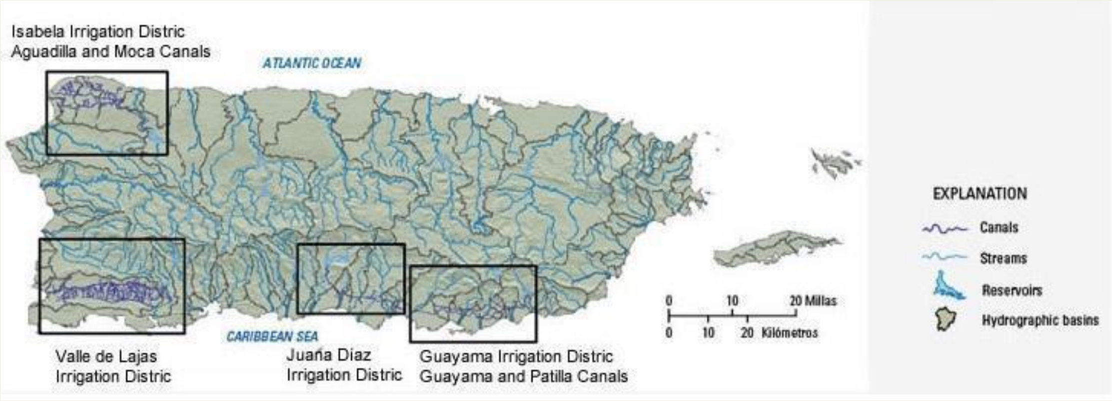

Figure 1. Puerto Rico's four irrigation districts: Isabela, Lajas Valley, Juana Díaz and Guayama (from USGS). In this paper the Juana Díaz and Guayama Districts are referred jointly as the South Coast Irrigation District

Prior to 1930, in the Santa Isabel-Juana Díaz area, groundwater recharge from over application of surface irrigation was estimated to be 18.7 million gallons per day as compared to 17 million gallons per day released to the ocean by groundwater discharge (Ramos-Ginés, 1994). Consequently, groundwater levels in the south coast aquifer remained relatively high. This "convenient" or "beneficial" inefficiency also resulted from loss of water transported through the irrigation canals and through the streams of the south coast. For example, it is estimated that 60% of the Guamaní and Patillas channels' flow percolated to groundwater, recharging the south coast aquifer and reducing salt water intrusion from the ocean (personal communication, Luis Pérez Alegría).

After 1930, electricity became available on many farms, making it possible to use groundwater by means of irrigation wells. Over pumping of groundwater in the southern coast during the late 1960s resulted in groundwater levels well below sea level and elevated chloride concentrations in parts of the aquifer. During this period, in the Santa Isabel-Juana Díaz area, recharge of irrigation water to the aquifer was estimated to be 37 million gallons per day, while the amount of water being pumped from the aquifer was 77.3 million gallons per day, representing an over extraction of 2 times the capacity of the aquifer.

Because of policies of the Puerto Rican Government to stifle the growth of the industry (Maio et al., 2012), sugarcane began to decline until it disappeared during the 1980s (Ramos-Ginés, 1994). Vegetables and fruit crops started replacing sugarcane during the 1970s and low volume, high efficiency drip irrigation was used instead of surface irrigation. In the southern coast, the result was that groundwater levels recovered, mainly due to the reduced volume of water required by drip irrigation. Fast forward to the drought of 2014-2016 and groundwater levels in the southern coast were at record low levels, owing to over-pumping of the aquifer, reduction in historical recharge rates, and possibly due to a small rise in sea level (Jury, 2015). Currently, there is a moratorium (DRNA, 2016c. Orden Administrativa 2016-018) on the construction of water supply wells in portions of the southern coast, because groundwater levels in the aquifer have dropped to dangerously low levels.

Numerous reservoirs around the island have volume capacities that are dropping each year due to accumulation of sediments derived from soil erosion (Quiñones, 2016). In the southern coastal area, the weight-averaged loss of capacity of the reservoir system used to supply water for irrigation (Carite, Guayabal, Coamo, Patillas and Toa Vaca reservoirs) is approximately 22%. The worst case is for the Coamo reservoir with an 82% loss in capacity. Per the Puerto Rico Electric

Authority (AEE) (the agency responsible for the management of the irrigation districts in Puerto Rico), the loss of water from the canals by seepage is around 10-12%.

Lake Guajataca, which is the source of water for the Isabela irrigation district, has lost only about 15% of its capacity since 1928. However, this reservoir was seriously damaged during Hurricane Maria and needed to maintain lower water levels to protect its structural integrity through May of 2019. Quiñones (2016) estimated that approximately half the water that leaves Lake Guajataca is lost through leaks and breaks. According to Torres (2014), Lake Lucchette, the principal source of water for the Lajas Valley, has lost 40.6% of its original capacity and the small Loco reservoir has lost 59% of its capacity. During 2003, 83% of the water entering the Loco reservoir needed to be released to the ocean to avoid exceeding its volume capacity (Quiñones, 2016). In that same year, approximately 12% of the water was lost by seepage from the canal system.

The cost of water to a farmer within each of the irrigation districts is based on Puerto Rico law (Title 22 L.P.R.A. Chapter 13) and ranges from $2-$6 per acre-ft. (One acre-ft of water is the volume of water that will fill a 1-ac area to a depth of 1 ft and is equivalent to 235,853 gallons). The prices were established by the Puerto Rico Legislature for each of the irrigation districts. The Southern Coast Irrigation District was the first district established in law in 1908 and started operation in 1914. The subsidy to farmers in the irrigation districts is approximately $135 per acre-ft of water.[9] Title 22 also establishes that a farmer within the district has a right to receive up to 4 acre-ft of water per acre per year (referred to as a "*standard amount of water*"), if water is not limited by conditions such as drought.

The average farm size in Puerto Rico was 43 acres in 2012 (USDA, 2014). Therefore, the average farm could have potentially benefited from a water subsidy of $23,220 per year[10], assuming

[9] Assuming that most farmers are charged the higher rate of $6 per acre-ft, and that the average annual rate of inflation between 1914 and 2016 is 3.15%, the current day cost of 1 acre-ft of water, accounting for inflation, is $141.91. This amount accords with a cost of $140 to produce 1 acre-ft of water reported by a manager of the AEE off the record.

[10] 43-acre x $135/acre-ft x 4 acre-ft/acre-year = $23,220 per year

the standard amount of water. The actual average application rate was closer to 1 acre-ft per acre per year during 2010 (Molina-Rivera, 2014), therefore an average size farm within one of the irrigation districts would have benefited from a water subsidy of approximately $5,800.[11] During 2015 (a severe drought year), the average subsidy paid for an average sized farm in the Southern Coast Irrigation District was approximately $20,028 per farm, a factor of 3.5 increase relative to the non-drought year of 2010.[12] We will discuss the implications of this subsidy under a system of expanded agriculture in a subsequent section.

A portion of the water from the lakes associated with the irrigation districts is sold to the Autoridad de Acueductos y Alcantarillados (AAA) de Puerto Rico (Water and Sewer Authority) and is used for non-agricultural purposes. Although the AAA water is not used by farmers for irrigation in the subsidized areas, it is interesting to note that the price charged to consumers for potable water by the AAA is approximately $1,800 per acre-ft. For farmers who do not have access to irrigation district water or other local sources (e.g., pumping well or farm pond), AAA water is prohibitively expensive. Referring back to Figure 1, it can be seen that nearly two thirds of the island is not within these irrigation districts and therefore would not qualify for the subsidy.

The amount of water from the irrigation districts that is sold to the AAA for non-agricultural purposes has increased since the irrigation systems were constructed. Quiñones (2016) has estimated that 38%, 54% and 97% of the surface water from the Lajas, Southern Coast and the Isabela Irrigation Districts, respectively, is used by the AAA for non-agricultural purposes, respectively. If agricultural production expands in the future, the increased water requirements by agriculture will undoubtedly lead to conflicts between the agricultural and non-agricultural sectors

[11] The number of acre-ft used by farmers during 2010 within the irrigation districts (surface water) reported by Molina-Rivera (2014) was 17,620 acre-ft, on 16,780 acres.
[12] In 2015, the rainfall deficit in the southern coast was 41.4 inches or 3.45 acre-ft per acre. The rainfall deficit is defined here as the annual rainfall minus the annual reference evapotranspiration (Harmsen et al., 2018a).

of society. Unlike the government mandated home cisterns in the U.S. Virgin Islands (Smith et al., 2018), most homes in Puerto Rico do not have water capture systems and depend on AAA water.

In Puerto Rico, groundwater is a larger source of water for irrigation than surface water. Molina-Rivera (2014) reported that 17,620 and 25,113 acre-ft of surface water and groundwater, respectively, were used for irrigation in 2010. Most of the groundwater (21,731 acre-ft) was extracted from the southern coast, extending from Arroyo to the Lajas Valley. Farmers are not required to pay for groundwater, however, the amount they can pump is determined by the Department of Natural Resources and the Environment (Departamento de Recursos Naturales y Ambientales, DRNA). They must also submit an annual report of the amount of water used and its quality. Commercial and industrial entities pay approximately $650 per acre-ft (1/5 cent per gallon) for groundwater in Puerto Rico. However, the agroindustry is exempt (DRNA, 2000), and this presumably includes the large multinational seed companies.

During several months in 2015, reservoirs dropped to critically low levels due to a lack of rainfall and rationing of AAA water was imposed within many of the island's eastern municipalities. Quiñones (2016) has reported that 48.7% of the AAA water released from its treatment facilities is lost. Other non-billable water losses include 7.2% meter errors, 3% non-authorized consumption and 2.7% authorized non-billed consumption. The water rationing that occurred in Puerto Rico in 2015 could have been largely avoided if there weren't these large losses from the AAA system (Eng. F. Quiñones, personal communication).

Farm-Scale

Consideration of the individual farmer is important since he or she is the end user of the water resource, and to the extent that the resource is managed well, this will contribute to sustainable water management and food security. In practical terms, under-application of water can result in a reduction in crop yield, while over-application of irrigation can result in the loss of water, fuel, pesticides, fertilizer and crop yield, and may contaminate surface or groundwater. (Harmsen et al., 2010).

A survey conducted among farmers in the south coast of Puerto Rico indicated that 54% of the respondents use “experience” or “other” methods for scheduling their irrigation, while 35% use the soil moisture method, 8% use the evapotranspiration method and 3% use the water balance method. The latter three methods constitute scientifically based methods, whereas “experience” or “other” may not constitute scientifically based methods. “Experience” or “other” methods may mean, for example, that the farmer applies 1-inch of water per week, or they turn on their pump for an arbitrary amount of time, or they wait until they visibly observe crop stress before they start to irrigate.

There is an optimum amount of water a crop needs to achieve maximum yield. Insufficient water reduces crop yields due to water stress, which can adversely affect photosynthesis, respiration, translocation, ion uptake, carbohydrates, nutrient metabolism, and hormones (Lisar et al., 2012). Over application of water can also reduce crop yield. This may be caused by saturated conditions, which interferes with root respiration, or may be due to the leaching of fertilizer from the root zone. Figure 2 shows an example of this relationship between crop yield and the seasonal crop water requirement (Harmsen, 2018b). The curve is based on yield and water-use data for corn, wheat, cotton, barley, pepper and rice, and assumes there are no yield reductions related to fertility, pests or diseases.

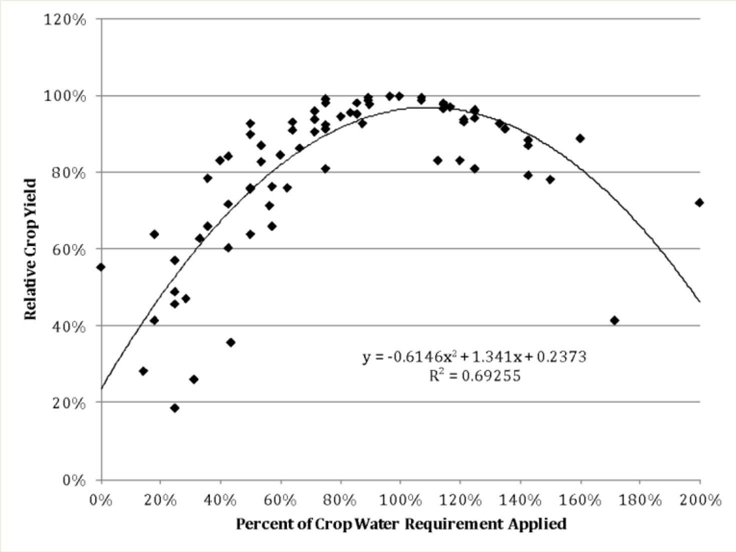

Figure 2. Relationship between relative crop yield and percent of crop water requirement applied (from Harmsen, 2018a).

Table 1 shows the loss in dollars per acre for 17 crops grown in Puerto Rico depending on the percent of the crop water requirement applied (Harmsen, 2018b). The data in Table 1 assume that the regression equation from Figure 2 is generally applicable to crops grown in the Caribbean Region, and that the loss in net revenue for a crop is directly proportional to the relative yield reduction. The best potential revenue (i.e., zero loss) can be obtained when 100% of the crop water requirement is applied.

Table 1. Dollars lost per acre as a percentage of crop water requirement applied. (taken from Harmsen, 2018b)

	PERCENT OF CROP WATER REQUIREMENT APPLIED						
	40	50	80	100	130	150	180
CROP	**$ LOSS / ACRE**						
Cowpeas	47	32	10	0	12	35	69
Cucumber	111	76	25	0	15	56	124
Cabbage	256	174	57	0	21	103	247
Watermelon	293	199	65	0	23	114	277
Plantain and Banana (Plantilla)	318	216	71	0	24	122	299
Squash	390	265	87	0	27	146	359
Onion	543	369	121	0	34	195	490
Pepper	578	393	129	0	36	206	519
Eggplant	757	514	169	0	44	264	670
Plantain and Banana (Retoño)	1,006	684	225	0	76	388	945
Melon, Cantaloupe y Honeydew	1,027	698	229	0	56	352	899
Roots and Tubers	1,041	707	232	0	57	356	911

*Based on model budget data from the *Conjunto Tecnológico,* University of Puerto Rico Agricultural Experiment Station, Model Budgets for pumpkin, avocado, cabbage, coriander, cucumber melon, water melon, onions, plantain, banana, roots and tubers.

An example is presented below of water and economic losses from *under-application* of irrigation. Harmsen (2018b) analyzed the amount of water and money that a farmer could lose on a pepper crop grown in the south coast of Puerto Rico, resulting from the improper application of irrigation water. The analysis considered the commonly used practice of applying 1-inch of water per week during the growing season. Based on data from Figure 2 and Table 1, the estimated relative yield was 69.5% and the dollar loss was $300.60 per acre. In this example the total seasonal irrigation was 1 acre-ft per acre (305 mm) and the required irrigation to achieve maximum yield was 1.6 acre-ft of water per acre (485 mm). The interested reader may wish to refer to Harmsen (2018b) to obtain the details of the analysis. In this example the farmer under applied water and the result was a more than 30% loss in crop yield. If the farmer had applied the correct amount of irrigation district water the cost of water (cost of fuel for pumping not included) would have been $9.60 per acre and 100% of the yield would have been achieved (ignoring yield losses related to fertility, pests and disease).

Another example is presented of water, fuel, fertilizer and economic losses from *over-application* of irrigation. We will now consider a case where water is over applied on an average sized farm. Let us assume that 2 inches of water are applied per week during the growing season. In this case the farmer over-irrigates by 0.4 acre-ft per acre (125 mm) or 133,634 gallons per acre. To put this volume of water in perspective, this is enough water to fulfill the daily water requirement for 2,390 people[13], or to satisfy the water needs for a family of four for 1.6 years.

The financial loss, in terms of yield, is equal to $34 per acre (based on Figure 2 and Table 1). Although the loss in yield in this example is relatively low (compared with first example), there are additional losses to consider. The approximate cost of the lost water, the cost of the fuel used to pump the excess water and the cost of the fertilizer leached past the root zone. We may assign a cost of approximately $50 per acre for these other losses[14], bringing the total to $85 per ac, which is still considerably less than the loss in previous example, in which water was under applied.

Obviously, if a farmer does not know how much water to put on his or her crop, it would be less expensive to over apply irrigation. This is primarily because the farmer can use water from the irrigation district, which is highly subsidized. Suffice it to say that the farmer located within the Irrigation District receives essentially free water, and there is a disincentive to conserve water. On the other hand, a farmer who is not fortunate enough to be located within the service area of the Irrigation District cannot afford to pay for water from the AAA. Applying the optimal amount water to achieve maximum yield for the conditions in the first example with AAA water, the farmer would

[13] Assuming a person uses 55.9 gallons of water per day in Puerto Rico (Molina-Rivera, 2014).

[14] In this example the water lost is 0.4 acre-ft per acre (125 mm) of water. The approximate cost of water for a farmer in one of the irrigation districts is $6 per acre-ft per acre. Therefore, the cost of the lost water is $2.40 per acre. It is difficult to estimate a cost for the fuel required to pump the water because the calculation depends on the type of pump motor used (e.g., electric, gasoline, diesel), the vertical elevation that the water needs to be lifted, the lateral distance the water needs to be transported, the pump flow rate, pump efficiency, etc. Nevertheless, it is possible to assign a rough cost estimate to the fuel of approximately $15 per acre, based on the estimation procedure presented by Schwab et al. (1993), updated with an electricity cost of $0.20 per kWh. (U.S. Energy Information Administration, 2016). Another loss of money is for the fertilizer leached past the root zone. Assuming $133 per acre for fertilizer (Schnitkey, 2016) and 25% of the fertilizer was lost, then this is equal to $33 per acre. Therefore, additional other losses are equal to approximately $50 per acre.

pay $2,880 per acre for his or her water vs. $9.60 per acre for a farm located within the Irrigation District.

Over-irrigation may also include an environmental cost, namely, contamination of the underlying groundwater (Harmsen et al., 2003; Paulino Paulino et al., 2008). Soluble chemicals are leached into the groundwater when rainfall or irrigation is added to a soil that is already close to saturation. Contaminated groundwater may make its way to water supply wells, resulting in health-related expenses to the individuals that ingest the water. Affected water supply wells could be individual private wells or public water supply wells. If a person or group of persons adversely affected by the contaminated groundwater can prove that the source of contamination is a specific farm, then the owner of the farm might incur significant legal expenses. Another possibility is that the contaminated groundwater might be consumed by farm animals resulting in health-related problems and a drop in the quality and rate of production.

Preliminary Estimates of Future Water Requirements

What might the demand for water within the Irrigation Districts be if local agriculture expands to 50% of our food supply (currently approximately 20%)? In this section, a projection is presented (Table 2) for this scenario based on a proportional increase of the 2010 surface water volume used for irrigation. To illustrate an upper limit, the scenario was also analyzed using the standard amount of water (SAOW) application rate of 4 acre-ft per acre per year. This volume of water is slightly above the annual rainfall deficits in the southern coast during 2014 and 2015 of 3.9 acre-ft per acre (1,250 mm) and 3.45 acre-ft per acre (1050 mm), respectively.

Table 2 summarizes the volume of irrigation, water subsidy and subsidy paid for lost water for 2010 and for expansion of agriculture to 50% of Puerto Rico's food supply, relative to 2010. The table also includes estimates associated with using the SAOW, which may better approximate water requirements and costs during drought years. The data in Table 2 are for all the irrigation districts combined. Groundwater used for irrigation is not included. The subsidy is based on $135 per acre. The subsidy associated with wasted water assumes that one-half of the irrigators (based on above survey) over-irrigate by 25%.

Table 2. Comparison of volume, water subsidy and subsidy for lost water considering expansion of agriculture to the 50% and standard amount of water (SAOW) application rates, respectively[15]. The data are for all the irrigation districts combined.

Application Rate	Volume (acre-ft per yr.)	Water Subsidy (million $)	Subsidy for lost water (million $)
2010 acreage (1 acre-ft per acre per yr.)	17,620	2.4	0.3
50% agricultural production level (2010 application rate)	44050	6.0	0.8
2010 acreage. Standard amount of water (SAOW) application rate (4 acre-ft per acre per yr.)	70,480	9.5	1.2
50% agricultural production level (SAOW application rate)	176,200	23.8	3

The “50%” scenario assumes that the proportion of surface and groundwater remain the same under expanded agriculture. However, given the limitations of increasing groundwater extraction in the south coast, more water would be required from surface water sources. Given the current limitations of the lakes that supply water to the canal system, as witnessed during the drought of 2015, capital projects would be required to expand the infrastructure capacity, therefore the water subsidy may be underestimated. To put the values in Table 2 in context, the amount of water being lost from the AAA system is 352,800 acre-ft per year, double the 50% agricultural production level using the standard amount of water (352,400 acre-ft per year). **Therefore, reducing the loss of water from the AAA system needs to be the highest priority of the AAA and the current Puerto Rican Administration.**

[15] Increased water volume was estimated by multiplying the 2010 or SAOW volumes by the ratio 50/20 (50% agricultural expansion). The value of 20 in the ratios is the current percentage of food grown in the island relative to the total consumed.

Recommendations for Agricultural Water Management

1. A study should be conducted specifically to stress-test Puerto Rico's water infrastructure to evaluate its capability to function under different levels of increased agriculture, and under the scenario of extreme drought. Based on climate change predictions, the need for irrigation will become more widespread in Puerto Rico. Studies are needed to evaluate the additional acreage that will require irrigation and how water can be provided to those areas. The analysis should also evaluate how the areas needing irrigation may expand during drought years. The technical studies should evaluate the capital and operating costs associated with expanding the irrigation infrastructure in the island, including the cost of subsidies for farmers that use water from the expanded system.
2. Currently, water in the irrigation districts is essentially free, which, as illustrated through the example of overapplying irrigation, may discourage farmers from applying the optimum amount of water. The correct application of water will benefit both the farmer and society. Therefore, scientific methods need to be devised to help farmers schedule irrigation. Evapotranspiration, soil moisture or water balance methods should be encouraged. The UPR Agricultural Extension Service could provide educational programs related to the use of these methods. Applied research projects should be funded by the Department of Agriculture to develop decision support tools such as smart irrigation scheduling mobile applications (apps). Mobile apps can derive their irrigation recommendations from ground-based and/or satellite-based methods (e.g., Harmsen et al., 2010 and Harmsen et al., 2018b).
3. Determining crop water requirements in Puerto Rico is difficult because few crop coefficients have been developed for the island. In practice, the potential crop evapotranspiration (equivalent to the crop water requirement) is estimated by multiplying a crop coefficient by the potential or reference evapotranspiration. Ramirez-Builes et al. (2014) developed crop

coefficients for two varieties of common bean in Puerto Rico. The authors are not aware of any other crop coefficients that have been developed for the island. The typical practice is to use crop coefficients that have been developed in other parts of the world, however, for some crops that are local to the Caribbean region, no coefficients exist. Studies are needed to determine crop coefficients, especially for local crops. Furthermore, determination of crop water requirements on the island-scale is necessary for better water management planning.

In addition to the research specified above, other areas of research that can be supported by the island's universities include:

- Plant breeding for extreme conditions (drought, flood, heat, etc.) for Puerto Rico's major crops.
- Crop modeling research to evaluate potential crop response to climate change and extreme weather.
- Research in methods for improving soil health that will provide improved fertility, reduce erosion and increased carbon sequestration.
- Technologies to incorporate organic farming into large scale farming operations.
- Optimization research in the operation and management of Puerto Rico's water infrastructure.
- Economic studies into the effects of expanding agriculture in the island and how different options will impact different sectors of society including the poor, and
- Incorporation of more technology on farms to increase efficiency and profitability.

4. An example was presented above that showed a farmer using AAA water would pay $2,880 per acre as compared to $9.60 per acre for a farmer using irrigation district water. This result is relevant because as noted, two thirds of the island is located outside the irrigation districts. Also, there is currently a worldwide movement to promote urban agriculture (e.g., Hund et al., 2013). For urban farms that are located in dry areas of the island, AAA water may be

prohibitively expensive, especially for those low-income populations whose development we seek to promote. The AAA will need to plan for the expected increase in demand for water from the future growth of urban farming. Extension of irrigation districts into urban areas should be considered, in order to provide an affordable water source for urban farming and for farming outside the districts where water is subsidized.

5. New sources of surface water need to be developed for the island. As an example, increased water harvesting in northwestern Puerto Rico should be considered. Figure 3 shows the annual rainfall for 2015 in Puerto Rico.[16] The map indicates that the northwestern portion of the island received near normal rainfall, even though the eastern side of the island experienced devastating drought.

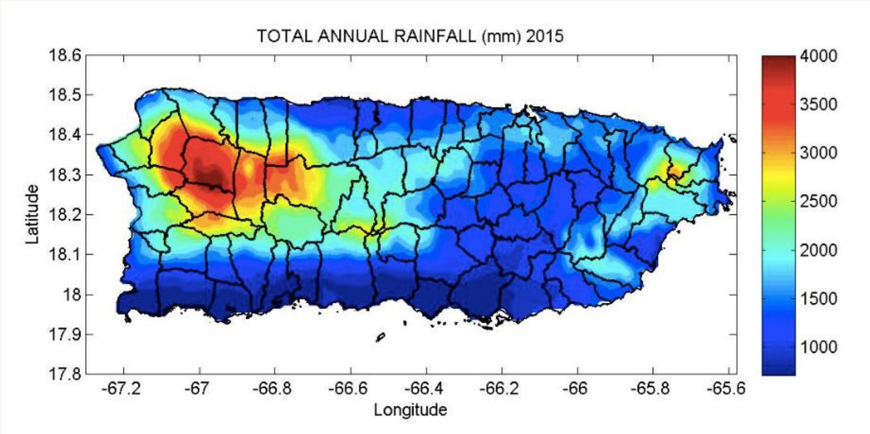

Figure 3. Annual rainfall for Puerto Rico during 2015.

Table 3 shows the annual average rainfall from selected rain gauges in the northwest part of the island, comparing drought years and non-drought years.[17] Although the average annual rainfall for the rain gauges were lower during the drought years, in real terms, the

[16] The rainfall map was obtained with rainfall data from the National Oceanic and Atmospheric Administration's (NOAA) Advanced Hydrologic Prediction Service (AHPS). In Puerto Rico, the source of the AHPS rainfall is NEXRAD radar, bias corrected with rain gauge data.

[17] The drought years included 1923, 1930, 1947, 1957, 1964-1967, 1973-1976, 1994-1997 Colón (2009) and 2014-2016 (DRNA, 2016a).

average rainfall for the drought years (1,805 mm) was excellent, far exceeding the 2015 annual crop water requirement of approximately 1,500 mm.

Currently, water in this part of the island is only captured in Lake Guajataca, with its drainage area located mainly in San Sabastian and Lares Municipalities. Lakes Yahuecas, Guayo, Prieto, and Toro are in Lares and Adjuntas Municipalities, but their water is diverted to the Lajas Valley in southwest Puerto Rico. Previous investigations regarding development of additional surface water sources from the northwest have concluded that the unfavorable construction conditions at some locations and the large expense of pumping water to the east to the Caonillas and Dos Bocas Lakes is not economically feasible (Ferdinand Quiñones, personal communication). However, the cost of developing a source(s) of water in the northwest and pumping it to the east needs to be weighed against the extremely high cost incurred from a devastating drought. The design and management of Puerto Rico's reservoir network is extremely complex. A team of experts, including engineers, urban planners, irrigation specialists, climate change researchers, economists, etc., should be formed to determine the water management infrastructure requirements for the remainder of the century and beyond.

Table 3. Comparison of average annual rainfall for selected rain gauges[18] in NW Puerto Rico during drought and non-drought years (Harmsen et al., 2016).

Weather Station	Average Annual Rainfall (mm) Drought Years	Average Annual Rainfall (mm) Non-Drought Years
Coloso	1851	1968
Hacienda Constanza	1541	1766
Maricao Fish Hatchery	2081	2505
Mayaguez City,	1582	1713
Mayaguez Airport	1586	1784
San Sabastian 2WNW	2191	2318
Average	**1805**	**2009**

[18] Length of the rainfall data sets along with the starting and ending years are as follows: Coloso 55 years (1955-2010); Hacienda Constanza 41 years (1969-2010); Maricao Fish Hatchery 55 years (1955-2010); Mayaguez City 110 years (1900-2010); Mayaguez Airport 53 years (1957-2010); and San Sabastian 2WNW 44 years (1955-1997).

6. The AAA needs to develop alternative sources of water to meet the water supply needs of residential, industrial and commercial consumers. Currently, 63% of the irrigation district water is used by the AAA. This clearly represents a potential limitation for the expansion of agricultural production in the island. Groundwater resources could be further developed in the island, taking advantage of new technologies for discovering and exploiting groundwater resources in the non-coastal areas, traditionally thought to have negligible potential for groundwater production. Emerson (2015) conducted a study in the Dominican Republic (DR) to identify groundwater resources in areas throughout the country previously deemed to lack sufficient renewable water supplies. The investigators discovered new sources of groundwater using remote sensing/lineament and bedrock fracture fabric analyses combined with the use of a numerical groundwater potential model. Newly discovered groundwater sources in Puerto Rico could, for example, be held in reserve until drought conditions develop, at which time they could be used to augment water supplies in the island's reservoirs.

Recommendations for Disaster Recovery

1. Disasters raise awareness of the need for risk reduction, but after the passing of time people lose interest. In the case of the 2014-2016 drought, not everyone in the island was affected by the drought and over time, a general disinterest became apparent. In the case of Hurricane Maria, on the other hand, literally everyone on the island was affected. Consequently, we have witnessed on-going community forums for discussing how to be better prepared when the next hurricane visits the island; these workshops and communal conversations continue more than a year after the natural disaster occurred. This is a very positive outcome that must be encouraged. There were many lessons learned after the hurricane that translated into the

everyday lives of citizens. For example, after the hurricane, there was a noticeable increase in homes adopting solar energy; capture of rainwater became the norm; composting of waste was used to reduce garbage when garbage pick-up was non-existent; the sense of community was strengthened, with neighbors sharing resources and capabilities, while caring for the vulnerable; there was a decrease in consumerism and a "making do" attitude emerged; natural remedies were used when healthcare was still inaccessible; machete yielding brigades (some of them all women) were seen clearing obstructed pathways and opening inundated sewers.

2. After Hurricane Maria, citizens endured a total loss of water for many months due to the breakdown of the electrical systems used to pump water and the widespread lack of backup generators at AAA pumping stations. For agriculture, the loss of electricity resulted in a man-made drought on farms that use electric powered pumps. In the Irrigation Districts, even though water in the irrigation canals is moved by gravity, most farmers rely on pumps to take that water and apply it to their crops. As an effort to become less dependent on the power grid, the UPR Agricultural Experiment Station (AES) in Juana Diaz is currently conducting a pilot study to evaluate solar pumping for irrigation. Hopefully, the results of the evaluation will be widely disseminated by the AES.
3. Public policy should encourage not only independence from the electrical grid, but from the water "grid" as well. Homes and commercial buildings should be designed to capture rainwater. New structures should be required to incorporate water capture in their design, similar to the U.S. Virgin Islands (Smith et al., 2018), and methods should be devised to promote the installation of rainwater capture equipment on existing structures. Widespread use of rainwater capture systems in Puerto Rico could significantly reduce the volume of water transferred from the Irrigation Districts to the AAA, decreasing competition between the two sectors for water.

4. The impetus for Puerto Rico's own development priorities should come from within. It should be informed by a wide range of stakeholders. Important movements such as *ReImagina Puerto Rico* (Resilient Puerto Rico Advisory Commission, 2018b), which seeks to define priorities of reconstruction post Hurricane Maria based on citizen input are a start. However, while addressing the shortcomings that relate to potable water, *ReImagina Puerto Rico* makes no mention of vital water for agriculture.

   Hundreds of on-the-ground non-governmental organizations (NGOs) can also have an influence, if they find a way to unite as a common voice, in order to connect with aid funding. To grow the agriculture sector, farmers also need to be united, cooperative, not competitive. Similar to how the coalition of global NGOs pressure the governmental summits of the United Nations, small local NGOs working as a coalition can help set the agenda of governmental entities in Puerto Rico.

5. Numerous forums have been held in Puerto Rico related to developing resilience in the face of natural disasters, especially since Hurricane Maria. A few examples of organizations that have hosted analysis and planning activities include: Casa Pueblo in Adjuntas, ReImagina Puerto Rico, Manejo Integral de Cuencas Hidrográficas de Rio Grande de Añasco (FEMA), El Centro de Resiliencia Costera (UPRM), Centro Hemisférico de Cooperación en Investigación (CoHemis), the Bahá'í Communities of Mayaguez, Aguada and Guaynabo, National Institute for Energy and Island Sustainability-UPR, Graduate Research & Innovation Center (GRIC), Acción Ciudadana para un Puerto Rico Resiliente, Sea Grant-UPRM, Educación en Ingeniería y Ciencia Aplicada, etc. These planning activities, reaching all segments of society, have stimulated great interest and have promoted a new culture of resilience and resource management in the island.

6. Most important of all, is to build resilience within communities, in order to empower people to recover from within. It has been observed that people can take charge of their own

development and show resilience due to a legacy of capacity in their culture (BIC, 2016). Puerto Rico has a rich legacy of capacity to be resilient due to its Taino heritage, its slavery resistance and its negotiation of life under colonial systems. It has also weathered numerous natural disasters. All these elements of culture can be harnessed going forward. Effective response to disaster or to development challenges is a result of relationships: within communities, between groups, and with governance. Capacities to be developed range from technical, to social, to moral. They are needed to counteract materialism, social fragmentation, selfishness, and passivity. Especially noted, was the fact that low income communities have much to teach the "developed" world.

Considerations for Growing Puerto Rico's Agriculture

1. According to Santiago (2012), an increase in local production of the food consumed in Puerto Rico will potentially produce tens of thousands of new jobs. It is essential that the majority of these be well paying jobs in high tech fields and that the lower paying jobs provide a living wage.
2. Technology positions could be developed in many fields, including soil and water management, irrigation and drainage, agroclimatology, agriculture structures, agriculture machinery, electric power and processing, land leveling, remote sensing, sensors and controllers, software development, waste management, unmanned aerial vehicles (drones), plant breeding, crop protection, food technology, food packaging, farm safety, greenhouse technology, etc. If the goal is to increase agriculture, then the number of jobs in agriculture must be increased and the training of agricultural professionals must be made a priority.
3. Unskilled agricultural jobs could also contribute to higher employment and decreased poverty if wages and conditions are improved. Harvesting coffee by hand, for example, is difficult and sometimes even hazardous work and pays an egregiously low wage. Tax legislation was enacted in 2011 to exempt income earned from picking coffee. This is an irrelevant benefit if

the worker's income is below the poverty level and he or she does not file an income tax report. Allowing foreign workers to temporarily migrate to Puerto Rico had disappointing results as coffee farmers still reported insufficient workers to harvest their coffee (Marxuach, 2012). Mechanization of coffee production, for example harvesting, fertilizing and other production practices, is difficult because the crop is often grown on steep slopes and the coffee beans do not ripen at the same time (Gregory, 2008). Technologies are needed to help mechanize production processes for crop commodities that are perceived to be unattractive to workers, or conversely, social conditions for workers need to be significantly improved in order to attract them.

4. The vast reservoir of capacity constituted by women should be tapped for increasing agriculture. Training of women in the technical and entrepreneurial aspects of agriculture can be expanded through programs like the Entrepreneurship Center for Women in Puerto Rico's Agriculture (Centro Empresarial para la Mujer en la Agricultura), whose stated vision is "To empower women engaged in agricultural activities to contribute to Puerto Rico's sustainable economic development." (Gonzalez Martinez and Gregory, 2013).
5. If agriculture is the foundation of society, then it must be encouraged and strengthened on all levels, not just by large scale entrepreneurs, but also formal and informal, the rural and semi urban, among the poor and the middle class. Children must be taught and encouraged to plant a fruit tree, an avocado tree, a mango or papaya tree, the breadfruit tree, a plantain tree or banana tree. In times of food crisis these might be the difference between starvation and survival, while in normal times these may be the source of needed vitamins or of the supplementation of meager family resources. The love of growing things must be nurtured, not allowed to perish. One low income person interviewed commented that "if a food shortage ensues, the poor will still know how to feed himself but the rich will starve."

6. Many persons living on public assistance have a great ingenuity for devising additional sources of income from agricultural endeavors, such as the production of fruit and small animals, the making of cheese or foodstuffs. Public policy should embrace this. These micro enterprises must be aggressively encouraged so that the entire population views it as a much-needed civic duty to engage in agriculture to strengthen the fabric of the community. A vibrant culture of farmer's markets and roadside fruit vendors must be promoted, so that Puerto Rico may be on a par with other countries, where daily street market culture competes with the supermarket chains. All barriers and excessive regulations preventing the growth of this sector should be removed. It is counterproductive to try to derive tax revenue from micro enterprises (while letting the big fish slide). The population receiving public assistance must not be afraid to add to their income, or feel it is illicit to do so. All such endeavors can only contribute to the island's overall food security. It is in the diversity and variety of approaches that the systemic deficiencies in food production will be overcome.
7. The elimination of extreme poverty is acutely tied in with the growth of the agricultural sector. And the devising of full employment is also tied in with the growth of the agricultural sector. Just as the ethical stewardship of water and energy resources must be devoted to these two ends, so can these issues be attacked in a thoughtful manner through deliberate planning for the future. All planning should consider the needs of not just the present but also "the exigencies and requirements" of the future. The unfortunate decimation of agriculture, which characterized Puerto Rico's 20th Century history (Carro Figuero, 2002), need not define its future if there is a clear vision and direction going forward. The perceived "weaknesses" of its social fabric can actually be used as positive building blocks. For example, a country where a large portion of its poor has their subsistence needs met (through public

assistance programs), while at the same time having access to high levels of education[19], has a potential reservoir of human capital for its own development. Its jobs sector must keep up, providing growth in job opportunities however, otherwise the end product will be the migration of the young and educated to the U.S. (to which they have unique access as U.S. Citizens) and the social unrest of those who remain in a stagnant economy. The key to job creation planning for the island must be to enable "every man and woman to fish". Bringing the population back to agriculture (a more modern version) has a great potential for doing so.

8. The growth of agriculture could be accompanied by a green energy revolution in Puerto Rico's economy. Puerto Rico will not be able to turn its economy around through austerity measures alone. That scenario will lead to extreme uncertainty for investors, continuous exodus of our younger population, a contracting tax base, severe erosion in the quality of public education, reduction in public services in general, negative economic growth, etc., etc. Page-Hoongrajok et al. (2017), in their report *Austerity Versus Green Growth for Puerto Rico* argue that there is a much better alternative. The alternative is primarily based on a carbon tax on fossil fuel (approximately 1 cent per gallon of gasoline, equivalent to $25 per ton of CO_2), which will allow Puerto Rico to transition to 100% green energy by 2050. In their plan, the carbon tax would be used to provide investment funding for renewable energy (combined with private investment), provide rebates for low income people who would be most affected by a carbon tax, and to service the Government debt (currently around $70 billion). The advantages of the plan include the following:

- Approximately $4 billion per year that is currently being spent on imported fossil fuel would be reinvested back into the island's economy;

[19] In Puerto Rico primary and secondary education are universally accessible, while the federal grant covers the cost of most college and post-secondary school training programs.

- the green energy used in the island will be up to three times less expensive than the imported fossil fuel;
- the net job creation through both clean energy investments and energy import substitution would result in an increase in 25,000 jobs by 2020 and up to 80,000 jobs by 2050;
- energy efficiencies (e.g., public transportation, home solar energy systems, hybrid and electric cars) will reduce expenses for families;
- Puerto Rico will be more resilient, able to recover more rapidly after natural disasters like Hurricane Maria due to a more distributed energy network; and as an added bonus
- Puerto Rico would essentially eliminate its greenhouse gas emissions by 2050, thereby contributing to the goals of the Paris Agreement, which aims as maintaining global average air temperatures below 2 degrees Centigrade.

Although not entirely aligned with the proposal of Page-Hoongrajok et al. (2017), there are encouraging developments in the island with respect to the adoption of green energy. In April and May of 2019, respectively, the Public Energy Policy Law of Puerto Rico and the Mitigation, Adaptation and Resilience to Climate Change Act were signed into law. The former aims to power the island solely by renewable energy by 2050 and the latter seeks to gradually eliminate fossil fuel as a source of energy in the island, and to reduce by 10% the island's energy use by 2030. Although these goals are highly encouraging, it will require a high degree of vision and unity on behalf of the countless stakeholders in the island to guarantee their achievement.

Summary and Conclusions

Puerto Rico is confronted with serious economic, social and environmental problems, which will become worse under a changing climate. This demands a holistic approach to solutions on the deepest level of principle if the island is to overcome its current plight and develop coherently. Several examples were cited as evidence that planning is becoming increasingly integrated, incorporating stakeholders at all levels and resulting in a new culture. However, there is still a need to canalize the knowledge gained so as to better inform a strategic public policy process.

Numerous issues were raised in this paper related to water management in the island, including the limitations of the current irrigation infrastructure, the implications of an expanded agricultural industry (e.g., 50% local production level) and its irrigation demands. Recommendations for numerous studies were given.

Agricultural production should be significantly expanded in the island, with a transition period of 20 to 30 years. Initially, studies in diverse fields (e.g., engineering, economics, business, administration, law, energy, agriculture, climate, education, etc.) should be conducted to design and plan the expansion project.

As part of the design studies, the optimum balance between imported food and locally grown food should be determined. This determination should not be based on the capability of the current social and resource infrastructure; nor should it be limited by Puerto Rico's current fiscal crisis. Rather, it should be based on the needs of society and future generations. The final design and implementation should be based on at least six basic principles, namely that agriculture is the foundation of society, the necessity for economic and environmental sustainability, the necessity for the healthy flow of international trade, the elimination of extreme poverty, universal employment and careful planning for the future, with input from stakeholders at all levels of society.

Acknowledgements

Support for this study was provided by NOAA CREST (NOAA/EPP grant #NA11SEC4810004), USDA Hatch 402 Project and NSF CRISP (grant # 1832576). Special thanks to Sofía Burgos Caraballo of the DRNA, Ing. Sigfredo Torres, Senior Science Advisor at the USGS and Dr. Ferdinand Quiñones, Consulting Water Resources and Environmental Engineering. Thanks to Dr. Roberto Rivera of the

UPRM School of Business and Ada Vilches Ortega, graduate student in the Department of Agro-Environmental Sciences, UPRM, for their analysis of the rainfall data for NW Puerto Rico.

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