Water Supply and Water Quality Challenges in Panama

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3.1 Introduction

Urban Panamanian citizens in the first few centuries following European arrival typically obtained drinking water from a pipotero, who sold water out of a barrel transported on a horse-drawn carriage (Fig. 3.1). Rural citizens drew water from hand-dug wells and from streams. The roots of modern Panama's efforts to supply potable water to the public are linked to events that occurred thousands of kilometers away, when the discovery of gold in California created a sudden demand for transportation across the isthmus by gold seekers from the Eastern North America, South America, and Europe. This accelerated economic development and the initiation of the trans-isthmus railroad in 1850. In addition to the ephemeral presence of gold seekers, the railroad-building project brought thousands of immigrant workers to the Isthmus of Panama, which was then part of the new (1821) independent nation of Gran Colombia, intensifying demand for good quality water supply in the cities of Colon, Panama City, and points in between.

The building of the Panama Canal further increased population, economic development, and associated potable water demand, leading to the first aqueducts in Panama City in 1905. The first aqueducts in the interior of Panama were completed in several communities during the period 1914 20. By 1975, a water treatment and storage facility for Panama City, capable of producing 473 million liters of water per day, had been completed.

The Republic of Panama produces 1.07 million m^3 of water per day (data from 2014) for the nation of 4 million people, through more than 60 water treatment plants and a combination of more than 5000 rural aqueducts and wells, at an average cost of 0.25 per m^3 to the consumer [1 personal communication, Julia E. Guardia, Technical Secretary, CONAGUA (Consejo Nacional del Agua)]. More than one half of the nation's population, 55%, receives their water from eight water treatment plants that draw water from the principal reservoirs in the Panama Canal Watershed (PCW): Lakes Alajuela and Gatun [1].

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Fig. 3.1
Pipotero (water carrier), Panama, ca. early century.

Panama, located at 9 latitude (Fig. 3.2), experiences abundant annual rainfall, but like other nations located in the seasonal to humid tropics, nonetheless contends with periodic droughts that limit the availability of potable water. The nation also confronts water quality challenges associated with surface water contamination, sedimentation resulting from deforestation, and diseases associated with water-borne parasites to name a few. Development is uneven, with half the population living in the nation's interior, where water supply and water treatment administrators must manage water infrastructure (including the extensive network of rural aqueducts and wells) across great distances in the 75,845 km^2 country [1]. About 75% of the population of Panama is in urban areas, and national averages in Panama indicate high levels of water access, 98% in urban areas, and 89% in rural areas [2], but these statistics fail to capture the limited access in the remote communities, particularly in the five semiautonomous indigenous regions known as Comarcas, which are generally underdeveloped. For example, according to 2010 Panamanian census data, 91% of the population in the Ngobé-Buglé Comarca lives in extreme poverty and only 59% have access to piped water sources [3].

In 2015, the president of Panama, Juan Carlos Varela, inaugurated a national water plan, meant to improve water availability and reduce hydrological hazards by 2030 [1]. This ambitious effort aims to meet the elements of United Nations Sustainable Development Goal #6: Clean water and sanitation [4]. These elements are as follows:

By 2030, achieve universal and equitable access to safe and affordable drinking water for all.

By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.

Fig. 3.2
Panama location map showing generalized relief and principal urban centers.

By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.
By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.
By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.
By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes.
By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, and recycling and reuse technologies.
Support and strengthen the participation of local communities in improving water and sanitation management.

3.2 Setting

3.2.1 Geography

The Republic of Panama has remarkably good fortune with respect to its geography. At 9 latitude, the country is just far enough south of the Atlantic-Caribbean hurricane zone to escape direct strikes (Fig. 3.3). Furthermore, the central part of the country, where the Canal is located and most of the population resides, is much less seismically and volcanically active than neighboring countries [5 7]. Moreover, as first described by Europeans in the exploration report of Vasco Nunez de Balboa in 1513, the narrow isthmus is an ideal location for an interoceanic canal (and railroad) (Fig. 3.2).

The nation is divided into 10 provinces, 5 comarcas (Guna Y ala, Ngobé-Buglé, Embera Wounaan, Wargandi, and Madugandi), 75 districts, and 623 corregimientos (subdistricts) [8]. Approximately one half of the population resides in the central part of the country, along the route of the canal and railroad, mainly in Panama City and Colon.

On average there is 40% forest cover in the nation's watersheds (Fig. 3.4). The government of Panama and the Panama Canal Authority (ACP) are undertaking measures to combat deforestation and encourage reforestation in the PCW. In 1992, the nation enacted Ley 24 (law 24) that provided incentives for landowners to reforest [9]. In further recognition of the importance of forest cover for assuring good quality water by reducing erosion and reservoir sedimentation, as well as maintaining the rich biodiversity of the region, in 2014, several nongovernmental organizations initiated an ambitious 20-year plan to reforest a land area of

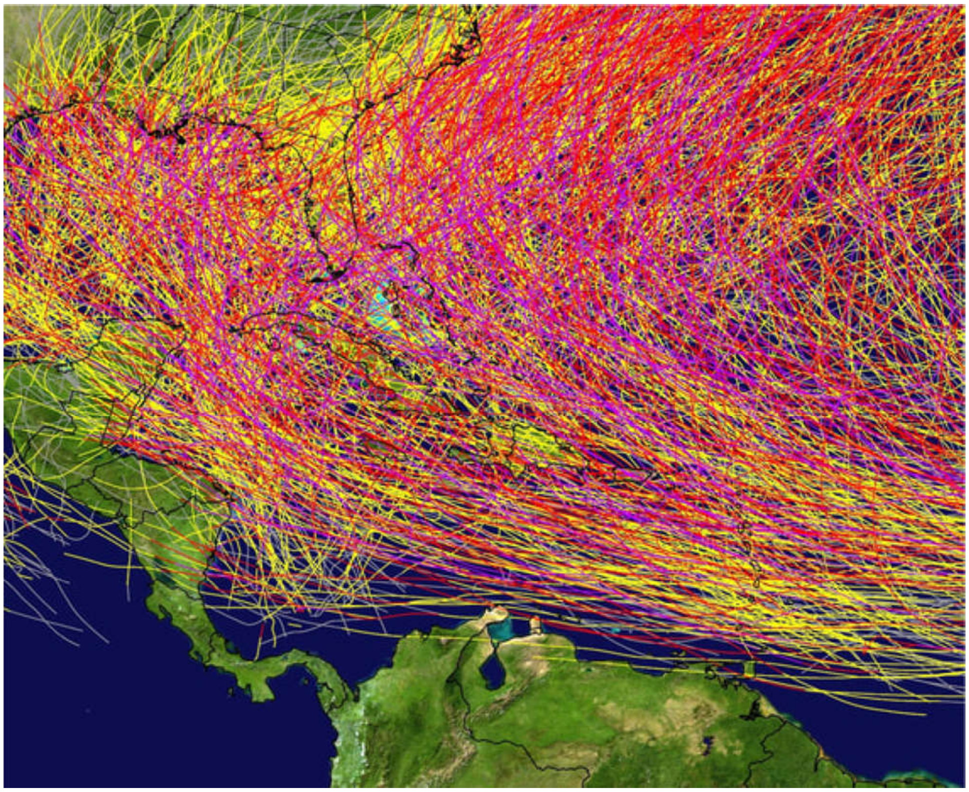

Fig. 3.3
Map showing Atlantic-Caribbean hurricane tracks, 1850 2016, NOAA [7].

1 million hectares, which is 13% of the land surface of Panama [10]. This plan has been adopted and championed by the President of the Republic of Panama, Juan Carlos Varela, as part of the nation's strategy to meet United Nations climate change mitigation goals [11].

3.2.2 Climate

Panama is warm all year round. Mean monthly temperature is 18 C in the lowlands of central Panama, and in the cooler highlands of Western Panama, average monthly temperatures range from 10 C to 18 C [2]. Most of the country experiences strong wet-dry seasonality with a rainy season, controlled by the position of the Intertropical Convergence one (ITC) (see below) from May through December [2].

Panama is water rich with annual precipitation that averages 2924 mm, draining into 500 rivers in 52 watersheds with a total annual discharge of 119 billion m^3. This translates to 29,000 m^3 per capita [1]. Panama's richness in water resources is reflected in its being the eighth highest of 25 Latin American nations in per capita water availability [2]. However, as is often the case,

Fig. 3.4
Landscape in the Panama Canal watershed showing a mosaic of land use types: forest, agriculture, and pasture [54].

this abundant water supply is not well distributed temporally and spatially with respect to the location of population and economic activities.

In the center of the Isthmus, average annual rainfall is 2659 mm (from 1925 to 2017), at the Smithsonian Tropical Research Institute administered Barro Colorado Island Nature Monument, located within the PCW. Annual rainfall totals have a large interannual variation in accumulation, with a low of 1699 mm in 1997 and a high of 4487 mm in 1981 (Fig. 3.5). In addition to the interannual and seasonal variation, rainfall is geographically variable in Panama, with average annual totals of as little as 1500 mm in the Azuero Peninsula (Los Santos area, Fig. 3.2), to as much as 7000 mm in the western mountains (Fig. 3.6). During drought years, which are usually associated with strong El Nino cycles (see below), potable water availability is constrained and the ACP sometimes requires that vessels transiting the Canal do so with reduced draft, which means that the transit fees that ACP receives from the shipping companies are also reduced.

The PCW (Fig. 3.7), with an area of 3313 km^2, is economically the most important watershed in the nation, as it is the primary source of water for the transit of ships. Furthermore, the

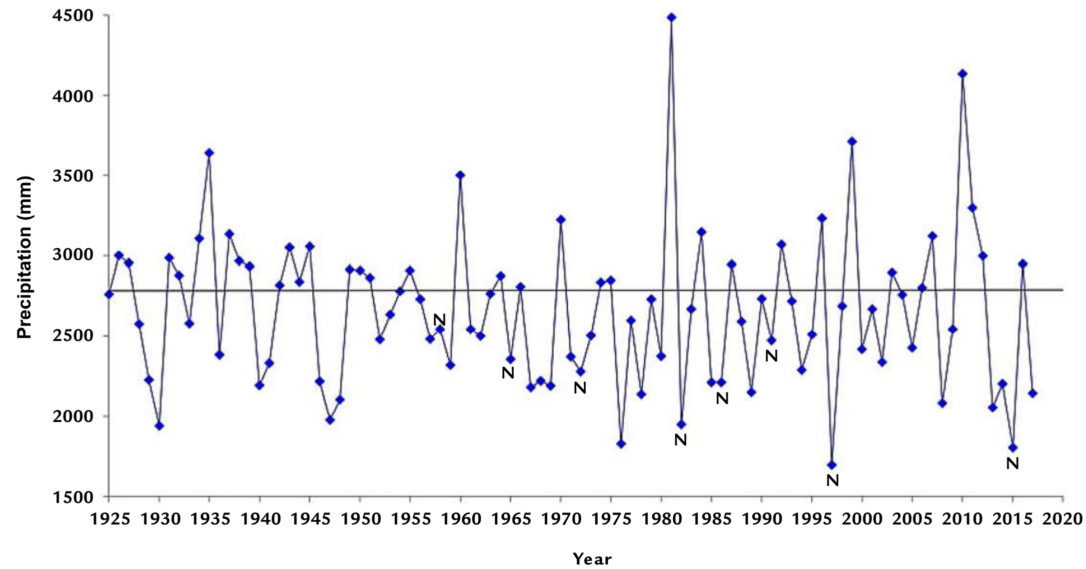

Fig. 3.5
Annual rainfall totals, 1925 2017, Barro Colorado Island, central Panama. Note the low rainfall years associated with the eight strongest El Nino events in from 1950 to 2015. Data from S. Paton, written communication, Smithsonian Tropical Research Institute C.A. Vargas, Panama Canal water resources management, in J. Wallace (Ed), Hydrology and Water Law: Bridging the Gap, London, IWA Publishing, 2006, pp. 143 158.

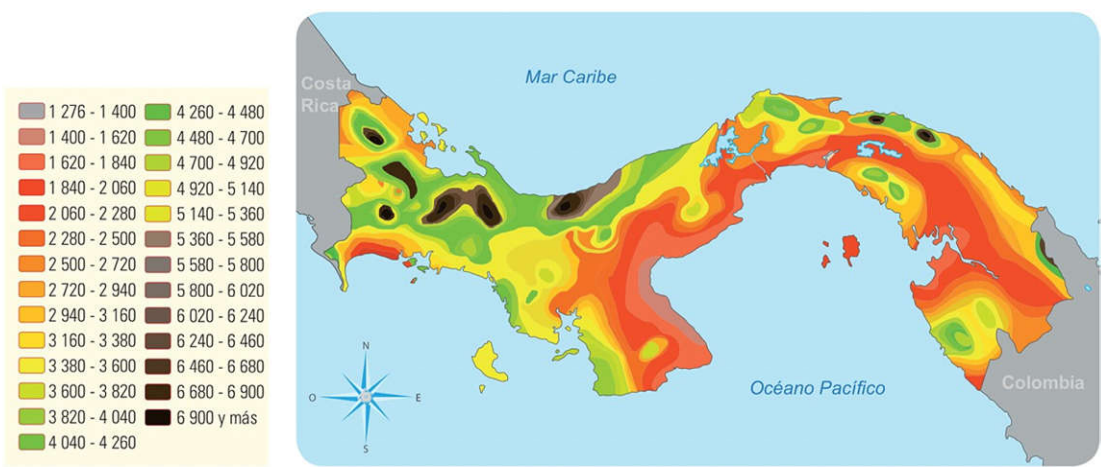

Fig. 3.6
Map showing average geographic distribution of rainfall in Panama, in millimeters per year [2].

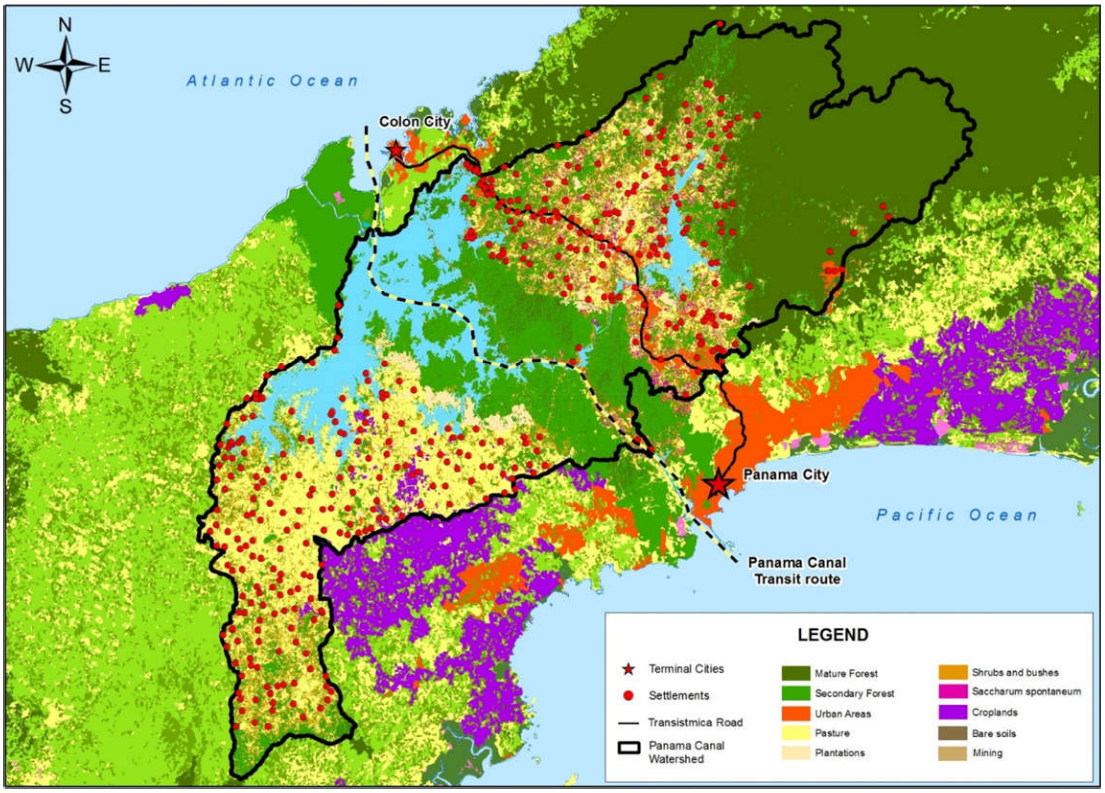

Fig. 3.7
Panama Canal watershed map showing generalized land use [54].

watershed provides 95% of the drinking water for the inhabitants of the cities of Colon, Panama, and San Miguelito, where more than one half of the country's population is concentrated [12]. Additionally, hydroelectric generation facilities at the principal reservoirs in the watershed, Gatun and Alajuela, supply some of the nearly one half of the electrical energy of the country that is derived from hydropower generation [13]. As much as 10% of the electrical energy demand of the nation is derived from wind turbines [14].

Climate and seasonality are dominated by two synoptic drivers: the Inter-Tropical Convergence one (ITC) and the El Nino Southern Oscillation. The ITC is an area of low pressure circling the Earth at or near the equator where the trade winds of the northern and southern hemispheres converge, known by early seafarers as the doldrums (Fig. 3.8). This convergence results in atmospheric turbulence and convection, generating thunderstorms and delivering much of the annual rainfall to the ITC region around the world. Seasonality in Panama is controlled by the latitudinal location of the ITC , which shifts, as a result of sun angle, to the north from May to December, bringing abundant rainfall to the region, particularly toward the end of the season. From mid-December to early-May, the ITC shifts south, resulting in a dry season, bringing cloudless days and an increase in trade winds [16].

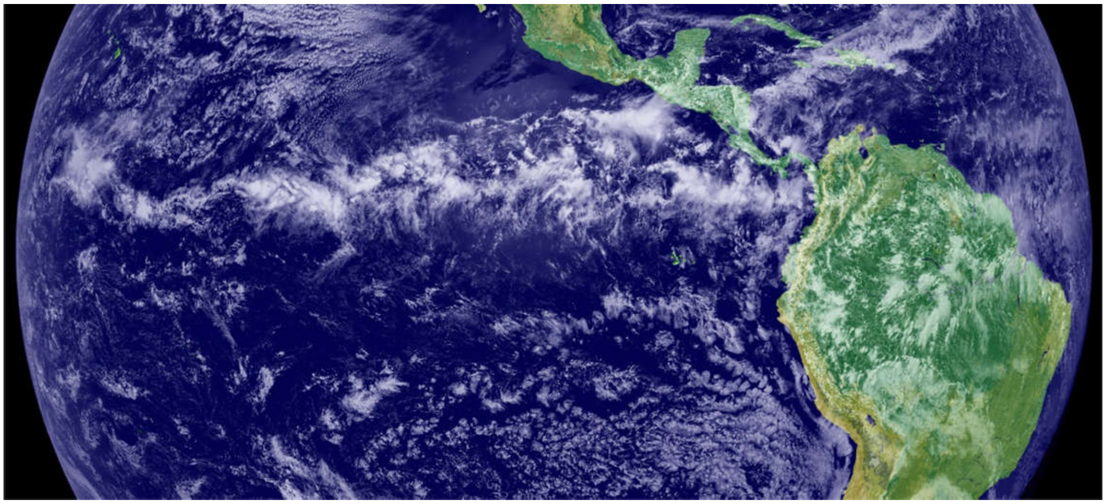

Fig. 3.8
The Intertropical Convergence one (ITC), visible as a combination of cloud data from NOAA's Geostationary Operational Environmental Satellite (GOES-11) and color land cover classification data. The ITC is the band of bright white clouds across the center of the image [15].

El Nino is defined as an irregularly occurring and complex set of climatic changes that directly affect the equatorial Pacific region and beyond every few years [17]. It was first described by fishermen on the South American coast in the 1600s because of the effect it had on their catch. El Nino is characterized by the appearance of above-average warm and nutrient-poor water off the Northern Peru and Ecuador, typically in late December at the time of Christmas, hence the name. Strong El Nino periods (Fig. 3.9) are associated with drought in Central America, including Panama, and can result in severe water shortages across the country [18].

3.2.3 Economy

More than three-fourths of the national economy measured by GDP is concentrated in industries directly linked with shipping (ports, transshipment, logistics, and ship registry) or adjacent sectors such as banking, finance, and insurance [19]. Shipping through the Canal is entirely dependent on annual rainfall and operation of the two major reservoirs in the PCW: Gatun and Alajuela. Most surface water reservoirs around the world are operated with three principal but conflicting goals: water supply, flood control, and power generation. The ACP contends with the annual late wet season challenge of maximizing water storage in preparation for the dry season, while at the same time retaining some excess storage capacity to manage possible flooding if heavy rains occur, such as in December 2010 [20]. Recreational use and sustaining biodiversity are also important reservoir management goals in Panama, however, the top goal, unique to Panama, is for lockage of vessels transiting the canal (Fig. 3.10). This is the lifeblood of the nation, generating 2B+/year gross revenues, half of

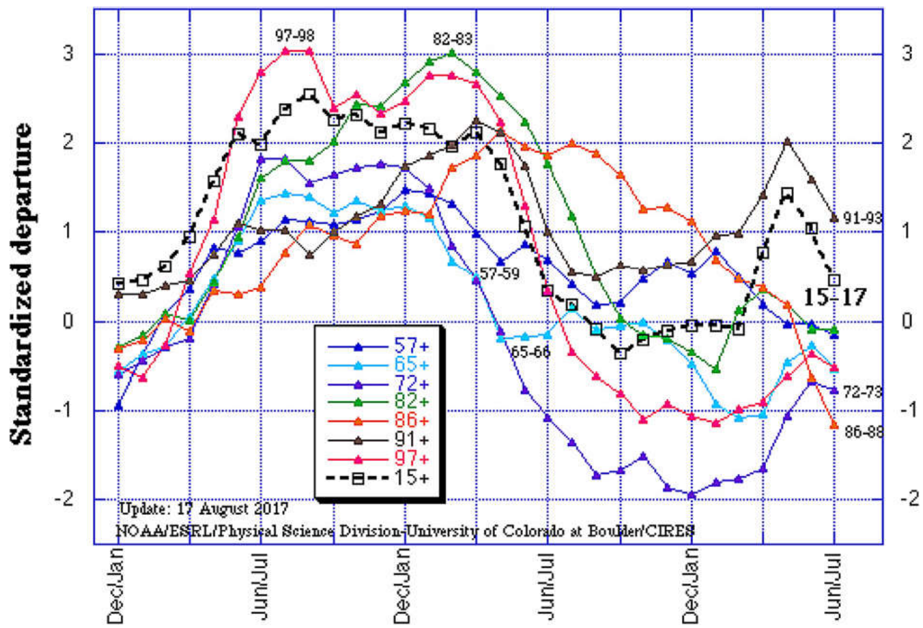

Fig. 3.9
Graph of ENSO index for the eight strongest El Nino events from 1950 to 2015 [43].

which is used for canal operations. The canal sustains 10,000 direct jobs and an estimated 200,000 related jobs. In addition to this key economic activity, the ACP, which is a quasi-autonomous state institution, provides approximately 1 billion per year in net income from Canal operations to the national treasury [21]. As such, the Canal and, by extension, the national economy, are highly dependent on a readily available quantity of freshwater supply in the watershed, which prior to the completion of the Canal expansion project [21, 22] in 2016, annually averaged a total of 4.4 km^3 (4.4 billion m^3) in volume, with 59% (2.6 km^3) used for canal lockages, 27% for hydroelectric power generation, and 6% for potable water supply [23, 24]. The balance is mainly water consumed by evaporation, groundwater infiltration, and uncertainties in the data.

Industrial activity not associated with the shipping industry includes production of fish oil, rectified alcohol, poultry, sugar, alcoholic beverages (aniseed, beer, cognac, gin, rum, wine, vodka, whiskey), cement blocks, footwear, cigars, dried fruit, tomato derivatives (concentrate, juices, pasta, sauces, whole tomatoes, etc.), detergents, fishmeal, ice cream, bar soap, condensed milk, evaporated and powdered, pasteurized milk, pasta, and salt [2].

Tourism and ecotourism are a modest but growing element of the economy, for example, Panama is home to 1000 species of birds, 10% of the global count, and to 13% of bat species. For a small country, biodiversity is impressive, in part because the isthmus serves as a corridor for annual migration of many birds and mammals [25]. Expansion of tourism is ongoing and in

Fig. 3.10
Panama Canal infrastructure: (A) Panamax vessels transiting Miraflores Locks, near Pacific coast, 2017 (B) Construction of new locks at Agua Clara, near Caribbean coast, to accommodate NeoPanamax vessels (C) Construction of new locks at Agua Clara, lock door housing visible in center of image (D) Aerial view of old and new locks at Miraflores, showing water reuse basins on center left. Photo sources: author, and Autoridad del Canal de Panama.

2017, the government of Panama announced that a 166M cruise ship terminal in Panama City would open in 2019 to accommodate two cruise ships at a time [26]. In the meantime, the ACP expects 235 cruise ships to transit the canal during the 2017 18 seasons [27].

3.3 Water Availability and Infrastructure

Like most countries, the Republic of Panama does not conduct a detailed regular national water use assessment [28]. Various compilations of water use information have been published, but because they vary in scope, methodology, and frequency, it is difficult to make direct comparisons and analyze changes in water use with time [1, 2, 8, 29]. As such, the data presented in the most recent compilation, 2015 National Water Plan, are used here as the principal and authoritative source for water resources information [1].

3.3.1 Water Availability

Panama's average annual precipitation is 2924 mm (ranging from 1000 to 7000 mm) [1]. According to the National Water Plan, approximately 50% of this is converted to infiltration, runoff, and evaporation. The balance is presumably consumed by evapotranspiration by vegetation, or is converted to temporary storage. Note that infiltration recharges groundwater supply, but although groundwater is estimated to supply 10% of the population, mainly in rural areas, only limited groundwater data exist for the nation [1, 30].

In a rating of the physical and socioeconomic factors associated with water scarcity called the International Water Poverty Index, Panama was ranked at 25 in a list of 147 countries, in which number 147 is estimated to be the most water impoverished [1, 31]. The index is meant to reflect measures of resources, access, capacity, use, and environment, and links household welfare with water availability. At rank 25, the index puts Panama in a favorable position, in the top 20% of nations. The index serves as a general tool to evaluate the resources available and the socioeconomic factors which affect access and use of those resources, but, as noted above, there are strong differences in water access between urban and rural areas, particularly when considering water access in the Comarcas.

With respect to water pricing, in a 2014 World Bank assessment of more than 130 countries, Panama had an average price of potable water and sanitation service of 0.25 per m^3 [1, 31]. This places Panama at rank 13 for the least expensive cost.

3.3.2 Water Infrastructure

3.3.2.1 History

With the completion of Lake Gatun in 1914, Panama had the largest artificial freshwater lake in the world. The lake, created by damming the Rıo Chagres, was impounded mainly for the passage of ships through the newly opened Canal, but also serves as a source of high-quality water. In 1935, a second reservoir was completed, Lake Alajuela, also in the PCW, upstream of Lake Gatun. These reservoirs supply drinking water to about one half of the population of Panama, principally in the Canal region, including the cities of Colon and Panama. As such, in the early decades of the 20th century, water supply for the Republic's two largest cities, Panama City and Colon, was provided through facilities in the US occupied Canal one.

In the 1950s, the United States Panama Canal Company transferred control of its pumping stations, valves, and pipe networks in the Republic of Panama to the first Panamanian national water utility, Comision de Acueductos y Alcantarillados de Panama (Water and Sewer Commission), which was established in 1956. The Panama Canal Company continued to provide water service in the Canal one but this arrangement was phased out after the Torrijos

Carter treaty was signed in 1977, with the principal goal of transferring the Canal and Canal one to Panama, and closing US military bases, starting in 1979 and concluding in 1999 [19].

The current principal water utility, Instituto de Acueductos y Alcantarillados Nacionales (IDAAN) (National Institute of Aqueducts and Sewers), was established in 1961 to improve the national system of water and sewerage services and meet demand in expanding urban areas [1].

3.3.2.2 Hydrologic and meteorologic monitoring

Several agencies in Panama manage the operation of a national meteorological and hydrological observation and monitoring network. As of 2013, this hydrometeorological network included 90 hydrological stations and 194 meteorological stations [2].

The 90 hydrological stations were mainly (63) operated by the ACP, with the balance, 27, operated by the Electric Transmission Company (ETESA). Only 19 of the 90 stations transmit information in real time 12 of these are located in the PCW and the other seven in the Bayano watershed. Without real-time information, decision-making during droughts, and particularly during floods, is hampered.

The 194 meteorological stations are managed by MiAmbiente (26), the Civil Aviation Authority (14), the ACP (54), and ETESA (100). Most of the stations are located on the Pacific slope, so the central mountain range, the source of many of the largest rivers of the nation, has limited information for effective watershed management [2].

According to the 2015 national water plan [1], the nation operates 263 hydrometeorological station, which includes 165 meteorologic stations and 67 hydrologic stations. The slight decrease since the 2013 report cited above suggests that some stations in the hydrometeorological network have been discontinued in recent years.

3.3.2.3 Reservoirs

In all, 10 multiuse reservoirs provide surface water resources to the nation: Alajuela, Bayano, Changuinola, La Estrella, Fortuna, Gatun, Mendre I, Miraflores, Los Valles, and La Yeguada [1]. The most important of these are Alajuela, with a surface area of 50.2 km^2 (volume of 643 million m^3), Bayano, surface area of 353 km^2 (4787 million m^3), Fortuna, surface area of 10.9 km^2 (volume 221.7 million m^3), and Gatun, surface area of 436.2 km^2 (volume 769 million m^3) [2]. When construction and impoundment were completed in 1914, Gatun was then the largest artificial lake in the world, with a surface area that is five times the area of Manhattan, New York.

3.3.2.4 Water and sewage treatment

In 2010, 51 water treatment facilities served a population of 2,072,351 [2]. The main provider of the service, IDAAN, with approximately 500,000 customers, provides drinking water services, and collects and disposes of wastewater in communities larger than 1500 inhabitants.

According to IDAAN, these 500,000 customers represented approximately 74% of the population. Only 57% (1,483,321) of the population (43% of customers) receive sewerage services from IDAAN. Much of the remaining population uses septic tanks [2]. According to the national water plan [1], as of 2014, there were 60 water treatment plants producing 1.07 million m^3/day of potable water.

3.3.2.5 Groundwater

Estimated groundwater use across the nation in 2002 was reported at 87,200 m^3 per day, about 10% of the total annual human water consumption [2]. Groundwater is reported by Autoridad Nacional del Ambiente (ANAM) [30] to be abundant and of good chemical quality in most provinces. However, in the provinces of Coclé, Darién and in the Azuero Peninsula, groundwater is scarce and has elevated levels of salinity and hardness [30]. In general, groundwater resources in Panama are not well studied, and their recharge zones and characteristics such as transmissivity, hydraulic conductivity, recharge rates, contamination sources, saline intrusion (for coastal aquifers) and hydrogeochemistry are poorly known.

In 1999, ETESA published a hydrogeological map of Panama at a scale of 1:1,000,000 (Fig. 3.11). The map is a first approximation of the classification and delimitation of aquifers in Panama, but, at this scale, the map only provides a general tool for aquifer characterization and management [32]. Three types of aquifers and their respective hydrogeological units are described in the map:

1. Predominantly intergranular aquifers (continuous, usually unconsolidated).
2. Predominantly fractured rock (discontinuous) aquifers.
3. Areas with local aquifers (intergranular) of limited or insignificant productivity.

3.4 Water Use

As noted above, Panama's average annual precipitation of 234 billion m^3 averages out to 2924 L/m^2 across the country, which equals 119.5 billion m^3, after infiltration, runoff, and evaporation are excluded [1]. Only 26% of the 119.5 billion m^3 are used but estimates are that increasing water demand will raise this value to 50% by 2050 [1].

The greatest single user of freshwater at more than 2 km^3 per year is the ACP, because the Panama Canal operates almost entirely on a gravity-driven freshwater system of locks supported by the Alajuela and Gatun reservoirs. Each lockage through the canal is accomplished through the gravity flow of freshwater into the lock, which after several steps, is spilled into the Caribbean Sea or Pacific Ocean. Panamax vessels, those designed for the original locks completed in 1914, use on average 200,000 m^3 of water per single transit [23].

Water use is characterized into two general sectors: consumptive use, and nonconsumptive use. Consumptive use is that water which is not returned immediately to the water cycle, and

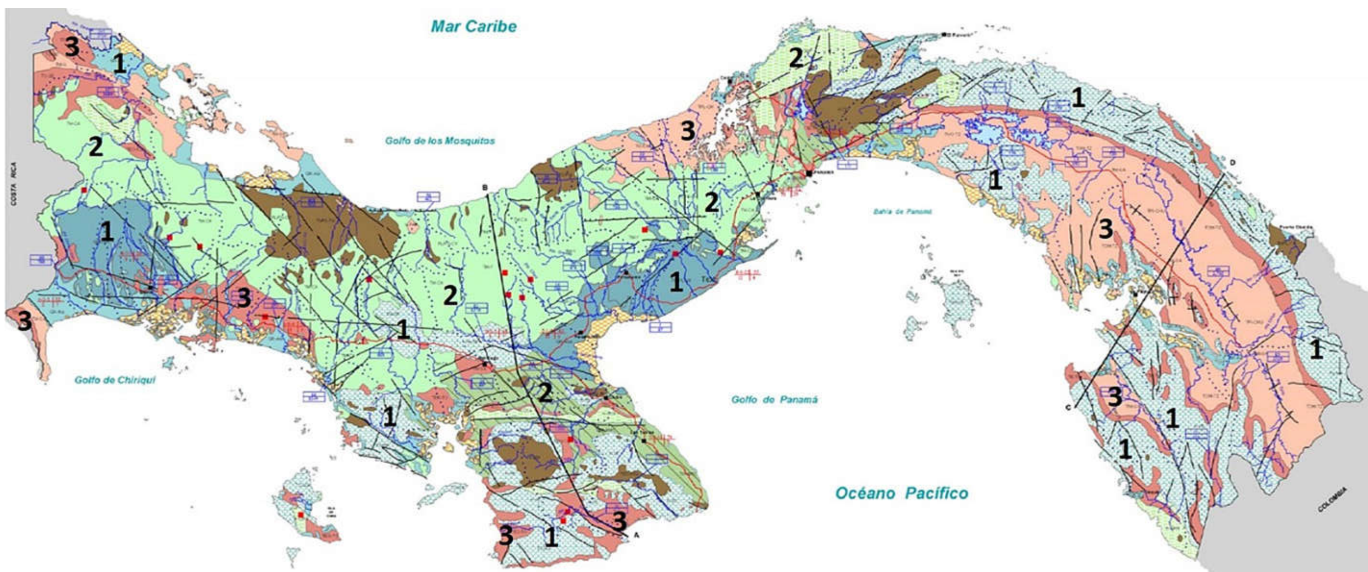

Fig. 3.11

Generalized hydrogeological map of Panama showing three aquifer types: 1. Predominantly intergranular aquifers (continuous, usually unconsolidated). 2. Predominantly fractured rock (discontinuous) aquifers. 3. Areas with local aquifers (intergranular) of limited or insignificant productivity. *Modified from ETESA. Mapa hidrogeológico de Panama, Escala 1:1000000. Available from: http://www.hidromet.com.pa/Mapas/Mapa_Hidrogeologico_Panama.pdf; 1999.*

includes human consumption (1.3% of the total of fresh water used), the agricultural sector (1.7%), industrial use (0.02%), and recreational tourism sector (0.01%).

Only 12% of agriculture is irrigated, mainly in the area of the Azuero Peninsula for the production of rice, pineapple, and melon. In addition, the Azuero Peninsula is key to the livestock sector, which accounts for approximately 7% of GDP [2]. Most irrigation systems are gravity systems, followed by spray, and a small but increasing amount of drip irrigation. Approximately 25,000 ha of land were irrigated in 1997 and data from 2009 indicate that 503 million m^3/year of water was used for irrigation [2]. The balance of agriculture is rainfed, much of it in the western province of Chiriquı. The principal crops in Panama are rice (32%), with a combination of sugar, corn, coffee, and citrus accounting for a total of 80% of agriculture. The remaining 20% is mainly bananas, plantains, beans, and pineapple.

Nonconsumptive water use includes the hydroelectric sector (89.6% of total use), and the operation of the Panama Canal (7.4%), for the lockages of ships [1].

Lastly, unaccounted water use, that is, water lost in the system through leaks, broken pipes, and informal connections, was estimated at 232 million m^3 [1, 33]. Note that 232 million m^3 is greater than the volume of the Alajuela reservoir.

3.5 Water Quality

The Republic of Panama does not conduct a robust, regular, detailed national assessment of water quality conditions in rivers, streams, lakes, and groundwater aquifers [2]. These types of assessments are costly and require a sustained system for sample collection, analysis, quality assurance/quality control, and publication of data [34]. Nonetheless, some water quality data are available. These data are mainly collected and published by the ACP at 643 sites in the PCW [35] and by MiAmbiente [36] at 292 sites in other watersheds. MiAmbiente used the data to establish an Indice de Calidad de Agua (ICA, or Water Quality Index) based on dissolved oxygen levels, biochemical oxygen demand, and other parameters [2].

A total of 643 ICAs were calculated for sampling sites in the PCW of these, 111 records correspond to the Alajuela reservoir, 288 are from the Gatun reservoir, and 60 records correspond to the Miraflores reservoir. The balance are from other sites in the PCW, many on the Chagres River [35].

The ACP characterized 17% of the records as indicating excellent water quality, 78% had a good ICA, and 5% were characterized as average quality. The ICAs with average water quality were mainly found in the Chilibre, Cano Quebrado, Los Hules watersheds, and along the middle section of the Chagres River. This lower rating was assigned because concentrations of Escherichia coli and orthophosphates were above the desired levels.

The quality of the water in the Alajuela and Gatun reservoirs complies, in general terms, with requirements for: supply for human consumption with simplified treatment (i.e., slow filtration and disinfection or only disinfection) conservation of aquatic communities irrigation of vegetables that are consumed raw recreation of low risk and aquaculture [35].

On comparing 2009 data with the average conditions reported for the period 2003 07, concentrations and values of total coliforms, nitrates, total dissolved solids, sulfates, pH, and dissolved oxygen all registered declines in most stations of the main rivers, although some sites showed an increase in nitrate levels. Water temperature registered an increase in almost all the stations of the main rivers, between 1.2 C and 1.6 C warmer at some stations, possibly reflecting the multiyear atmosphere warming observed in Panama and around the world [37, 38]. Not surprisingly, according to the ANAM 2009 report, rivers in the Panama City metropolitan area (Curundu, Matıas Hernandez, Juan Dıaz, Matasnillo, Abajo, and Tapia) were the most contaminated.

According to ANAM [36] the principal industrial activities that degrade water quality in Panama include: processing of fish, crustaceans, and other marine products packaging and preservation of fruit and vegetables manufacture of paper and paperboard cattle slaughtering, preparation, and preservation of meat cattle breeding for milk production and the manufacture and bottling of nonalcoholic and aerated mineral waters.

In addition to these types of chronic human-caused contamination and degradation, rare, large magnitude storms such as La Purisima (December 7 9, 2010) have significant impacts on water quality. Rainfall associated with this extreme event, characterized as a 1 in 300-year storm [20] caused major flooding along the main tributaries to the Alajuela reservoir, and transported a heavy sediment load (derived from hillslope, channel, and bank erosion plus upstream landslides). The storm increased suspended solids and turbidity, which degrades the water for human consumption and negatively affects the lake ecosystem by decreasing light penetration through the water column. These effects lasted for many weeks after the storm [20].

3.5.1 Water Quality Degradation and Disease

The Republic of Panama has an estimated 7.5% 31% of the population living in remote, underdeveloped areas including indigenous people in the five Comarcas, who have limited access to good quality potable water and sewage treatment facilities [1]. In 2007, waterborne diseases reported were as follows: 5268 cases of amoebiasis, 186,760 cases of diarrhea, 1179 cases of intoxication, 76 cases of salmonellosis, and 26 cases of shigellosis [2, 36]. In 2014, the leading cause of death in the Comarca Ngabe-Buglé was diarrhea and gastroenteritis [39].

These water-borne diseases are mainly associated with a lack of disinfection treatment of potable water. An additional cause can be attributed to inadequate maintenance of water infrastructure and water supply systems, described here with an example from Arraijan, Panama, published by Nelson and Erickson [40]. In areas with inconsistent water pressure, negative pressures in the distribution system represent a risk to water quality because the lower pressure allows ambient water to enter pipes, raising levels of total coliform and E. coli bacteria and lowering free chlorine residual levels. Intermittent supply leads to microbiological problems in water quality, because of several factors: the intrusion of contaminated groundwater via leaks in underground pipes or backflow of contaminated water through customer connections during periods of low and negative pressure the potential for regrowth of microorganisms in the water and in biofilms on pipe walls when the water is turned off and sits stagnant in pipes and recontamination and microbial regrowth during household storage [40].

In their study, Nelson and Erickson document that Arraijan's network experiences frequent pipe breaks. During 2014, IDAAN's operations crews repaired 604 breaks in pipes of diameter 5 cm or larger (1.46 breaks per km per year). Although this break rate puts IDAAN's Arraijan system near the average of 13 Latin American utilities that participated in a regional benchmarking report, it is much higher than the average of 0.068 breaks per km per year documented in a study of 188 utilities in the United States and Canada [40].

Nelson and Erickson [40] also noted that despite a high per capita production of 590 L per person per day, service is deficient in much of the Arraijan network. High measured flows entering the study zones and high flows during nighttime hours suggest that significant water losses were occurring within the study zones, either in distribution pipes or household plumbing.

3.6 Challenges and Opportunities

3.6.1 Challenges

Water availability or scarcity is a function of a host of factors, including governance, climate- and weather-controlled supply, consumer behavior, management and condition of distribution networks and infrastructure, as well as political and management choices such as pricing [19].

The population of the Republic of Panama, at 4 million, has doubled since 1980, a period of 37 years. (For comparison, the current US population took 67 years to double.) This high rate of growth and associated rapid economic development, urbanization, adverse effects of global climate change, and environmental deterioration, combine to increase pressure on water resources. Panama's economic growth rate in 2017, according to the International Monetary Fund, at 5.3%, was the highest in Latin America [41]. Intensifying the challenges ahead, population is expected to reach 5.6 million by 2050 [1].

When the largest water infrastructure project in the nation's history, the Panama Canal, was undertaken at the beginning of the 20th century, the new nation of Panama had a population of approximately 300,000 and the number of vessels making the canal transit was a fraction of the current 15,000 per year. The assumption at the time was that freshwater resources were plentiful beyond the expected requirements [42]. In recent decades this notion of abundance has been questioned, because of increasing conflicts over the use of water, particularly during droughts. As noted above, prior to the completion of the Canal expansion project in 2016, the annual average of water used by the Canal totaled 4.4 km^3 (4.4 billion m^3) in volume, with 59% (2.6 km^3) used for canal lockages by ships up to Panamax in size [23, 24]. Each Panamax ship that transits the original canal requires approximately 200,000 m^3. The ACP estimates that in 2017 a total of 1.67 km^3 was used for Panamax transits, with 0.6 km^3 used for NeoPanamax (vessels that use the new, larger locks) transits, totaling 2.27 km^3 and projected to increase to 2.77 km^3 by 2050 [1]. This projection may be too modest, considering the success of the Panama Canal operation since ACP began managing the Canal in 2000.

Potable water, energy, food, and navigation systems all make demands on the same water sources. As such, the Panama Canal's hydrological reliability— the ratio of available water volume to the volume demanded for normal transportation operations and various municipal uses [43] must be considered in relation to circumstances beyond the control of the Republic of Panama: a global transportation infrastructure that is a key element of economic globalization [19].

With respect to water resources, it has been said that you can't manage what you don't measure [44]. Without a sustained robust, regular, detailed national assessment of streamflow, lake level, groundwater conditions and water quality conditions in rivers, streams, lakes, and groundwater aquifers, effective management of water resources will be constrained. Furthermore, at least some of this type of hydrometeorological network must have real-time data transmission capability if flood hazard warnings are to be effective. As noted above, these types of assessments are costly and require a sustained system for sample collection, analysis, quality assurance/quality control, and publication of data.

Since 1950 there have been six strong or very strong El Nino periods, each of which has reduced water availability in Panama [1, 45]. It is possible that with global warming and the greater uncertainty in the extremes of weather and climate expected in the future, we will see increased frequency and intensity of El Nino and associated drought in Panama and elsewhere in Central America [37]. The drought associated with 2015 16 El Nino strongly affected the PCW, and in May 2016, the Gatun and Alajuela reservoirs registered their lowest levels in 103 years [1]. In addition to the impact on Canal operations (vessels were required to transit with reduced draft, hence reduced load and tariffs paid to the ACP), the drought strongly affected livestock activity in the Azuero Peninsula, where many cattle were lost.

Regardless of changes in El Nino, increasing global air temperatures will have an effect on water resources in Panama because of increased evaporation and temperature and evapotranspiration stress on vegetation [7, 37, 46]. It is unknown whether the increased evaporation will lead to more precipitation in Panama, but most climate models predict higher intensity and more episodic delivery of rainfall, which may mean that Panama will experience shifts in the temporal distribution. An associated challenge is that reservoir storage may sometimes be overwhelmed and flooding, particularly in urban areas, where natural controls such as wetlands and mangrove forests have been greatly reduced in area, may increase [7, 37, 47].

In 2015, 71% of the global population (5.2 billion people) used a safely managed drinking-water service, defined as one that is located on premises, available when needed, and free from contamination [48]. Many of these people are first-time users connected to newly built systems. This means that the challenge facing universal water access is shifting from building infrastructure, to maintaining it [49, 50]. Governments rarely price water at a level sufficient to guarantee the revenue needed to maintain infrastructure [51]. This is a near universal challenge, resulting in deterioration of distribution networks, with system leaks that can often equal half or more of water produced [49]. The Republic of Panama encounters the two-sided challenge of both expanding and enhancing national-scale water resources infrastructure, as described in the Water Plan [1] and also faces the difficulty and cost of maintaining existing infrastructure.

3.6.2 Opportunities

The Republic of Panama faces a number of challenges, briefly described above, but these also serve as opportunities for government, private sector, nongovernmental organizations, and citizen leaders to collaborate and develop solutions that will mitigate some of the problems and prepare the nation to adapt to others. With the economy growing at a rapid rate, and population expanding at the same time, government income derived from corporate and individual taxes can provide the necessary revenue to improve the water infrastructure. This requires not only the government investment over a sustained period, as described in the National Water Plan [1], but also depends on appropriate water pricing to incentivize careful water use. The evaluation of water pricing, which has been static in Panama for nearly 40 years, is long overdue but politically and socially sensitive [1]. Sustained political will is essential as each 5-year presidential administration will have to decide what priority to place on the multiple goals of the water plan.

The water plan has ambitious goals for improving water infrastructure. One of these is the recognition of the importance of reducing leaks in the system, which are estimated at 40% 48% of production [1]. New reservoirs are a typical solution for water resource needs, but are increasingly recognized as problematic because of ecological concerns as well as the social impacts resulting from the displacement of communities in areas slated for water impoundments [52]. By reducing system leaks to under 1%, the nation could achieve the equivalent of constructing a new reservoir of the size of Alajuela.

As the largest single user of freshwater, the ACP has a key role in the future of water resources in Panama. They have long recognized the need for greater efficiency in water use, for example, with the reuse of water (estimated at 60%) in the new locks of the expanded 2016 Canal (Fig. 3.10D). It remains to be seen how effective this design will be in the long run and if other efficiencies can be found [53, 54]. Because of their annual (2015) water use of 2.6 km^3, ACP decisions regarding water management will likely have the greatest effect of any decision on the water resources regarding the future of Panama. One of these decisions pertains to the use of hydropower for electric energy generation, which currently averages 1.2 km^3 per year, or 27% of the total annual water flow through the PCW. The expansion of wind power in Panama demonstrates that future energy needs can be at least partially met with renewable energy sources such as wind and solar [14].

As stated above, you can't manage what you don't measure. Development of a sustained, more sophisticated hydrometeorological monitoring network, including real-time capability for some portion of the monitoring stations, will improve the ability of the Republic to manage water resources and strive for increased efficiency [49]. The real-time monitoring capability is critically important in managing flood hazard, in order to give timely evacuation warnings to communities at risk. Good governance is equally important, in assuring that development of flood plains, wetlands, and mangrove forests is not allowed [47].

Global climate change is of course the external driver that is beyond the ability of Panama to control. It is a challenge that Panama, like all nations, increasingly faces, made more complex by the greater uncertainty of future temporal and spatial rainfall distribution [37]. The fundamental adaptation required is to design water supply systems for as much resilience as possible.

Although there is little that a small nation can do directly to mitigate the problem of increasing global temperature and rising sea level, there are indications that even the United States, which has one of the highest per capita carbon emissions and has recently announced its intention to withdraw from the Paris Climate Agreement, continues to make progress in national policy. For example, the United States National Defense Authorization Act, signed into law in 2017, requires the secretary of defense to prepare a report about the impact of climate change on military installations. The law states that it is the sense of Congress that climate change is a direct threat to the national security of the United States [55].

Watershed protection and reforestation are essential steps that increase resilience and provide a number of additional benefits to the nation, as the world faces temperature and precipitation uncertainty resulting from global climate change [37]. Between 1992 and 2000, Panama's forest area decreased by a total of 330,599 ha, and in the period 2000 08 it fell by 109,055 ha (from 44.9% to 43.4% of total cover) [36]. The recent national goal to reforest 1 million hectares of land (13% of the nation) is an ambitious but reachable goal that will help reduce seasonal and interannual variation in water availability in the future, through the effect of forest cover in reducing runoff, improving soil permeability, among other enhancements, such as maintaining biodiversity [56].

3.7 Conclusions

The Republic of Panama has a unique and fortunate geographic setting that combines abundant annual precipitation, relatively low seismic risk, and a neotropical location that is just south of the Atlantic-Caribbean hurricane zone, thereby sparing the nation from the intense destructive capability of these storms, which seem to be worsening as global warming advances. The importance of the last point, that is, the catastrophic effects of hurricanes, is evident in what was recently witnessed with the complete disruption of the water and power distribution system by Hurricane Maria (September 2017) affecting 3.5 million people on the 9000 km^2 island of Puerto Rico [57].

The most important aspect of Panama's geographic setting is of course the isthmus itself, which provides the remarkable transit opportunity in the global shipping arena. The advantage of the isthmus for international transit is key to a long history of relative economic stability, with sustained development, starting with the first transcontinental railroad in the new world, to the only interoceanic canal in the hemisphere. The railroad and the Canal have provided a base for economic activity that sustains the national economy, thereby providing income for a good water supply system across the country.

A key factor within the control of the government of the Republic of Panama is improving the maintenance of water resources, treatment, and distribution infrastructure, a challenge common to most nations. This depends on strong governance in the water sector, and may require consideration of water pricing. Additionally, centralized water and climate monitoring can help assure the consistent collection, quality control, and publication of hydrometeorological data. The National Water Plan launched in 2015 is ambitious and if fully implemented will make substantial progress toward these goals. This long-term action plan identifies five major objectives over a 35-year horizon, which are as follows: (1) universal access to quality water and sanitation services (2) water for inclusive socioeconomic growth (3) preventive management of risks related to water (4) healthy watersheds and (5) water sustainability. Under the water authority of Panama, IDAAN, the plan includes a 1.9B investment for 181 infrastructure projects that would construct water and sewage treatment projects to serve 1.3 million people [1].

If the national leadership successfully partners with private and public sector interests, the Republic can address the many internal challenges affecting water resources and will be prepared to adapt to the external uncertainties ahead. Engaging all stakeholders in solving water resources challenges is essential to any long-term, sustainable solution [1, 49, 56, 58].

The resulting resilience of the nation's water resources systems will be critical in helping the nation manage these external forcing factors, such as climate change and sea level rise, which pose serious challenges— with increased variability in the amount and timing of precipitation being the most important.

Warmer temperatures, already being observed, will further stress natural and human systems, mainly in agriculture, cattle ranching, and in the forested watersheds that are particularly important for the water supply of the nation. Since 1970, global surface temperature rose at an average rate of about 0.17 C per decade [38]. In the longer term, some decades in the future, the ACP may have to compete with shipping through the Arctic passage, at least for part of the year, if summer sea ice extent continues the current shrinking trend [59, 60]. From 1979 to 2012, annual mean Arctic sea ice extent decreased 3.5% 4.1% per decade [37, 38]. Arctic sea ice extent in January 2018 was the lowest January extent in the satellite record and was below the previous record January low in 2017 [60].

For recognizing these and other serious challenges for water resources that lie ahead, the government of Panama has initiated active steps. As stated in 2016 by the Minister of Environment, Mirei Endara, Panama's water plan represents a key stepping stone toward guaranteeing fair access to water for all residents and the productive sectors, insuring the protection of water resources and the ecosystem in a changing climate [61].

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