

Cuba



Panoramic view over Havana. Down to the left it is possible to see the chamber of the groundwater grid, used to impede the entrance of objects and sands into the siphon through the tunnel which crosses the bay from one side to the other. Photo credit: ©iStock.com/FrankvandenBergh

“The principal threats to the inland water system and water quality in island territories in the Gulf of Mexico and the Caribbean are associated with the rise in sea level. In general, processes associated with climate change represent an important threat to life and livelihoods in communities in Cuba and all regions of the world”



Singularities of Island Aquifer Management in the Humid Tropics: the Urban Water Cycle in Havana, Cuba

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Summary

This chapter explores the geological environment giving rise to the terrestrial phase of water cycle development in the islands of the Gulf of Mexico and the Caribbean. We review the status of water resources in this geographical region, using Cuba, and specifically Cuba's capital, Havana, as our example, and include information on the status of waterborne illnesses in Cuba. Because of the usefulness of the subject, particularly for new generations of Cubans dedicated to water management and conservation, we present a history of Cuba's water distribution system and problems related to Havana's water supply and sanitation systems from their creation in 1516 to the present day, keeping in mind that the city center's sewer system, completed in 1915, has been in operation for almost one hundred years. As a final note, the authors summarize situations associated with principal threats to ground water regime and quality in insular territories of the Gulf of Mexico and the Caribbean.

1. Introduction

Problems inherent to the proper management of urban hydrology on islands and small islands in Wet Tropical zones are directly related to the physical-geographical environment, natural threats arising from geographical position, water supply infrastructure, rainwater and wastewater drainage, vulnerabilities brought about or increased by social and economic inequalities, as well as the cultural and socio-economic standards, distribution and composition of the population.

These determining factors are manifested in the following ways in the Gulf of Mexico and the Caribbean:

- The predominance of coastal cities.
- The growth of some large cities.
- Social vulnerability.
- Lack of water supply in and around cities.
- Deficiencies in the household water supply system; and the evacuation and disposal of rainwater and human waste.
- Population concentration, pressure from internal migration; and local and international tourism.
- Endemic threats from natural events such as hurricanes, earthquakes, volcanic activity, landslides, floods, drought, land subsidence, erosion, etc.
- Antiquated and poorly functioning potable water supply and drainage systems.
- Insufficient liquid and solid waste treatment.
- Deficiencies in land management and physical planning.
- Non-compliance with or absence of municipal or national ordinances regarding urban drainage system administration.

These issues increase in complexity as worldwide environmental problems alter the urban water cycle. High on the list of problems are threats stemming from climate change, particularly from the rise in sea level and collateral effects such as inland incursion of sea water, increased soil salinity, modifications to current coastlines, increased internal migration, among others.

We tackle these questions in general terms, in the context of the islands of the Gulf of Mexico and the Caribbean. This particular geologic

setting determines how the land phase of the hydrologic cycle develops. Island cities in this area of the Wet Tropics possess not only important local populations, constantly growing due to internal migration; but an enormous floating population as well, linked to the service sector, and tourists which support this sector of the economy. We review the situation of water deterioration and sustained scarcity in this geographic region using Cuba and its capital, Havana, as an example. We discuss the principal consequences of negative effects of island city growth in terms of urban hydrology and the manner in which urban drainage is currently managed. In the case of Havana, founded half a millennium ago, the population reaches almost 2.5 million inhabitants concentrated in an area no greater than 730 km². Havana receives an influx of nearly 1 million tourists, primarily during the dry (low water) season, supported by aqueducts and sewer systems built in 1925, whose last major modification was carried out more than fifty years ago. This system now supplies services to prodigious consumers of water, such as hotels, restaurants, housing and room rentals, and urban agriculture. Continual efforts to supply the demands of a developing city, growing at the cost of importing water from sources at distances increasingly remote requires a change in paradigm in order to guarantee sustainability based on the best science currently available to us.

2. Physical environment and hydrology of small and very small islands

According to the United Nations Education, Science and Culture Organization (UNESCO), small islands are conventionally considered to be those with an area no greater than 2 thousand km², and a breadth of up to 10 km (Falkland, 1991). Depending on an island's geological and hydrological characteristics, and the way in which subterranean water flow is organized, small island classification can include land areas up to 10 thousand km².

Very small islands are considered to be those whose area is no greater than 100 km², with a breadth no greater than 3 km. In the Gulf of Mexico and Caribbean regions there are hundreds of islands within these limits comprising island states (Figure 1). These islands represent two geological extremes –carbonate and volcanic– each extreme having its own particular topography which provides the conditions for structuring superficial and subterranean runoff on the islands.

Carbonate islands have experienced important cave and karst development processes which have controlled the development of diffuse flow, epigenetic and syngenetic karst systems, meaning subterranean waters form locally discontinuous flow systems with highly variable density, short run, small volume and scarce reserves. The aquifers' natural replenishment zones (recharge zones) are linked to small ridges and furrows. These are generally dolines caused by corrosion or collapse (in many cases, ancient blueholes) towards which rainwater circulates and recharges the mantle aquifer.

These depressions are sometimes filled with debris, earth or rubble as a consequence of poor land use practices and deficient solid waste management. The waters that reach these depressions suffer deterioration in quality and as a result, contaminated

water infiltrates the aquifer. The inland intrusion of tidal water also affects water quality. For this reason, water and sludge disposal sites must be carefully evaluated to prevent negative impacts on a site's environmental quality. A monitoring system for water management and quality is indispensable for guaranteeing the sustainability of any development project.

Local cave development, dependent on varying sea levels during the last glacial periods, has established zones with varying foundation capacity which can result in differential settling. The scale of construction of projected civil works and the necessary earth excavation and removal requires detailed knowledge of the geotechnical properties of the construction materials and terrain in these sites. Of special importance is the often overlooked fact that these civil works projects and paving of land surfaces, etc., substantially reduce the aquifers' natural recharge capacity.

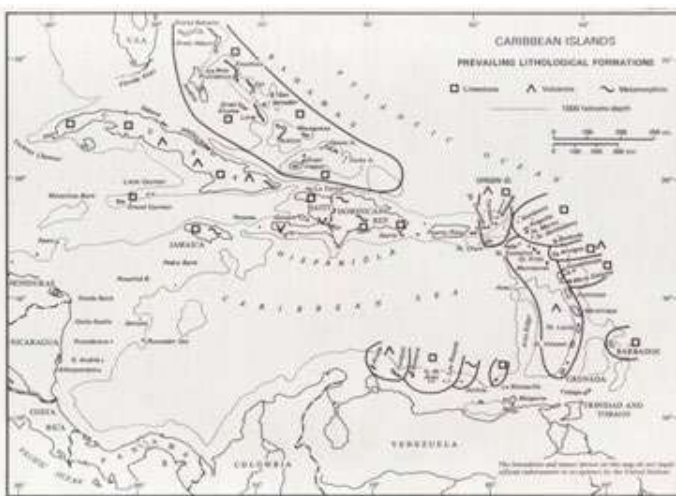
Some superficial water storage can be found in *maars* within volcanic cones on volcanic islands (such as the Grand Etang *maar* in Grenada), however the dominant mountainous topography presents serious limitations for the development of a subterranean aquifer system. In some cases one finds a well developed, short-run river network forming very narrow and elongated basins.

The rapidly concentrated flow, steep gradient and geographical substrate place substantial restrictions on the development of important coastal aquifers, although some subterranean water, basically interflow or hypodermic flow, and bank storage can be found in the lower third of these basins. In addition, the rapid response to torrential rains occasions the formation of flash floods carrying great quantities of sediments which are usually carried out to sea rather than being deposited along the flat sections of the basins.

Sustained erosion acceleration along riverbeds also affects fluvial terrace growth, subsequently reducing the possibility of increasing the quantity of available water; erosion hinders the development of cumulative terraces and causes constant loss of agricultural soil. This process can be mitigated only through engineering improvement methods that contribute to the recuperation of soil lost to erosion.

The prevailing aggressive erosion and meager river basin development are also limiting factors

Figure 1. Fundamental lithologies of the small islands of the Caribbean (taken from United Nations (1976): Ground Water in the Western Hemisphere. Natural Resources, Water Series No. 4. Dep- Econ. Soc. Affairs, New York, 337.)



for building retention structures for superficial runoff and artificial recharging of subterranean waters. In the case of the former, the accumulation of residue, debris and sediment within engineering work, such as dams, dikes and barriers, occurs with great rapidity, and in the case of the latter, there is practically no aquifer to recharge.

At the same time, strong fluctuations in river flow during the course of the year, including even shorter periods, results in substantial inland penetration of sea water, above all at high tide, increasing the salinity of inland waters. Prevailing wind velocity and direction is an additional cause of soil salinity and consequently, of inland waters through the penetration of aerosols. Measurements made by Molerio (1992) have shown aerosol penetration up to 50 kilometers inland. As none of the small islands reach that magnitude in breadth, the entire territory is covered by the aerosols.

The territory is exposed to tropical hurricanes as well as drought conditions. Thus, vulnerability to hurricanes is a topic to be considered in detail in the planning and building design phase of water supply and sanitation civil works projects; damage from winds and torrential rains must be minimized and mitigations measures made available to reduce response and repair costs to a minimum following these extreme events. Volcanic activity and earthquakes are also permanent threats profoundly complicating not only water resources management but the proper administration of the territories themselves. Small and very small island hydrology in the Gulf of Mexico and the Caribbean is tremendously complex, encompassing extremely fragile and vulnerable tropical ecosystems. Their inland water resources are always scant and difficult to manage for the following reasons:

- a. Fresh water availability depends on the abundance and distribution of rain and on subterranean storage capacity – generally quite limited and dependent on island topography and geological makeup. In fact, rain distribution throughout the territory is highly variable. In Guadalupe, for example, the western slopes of its mountains receive between 2.5 thousand and 10 thousand mm annually, while in the rest of the country, average annual rainfall is around 1.4 thousand mm. Lower annual rainfall averages are recorded in the Bahamas (with minimum

annual rainfall on the order of 600 mm) and in some areas of the interior of Hispaniola (Haiti and the Dominican Republic).

- b. Superficial runoff tends to be weakly organized and generally present only on mountainous islands –the only islands exhibiting some possibility of artificial runoff regulation. However, on small volcanic islands the majority of rainfall escapes to the sea through superficial runoff.
- c. Discharge of subterranean waters occurs through a precarious equilibrium with sea water; the intrusion of sea water directly affects the quantity and quality of subterranean freshwater resources. This is, without a doubt, the principal problem limiting the development and full use of subterranean water resources on the islands and coastal zones, and this problem will grow in coming years as a consequence of the rise in sea levels associated with climate change.
- d. Due to the small size of the islands, problems associated with superficial and subterranean water contamination tend to be extremely serious and costly to repair. The proximity of subterranean waters to the surface, and consequently, the narrow width of the non-saturated zone make this zone an inefficient barrier against the flow of contaminants from the surface to the aquifers. At the same time, the existence of numerous housing settlements on the higher slopes of the valleys, and the release of virtually untreated wastewater into the ground and superficial waterways pose a continual threat of deteriorating superficial water quality.
- e. The prevailing lithology is one of the major controlling factors over the distribution of superficial and subterranean water resources on small islands. Two basic lithologies are recognized in the formation of the islands' geological structure: one being essentially carbonate, in which karstic processes take place; and the other, volcanic, in which sand and gravel aquifers and fractured-rock aquifers are equally prevalent. In the Greater Antilles (Cuba, Hispaniola, Puerto Rico and Jamaica) both lithologies are present with karstic carbonate aquifers predominating.
- f. The economies of these small islands –many of them island states– tend to be based on

Table 1. Variation in potential water resources in Caribbean countries (Planos 2000 & 2001)

Country	Potential Water Resources Prior to 1961-1990 (10 ⁶ m ³)	Potential Water Resource 1961-1990 (10 ⁶ m ³)
Cuba	38150	30067
Haiti	11000	9603
Dominican Republic	22505	16559

Table 2. Potential Water Balance 1961-1990

Region	Area Km ²	T °C	P mm	Eo mm	E mm	Q mm
Caribbean	4160000	26.8	1880	1633	1208	2797.3
Cuba	184000	24.9	1326	1540	989	62.0
Belize	22500	27.1	2368	1677	1337	23.2
Jamaica	45000	28.3	1868	1751	1252	27.7
Española	100000	24.8	1469	1534	1042	42.7
Lesser Antilles	360000	27.1	2368	1677	1337	371.0

T: temperature (°C); P: precipitation (mm); Eo: potential evaporation (mm); E: evaporation (mm); Q: volume of runoff (mm)

Source: Llanes et al., 2012.

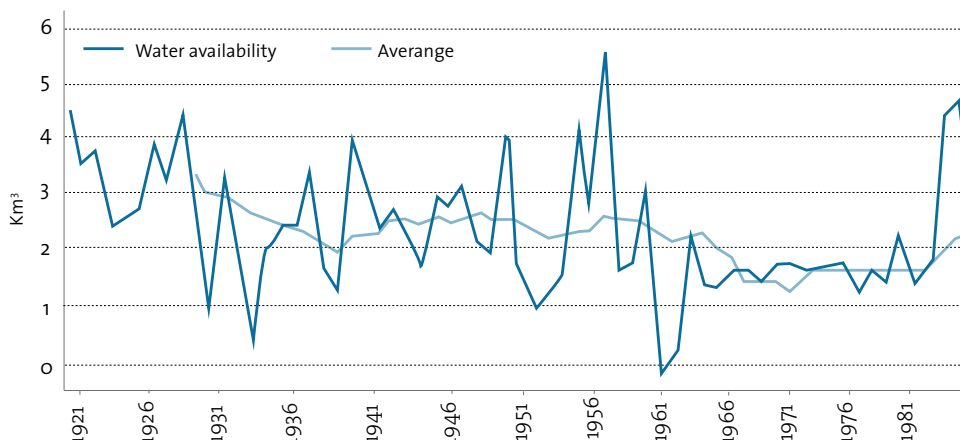
services oriented primarily toward the tourism industry, an extremely high and increasingly demanding (but frequently poorly administrated) consumer of good quality water. Additionally, small islands suffer from other economic and demographic problems due to the scarcity of natural resources, such as the limited availability of cultivatable land, minerals and conventional sources of energy.¹ The isolation of many of the islands and their exposure to the most destructive natural events such as hurricanes, typhoons, earthquakes, volcanic eruptions and tsunamis contribute to difficulties in hydrologic resource management. High population density, which comes close to 800 inhabitants per sq. km. in New Providence, Bahamas, also conspires against the availability of good quality water as it continually increases demand and the ensuing danger of contamination.

- g. Extreme rainfall events associated with torrential rains and hurricanes constitute one of the elements of greatest risk for natural resources and society; droughts tend to exert disastrous effects on supply among the population in these regions, characterized by a persistent shortage of water.

The availability of water resources in the region has also been dwindling, corresponding to changes observed in the climate. Planos et al. (2000), and Planos and Rodriguez (2004) confirmed this in Cuba, the Dominican Republic and Haiti when comparing potential water resources evaluated for these countries prior to 1970 against the period 1961 to 1990 (Table 1). In the last few decades, identical behavior has been seen in runoff, reflecting a negative tendency, in the case of Cuba, Jamaica and the Dominican Republic.

Variability and observed changes in the Caribbean climate since the 1970's and the manner in which these changes are manifested through water availability was corroborated by Shiklomanov (1998). By analyzing the dynamic of water availability in Mesoamerica and the Caribbean between 1921 and 1985, Shiklomanov discovered a negative tendency in the time series beginning in the 1960's in which statistical homogeneity was broken around the year 1970 (Figure 2). In a report on the potential hydrologic balance, estimated by Llanes et al. (2012) for CEPAL, the investigators analyze annual precipitation during the period 1931-2000, which shows a tendency toward a decrease in precipitation in many areas of the Caribbean region (Table 2). Figure 3 shows the prevalence of the tendency toward decreasing annual precipitation in almost the entire area.

1. Cases such as Trinidad and Tobago, with abundant availability of petroleum and gas, are a notable exception.

Figura 2. Dynamic of water availability in Mesoamerican and the Caribbean

3. Water and Environmental Health

In the last two decades, access to potable water and basic sanitation increased in Latin America and the Caribbean, principally within urban zones. Access to basic sanitary conditions was also greater in urban zones. Between 2002 and 2010, the proportion of the urban population benefiting from adequate solid waste collection services surpassed the urban population growth. Nevertheless, these achievements were not spread uniformly across all countries or even within a given country. Progress was also made in terms of specific legislation including guidelines for water and sanitation policies supported by an evaluation of services provided in urban zones. Of note is the challenge in providing services to marginal neighborhoods with low quality housing, lack of access to basic services and wastewater treatment, as well as monitoring chemical contamination of the water supply. Discharge of untreated urban waste into basins and springs is an emerging topic in various countries (PAHO, 2013).

Half of the world's population now lives in cities; and within two decades, almost 60% of the world's population will live in urban centers. Urban growth is greater in developing countries where the cities gain an average of five million inhabitants each month. The urban growth explosion brings with it unprecedented challenges, the lack of water

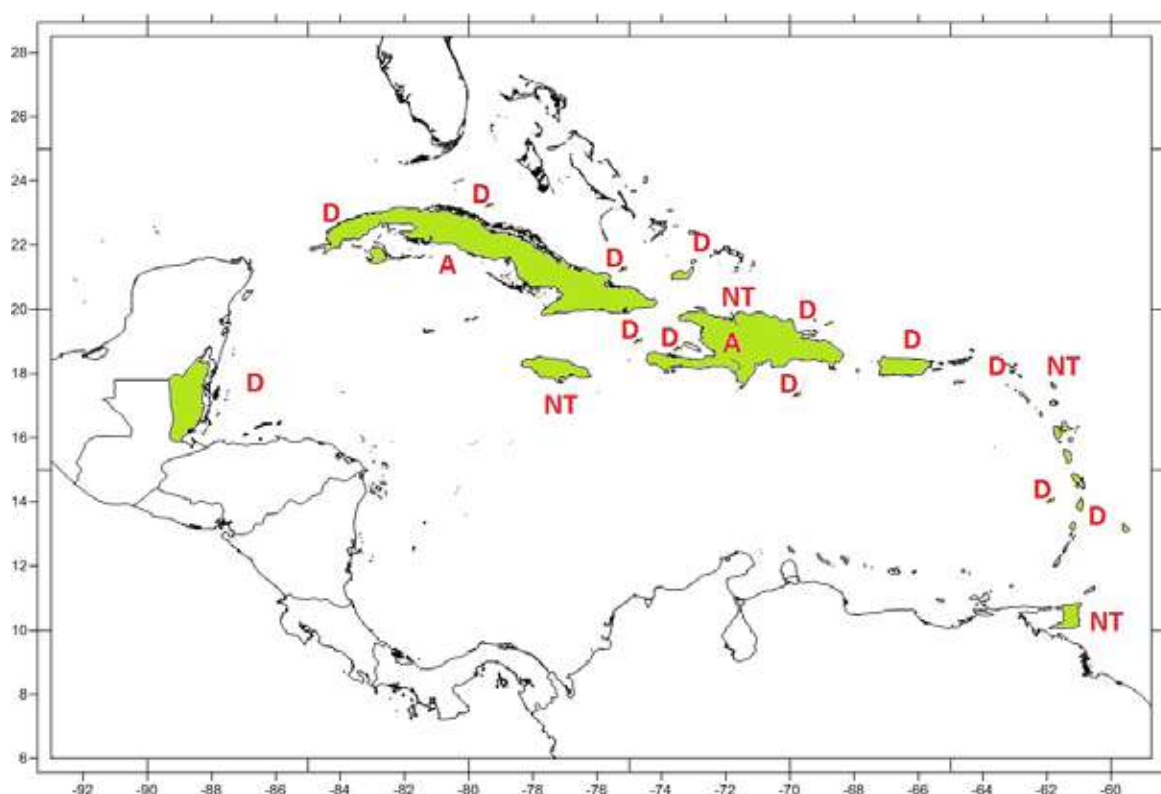
and sanitation services being the most urgent and damaging among them (PAHO, 2010).

Overexploitation of water resources is increasing. Thus, with the rapid pace of urbanization, cities are facing increasing demand for water and sanitation services. According the United Nations (2010), 77% of the Latin America's population is urban and urbanization rates continue to increase, affecting access to safe potable water and sanitation in some countries. At the same time, contamination of rivers and oceans is a critical problem affecting coastal cities where more than 60% of this region's population lives.

Classification of Water Related Illnesses

In terms of illnesses associated with water and sanitation, water related illnesses are seen as the most extensive. These illnesses are defined as any significant or widely distributed adverse effect on human health, such as incapacity, illness or suffering, directly or indirectly caused by the condition of, or changes in, the quantity and quality of water. Three essential components exist for classification purposes: pathogens and other agents involved in water related illness; type of water exposure; and the degree of probability that the illness is water related. Host factors, such as nutritional status,

Figura 3. Tendency of annual precipitation in the Caribbean region for the period 1931-2000



D: Decreasing; A: Increasing; NT, Tendency Not Significant (according to Llanes et al., 2012).

are important in terms of the details and priority required for surveillance systems in countries with high levels of malnutrition, immunodeficiency or significant mortality resulting from waterborne pathogens (Stanwell-Smith, 2009).

Status of Water Related Illnesses in Cuba. Health Statistics

Cubans enjoy a high life expectancy at birth (77.97 years); infectious disease incidence and mortality are low; and the infant mortality rate is very low (4.5/1,000 live births). Fifteen infectious diseases have been eliminated from Cuba and another eight appear so infrequently as to preclude public health problems (less than 0.1/100,000 inhabitants). All State and social sectors participate in environmental protection and improvement, including the health sector, through comprehensive programs that span water, protection and care of oceans, soils and woodlands, air and noise quality, liquid and solid

waste (especially biological waste) and public health surveillance (PAHO, 2012).

The health status of the Cuban population improved between 2006 and 2010. Fundamental aspects of public health in Cuba include the accelerated rate of population aging; low levels of fertility and generation replacement; low infant and young child mortality rates with mortality trending more toward advanced age; and elevated life expectancy. Infectious diseases have been eliminated or controlled to the point where they no longer represent public health problems, although environmental conditions and risky lifestyles in terms of the introduction and spread of disease still persist. The vaccination program protects the population from respiratory infections, and acute diarrhea infections are the primary reasons for medical consultations (PAHO, 2012).

The Cuban population numbers 11,210,064, distributed throughout 15 provinces and 168 municipalities; the male to female ratio is 995 men

to 1,000 women; the percentage of urbanization is 76.8%; and 18.3% of the population is 60 years old or older (Statistical Yearbook, 2013).

A total of 92,270 deaths were reported in 2013; 2,898 more than in 2012. The increase in mortality occurs primarily in those 65 years of age and older. The general (crude) mortality rate is 8.3/1000, an increase of 4.8% over 2012; the age-adjusted mortality rate remains at 4.5/1000. The greatest increase in mortality during the five year period between 2009 and 2013 occurred between 2009 and 2010 with 4,125 additional deaths; then, between 2010 and 2011, deaths decreased by 4,021; in 2012, deaths increased by 2,328 and by 2,898 in 2013. The increase in deaths in 2013 is 30% less than the maximum increase recorded during the five year period previously mentioned. Fluctuations such as these correspond to variations in mortality, and to the country's demographic profile of illness and death. According to classification into three large mortality groups, the mortality rate for non-infectious chronic diseases is the highest (680.7 deaths/100,000), followed by deaths from infectious diseases and maternal, perinatal and nutritional causes (72.0/100,000) and death from external causes (66.8/100,000). The mortality rates for these three groups have increased compared to 2012 (National Health Statistics and Medical Records Bureau, 2013).

The vaccination program protects against thirteen illnesses with almost 100% vaccination coverage for children less than one year old. Fourteen infectious diseases and another nine non-infectious diseases represent no health problems for the country because the incidence rate is less than 0.1/100,000 inhabitants. Acute diarrheal infections increased in the beginning and the end of the summer season. Cases of illness caused by *V. cholerae* biotype eltor serogroup O1, with Ogawa as the prevalent serotype, were reported and controlled. Coordinated actions were directed towards reducing *Aedes aegypti* infestations, resulting in a 17% reduction compared to 2012 (Statistical Yearbook 2013).

The 2013 Annual Report of the Pan American Health Organization/World Health Organization (PAHO/WHO) presents all alerts and epidemiology updates published throughout the year regarding public health events occurring in the Americas and other parts of the world which had or could have had international public health repercussions in the

region. Referring to cholera outbreaks in the region, the report recommends that member States put into action their preparation and response plans, and strengthen their cholera surveillance systems. PAHO/WHO also exhorts countries to accelerate their work to improve water quality and sanitation (PAHO/WHO, 2013).

A study of water quality within the homes of Old Havana's urban population, and the possible relationship to waterborne diseases between November 2010 and December 2012 shows that water is untreated in 57.6% of homes; 34.6% boil their water; 6.2% filter it; and 1.2% use chlorine. Some 98.8% of this population relies on an erratic or intermittent water supply. The microbiological study finds that 51.8% of samples contained heat-tolerant coliform bacteria and 66% of homes had water with chlorine levels below the limit established by the potable water safety standard. Among those presenting with diarrhea in the last thirty days, 63.6% did not treat their potable water in any way. This reveals a statistically significant association between water treatment and the occurrence of diarrhea during the last thirty days (Concepcion et al., 2013).

Cholera in Cuba

The first cases of a cholera outbreak on the island of Cuba were reported in July 2012. The total number of confirmed cases of cholera during that year was around 500. Only three deaths occurred from cholera as reported in the Epidemiology Alert of July 31, 2012. After the passage of Hurricane Sandy through the country's eastern provinces in October 2012, isolated cases of cholera were reported in the provinces of Santiago de Cuba, Camagüey and Guantánamo. A total of 47 cases were confirmed in these three provinces. No additional cases were detected after December 15, 2012. Among the control methods applied by national authorities were reinforcement of environmental sanitation and hygiene methods; guarantees of potable water supplies; strict control over the populace's food and sanitation education with an emphasis on hand washing, safe food consumption and potable water ingestion (PAHO/WHO, 2013).

After having detected cholera in Manzanillo in 2012, with 417 cases and three deaths, Cuba's Health Ministry registered two other outbreaks:

the previously mentioned outbreak following Hurricane Sandy in October, 2012; and another at the beginning of 2013 in the province of Havana, with 51 confirmed cases. In 2013, the National Focal Point for International Health Regulations (CNE) reported that beginning on January 6 there had been an increase in the number of acute diarrheal infections in the municipality of Cerro and in other municipalities of Havana. Samples were taken from suspected cases of cholera, which were analyzed by the Pedro Kouri Tropical Medicine Institute. By January 14, 2013, a total of 51 cases of cholera had been confirmed, all characterized as *V. cholerae* biotype eltor serogroup O1 enterotoxigenic serotype Ogawa. The outbreak in Havana occurred as a result of improper food handling. As a result, Cuban authorities reinforced sanitary education among the populace with an emphasis on hand washing, safe food and potable water consumption. They simultaneously continued taking measures to guarantee the supply of potable water and strict food control. Active and strict clinical-epidemiological surveillance of acute diarrheal infection was also maintained and all detected cases were treated as possible cases of cholera.

The most recent Pan American Health Organization Alert Bulletin reported that in Cuba, between epidemiological week (EW) 35 of 2013 and EW 8 of 2014, suspicious cases were investigated, and 23 additional cases of cholera were confirmed. Including this data, the total number of confirmed cases of cholera in Cuba since the beginning of the outbreak in EW 27 of 2012 until EW 8 of 2014 came to 701, including three deaths. National authorities are maintaining the clinical-epidemiological surveillance system operational and are regularly investigating suspected cases of cholera. Hygiene measures have been intensified, especially those related to hand washing, water chlorination and cleaning, as well as proper food handling and cooking (PAHO/WHO, 2014).

Challenges related to water will increase significantly in the coming years. Continued population growth and an increase in income will bring with them an enormous increase in water consumption and the generation of waste. Urban populations in developing countries will grow at an alarming rate, generating an increase in demand beyond the capacity of services, the water supply

and sanitation infrastructure, already insufficient. According to the United Nations report on water resources development throughout the world, at least one out of every four persons in 2050 will live in a country with chronic and recurring water shortage (WHO, 2015).

4. Hydrological characteristics and sources of water in Havana

Cuba's inland waters have their origin in rainfall. Identical problems confront the exploitation of superficial and subterranean waters participating in the urban water cycle, including pipeline leaks, loss of water quality, dwindling resources and an increase in the water footprint. These problems grow in areas related to sanitation; the disposal and collection of urban wastewater are carried out through insufficient networks of sewage systems that require the use of latrines and septic tanks accompanied by treatment systems using stabilization ponds, and compact (and traditional) water treatment plants. Rainwater is channeled into rivers, streams and superficial waterways in general, which circulate through urban zones, as well as through storm drains, with the particular difficulties presented by each, and which are common in urban zones.

Havana, the capital of the Republic of Cuba, with 2,168,255 inhabitants, has suffered since its founding in 1516 from persistent water supply and urban drainage problems which have become more serious with time due to systemic structural deformation and the disproportionate concentration of the population in the last few decades. In 1545, Joanes de Avila was already making it known in a letter to the King of Spain that "*in this village of "Avana" there is great need of water to be brought by the ships which arrive here...*"² Two years later, His Majesty stated in the Royal Charter of February 11, 1547 that "*I command you to arrange with the person or persons whom you deem appropriate to bring you said water to said village...*"³ In fact, the city was built around

2. Letter from Joanes de Ávila to the King, May 31, 1545 (Eguren, 1986).

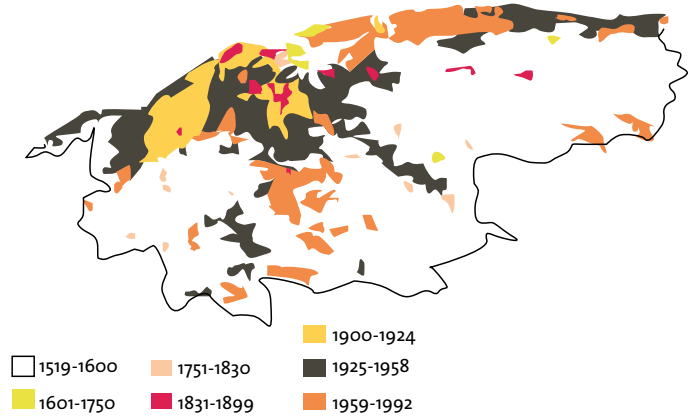
3. Royal Charter of February 11, 1547.

wetlands and springs which were drained, where the Cathedral Plaza is found today for example. The urban topography provides evidence of an ancient and now inexistent drainage system in streets such as Monte, Lagunas, Manglar, Cienaga, Cardenas (previously called Basurero), El Chorro and Zanja.

Havana (Figure 4) is a coastal city that has grown in its current location (it has moved at least twice in 1515 and 1516, prior to its current position) around a “pocket bay” into which drain three rivers from small basins (Luyanó, Martín Pérez and Arroyo Tadeo). For only a short time in the epoch of its founding did these basins supply potable water, limited to very small communities which also relied on subterranean waters, as in the cases of the Cisterna de la Cienaga (Swamp Cistern), situated in the current Cathedral Plaza; and the Pozo de la Anoria (Anoria Well) very close to where Parque de la Fraternidad (Brotherhood Park) is located today. In general, the city was founded on the coast but eventually grew inland on rocky soil with low aquifer productivity, which forced the inhabitants to seek reliable sources of water outside of the urban perimeter beginning practically from the city’s founding. The Cisterna de la Cienaga, the Pozo de la Anoria and even the Cisterna del Jagüey at the foot of Loma de la Cabaña, on the eastern edge of the bay’s channel proved insufficient. At a distance of some 10 km to the west, however, the early population of the city had the waters of the Río Almendares (Almendares River) which supplied the city’s second location with water when it moved from the south coast to the north. For some time, water was brought by sea or by land in barrels, from the town known at that time as Pueblo Viejo (Old Town), to the city situated on the edge of the bay, protected from tropical storms and winds, and capable of harboring tens of ships which, beginning in 1540 with the establishment of the shipping fleet system, gathered together to make the return journey to Spain.

The systemic importation of the water supply reached notable levels in the 15th century when in 1566, Calona began construction of the Royal Trench (completed in 1592) which carried 70 thousand m³/day of water for eleven kilometers westward from the Almendares River to a point close to the current Cathedral Plaza (Figures 5 and 6). Improvements were later introduced –but less than expected– with the construction of the Fernando VII Aqueduct

Figure 4. Stages of urban development in Havana



(Figure 7). At the end of the 19th century, with the construction of the Vento Canal (Figures 8 and 9), an efficient system was created which improved water supply even up to today.

The practice of importing water didn’t end, and today the city’s water footprint requires the support of a system of aquifers occupying an area close to 2,235 km². It consists of various subterranean basins, tens of kilometers distant from the capital city, including the Ariguanabo, Sur, Jaruco-Aguacate, Jaimanitas-Santa Ana, and Vento basins which, in no small measure, has compromised peripheral development in other areas –such as industry and agriculture– by subordinating water resources to the interests of the capital city and its need for potable water.

The city’s entire water supply system is centralized into great aqueduct systems that take advantage of subterranean water in very rich karst aquifers. The eastern sector of the city receives support from systems supplying superficial water through a series of dams (La Coca-La Zarza and Bacuranao) incorporated into the water supply system in the 1970’s. To a large degree, this systematic increase in the water footprint is associated with deficiencies in the networks and a lack of methodical maintenance over the course of decades.

All subterranean basins supplying water to the city are karstic in nature. Marked karst development has been advantageous as well as disadvantageous for efficient subterranean water resources management. Guaranteeing water supply to the city has required the systematic development

of integrated management tools for Tropical Wet karst aquifers, a phenomenon without antecedents in other regions, combining management of coastal and closed inland basins in rural and partially urbanized areas. These partially urbanized areas are accompanied by a systematic process of varied and highly contaminating industrial development, including the sugar industry. The rural areas suffer pressure from a gamut of agricultural activities that

Figure 5. Map of the route of the Royal Trench, created by don José María de la Torre in 1857, showing branching canals supplying water to “El Chorro” and “Muelle de Luz”

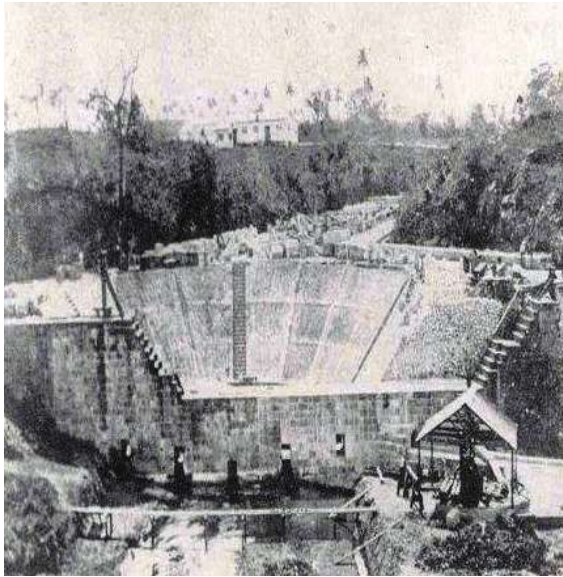


Figure 6. Stone sign in Callejon del Chorro (Chorro Alleyway) on a corner of the Cathedral Plaza in Havana indicating the final destination of the waters brought to the city from the Almendares River, highlighting the name of the governor at that time, Juan de Tejeda, and the year 1592, the year in which construction of the trench was completed



Figure 7. Principal Facade of the Fernando II Aqueduct (Photo taken in 1926)



Figure 8. Construction of the Vento Springs water intake**Figure 9.** Vento Springs water intake today

demanding the construction of hundreds of wells for local supply and irrigation systems that, with greater or lesser efficiency, made use of, exploited and overexploited water resources in a vast zone surrounding the capital city. Figure 10 shows the aquifer system which supplies the nation's capital with water.

The inland basins (Ariguanabo, Vento, Mampostón-Jaruco and Aguacate) are karst poljes or fields, with varying phases of vertical deepening, surrounded by impermeable rocks creating within them different levels of cave development. They constitute closed basins in the geological sense; that is, they are storage basins in which the packets of karstic carbonate rocks reach up to 350 meters in thickness in the Vento Springs Basin.

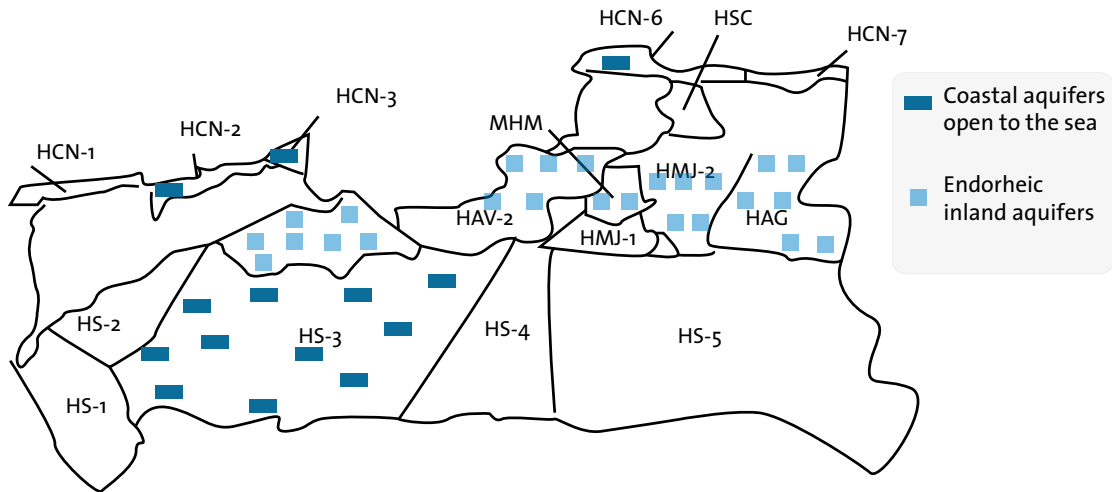
These closed basins basically lack superficial runoff which depends primarily on the poljes' state of hydrologic evolution. In consequence, discharge occurs through one superficial point while the basins themselves form a complex subterranean relationship. This overall situation implies stratification of the different ages of the water (their time in residence) which mandates serious consideration of the exploitation regimen of these waters, to guarantee the sustainability of their usage.

In the city's urban area, flooding is a common phenomenon resulting from the elevated coefficient of runoff and a reduction in water infiltration. But in the case of Havana, flooding has been accentuated by violations of municipal ordinances, building construction and demolition, and an elevated load of sediment associated with a collapse in the networks.

The systematic obstruction or rerouting of superficial runoff routes has created serious urban water problems that have become more serious due to an absolute lack of caution in preventing blockage of sewage and rainwater drains by all manner of debris and rubble. The networks have become almost unusable, contributing to the now common and bothersome problem of sea water intrusion and coastal flooding, systematically aggravated by human activity on top of storm surges and elevated sea levels.

In the end, we have a coastal water system receiving imported water which, through differential treatment, drains to the sea. Waters do not recirculate to resupply the aquifers and the final hydrologic balance is clearly unsustainable.

Figure 10. Map (not to scale) represents aquifer systems currently supplying Havana with water



5. Potable Water System

Access to Potable Water in Cuba

Currently, 95.5% of the population has access to potable water, in both the urban and rural sectors. Access to water in Cuba is provided in the following manner (Cubadebate, 2013; Cubahora, 2014):

- Water piped to the home: 8,401,868 inhabitants, 75.0%
- Water supplied by water tankers: 525,696 inhabitants, 4.7%
- Easy access to water at a distance of 200-300 m: 1,310,014 inhabitants, 11.7%
- Low population density areas: 963,200 inhabitants, 8.6%.

Supply:

- Pumping stations (PS): 3,729 for supplying the population
- From INRH (National Water Resources Institute): 2,592 PS
- Local networks and pipelines: 22,541 km
- Dams: 242, for supply 77
- Water tankers: 1,051 in all institutions
- From INRH: 359, average working 110
- Other institutions: 692

Sanitation:

- With sewer system: 3,980,360 inhabitants

- With 293 systems of stabilization ponds, 534 septic tanks and 10 compact water treatment plants
- With septic tanks and latrines: 6,257,228 inhabitants in 869,829 septic tanks
- Of the total volume of transported wastewater only 34.6% is treated.
- Sewer system networks: 5,310 km
- River and trench cleaning: 3,300 km
- Sewage pit cleaning vehicles: 224
- High water pressure vehicles: 29
- Obstructions: 150,000 per year
- Sewage pit cleaning: 323,000 per year

Within this infrastructure and in compliance with the National Water Policy implementation timeline, works are carried out with an emphasis on indicators that evaluate water supply service quality, prioritizing those that ensure sustainability:

- Maintain elevated coverage in providing public with access to potable water:
- Increase control in hydrometry measurements.

The fundamental problem of access to potable water lies in losses during transport and distribution, advanced age and poor state of water

supply systems and the need to rehabilitate these systems, water sources and potable water treatment plants. A large percentage of total water available in the country is employed by the agricultural sector (in which there is an enormous degree of waste) and in industry; and only 20% is employed in aqueducts destined for the State and residential sectors.

The population receives water in three primary ways: 1) water connection in the home; 2) through public water tankers; 3) easily accessible and locally available water within the community through a public faucet or tank, in the case of zones with no existing pipe network or with deteriorated networks. According to Cubahora (2014), National Water Resources Institution (INRH) enterprises serve 8.24 million people; 900 thousand people are supplied water by the Ministry of Agriculture and AZCUBA; approximately another million are supplied by water tankers; and 800 thousand rely on water which they carry for a distance of up to 300 meters. In spite of the high degree of coverage, 200 thousand people in urban zones and 400 thousand in rural zones lack adequate access to water.

Havana is a city with more than 2 million inhabitants (see data from the most recent census). The potable water supply system today is fed by four source groups, with a structure that provides water to 99.7% of the population through a system of aqueducts requiring adequate potable water treatment (99.1%). Because of insufficiency or the poor state of the distribution network, some 40 thousand people receive water services via cistern carrying vehicles (water tankers). Water is provided for an average of 10 to 12 hours per day, every other day, in most sectors of the city, with insufficient pressure, representing a deficiency in services provided.

The city receives water through some 4 thousand km of pipelines and primary local networks, some with more than 100 years of use, such as the Albear Aqueduct. The pipelines between the sources of water and the local networks have an extension of more than 330 km. Only 18.6% of the Vento Springs Basin feeds the Albear Aqueduct supply system through gravity without any energy costs. The rest of the systems do require high volume pumps, some of which are located a little over 50 km from the capital (e.g. El Gato in the Jaruco Basin).

A common characteristic of the city's subterranean supply sources is that in all cases the aquifers

are non-confined inland karst aquifers, while one of them (South Basin or Cuenca Sur) is coastal. This characteristic translates into elevated supply system vulnerability to multiple source contamination: industrial, domestic and agricultural.

6. Sewer System

The central sector of the city's sewer system has been in operation for almost 100 years; construction on the system was concluded in 1915. It consists of 1,567 km of pipes including the central sewer system and the local systems on the periphery; two treatment plants; 23 wastewater pumping stations; and fifty stabilization ponds (Table 3). Two more are under construction along the margins of the Luyano River, one of which will treat water that drains from the basins discharging to Havana's bay.

The central sewer system provides services to almost half the city's population. Nevertheless, as the system was constructed for a maximum population of 600 thousand inhabitants, its capacity has been superceded for several decades, resulting in discharges and spillage into streams, rivers, rainwater drains and the coast.

The central network of collection pipes extends 1,130 km in length, divided into local networks, sub-collector pipes and principal collector pipes which transport human waste through physical and mechanical treatment processes prior to being deposited in the ocean via a tunnel submerged to a depth of 10.7 meters at a distance of 147 meters from the coast. Havana's Sewer Tunnel, popularly known as the Playa del Chivo Emissary –one of the Seven Marvels of Cuban engineering– was built between May 1911 and April 1912 with a length of 375 meters, excavated through the rocks under the bay between the old Muelle de Caballeria (Caballeria Wharf) and the Casablanca (Whitehouse) on the eastern side of the bay. The Tunnel drains slightly more than 110 Hm³/year of wastewater via gravity to a pumping system situated on the eastern side.

Obviously, smaller local systems exist; and in the city's periphery a considerable volume of wastewater is treated in septic tanks using infiltration wells and the Quibu River water treatment system, with a designed capacity of 300 liters per second and which is currently employing only 30% of its capacity.

The disposal and recollection of urban wastewater is carried out through insufficient sewer networks, supported by latrines and a great number of septic tanks, which accompany treatment systems using stabilization ponds and compact (and traditional) water treatment plants. Rainwater is drained to rivers, streams and superficial waterways in general that circulate throughout the urban zones as well as to storm drains.

7. Associated Hydrological and Technical-Economic Problems

Hydrological Problems

In terms of supply basins, the most important hydrological problems consist of the following:

- Sustained increase in the exploitation of subterranean basins supplying water to the city and the extraction of waters with elevated time in residence in the aquifer, to the extent that resources are mined, a portion of which ceases to be renewable.
- Increasing sea water intrusion into coastal aquifers that serve as a source of water for the city, aggravated eventually by the systematic rise in sea level as a consequence of climate change.
- Pressures on some basins caused by urbanization and internal migration.

In terms of the city's hydrological system per se, the city faces a host of eco-hydrological problems of special importance such as (Molerio, 2012):

- Differential settling and subsistence associated with cavern collapse.
- Flooding due to intense rainfall, sea water invasions and storm surges which occur simultaneously under certain weather conditions.
- Landslides.
- Occurrences of waterborne diseases.
- Sedimentation and accumulation of debris in rainwater drains and sewer systems.
- Swamp development in peripheral areas.

Technical-Economic Problems

The most important problems which limit efficient management of Havana's water resources are:

- Loss of water conduction facilities (pipelines, networks of aqueducts and household plumbing) that, according to Kalaff (2013) reaches 58% of flow delivered annually.
- Water recycling.
- Overexploitation of subterranean waters.
- The loss of extended life of the reservoir complex on the east side of the city as well as the accumulation of debris in waterways and long-term exploitation.

8. Conclusions and Recommendations

The principal threats to the inland water system and water quality in island territories in the Gulf of Mexico and the Caribbean are associated with the rise in sea level and consist of the following:

- Progressive intrusion of sea water inland, impacting the fresh water/salt water interface and secondary water mineralization.
- Redistribution of discharge zones of superficial (overflow) and subterranean waters.
- Flooding in low coastal aquifer zones and hydraulic gradient reversal.
- Greater penetration inland of aerosols contributing to soil salinity in higher sectors of the basin and consequently the incorporation of external sources of salinity in superficial and subterranean waters.
- Greater pressure on inland subterranean basins, some of which show evidence over the past 15 years or more of water drainage not pertaining to the actual hydrologic cycle.
- Greater pressure on superficial basins that will shrink in size and become exposed to greater danger of quality loss and alterations in the hydrologic regimen as a consequence of changes in local and regional base levels.
- Deterioration and consequent abandonment of subterranean water supply sources close to the shore.
- Displacement of contamination sites toward other sites near superficial and subterranean basins which can worsen water quality.

Brown (2006) has summarized the following effects of climate change resulting from global warming:

1. The planet's coastal zones will be lashed with storms and flooding of increasing severity, and coastal flooding will displace millions of people.
2. Salt water intrusion due to a rise in sea levels will have repercussions on the quality and availability of fresh water, worsening the world's growing water crisis.
3. As global warming will impact the forests, marshlands and pasture lands, damage to the earth's ecosystem will be far-reaching and

irreversible: close to 25% of mammals and 12% of birds could become extinct in the coming decades.

4. The displacement of agricultural soils and the slow advance of desertification will render many zones inutile for cultivation and pasture land.
5. Warming, along with an increase in humidity, can accelerate the incidence of new as well as existing infectious diseases such as malaria and yellow fever.

In general, processes associated with climate change represent an important threat to life and livelihoods in communities in all regions of the world. Yet, without a doubt, small island states are the most vulnerable.

Constantly scarce reserves of superficial and subterranean water resources place these countries in or very close to a state of water stress. Their water resource management tends to be inefficient and they are permanently affected by additional pressures as a consequence of water and soil contamination and exploitation to satisfy growing demand. The intrusion of the seas which advance ever inland as a consequence of the rise in sea levels will be the major cause of a loss in quality and quantity of subterranean fresh water.

Sustainable water management should move forward in the following directions:

- Programs for recharging subterranean waters.
- Improved capacity in artificial regulation of runoff.
- Substitution of treatment technologies in extenso for compact wastewater treatment plants.
- Sewer system improvements.
- Reduction in conduction loss (reduction in leakage in general).
- Implementation of economic incentives against waste and in favor of responsible use.
- Wastewater recycling.

In Havana's case, recommended and approved solutions and perspectives for improving water resources management are incorporated within an

engineering and sanitation program in the city and are a component of a policy for pricing readjustment that takes into account the following fundamental elements (Kalaff, 2013):

1. Modifications in State and private sector fees.
2. Rehabilitation of the aqueduct system would include rehabilitating 3.2 thousand km in Havana over 12 years, at a cost of 62.9 million Cuban pesos annually.
3. Recycling 3 m³/second of wastewater to a filtration field that would permanently recharge the Vento Springs Basin and the Albear Springs is under evaluation; this would provide a constant source of water which would increase the exploitable reserves of this important basin, and increase the possibility of exploiting its waters during normal rainy seasons.

As of today (Kalaff, 2013):

- 691.3 km of local water networks have been rehabilitated with HDPE technology, primarily in zones with deficient supply and low pressure.
- Construction and reparation is pending in Havana for 3.2 thousand km of local water networks and pipelines, including 2,422 km of networks in poor condition and 235 km of amplification.
- In terms of local water networks, 20% of the rehabilitation/amplification of sewer systems will be carried out, for a total of 543 km.
- An 898 km project is planned for the rehabilitation of networks and pipelines.

We highly recommend continued planning and development of more detailed studies on the regime and quality of inland waters (superficial and subterranean) supplying the nation's capital, keeping in mind that we have as the only source the karst aquifers. In terms of management, refinement of the hydrologic surveillance network (including superficial and subterranean waters) provides us with a basic instrument for planning and for the sustainable use of this resource. The incorporation of more rigorous mathematical modeling tools for

transportation of mass, momentum and energy is vital for simulating increasingly complex scenarios for interaction between superficial, subterranean and marine waters carrying contaminants differentiated by time, manner and place; with increasing water stress resulting from the demand for water under more adverse climatic conditions and more frequent extreme, prolonged events, it becomes a necessity for small islands and for island states above all.

The incorporation of techniques for intensive water treatment and recuperation, to increase resources through artificial recharge of subterranean aquifers, and/or recirculation and recycling of treated waters primarily from industry and agriculture, is of such importance that it points in the direction of slowly substituting the classic oxidation ponds – which occupy useful lands – for compact water purification and treatment plants accessible to small islands through the transfer of appropriate technology. In the immediate future we must identify and preserve coastal karst areas into which fresh water is discharged, minimizing the salinity of the resultant mixing with marine waters, to reduce the eventual desalination costs that might be incurred in the future. The quality of coastal and marine waters must also be preserved against the high levels of salt and metals extracted by these plants when water with ever increasing levels of salinity are used.

The idea of achieving sustainability of water resources is not just a utopian concept as long as the true magnitude of the complexity of its management, and the need to confront this complexity with the appropriate structural and non-structural measures, is completely understood. Interest groups play more than just an important role in the struggle to achieve sustainability in this area; and this goal is achievable if the government, business sector, population and academia take an active, consensus driven part in the process, fully conscious of the challenge implied in providing safe water for all needs, not in the immediate future, but today, and right now.



“One of the Seven Marvels of Cuban Engineering” Visitors and residents of Havana walk along the city’s “malecón”, or seawall esplanade, bordering Havana Bay. They enjoy an outing through the city’s historic center, transported by a horse-drawn carriage, following the custom of the colonial period. Many are unaware that this grey steel structure to the left disguises a subterranean chamber containing grates which prevent the passage of objects and sand into the siphon. Through a tunnel extending underneath the bay, from one end to the other, waste water from much of the city is removed with the aid of specialized pumps to its ultimate disposal site. Source: Juan de Las Cuevas and Collaborators. Publication of the Office of the Historian of the City of Havana, Cuba, Year 2012, pages 38-56

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