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SEAWATER DESALINATION, THE SOLUTION FOR DRINKING WATER AUGMENTATION IN ARUBA FOR MORE THAN 85 YEARS: A HISTORICAL OVERVIEW

DESALINIZACIÓN DE AGUA DE MAR, LA SOLUCIÓN PARA EL AUMENTO DE AGUA POTABLE EN ARUBA DESDE HACE MÁS DE 85 AÑOS: UN PANORAMA HISTÓRICO

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Abstract

Aruba, one of the Dutch Caribbean islands with a semi-arid climate, has practically no natural freshwater resources. It is geographically located approximately 20 miles north of the coast of the Península de Paraguaná of Venezuela. In the pre-industrial era, before seawater desalination, the small population (mainly immigrated aboriginal inhabitants from the mainland of South America) used the scarcely available surface and groundwater for their drinking water supply. In the rainy seasons rainwater is collected in the dry stream beds and in the colonial-period houses were built with cisterns to effectively collect rainwater. In those days peeled off cactus plants were applied as a natural coagulation treatment of the muddy surface water to improve its quality as drinking water. The first application of the seawater desalination technology started already in the period of 1903 to 1917 for the production of process water for the Gold Mining Company. Commercial desalination however started in 1932, with the beginning of the booming economy era due to industrialization and further on with the increasing tourism. Since then seawater desalination became the most import source for water augmentation especially for the production of drinking water and industrial water. The desalination activities in Aruba have followed the desalination development trend in the world. Since the early desalination years till recently the thermal desalination (the Multi Effect Distillation and the Multi Stage Flashing evaporation) was the main dominating desalination technology. In 2008, their desalination supremacy had been taken over by the nowadays more energy efficient Seawater Reverse Osmosis membrane technology. Freshwater produced by seawater desalination is very pure and re-mineralization and addition of effective corrosion inhibitors are very important for the conditioning of drinking water. In Aruba natural dissolution of fossilized coral stones and addition of polyphosphates were always used for the post treatment to mitigate iron and copper corrosion causing brown water and blue water in the water distribution network. This paper outlines the important history of drinking water supply in Aruba from primitive treatment and supply toward seawater desalination for the reliable production of fresh water and will also elaborate on the effective post physicochemical conditioning of one of the world's highest chemical and bacteriological quality drinking water. The high quality drinking water and good maintenance of the distribution system resulted in a low percentage of Non-Revenue Water and a low Infrastructure Leakage Index. The subject discussed in this paper may be beneficial for Small Islands Developing States with limited fresh water resources to consider the application of seawater desalination for their freshwater augmentation and to effectively reduce the water losses in the distribution system which is very important for cost effective drinking water management.

Keywords: Seawater Desalination, Drinking Water Conditioning, Non-Revenue Water, Infrastructure Leakage Index.

Resumen

Aruba, una de las islas Caribeñas Neerlandesas con un clima semiárido, prácticamente no tiene recursos naturales de agua dulce. Está geográficamente ubicada aproximadamente a 20 millas al norte de la costa de la Península de Paraguaná de Venezuela. En la era preindustrial, anterior a la desalinización del agua de mar, la pequeña población (principalmente inmigrantes indígenas del continente de América del Sur) utilizaba la escasa agua superficial disponible y el agua subterránea para su suministro de agua potable. En las estaciones lluviosas, el agua de lluvia se recogía en los lechos de arroyos secos y en el período colonial se construyeron casas con cisternas para recoger efectivamente el agua de lluvia. En aquellos días, las plantas de cactus peladas se aplicaban como un tratamiento de coagulación natural del agua superficial fangosa para mejorar su calidad como agua potable. La primera aplicación de la tecnología de desalinización de agua de mar comenzó ya en el período de 1903 a 1917 para la producción de agua de proceso para la Compañía Minera de Oro. La desalinización comercial comenzó sin embargo en 1932, al comienzo de la era de la economía en auge, debido a la industrialización y más adelante con el creciente turismo. Desde entonces, la desalinización de agua de mar se convirtió en la fuente más importante para el aumento de agua, especialmente para la producción de agua potable y agua industrial. Las actividades de desalinización en Aruba han seguido la tendencia de desarrollo de la desalinización en el mundo. Desde los primeros años de desalinización hasta hace poco, la desalinización térmica (la Destilación Múltiple Efecto y la evaporación Flash Múltiple Etapa) fue la tecnología principal de desalinización. En 2008 su supremacía de desalinización había sido asumida por la tecnología de membrana, Osmosis Inversa de agua de mar, que

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es energéticamente más eficiente hoy en día. El agua dulce producida por la desalinización del agua de mar es muy pura y la re-mineralización y la adición de inhibidores de corrosión efectivos son muy importantes para el acondicionamiento del agua potable. En Aruba la disolución natural de las piedras de coral fosilizadas y la adición de poli-fosfatos se utilizaron siempre para el post tratamiento para mitigar la corrosión del hierro y del cobre causando agua marrón y agua azul en la red de distribución de agua. Este artículo destaca la importante historia del suministro de agua potable en Aruba desde el tratamiento y suministro primitivos hasta la desalinización de agua de mar para la producción confiable de agua dulce, y también tratará el post-acondicionamiento físico-químico efectivo de una de las aguas de calidad química y bacteriológica más altas del mundo. El agua potable de alta calidad y el buen mantenimiento del sistema de distribución dieron como resultado un bajo porcentaje de Agua no Contabilizada y un bajo Índice de Fugas en Infraestructura. El tema tratado en este artículo puede ser beneficioso para los Pequeños Estados Insulares en Desarrollo con recursos limitados de agua dulce para considerar la aplicación de la desalación de agua de mar para su aumento de suministro de agua potable y reducir eficazmente las pérdidas de agua en el sistema de distribución, lo cual es muy importante para una gestión costo-efectiva de agua potable.

Palabras clave: Desalinización de Agua de Mar, Acondicionamiento de Agua Potable, Agua No Contabilizada, Índice de Fugas en Infraestructura.

1. INTRODUCTION

Water is a fundamental necessity of life for all known life forms on Earth and is with food the primary needs of men. It is therefore not surprising that men have always looked for ways to desalinate brackish water or seawater to produce drinking water in arid areas. The desalination of seawater has given an enormous boost to the economic development of the Island of Aruba. This leeward Dutch island, in former times denoted as *"Isla Inútil"* (useless island) by the Spanish Conquistadores, has developed as a prosperous island since then primarily due to the availability of a trustworthy production of drinking water and industrial water, supporting the flourishing tourism industry and other industrial activities. Also, Aruba has contributed with its more than eighty five years' experience in seawater desalination to the further development and improvement of the desalination technology. The applied technologies have been adapted and improved during the years by the manufacturers through the important input gained on the island from the experienced and knowledgeable operations and maintenance personnel of the water production company. Actually, Aruba was in the late 1950s for a very short period of time the largest producer of drinking water using the seawater multi effect desalination technology. The first place is now taken over by countries such as Israel and Oman Sur in the Middle East and Australia with their desalination capacity of more than 500 000 m^3/day.

Aruba has assured its population during the years the hundred percent security of continuous availability of drinking water of both chemical and bacteriological high quality because of a trustworthy efficient production, distribution and storage of drinking water. It is a small semi-arid island in the sub-tropical Caribbean Region with practically no natural resources of drinking water that still is considered in the world as a role model for the effective solution of the water shortage problem for its population. In this article a short description is given of the water supply and water treatment prior to the desalination period, the desalination history and the actual production capacity and process and the conditioning and quality of the drinking water in Aruba.

2. METHODOLOGY

In this paper the important history of drinking water supply in Aruba from primitive treatment and supply toward the sophisticated seawater desalination technology for the reliable production of fresh water will be outlined. This paper will also elaborate on the effective post physicochemical treatment including the natural re-mineralization process with fossilized coral stones and the addition of polyphosphates for the optimal conditioning of one of the world's highest chemical and bacteriological quality drinking water.

2.1. The history of the drinking water supply of Aruba

2.1.1 Drinking water supply before Seawater Desalination

Aruba is one of the six Dutch Islands in the Caribbean Region situated approximately 20 miles off the northern coast of the Paraguaná Peninsula, Venezuela. They are very small semi-arid Islands with practically no surface water and insufficient groundwater, therefore no wonder that they were characterized as unworthy islands centuries ago by the Spanish Conquistadores. As a result of the unavailability of natural fresh water resources, for many decades seawater desalination has been for these islands the only reliable source of drinking water supply. Prior to the period of seawater desalination the source of drinking water for the small population of Aruba was rainwater collected in the dry ephemeral streams and natural water catching areas (Marchena, 2013). Although heavy rainfall in the rain season from August to February, practically most of the rainwater that reaches the ground flows back to the sea through these ephemeral streams. The collected surface water is used in the household and for small-scale husbandry activities.

In the rain season the surface water can be abundant but nevertheless in the dry season the available surface water is very little due to evaporation and absorption by the porous ground layers. The rainwater that flows through the porous ground layers are collected in underground aquifers and in underground channels forming the so called underground rivers. At the north east coast of Aruba there is a very small creek with a constant stream of clear water the whole year. This is in contrast with the ephemeral streams, where water flows only after days of heavy rain fall. The water of this creek was used for a long time as water supply by a group of Chinese families for their commercial horticulture growing special Chinese vegetables.

At different places on the island wells were dug usually by hands using small cold chisels and hammer to collect groundwater. The depth of these wells can vary from some 6 feet near the coast line to more than hundred feet land inward. The groundwater has a high hardness due to dissolution of minerals and calcium carbonates during the absorption process in the porous layers. The *Total Dissolved Salts* (TDS) concentration of well water of Aruba is in the range of 1 000 - 12 000 ppm (parts per million). Especially in the coastal area the TDS can be much higher due to seawater infiltration. The well water is pulled up with a wooden bucket tied up to a rope either manually or with wooden winches in bygone days. Later on, wind mills of wooden or metal framework were installed to pump the water to the surface.

The first population of Aruba consisted of Arawak Indians (particularly aboriginal emigrants of the mainland of South America), nomads that stayed only for a short period of time at places where enough food and water could be found and after a while they moved on. It is also known that they dig little holes near the beaches and dish up the natural filtered seawater as drinking water. They only build temporary little cabins made of tree branches and leaves. In the later colonial period houses of clay or stones were built with cisterns to collect rainwater from the roofs. The rainwater collected in cisterns was mainly used in households and gardening. Figure 1 illustrates the different historical freshwater supplies in Aruba.

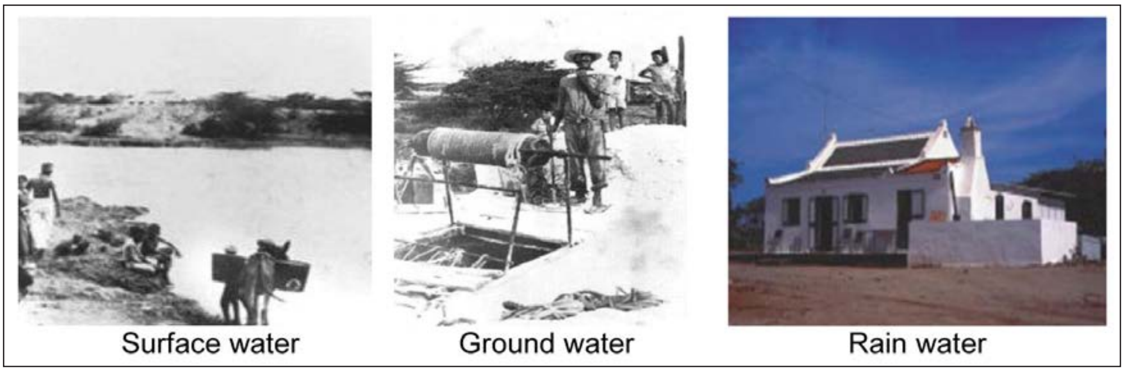


Figure 1. The historical water supply of Aruba

The rainwater flowing over the ground end up very contaminated and saturated with suspended sand particles picked up during their transport to the natural catching areas. Large particles settle down after some time on the bottom but smaller particles will stay in colloidal solution given the water a brownish muddy color. In those days already some primitive ways of water treatment were practiced to clear the drinking water.

Suspended particles were filtered out of the water in a lime stone jar and some form of water cooling was also achieved due to natural evaporation of water in a jar made of clay. The low heat transfer of the clay further helps to keep the water cool. To further clarify surface water, cactus juice or dried cactus pulp was used in a primitive coagulation, flocculation and sedimentation process to remove colloidal particles.

Also a little bit of seawater was used. A piece of iron was used to mineralize rainwater in the cisterns. It so happened that the soft rainwater was hardened by the leaching out process of the calcite mortar of the cisterns. There is no indication that the piece of iron, heated by the sun or in any other way was used to disinfect the cistern water, a technique already used about 2000 years B.C. in India (Marchena, 2013).

It is also worth to mention that in the time of the Lago Oil Refinery (1929-1985) a modern underground rainwater catching basin with water distribution system was constructed for the purpose of gardening water supply for the refinery employee's houses at the Lago Colony located at the east coast of Aruba.

2.1.2 The first commercial drinking water distribution of Aruba

In the period of 1900 to 1914 the first water distribution network was in operation by a private company for the supply of drinking water. Groundwater was delivered as drinking water without prior treatment to the ships in the harbor and for the inhabitants of the capital Oranjestad of Aruba. With wooden wind mills, as shown in Figure 2, groundwater from wells was pumped in the distribution pipelines. Figure 2 also shows the remains of a water reservoir of the company built with stones (Stichting Rancho, 2015).

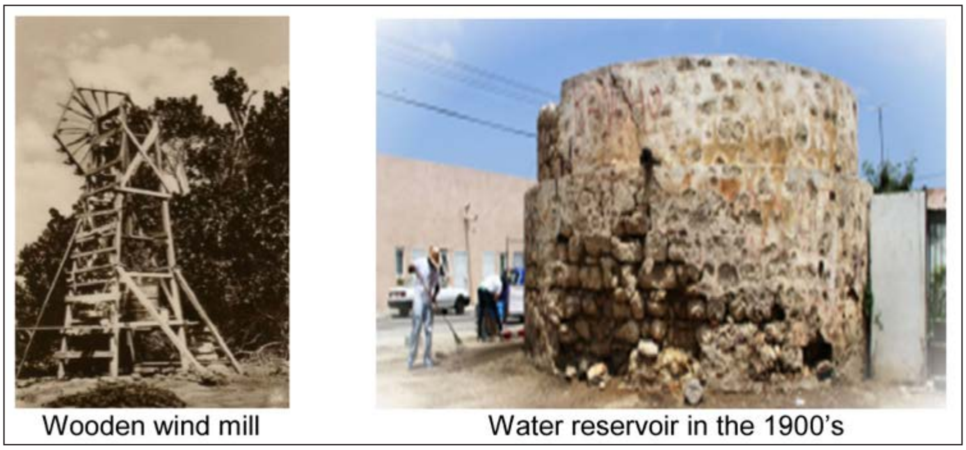

Wooden wind mill
Water reservoir in the 1900's

Figure 2. Groundwater distribution in 1900 to 1914

In that time, a client only paid about 75 cents for a water connection and the amount of water for consumption was not restricted.

2.1.2 The Desalination History of Aruba

The desalination history of Aruba started more than hundred years ago with the production of process water around 1903 at the Gold Mining Company (1899-1916) for the coal fired steam engines. Already in that period it was obvious that available groundwater and rainwater to be insufficient for the production of steam and for the high consumption of process water by the physicochemical gold extraction process. Boiling of saline groundwater also caused serious scaling problems in the boilers that resulted in explosions.

The decision was then made to desalinate the seawater of the nearby Spanish lagoon (Walhain, 2005). Figure 3 illustrates a picture taken around 1911 of the Gold Mining Company and a picture of the construction of single stage evaporators with the so called serpentine heating coils in a construction place of the WEIR Company in Scotland around 1912. This type of evaporators was commonly used for seawater desalination at the end of the nineteenth century and at the beginning of the twentieth century (Birkett *et al.*, 2012). The Gold Mining Company was closed at the beginning of the First World War because the export of chemicals and dynamite to Aruba was stopped.

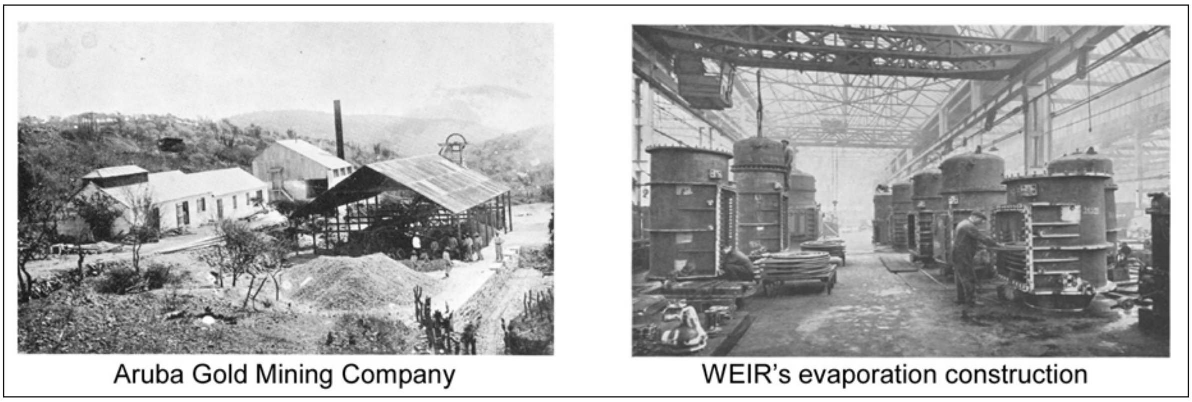

Aruba Gold Mining Company
WEIR's evaporation construction

Figure 3. Aruba's early desalination (1903-1916)

The Water and Power Company of Aruba, WEB Aruba, has been producing drinking water for the island of Aruba since 1932 and industrial water since 1958 for boiler water for the Power House and process water for the Oil Refinery. In the period of 1932 to 1983, the WEIR submerged tubes *Multi Effect Desalination* (MED) technology was used for thermal desalination to produce drinking water and industrial water. The first installed evaporators had a capacity of 200 m^3/day and a *Gain Output Ratio* (GOR), the ratio of mt (metric tons) produced distillate and mt of steam consumed, of about 2. From 1932 to 1958, ten 200 m^3/day evaporators were installed and stayed in production for 13 to 25 years. In 1958, the beginning of combined power and water production was initiated. Five MED evaporators with a capacity of 2,000 m^3/day and GOR of about 5 to 6 were installed. Low pressure waste steam of the back pressure turbines of the Power House was used as heating steam for the

MED evaporators. These evaporators stayed in production for 25 years and were demolished in 1983. In Figure 4 the submerged tube Weir MED evaporators are illustrated. The total water produced with the MED technology was about 55.3 million m^3 (14,607 million US gal).

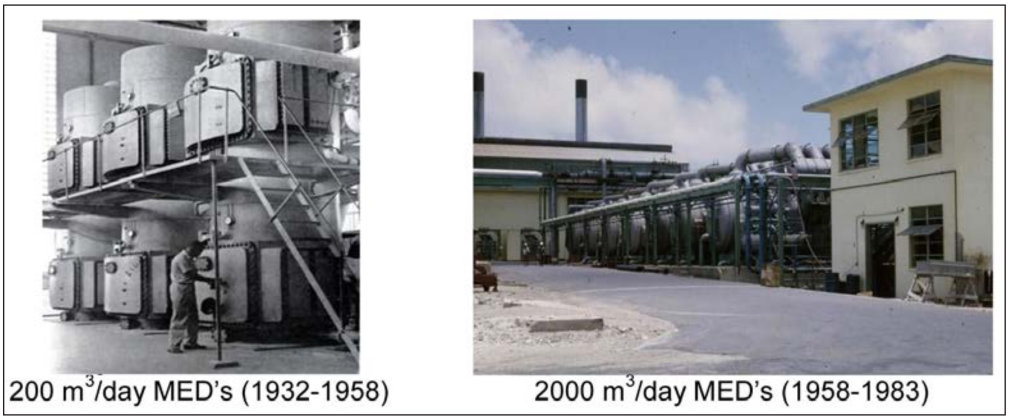

200 m^3/day MED's (1932-1958)
2000 m^3/day MED's (1958-1983)

Figure 4. Weir MED evaporators from 1932 to 1983

As already mentioned in the introduction, in the MED desalination era Aruba was for a short period of time the largest seawater desalination country in the world, in 1959, until the introduction of the large capacity *Multi Stage Flashing* (MSF) evaporators in the Middle East, especially Kuwait with the exploitation of oil.

In 1965, this MSF desalination technology was also introduced at WEB Aruba with the installation of a 3 000 m^3/day recirculation brine MSF evaporator from Aqua Chem Inc. (Arrindell *et al.*, 2002). This evaporator had a design GOR of 9. In the 1970s, the desalination production capacity was extended with two Aqua Chem evaporators of the second generation with a nominal capacity of 6 000 m^3/day also with a GOR of 9.

These MSF evaporators stayed in operation up to 1985. In 1983 and 1984, the first two next third generation of 6 000 m^3/day Aqua Chem recirculation brine MSF evaporators with a GOR of 10, Aqua Chem 1 and Aqua Chem 2 were installed closing the era of the MED evaporators. From 1978 to 1995, the vertical *Multi Stage Controlled Flashing* (MSCF) evaporators were used. This revolutionary Dutch-Hungarian design with the usage of chlorine gas for the control of marine biofouling in the condensers was intended to increase flash evaporation efficiency and to decrease operational cost. However it turned out to be a failure.

These aluminum evaporators had poor performance and were susceptible for corrosion. With the poor operation experience with these Aquanova evaporators fresh in mind and a short time to evaluate proven new technology the choice was made to continue installing Aqua Chem MSF evaporators to cope with the fast increasing water demand due to fast economic growth in the 1990's. In Figure 5 the pictures of the Aqua Chem and the Aquanova MSF evaporators are shown. During the period 1990 to 1998, WEB Aruba was forced due to rapid economic growth, to increase production capacity with new MSF evaporators each of three successive years: Aqua Chem 3 in 1990, Aqua Chem 4 in 1991 and Aqua Chem 5 in 1993. Two additional MSF evaporators were built in two three-year period namely Aqua Chem 6 in 1995 and Aqua Chem 7 in 1998. As mentioned before, MSF technology was chosen because of reliability, good operation experience and lack of time to evaluate new technology (Marchena, 2013).


3000 m3/day (1965-1984)
6000 m3/day MSCF (1978-1995)
6000 m3/day (1981-2015)

Figure 5. Multi Stage Flashing technology from 1965 to 2015

In 1982, 1983 and 1990 WEB Aruba had experienced problems with sufficient water production capacity mainly due to aging of MED evaporators, poor operation of the existing Aquanova evaporators and delay in the installation planning of the new Aquanova evaporators. To cope with the increasing demand, drinking water was imported in 1982, 1983 and 1990 from the United States, Venezuela and the Island of Dominica.

The quantity of imported water is as follows:

- 1982: 41,918 m^3; from Rio Caroni, Venezuela
- 1983: 741,122 m^3; from the Hudson River, New York
- 1990: 252,115 m^3; from the Hudson River, New York and from the island of Dominica.

The cost of import water was very high and to reduce water cost, WEB Aruba contracted Geveke B.V. to install a 1,000 m^3/day *Sea Water Reverse Osmosis* (SWRO) production unit in 1983 on a *Build Own and Operate* (BOO) contract basis to minimize import of water. This *Plate and Frame* (PF) SWRO production unit stayed in operation from 1983 to 1985. There were a lot of membrane biofouling problems and this SWRO production unit never had an optimal operation. The total amount of water produced with this SWRO production unit, during the whole period, was 257 543 m^3. In Figure 6 pictures of this SWRO production unit are illustrated (Marchena, 2013).

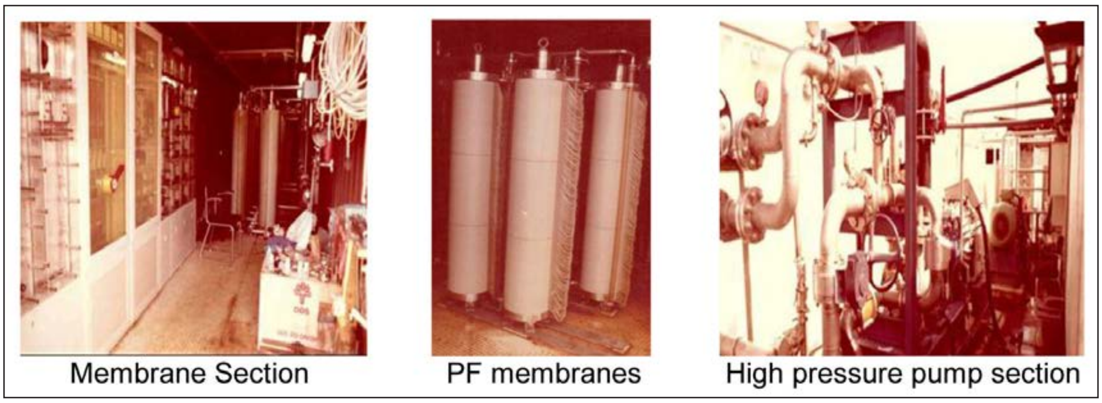

Membrane Section
PF membranes
High pressure pump section

Figure 6. The 1 000 m^3/day BOO SWRO from 1983 to 1985

2.1.3. Current Production and Process of WEB Aruba; the membrane technology

Ironically the SWRO technology, which was put out of the picture in 1985 with commissioning back then of the supreme MSF technology closing the era of MED technology has now pushed the MSF technology out of the desalination activities of Aruba. In March 2008 a new 8 000 m^3/day SWRO production unit constructed by GE Ionics went in operation. It is a three trains-two pass RO consisting of a SWRO and a two-stage *Brackish Water Reverse Osmosis* (BWRO) with an overall design recovery of 39.5% and an energy consumption ratio of 4.00 kWh/m^3. The Aqua Chem evaporator constructed in 1983 was taken out of production in June 2008 for economic reasons after more than 25 years in service and still in excellent operation condition. In the last quarter of 2012 the second SWRO with a nominal capacity of 25 500 m^3/day constructed by Veolia VWS went in operation. It is a two pass RO consisting of four SWRO trains and two trains of a two-stage BWRO unit with an overall recovery rate of 43.2% and a nominal energy consumption ratio of 3.75 kWh/m^3. The two SWRO units produce high quality product water with a TDS of about 15 ppm. As a consequence four of the existing MSF evaporators have been put out of production. In the second quarter of 2015, SWRO mobile units rating 12 000 m^3/day replaced the remaining two MSF evaporators. These mobile units under a BOO contract with GE WPT is a transition phase toward the installation of the third SWRO unit. Additionally the new *Electro Deionization* (EDI-) membrane technology rating 4 500 m^3/day was introduced for the production of very pure industrial water so totally banning the MSF technology from the desalination activities in Aruba. In Figure 7 the new membrane technologies are illustrated (Marchena, 2013).


GE SWRO: 8,000 m^3/day VWS SWRO: 24,000 m^3/day GE EDI: 4500m^3/day

Figure7. The actual desalination technology at WEB Aruba

To conclude the more than 85 years of thermal and membrane desalination history, the trend of the annual production increase since 1933, the population growth and the chronology of the desalination in Aruba is given. The annual water production has increased from 0.01 million m^3 in 1933 to 13.49 million m^3 per end of December 2016. In the period 1958-1980 and after 1985, the water demand has increased rapidly respectively due to industrial water delivery to the Lago Oil Refinery in 1958, the rapid economic growth and the reopening of the oil refinery in 1985 (Marchena, 2013). In Figure 8 the annual water production from 1933 to 2016 and the production of the different desalination technologies are shown. The decrease in 2010 is due to the shut-down of the oil refinery.

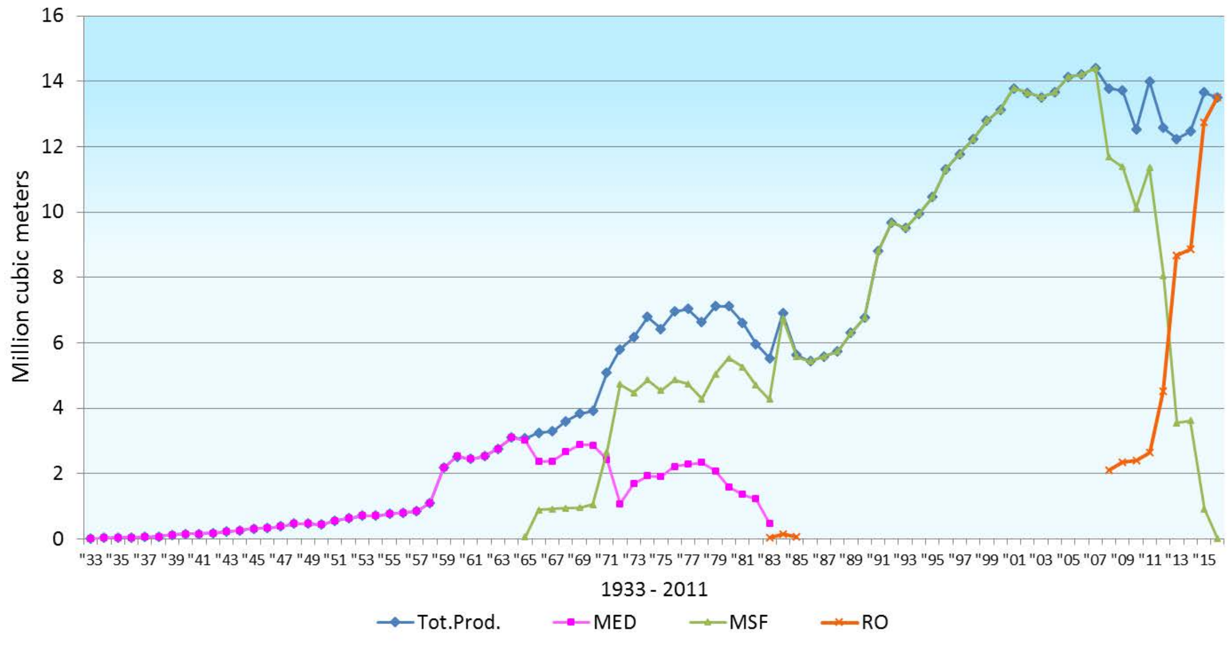


Figure 8. Total annual water production since 1933 including the production of MED, MSF and SWRO

Since the opening of the Lago oil refinery in 1929 the population of Aruba has increased rapidly with a steep increase in the 1990 due to rapid growth in the tourism industry. As a comparison for the water production trend the population growth of Aruba since 1803 is shown in Figure 9.

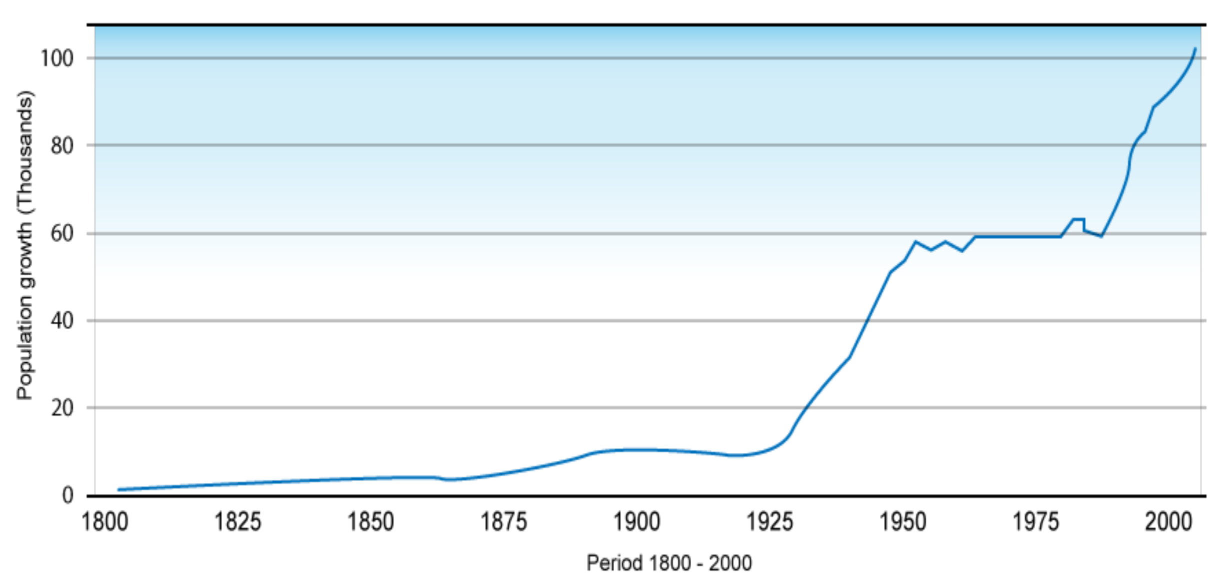


Figure 9. The growth of the population of Aruba since 1803

As can be seen the two graphs show a similar trend. Furthermore, in conclusion the chronology of the desalination in Aruba is given in Table 1.

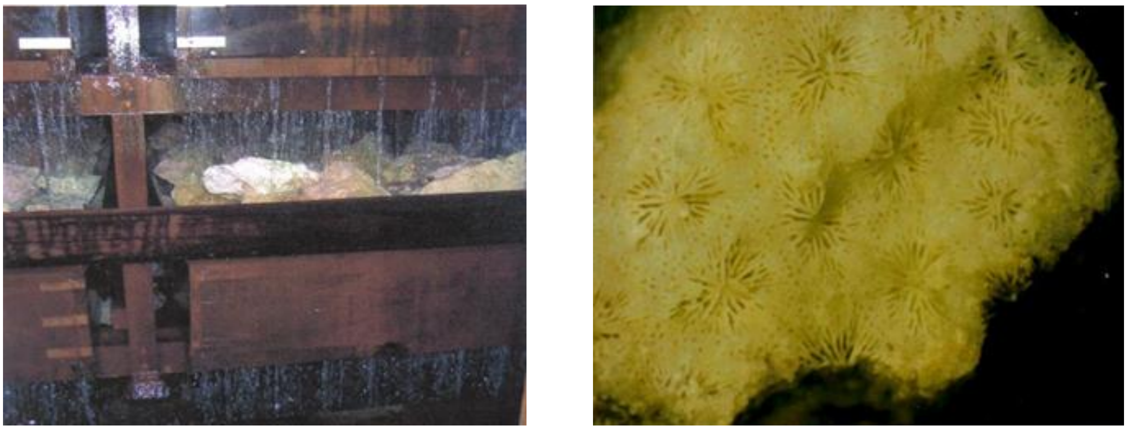
Table 1. The chronology of seawater desalination in Aruba

Desalination unit	Technology	Design capacity (m^3/day)	Year of star up	Out of service	
				in	after
10 Weir	submerged tube MED	200	1933-1945	1958	
5 Weir	submerged tube MED	2000	1958	1983	25 years
1 Aqua Chem	long tube MSF	3000	1965	1984	19 years
1 Aqua Chem	long tube MSF	6000	1970	1984	14 years
1 Aqua Nova	vertical MSF CFE	4000	1978	1983	5 years
1 Aqua Nova	vertical MSF CFE	4000	1980	1985	5 years
1 Aqua Chem (AC#1)	long tube MSF	6000	1983	2008	25 years
1 Aqua Nova	vertical MSF CFE	3700	1983	1991	8 years
1 Aqua Nova	vertical MSF CFE	6000	1984	1995	11 years
1 Aqua Chem (AC#2)	long tube MSF	6000	1984	2013	29 years
1 Aqua Chem (AC#3)	long tube MSF	6000	1990	2013	23 years
1 Aqua Chem (AC#4)	long tube MSF	6000	1991	2013	22 years
1 Aqua Chem (AC#5)	long tube MSF	6000	1992	2015	23 years
1 Aqua Chem (AC#6)	long tube MSF	6000	1995	2015	20 years
1 Aqua Chem (AC#7)	long tube MSF	6000	1998	2015	17 years
1 GE Ionics (SWRO#1)	2 pass-2 stage SWRO	8000	2008		
1 Veolia (SWRO#2)	2 pass-2 stage SWRO	25500	Dec 2012		
1 GE Mobile SWRO	2 pass-2 stage SWRO	6000	Mar 2015		
	2 pass-2 stage SWRO	6000	Apr 2015		
1 GE EDI unit	(industrial Water)	4500	Apr 2015		

2.2.The drinking water conditioning, quality control and assurance

2.2.1. Addition of calcium and alkalinity in the Coral House

Since the start of the desalination activities in 1932 in Aruba until mid-2007, WEB Aruba produces distilled water, which is adjusted to approximately 12 mg/L total hardness, 12 mg/L alkalinity, and pH 8.8-9.3 by cascading it down over a bed of natural crushed fossilized coral stones, as shown in figure 10. The coral stone serves as an economical source of calcium carbonate (lime stone) which dissolves at a controlled rate, raising the pH above neutral and imparting some calcium (hardness) and carbonate/bicarbonate buffering (alkalinity) to the water before it enters the distribution piping (Post *et al.*, 2002).



Bed with coral stones

Fragment of coral stone

Figure 10. Distillate Re-mineralization in the Coral House

Elemental analysis by Betz Laboratories in 1990s of a fragment of used coral stones, as shown in figure 10, indicate that it contains about 96.2% calcium (Ca), 1.4% magnesium (Mg) and minor amounts of sulfur (S), aluminum (Al) and Iron (Fe). The analyses were performed with *Scanning Electron Microscopy* (SEM) and *Energy Dispersive X-ray Analysis* (EDXA) (Post *et al.*, 2002). In 2007, the Coral House was replaced by a modern automated re-mineralization pressurized lime stone fixed bed system especially to increase the biologically integrity of the re-mineralization process eliminating the free aeration process of the distillate in the Coral House. This reduces the possibility to induce air-born *Legionella pneumophila* bacteria contamination of the drinking water. Especially warm water in sub-tropical distribution systems might enhance Legionella growth increasing potential health risks (Van der Kooij *et al.*, 2005). Both the MSF distillate and the SWRO product water (after carbon dioxide, CO_2 injection) although acidic with a pH in the range of 6.3 to 6.7 still contains low CO_2 concentrations. Thus the natural dissolution of calcium carbonate enhanced by carbon dioxide remains very low. Compared to natural surface water and well waters in most areas of the world and hard water (hardened distilled water with CO_2 enhanced lime stone re-mineralization as in the neighboring Dutch Caribbean Islands) the resulting water as it leaves the coral beds is still relatively soft (low hardness) with a comparatively low alkalinity and an alkaline pH.

2.2.2. Chemical treatment before 1990 and in the period 1990 to 1995

Although the calcium, alkalinity and pH elevation provided by the Coral House reduced corrosivity of the water, it was still relatively aggressive to the piping, so corrosion inhibitors were used to further reduce corrosion. Prior to 1990, sodium hexametaphosphate alone was used to inhibit corrosion. The hexametaphosphate is a cathodic inhibitor that forms a protective film on the steel surface. Hexametaphosphate has some iron sequestering capabilities which help it to reduce brown water complaints, but not as strong as other polyphosphates. Further it has also the capability to sequester calcium ions reducing the film forming potential for corrosion inhibition. The concentration of iron in the drinking water exceeded 0.5 mg/l, which is above the *World Health Organization* (WHO) guidelines for iron of 0.3 mg/L (Marchena, 2013). Alternative treatment programs were evaluated to further reduce corrosion and iron concentration (Post *et al.*, 2002).In 1990, WEB Aruba replaced the hexametaphosphate-based program with a multifunctional program. Pyrophosphate replaced hexametaphosphate to take advantage of its superior iron sequestering capabilities to slowly clean up the piping system and eliminate the brown water complaints. A very low level of zinc, an excellent corrosion inhibitor for low hardness water, also supplemented the pyrophosphate (Post *et al.*, 2002). As shown in Figure 11, the change in treatment program significantly reduced iron levels from 0.67 mg/L in 1990 to 0.05 mg/L in 1995 well within WHO guidelines for iron. The point was reached when the bulk of the iron corrosion products had been removed from the system and the treatment was shifted toward eliminating the production of the iron in the system. A portion of the pyrophosphate was replaced with orthophosphate, which is both an anodic and cathodic inhibitor and more cost-effective. This was done by replacing the single component zinc product with a blended liquid product containing zinc and orthophosphate.

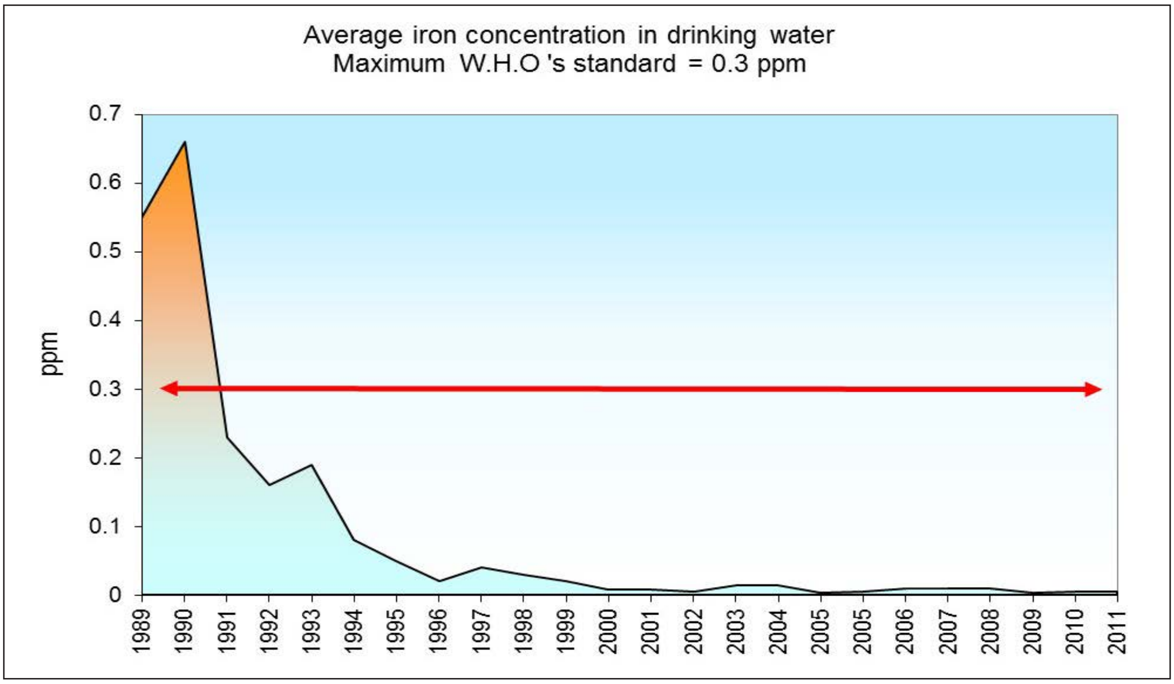


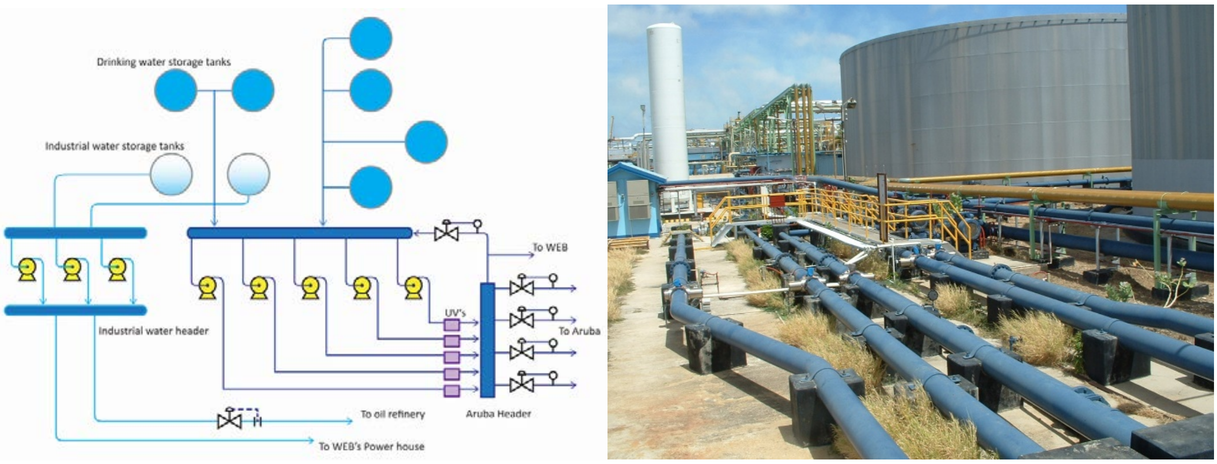
Figure 11. Effective reduction of the iron corrosion in the drinking water

2.2.3. Chemical treatment from 1996 to date

The current treatment program consisting of 0.2 mg/L of zinc (as Zn), 0.6 mg/L of orthophosphate (as PO_4) and 0.5 mg/L of pyrophosphate (as PO_4) has reduced the iron levels to approximately 0.01 ppm, a reduction of nearly 99% from levels prior to the changes in the treatment program. Since the introduction of the pyrophosphate/zinc orthophosphate corrosion inhibition program in 1990 no occurrence of brown water in the distribution system has been reported.

After the chemical post treatment system the drinking water is pumped to 6 water storage tanks with a capacity of 12,300 m^3 each. The water tanks serve as a buffer for the desalination process. Further on the island there are water tanks installed with a total capacity of 65 393 m^3. For further quality improvement and to guarantee a biological high quality drinking water, Berson in line UV-equipment were installed since 2001 in all of the five distribution pipelines going to the water distribution header. The UV dosage is set at 60mJ/cm^2 and the minimum allowed value is set at 25mJ/cm^2. This was never done before because of the high temperature (110 °C) drinking water production process by thermal desalination at WEB Aruba.

The industrial water is chemically treated with caustic soda at a concentration of 2 ppm to increase the pH from 6.3 to 8.7-8.9. Further sodium hexametaphosphate is dosed at concentration of 3 ppm to inhibit corrosion. After chemical treatment, the industrial water is pumped to two storage tanks both having a capacity of 12 300 m^3. From the storage tanks industrial water is pumped to the Aruba Oil Refinery and to the Power House as boiler make up water. In conclusion of the chemical treatment section, the schematic and a picture of the water distribution header are illustrated in Figure 12.



Schematic of WEB Aruba’s water header

View of the WEB Aruba’s water header

Figure 12. The WEB Aruba’s water distribution header.

2.3 Some aspects of the distribution network related to drinking water quality

2.3.1. The water distribution network of Aruba

WEB Aruba is responsible for the production and distribution of high quality and safe drinking water for the population, the trade and industrial sector of Aruba and the delivery of industrial water for the Aruba Oil Refinery. The distributed drinking water in Aruba is of the very highest chemical and bacteriological quality. Chemical and bacteriological quality control and assurance is performed by respectively the Water laboratory of WEB Aruba and the Bacteriological laboratory of the Aruban Government Health Department.

In 2000 after the Legionella incident in Bovenkarpsel in the Netherlands, Europe, WEB Aruba has taken proactively actions to guarantee the bacteriological quality of the drinking water (Marchena, 2013).

Aruba with a population of about 110 thousand inhabitants has a high living standard and a high developed tourism industry with more than one million yearly overnight tourists. Especially for the tourism industry, the most important economical pillar of Aruba, the hundred percent operational and delivery assurance of this high chemical and bacteriological quality drinking water is of utmost importance. According to procedure the common bacterial counts of the Aruba drinking water header before entering the water distribution system should be lower than 50 cfu/mL (colony forming units per milliliter) and especially regarding the *E-coli* and the *Legionella pneumophila* bacteria, counts should be 0cfu/mL (Marchena, 2013).

The Desalination Department makes daily a balance of the produced and distributed water. Due to the high cost of this high quality conditioned desalinated water the main objective of the Desalination and the Water Distribution Departments of WEB Aruba is to optimally minimize the loss of drinking water. The production of well-conditioned drinking water, good operation and maintenance of the distribution network and a strict water control program objectively resulted in a very low leakage percentage due to corrosion, breakages and flushing of the dead ends. Furthermore water theft is practically non-occurring.

2.3.2. The Non-Revenue Water (NRW)

According to the *International Water Association* (IWA) standard, the *Non-Revenue Water* (NRW) is defined as the difference of the distributed water and the water sales or the total yearly distribution and the billed water sales (Lambert, 2001). The NRW accounts for water meters’ errors, administrative losses such as fire water, rinse and unauthorized water consumption such as theft and leakages. Important for lowering the NRW is a water balance of the whole water distribution system making possible the detection of all components contributing to the NRW. Optimal inspection of the water distribution system, timely detection and repair of leakages contribute to lowering the water losses. The Desalination Department and the Water Distribution Division of WEB Aruba make monthly a water balance in their monthly reports and it is controlled yearly by the department of the Internal Control and by external consultants. Because of an optimal chemical conditioning of the drinking water and a good maintenance the water losses in the distribution system are very low. Figure 13 illustrates the NRW percentages of Aruba in the period 1988 to 2016. As depicted in this figure, the NRW percentages were in the period of 1988 to 1998 in the range of 13.5 to 4.7% and since 1999 in the range of 1.8 to 4.7% of the total produced water (Marchena, 2013).

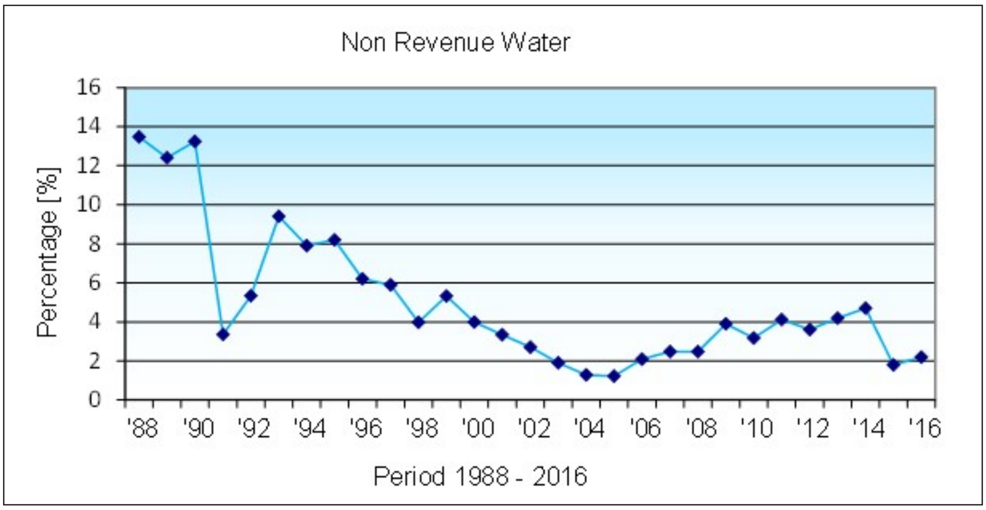


Figure13. The NRW in the period of 1988 to 2016

For comparison the NRW of the other island in the Caribbean region are illustrated in Figure 14. In general a NRW of 15-20% is considered acceptable for a good maintained water distribution system (Marchena, 2013).

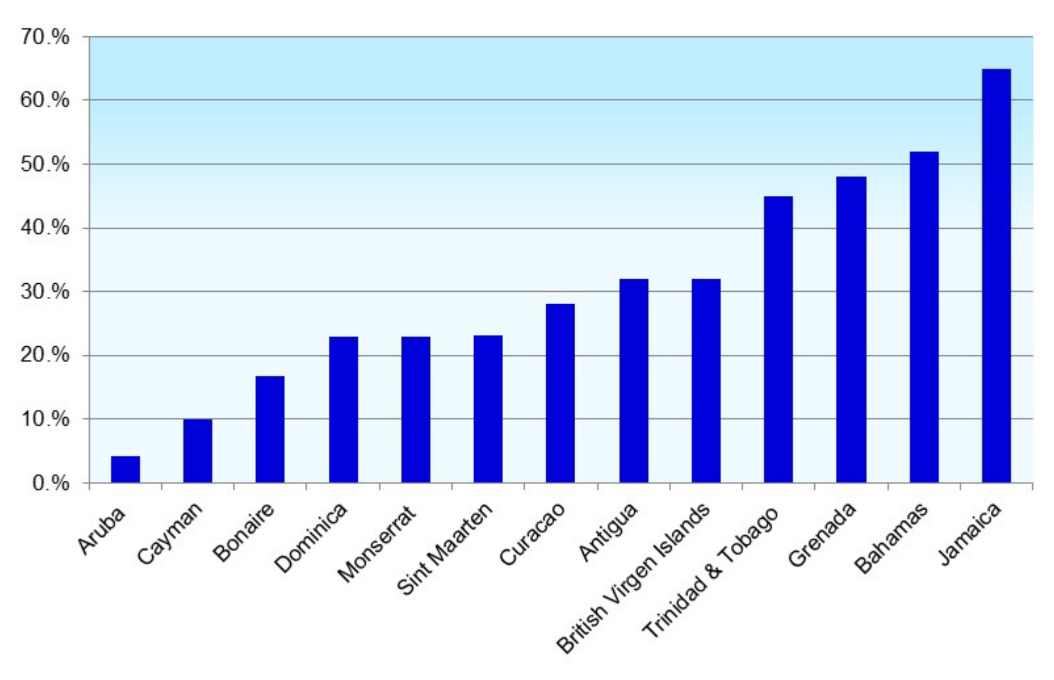


Figure 14. The NRW of some islands in the Caribbean region

As Figure 14 indicates, the NRW for most of the Caribbean islands are between 20-70%, actually outside the range for a well maintained water distribution system (Marchena, 2013).

2.3.3. The Infrastructure Leakage Index (ILI)

The NRW percentage was introduced by the *International Water Association* (IWA) to improve performance indicators for water distribution system. Although recognized as a better indicator it does not give any indication about the maintenance and management status of the water distribution system. In cooperation with the *American Water Works Association* (AWWA) the *Infrastructure Leakage Index* (ILI) was introduced at the end of 1999 as a new performance indicator specifying the maintenance condition of a water distribution system (Preston *et al*., 2007). The ILI is the ratio of the *Calculated Annual Real Losses* (CARL) and the *Unavoidable Annual Real Losses* (UARL) and is based on the best practice water balance of IWA.

In a preliminary study in 2010, a very low ILI value of 0.51 has been calculated for the distribution system of Aruba which corresponds with the guidelines for ILI target set forth by AWWA for systems with very costly water production and practically no natural water resources (Marchena, 2013). The value is the lowest in comparison with the other Dutch Caribbean Islands with seawater desalination as Table 2 indicates.

Table 2. Calculated ILI value for Aruba and the Dutch Caribbean Islands with desalination

	Aruba	**Curacao**	**Bonaire**	**St.Maarten**
Volume Sytem imput (m^3/Yr)	13 372 149	12 580 777	1 122 221	4 835 958
Pipe length (km)	642.1	2 199.6	115.5	290
Number of service connections	28 638	49 300	9 008	4 342
Average pressure (m)	55	45	50	80
UARL (m^3/Yr)	693 390	1 298 100	169 460	235 850
CARL (m^3/Yr)	356 450	3 061 010	171 500	1 209 310
NRW (%)	3.0	27.5	15.4	26.6
ILI	0.51	2.36	1.01	4.76

2.4. The chemical and bacteriological quality control and assurance in the water distribution

2.4.1. The chemical water quality management

WEB Aruba maintains minimal the chemical guidelines specified by the WHO (Marchena, 2013). The Water laboratory of WEB Aruba has 26 strategically regional sample points in the water distribution network for monthly measurements of the pH, turbidity, iron and copper concentrations. The analysis results are monthly reported to Senior Management, the Aruban Government Health Department and to the Production and Water Distribution departments. A good quality control program enables proactive action to possibly needed chemical adaptation of the chemical conditioning in case of eventual occurring corrosion in certain section of the drinking water distribution network and to set up an effective flushing program. Once a year, a chemical and bacteriological quality audit is performed through a thorough water analysis by an external renowned and certified laboratory. The *Pan American Health Organization* (PAHO) is regularly invited to perform an intensive quality audit of the drinking water. According to their report the drinking water of Aruba is qualified as one of the highest chemical and bacteriological quality in the world (Muñoz Elguera, 2008).

2.4.2. The bacteriological water quality management

The Desalination and the Water Distribution Departments are in cooperation with the Water Laboratory Department responsible for the bacteriological quality control of the distributed water. The bacteriological analyses are performed independently by the Bacteriological laboratory of the Aruban Government Health Department. At the strategic sample points, the Health Department takes monthly samples in cooperation with the Distribution Department. It is mandatory that all process' components before taken in operation either at the Production or the Distribution Department should be disinfected and bacteriological approved.

The guide line is a value lower than 50cfu/mL. Since 2000 a close work relationship is set up with Kiwa Water Research BV from the Netherlands for advice on Legionella research and monitoring program for proactive preventive measures. Legionella is a water-borne microorganism that is not harmful for normal water consumption only as inhaled in water mists containing a high concentration of the microorganism.

The genotype *Legionella pneumophila* can cause legionellosis better known as Pontiac fever (Van der Kooij *et al.* 2006). In every drinking water system worldwide water borne microorganisms form biofilm on the distribution pipe surfaces. Of importance for bacteriological control is the production and delivery of well-conditioned bio stable water not to promote further growth. Recent study showed that for Legionella to grow in the biofilms, protozoan hosts such as *Hartmannella vermiformis* should be present. These protozoans feed on the Legionella bacteria and once in the protozoa they parasitically reproduce themselves killing their hosts (Valster, 2011). It is also known that variation in pH and temperature especially trace elements have a growth enhancement effect on microorganism in the biofilm (Van der Kooij *et al*., 2005). In this context effective conditioning of the drinking water is an aspect of major importance to guarantee the biological and chemical quality of the drinking water. The Aruba drinking water produced by thermal desalination since 1932 and with the membrane desalination since 2008 has a high bio stability that no residual chlorine is necessary to guarantee biological quality. Up to now no bacteriological regrowth has been reported in the distribution system (Marchena, 2013). Research in the Netherlands showed that even though chlorine disinfection increases drinking water safety it poses more problems than benefits and the Dutch have gradually adopted a total drinking water system approach allowing production and distribution of biological safe drinking water without chlorine dosage (Smeets *et al.*, 2009).

2.5. The average annual water distribution and costs

The annual average water distribution is approximately 13.5 million m^3. The water consumption share of the Population is 49.7%, the Hotels 23.4%, Oil Refinery 13.1%, Commercial 11.0%, Government Departments 1.9% and Aruba Ports Authority (ships) 0.9%. The water consumption of the hotels can be specified as 30% for gardening, 35% for laundry, toilets and cooling towers and 35% for potable water. The monthly domestic water consumption according to WEB Aruba's estimation can be specified as 4 m^3 (130 L/day) per person, 0.16 m^3 for each cycle of was machine usage, 13 m^3 for swimming pool (with a dimension of 8x4 m) and 3-12 m^3 for gardening. The water consumption for a small, medium and large garden is calculated to be respectively 3 m^3, 6 m^3 and 12 m^3, (Marchena, 2013).

Drinking- and industrial water produced by seawater desalination is very costly, especially due to the high cost of heavy fuel oil for energy production. For client satisfaction and further to promote a good payment conduct and conscious use of water, an adequate tariff is due necessary. WEB Aruba has a socializing tariff system for house hold, a so called layer system consisting of five layers dependent on the amount of water consumed. The first three layers are based on a fixed price and the other two are based on a variable price dependent on the price of the heavy fuel oil. The first layer is a fixed price for the consumption of the first three cubic meters of water and the second layer a fixed price per consumed cubic meter for the consumption within three to six cubic meters. The third layer is the same as the second layer with a different fixed price per consumed cubic meter for the consumption between six and twelve cubic meters.

The last two layers based on variable prices are for the consumption between twelve and twenty cubic meters and for consumption higher than twenty cubic meters. For commercial and trade, construction, hotels and Government there is a fixed tariff of US$ 5.28/m^3. In the tariff all financial cost, depreciation cost, operation and maintenance cost are incorporated. Since 1992, no tariff increase has been introduced on components not related to the heavy fuel oil cost. In Table 3 the new water tariff for the water billing per August 2012 in comparison with the previous water tariff is shown (Winterdaal, 2017).

Table 3. The Water tariff of WEB Aruba as per August 2012

Customer	Monthly consumption in m3	Previous Tariff in US$/m3	New Tariff i n US$/m3	Tariff reduction in US$	Tariff r eduction in percentage
Residential	< 3	2.53	2.53		
	4 - 6	3.00	2.53	0.47	16%
	7 - 12	4.19	3.47	0.72	17%
	13 - 20	11.17	6.25	4.92	44%
	> 20	13.44	8.47	4.97	37%
Non residential	Fixed amount/m^3	7.11	5.28	1.83	26%

The reduction in water tariff was possible due the commissioning in 2012 of the second new more efficient SWRO with a capacity of 25,500 m^3/day. Additionally, the year average sales prices and the water production cost price in the period of 2008 to 2016 are shown in Table 4 (Winterdaal, 2017).

Table 4. The year average water sales and production cost of WEB Aruba

Water year average sales and cost price in $ per m^3									
	2008	2009	2010	2011	2012	2013	2014	2015	2016
Commercial sales price	6.20	5.12	5.96	6.56	6.41	5.32	5.32	5.32	5.30
Residential sales price	5.80	4.90	5.50	5.87	5.52	4.45	4.48	4.52	4.52
Industrial sale price	5.52	4.26	5.28	5.83	5.98	4.85	5.62	5.27	5.25
Water production cost price	4.23	4.58	5.08	5.67	5.27	4.48	4.50	3.77	3.32

As indicated in Table 4, the introduction of the more efficient membrane technology resulted in a reduction of the water production cost from US$ 5.67 to US$ 3.32 per cubic meter in the period of 2011 to 2016, a reduction of about 41.4%. It is noteworthy that despite the high increase in water cost in the period of 2004 to 2010 due to the rapidly increase in the heavy fuel oil costs, the water demand per capita practically stayed constant as indicated in Figure 15 (Marchena, 2013).

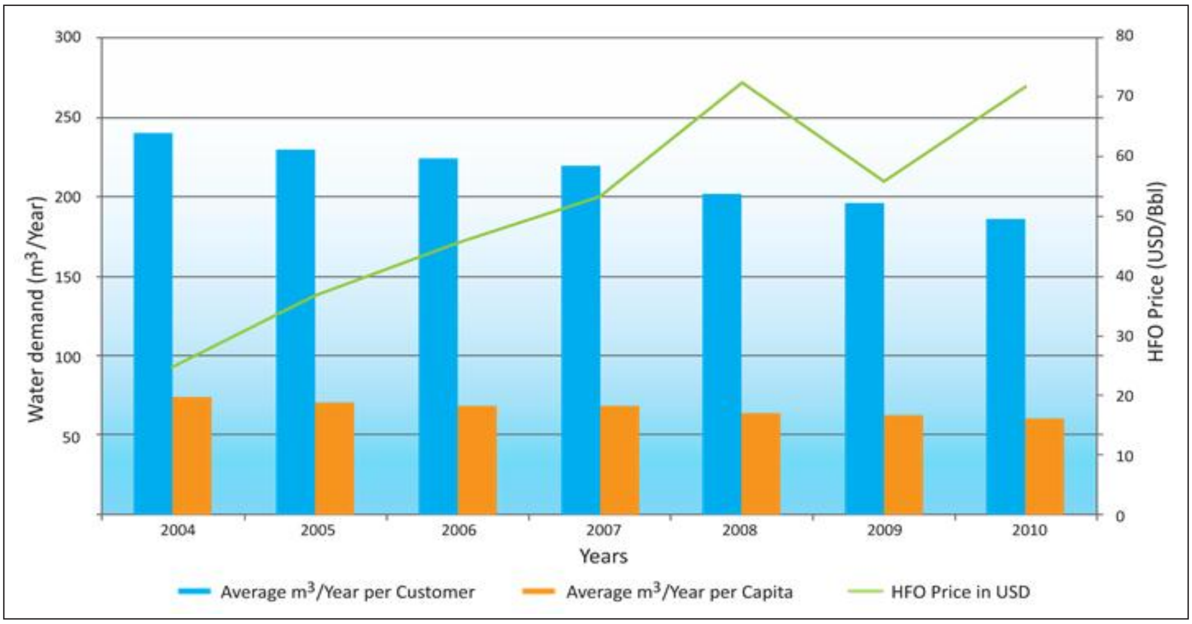


Figure 15. The domestic water demand of Aruba

3. DISCUSSION AND CONCLUSIONS

The desalination activities in Aruba were governed for almost 80 years by the thermal desalination and this supremacy is taken over since 2008 by the membrane technology. Throughout its desalination activities, Aruba has gained enormous operation experiences that contributed to the improvements of the desalination technology due to continuously seeking to improve efficiency and application of well proven new technology. According to Pan American Health Organization, the drinking water of Aruba produced by seawater desalination with the thermal and membrane technology is of high chemical and bacteriological quality (Muñoz Elguera, 2008).

WEB Aruba, the water company, has succeeded due to the optimal corrosion inhibition program of the drinking water, good operation and maintenance of the water distribution system to obtain low NRW values in the range of 1.8-4.7% and an ILI value of 0.51, the lowest value in the Caribbean Region (Marchena, 2013). This paper has outlined an important desalination history for drinking water augmentation and the main conclusion is that the Island of Aruba took a journey from primitive water treatment and supply to successful sophisticated water production and distribution and still gives its population the security of reliable healthy drinking water thanks to the seawater desalination technology.

However, and despite many innovation and efficiency improvement in seawater desalination, the cost of the produced drinking water is still very high mainly due to the high cost of the heavy fuel oil to produce the needed energy. WEB Aruba's biggest challenge in seawater desalination in the very near future is to increase its application of alternative energy such as wind energy and solar energy on a larger scale reducing fossil fuel toward cost effective and sustainable seawater desalination. Furthermore, evaluation of an effective energy and water demand side management to optimize daily water and power production with alternative sustainable energy may also result in effectively seawater desalination's cost reduction.

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