# HERITAGE INSPIRED AND NATURE-BASED DECENTRALIZED WATER SUPPLY FOR URBAN CONTEXT OF WILLEMSTAD, CURAÇAO

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***ABSTRACT***

As water scarcity has become one of the most important environmental and social issues of the 21st century, the way the built environment interacts with water must be reconsidered. Today's urban water cycle in Curaçao is characterized by linear, centralized, polluting, costly, time and energy consuming and does not contribute to cultural value. Architecture can play part in creating a more efficient and sustainable urban water system, while increasing the public awareness of issues related to the water cycle. Heritage of water typologies and systems like water plantations, cisterns and wells give example of how Curaçao used decentralized micro water catchment systems (MWCS), in the pre-desalination period, to provide freshwater for the communities inhabiting it. In addition to the concept of these heritage inspired designs and solutions (HIDS) the concept of current nature-based solutions (NBS), referring to ecosystem-based and biomimetic approaches, are analysed as alternatives. The integration of HIDS and NBS is a much-needed step forward towards an integrated and holistic approach of spatial planning and design in general and water related design and management in particular.

***KEYWORDS:*** *Hydrological cycle, Closed City, decentralized water systems (DWS), wastewater treatment (WWT), urban water cycle, micro water catchment system (MWCS), heritage inspired design solutions (HIDS), nature-based solutions (NBS, Bario (neighborhood)*

## I. INTRODUCTION

*''Architecture must serve the people.''* – (Pohl & Nachtigall, 2016)

Freshwater sustains human life and is vital for human health (Gurera & Bhushan, 2020). According to GSO (2017) only 1 percent of the water on earth is available as fresh surface and ground water, making this a scarce good (Figure 1). How to treat water properly is an urgent challenge that many *Small Island Developing States (SIDS)*, such as Curaçao, face, especially if they are largely urbanized. According to Pawlyn and Safari (2019) architecture and its conventional building structures have tended to draw down on natural capital, like the *hydrological cycle*, whereas ecosystem thinking and looking at nature as examples provide opportunities to do the opposite. Like the quote mentioned above from Pohl & Nachtigall (2016), architectural structures should not solely fulfil a functional purpose for human beings, but help regenerate the environment where they are built in. This is also in line with the idea of Pawlyn and Safari (2019) where they state that there is a need to change from the industrial age of thinking, where ecosystems are neglected, to an ecological age of human kind. If we increasingly shape the built environment with this in mind then, I believe, over the next few years, we can create spaces that are healthy and regenerative for their inhabitants and infrastructure that becomes integrated with natural systems.

The personal interest that has grown over time is to analyse how technical solutions in the built environment can help harvest and reuse water in order to relieve the pressure on freshwater demand in semi-arid climates, like that of the urbanized context on Curaçao, Willemstad. Water consumption by man continues to grow with the increasing population (Pohl & Nachtigall, 2016). The current supply of freshwater needs to be supplemented to meet the future needs. Solutions to these problems may come from looking at principals of decentralized water management systems, like the Closed City concept, explained by Hooimeijer et al (2019) and the principals of HIDS and NBS, where former inhabitants and living nature dealt with these same issues. Because urban settlements contribute to these problems greatly, this research paper focuses on using decentralized sustainable water treatment systems and technologies in the built-environment.

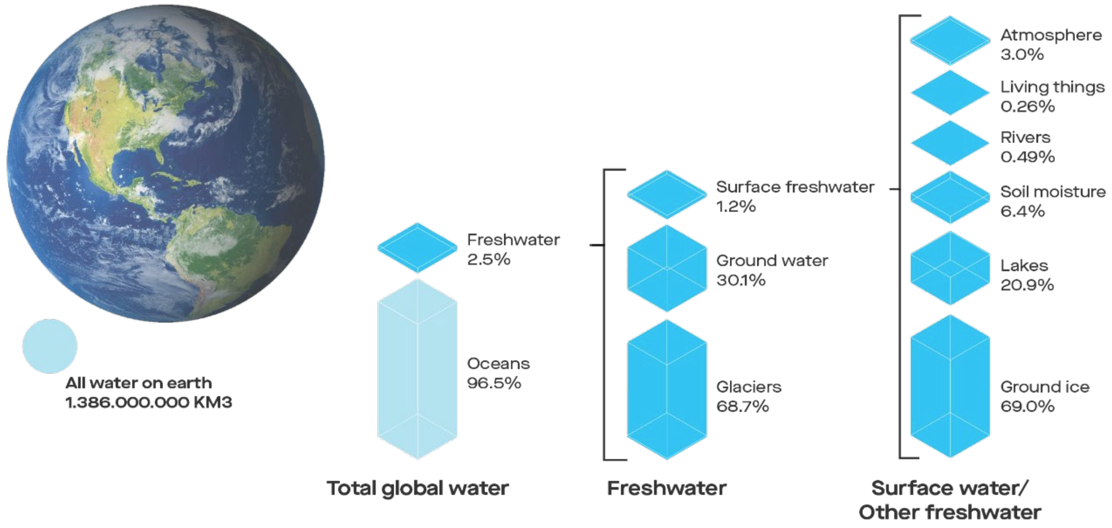


Figure 1. Available freshwater supply on Earth (Authors image)

## 1.1. Problem statement

The problem statement is derived out of 3 components from more generic to site specific:

1. Water treatment issue in the urbanized regions in SIDS
2. Water treatment issue in Curaçao
3. Urban area of the city Willemstad, Curaçao

**1) Water treatment issue in urbanized regions and SIDS:**
According to Gurera and Bhushan (2020) it is estimated that 2 billion people live in countries that are experiencing problems related to high water stress. These problems are often found in urbanized areas around the world. The increases in population and building density that occur in these progressively urbanised areas can have a far-reaching effect on the *hydrological cycle* and therefore on both the quantity and quality of water resources (Hall & Ellis, 1985).

A trend to live in urbanized area has developed greatly in Curaçao. According to the Government of Curaçao et al (2019) 75% of the population on Curaçao lives in urbanized regions, that makes up a quarter of the total area of the island. This classifies Curaçao as a highly urbanized country. Looking at the hydrological cycle of SIDS numerous challenges occur due to their biophysical settings (Figure 2). SIDS are at the forefront of climate change and its consequences, particularly with regards to their freshwater resources, where 91% is threatened by water shortages (UNESCO, 2019). Also problems relating to the pollution of ground water and surface water due to saline intrusion can be found on these types of islands. As stated in UNESCO (2019), SIDS are often surrounded by the ocean, making their ground prone to saline intrusion, causing 73% risking groundwater pollution.

As mentioned above there are many residents living in urbanized areas facing the issue of the quantity and quality of freshwater resources. Researchers like Pawlyn and Safari (2019) state that our standard approaches to water have an inherent technological laziness to them that has developed from the same assumptions of limitless supply that characterised our attitude to resources at the start of the Industrial Revolution. By introducing the hydrological cycle in our built environment, buildings and public space could be seen as the connection between the natural water systems, water chains and its inhabitants.

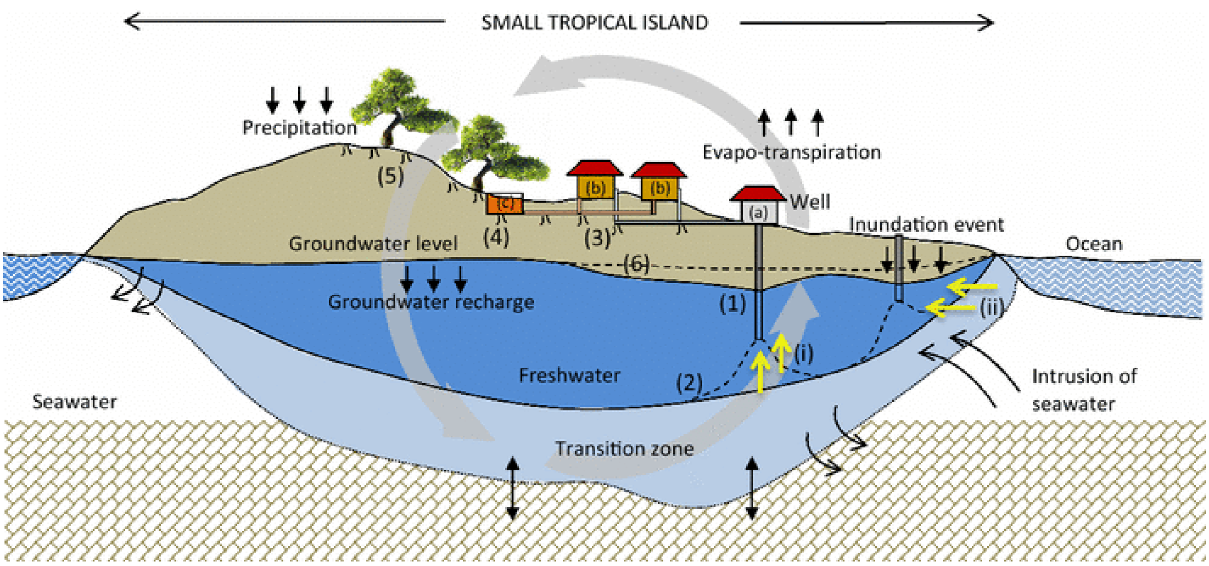


Figure 2. Overview of small tropical island's conceptual model showing simplified hydrological cycle and hydro geochemistry mechanisms (Mohd Isa et al., 2017)

**2) Current water production and treatment in Curaçao:**

On Curaçao the importance of freshwater is tangible (GSO, 2017). One of the main problems on the island is the lack that management and infrastructure of freshwater have in order to cope with the natural water system and water chains. This main problem can be divided into the following: 2.1) issues in the catching and managing of rainwater and groundwater, 2.2) issues in the harvesting of freshwater and 3.3) the lack of treating wastewater.

2.1) Despite imminent shortages, Curaçao allows rainwater to drain unused into the sea (GSO, 2017), which not only effects the quantity of freshwater resources on land but also pollutes the ecosystems in the ocean. This inadequate management contributes to the pressure of harvesting enough freshwater for the inhabitants and tourists, but also for flora, fauna and agriculture.

2.2) To produce freshwater, a land based reverse osmoses production plant, named Aqualectra, was built on the island. This plant produces freshwater for 98% of the households (Central Bureau of Statistics, 2018). However, the production is a time and energy consuming process which makes the production of freshwater expensive. According to Wesselink (2015) the cost per cubic meter of freshwater in Curaçao is seven times more expensive than that of the Netherlands. In addition to this, Curaçao faces the pressure of producing enough freshwater for the inhabitants and tourists (Antilliaans Dagblad, 2019). Although the population growth on the island has flattened, there is still a big growth in tourists visiting it. According to Antilliaans Dagblad (2019), tourists use up to 300% more water than inhabitants of the island. Another problem the plant faces is the loss of produced water, due to deteriorated pipe lines and illegal tapping of freshwater. It has been stated in the 2019 Annual Report of Aqualectra (2019) that 27% of the produced water of Aqualectra is lost in the process of distributing it to the people naming it 'Non-revenue'.

2.3) Another challenge facing Curaçao is the lack of infrastructure and treatment of domestic and industrial wastewater. Stated by UNOPS et al (2018) , around 16% of wastewater produced in Curaçao is treated due to deficiency in sewage treatment facilities. The remaining untreated wastewater is discharged into the terrestrial and marine environment. According to Hendriksen (2019) 1.6 million guilders was invested to build a new WWTP, specially designed to treat polluted water in order to dump it back in the ocean. Linear solutions like these are implemented even though 2% of the people on the island can't afford their monthly water bill (Ministry of Economic Development, 2021). Currently, there are four different WWTP's on Curaçao built by the government, but these do not function well due to inadequate machinery and treatment techniques (UNOPS et al, 2018).

To conclude, there is a high freshwater demand on the island which is currently provided by an expensive, energy consuming production method (reverse-osmoses desalination method), while much water is lost due to inadequate water management.

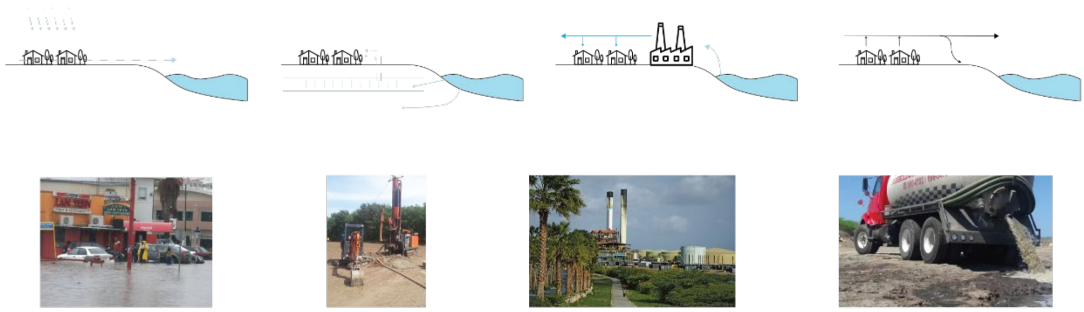

Figure 3. Diagrams that summarizes the current lack Curaçao has on the that management and infrastructure of freshwater and wastewater, in order to cope with the natural water system and water chains (Authors image)

**3) Urban neighbourhoods 'barios' of Willemstad, Curaçao**
The urban region of Curaçao is concentrated in the city called Willemstad (centre and periphery). This part of the island is in transition from a unsustainable developed urban area, that grew out of new neighbourhoods built for the labour class during the early days of the prosperous oil refinery and 20th century modernist suburban expansion (Ministry of Economic Development, 2021), into a green and healthy living environment. In the past, water reservoirs and greenery where depleted in order to build these scattered neighbourhoods and car infrastructures. Due to this depleting of natural environment, problems related to quality and quantity of freshwater started increasing. Therefore, in the Objectives for the community-based vision 2030 of the New Urban Agenda, it is stated that the drainage system, wastewater collection and treatment system functions would be optimized and integrated in a sustainable water management cycle (Government of Curaçao et al., 2019).

## 1.2. Design and Thematic research question

The above mentioned research fascination together with the problem statements, resulted to the following **Design question:**
*How can a decentralized water management system, on neighbourhood scale, in the urban area of Willemstad be implemented on delipidated monument sites and be connected to a public programme to increase the communal awareness of the finite resource of freshwater?*

The thematic research focuses on the life cycle of water in the built environment. Harvesting of freshwater and reusing of wastewater in the urban water cycle is seen as an essential part of a circular approach to this natural resource. Thus the following **Thematic research question:**
*How can a decentralized water system be implemented to provide freshwater in a neighbourhood in Willemstad, Curaçao?*

Developed further via **sub questions**:
- *What are the current situations and potentials of the natural water cycle and water chains of Willemstad, Curaçao?*
- *What decentralized water systems and technologies in the built environment are available?*
- *How can these systems and technologies be integrated on neighbourhood or building scale in a neighbourhood of Willemstad?*
- *What are the spatial and architectural impacts of these systems and technologies?*

## 1.4. Methodology

**Overarching methodology:**
For this project is *scenario planning*. Inspired by the 'Closed City concept' described by Hooimeijer et al (2019), scenarios are imagined relying on the ideas of decentralized water management system and circular economies. In order to formulate scenarios that will assist me in gaining knowledge for the research, as well as for the design, the theory of Nature-based solutions in architectural design principles (Pawlyn & Safari, 2019) is also studied.

**Defined scenario for the thematic research:**
Where decentralized closed water systems are implemented as part of an advanced circular approach to relieve the pressure on freshwater availability in Curaçao. This scenario shifts the emphasis from current conventional centralized water management to technical and practical challenges of the transition into a decentralized closed water system where building constructions are needed to be designed as part of an advanced regenerative circular economy. Allowing exploration in techniques of freshwater harvesting and wastewater treatment.

The findings of the sub-questions above will likewise form the structure of this thematic research paper. In the section on current situation and potentials of the urban water cycle, the current situation is sketched and the existing water usage in the area calculated based on information acquired from the Annual rapport in 2019 of the local desalination plant Aqualectra and statistics from Central Bureau of Statistics Curaçao. The information was conducted for the water flows of the whole island population. In order to estimate the water usage of one neighbourhood in urban area of Willemstad, consisting on average of 2800 inhabitants (see appendix B), the results found in the above mentioned rapports where extrapolated to neighbourhood scale.

In the sections on decentralized water providing systems and technologies and their spatial and architectural impacts, findings are based on literature review and scientific papers introducing technologies inspired by HIDS and NBS that have the potential to be applied to the scale of a building.

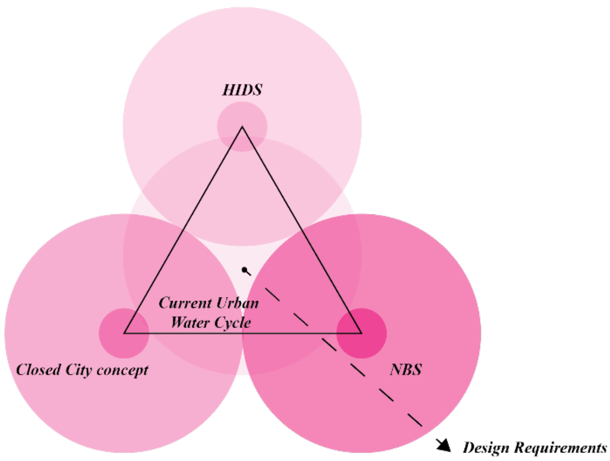


Figure 4. Design requirements from analyzing the Current Urban Water cycles, Closed city concept and HIDS and NBS (Authors image)

## 1.5. Defining the site boundaries for BarioA

BarioA in this paper is an average neighbourhood found in the urban area of Willemstad, Curaçao. The reason I used a fictional neighbourhood is to make the process of implementing a decentralized water system repeatable in other parts of Willemstad. Based on the fact that 75% of the inhabitants live in the peri-urban area of Willemstad, which makes up of 25% of Curaçao, and the fact there ae 42 barios / neighbourhoods in this area the next calculation could be made (see appendix B for calculations):

- Size BarioA: 2,65 km$^2$
- Inhabitants living in BarioA: 2800 inhabitants
- Number of households in BarioA: 1102 Households
- Water consumption BarioA: 10.579 m$^3$ / month

# II. Mapping of current and potential waterflows in Willemstad

## 2.1. Water flows in urbanized area of Willemstad

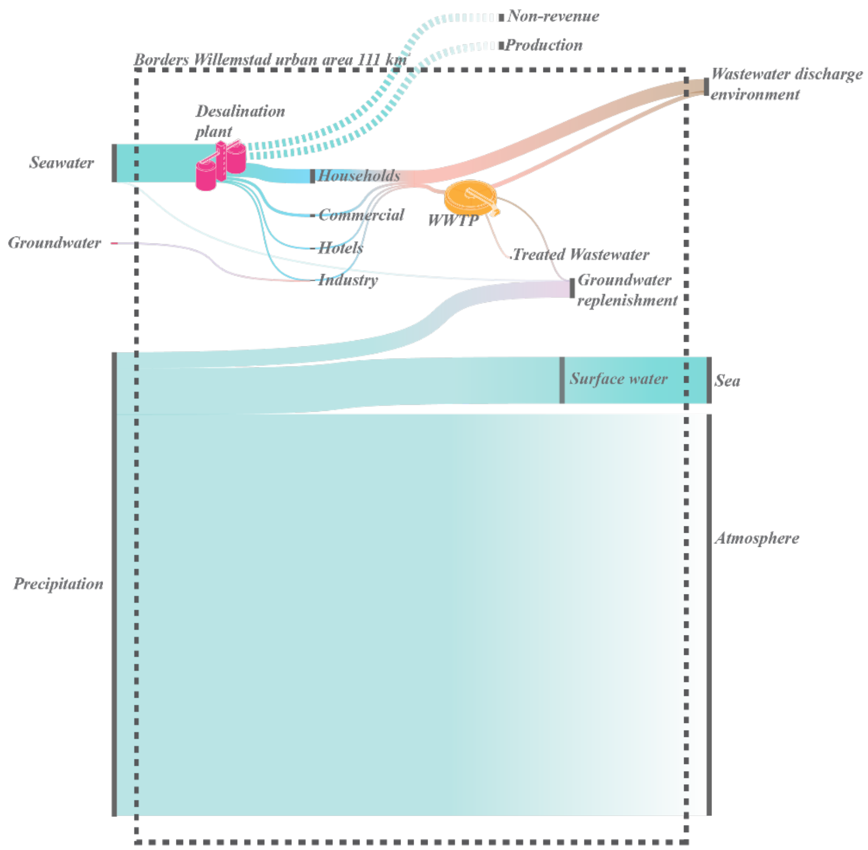


Figure 5. Sankey diagram showing SFA of waterflows in wet month in Willemstad (Authors image)

The Substance Flow Analysis (SFA) displays the current way waterflows are distributed in the wet and dry months in Willemstad (Figure 5 and 6). Detailed explanations and calculations can be found in Appendix C (See appendix).

The ***average precipitation per month*** in the wet period, October to December, of Curaçaos is 95mm (*Curaçao Climate: Average Weather, Temperature, Precipitation, When to Go*, z.d.). This can be calculated to 0,095 m$^3$ per month of potential rainwater catchment per m2 area. For the dry months, January to September, the average precipitation is 30 mm or 0,03 m$^3$ per month of potential rainwater catchment per m$^2$ area. Consisting of an area of 117.000.000 km$^2$, Willemstad, has an average rainfall of 11115000 m$^3$ per average wet month and 3510000 m$^3$ per average dry month.

The potential ***evapotranspiration*** on Curaçaos is 2500 mm/year and thus far exceeds the average annual precipitation (Van Houselt, 2021). Due to urbanization in Willemstad the evaporation of water from soil and other surfaces and consumptive water use by plants is also expected to be reduced. In the Sankey diagram I used a 90% coefficient for the total evapotranspiration of the precipitation.

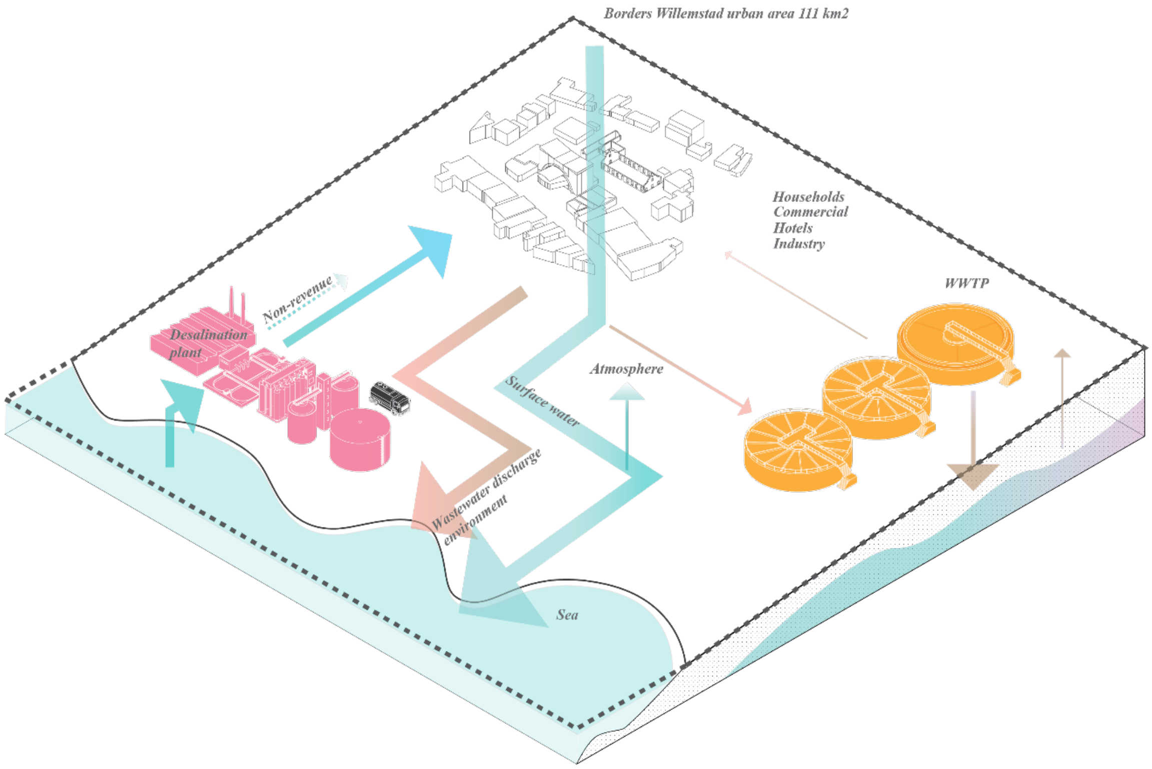


Figure 6. Conceptual representation natural waterflows and water chains in Willemstad (Authors image)

In Curaçaos the fraction of ***precipitation that replenishes the groundwater*** is estimated at a maximum of 3.5%, corresponding to 20 mm/year (Van Houselt, 2021). For the area of Willemstad this would signify a monthly replenishment of groundwater of 389025 $m^3$/month in the average wet month and 122850 $m^3$/month in the average dry month. However researchers found that the increase in urbanization is expected to increase runoff and restrain water to be absorbed into the ground as groundwater.

In addition to the absorption of precipitation there is also a ***absorption of wastewater in the soil***. The amount of wastewater that ends up in the groundwater is estimated at 25 litres per person per day on Curaçaos (UNOPS et al, 2018). Seeing that the total amount of Inhabitants living in Willemstad is equal to 75% of total population on Curaçaos making up a total of 116000 inhabitants the monthly abortion of wastewater in groundwater equals 87000 m3/month.

Mentioned in the introduction the current supply of freshwater comes namely from two desalination plants, using steam driven flash evaporators and reverse osmosis (CBS, 2020), who together belong to the ownership of the company Aqualectra. In order to produce enough freshwater, quantified to 6545463 m3/month, for the area of Willemstad, Aqualectra uses 909625 m3/month of seawater.

In the current distribution of freshwater to neighbourhoods water losses can be significant. Unfortunately, in Curaçao this is the case. According to the CBS (2020) the 'non-revenue water' amounted to 30% of the distributed volumes of water. Of this percentage 13.5% was due to physical losses and 17.5% to so-called administrative losses, including water use through illegal connections. Figures of 2019 from the annual report of Aqualectra (2019) show that the losses of non-revenue water were 27% of total production. According to BTP&U (World Bank 200617) a level of non-revenue water for developing countries of 17.5% is reasonable. Bearing in mind that freshwater production in Curaçao is strongly related to energy, the high levels of unaccounted water represent a serious economic cost (Central Bureau of Statistics, 2020). In 2019 this can be estimated, with the average water tariff per m3 being 10,4278 ANG (Aqualectra, 2019), to a total amount of 29mln Antillean guilder, or 14 mln euros.

For this reason several actions and programs of reducing water losses had been taken in the past by Aqualectra and the government. The most recent action plan found focused on reducing the water losses in 3 years to 17 percent by 2018. According to UNOPS et al (2018) the percentage of non-revenue for 2017 was 23%. This means that the 'non-revenue water had only increased with 4% until 2019.

Quantifying this information provides the following insights.
Willemstad freshwater consumption from the two desalination plants is the total produced water subtracted by 27% of non-revenue water, making up 6364869 m3/month and divided in:

- Household = 72% x 6364869 m3/month = 4582705,7 m3/month
- Commercial = 15% x 6364869 m3/month = 954730,4 m3/month
- Hotels = 8% x 6364869 m3/month = 509189,5 m3/month
- Industry = 5% x 6364869 m3/month = 318243,5 m3/month

On domestic scale the current supply of freshwater for households in Curaçao comes:

- 98,8 % from desalination plant
- 3,7% from groundwater or cisterns
- 0,1% from water trucks
- 0,3% from bottled water
- 0,8% other

*The sum of the percentages surpasses the 100 percent mark due the fact that some households use multiple ways in order to supply freshwater.*

UNOPS et al (2018) states that 33% of the island's properties are connected to the sewage systems. The areas which don't have access to a centralized sewage systems, use underground septic systems as alternatives. The sludge in these tanks is collected by trucks and transported to sludge treatment facilities, whereafter treatment the extracted sludge is dumped on landfills and the liquid components used for irrigation (UNOPS et al, 2018)

Wastewater generation rate per month equal 80% of consumed water for domestic, commercial and Hotel purposes and 25% of consumed industry purposes. *Wastewater quantities generated from industries depends on type of industry and production capacities.*

- Household = 273005 m3/month
- Commercial = 56876 m3/month
- Hotels = 30334 m3/month
- Industry = 5925 m3/month

Currently the discharge of wastewater for the households in Curaçao is:

- 77,1% of households cesspool
- 3,1% of households septic thank
- 18,6% of households sewage
- 0,4% other

According to CBS (2020) sewage pollution of nearshore water is highest in the zone near Willemstad, being the most developed region on the island.

## 2.2. Potential water flows to intervene in Willemstad

In attempt to reduce the usage of produced potable water from Aqualectra, this section will analyse the suitability of alternative sources of freshwater for the area of Willemstad.

### 2.2.1 Suitability of rainwater as freshwater resource in Willemstad

Currently Curaçao allows rainwater to drain unused into the sea (GSO, 2017), which effects the quantity of freshwater resources on land, creates soil erosion and pollutes the ecosystems in the ocean. Another problem relating to unused drainage of rainwater is that the groundwater does not get the chance to recharge, resulting in salination of groundwater on the island. Rainwater in Willemstad could potentially be a resource in supplying freshwater for people and agricultural usage seeing that the yearly precipitation is around average 550 ml. However it is important to mention that Curaçao copes with long seasons of drought and short periodical seasons of heavy rainfall. Therefore storage and minimizing loss of precipitation should be accounted for. Also other additional waterflows have to be taken into account for a constant supply of freshwater in these drought periods.

### 2.2.2 Suitability of groundwater as freshwater resource in Willemstad

According to (Van Sambeek et al., 2000) almost 40% of the sampled wells in Curaçaos contain nitrate above the WHO and Dutch drinking water standard of 50 mg/l, while 70% of the wells have a chloride concentration above the WHO standard of 250 mg/l. It is stated by Van Sambeek et al. (2000) that the groundwater of the islands is brackish, with chloride concentrations varying between 115 mg/l (freshwater) and 17.000 mg/l, qualifying it almost as seawater. Only 15% of the wells meet the WHO standard for both nitrate and chloride (Van Sambeek et al., 2000). Therefore the availability of groundwater in Willemstad as potable water is limited and more likely to be used for agricultural practices.

### 2.2.3 Suitability of Surface water as freshwater resource in Willemstad

Available surface water from lakes and rivers is scarce and groundwater abstraction is widely practiced for agriculture (Van Houselt, 2021).

### 2.2.4 Condense and vapor as freshwater resource in Willemstad

Condensation was considered to be investigated, but after concluding that the air temperature in Willemstad never drops below the dewpoint, of 25 Celsius (*Weather for Willemstad, Curaçao*, 2021), it was not further investigated. This is necessary in order to saturate the air, where excess moisture will be released in the form of condensation.

### 2.2.5 Wastewater as freshwater resource in Willemstad

Other potential water sources could come from the reusing of wastewater in the area. Currently there are four sewage treatment plants, managed by Public Works Curaçao, on the island: Klein Kwartier, Abbattoir, Klein Hofje and Tera Kora (UNOPS et al, 2018). In order to collect and reuse wastewater on the site, it is necessary to introduce new water-related facilities that are able to collect and treat wastewater. These will be explained in the next paragraph.

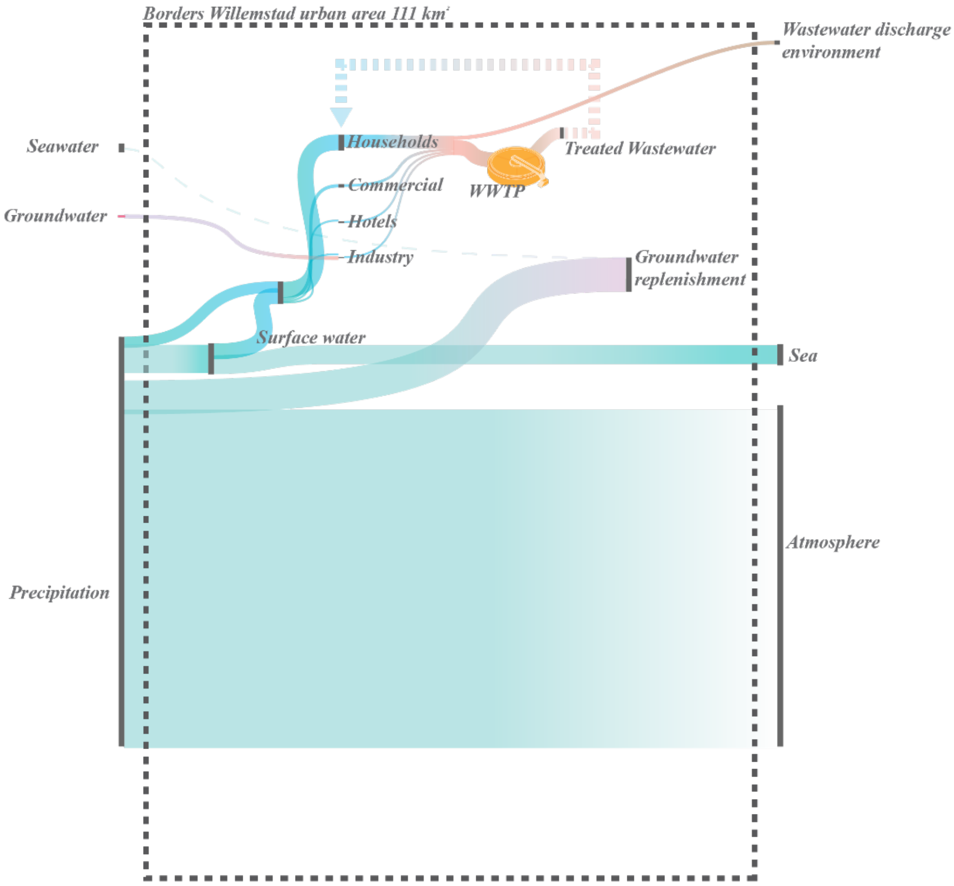


Figure 7. Sankey diagram showing SFA of potential waterflows in wet month in Willemstad (Authors image)

The current hydrological cycle of Willemstad is examined and insight in unused waterflows is clarified. The next chapter will describe how technologies inspired by HIDS and NBS could anticipate to these unused waterflows, in order to examine what potential systems or technologies exist to harvest freshwater.

# III. Closed City concept and technologies inspired by HIDS and NBS for decentralized supply of freshwater

## 3.1. Closed City concept

The 'Closed City' theory, described by Hooimeijer (2019), calls to reinvent the connection between urban space and water management and insist in designing decentralized water circulation systems. This proposal is to improve the water storage and water purification capacity of cities, to store and recycle rainwater and sewage (Hooimeijer et al, 2019). This is believed possible by creating a self-sustaining water circulation system that responds to water shortages and floods. Hooimeijer et al (2019) state also that when applying these new water cycles to urban areas, it is important to evaluate the applicability and performance of Closed City in the urban hybrid system. The urban hybrid system is defined as "Environmental Hybridity" that evaluates the relationship among the geosphere, biosphere and technosphere, and "Spatial Hybridity" that evaluates visual perception of the water system and water chain as part of urban space.

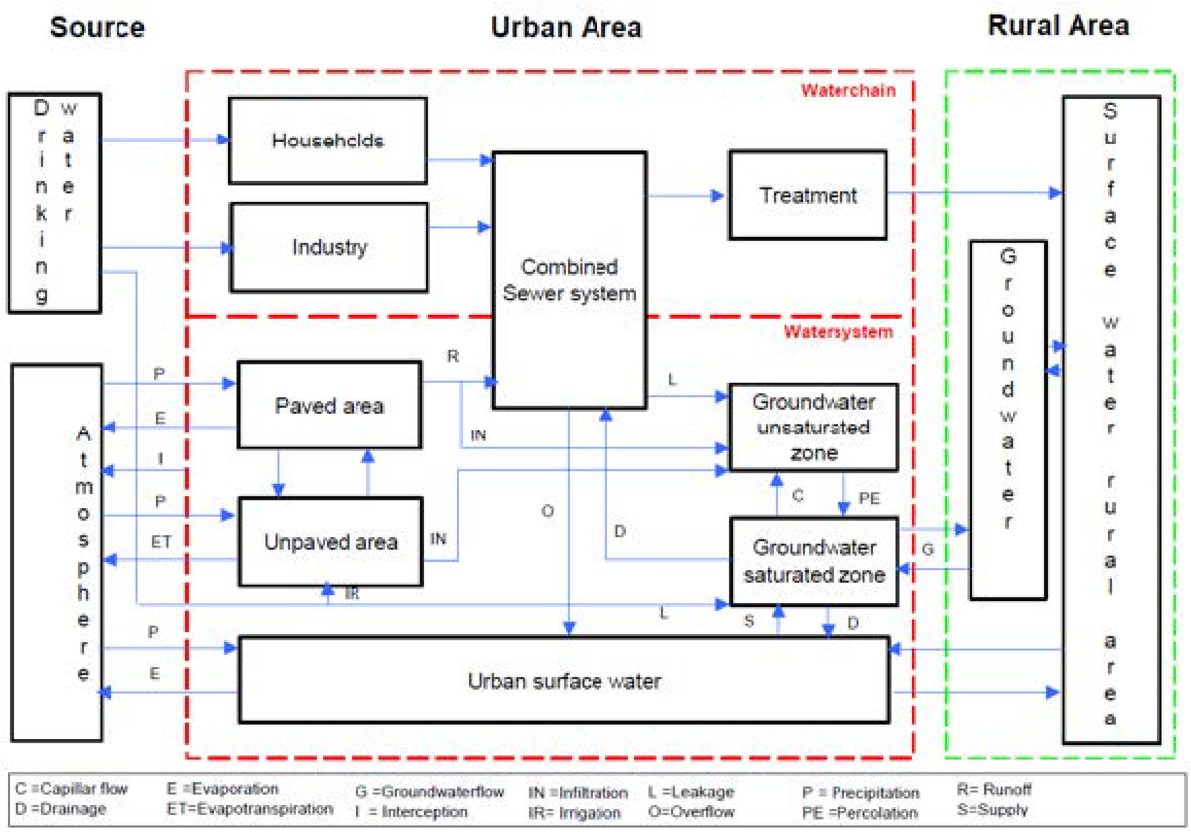


Figure 8. Diagram of artificial and natural waterflows (source: Hooimeijer et al, 2019)

The next section will explore different alternatives, inspired by HIDS and NBS, of providing water to the area in a decentralized and sustainable manner. For detailed catalogue, see the appendix C and D. The reason why HIDS and NBS are both researched is that these two could potentially benefit each other (Figure 9).

| Benefits of NbS in cities (after Xing et al., 2017). | Benefits of NbS for built heritage conservation in urban areas | Benefits of built heritage conservation for the successful delivery of NbS in urban areas | Examples |
|---|---|---|---|
| Sustainable water | Reduced risk of water-related damage to heritage assets and sites, e.g., flooding and water ingress to historic buildings. | Heritage sites offer additional locations for sustainable water management schemes in cities, and provide historical examples of successful low-tech approaches to water management. | Engineering knowledge of ancient civilisations provides inspiration for modern sustainable water management (Gonzalez Cruz, 2017). |

Figure 9. Overview potential benefits using NBS with HIDS (source: Coombes & Viles, 2021)

## 3.2. HIDS

### 3.2.1 HIDS for freshwater harvesting

Looking at the heritage, before the centralized desalination era of Curaçao, water systems and typologies depended on the winning of rainwater and groundwater. In the colonial time MWCS where developed on the island in order to harvest enough water for the inhabitants and industries like agriculture (Loen, 2019). Renkema's study into the plantation economy of Curaçao has a strong focus on the water supply systems (Renkema, 1981) and Debrot (2009) studied the cultural ties to the land in an arid plantation setting. By putting together the findings it is possible to get an informed idea of how the water supply chain developed in the past on Curaçao. A brief history of the water related developments and a catalogue of different water topologies and systems can be found in the appendix C. Typologies like cisterns, aqueducts, water-windmills and colonial water wells, as well as systems like the Tanki-dam, Waterkuilen-faha and Water plantation where studied and catalogued (see appendix C). The systems and typologies which were used in the past on Curaçao could become an heritage inspired alternative to supply Willemstad and BarioA with freshwater.

### 3.2. NBS

#### 3.2.1 NBS for freshwater harvesting

Alternatives of harvesting freshwater can be inspired by NBS. According to Brears (2020) these type of solutions refer to "ecosystem-based approaches, biomimicry and biodiversity" and offer an "alternative approach to increasingly relying on engineering solutions" in the face of climate change. Due to the countless NBS that exist, it is not possible to investigate all aspects. For the case of rainwater, stormwater runoff and groundwater investigations where made on biomimetic examples that can be found in plants and animals (see appendix D). The solutions found are very conceptual, however I do believe in a later stage the found case studies might be of use for the design.

According to Pawlyn and Safari (2019) Biomimicry calls to reframe conventional design methods of architectural structures by recognizing that ecosystem thinking an looking at nature as example for designing could provide opportunities for architects in order to create architecture that could for example harvest, capture, store, transport and reuse water. Therefore, the principals of harvesting water with constructions in the built environment will be used as a tool to enhance this approach.

#### 3.2.2 NBS for wastewater reuse

Over the past half century we lost vast quantities of minerals from the world's soils in the linear flow of nutrients via food, the human gut and our dominant wastewater treatment paradigm (Pawlyn & Safari, 2019). Between 1940 and 1991, this translated directly into a drop in the mineral content of food. Alternatives of using treating wastewater can be inspired by NBS. Biological systems have evolved to thrive in closed loops, in which the concept of waste does not exist: everything is nutrient.

For agriculture in Willemstad produced desalinated water is currently used as irrigation. The problem related to this is the poor nutrient quality found in the desalinated water and the costs of energy. Nature-based treatment of wastewater, true for example constructed wetlands or Living machines (see appendix D), could become a solution to this problem. Also, the use of treated wastewater conserves groundwater and the ecosystem (UNOPS et al, 2018).

## IV. PROPOSED WATER SYSTEMS

In the opinion of Pawlyn and Safari (2019) buildings can be seen as the scale that connects the city and its urban water system to its inhabitants. Therefore, this research focusses on the role that architecture could play in the natural water cycle and water chain of Willemstad.

In order to collect rainwater and groundwater on the site (during the rainy season), it is necessary to introduce new water-related facilities based on the above mentioned HIDS and NBS. Firstly it is important to understand what facilities will be introduced in order to create a decentralized water system on the scale of BarioA. To understand the quantity of water they can manage and what the spatial and architectural impacts of these systems and technologies are will be further developed during parallel with the design phase.

The new facilities that can be introduced on building scale are rainwater catchment, stormwater catchment and a wastewater treatment typologies and systems. These elements should harvest, capture, store, transport and minimise the loss of water. On the scale of BarioA in Willemstad it could be a possibility to convert an existing building plot, for example an dilapidated monument or plantation, into a water production facility by adding the above mentioned typologies and systems.

Despite the addition of the new facilities, most of the existing system remains unchanged. In period of drought water there are simply not enough water resources within the area to satisfy the needs. If these needs cannot be satisfied by decentralized, neighbourhood scale infrastructure, they will need to be supplied by the existing centralized infrastructures, such as the existing desalination plant. However if harvested water is stored and loss is minimized, Curaçao could potentially enter a post-centralized water production and treatment era.

***Diagram of system used in heritage (MWCS):***

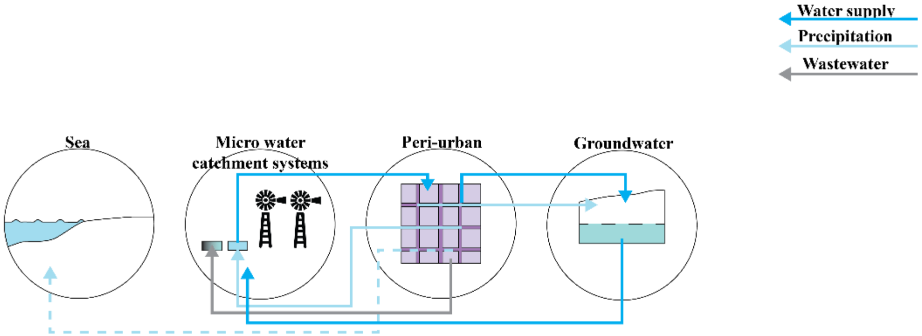


Figure 10. Schematic diagram urban water system used in colonial time. (Authors image)

***Diagram of currently used systems:***

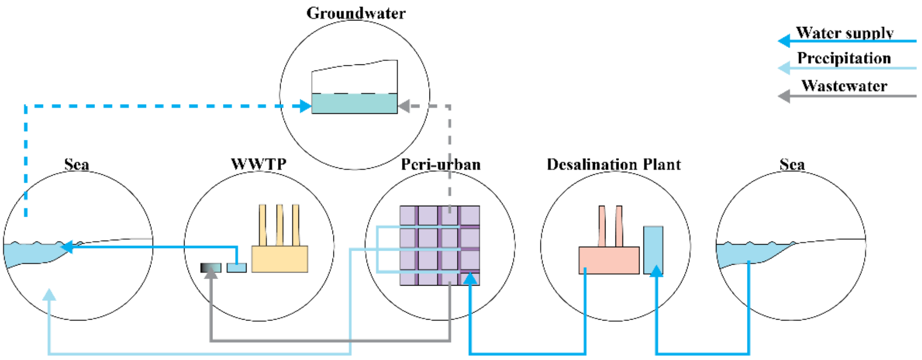


Figure 11. Schematic diagram urban water system used currently. (Authors image)

***Diagram of proposed system:***

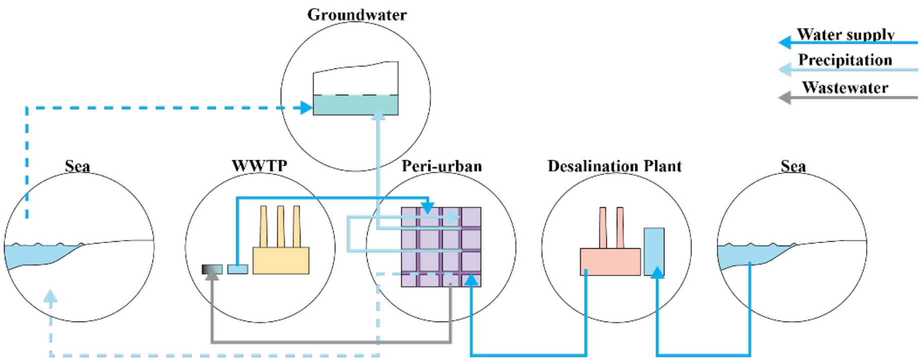


Figure 12. Schematic diagram proposed urban water system. (Authors image)

## V. CONCLUSION

This paper answers the question: *How can a decentralized, circular water system (inspired by the closed city concept, HIDS and NBS) be implemented to provide freshwater in a urban neighbourhood in Willemstad, Curaçao?*

Currently Curaçao is coping with high pressure relating to freshwater resources. Challenges on the island are:

- Rainwater unused and drained into the sea
- Groundwater does not get the chance to recharge
- Unsustainable freshwater production (high energy and big number of non-revenue water)
- Wastewater treatment underdeveloped

Rain water in Curaçao could potentially be a resource in supplying freshwater for people and agricultural usage seeing that the yearly precipitation is around 550 ml. However it is important to mention that Curaçao copes with long seasons of drought and short periodical seasons of heavy rainfall.

Historically, in the colonial era and even before that, the inhabitants of Curaçao managed its freshwater in an ecosystem-based approaches. MCWS where implemented in order to catch rainwater and recharge the groundwater. The recharged groundwater functioned as a natural water reservoir, so in periods of drought this source could be used for the production of freshwater. These micro catchment water systems, like the *Tanki-dam system*, *Waterkuilen-faha system and Waterplantations* made it possible to create resilience in freshwater production. However it must be stated that even in the colonial period problems relating to salinized groundwater started occurring when unsustainable deforestation took place.

This paper expects that longer periods of drought and heavier periods of rainfall due to climate change will be a possible scenario phasing Curaçao.

This paper proposes to implement a water facility on the currently unused or dilapidated spaces in the urban area zones of Willemstad. Despite the addition of new water facilities in BarioA, most existing systems remains unchanged. In period of drought water there are simply not enough water resources within the area to satisfy the total needs (Domestic needs and agricultural needs). If these needs cannot be satisfied by decentralized, neighbourhood scale infrastructure, they will need to be supplied by the existing centralized infrastructures, such as the existing desalination plant. However if harvested water is stored and loss is minimized, Curaçao could potentially enter a post-desalination era.

## VI. ARGUMENT OF RELEVANCE

**Disciplinary relevance:**
Circular water treatment is one of the key elements in order to tackle the contemporary issue of climate change and consequent changing of the hydrological cycle in urban areas. In Curaçao water processing companies and wastewater treatment facilities have already made steps in order to down the pressure on freshwater resources, like desalination reverse osmoses plant and wastewater treatment plants. However, there remains problems in the urban hydrological cycle in SIDS on how to collect and treat water properly and efficiently.

A lot of research is done on how to create closed water cycles that inspired by mimicking solutions found in nature and heritage. For the building level there has been extensive research done based on biomimetic approaches for freshwater treatment and wastewater reuse.
Thus, based on the existing knowledge on decentralized closed water cycles and freshwater harvesting and wastewater treatment technologies, this research tries to get an insight into the feasibility of managing the natural water system and water chain on the scale of a building.

**Societal relevance:**
This research is also of great societal relevance because currently, many residents of SIDS are not aware of the importance of creating closed urban water cycles. In order to realize the circular hydrological cycle in urban areas, community involvement and awareness can be a crucial part. A closed urban hydrological cycle is not only beneficial for the quantity and quality of freshwater resources but also beneficial for providing a healthy living environment for residents. Residents will have more possibilities to work together with their communities on treating the freshwater from their neighbourhoods. This would enhance the cohesion in the sprawled neighbourhoods of Curaçao which is missing at this moment.

## GLOSSARY OF KEY TERMS

The ***hydrological cycle*** crosses three environments: the geosphere, the biosphere, and the technosphere. In urban areas it consists of two systems, the natural water system and the water chain (Hooimeijer et al, 2019).

The ***natural water systems*** defines the natural systems and chains of ground, open and rain water (Hooimeijer et al, 2019).

The ***water chain*** defines the artificial chain of freshwater and wastewater (Hooimeijer et al, 2019).

***Small Island developing states (SIDS)*** are a distinct group of 38 UN Member States and 20 Non-UN Members/Associate Members of United Nations regional commissions that face unique social, economic and environmental vulnerabilities.

***Circular economy***, is based on three main principles: 1) designing out waste and pollution 2) keeping products and materials in use and 3) regenerating natural systems. It provides a framework for "*a new way to design, make, and use things within planetary boundaries*" (Ellen Macarthur Foundation, 2020).

***Closed City*** is defined as "a city that does not have adverse effects on its surroundings, such as water depletion or emission of pollution" (Hooimeijer et al, 2019). This proposal is to improve the water storage and water purification capacity of cities, to store and recycle rainwater and sewage.

***Biomimicry*** is "design inspired by the way functional challenges have been solved in biology" (Pawlyn and Safari, 2019)

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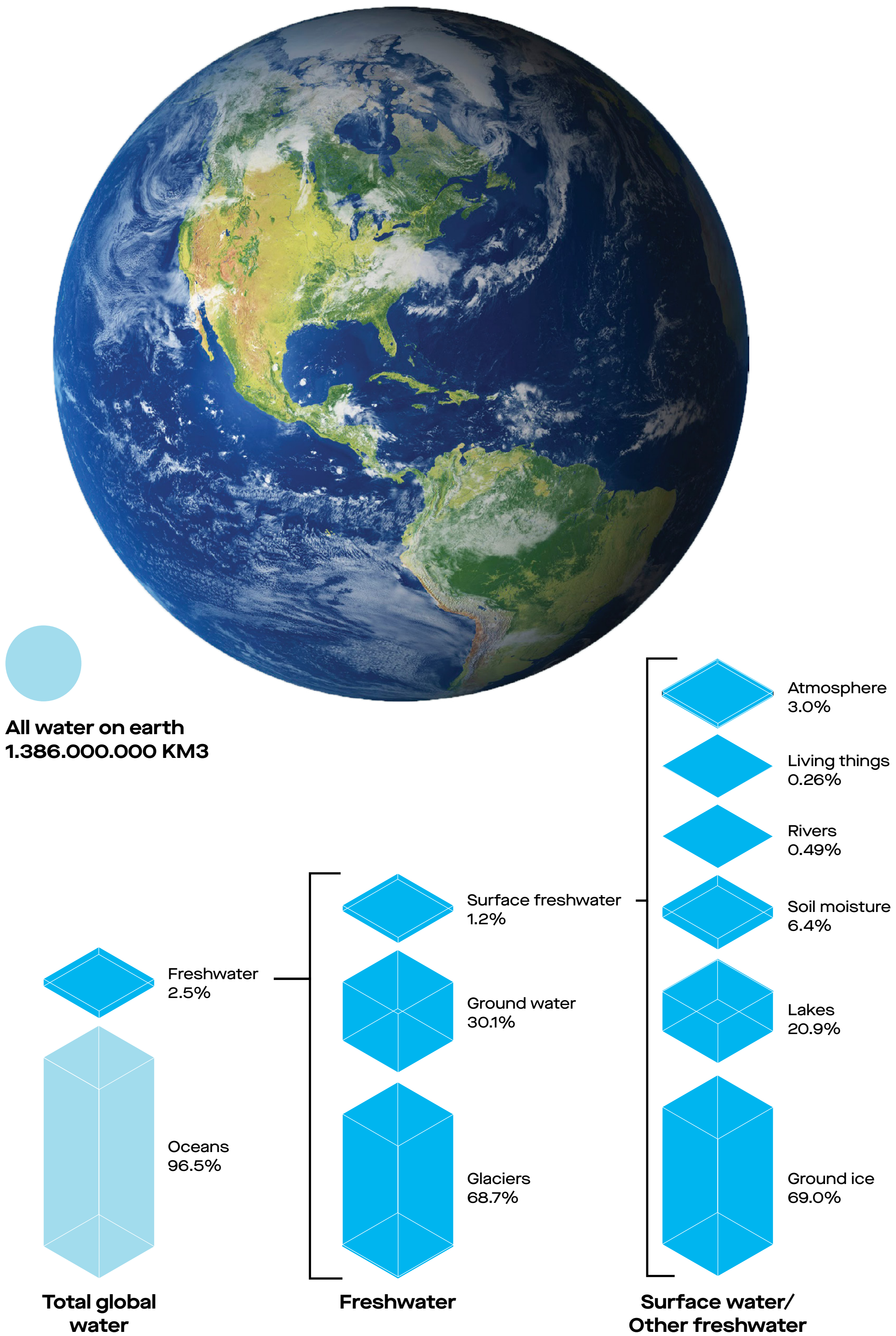
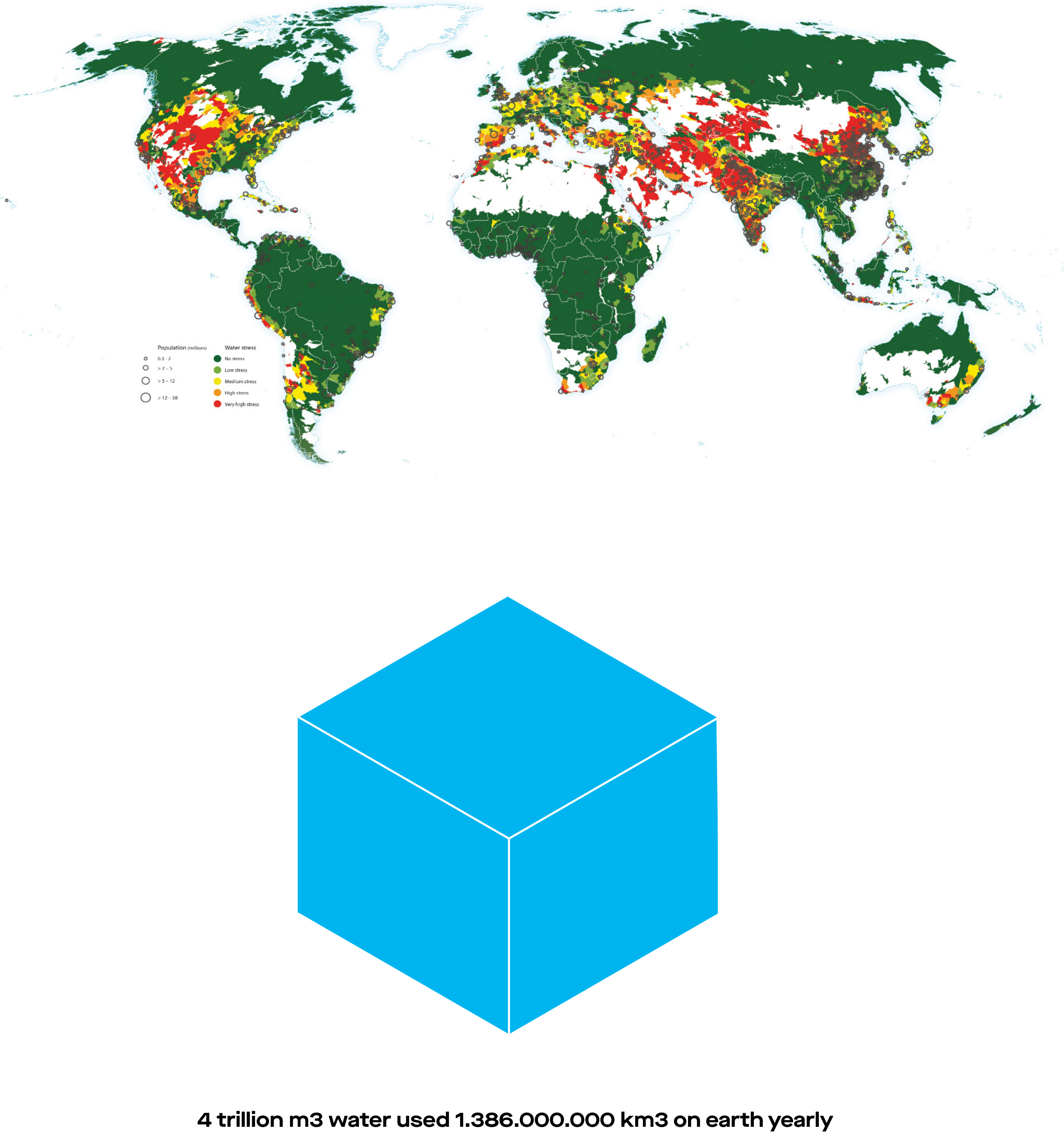
# Appendix

See next pages

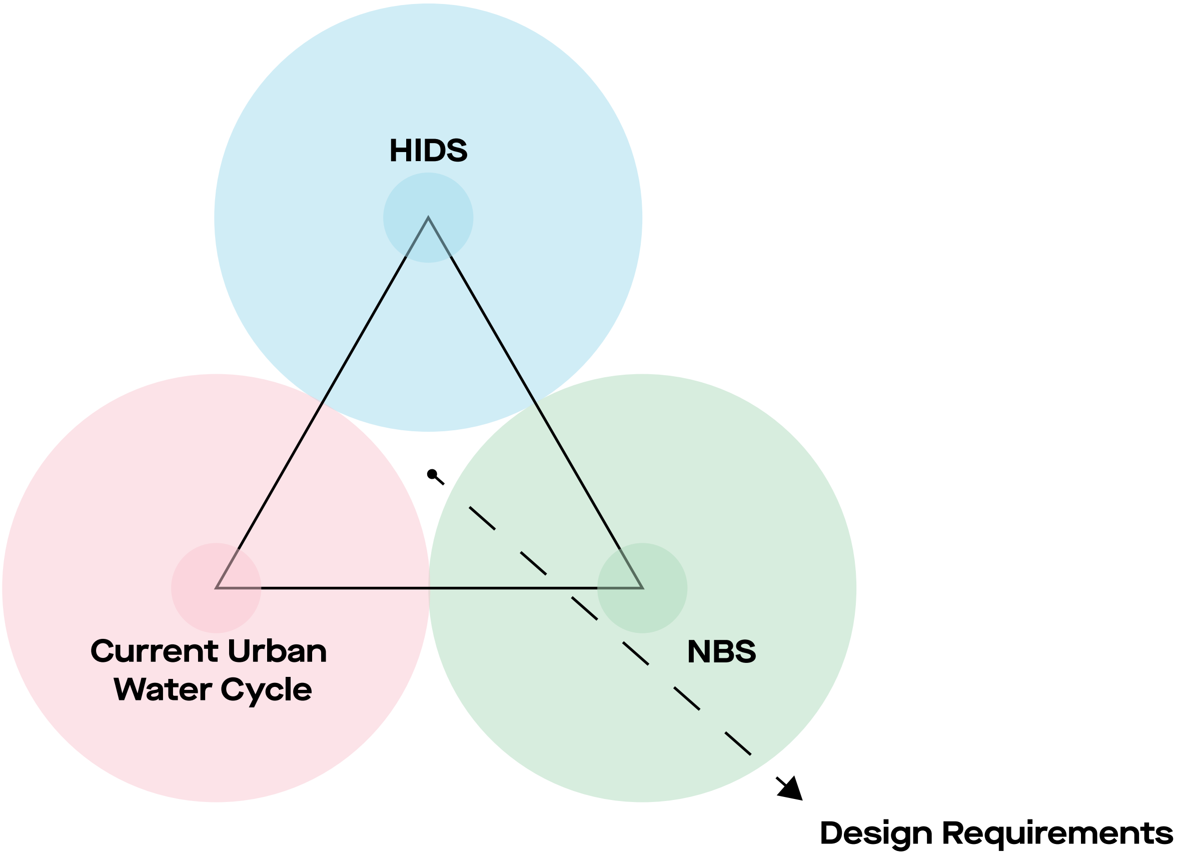
## *Appendix A:*
## *Introduction explanatory diagrams and images*



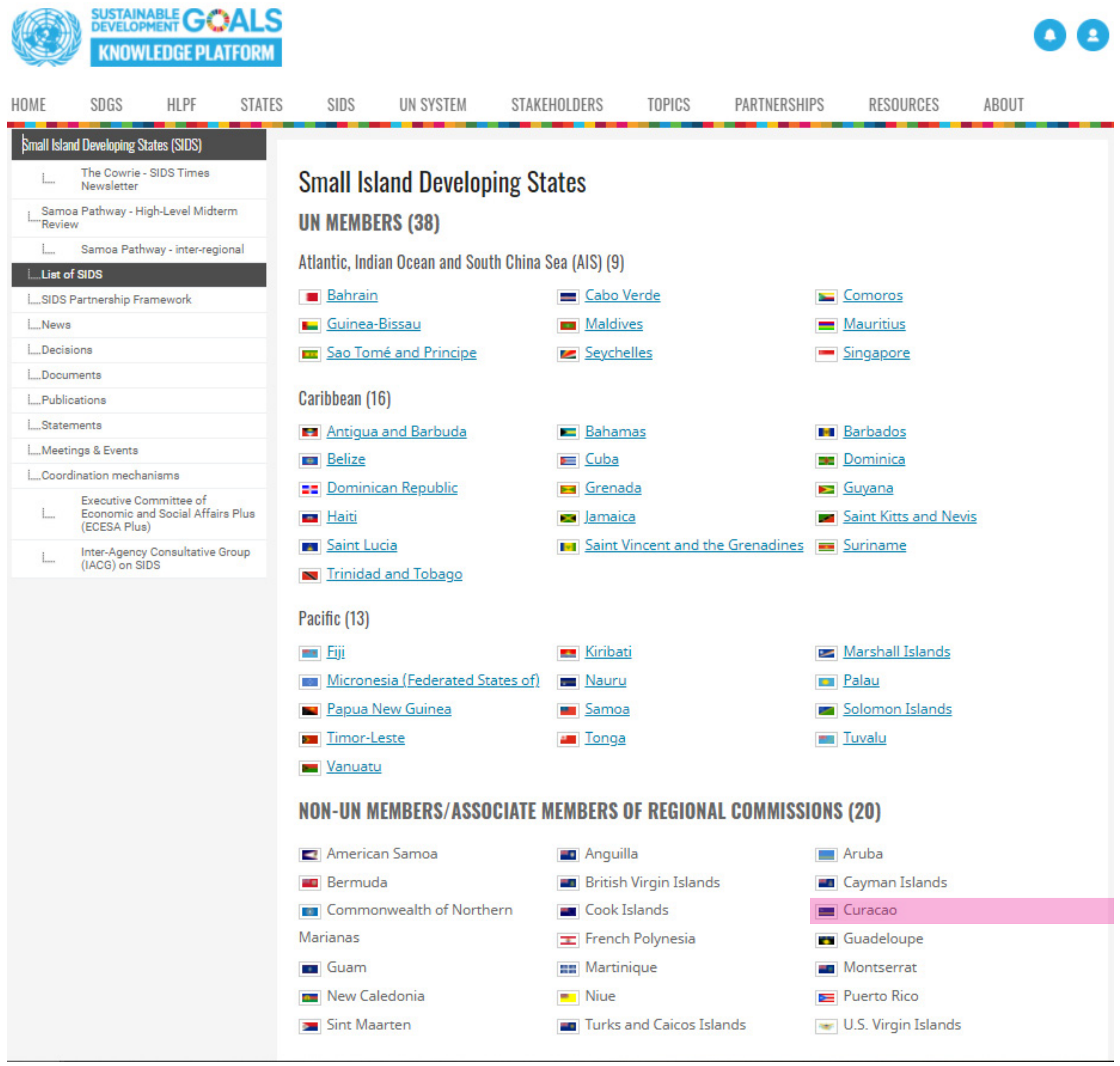

*World's available water supply (Authors image)*



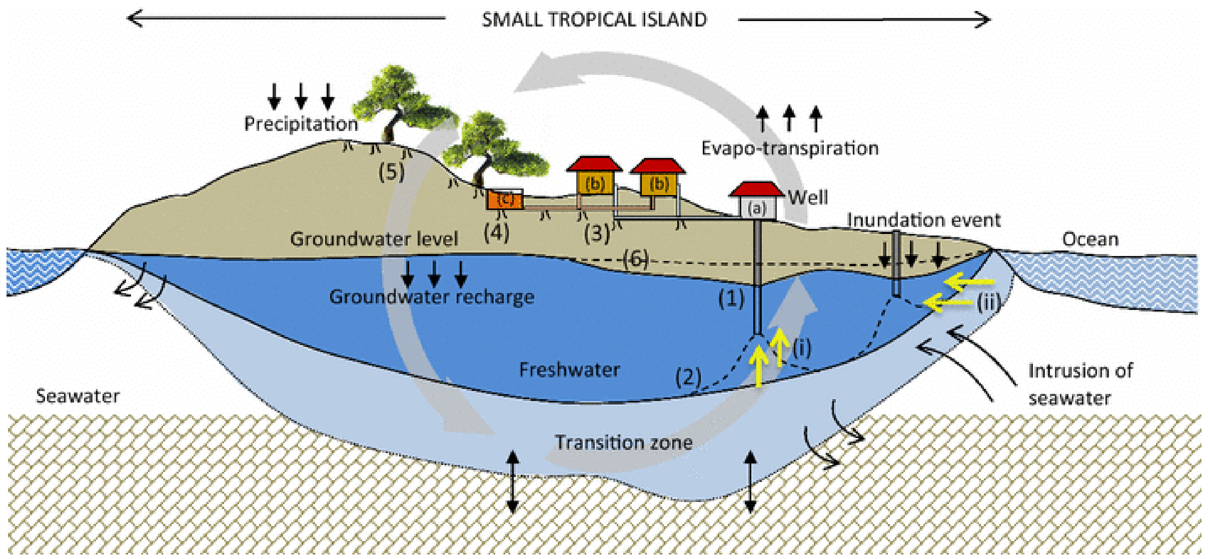

*World's water usage (Authors image)*



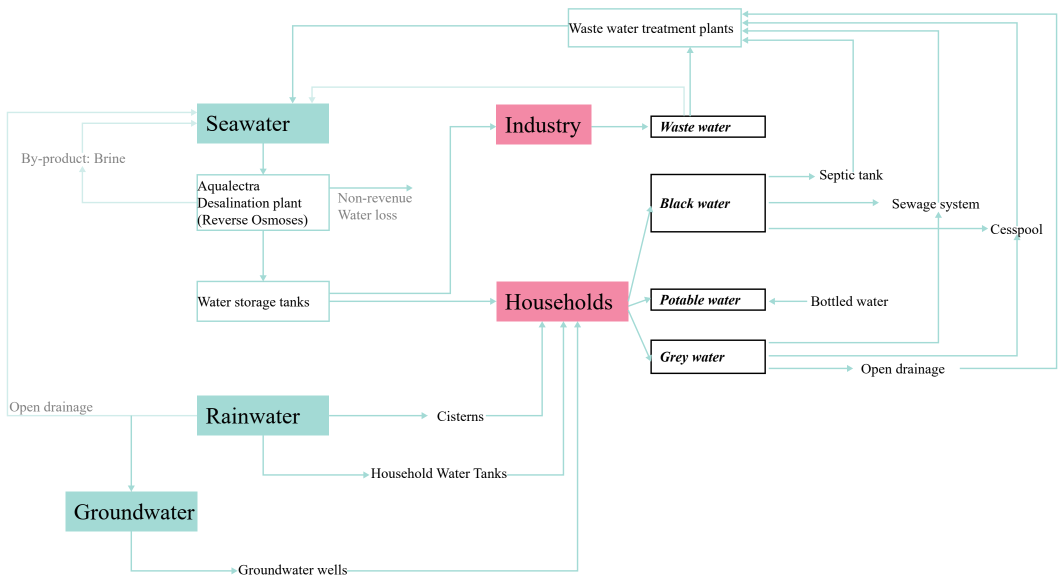

*Design requirements from analyzing the Current Urban Water cycles, Close city concept and HIDS and NBS (Authors image)*




*Website of United Nations showing Curacao is a listed SIDS (source: United Nations, 2021)*



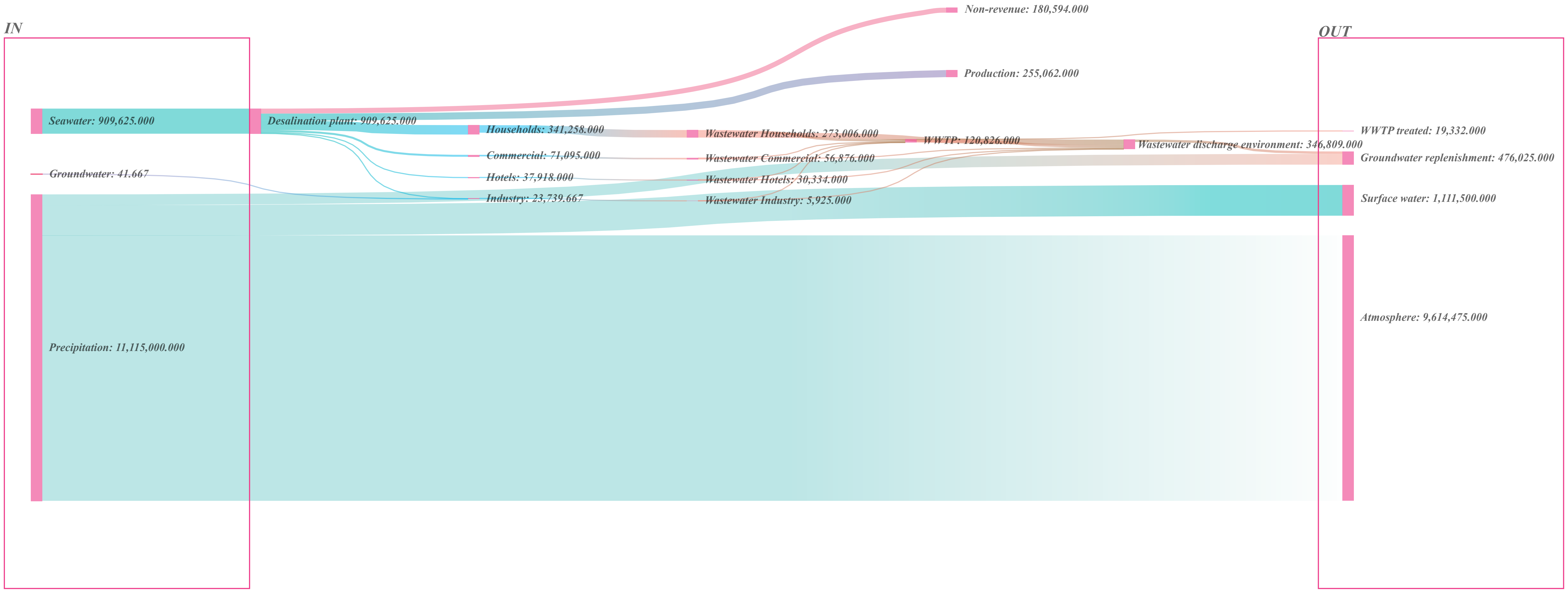

*Overview of small tropical island's conceptual model showing simplified hydrological cycle and hydrogeochemistry mechanisms (Mohd Isa et al., 2017)*



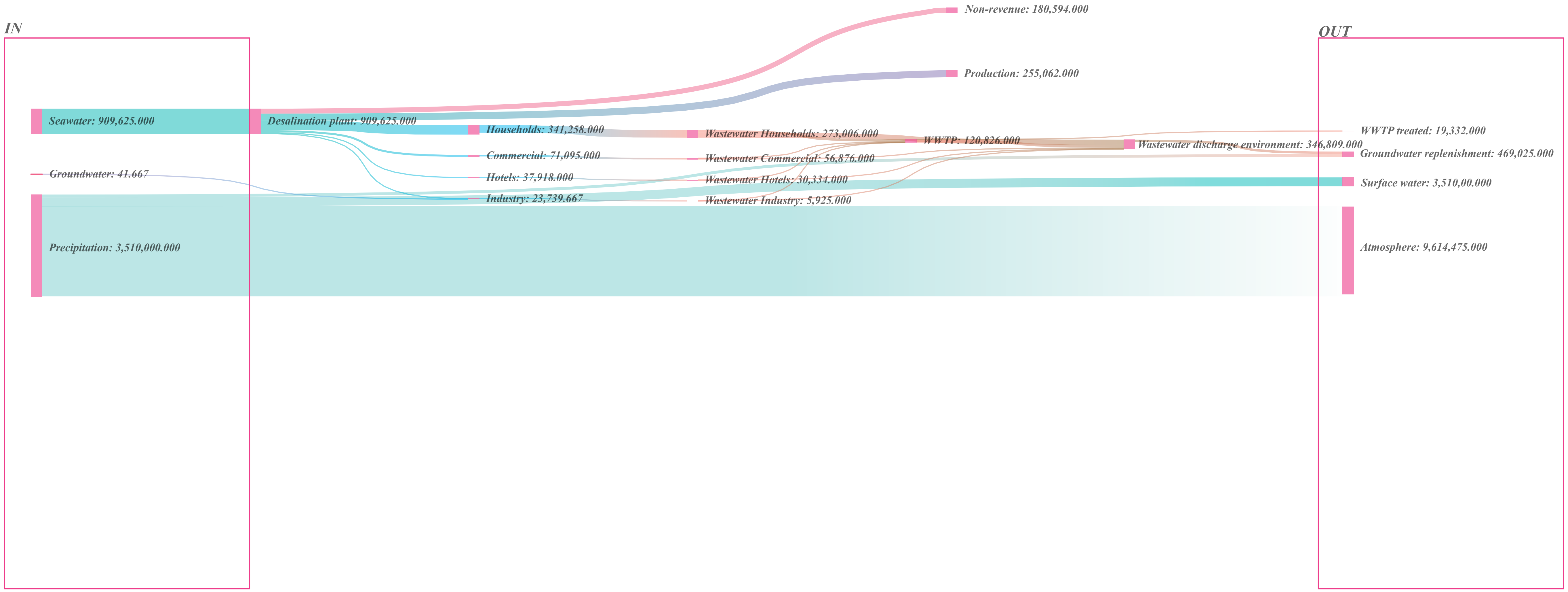

*Overview of small tropical island's conceptual model showing simplified hydrological cycle and hydrogeochemistry mechanisms (Mohd Isa et al., 2017)*


*Diagrams that summarizes the current lack Curaçao has on the that management and infrastructure of freshwater and wastewater, in order to cope with the natural water system and water chains (Authors image)*

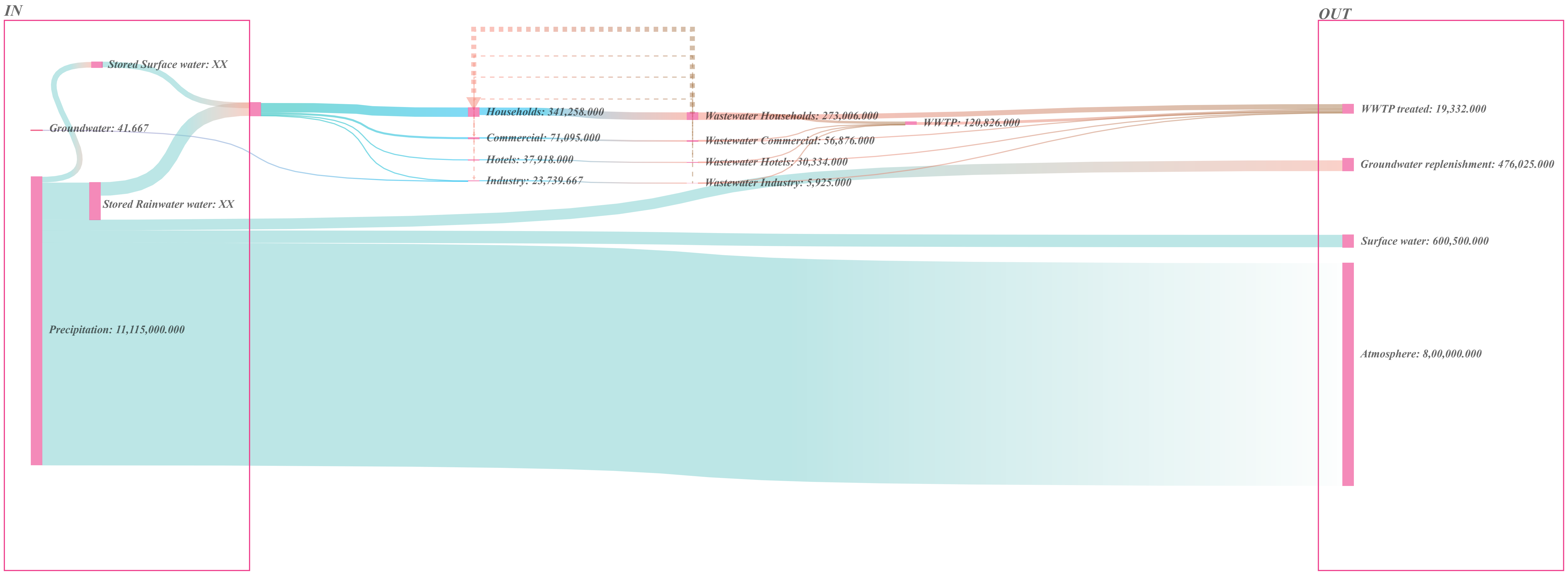
## *Appendix B:*
## *Sankey diagrams, images and calculations*



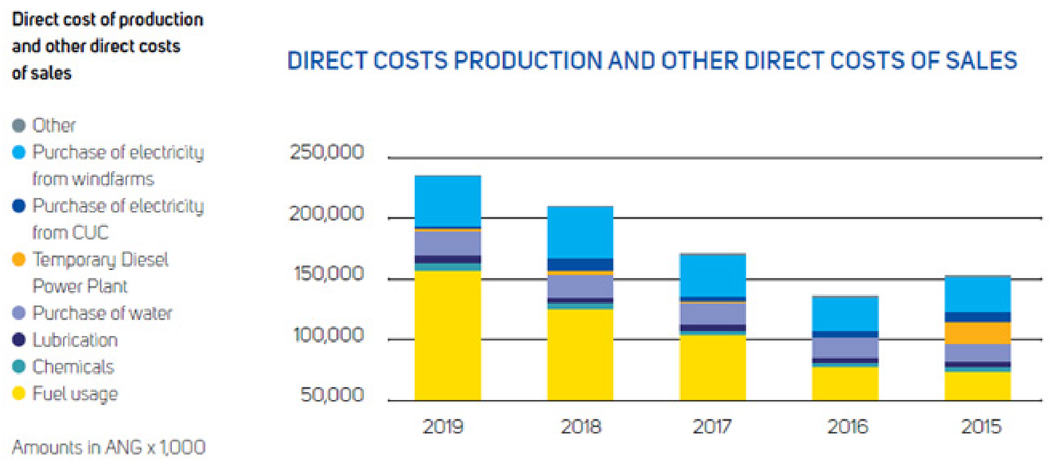

*Sankey diagram showing SFA of waterflows in wet month in Willemstad (Authors image)*



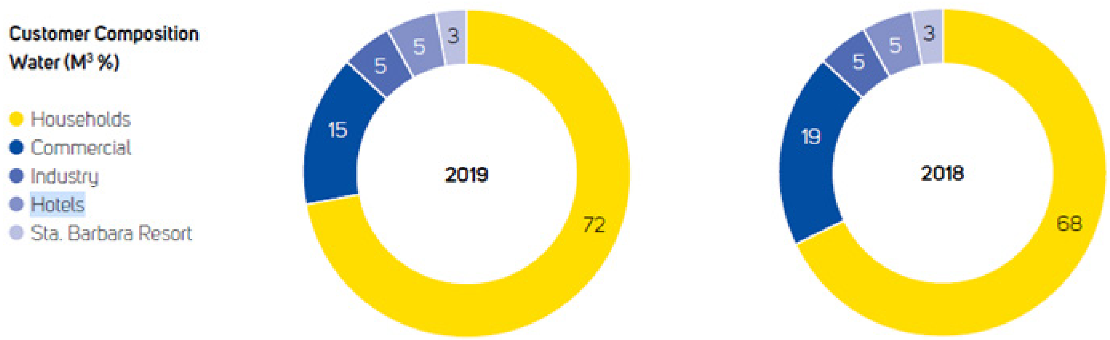

*Sankey diagram showing SFA of waterflows in dry month in Willemstad (Authors image)*




*Sankey diagram showing SFA of potential waterflows in wet month in Willemstad (Authors image)*




The graphs below provide insight in the sales to customers per tariff group based on M³'s sold and generated sales in ANG:




| Water | | |
|---|---|---|
| Sales water in 1000 m³ | 10,473 | 10,677 |
| Water intake from production in 1000 m³ | 14,554 | 15,189 |
| Number of postpaid connections at year end | 86,717 | 83,654 |
| Average usage households per month in m³ | 7.906 | 7.8999 |
| Average sales tariff households in ANG per m³ | 10.0354 | 10.0104 |
| Average sales tariff in ANG per m³ | 10.4278 | 10.3092 |
| Unaccounted for usage in % of m³ intake | 27.59% | 25.72% |

▲ Amounts in ANG x 1,000 / % / avg

*Information on water distribution, water tariff and 'non-revenue' water from centrelized desalination plant Aqualectra (source: Aqualectra, 2019)*

Average inhabitants living in one zone in peri-urban area:
42 zones in peri-uran area of Willemstad
75% of people live in peri urban area
People living in Curaçao: 157.538 inhabitants
People living in Peri-urban area Willemstad: 118.154 inhabitants
Average inhabitants per zone: 2800 inhabitants

Density inhabitants living in one zone in peri-urban area:
Peri-urban = 25% of total area island
Total area island = 444 km2
Pei-urban area = 111 km2
Size BarioA= 2,65 km2

Average households living in one zone in peri-urban area (BarioA) (https://www.cbs.cw/_flysystem/media/060920_-_woningtekort_op_curacao.pdf):
Average inhabitants per zone: 2800 inhabitants
People per household: 2.54
Number of households in Neighbourhood A: 3750 inh / 2.54 = 1102 Household

https://www.curacaovoorjou.nl/levensonderhoud/elektriciteit-water-kosten.html#:~:text=Er%20wordt%20geschat%20dat%20een,Naf%20210%2C95%20per%20maand.
□

Water consumption per household of 4 persons: 15m3 / month
Water consumption per average household of 2.54 persons: 9.6 m3 / month / avg. household

Water consumption per avg. neighbourhood in Willemstad: 10.579 m3 / month / avg. neighbourhood

| Willemstad - Average precipitation | | | |
|---|---|---|---|
| Month | Millimeters | Inches | Days |
| January | 45 | 1,8 | 9 |
| February | 25 | 1 | 5 |
| March | 14 | 0,6 | 3 |
| April | 20 | 0,8 | 3 |
| May | 20 | 0,8 | 2 |
| June | 19 | 0,7 | 3 |
| July | 40 | 1,6 | 6 |
| August | 42 | 1,7 | 5 |
| September | 49 | 1,9 | 5 |
| October | 84 | 3,3 | 7 |
| November | 97 | 3,8 | 10 |
| December | 100 | 3,9 | 12 |
| Year | 555 | 21,9 | 70 |

## Neerslagmeting

De hoeveelheid neerslag wordt gemeten met een regenmeter. Dit is een trechtervormig instrument dat de neerslag in een verzamelbak opvangt.

De hoeveelheid regenwater wordt uitgedrukt in millimeters. 1 millimeter regen komt overeen met 1 liter water op een oppervlakte van 1 vierkante meter. Valt de neerslag in vaste vorm, bijvoorbeeld als sneeuw of ijzel, dan wordt de neerslag door een verwarmingselement in de regenmeter gesmolten. 1 millimeter smeltwater is te vergelijken met een sneeuwhoogte van 1 centimeter.

Average precipitation BarioA:

Wet months: October, November and December
Average precipitation per month in the wet period: 95mm = 95 L / m2 = 0,095 m3 / m2 / month
Potential rainwater catchment BarioA: 0,095 x 4,65 mln = 441.750 m3 / month

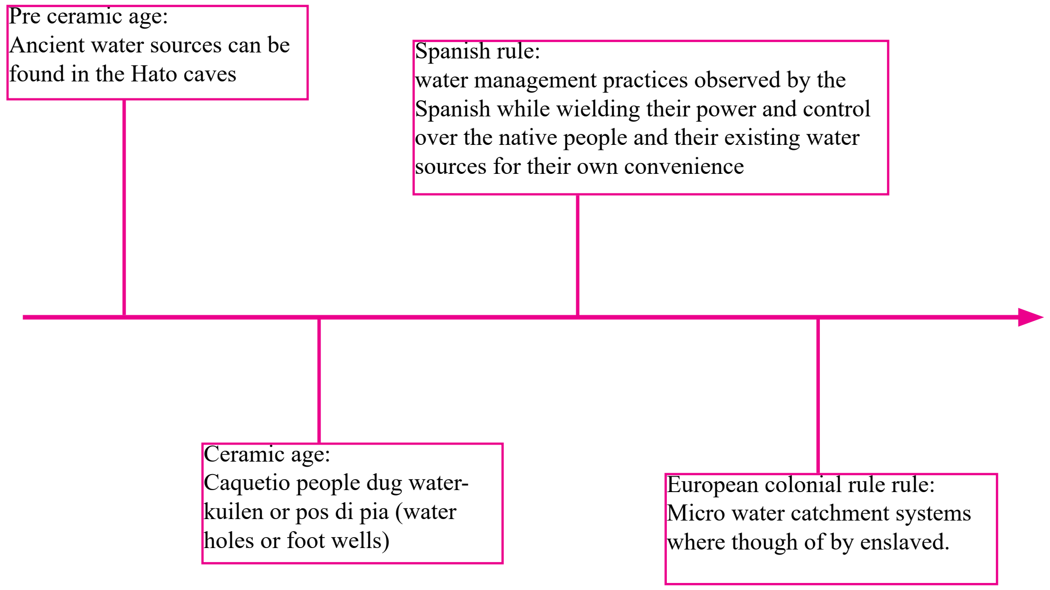
Dry months: January – September
Average precipitation per month in the dry period: 95mm = 30 L / m2 = 0,03 m3 / m2 / month
Potential rainwater catchment BarioA: 0,03 x 4,65 mln = 139.500 m3 / month

https://www.knmi.nl/kennis-en-datacentrum/uitleg/neerslagmeting#:~:text=Dit%20is%20een%20trechtervormig%20instrument,oppervlakte%20van%201%20vierkante%20meter.

# *Appendix C:*
# *Heritage Inspired Design Solutions (HIDS)*

***In almost every study related to the subject of HIDS the researchers report a lack of research on their subject in the (Dutch) Caribbean. However, for Curaçao that at some time in history rose to global importance in the international trade of goods and oil, relatively more research and resources on the subject is available (Loen, 2019).***

# I. Catalogue of different HIDS elements



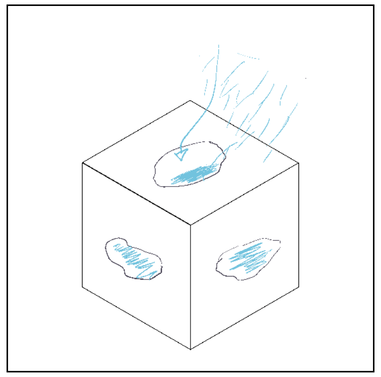

*History of water related developments on Curaçao.*

**Table of short history of water related developments on Curaçao**

| | |
|---|---|
| **Pre ceramic:** | In pre-Columbian time the islands were semi-permanent inhabited by Amerindians. Their settlements were oriented on the coastal mangrove forest were fresh water could be found on the foot off cliffs and in the cave system. **Ancient water sources can be found in the Hato caves** (Debrot, 2009). The land was covered with dry forests. The Arawak or Caquetio tribes would cultivate the land with slash and burn practices. Pollen research suggest large scale forest clearing and land erosion in that period. |
| **Ceramic age:** | In the ceramic era settlements moved more inward uphill to terrain more suitable for agriculture. In this period native inhabitants had profound influence on the natural vegetation (Loen, 2019). There is however little known about the way the Amerindian people secured their water supply other than obtaining water from the karst. Research by Mary van Soest and fieldwork by Debrot (2009) suggest that the **Caquetio people dug waterkuilen or pos di pia (water holes or foot wells)** and that this practices and some of these elements may have survived and where later in use by landowners and/or the enslaved Afro-Caribbean community. |
| **Spanish rule:** | Despite the given name Islas Inutiles (useless islands) the impact of the exploitation of the wood resources and agricultural practices can be felt up until today (Loen, 2019). Pollen research indicates large scale land clearings and deforestation in early colonial time of mangrove forest and dry forest for brazilwood, a textile dye. The import of cattle for grazing prevented regrowth of green cover. Indigenous agricultural and **water management practices must have been observed by the Spanish** while wielding their power and control over the native people and **their existing water sources for their own convenience**. |
| **European colonial rule:** | Van Walbeeck, the first Dutch West Indian Company (DWIC) director of the Island until 1639, described Curaçao as covered with forest (Loen, 2019). **Walbeeck built a fort and castle at St. Anna Baay near a water source to protect water supply which is depicted in the 1715 map** of Werbata. On the 1715 maps also other watering places are indicated. In absence of Dutch governing bodies the DWIC were also responsible for securing public water supply (Renkema, 1981). **Public wells were established to secure free access for watering cattle**. To secure food supply the DWIC relied on the produce of the Caquetio people and African enslaved labourers. The first plantations that were established were managed by the DWIC, so called compagnietuinen, but due to a lack of know-how, time and money they never flourished (Renkema, 1981). In order to secure the supply of fresh produce DWIC allowed the enslaved to cultivate small patches of land on the least favourable sloped terrains. **There are strong indications that the enslaved labourers (and after emancipation Afro-Caribbean small holder farmers) developed and managed their own micro water catchment systems on the sloping terrains (Renkema 1981)**. When the first private plantations were established there were often conflicts between landowners about illegal confiscations of the public watering places or so called public compagnieputten as water was a scarce and valuable commodity. Throughout the Dutch rule agriculture remained on subsistence level and land clearings and deforestation continued. Meanwhile clearing of more land took place for (failed) experiments with sugar, cotton and indigo. Mangrove forest were cleared to use the wood for the construction of buildings. The grazing of cattle caused further soil erosion and prevented regrowth of quality green cover. The introduction of wind powered wells around 1880 allowed for a short-lived modest boom in the cultivation of a local species of lime tree used in a liquer. **The wind powered wells not only supplied agricultural irrigation systems with steady amounts of water for the orchard but were also beneficial for the operation of the so called commercially operated waterplantages (water plantations).** The **waterplantages supplied urban residents, cargo ships, businesses, governing bodies and army of water up until the introduction of the first water desalination plants in the slipstream of the oil boom in the 1920's**. |

Catalogue of different HIDS elements (Authors image)

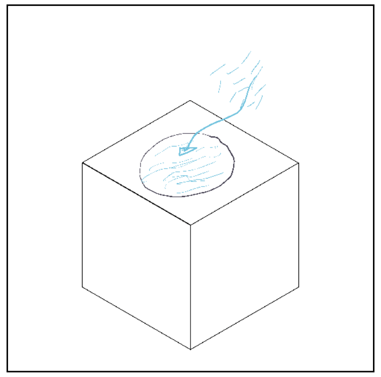
## Karstputten



### Characteristics

*According to Hartog (1968) the use of shallow karstbronnen or karst wells was well developed upon arrival of the Dutch. Debrot (2009) also refers to them as shallow water holes. Water moving through to karst is recharged by surface and point infiltration in the naturally occurring holes, pits and cracks in the surface. During periods with significant rainfall these cracks and pots, the karstputten, would fill up and sometimes even spill over forming water pools. During droughts the pits and pools would run dry quickly. According to Versluys (1934) the quality of karst water on higher altitude at a distance from the coast is less brackish and of better quality. It is highly probable the Caquetio built dams or walls around these pits to prevent water loss from overflowing karstputten (Loen, 2019).*

## Rooi

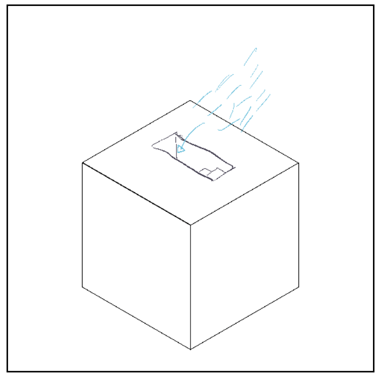


### Characteristics

*According to Werbata's legend (fig. 1 nr. 6). a rooi is a "in the rain season filled dry bed of a brook". During rain runoff water flows downhill through the bed of the rooi. Some rooi are also fed with seepwater that flows out at the foot off porous karst formation hills, cliffs and notches. The rooien played an important part in the islands water catchment system.*

Catalogue of different HIDS elements (Authors image)

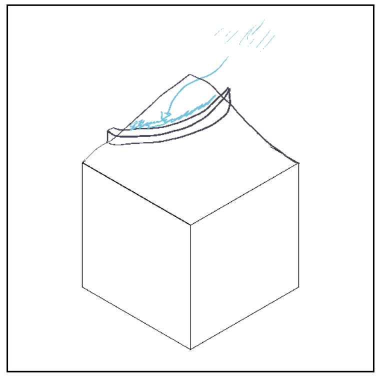
## Pos di pia



### Characteristics

*Debrot (2009) refers to shallow hand dug water holes or pos di pia, a native Carib practice. Local resident Mary van Soest made an inventory of water supply related heritage. Soest describes a "sunken water hole" called Pos di orashon in Papiamento, which translates as 'source for prayer. Local people believe it was used by the native Caribs. It is possible that waterkuilen are either seasonally overflowing karstputten, sinkholes or dolines (geological terms), rainfed natural depressions (transformed by man) and/or manmade pools. The waterkuilen are fed directly and via runoff in brooks and streams (rooien) and via dams. Waterkuilen / pos di pia are usually located in forested terrain.*

## Faha

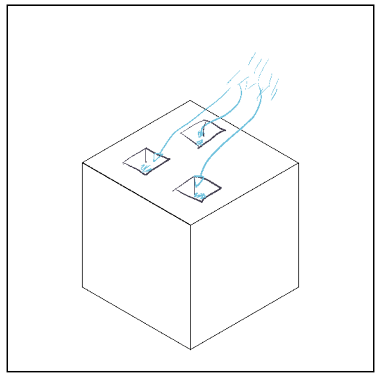


### Characteristics

*According to Renkema there were two types of dam systems in use. A small dam system and the large dam system. The small dam system could be found primarily on the domeingronden or unfavourable grounds of plantations with irregular and steeper terrain (Renkema 1981). As mentioned before during slavery these kostgrondjes were in use by the enslaved as kitchengarden. After 1863 the African-Caribbean community continued this practice as subsistence / small holder farmers. Renkema describes "many small dams as no higher than a few decimetres to maximum 1 meter" constructed "on the slopes and in small rooien". Henriquez (1962) describes the system in the Schottegat area (fig. 8). The small earthen dams are called faha (girdle in Papiamento) suggesting that they have a circular shape.*

Catalogue of different HIDS elements (Authors image)

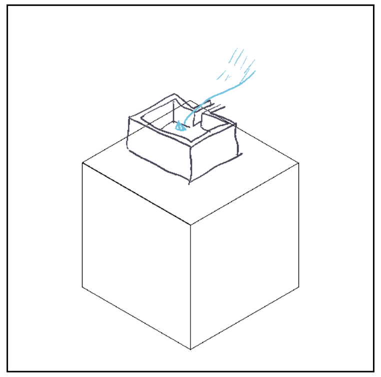
## Tanki



### Characteristics

*The difference between a waterkuil and tanki (fig. 7) is not clear. It seems they both refer to pits or pools either manmade or natural depressions transformed by men. According to Werbata's definition a tanki is "dug reservoir for rainwater". tanki were fed by rainfall and runoff from the catchment area and consisted of a system of large stone dams, rooien and gutters directing water to the catchment pools: the tanki. This large dam system was based on the micro catchment waterkuil-faha system but adjusted and enlarged at the discretion of the landlords on their privately-owned plantation grounds in the valleys (Renkema, 1981)*

## Cistern

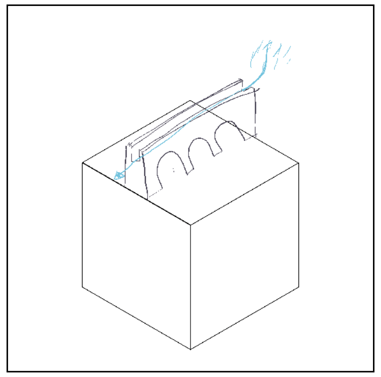


### Characteristics

*Rainwater was collected from the roofs of the manor house and other buildings and directed to waterbakken or regenbakken (rainwater cisterns). These regenbakken were located near the manor house, usually half below surface (fig. 17).*

Catalogue of different HIDS elements (Authors image)

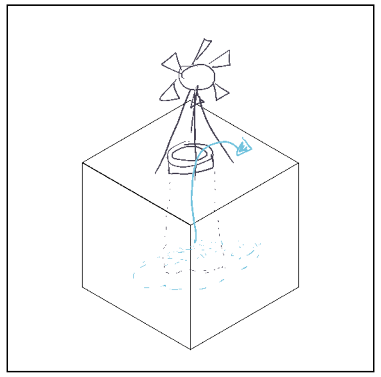
## Aquaduct



### Characteristics

*The manor house of plantation San Juan is even supplied with rainwater via an aqueduct architecturally integrated in the architecture of the complex (fig. 14). Monumentenzorg (monuments, 2020b) describes the complex as "A group of magasina's with cistern connected with an aqueduct to the main building"*

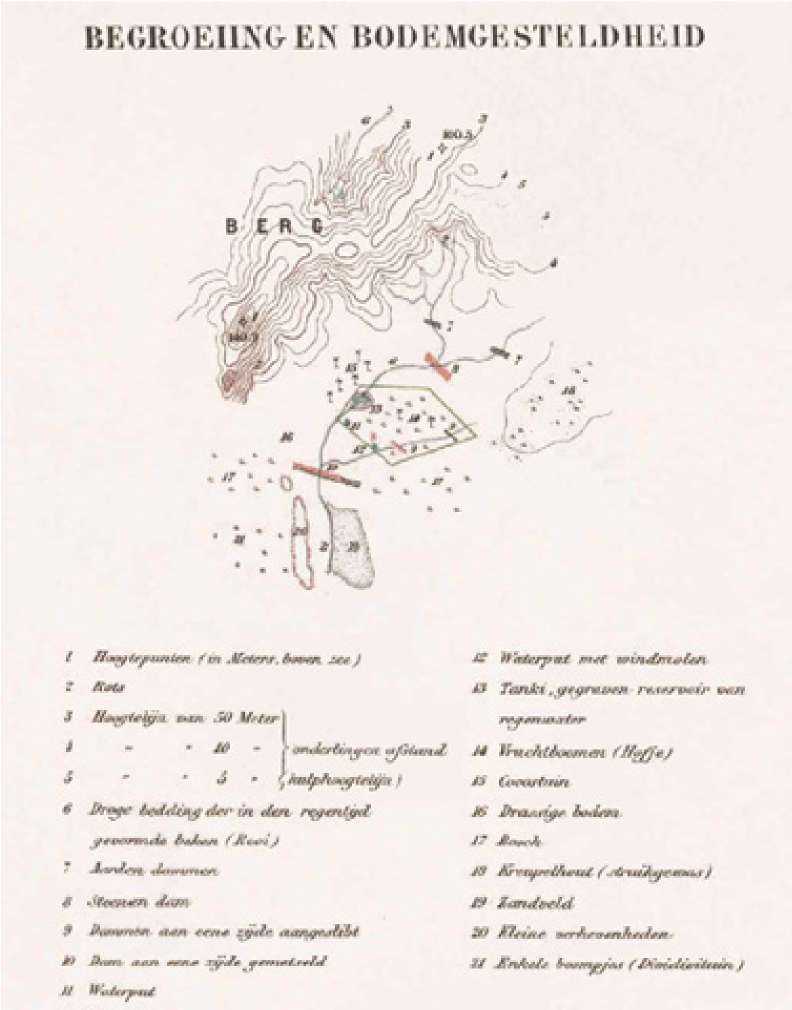
## Windwell



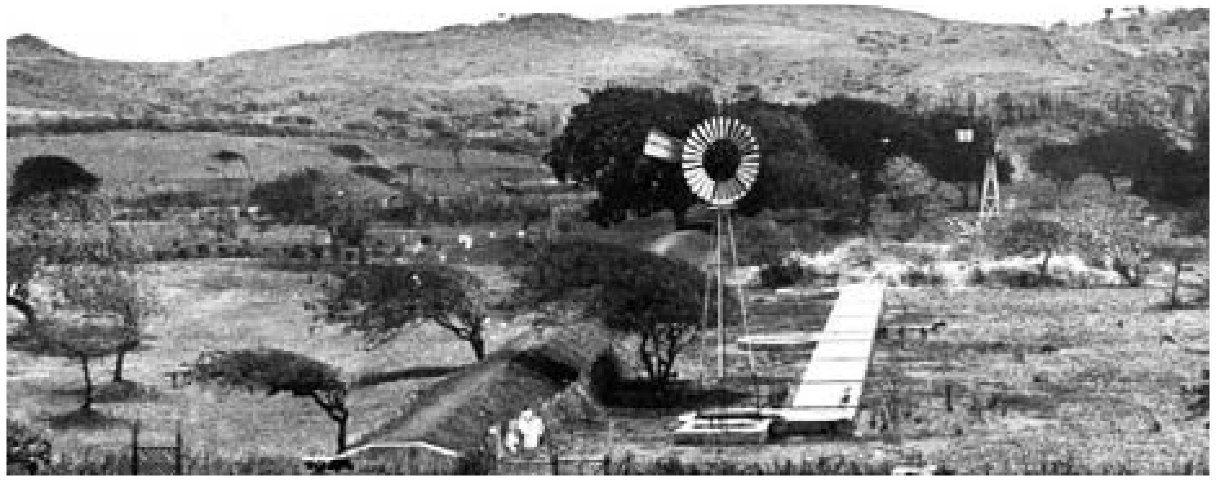
### Characteristics

*Plantageputten (plantation wells)*
*plantageputten were located in the valley just below the foot of the hills where the manor house was located. According to Renkema (1981) the plantageputten in the hof were surrounded by fruittrees, the owners vegetable gardens and sometimes slave gardens and huts all conveniently located near this source of putwater.*

*Windwaterputten (wind powered wells)*
*In the overseas territory of the Dutch Caribbean the windmills were applied to overcome water shortages by mining groundwater for irrigation and consumption. This extensive system of wind powered wells, waterbassins, terraces, stone gutters and iron pipes was only viable if the groundwater was sufficiently replenished with zakwater (infiltrated rainwater). The windmotoren also made work easier for so called 'waterplantages', plantation whose primary source of income was the selling of water (and salt) to the urban population, docking ships and army (Renkema, 1981).*




**Waterkuilen-faha system:**
An image of Werbata's map shows a tanki with a circular faha on the course of a rooi (fig. 1). Explicitly connecting the three elements of the system. according to Renkema the government considered the small waterkuilen-faha system to be more effective than the large tanki-dam system to raise the groundwater table. Governor De Jong van Beek and Donk promoted the use and renovation of this system in an attempt to help improve the ailing agricultural sector (Renkema, 1981). Boers (1994) refers to these types of rainwater harvesting micro-catchment systems as highly beneficial and effective for land reclamation and soil improvement in arid and semiarid regions. According to Renkema the waterkuil-faha system was found in disrepair after emancipation of the enslaved (Renkema, 1981). In spite of government funding the planters were not enthusiastic to adapt to the micro catchment waterkuil-faha system




**Water plantation system**
For plantations located at comfortable distance from Willemstad the trade in freshwater was in fact the only commercial pillar of their enterprise (Loen, 2019). The introduction of American windmills around 1880 had profound impact on the volumes and speed with which water could be drawn from the ground. The lack of water was compensated with a secure supply of passaatwind allowing for a continues supply of putwater (Versluys, 1934). Putwater drawn from the wells was stored in stepped waterbassins and via gutters and pipes channelled to the shore of the bay (Loen, 2019). There the water was loaded onto waterkanoes or waterboats and sailed to the clients..

# I. HIDS: Case Study

Case study: Plantage Hato

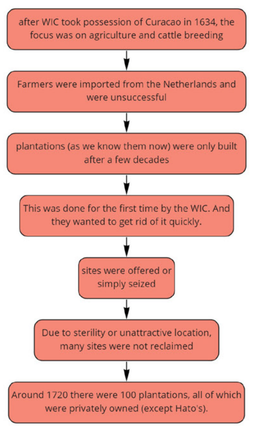
The first known settlement was form the native Amerindian community at Rooi Rincon near the airport of Hato. Here water moving through the karst formation would have poured out from the rock formation below a natural overhanging cliff or notch (Versluys 1934). Enslaved people who fled captivity sought hiding in the caves making use of these water sources. Today water stills flows through the Hato caves. According to Versluys infiltrated rainwater moved too fast through the porous karst, eventually spilling out to sea at the foot of cliffs, and that therefore 'bronnen' quickly ran dry. Loen (2019) states that it is highly probable that the native Caribs would have developed micro water catchment systems such as faha to secure water supply by storing and harvesting and saving it from running into sea. According to Versluys the quality of the water from these springs was low

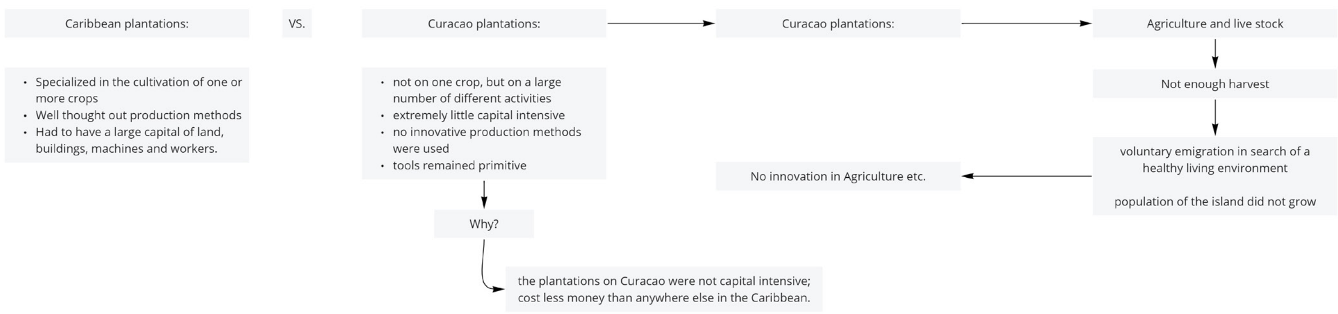
Upon seizing control from the Spanish in 1634 over the island the Dutch discovered the abandoned settlement at Hato. Here the DWIC established the first plantage founded on prior native and Spanish settlements with ready access to fresh water (Renkema, 1981). Sold in 1796 by the DWIC it was also the last plantation the DWIC managed themselves (Renkema, 1981). Monumentzorg Curaçao describes a regenbak (rainwater cistern) next to the manor house, with overflows to a terrace, probably the pond, and also the hof with putten (wells), terraces, kanalen (gutters) and "other constructions" for an irrigation system (Curaçaomonuments, 2020a). The irrigationsystem in the hof was supplied with putwater.

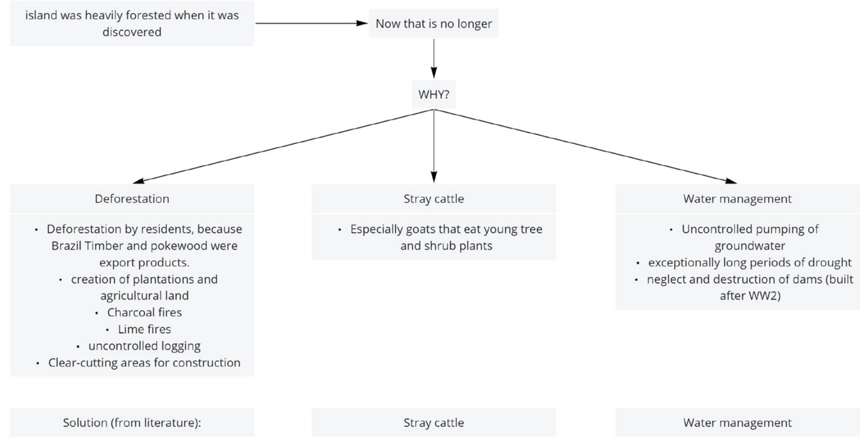
Interestingly there was a pond included next to the manor house was, in a region were water was a valuable and scarce good water, an important status symbol and an indication of wealth. Hato is an interesting example of how native water sources and settlements were occupied, transformed and adjusted to meet the practical needs and architectural style of the colonial power. On map fig. 4 Plantage Hato is named "Landhuis Hato". Here "bronnen" and "waterbassins" are indicated. These waterbassins refer to the terraces described by Monumentenzorg Curaçao.

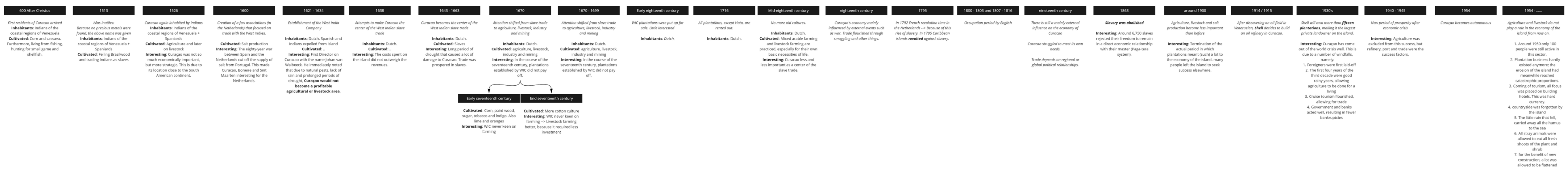
Case study: Plantage Poos di Wanga

In his description of the waterplantage economy Renkema argues that rainwater was more sought after then 'putwater' (Renkema 1981). Versluys also states the inferior quality of brackish springwater from the karst near the coast. Water obtained from bronnen on higher altitudes was less brackish and of better quality. Although Werbata does not provide an individual symbol for 'bron' in his legend on map C.08 he indicates a 'bron' (fig.9) surrounded by an earthen dam or faha on plantage Poos di Wanga located on the foot of a hill just north-east of plantation Hato. In the local Papiamentu language faha is translated as girdle.



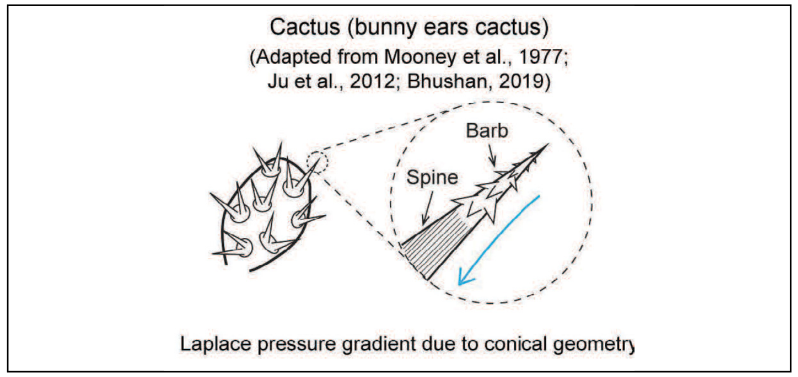



## *Appendix D: Nature-based solutions (NBS)*

Catalogue of different NBS elements (Authors image)

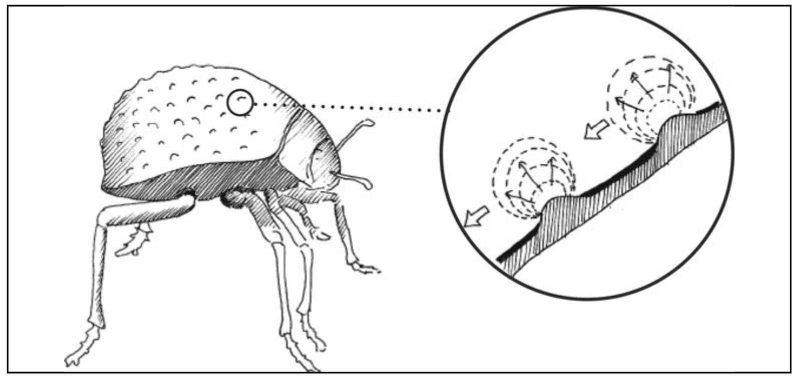
## Capturing water (against gravity)




### Characteristics

*The Chihuahua Desert cactus (Opuntia microdasys) has evolved water-harvesting clusters of very fine conical spines. Its success relies on two physical phenomena: first, a gradient of Laplace pressure and, second, a gradient of surface-free energy. Laplace pressure refers to the pressure difference (between inside and outside) created within bubbles. When a droplet of water forms on the end of the conical spine, it forms asymmetrically – wider at the tip of the spine. The result is a pressure gradient that drives the droplet along the spine (even against gravity) towards the wider part of the cone. The effect is enhanced by microgrooves along the spine, which widen towards the base, creating another means by which the droplet is driven along the spine towards the base (referred to as a gradient of surface-free energy).*

## Capturing water (with gravity)



### Characteristics

*Namibian fog-basking beetle (Onymacris unguicularis) (fig. 102). This creature has evolved a way of harvesting its own fresh water in a desert. The way it does this is by climbing, at night, to the top of a sand dune and, because it is matt black, it is able to radiate heat to the night sky (the heat sink is actually outer space which is at a temperature of -273 °C) and become slightly cooler than its surroundings. When the moist breeze blows in off the sea, droplets of water form on the beetle's back. Then, just before sunrise, it tips its shell up, the water runs down to its mouth, it has a good drink and goes off and hides for the rest of the day. The effectiveness of this beetle's adaptation goes even further because it has a series of bumps on its shell that are hydrophilic and between them is a waxy finish that is hydrophobic. The effect of this combination is that, as the droplets form on the bumps, they stay in tight spherical form, which means that they are much more mobile than a film of water over the whole beetle's shell would be.*

Catalogue of different NBS elements (Authors image)

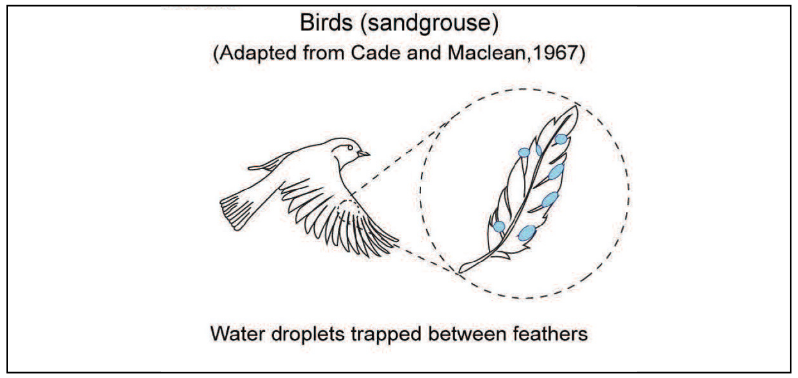
## Water storage

### Characteristics

*The cacti's ribbed stems, which resemble concertinas, respond to this situation. These structures can absorb large quantities of water very quickly without any significant new growth – simply by expansion.*

*Other plants have adapted by storing their water below ground in large, swollen roots. An extreme example of this is the elephant foot – a species of yam that can grow tubers that weigh as much as 300 kg.*

## Minimizing water loss




### Characteristics

*Some birds that live in deserts have black plumage, which might seem like a bizarre strategy but the feathers are protein structures (made from non-living keratin and containing UV-absorbing melanin) that, through their opacity, prevent most of the sun's heat reaching the birds' skin and consequently reduce water loss*

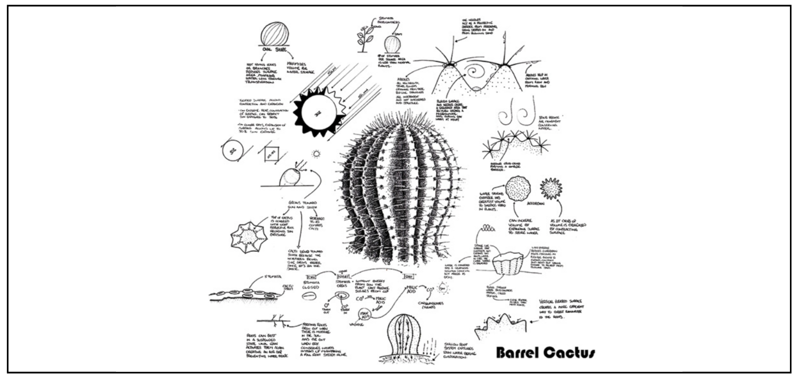
Catalogue of different NBS elements (Authors image)

## Water transport

### Characteristics

*It may seem obvious that a straight line is the most efficient way to connect two points: but 'flow in nature is helical',133 Emeritus Professor Colin Caro at Imperial College London discovered. He has studied the flow characteristics in human arteries and demonstrated that a damaged artery fitted with a helical stent is subject to far less deposition of fatty substances than a straight stent. Deposits occur where flow stagnates, which a helical stent minimises. A spin-out company is now commercialising the use of helical tubing, focusing on specialist applications where an even flow rate is needed. As the manufacturing cost of helical pipework decreases, more widespread application of the idea in the construction industry is likely to follow, with the potential for significant energy savings and reduced maintenance.*

## Minimizing water loss

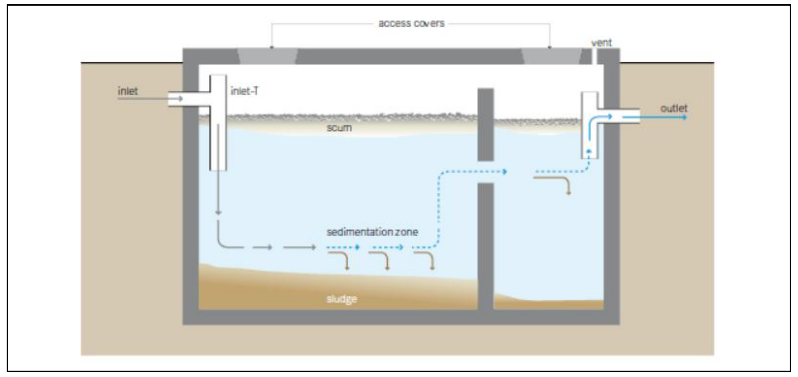



### Characteristics

*Numerous species of cacti are covered in fine white filaments, which not only reflect the sun but also help to trap humid air next to the living tissue so that the exchange of gases necessary for photosynthesis can continue while water loss is minimized.*

Catalogue of different NBS elements (Authors image)

## Septic tank

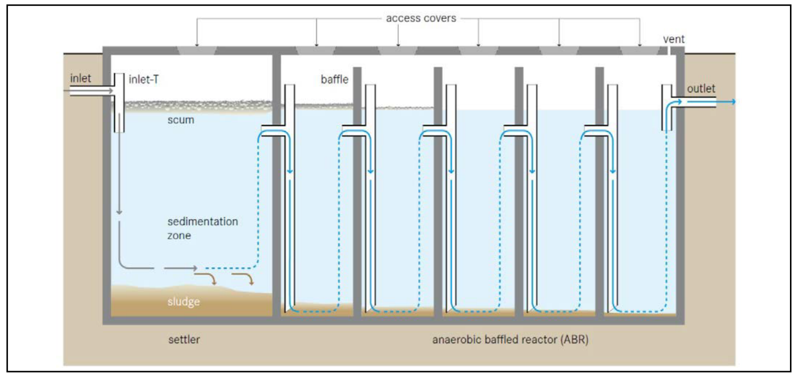



### Characteristics

*'inputs: blackwater and greywater. outputs: effluent and sludge.*

*A septic tank is a watertight chamber through which blackwater and greywater flows for primary treatment. settling and anaerobic processes reduce solids and organics, but the treatment is only moderate.*
*Removal of 50% of solids, 30-40% of BOD, and a 1-log removal of E.coli can be expected in the well-designed and maintained septic tank. The retention time should be 48 hours.' (Tilley, et al., 2014, p. 74)*

## Aerobic baffled reactor



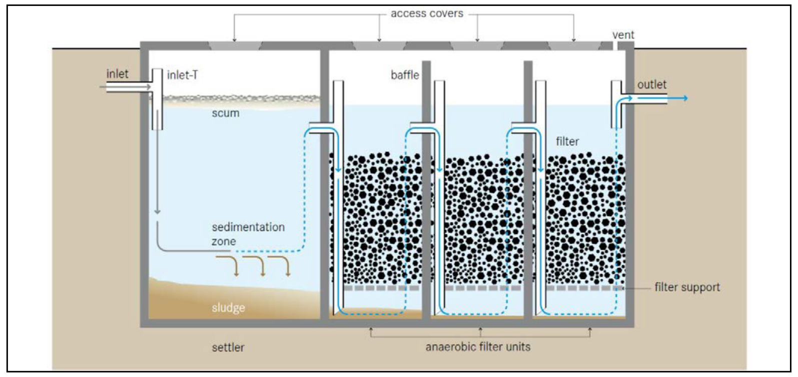

### Characteristics

*'Inputs: blackwater, greywater. Outputs: effluent, sludge.*

*An anaerobic baffled reactor is an improved septic tank with a series of baffles under which the wasterwater is forced to flow. the increased contact time with the active biomass (sludge) results in improved treatment.*
*BOD may be reduced by up to 90%. Typical inflows range from 2 to 200m3 per day. Retention time should be 48-72 hours. Usually, the biogas produced in an ABR through anaerobic digestion is not collected because of its insufficient amount.' (Tilley, et al., 2014, p. 76)*

Catalogue of different NBS elements (Authors image)

## Anaerobic filter

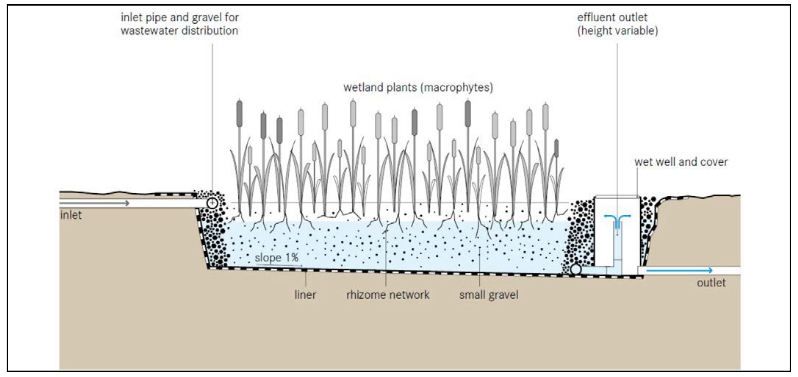



### Characteristics

*' Inputs: blackwater, greywater. Outputs: effluent, sludge.*

*An anaerobic filter is a fixed-bed biological reactor with one or more filtration chambers in series. As wastewater flows through the filter, particles are trapped and organic matter id degraded by the active biomass that is attached to the surface of the filter material.*
*Suspended solids and BOD removal can be as high as 90%, but typically between 50-80%. Nitrogen removal is limited and normally does not exceed 15% in terms of total nitrogen (TN).*
*Retention time should be 12-36 hours.' (Tilley, et al., 2014, p. 78)*

## Horizontal subsurface flow constructed wetland

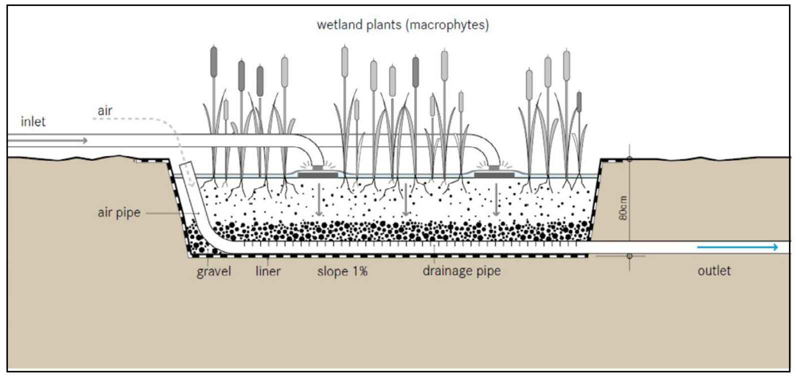



### Characteristics

*'A horizontal subsurface flow constructed wetland is a large gravel and sand-filled basin that is planted with wetland vegetation. As wastewater flows horizontally through the basin, the filter material filters out particles and microorganisms degrade the organics.' (Tilley, et al., 2014, p. 116)*

Catalogue of different NBS elements (Authors image)

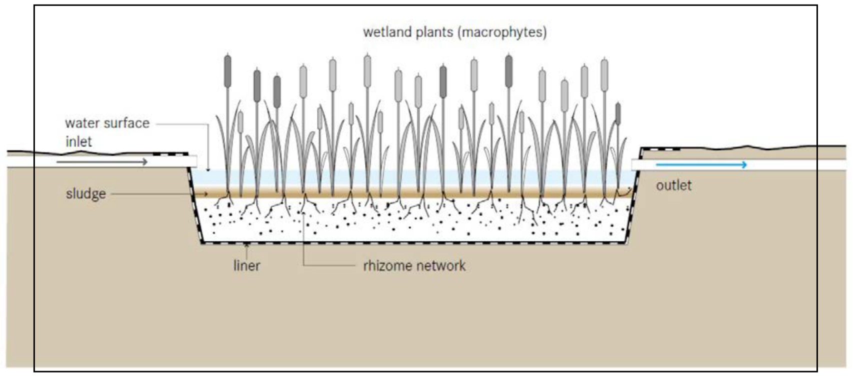
## Vertical flow constructed wetland




### Characteristics

*'A vertical flow constructed wetland is a planted filter bed that is drained at the bottom. Wastewater is poured or dosed onto the surface from above using a mechanical dosing system. The water flows vertically down through the filter matrix to the bottom of the basin where it is collected in a drainage pipe. The important difference between a vertical and horizontal wetland is not simply the direction of the flow path, but rather the aerobic conditions.' (Tilley, et al., 2014, p. 118)*

## Free-water surface constructed wetland

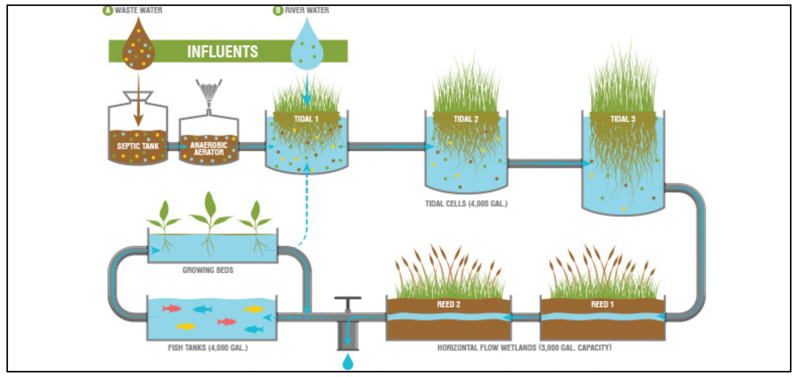



### Characteristics

*'A free-water surface constructed wetland aims to replicate the naturally occurring processes of a natural wetland, marsh or swamp. As water slowly flows through the wetland, particles settle, pathogens are destroyed, and organisms and plants utilize the nutrients. This type of constructed wetland is commonly used as an advanced treatment after secondary or tertiary treatment processes.' (Tilley, et al., 2014, p. 114)*

Catalogue of different NBS elements (Authors image)

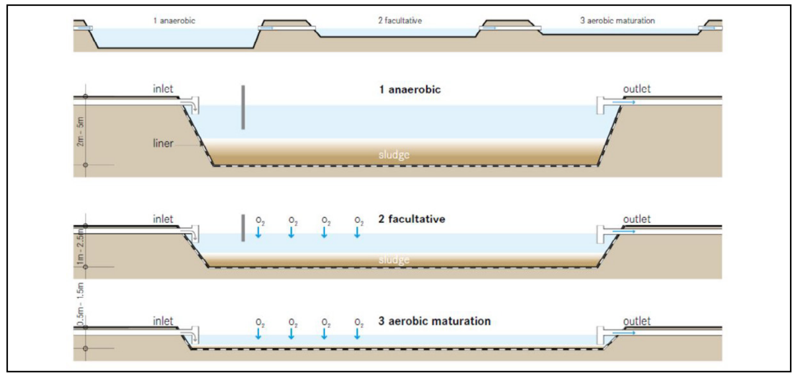
## Living machine




### Characteristics

*A Living Machine (capital letters, it's a patented invention) is a series of tanks teeming with live plants, trees, grasses and algae, koi and goldfish, tiny freshwater shrimp, snails, and a diversity of microorganisms and bacteria. Each tank is a different mini-ecosystem designed to eat or break down waste.*

## Waste Stabilization Ponds




### Characteristics

*'Inputs: blackwater, greywater. Outputs: effluent, sludge.*

*Waste Stabilization Ponds (WSPs) are large, manmade water bodies. The ponds can be used individually, or linked in a series for improved treatment. There are three types of ponds, (1) anaerobic, (2) facultative and (3) aerobic (maturation), each with different treatment and design characteristics.*

# I. NBS

Constructed wetlands

Constructed wetlands are regarded as key elements in polishing conventionally treated wastewater for recreational and environmental applications. In general one can distinguish three types of constructed wetlands:1 Surface flow constructed wetlands, 2) Horizontal subsurface flow constructed wetlands and 3) Vertical flow constructed wetlands. The appendix further explains each type.

Living machine

Where waste-water treatment usually involves heavy infrastructure and complicated 'end-of-pipe' solutions, Living Machines avoid long-distance transportation and often unnecessarily high standards of treatment (when the end-use may not be human consumption). These systems, available now, are the antithesis of a centralized approach and come much closer to the local and resilient ways in which water is cycled in nature. Living Machines uses a complex ecosystem of plants and micro-organisms cultivated in wetland beds to treat sewage or industrial waste-water to a level that allows it to be re-used locally for toilet flushing or irrigation, or reintroduced into the environment.

## I. Water area requirements (Own calculation)

Average water-usage Willemstad household: 9.6m3 / month
Average household Willemstad: 2.54 persons

Wet months: October, November and December
Average precipitation per month in the wet period: 95mm = 95 L / m2 = 0,095 m3 / m2 / month
Dry months: January – September
Average precipitation per month in the dry period: 95mm = 30 L / m2 = 0,03 m3 / m2 / month

80% wastewater generation rate of consumed water for domestic purposes

**Step 1: Water consumption rate**

Water consumption (person / day) = 0.125 m3 / person / day
Water consumption rate 200 people = 0.125 x 200 = **25 m3 / day**

**Step 2: Wastewater generation rate**

80 % of Water consumption rate 200 people = 25 x 0.8 = **20 m3 / day**

**Area of Wastewater treatment programs**
Area septic thank = wastewater generation rate x 0.5 m2
Area septic thank = 20 x 0.5 m2 = 10 m2

Area ABR = wastewater generation rate x 1.0 m2
Area ABR = 20 x 1.0 m2 = 20 m2

Area VF wetland = wastewater generation rate x 3.75 m2
Area VF wetland = 20 x 3.75 m2 = 75 m2

Area HF wetland = wastewater generation rate x 6.5 m2
Area HF wetland = 20 x 3.75 m2 = 130 m2

Area SF wetland = wastewater generation rate x 6.5 m2
Area SF wetland = 20 x 1.2 m2 = 24 m2

**Area of Micro Water Catchment Systems**
71 % of household consumption rate from rainwater
29 % of household consumption rate from storm water
Water consumption rate 200 people = 0.125 x 200 = **25 m3 / day**
**= 750 m3 / month**

Area MWCS dry month = 0.030 x 750 = **25000 m2**
Area for rainwater catchment = 0.71 x 25000 = 17750 m2
Area for stormwater catchment = 0.29 x 25000 = 7250

Area MWCS wet month = 0.095 x 750 = **7800 m2**
Area for rainwater catchment = 0.71 x 7800 = 5538 m2
Area for stormwater catchment = 0.29 x 7800 = 2262 m2