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Hydrogeological conceptualization of a small island groundwater system using historical data

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Original Article

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Abstract

Past hydrogeological processes and human impacts may exert substantial memory effects on today's groundwater systems. Thorough characterization of such long-term processes is required for scientists and policymakers to predict the hydrogeological impacts of land management options. Especially in data-scarce areas, historical data are essential to unravel long-term hydrogeological processes, which could not be identified by short-term fieldwork or model simulations alone. However, historical data are often overlooked or only used as background information in most hydrogeological studies. We show that the combination of historical reports and quantitative data yields major insights in the hydrogeological system of Curaçao, a small semi-arid Caribbean island. Reconstructing the island's groundwater conditions over the past 500 years revealed that deforestation and excessive abstraction has had a detrimental effect on the island's groundwater reserves. Historical notes and data revealed major signs of seawater intrusion, especially during abstraction peaks in the island's industrial era. Intrusion effects are still observed locally on the island today, but additional groundwater recharge by waste water has caused freshening elsewhere. We hypothesize that the observed aquifer replenishment locally enhances submarine groundwater discharge, flushing accumulated nutrients and pollutants towards Curaçao's fringing coral reefs. We expect that this study's insights motivate more hydrogeologists to use historical reports and data in future studies.

Introduction

Understanding the past development of groundwater systems can be of great help to hydrogeological studies today. Even more so in data-scarce areas, historically collected data provide insights that could not be gained from short-term fieldwork campaigns or groundwater modelling. Nevertheless, historical groundwater data are often overlooked in present-day research. This may be related to the required time and effort to collect, digitize and analyse historical data, especially for non-historians like most hydrogeologists. Taking the time to process and interpret historical datasets can however prove to be a time-effective and useful addition to the hydrogeologists' toolbox.

The use of historical data is relatively common in the field of climatology (e.g. Nicholson, 1979; Zhang and Crowley, 1989; Yoshimura, 1993; Metcalfe et al., 2002; Ge et al., 2008; Rosario Prieto and Herrera, 2009; Ogilvie, 2010; Chen et al., 2020), but recently also emerged in hydrogeological research (e.g. Ascott et al., 2020; Dassargues, et al., 2021). Analysis of historical groundwater level data from the city of Berlin revealed that today's problematic high groundwater levels are caused by recent relocation of abstraction sites and actually resemble natural conditions (Frommen, et al., 2021). Evaluating the historical context of abstraction-induced groundwater depletion in the Mediterranean region helped hydrogeological characterization and the selection of realistic management options (Leduc, et al., 2017).

These studies underline that long-term memory effects can impact today's hydrogeological field conditions. Time-constrained field campaigns could hardly capture such long-term effects, and memory effects are likely overlooked when historical data are neglected. Thereby, historically collected data may simply be the only available information source in data-scarce areas without active groundwater monitoring schemes.

Memory effects of past human or natural disturbances may be especially apparent in small and constrained groundwater systems. A minor buffer capacity renders island hydrogeological settings for example relatively vulnerable to human abstraction or extreme droughts (e.g. Werner et al., 2017; Post et al., 2018; Babu, et al., 2020). Post et al. (2018) revealed that the freshwater lens below a permeable atoll island in Kiribati was still contracting after 27.5 years of enhanced pumping, without reaching an equilibrium. This suggests that memory effects of past pumping regimes on small island aquifers can last for decades, and can be extra pronounced in less resilient island groundwater systems in arid climates or with limited groundwater storage capacity.

The small volcanic Caribbean island of Curaçao does not have an active groundwater monitoring scheme at the moment, and can be considered data-scarce. However, the island does have a long history of groundwater use and investigation.

Current environmental concerns stress the need for improved understanding of the island's hydrogeological system. The system is highly vulnerable for seawater intrusion by groundwater abstraction, while uncontrolled pumping from domestic wells increases continuously (Abtmaier, 1976; CBS Cura çao 2021). At the same time, infiltration from cesspits and irrigation with poorly treated waste water locally causes eutrophication of the groundwater system, as nutrients are not or insufficiently removed before being released in the environment (Louws et al., 1997).

Local groundwater eutrophication introduces major concerns about the impact of nutrient-rich groundwater inputs on coral reef ecosystems along the island's southern shoreline. Seaward transport of land-derived solutes and nutrients may cause pollution and eutrophication of the reef ecosystems and decrease their resilience to other threats, such as ocean warming (e.g. Moore, 2010; Dadhich et al., 2017; Santos et al., 2021; Pouye et al., 2023). Gibson, et al. (2020) found that 93 to 100% of irrigated treated waste water in a temperate coastal forested catchment was directly drained to sea. Another study revealed that Brazilian coral reefs suffer from eutrophication as a result of percolating nutrients from septic tanks in a rapidly urbanizing region (Costa et al., 2000).

On Curaçao, Govers et al. (2014) found enhanced nutrient levels in seagrasses of two inland bays, suggesting long-term increased nutrient inputs. Others found strong indications for land-derived nutrient pollution in the island's reefs by sampling reef macroalgae (Wieggers, 2007; Lapointe and Mallin, 2011).

Thorough understanding of Curaçao's hydrogeological system is lacking, but essential to prevent problems related to ground- and seawater pollution and eutrophication. The availability of recent groundwater data is limited, but documented data from past studies may provide useful insights.

The aim of this paper is therefore to analyse the historical development of Curaçao's groundwater system over the past 600 years and hydrogeologically characterize the island using historical reports and data. The period between 1400 and present was selected to cover pre-Columbian times, the arrival of European colonists, agricultural efforts and recent industrial developments. Qualitative and quantitative groundwater salinity and level data were compared to relevant data on land cover, groundwater abstraction and seawater desalination to identify the suite of hydrogeological processes that together shape the island's groundwater system.

Study area

Geographical setting and climate

The island of Curaçao is located in the Southern Caribbean sea around 60 km north of Venezuela (Fig. 1), as part of the *Leeward Antilles* island range. The elongated island with a total surface area of 444 km$_2$ stretches 60 km in a Southeast–Northwest direction and has a width between 4 and 11 km (CBS Cura çao 2024; Google, 2024).

This study focuses on the populated area around the inland bay *Schottegat*, that currently serves as a major industrial port and hosts the island's oil refinery (Fig. 3b). The refinery has been largely out of use since 2018 due to geopolitical and economical issues (Curaçao.nu, 2023).

Figure 1. Geographical setting of the islands Aruba, Curaçao and Bonaire *(ABC islands)* within the wider Caribbean region *(ESRI National Geographic world map)*.

Curaçao counted 148,925 inhabitants in 2023 (CBS Curaçao, 2024), with a population density of 335 persons per km2. The majority of the country's inhabitants live in the capital *Willemstad*, with a population of 100,000 in 2011 (Ter Brals, 2014). The actual amount of people on the island is mostly higher than the total population due to the growing tourism industry, an important pillar of the island's economy. 2023 was a record-breaking year for the sector with over 580,000 stay-over arrivals and 710,00 cruise guests, resulting in an average year-round population of *163,000* over 2023 (residents and visitors) (Curaçao Tourist Board, 2024).

Curaçao has a semi-arid tropical climate (Van Sambeek, et al., 2000). Precipitation records are available since 1830 (Molengraaff, 1929), but the longest and most accurate precipitation dataset is recorded since 1935 at *Hato airport* (Figs. 2, 3b). The mean annual precipitation is 561 mm, with a standard deviation of 222 mm that reflects substantial inter-annual variability. The precipitation record does not reveal substantial trends in annual precipitation *(this study)*, hence any climatological effects on the island's hydrogeology since 1830 are considered negligible. Precipitation on Curaçao is further characterized by substantial spatial and seasonal variability, with over 62% of all precipitation in the wet season between October and January (average for weather station *Hato*, 1935-–2023).

Geology and geomorphology

Geology

Curaçao's geology is constrained by five main geological units (Beets, 1972; TNO – GDN, 2023): The *Curaçao Lava Formation*; *Knip Group*; *Midden Curaçao Formation*, *Seroe Domi Formation* and *Vader Piet Formation* (Fig. 3a). The Late-Cretaceous *Curaçao Lava Formation* forms the island's geological base and consists of submarine mafic extrusive rocks (basalts) (Beets, 1972; TNO – GDN, 2023), locally intersected by tunnels and sills. The *Knip Group* and *Midden Curaçao Formation* mainly consist of partly flint-bearing marine siliciclastic material that were deposited in the Late-Cretaceous and Palaeocene. The *Curaçao Lava Formation*, *Knip Group* and *Curaçao Midden Formation* are all locally covered by Eocene limestones. The *Seroe Domi Formation* is characterized by partly dolomitized reef and clastic limestones and siliciclastic

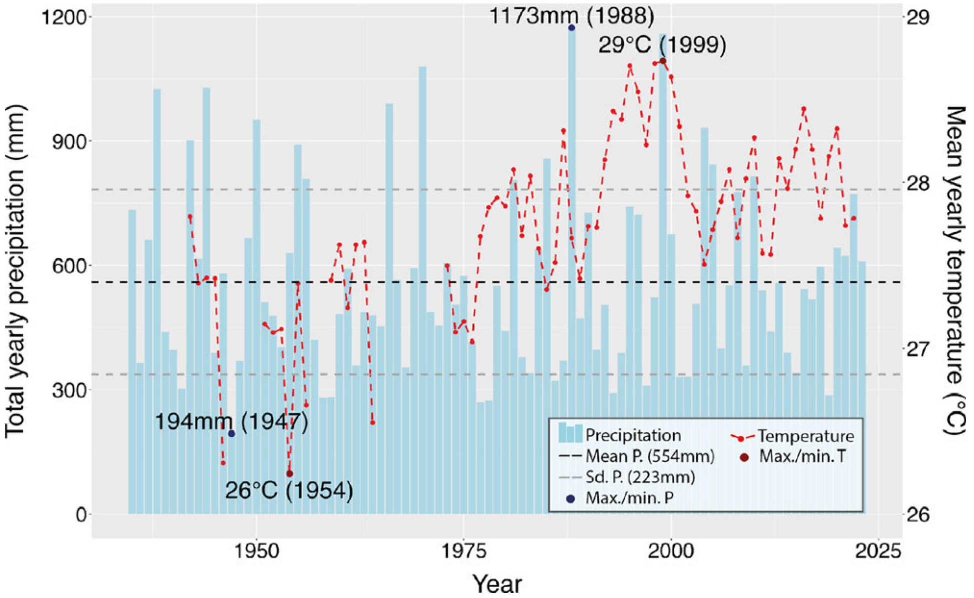


Figure 2. Mean annual precipitation and temperature recorded at *Hato*, Curaçao. Main statistics are displayed in the figure (mean annual precipitation (Mean P), standard deviation in annual precipitation (Sd. P.), maximum and minimum recorded values). Data from: Meteorologische dienst (1946); Grontmij and Sogreah (1968); Meteorological Department Curaçao (2024); Girigori (2009); Meteorologische dienst (1972).

sandstones. The Quaternary *Vader Piet Formation*, the youngest geological unit, comprises of reef limestone terraces and coastal dune, beach and alluvial deposits.

Geomorphology

The geomorphology of the highly weathered *Curaçao Lava Formation* is characterized by a moderately undulating landscape of gently sloping hilltops (Fig. 3c) (Abtmaier, 1976). Covers of Eolian limestone deposits have locally prevented erosion of the basaltic rocks, resulting in table mountains that stand out in the landscape. Folded and uplifted *Knip Group* and *Midden Curaçao Formation* deposits are less prone to weathering and erosion, explaining why the group hosts the island's highest hilltops (including the 372 m high *Sint Christoffelberg* in the west, Fig. 3a). The island's coastline hosts multiple inland bays (*bocas*), of which the *Schottegat* is the largest and most well-known example (De Buisonjé and Zonneveld, 2013) (Fig. 3b).The majority of the relatively high number of catchments discharge into any of the island's inland bays (Fig. 3b) (Beets, 1972; De Buisonjé, 1974). The Neogene *Seroe Domi* limestones and Quaternary *Vader Piet* limestone terraces feature varying degrees of karstification (Stienstra, 1983) (Fig 3c).

Hydrogeology

Table 1 displays general data of the island's main geological units. The conceptual hydrogeological cross-section in Fig. 3c is based on the island's surface geology map and digitized borehole descriptions (Beets, 1972; Abtmaier, 1976; TNO – GDN, 2023).

The *Curaçao Lava Formation* host the island's main aquifers (Abtmaier, 1976). Multiple borehole logs in this formation reveal a downwards decrease in weathering degree and fracture density over 10 to 50 m in depth (3c) (Grontmij and Sogreah, 1968; Abtmaier, 1976). Slug test data indicate that the weathered basalts feature relatively high transmissivity values (Abtmaier, 1976). Observed spatial variation in transmissivity suggests large heterogeneity in hydrogeological properties of the basaltic subsurface.

Slug tests revealed considerably lower transmissivity values for the *Knip Group* and *Midden Curaçao Formation*, compared to the *Curaçao Lava Formation* (Abtmaier, 1976). This gap is attributed to differences in geology and weathering degree, but it should be noted that only 13 tests were conducted in these two formations, against 96 in the *Curaçao Lava Formation*.

The *Curaçao Lava Formation*, *Knip Group* and *Midden Curaçao Formation* have experienced extensive folding and faulting in response to tectonic activity in the Palaeogene/Neogene (Beets, 1972). Fracture zones and anisotropic fracture networks in these formations (3c) (Beets, 1972; Hippolyte and Mann, 2011) can be expected to function as hydraulic conduits (Bense et al., 2013).

Similarly, karst features in the *Seroe Domi* and *Vader Piet* limestone deposits will function as preferential groundwater flow routes (3c). Springs emerge from the middle Quaternary limestone terrace unit at two locations, at the boundary between the limestones and the underlying *Curaçao Lava Formation*. These springs form the only year-round surface water streams on the island with a varying discharge between 0.2 and 1.4 L/s (in 1976−1978) (Grontmij and Sogreah 1968).,

Multiple scholars have attempted to quantify volumes of seaward groundwater discharge along the island's coastline (e.g. Molengraaff, 1929; Rijksbureau voor Drinkwatervoorziening, 1937; Krul, Visser, and Santing, 1949; Roos, 1961; Grontmij and Sogreah, 1968; Abtmaier, 1976). Quantification of the ratio between groundwater infiltration, surface runoff and evapotranspiration represented a major interest in most of these studies. This ratio is an essential aspect of the island's groundwater balance, but challenging to quantify due to climate extremes with intense rainfall events and high evaporation rates. Efforts to quantify recharge rates were hindered by uncertainties, but were nevertheless used to identify sustainable groundwater abstraction regimes and to design water conservation measures (Grontmij and Sogreah, 1968; Roos, 1961). Abtmaier (1976) calculated groundwater recharge from specific yield data and observed differences in groundwater storage over time. He reported an average recharge percentage of *3.7%* of yearly precipitation for the

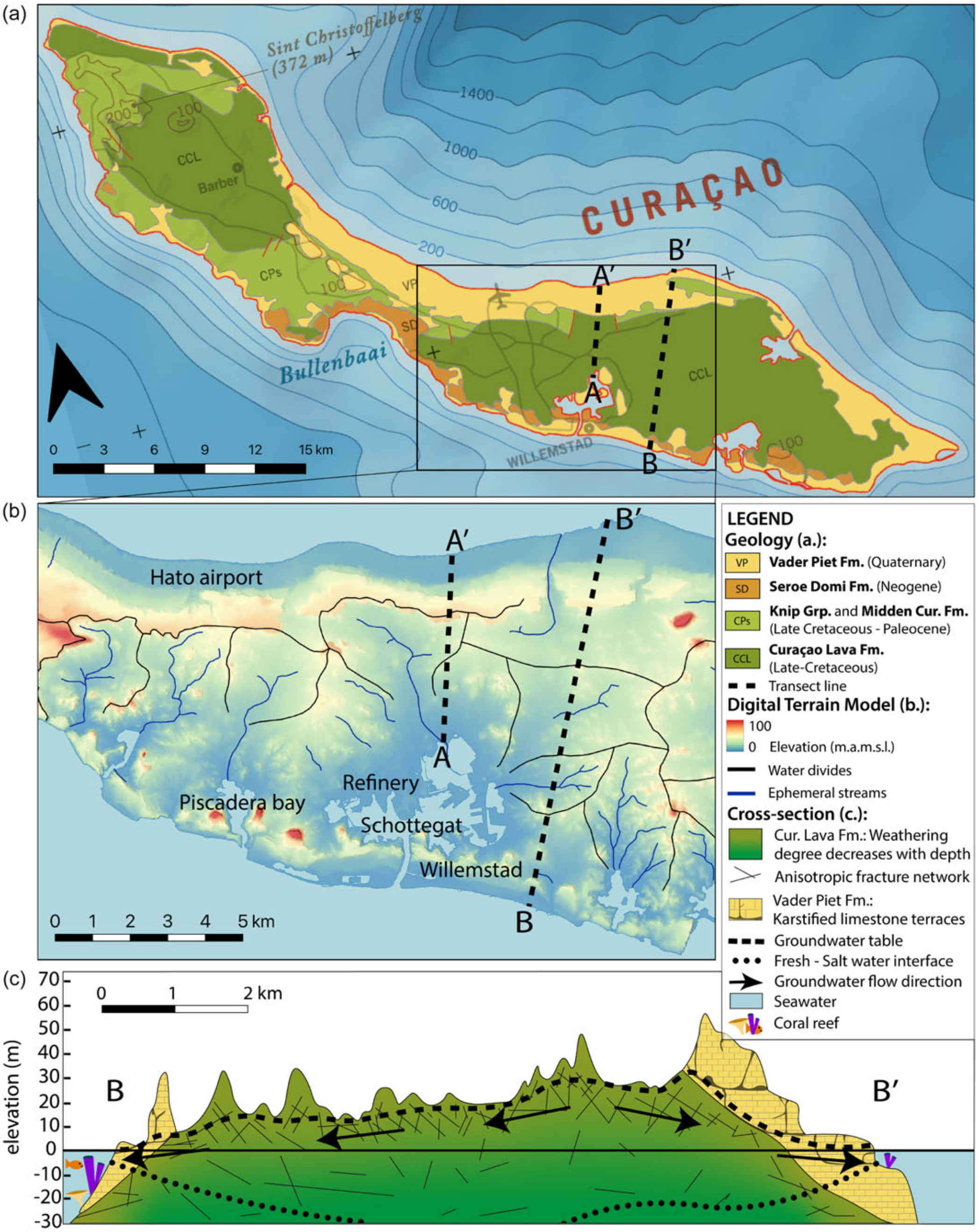


Figure 3. a.: Surface geology map of Curaçao (simplified legend) (TNO – GDN, 2023), transect lines and zoom frame were added for this study; b.: Digital elevation model including major water divides and ephemeral streams (Abtmaier, 1976); c.: Conceptual hydrogeological cross-section along transect line B-B'.

Curaçao Lava Formation, against only *0.2%* for the *Knip Group* and *Midden Curaçao Formation*. With an average yearly rainfall of 560 mm, these percentages would respectively yield 20.72 mm or 1.12 mm of groundwater recharge per year.

Materials and methods

Literature collection

Relevant literature was collected from a range of personal and institutional archives on Curaçao and in the Netherlands. The selection was limited to publications that cover Curaçao's hydrogeological conditions or hydrogeologically relevant activities and was further constrained by the study's timespan. Relevant activities included groundwater abstraction, dam construction and (waste) water infiltration, as well as deforestation and urbanization.

Data processing and analysis

The collected literature was read, and relevant information was chronologically documented in a database covering the island's hydrogeological conditions and relevant human activities. We documented the reference, data type, the location covered by the data, and a description of the hydrogeological relevance divided over the categories *hydrogeological insights*, *hydrogeological conditions*, *land use or cover*, *water management and climate variations* for each item in the database. Paper reports were

Table 1. Estimated thickness and mean Transmissivity (T) values of three geological units on'Curaçao

Geological unit	Thickness (m)	T (m^2/day)	St. Dev.	n
Cur. Lava Fm., weathered	10–40	121.1	96.5	96
Cur. Lava Fm., unweathered	>1000	–	–	–
Knip Group	100–2000	22.5	26.7	8
Cur. Midden fm.	>1000	7.5	5.4	3

scanned and digitized, maps were georeferenced in *QGIS* to ease comparison and data digitization (QGIS Development Team, 2024).

Qualitative descriptions of groundwater occurrence, level and quality were extracted from written reports and included in the database. Quantitative groundwater level and salinity indicators were either manually digitized or using *Adobe Acrobat*'s text recognition software *Scan & OCR*. Reports of measured nutrient contents were included in the database but not quantitatively analysed.

Groundwater levels were either documented in metere above sea level or below surface. A digital terrain model was used to convert the groundwater depths to levels in metres above sea level. Both chloride content and electrical conductivity (EC) were published as groundwater salinity indicators in the selected literature. Chloride contents were conversed to EC values to allow tracking of salinity in time (Abyaneh et al., 2005; Peinado-Guevara et al., 2012), using a conversion equation based on recent groundwater sample data of both EC and chloride *(this study)*: $EC = 651 + 3.73 * [Cl] - 0.000342[Cl]^2$, where EC represents the groundwater electrical conductivity in $\mu S/cm$ and Cl the chloride content in mg/l (Fig. 4).

The constructed database was qualitatively analysed to assess the historical effects of human activities on the hydrogeological state of Curaçao. The insights were visualized in cartoon-like conceptual hydrogeological cross-sections showing the hydrogeological conditions and land use that were considered characteristic for the selected periods in time (Fig. 5). Major hydrogeological processes that emerged from the analyses were identified and their implications for the island's hydrogeological understanding were discussed.

Data uncertainty

Uncertainty inherently arises from the diverse variety of data types that was used for this study.

The first source of uncertainty is introduced by the use of qualitative data to assess the historical groundwater conditions. Indirect descriptions induce more uncertainties than direct observations of groundwater level or quality. Special caution was taken for the hydrogeological interpretation of archaeological findings.

Another aspect of uncertainty is related to the trustworthiness of the observer and documentation of historical data in reports and maps. In contrast to modern scientific literature, historical publications are not peer-reviewed and are written by only one or at most a handful of observers (e.g. De Laet, 1625; Van Keulen, 1728; Euwens, 1929; Wright and Dam, 1935). Certain notes may be validated by comparison to other references or environmental proxies, but most of this uncertainty could not be avoided. Historic maps also introduce uncertainty in the location of specific observations, affected by cartography skills and knowledge at the time. Mapped location names and landscape features may help the interpretation of older maps, if the same units are mapped correctly on more recent maps.

Different sources of uncertainty are introduced by the use of quantitative groundwater level and salinity data. A bias towards more regularly monitored locations may emerge in areas or periods without consistent groundwater monitoring schemes and may be aggravated by the substantial spatial variation in hydraulic transmissivity on the island (Abtmaier, 1976; Winkel, 1981). Uncertainty related to this spatial bias could be addressed by selecting data from a representative selection of wells with varying hydraulic properties. This was however not realistic for this study due to the low spatial resolution of available data points for different time periods.

Low or irregular temporal data resolution introduces the next bias in our interpretation. Rainfall on Curaçao substantially varies between seasons and consecutive years. Hydrogeological studies that were only conducted during extraordinary wet or dry periods will introduce a bias towards such climate extremes. Interpretation of these short-term data sources may be improved by comparison to precipitation data to assess the climate during selected research periods.

The last uncertainty that rises from the combination of data types is related to the variation in used equipment and reported hydrogeological properties and units. The applied conversion of groundwater chloride content to EC introduces a source of uncertainty, as EC may be affected by more ions than chloride alone (Abyaneh et al., 2005; Peinado-Guevara et al., 2012). The local relation between chloride content and EC that was used to convert historical chloride data may have been different in the past, as groundwater ion contents could have changed over time. Last, used equipment was unknown for most of the cited studies; hence, the bias from differences in tools could not be addressed.

Results

Overview

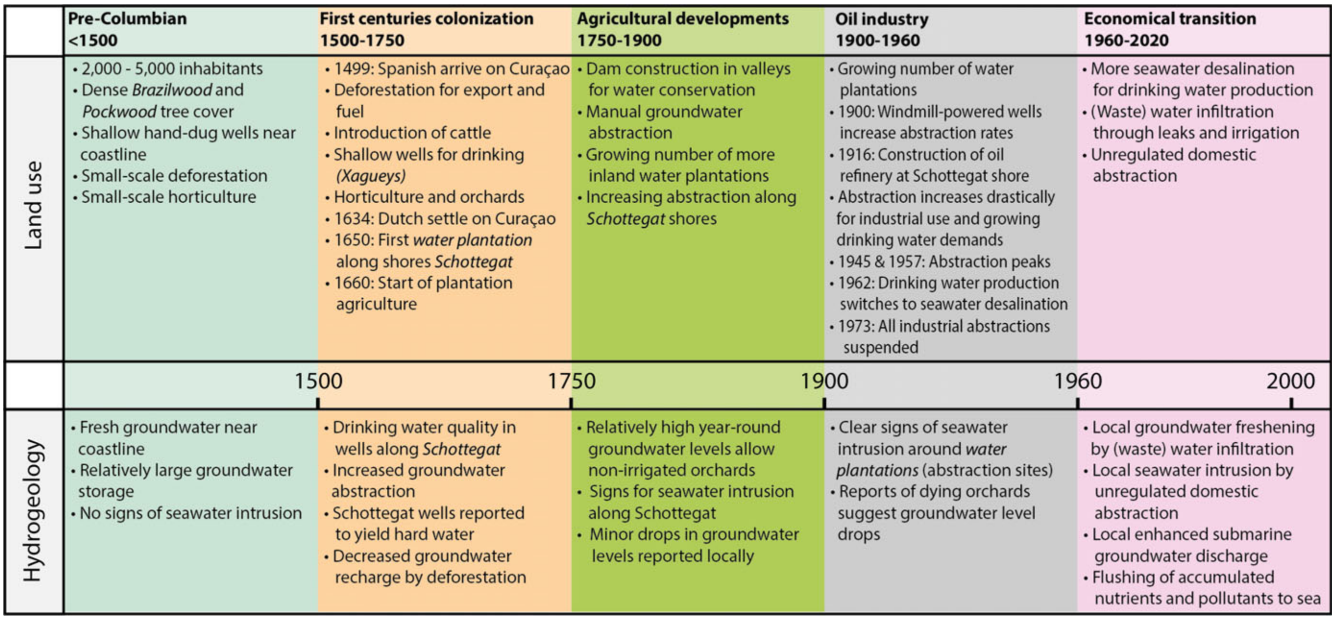
Figure 4 displays a chronological overview of relevant historical events and hydrogeological data. The covered timespan was subdivided in five distinct periods with characteristic land uses, human activities and groundwater conditions. The island's hydrogeological conditions during each of the five identified periods were conceptualized in Fig. 5. Detailed results of all five periods are provided in the sections below.

Pre-Columbian era

Land cover, groundwater use and climate

Two phases of human occupation preceded the arrival of the Spanish *conquistadores* in 1499 (Haviser, 1987). The first phase (not covered in this study) is referred to as Curaçao's Pre-Ceramic Period and roughly lasted between 3400 B.C. and 1800 B.C.

The second stage of human occupation, the Ceramic Period, lasted between 500 and 1515 A.D.. Curaçao was inhabited by the Caqueto people (Haviser, 1987). Pollen research and archaeology reveal that the Caqueto applied horticultural subsistence practices, allowing more permanent sedentary settlements located further inland than in the Pre-Ceramic (Haviser, 1987; Loen, 2021). Estimates of the total Caqueto population are based on oral information and range between 2,000 and 5,000 (Van Meeteren, 1945; Haviser, 1987).



	Pre-Columbian **<1500**	**First centuries colonization** **1500-1750**	**Agricultural developments** **1750-1900**	**Oil industry** **1900-1960**	**Economical transition** **1960-2020**
Land use	• 2,000 - 5,000 inhabitants • Dense *Brazilwood* and *Pockwood* tree cover • Shallow hand-dug wells near coastline • Small-scale deforestation • Small-scale horticulture	• 1499: Spanish arrive on Curaçao • Deforestation for export and fuel • Introduction of cattle • Shallow wells for drinking *(Xagueys)* • Horticulture and orchards • 1634: Dutch settle on Curaçao • 1650: First *water plantation* along shores *Schottegat* • 1660: Start of plantation agriculture	• Dam construction in valleys for water conservation • Manual groundwater abstraction • Growing number of more inland water plantations • Increasing abstraction along *Schottegat* shores	• Growing number of water plantations • 1900: Windmill-powered wells increase abstraction rates • 1916: Construction of oil refinery at Schottegat shore • Abstraction increases drastically for industrial use and growing drinking water demands • 1945 & 1957: Abstraction peaks • 1962: Drinking water production switches to seawater desalination • 1973: All industrial abstractions suspended	• More seawater desalination for drinking water production • (Waste) water infiltration through leaks and irrigation • Unregulated domestic abstraction
	1500	1750	1900	1960	2000
Hydrogeology	• Fresh groundwater near coastline • Relatively large groundwater storage • No signs of seawater intrusion	• Drinking water quality in wells along *Schottegat* • Increased groundwater abstraction • Schottegat wells reported to yield hard water • Decreased groundwater recharge by deforestation	• Relatively high year-round groundwater levels allow non-irrigated orchards • Signs for seawater intrusion along Schottegat • Minor drops in groundwater levels reported locally	• Clear signs of seawater intrusion around *water plantations* (abstraction sites) • Reports of dying orchards suggest groundwater level drops	• Local groundwater freshening by (waste) water infiltration • Local seawater intrusion by unregulated domestic abstraction • Local enhanced submarine groundwater discharge • Flushing of accumulated nutrients and pollutants to sea

Figure 4. Timeline of relevant land uses and indicators for hydrogeological conditions of Curaçao, spanning the period of investigation in five distinct periods. Note that the identified periods vary in duration and the transitions between periods were smoother in reality. Colours correspond to period labels in Fig. 5.

Klosowska et al. (2004) analysed two sediment cores from an inland bay on Curaçao and found evidence of land clearing by forest burning, starting during Caqueto occupation in 850 A.D.. Signs for forest burning were accompanied by evidence for increased erosion and freshening of the bay waters. This indicates that Caqueto deforested the land, causing increased erosion and freshwater inputs to sea.

Although deforestation occurred locally, sparse reports from early European colonists suggest that dry-climate forests covered the majority of Curaçao upon their arrival in the sixteenth century (Loen, 2021). In 1502, Spanish conquistador Ojeda reported forests and growing *Brazil wood (Haematoxylum brasiletto)* at multiple locations (Brusse, 1882; Amelunxen, 1929; Terpstra, 1948). Ojeda also mentioned to have found shelter *in the forests*, an indication for a relatively dense forest cover (Terpstra, 1948). *Pockwood (Guaiacum officinale)* was reported to grow abundantly as well and was later used for ship construction by the Dutch (Henriquez, 1965).

The Caqueto must have needed a year-round freshwater supply for drinking and irrigation, but little is known about their water resources (Van Meeteren, 1945; Loen, 2021). Permanent freshwater sources that were available in pre-Columbian times included permanent springs, natural karst waters and shallow groundwater that could be reached with stone-age instruments (Debrot, 2009). Geographical analysis of archaeological sites shows that all Caqueto settlements were located in ephemeral stream valleys *(rooien)* or near one of the two continuous springs (*Hato, San Pedro*) (Koolwijk 1881; Haviser, 1987; Debrot, 2004b; Loen, 2021). Van Meeteren (1945) and Debrot (2004b) argue that most settlements were located far away from the two permanent springs and groundwater wells must have been required for daily water needs.

Relatively shallow groundwater levels can be expected throughout the year in the ephemeral stream valleys, making them plausible locations for shallow wells. It is reasonable that the Caqueto on Curaçao dug shallow wells to access groundwater resources, given that Caqueto on the South American mainland were known to dig wells (Haviser, 1987). Caqueto wells assumably did not exceed 3 m in depth, as the Caqueto did not use metal digging instruments (Van Meeteren, 1945). Such shallow wells may have resembled the groundwater-fed depression as depicted in Fig. 6. Indeed, Debrot (2009) and Van Soest (2010) found remnants of *walk-in wells (pos di pia)* in loose soils of ephemeral streams near indigenous settlement sites.

No descriptions are known about the climatic conditions on Curaçao during the pre-Columbian period, but climate reconstructions have been made for different Caribbean areas using indirect climatic proxies (e.g. Beets et al., 2006; Kilbourne et al., 2008; Burn et al., 2016). Gradual freshening of a Curaçaoan inland bay around 900–1000 AD indicated enhanced freshwater inputs at the time. Klosowska et al. (2004) attributed this effect to local deforestation after 850 A.D., but increased precipitation may also explain part of the risen freshwater inputs. Wetter climate conditions could be related to the Mediaeval Warm Period between 1,000 and 1,300 AD, that was identified in isotopic data from Guadeloupe (Beets et al., 2006). Abundant *Brazilwood* and *Pockwood* forests upon Spanish arrival indicate a semi-arid climate at the time, similar to today's climate (Terpstra, 1948; Henriquez, 1962; Henriquez, 1965).

Hydrogeological conditions

Hydrogeological data of pre-Columbian Curaçao are sparse, but a rough idea of the prevailing conditions can be constructed. All Caqueto settlements were located near permanent springs or ephemeral streams (Haviser, 1987). This indicates that shallow groundwater tables were present year-round in ephemeral stream valleys to allow the construction of shallow wells. Moreover, the groundwater salinity in such shallow wells must have been sufficiently low for human consumption. The low population and absence of mechanical pumping equipment imply that groundwater abstraction did not have major impacts on the island's groundwater balance.

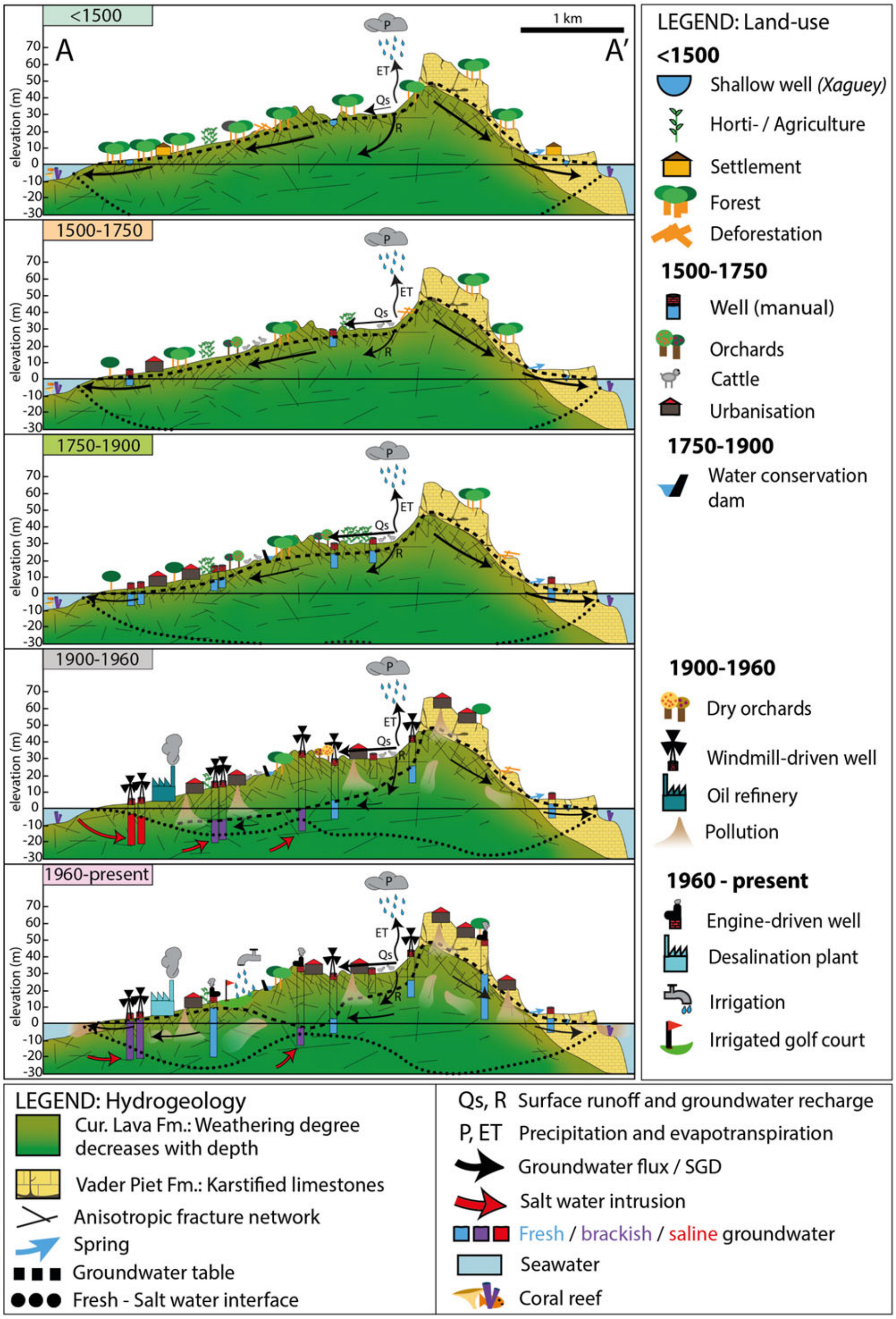


Figure 5. Hypothetical conceptual hydrogeological cross-sections for the different periods covered in this study, along transect line A-A' (Fig. 3). The length and thickness of the flux arrows correspond to their relative magnitudes. Displayed notes of fresh, brackish and saline groundwater report relative conditions. Object drawings are not to scale.

It is challenging to estimate the effect of a denser forest cover on the island's water balance. Plant roots may improve soil structure and create preferential flow paths, resulting in higher groundwater recharge and lower surface runoff (Qiu et al., 2023). However, canopy interception may hinder groundwater recharge and storage may be decreased through water uptake by trees (Yin et al., 2015; Folch and Ferrer, 2015). Additionally, specific vegetation types can impact the water balance through microclimatic interactions, such as canopy interception of cloud water (Brauman, et al., 2012; Brewington, et al., 2019); Trees can favour evaporation through decreased albedo and increased aerodynamic roughness (Hoek Van Dijke et al., 2022). Forests can enhance atmospheric moisture recycling, resulting in increased precipitation rates (Hoek Van Dijke et al., 2022).

Local site and vegetation characteristics must be considered to estimate the impacts of deforestation on the island's hydrogeology. A large part of Curaçao can be classified as sloping terrain; hence, forest cover can be expected to decrease surface runoff and increase groundwater recharge (Qiu et al., 2023). The two reported abundant tree species *Brazilwood* and *Pockwood* commonly grow in semi-arid and arid conditions, and feature limited transpiration rates (Henriquez, 1962; Henriquez, 1965). Thereby, microclimatic

Figure 6. A groundwater-fed shallow depression filled with water in *Christoffel National Park*, Curaçao *(own photograph)*. This depression may resemble shallow hand-dug wells that were used by the Caqueto.

processes may have caused increased precipitation locally (Brauman, et al., 2012; Brewington, et al., 2019; Hoek Van Dijke et al., 2022). We therefore assume that the denser forest cover on Curaçao during pre-Columbian times caused an increase in groundwater recharge.

The presumed hydrogeological conditions at the time are visualized in Fig. 5. Groundwater levels in ephemeral streams in pre-Columbian Curaçao were relatively shallow throughout the year, and water quality allowed for year-round human consumption. High groundwater levels suggest a large volume of groundwater storage and relatively substantial fluxes of submarine groundwater discharge at the time.

First 250 years of colonization (1500–1750)

Spanish occupation (1499–1634)

The arrival of the Spanish in 1499 marked the introduction of various new human activities with hydrogeological impacts. Historical reports and sediment core analyses reveal that the Spanish started the large-scale felling and export of *brazilwood* and *pockwood* trees from the island (De Laet, 1625; Amelunxen, 1929; Terpstra, 1948; Klosowska et al., 2004). Horticulture and cattle farming were expanded with the introduction of various fruit trees and goats, donkeys and horses (De Laet, 1625; Amelunxen, 1929; Euwens, 1929; Van Meeteren, 1945).

A year-round freshwater supply was required for the Spanish horticultural activities. Spanish maps *(drawn in Madrid after the Dutch seized Curaçao)* indeed display 17 shallow water holes (*xagueys*) across the island (Euwens, 1929; Van Buurt, 2018). These maps provide the first documented indications for the use of fresh groundwater from wells on Curaçao. Most documented and reported *xaguey* locations are located in loose soils near the shoreline or in ephemeral streams (Euwens, 1929; Van Meeteren, 1944). A Spanish map by *Francisco de Ruesta* (Fig. 7) reveals *xagueys* along the eastern shores of *Schottegat*, near Santa Barbara bay further east and St. Joris bay in the northeast, and along a line near Santa Cruz in west Curaçao (Renkema, 2016). Some of these mapped *xaguey* locations can be validated by documented interviews that the Spanish conducted among Caqueto. In one of those interviews, a Caqueto informed the Spanish about a source of fresh water near *Santa Barbara bay* (Wright and Dam, 1935).

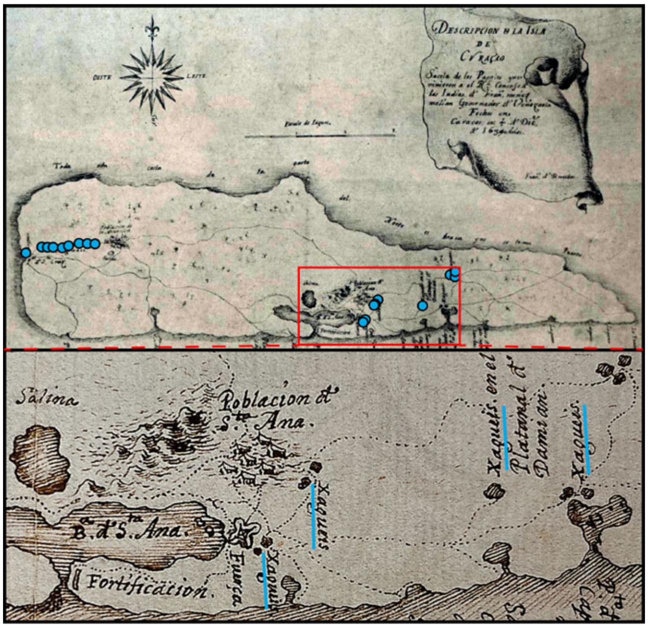


Figure 7. Spanish topographical map of Curaçao by *Francisco de Ruesta (shortly after 1634)*, displaying multiple *xagueys* (blue dots), with a map zoomed-in on the area east of *Schottegat* (Euwens, 1929; Renkema, 2016).

The questioned Caqueto chief Jacinto de Amaya mentioned fresh drinking water from a well or hole near the fortification of *Poos Cabaai*, along *Schottegat's* eastern shoreline (Wright and Dam, 1935; Van Meeteren, 1950) .

Dutch rule (1634–1750)

First observations. More hydrogeologically relevant details are available since the Dutch seized Curaçao in 1634. Early reports and maps frequently mention freshwater locations, one of the first Dutch priorities (De Laet, 1625; Gonggrijp, 1920; Amelunxen, 1929; Terpstra, 1948). These documents also suggest that Curaçao was (still) covered with *Brazilwood* and *Pockwood* trees upon Dutch arrival. The Dutch soon continued tree cutting for export and domestic uses, although the law forbade deforestation in some areas *(e.g. Punda and Poos Cabaai)* (Amelunxen, 1929; Van Meeteren, 1950).

Shortly after Dutch captain *van Walbeeck* had arrived in 1634, he reported several fresh groundwater wells and horticulture gardens east of *Schottegat* and near *Santa Maria*, more to the west (Gonggrijp, 1920; Amelunxen, 1929; Terpstra, 1948). These freshwater sites were indeed shown on the Spanish map (Fig. 7, and are partly depicted on the first Dutch map from *de Laet* in 1634 (Fig. 8) (Euwens, 1929). *De Laet* mapped drinking water wells close to the eastern shoreline of *Schottegat (Poos Cabaai)* and near the eastern coastline of Santa Barbara bay (Fig. 8) (Terpstra, 1948; Amelunxen, 1929; Van Meeteren, 1944). Spanish reports of interviewed Caqueto and Dutch captives after Dutch invasion support this image (Van Meeteren, 1950; Wright and Dam, 1935).

The first Dutch settlement was located at *Poos Cabaai*, where a number of wells provided good-quality drinking water (no. 1 on Fig. 8) (Euwens, 1929; Van Meeteren, 1950). This well site east of *Schottegat* was used by the Caqueto and Spanish for drinking water before (Wright and Dam, 1935; Van Meeteren, 1950). After a while, the Dutch moved from *Poos Cabaai* to *Punda* and built a fortress on the limestone coast (Amelunxen, 1929). No fresh water

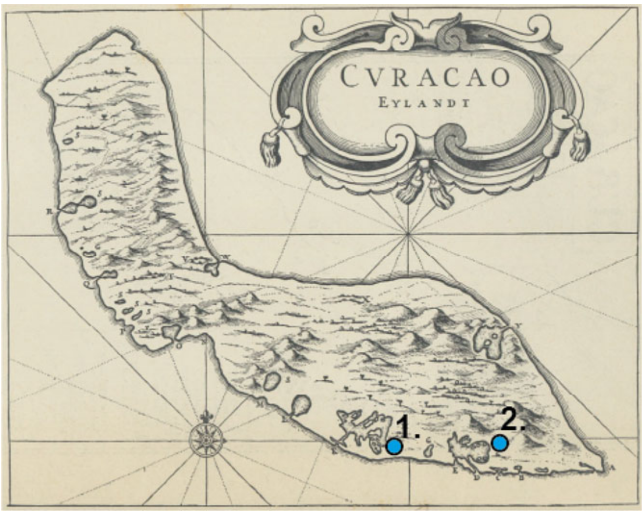


Figure 8. Dutch topographical map of Curaçao by *De Laet, 1634*, displaying locations of two freshwater sites. *1.: Our people's quarters and watering place; 2.: A freshwater spring or creek leading into a dug hole, that even in the driest times contains water which is used for cattle to drink* (Euwens, 1929).

was available there, drinking water was transported by ship from *Poos Cabaai*. Soon, more water was needed and groundwater was abstracted from *Xaguey de Careotabo*, east of *Poos Cabaai*, from where it was transported by foot (possibly, no. 2 on Fig. 8) (Van Meeteren, 1950).

Start of (water) plantations. The Peace of Münster in 1648 provided a boost to Curaçao's economy that was based on the upcoming trade in enslaved people (Amelunxen, 1929; Van Meeteren, 1950). Food production needed to keep up with the growing population, creating the incentive for plantation agriculture starting around 1660 (Renkema, 1981). Plots around *Schottegat* were cleared to create plantations, but plantation agriculture soon expanded to all corners of the island (Loen, 2021; Renkema, 1981). Curaçao hosted 111 plantations and gardens in 1696, and all suitable land was in use by private plantation holders in 1725 (Renkema, 1981). The remaining, unsuitable pieces of land were assigned as private grazing lands or *savanen* for limited amounts of cattle.

An increasing population, cattle and crops all required a continuous and growing freshwater supply around the city and plantations. Additional groundwater wells were dug along the coastline of *Schottegat* in around 1650 (Van Meeteren, 1950). Fresh groundwater was transported to Willemstad by water canoes *(canóa di awa)*, where it was sold. The wells along the *Schottegat* shores formed the first of the so-called *water plantations*. Additionally, the government *(Dutch West Indian Compagnie)* installed public walk-in wells *(pos di pia)* across the island to assist the plantations (Renkema, 1981). People could collect water from these wells, and the walk-in side allowed cattle to walk down and drink.

The topographical from 1728 clearly displays locations of freshwater wells and streams (Fig. 9) (Van Keulen, 1728) . The mapped freshwater location at *Poos Cabaai* (east of *Schottegat*) was reported before, but this is the first map that also displays well locations along the western and northern shores of the bay (Fig. 9a and b). Most probably, these wells were dus after 1650 as part of the first *water plantation* (Van Meeteren, 1950). The freshwater spring and pond east of *Santa Barbara* (Fig. 9c) likely resemble location 2 on Fig. 8, and a well that was used by French soldiers in 1673 *(Brakke Putje)* (Terpstra, 1948; Amelunxen, 1929; Van Meeteren, 1944).

Abstracted groundwater from the *Schottegat* shores was reported have a 'hard' taste (possibly Calcium-rich). People who could afford it constructed rainwater collectors to collect a better-tasting source of drinking water during wet periods (Van Meeteren, 1950; Landswatervoorzieningsdienst Curaçao, 1953). The 'softer'-tasting rainwater was mostly used for drinking while well water was applied for household tasks, such as laundry in so-called *labaderas (washing gardens)* (Van Meeteren, 1950).

Hydrogeological conditions

Quantitative data on the hydrogeological conditions on Curaçao between 1634 and 1750 are lacking, but anecdotal insights can be obtained from reports. For example, vice-director *M. Beck* argued in 1659 that Curaçao would not survive a foreign charge due to the limited drinking water supplies (Amelunxen, 1929). Another note describes that French soldiers in 1673 used fresh groundwater from a well in *Brakke putje (Dutch for little brackish well)*, located near Santa Barbara (Amelunxen, 1929).

Further reconstruction of groundwater conditions between 1499 and 1750 must be based on hydrogeological interpretations of other proxies. The installation of a *water plantation* on the shores of the *Schottegat* bay indicates that fresh groundwater could be abstracted from shallow wells close to the shorelines. No quantitative data on groundwater abstraction rates during this period exist, but abstraction along the bay's shoreline certainly increased after well construction. Groundwater abstraction must have grown elsewhere too, as public wells were constructed to assist plantation agriculture.

Sediment core analyses revealed increased sedimentation during the first centuries of Spanish and Dutch colonization (Klosowska et al., 2004). This may be explained by a loss of soil structure and infiltration capacity after the removal of tree roots (Qiu et al., 2023). Deforestation hypothetically rendered a drop in groundwater recharge, favouring surface runoff over infiltration.

Figure 5 summarizes the hydrogeological conditions of this period: Deforestation has induced decreased groundwater recharge, and increased surface runoff and erosion; Enhanced groundwater abstraction has caused minimal drops in groundwater level and minor instances of seawater intrusion.

Agricultural developments (1750–1910)

Rising water demands from an ever-growing island population required continuous investments in groundwater abstraction. Abstraction rose after 1750, when more *water plantations* were constructed at inland locations where *soft* quality drinking water was obtained (presumably low in Calcium) (Van Meeteren, 1945; Van Meeteren, 1950; Renkema, 1981). Donkeys were used to transport water from the inland plantations to the city, carrying two 40L barrels each (Van Meeteren, 1945). Plantation inventories reveal that almost all plantations and gardens around and east of *Schottegat* sold well water in the early 1800s (Renkema, 1981), with plantations *De Hoop, Valentijn, Asiento* and *Groot Kwartier* as the most important suppliers. The manually abstracted groundwater was conveniently transported from the plantations along *Schottegat* shoreline to *Willemstad* by water canoe or water ferry. Nevertheless, ensuring sufficient drinking water supply remained a challenge that continuously asked for innovations in both

Figure 9. Topographical map of Curaçao, displaying locations of three wells, a spring, and a stream (marked with blue) (Van Keulen, 1728), with three zoomed-in maps.

abstraction and transport. Deep wells were dug in search of fresh artesian springs. However, only *hard* and brackish groundwater was found in both a 27 m deep well in *Punda* and a 150 m deep well at plantation *Plantersrust* (west of *Schottegat*) (Van Meeteren, 1950). The introduction of donkey-hauled water carriages for transport in around 1860 meant an increase in transport capacity (Van Meeteren, 1950).

Groundwater was a vital commodity, sold to multiple parties (Renkema, 1981): The urban population completely relied on abstracted water during dry periods; Ships in the harbour used groundwater to restock for upcoming journeys; The government required groundwater for personnel, the military, the hospital and the navy.

Abstraction rates from *water plantations* have not been documented, but may be estimated from certain indicators. One such indicator is that groundwater was manually abstracted by enslaved people, with help of the innovative *turning wheel (putrad, rad di poos)*. Van Meeteren (1950) estimates that one man could obtain between *five* and *six* m^3 in a 10-hour shift. Documented volumes of sold water form another indication for abstraction rates. Plantation *de Hoop* reported to have sold the government *173* m^3 of groundwater in 1822, which was only one of their customers at the time. Plantation *Valentijn* supplied the government with around 1,630 m^3 of well water in the first eleven months of 1827 (Renkema, 1981). During the same period, between 160 and 300 m^3 were delivered from plantation *Saliña Abao* (East of *Schottegat*) to governmental location *De Pen*. Last, temporal variations in published water prices suggest that water supply became more challenging during periods of drought.

Plantation agriculture continued to fulfil an important role in the island's food supply. Drought-resistant sorghum was cultivated most abundantly and served as the main food source for enslaved plantation workers and cattle (Went, 1902). Sorghum production was however insufficient to serve the urban residents and food imports were necessary., Crops as melons, pumpkins and okra were cultivated in smaller-scale horticulture. These crops require daily irrigation and were mostly grown near dammed reservoirs or wells for irrigation (Renkema, 1981). The best pieces of land were often assigned to orchards *(hofjes)*, where coconut and citrus trees (among others) were cultivated. These fruit trees require a year-round freshwater supply through groundwater uptake, explaining why almost all *hofjes* were to be found in low-elevation ephemeral stream valleys (Renkema, 1981). The location of these orchards suggests year-round shallow groundwater of irrigation quality at these sites, which may have been helped by the construction of small earthen dams (Went, 1902; Havelaar, 1903). Indeed, Martin (1888) reported rows of multiple dams in certain valleys to prevent surface runoff and enhance infiltration (Versluys, 1927).

Hydrogeological conditions

No quantitative hydrogeological data are available for this period, but the prevailing hydrogeological conditions may be deduced from anecdotal details (Van Meeteren, 1950). It can be assumed that groundwater levels in the unirrigated orchards in ephemeral streams never dropped below five to six metres, the maximum rooting depth of most orchard trees on Curaçao (Van Meeteren, 1950; Krul, et al., 1949). Moreover, the inventories reveal a large amount of walk-in wells *(pos di pia)* that were never deeper than *five* metres Van Meeteren (1950). This suggests that groundwater levels did not drop below this level, as year-round water supplies were needed (Van Meeteren, 1950).

Another hydrogeologically relevant note was reported in 1830, as the owner of *Poos Cabaai* requested to fill up a well (Van Meeteren, 1944). The well had become brackish in 1800 and had become too saline to water cattle. Nearby wells were reported to still provide drinking water quality. Interestingly, this was the location of the first Dutch first settlement and groundwater abstraction site. The increased salinity of one of the wells may indicate seawater intrusion towards the coastal site, as a result of prolonged groundwater abstraction.

Figure 5 displays a simplified scheme of the presumed hydrogeological conditions between 1750 and 1900. Increased groundwater abstraction between 1750 and 1900 must have led to local minor drops in groundwater levels. Abstraction rates were limited by manual pumping capacity, but increased with more wells, innovations in abstraction and transport capacity. First signs of seawater intrusion were reported at *(Poos Cabaai)*, but groundwater levels and quality were sufficient to support non-irrigated orchards elsewhere (Van Meeteren, 1944).

Mechanization and industrialization (1900–1960)

American windmill-powered pumps initiate major increases in groundwater abstraction (1890). The introduction of American windmill-powered groundwater pumps (Fig. 10) in 1890 represented a major leap in groundwater abstraction on Curaçao. Higher pumping rates enabled the irrigation of areas that could not be irrigated before and allowed abstraction from deeper wells (Van Meeteren, 1950). Existing orchards were enlarged, new ones were constructed at formerly unsuitable locations higher up in the landscape. Livestock farming and animal feed production grew substantially and *water plantations* soon switched to windmill-driven wells that allowed higher drinking water production (Van Meeteren, 1950). Limited negative impacts were reported, dams were constructed at some valleys where drops in groundwater level had been observed.

Promoting agriculture. The early years of the twentieth century were characterized by increased efforts to promote agriculture on the island (Van Soest, 1977). Dutch professors *Went* and *Havelaar* visited the island in 1902 to study ways to promote agriculture and water production on the island. Havelaar (1903) reported multiple small dams to slow down surface runoff in certain valleys and noted that most vegetation on the island had been cleared for fuel and charcoal production.

Havelaar (1903) also provided the first quantitative data on groundwater abstraction volumes. 4 of the 21 wells on plantation *Groot Sint Joris* together yielded an average 30 to 37.5 m^3 of fresh water per day, during periods of high groundwater levels. Abstraction rates from all wells together at *water plantation Plantersrust* ranged between 50 m^3 per day in dry periods and 25 m^3 per day in wet periods (groundwater demand dropped in wet periods as people then switched to rainwater harvesting).

Werbata maps. In response to scientific advice (Went, 1902; Havelaar, 1903; Van Kol, 1904), the government subsidized land owners to promote the construction of public groundwater wells and earthen dams (Van Soest, 1977). Subsidies on windmill-equipped wells were popular among upcoming horticultural firms: 153 of such wells had been constructed around *Schottegat* in 1906, against only five wells in the areas further away from the city (Van Soest, 1977).

Figure 10. Windmill-powered abstraction wells near *Julianadorp*, Curaçao *(Nationaal Archief)*.

Later, dams were constructed more systematically in selected valleys. A high-resolution, updated topographical map was necessary to enable systematic dam construction (Van Kol, 1904). Two land surveyors were hired and mapped the island's topography in three years (Van Meeteren, 1950; Van der Krogt, 2006; Renkema, 1981). The resulting maps with extraordinary details became, known as the *Werbata maps (or Werbata-Jonckheer maps).*

The detail of the *Werbata maps* allows counting of the total amount of groundwater wells with and without windmills on Curaçao in 1906–1909, representing semi-quantitative data on groundwater abstraction activity (Fig. 11). The maps reveal that Curaçao hosted *865* wells at the time, of which *625* without and *240* with a windmill, assuming all wells are mapped. Most wells were concentrated on the *Curaçao Lava Formation*, around *Schottegat* bay. Highest abstraction rates can be assumed at locations with high densities of windmill-equipped wells. Records of abstraction rates are scarce, but rates can be estimated based on individual observations of well yields.

Havelaar (1903) reported an average daily abstraction rate of *8* m^3 for windmill-driven wells, which would result in a total abstraction volume of *1,920* m^3 per day from all windmill-driven wells together on the island in 1906-1909. Note that this abstraction rate was measured in a wet period and may have been different during drier times. Thereby, this calculation assumes that all windmill-equipped wells were continuously in use. The reported maximum daily abstraction volume of *5* m^3 from manual wells would yield a total daily volume of *3,125* m^3 (Van Meeteren, 1950). Continuous manual abstraction is however highly unlikely given the presence of windmill-powered wells and the abolition of slavery after 1863. Total manual abstraction volumes were presumably much lower (Amelunxen, 1929).

Oil boom ignites drastic increases in groundwater abstraction

Industrial water production. The construction of an oil refinery by the *Curaçaose Petroleum Maatschappij (CPM)* in 1916 induced a rapid economical transition from agriculture to (oil) industry in Curaçao (Amelunxen, 1929; Van Meeteren, 1950; Van Soest,

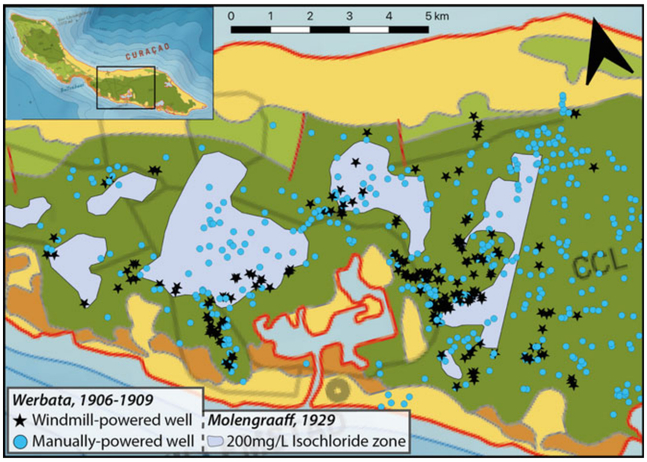


Figure 11. Wells as displayed on the *Werbata maps* (Verstappen, 1998) and *200* mg/L isochloride zones (EC = 1,675 *μS/cm*) as reported by Molengraaff (1929), displayed on the surface geology map (TNO - GDN 2023) (geological legend in Fig. 3a.).

1977). Freshwater demands drastically increased with the industrial growth and population rise (Abtmaier, 1976). The economical shift also resulted in a swift drop in agricultural activity (Henriquez, 1965). Most food was to be imported and soon no more (small) dams were constructed while existing dams deteriorated due to a lack of maintenance (Henriquez, 1965; Van Soest, 1977).

The *CPM* bought plantation *Asiento* to host the refinery, located on a peninsula within the *Schottegat* bay (Fig. 3b) (Van Soest, 1977). This location was mainly selected for the convenient harbour, the area's flat topography, and its' promising groundwater reserves: Crude oil refining required large volumes of fresh water for various processing and cooling steps. The few wells on the peninsula yielded drinking water quality groundwater (Van Soes 1977).

Multiple wells were added, until the *Asiento* peninsula hosted thirteen windmill-equipped wells in 1918, plus multiple engine-driven pumps. Four of these wells together supplied sufficient amounts of high-quality fresh groundwater, yielding between 100 and 200 m^3 per day (Van Soest, 1977). The wells at *Asiento* continued to supply sufficiently until 1920, but wells outside of the *CPM* terrain were needed when oil production was intensified later (Van Soest, 1977). The first *CPM* well outside of *Asiento* was constructed on *Monte Carmelo* in June 1920. More wells were added in the areas around the peninsula after a drought in 1921 caused all *Asiento* wells to run dry. Well yields recovered in 1922, but water quality never returned to the original values: *Asiento's* groundwater had become too *hard* for use in the refinery (Van Soest, 1977).

Apart from water supply for industrial use, *CPM* sold substantial volumes of water to other parties: *9,667* m^3 in 1920, *306* m^3 in 1921 (drought year), *7,605* m^3 in 1923 and *12,000* m^3 in 1924. These numbers suggest that water production from *Asiento* was still running in 1923, and reveal that *CPM* abstracted more than their industrial needs required.

The start of the *Curaçaose Petroleum Industrie Maatschappij (CPIM)* in 1925 (replacing *CPM*) marked the intensification of oil production on the island. A new refinery was completed north of the *Asiento peninsula* between 1923 and 1930. Oil production had increased from *1,000* m^3 per day in the old plant to a daily *21,000* m^3 in the new (uncompleted) refinery in 1928. This meant a growth in industrial water demands: A daily water use of *1,048* m^3 in July 1926 had grown to a daily *1,500* m^3 in June 1928 and had doubled to *2,300* m^3 in 1931 (Van Soest, 1977). The *CPIM* also continued selling water to third parties, selling *26,480* m^3 in 1928 (over double the volume of 1924).

Groundwater production at *Asiento* and *Monte Carmelo* could no longer meet growing demands, so the *CPM* had already purchased four additional plantations in 1924. *Water plantations Malpais (or Mount Pleasant* (*Landhuis Malpais, alias Mount Pleasant.*)) and *Brievengat* did not yield sufficiently, but water production from plantations *Cas Coraal* and *Zapateer* almost completely covered industrial water needs, replacing production at *Asiento* and *Monte Carmelo*. The *CPIM* further expanded water production in 1926 by purchasing plantation *Groot Sint Joris*. A ±10 km-long pipeline was constructed between the plantation and the refinery to ease the daily transport of *1,000* m^3 of fresh water (Van Soest, 1977).

More *water plantations* were added between 1927 and 1930, when the *CPIM* acquired plantations *Valentijn*, *Groot Piscadera*, *Klein Hofje*, *de Hoop*, and 18 hectares along the *Manzanillabaai* (Van Soest, 1977). Water was abstracted from newly dug wells and pipelines were constructed for rapid transport. The *CPIM* purchased a seawater distillation plant in 1928, to be used as backup during droughts. The first time that it was used on full capacity was during a drought in 1931, when only 600 m^3 of groundwater could be extracted daily (Van Soest, 1977).

Ever-increasing industrial water demands asked for the acquisition of more *water plantations* around *Schottegat* and *Willemstad* between 1930 and 1950 (Van Meeteren, 1950; Roos, 1961; Abtmaier, 1976; Van Soest, 1977). *CPIM's water plantations* covered *4,000* hectares in 1942, hosting around *100* production wells. The *CPIM* acquired plantation *Sint Michiel* in 1945, but dismantled wells in the upstream areas of *Zapateer* (Roos, 1961). At this time, *water plantations Groot Piscadera*, *Sint Michiel* and *Zapateer* were considered reliable and productive, as opposed to the smaller and less reliable sites *Groot St Joris*, *Cas Grandi* and *Muizenberg*.

The end of the war in 1945 introduced a difficult period for oil production on Curaçao (Van Soest, 1977). Venezuela implemented laws to increase inland oil production and limit crude oil exports. European countries started refineries on the mainland, near the users. Additionally, a drought period between 1945 and 1949 caused sharp drops in well yields (Van Soest, 1977).

The *CPIM* managed to maintain water production by raising the maximum limit of permissible abstraction water salinity from 300 to 400 mg/l. Thereby, a deep well that was dug in 1945 proved that fresh groundwater could be found in deeper zones, below sea level (Van Meeteren, 1950). New equipment was applied to dig more and deeper wells on all *CPIM water plantations* (Van Soest, 1977), although not all of the 30 to 100 m deep wells yielded fresh water (Van Meeteren, 1950).

Water conservation measures were taken to increase groundwater recharge and guarantee sufficient abstraction (Roos, 1961; Van Soest, 1977). For example, a large dam was constructed at *water plantation Muizenberg* (Van Meeteren, 1950; Van Soest, 1977). Interestingly, groundwater abstraction was also described as one of the measures to conserve groundwater resources, by preventing lateral flow to sea (Roos, 1961).

Despite all efforts, a study in 1952 concluded that well production could not be increased but was to be lowered instead (Roos, 1961). The *CPIM* responded by investing in water treatment systems to treat imported fresh water and by adjusting their abstraction regulations in 1953: Groundwater levels were not to drop below 1949 levels anymore.

However, groundwater production was intensified at the same time. Plantation *Sint Michiel* was purchased and deep wells were constructed. The *CPIM* water abstraction volumes even peaked between 1950 and 1958, as annual abstraction volumes over *one million* m^3 were achieved for the first (and last) time in 1951, 1956 and 1957 (Roos, 1961).

The *CPIM* was renamed to *Shell Curaçao NV* in 1959. The name switch coincided with a drop in groundwater abstraction rates, until all *Shell* wells were abandoned in 1973 (Abtmaier, 1976).

Uncertainties and incomplete data challenge a quantitative comparison of industrial abstraction to natural groundwater recharge volumes. A report by the refinery reveals that the industry adjusted their abstraction regime to annual variations in precipitation and groundwater recharge Roos (1961). Total abstraction over one rain cycle (about six years) was not allowed to exceed *3%* of groundwater recharge over the *water plantations'* catchment areas. This is confirmed by calculations made for this study, with abstraction volumes of the same order of magnitude as estimated recharge.

Governmental water production. Curaçao's government faced increasing difficulties in supplying drinking water to a growing population (Van Soest, 1977). Following advice from *G.J.H. Molengraaff*, the government had purchased several plantations in 1923–1924 to increase groundwater production (*Hato*, parts of *Buena Vista*, *Rozendaal*, *Marchena* and *Gasparito*). *Buena Vista* was equipped with fourteen wells, a pipeline to the *Schottegat* shores and several ferries *(waterponten)* to transport water to *Willemstad*. *Water plantations Klein Kwartier* and parts of *Scherpenheuvel* were added in 1927, after consultation by *dr. J. Versluys*. Together with *Buena Vista* and *Rozendaal*, these plantations yielded 450 m^3 of water per day (Van Soest, 1977). The newly founded governmental water supply service *(Landswatervoorziening)* was responsible for groundwater transport to the city and the connection of private houses to the water distribution system (*1,960* Houses in Willemstad were equipped with running water taps in 1929).

The government invested in seawater distillation plants for water production, as an addition to groundwater production. The first plant with a daily production capacity of *100* m^3 was soon replaced by three units with *240* m^3 capacities (Van Soest, 1977). The public however preferred cheap groundwater over expensive distilled water, and distilled water was only used by the island's ice and lemonade industries and the harbour (Rijksbureau voor Drinkwatervoorziening, 1937; Van Soest, 1977).

Periods of drought soon challenged the island's drinking water production. Seawater distillation was maximized when governmental wells ran dry during a drought period in 1929 and 1930, and *100* m^3 of groundwater was daily purchased from *CPIM* in the driest periods. The water supply service further subsidized deepening of more and more private wells, which were made accessible to everyone (Van Soest, 1977).

The service's director foresaw future water supply problems and advised a full switch to distillation water. Nevertheless, new investments were made to increase groundwater production. The governmental water supply used 63 wells in 1931, of which 48 were wind-driven and 14 by diesel-engine. A groundwater treatment plant was opened in December 1933 at plantation *Groot Kwartier*. All abstracted groundwater was softened (Calcium removal) and chlorinated (Chlorine addition) here before distribution to the city, allowing the abstraction of lower-quality groundwater. Many Curaçaoans however relied on rainwater harvesting and occasionally purchased groundwater from private sellers (Van Soest, 1977).

The second world war resulted in increased freshwater demands, as oil production increased and U.S. soldiers that were stationed on Curaçao required large amounts of fresh drinking water (Van Soest, 1977). Reports reveal that governmental groundwater production tripled between 1940 and 1945 (Van Soest, 1977; Abtmaier, 1976). In 1944, all governmental wells were pumped dry daily, in a constant cycle of recovery and maximum abstraction (Van Soest, 1977). The dry year of 1945 even marked a record in governmental groundwater abstraction, with *695,000* m^3 against a distillation of *178,000* m^3 (Van Soest, 1977).

Water supply became increasingly challenging and people started complaining about negative side effects of abstraction (Van Meeteren, 1950). The government installed the so-called *water committee (known as the Radulphus committee)* in 1945 to study if and to what extent the groundwater abstraction regime negatively affected Curaçao's groundwater resources (Van Meeteren, 1950). Based on reports of dying orchards *(hofjes)*, all but one committee member agreed that excessive groundwater abstraction had drastically decreased groundwater availability and quality (Landwatervoorzieningsdienst Cura çao 1946). The committee further concluded that over-abstraction and well deepening had induced seawater intrusion and advised to seriously decrease groundwater abstraction, switch to seawater distillation for drinking water production, and invest in modern large-capacity distillation plants (Landwatervoorzieningsdienst Curaçao, 1946; Van Soest, 1977). Moreover, the committee advised to construct dams and create reservoirs in multiple valleys to conserve water.

However, the committee's advises were not taken into account after the reports were handed to the island's government (Van Soest, 1977). A team led by *Professor Krul* was hired to study the island's water supply issues instead. Krul, et al. (1949) agreed with the *Water committee* that groundwater abstraction could have caused declining groundwater levels, but added multiple other possible causes, such as cacti transpiration. *Krul* concluded that groundwater production could be maintained, water distillation was only necessary to cope with growing water demands.

Nevertheless, drastic declines in well yields between 1946 and 1949 forced the government to reconsider the island's water supply system. Water distillation occurred at maximum capacity and *CPIM* supplied the government with additional groundwater and imported fresh water (Van Soest, 1977). The government also used water from *Hato spring* and even doubled the water prices to secure water supplies. After these dry years, the government decreased its' groundwater dependence and increased distillation capacity. The seawater distillation plant at the *Penstraat* was expanded, and a new plant at *Mundo Nobo* was completed in 1950. Distilled water soon represented *80%* of the governmental water production. All governmental groundwater production was suspended in 1962, 11 years before *Shell* followed (Van Soest, 1977).

No data were available on the comparison between governmental abstraction and natural recharge volumes. Reported abstraction rates were lower or comparable to the refinery's. It can thus be assumed that Curaçao's governmental water production was the same order of magnitude as estimated groundwater recharge volumes.

Hydrogeological conditions

Quantitative hydrogeological data are available from the twentieth century, although the first collection of data remains anecdotal. The first published quantitative groundwater quality data were obtained by military farmaceutist *Buys* (Havelaar, 1903). A chlorine content of 514 mg/l was measured in a certain well in February 1893. When the measurements were repeated seven years later in the same well (February 1900), chlorine contents had increased to 950, 1170 and 1250 mg/l. The increase in chlorine content was assigned to solute uptake in the subsurface and to saltwater intrusion. Havelaar (1903) predicted that wells prone to salt water intrusion could deteriorate quickly, especially in areas with large well concentrations. The note that wells at plantation *Asiento* yielded high-quality drinking water in 1915 forms another interesting piece of information (Van Soest, 1977).

Molengraaff (1929) conducted the first systematic hydrogeological study on the island. Analysis of groundwater samples revealed large variability in groundwater chloride content and hardness between and within geological formations. Zones of relatively low chloride contents below *200* mg/l were distinguished (recalculated to an EC of *1,675* $\mu S/cm$). The individual well data were not published, but it can be observed that the areas with the densest network of (windmill-equipped) wells on the *Werbata maps* lie outside of the isochloride zones (Fig. 11). Especially in the area east of *Schottegat*, a dense cover of windmill-equipped wells borders *Molengraaff's* isochloride zone.

More groundwater chloride content data is available from 1937, when the government studied opportunities to improve drinking water supply on Curaçao (Rijksbureau voor Drinkwatervoorziening, 1937). The 1937 data (recalculated to EC) (Fig. 12) show no major shifts from *Molengraaff's* isochloride zones (EC of 1,675 $\mu S/cm$) (Molengraaff, 1929). The data do reveal parts of the situation outside of the zones: Chloride contents between 200 and 840 mg/l were reported close to the *Schottegat* shoreline (EC of 1,675 to 3,200 $\mu S/cm$).

The first available groundwater level data date from 1939 (Fig. 12) (Krul, et al., 1949). No groundwater levels below sea level were reported at that time, but relatively low groundwater levels were documented in three areas around *Schottegat*, which are partly associated with groundwater abstraction from active *water plantations* at the time.

Groundwater chloride data from 1948 (Krul, et al., 1949) reveal an increase in salinity for multiple wells compared to *Molengraaff's* isochloride zones and the 1937 data (Fig. 12). In 1948, groundwater chloride content within active abstraction sites around *Schottegat* seems to be substantially higher than elsewhere, with EC values exceeding *10,000* $\mu S/cm$ in *water plantations* around *Schottegat*. Groundwater level data of the same measurement campaign in 1948 reveal a similar pattern, with groundwater levels of several metres below sea level in *water plantations* (12). The 1948 data even represent the lowest groundwater levels and highest electrical conductivity values that have been reported for Curaçao, only a few years after groundwater production peaked during WWII (Roos, 1961; Van Soest, 1977).

Grontmij and Sogreah (1968) published more groundwater level and EC data from their field campaign in 1966 and 1967. The sparse dataset reveals relatively low groundwater EC values, compared to the 1948 data (Fig. 12). Groundwater levels around *Schottegat* seem to have slightly recovered to levels above sea level, except for an area in the map's South-Western corner (between *St. Michiel's bay* and *Piscadera bay*) where groundwater levels had dropped below sea level. It is interesting to note that the vast majority of Shell's abstraction occurred in this area at the time, at *water plantations Sint michiel* and *Groot Piscadera* (Abtmaier, 1976; Grontmij and Sogreah, 1968).

Figure 5 depicts a simplified visualization of the presumed groundwater conditions during the period of industrialization between 1900 and 1960. Overall, groundwater chloride content and EC seem to have increased consistently at or near active *water plantations*. Groundwater levels have dropped at the same *water plantation* sites, reaching levels below sea level in 1948 and 1966. Simultaneous increasing groundwater salinity and dropping groundwater levels imply an effect of salt water intrusion towards the abstraction sites.

Land cover and human activity in recent time (1960–2020)

The 1960s marked the gradual end of the oil industry's dominant position in Curaçao's economy (Van Soest, 1977). This soon initiated rising unemployment levels on the island, stressing the need for economical transitions. The government invested in hotels, museums and infrastructure to boost tourism and made renewed investments in agriculture and fishery. Agriculture has not become a major economical driver anymore, which can partly be explained by the successful economical transition to tourism.

Groundwater abstraction and seawater desalination. The government had stopped groundwater abstraction in 1962, Shell followed in 1973. Nevertheless, groundwater abstraction continued for other industrial purposes, horticulture and domestic use (Abtmaier, 1976). Exact yearly abstraction rates are unknown, but a number of estimates have been made. Yearly repeated water balance calculations revealed that most urban areas on Curaçao experienced excessive pumping Abtmaier (1976); Winkel (1981). Abstraction for (smaller) industries, horticulture and domestic use had grown to substantial volumes, with an estimate of *4,000* wells in 1979 (Abtmaier, 1976; Winkel, 1981). The absence of regulations on groundwater abstraction allowed the number of wells to increase continuously (Winkel, 1981). A total number of *5,040* wells were reported in 2001, of which *3,846* were equipped with an electric pump and *1,194* with a windmill (CBS Curaçao, 2021). The total number of wells had grown to *7,835* in 2011: An increase of 2,795 *(55%)* in ten years. *5,719* Of these wells were equipped with electrical pumps *(+1,873)*, against *1,134* windmill-driven wells *(−60)* (CBS Curaçao, 2021). No more recent data on the number of active wells are available, but it can be assumed that the number has grown since 2011.

The government's decision to stop using groundwater in 1962 caused a drastic switch in the island's drinking water supply from groundwater abstraction to seawater desalination. The few data that are available reveal a steady increase in desalinated freshwater production in time. Yearly production ranged between *4,700* and *75,000* m^3 in the 1930s, when desalination purely served as a backup water supply (Rijksbureau voor Drinkwatervoorziening, 1937; Van Soest, 1977). Production had increased to a yearly *7.3 million* m^3 in 1975 (*20,000* m^3/d), of which *30%* was used for industrial purposes and the rest for domestic use (Abtmaier, 1976). Louws et al. (1997) reported a daily freshwater production of *33,000* m^3 for 1997, amounting to a yearly production of over *12 million* m^3. The most recent data reveal a yearly water production between *14* and *15 million* m^3 since 2010 (CBS Curaçao, 2021).

Part of the desalinated water enters the hydrogeological system as additional recharge through domestic cesspits, irrigation and leaks in the water distribution or sewage networks (Louws, et al.,

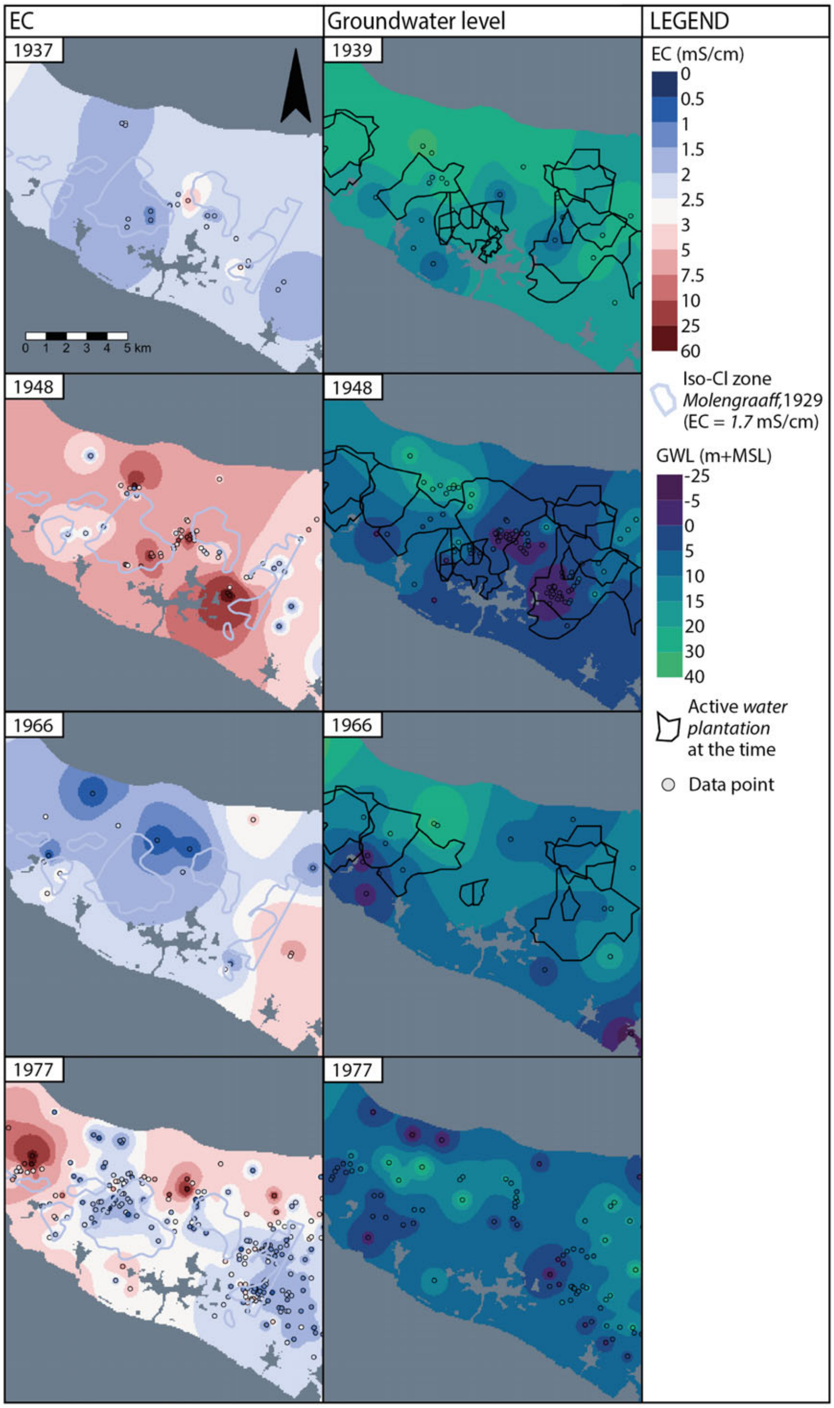


Figure 12. Yearly mean groundwater EC and level data for 1937/1939, 1948, 1966 and 1977. Zoomed-in on the area around *Schottegat* bay. Isochloride zones by Molengraaff (1929) and locations of active *water plantations* (Henriquez, 1962; Renkema, 1981) are displayed for reference. Point data are collected from various reports and spatially interpolated using *Inverse distance weighting (IDW)* (Molengraaff, 1929; (Krul, et al., 1949; Grontmij and Sogreah, 1968; Abtmaier, 1976).

1997). Indeed, (treated) waste water is commonly used to irrigate gardens, horticultural sites and golf courses (CBS Curaçao, 2021; Commissie Integraal Watermanagement Cura çao 2016). An estimated volume of *one million* m^3 of domestic waste water yearly infiltrated under *Willemstad* in 1992, which is the equivalent of a yearly recharge rate of *17* mm rainwater over the city's surface area (60 km^2) (Louws, et al., 1997). With an average annual recharge rate of *20* mm for Curaçao (Grontmij and Sogreah, 1968), the additional recharge would have equalled 1992's natural recharge in *Willemstad*.

Hydrogeological conditions

Abtmaier (1976) conducted 750 EC and groundwater level measurements at a large number of wells in 1976 and 1977. Repeated measurements revealed that groundwater EC did not increase during dry periods, but rose substantially (*30* to *50*%) in heavily pumped areas, indicating abstraction-induced salt water intrusion (Abtmaier, 1976).

The 1977 data in Fig. 12 display substantial spatial variation in both EC and groundwater level, compared to earlier years. Abtmaier (1976) attributed part of this variation to differences between geological formations. Groundwater EC remained below *2,000 μS/cm* in the Curaçao Lava Formation, but increased in direction of the coastline and other formations. Higher EC values were found in the less permeable Knip Group and Midden Curaçao Formation. EC was especially high on the Quaternary limestone deposits for wells that penetrated the underlying clay layer, which separates the relatively fresh limestone aquifer from more saline groundwater below (Abtmaier, 1976).

Rowbottom and Winkel (1979) continued the groundwater monitoring campaign in 1979. Depth profiles of electrical conductivity were obtained in 45 wells, in addition to groundwater level and EC measurements at the water surface. The EC-depth profiles revealed strong indications for salt water intrusion in multiple wells near the coastline (Winkel, 1981; Rowbottom and Winkel, 1979). Sea spray and irrigation were mentioned as other factors contributing to high groundwater chloride contents, while infiltration of sewage water through cesspits was observed to decrease salinity in densely populated areas (Henriquez, 1962; Rowbottom and Winkel, 1979).

The government initiated a groundwater monitoring campaign in 1980, in response to the indications for saltwater intrusion that were reported in the 1970s (Louws, et al., 1997; Van Sambeek, et al., 2000). Groundwater level and EC were monitored in around 100 wells in a one- to three-monthly interval (Louws, et al., 1997). The monitoring campaign was continued until 2009, with inconsistent spatial and temporal resolution. Either rising or decreasing trends in EC were observed in certain wells, but EC has been more or less stable in most areas.

The development in groundwater salinity between 1977 and 1992 was analysed by comparing chloride contents of 97 groundwater samples from 1991–1992 to the 1976–1977 data (Abtmaier, 1976; Louws, et al., 1997). Chloride content in 25% of the sampled wells had not substantially changed since 1978 (Louws, et al., 1997). An increase in chloride content of over 25% was observed in 30% of the well locations, predominantly in areas with high groundwater abstraction for horticulture and private garden irrigation. 45% Of the measured wells had experienced an over 25% decrease in chloride content. This substantial freshening in almost half of the sampled wells was attributed to a combination of decreased abstraction rates and increased recharge through waste water infiltration . High measured groundwater nitrate concentrations in urban areas indeed underlined the importance of waste water infiltration in areas with leaking cesspits.

The hydrogeological importance of waste water infiltration from leaking cesspits was further confirmed by Van Sambeek, et al. (2000), who measured groundwater EC, pH and temperature in 96 wells on Curaçao. Obtained salinity data indicated a freshening effect of infiltrating waste water in Curaçao's (sub) urban areas (Van Sambeek, et al., 2000). Groundwater freshening was further supported by measured enrichment of sodium over chloride in relatively fresh groundwater *(Cl <300 mg/l)* (Van Sambeek, et al., 2000), and high nitrate concentrations in multiple wells.

A similar image arises from the difference in interpolated mean annual groundwater EC and groundwater level, between 1977 and 2007 (Dienst Landbouw Veeteelt en Visserij Curaçao (LVV), 2010) (Fig. 13). These data confirm the earlier reported spatial variability in the island's groundwater conditions(e.g. Abtmaier, 1976; Louws, et al., 1997; Van Sambeek, Eggenkamp, and Vissers, 2000). Freshening was observed in certain areas, while groundwater salinity has increased elsewhere. The data display both drops and rises in groundwater levels.

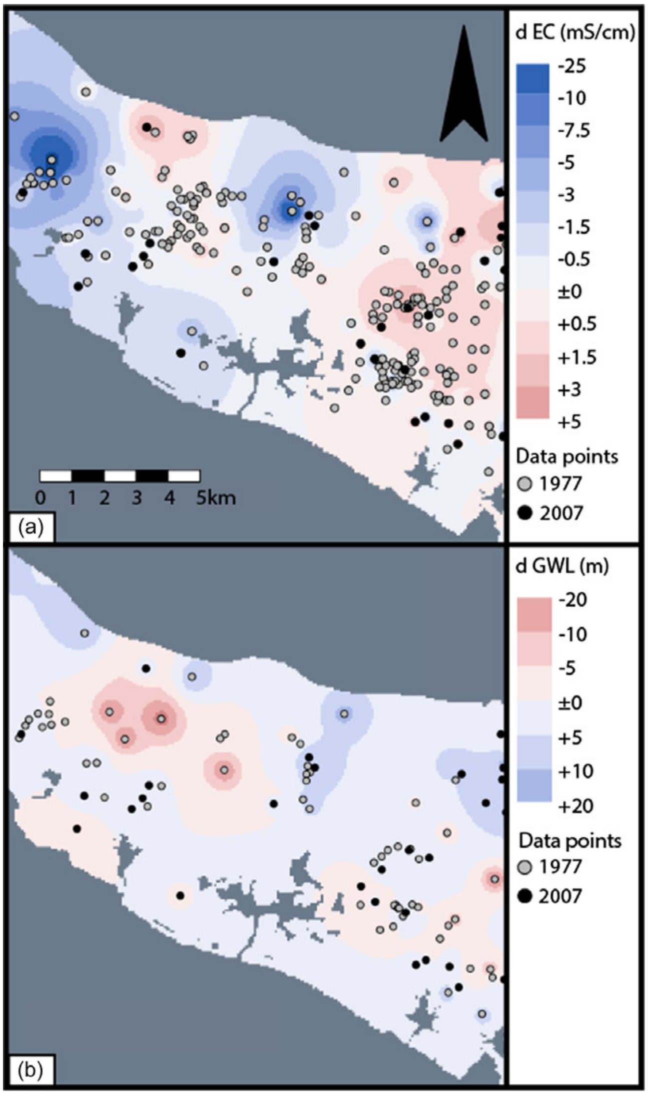


Figure 13. a. Difference in IDW-interpolated groundwater electrical conductivity between 1977 and 2007; b. Difference in IDW-interpolated groundwater level between 1977 and 2007. (Abtmaier, 1976; Dienst Landbouw Veeteelt en Visserij Curaçao (LVV), 2010).

Additional recharge from infiltrating waste water thus comprises a major addition to local groundwater balances. Losses through evaporation are known to seriously limit groundwater replenishment on semi-arid Curaçao, illustrated by an estimated recharge percentage of only *4%* of yearly precipitation (22.4 mm for a mean annual precipitation of 561 mm) (Grontmij and Sogreah, 1968; Abtmaier, 1976). In contrast, evaporation losses are limited from leaky water distribution lines, sewage systems and cesspits, which could serve as focused recharge zones. Small volumes of waste water could therefore substantially contribute to the groundwater balance.

Quantification and localization of these additional inputs is required to create realistic groundwater balances. Reliable quantification would require data and insights that fall beyond this study's focus, but an estimate based on available data and expert's assumptions was made.

Table 2 summarizes the calculated hypothetical recharge fluxes from four distinct sources, detailed calculations are provided below. The calculations show that additional groundwater

Table 2. Calculated hypothetical recharge fluxes from four identified sources, detailed calculations in text

Volume unit	Precipitation	Distribution pipes	Cesspits	Irrigation
$10^6 m^3$	5	2	5	1.88
mm	22	16.9	32	14.4
Rainfall %	3.7	2.8	5.3	2.4

recharge from distribution pipes and cesspits may exceed natural recharge in urban areas. Irrigation of horticultural sites, gardens and golf courses with (semi-)treated wastewater was found to locally add substantial recharge fluxes to the system.

A conceptual overview of the island's hydrogeological conditions from 1960 to present is depicted in Fig 5.

Additional recharge calculations. A water production of *15.2 million m^3* was reported for Curaçao over 018 (CBS Curaçao, 2021). Part of this water is expected to have ended up in the groundwater system through leaky water distribution pipes, sewage pipes, cesspits, septic tanks, irrigation and other routes. 13.5% Of all produced water was lost through leaky distribution pipes in 1989 (CBS Cura çao 2021). This percentage would lead to a recharge volume of *two million m^3* in 2018. Averaged over the *118 km^2* of urban areas on Curaçao (in 2015), this volume would equal *16.9* mm of water (World Bank Group, 2015).

We assume that the vast majority of the remaining *13 million m^3* of desalinated water is used and discharged in the island's urban areas. In 2011, *42,375* households discharged their waste water through cesspits (CBS Cura çao 2021). This equalled *77.1%* of all Curaçaoan households that thus together receive *10 million m^3* of water per year (*77.1% of 13 million m^3*). Most of these households are located in areas that are not connected to a sewage system, which comprised *67%* of the island's urban areas in 2018 (*79 km^2*) (CBS Curaçao, 2021). Hypothetically, *50%* of all desalinated water used within these areas ends up in cesspits, which amounts to a yearly total volume of *5 million m^3*. Assuming a recharge percentage of *50%* from cesspits, we hypothesize an additional recharge volume from domestic cesspits of *2.5 million m^3* or *32* mm of desalinated water over a surface area of *79 km^2*.

Additionally, desalinated water enters the system through irrigation with treated waste water at (hotel) gardens, horticultural sites and golf courts. Around *16%* of all waste water was treated in 2017, which amounts to *1.88 million m^3* (CBS Curaçao, 2021). The discharge area of this water is limited to certain horticultural sites, golf courts and gardens, which we assume do not exceed *3%* of the island's surface area (*13 km^2*). Assuming a recharge rate of *10%* in these areas (water conservative irrigation schemes are in place), an annual recharge of *0.19 million m^3* or *14.4* mm can be expected over an area 13 *km^2*.

597 mm of precipitation was recorded at *Hato airport* in 2018 (Meteorological Department Curaçao, 2024). Assuming a recharge percentage of *3.7%* on the *Curaçao Lava Formation* (Abtmaier, 1976), *22* mm rainwater replenished Curaçao's basaltic aquifers that year, or a total volume of *5 million m^3* over *226 km^2*.

Discussion

Uncertainty related to the variation in data sources

Only qualitative descriptions and maps could be used to characterize Curaçao's hydrogeological conditions before the first quantitative measurements in 1903 (Havelaar, 1903). A number of cited publications directly refer to groundwater-related aspects (e.g. wells on maps, descriptions of water quality), but more indirectly describe the island's hydrogeology (e.g. archaeological data, descriptions of forest cover and dying orchards).

Applied hydrogeological interpretations of archaeological findings rely on the geographical relation between archaeological sites and hydrological resources on Curaçao. Multiple scholars reasoned that the Caqueto must have dug shallow wells for drinking water supply, based on the great distance between continuous springs and settlement locations (e.g. Haviser, 1987; Debrot, 2004a; Loen, 2021). This is the most reasonable scenario and was assumed for this study. Alternatively, shallower groundwater levels may have prevailed in Pre-Columbian times, as a result of the relatively dense forest cover and absence of groundwater abstraction. This could have been accompanied by a higher number of continuous freshwater springs that may have served as a sufficient water supply (Terpstra, 1948). Spring amount and discharge indeed increase during wet periods on the island (Molengraaff, 1929).

Cited historical reports introduce uncertainty related to the quality of the observer and documentation. A number of observations could be validated with notes on other islands nearby or with environmental proxies. For example, relatively dense forest covers of *Brazil wood (Haematoxylum brasiletto)* and *Pockwood (Guaiacum officinale)* were also reported on the neighbouring islands of *Bonaire* and *Aruba* (Fig. 1) in early post-Columbian times (De Laet, 1625; Amelunxen, 1929; Derix, 2016). Sediment cores from both Curaçao and Aruba indicate deforestation and enhanced erosion after European settlement (Klosowska et al., 2004; Nooren, 2014). However, extensive comparison of hydrogeological insights to reports from nearby islands did not fit the scope of this study.

Localization of specific observations was challenged by the quality of historic maps. The oldest maps reveal difficulties in topographical mapping at the time, illustrated by flawed island outlines (Figs. 7, 8 and 9). Specific locations could however still be obtained with good certainty, using displayed place names and landscape features.

The availability of quantitative data after 1903 introduced sources of uncertainty related to data quality, data type and varying spatial and temporal resolutions. A bias towards regularly monitored locations was especially pronounced during periods of data scarcity. For example, no or limited data were available for areas with high reported abstraction activities in around 1966 (Fig. 12).

A bias related to varying spatial resolutions in time may be avoided by the analysis of continuous time series for specific wells. The variation in well coding systems and poor map spatial quality however did not allow the identification of continuously monitored well locations between studies. This was allowed after 1976, as Abtmaier (1976) introduced a well coding system that has been in use since (Winkel, 1981; Dienst Landbouw Veeteelt en Visserij Curaçao (LVV), 2010).

The available data points for each period in time are assumed to reflect the prevailing hydrogeological conditions on Curaçao, allowing the comparison of hydrogeological data between studies with different well coding systems. However, certain blind spots at specific areas and moments in time could not be avoided.

A second bias in the interpretation of quantitative data was related to the low and irregular temporal resolution. Abtmaier (1976) argued that Grontmij and Sogreah (1968) conducted their fieldwork during an extraordinary wet period and their findings would therefore not be representative. More short-term field surveys by visiting groundwater experts were cited in this study (Molengraaff, 1929; Rijksbureau voor Drinkwatervoorziening, 1937; Krul, et al., 1949; Louws, et al., 1997). Issues related to short-term field surveys may be addressed by comparison to long-term climatic records, but this did not fit this study's scope. Seasonal and inter-annual climate variation impacts on the groundwater system were assumed to be negligible in this long-term study, since the observed temporal variation in salinity and groundwater levels exceeds variations that may be expected from short-term climate variability (Abtmaier, 1976). Available precipitation records did not contain trends that would explain the observed groundwater salinity variations. The notion that most substantial declines in groundwater level and rises in salinity were observed in regions with groundwater abstraction forms another indication that not climatic factors but human activities most significantly impacted the island's groundwater system (Fig. 12).

Implications for hydrogeological processes

Historical changes in Curaçao's hydrogeological conditions have impacted hydrogeological processes that characterize the island's groundwater system.

Seawater intrusion

Historical reports and maps provide qualitative evidence for seawater intrusion in Curaçao's subsurface. Drinking water wells were mapped near the coastline in early maps (Figs. 7, 8 and 9) (Euwens, 1929; Van Keulen, 1728), but later landward relocation of *water plantations* implies deterioration of groundwater quality through salt water intrusion from these coastal wells (Van Meeteren, 1945). This image is supported by reports of dying orchards in the vicinity of abstraction sites (Landwatervoorzieningsdienst Curaçao, 1946; Van Meeteren, 1950; Henriquez, 1962).

Quantitative data from after the introduction of windmill-powered wells (1890) and the settling of the oil industry (1916) revealed substantial rises in groundwater salinity and dropping groundwater levels near the growing number of abstraction sites (*water plantations*) (Fig. 12) (e.g. Havelaar, 1903; Krul, et al., 1949; Grontmij and Sogreah, 1968). These data leave limited possibility for fresh drinking water quality from shallow wells near the *Schottegat* coastline in the course of the 20th century, again suggesting strong effects of seawater intrusion as a result of abstraction.

Seawater intrusion in response to (excessive) groundwater abstraction follows from the *Ghijben-Herzberg* freshwater lens relation, which describes that islands (in sea) feature a fresh groundwater lens that 'floats' on top of the underlying saline groundwater body. In absence of abstraction, the freshwater lens volume is governed by an equilibrium between the two water types, defined by buoyancy forces, freshwater-seawater mixing, geology and temporal variations in groundwater recharge (Ritzi et al., 2001; Post et al., 2019). Freshwater abstraction reduces the lens volume towards a new equilibrium, reflecting both natural and human impacts. Transition to a new equilibrium may take decades for small islands (Post et al., 2018), and may take even longer in low permeability semi-arid settings, such as Curaçao. Low recharge rates in semi-arid areas delay equilibrium conditions and may result in long lens recovery times after abstraction is ceased or reduced. Relatively small fresh groundwater storage volumes and historically limited alternative water sources commonly render small island states extra vulnerable for abstraction-induced intrusion, exactly the conditions on Curaçao in the early 1900s.

Curaçao's weathered- and fractured-rock geology may partly explain the observed spatial heterogeneity in intrusion effects, indicated by major differences in groundwater salinity and level between and within abstraction sites (e.g. Abtmaier, 1976; Roos, 1961; Grontmij and Sogreah, 1968). Intrusion in karstic and fractured aquifers is highly impacted by hydrogeological anisotropy (Costall et al., 2020), which is often reflected by large spatial heterogeneity in freshwater lens thickness (Giese and Barthel, 2021). Subsurface fractures and weathered zones may serve as conduits for groundwater recharge and flow (Giese and Barthel, 2021). Observed spatial variation in weathering degree and fracture density could thus induce spatial variation in freshwater lens thickness and susceptibility to seawater intrusion on the island (Abtmaier, 1976; Grontmij and Sogreah, 1968).

Fresh groundwater lenses generally grow thicker towards an island's centre. Abstraction-induced seawater intrusion will thus earlier affect wells along or near the coastline. Early abstraction activities concentrated near the coastline of Curaçao, where potable groundwater was accessible at shallow depths (Figs. 7, 8 and 9) (Euwens, 1929; Van Keulen, 1728). *Water plantations* were later relocated more inland, aided by the innovation in bores that allowed deeper well construction (Van Meeteren, 1950). The more inland location of abstraction sites may partly explain why first impacts of salt water intrusion were related to dying orchards near the coastline (Henriquez, 1962; Landwatervoorzieningsdienst Curaçao, 1946). Inland abstraction caused lens contraction across the subsurface. Most orchards *(hofjes)* were located near the island's shores, where trees could reach fresh groundwater at shallow depths (Krul, et al., 1949; Henriquez, 1962). The relatively shallow freshwater lens at the coastline makes that coastal orchards were first affected by intrusion effects, as a result of more inland abstraction activity. In retrospect, applied salinity limits for sustainable groundwater abstraction (Roos, 1961) could not prevent intrusion impacts near the coastline, as intruding salt water must have reached the coastline long before salinity limits were reached at the *water plantations*.

Multiple alternative or complementary explanations have been mentioned for the gradual salinization of Curaçao's groundwater, apart from salt water intrusion (Molengraaff, 1929; Abtmaier, 1976). One explanation refers to connate salts in the island's subsurface, that were trapped when parts of the island were submerged (Molengraaff, 1929). Molengraaff (1929) argues that these connate salts cause saline and brackish groundwater conditions in the *Knip Group* and *Midden Curaçao Formation* today, but have been flushed out of the more permeable formations.

Seaspray may be another cause of groundwater salinization, which could explain (part of) the observed patterns in groundwater salinity. Infiltrating rainwater on the nearby island of *Bonaire* (hydrogeologically and climatologically comparable to Curaçao) may attain electrical conductivity values of 2,000 µS/cm by seaspray and evapotranspiration effects (Borst and de Haas, 2005). This could indeed cause groundwater salinization, but the constant nature of seaspray does not align with the observed temporal variations in groundwater salinity on Curaçao.

Last, land cover changes may have substantially contributed to the observed variations in groundwater salinity. The first centuries of European colonization were characterized by the introduction of cattle, deforestation and plantation agriculture (Renkema, 1981).

Sediment core data suggest that these activities resulted in increased surface runoff and soil erosion, and a decrease in groundwater recharge (Klosowska et al., 2004). Decreased recharge may have caused drops in groundwater level and increases in salinity. Furthermore, urbanization and industrialization have caused increased surface sealing during the past century, minimizing groundwater recharge (Van Soest, 1977). Although this may have resulted in increased salinity levels, surface sealing effects are possibly compensated by additional groundwater recharge from drinking water distribution pipes, cesspits and irrigation.

Artificial groundwater recharge

Groundwater freshening by artificial recharge represents a recent addition to the island's groundwater balance. The production of desalinated water has increased continuously since Curaçao's drinking water supply switched to seawater desalination in 1962. Multiple studies revealed that the additional recharge by desalinated water represents a substantial contribution to the island's groundwater balance (Henriquez, 1962; Louws, et al., 1997; Van Sambeek, et al., 2000). Calculations show that the desalinated water volume that yearly enters the island's groundwater system locally matches or even exceeds natural recharge in years with average precipitation (Tab. 2) (Louws, et al., 1997). Relative contributions of additional recharge could even increase in dry years, when natural recharge is lower.

Leaking sewage systems are known to impact coastal water balances and nutrient fluxes, and intensify environmental pressures on reef ecosystems (e.g. Costa et al., 2000; Dadhich et al., 2017; Gibson, et al., 2020). For example, rapid groundwater transport in a porous limestone aquifer in Florida allowed waste water from cesspits to reach the *Florida keys marine ecosystem* within a day (Darden, 2001). Substantial additional recharge through cesspits and waste water irrigation can be expected to enhance seaward groundwater and nutrient fluxes on Curaçao, too (Louws, et al., 1997; Van Sambeek, et al., 2000).

Calculations of additional recharge (Table 2) rely on assumptions and are thus uncertain. No data exist on water volumes that end up in cesspits, and the volumes, timing and locations of irrigation with treated waste water are unknown. Recharge calculations are further limited by uncertain estimates of natural and additional recharge percentages. A recharge percentage of *3.7%* of precipitation was used, but this number is based on a limited dataset without accounting for preferential flowpaths (Abtmaier, 1976). Recharge rates from cesspits are determined by local factors as soil infiltration capacity and groundwater level, and can thus not be assumed with good certainty. Similarly, recharge rates of irrigated plots depend on irrigation strategies and crop characteristics that were not considered in this study. Last, the surface areas that were used to calculate rainfall equivalents of additional recharge fluxes are based on general statistics and assumptions, and may not represent actual conditions.

Submarine groundwater discharge fluxes

Seaward fluxes of nutrients and pollutants can negatively impact seawater quality (Santos et al., 2021; Moore, 2010). The described developments of Curaçao's groundwater system suggest temporal and spatial variations in the volumes and nutrient loads of seaward groundwater fluxes.

Enhanced surface runoff rates and minor drops in groundwater levels may have caused slight drops in submarine groundwater discharge and locally enhanced surface runoff and sediment inputs in the first centuries after colonization (Klosowska et al., 2004). Introduction of cattle farming and plantations after 1500 may have caused increased nutrient loads to sea, although limited by the extensive nature of these activities.

Groundwater abstraction from the first *water plantations* along the island's shores may have locally reduced submarine groundwater discharge by capturing seaward-flowing groundwater (Krul, et al., 1949; Abtmaier, 1976). Continuous increases in abstraction between 1560 and 1890 are expected to have enlarged this effect. However, the major intensification of groundwater abstraction following the introduction of windmill-powered wells and the settling of the oil industry hypothetically decreased submarine groundwater discharge fluxes on a much larger scale. Observed drops in groundwater level and rises in salinity suggest large decreases in fresh groundwater storage in the areas where most groundwater was abstracted. This suggests that the freshwater lens shrunk drastically in those areas, resulting in decreased submarine groundwater discharge. In contrast, seawater intrusion effects suggest that groundwater flows had reversed landward. The largest nutrient inputs from cesspits can be expected from residential areas near the abstraction sites. Reversed groundwater fluxes may have prevented seaward transport of these nutrients at the time, which may have accumulated in the subsurface of urban areas.

Seaward groundwater and nutrient transport through submarine groundwater discharge expectedly increased after abstraction for drinking water and industry ceased and completely switched to seawater desalination in 1973, although pumping volumes from domestic wells remain unclear (Abtmaier, 1976; CBS Curaçao, 2021). Observed groundwater freshening and eutrophication in and around *Willemstad* confirm the contribution of additional recharge from cesspits and pipe leaks to the groundwater system (Louws, et al., 1997; Van Sambeek, et al., 2000), suggesting enhanced submarine groundwater discharge below the city. These urban areas were earlier suggested to host accumulations of nutrients and pollutants, as a result of excessive pumping. Hypothetically, additional recharge in those areas may lead to *flushing* of those accumulations, enhancing seaward transport of nutrients and pollutants through submarine groundwater discharge.

Conclusions

The development of Curaçao's groundwater system has been characterized by analysing a diverse collection of hydrogeological data and insights. Seawater intrusion, artificial groundwater recharge and submarine groundwater discharge were identified as major hydrogeological processes that shape the island's hydrogeological system. Both qualitative and quantitative data revealed that the fractured-rock hydrogeology of the semi-arid island was substantially affected by a sequence of anthropogenic activities in the past. The identified processes and causes continue to this day, and the island's hydrogeological state may be expected to keep changing into the future.

Using historical data and insights proved useful for the hydrogeological characterization of a small data-scarce island setting. The obtained insights on the development of the hydrogeological system in response to anthropogenic stressors would not have been observed from the separate studies alone, due to their limited temporal and spatial resolution. However, valuable information was unlocked by the combination of studies.

Major hydrogeological processes were characterized from the combination of insights. The temporal variations in groundwater recharge, seawater intrusion and submarine groundwater discharge that were observed could not have been disseminated from contemporary measurements alone. The data analysis suggested that a period of seawater intrusion was locally followed by enhanced submarine groundwater discharge, possibly *'flushing'* accumulated nutrients and other contaminants. Understanding this temporal variability may be essential to quantify seaward groundwater fluxes and nutrient loads in time and possibly explains part of recently observed patterns in marine ecosystem decline.

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