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Investigating viable residential uses of old urban wells in Middelburg

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Abstract

This study assesses the feasibility of utilizing well water in historic Middelburg, Zeeland, the Netherlands, as a source of drinking or graywater for residential purposes. Wells are prevalent in century old Middelburg houses when these were dug to access otherwise scarce freshwater. These wells became obsolete as modern amenities made freshwater available in all houses. However, many of these wells remain and some still discharge water, to the extent that it has to be pumped out and wasted. Given the specific challenges faced in this delta, of increasingly dry summers and saltwater intrusion in aquifers, freshwater can become even more scarce and costly. It is essential to explore every potential freshwater source, including this neglected well water. Therefore, seven wells in Middelburg were tested for common water quality parameters over a period of 6 months, including pH, temperature, dissolved oxygen, conductivity, phosphate, lead, copper, and E. coli. The conductivity confirmed the water to be freshwater, pointing to rainwater as a source, which finds its way underground and flows on remnants of sandy tidal creek beds. Dissolved oxygen levels were low in all wells except one. E. coli was not found, but unidentified coliform bacteria were present. All other parameters tested were within a normal range for drinking water. Despite these yet unknown coliform bacteria, the water in some of the wells is still useable as graywater. As most of the water is now pumped out, the residents can use the results of this study to find useful applications for their water as water stress in the area is increasing. By investigating new freshwater sources, this study contributes to the ongoing search for solutions to mitigate the ever-growing pressures on global freshwater resources.

Introduction

Freshwater is a critical natural resource. It is considered to be one of the planetary boundaries that are crucial for maintaining a stable and resilient earth system; exceeding these boundaries will cause environmental and anthropogenic harm (Steffen et al., 2015). Richardson et al. (2023) conclude that freshwater has surpassed its planetary boundary, indicating a threat to the current functioning of the environment and human society. Although domestic water consumption for drinking and sanitation is relatively low, many other sectors rely heavily on freshwater, especially agriculture, industry, and hydropower generation (Wallace, 2000; Schewe et al., 2013). Sufficient freshwater supply is crucial for these sectors, and many countries already face limitations due to scarcity (Rijsberman, 2006) or diminished water quality (Du Plessis, 2022). The situation is expected to worsen with population growth, economic development, water pollution, and climate change, placing even greater demands on this finite resource (Arnell, 2004; Alcamo et al., 2007). Therefore, freshwater sources are becoming even more important. Groundwater is the third largest reservoir of water on earth (Kundzewicz & Doell, 2009) and the largest available liquid reservoir of freshwater (Lall et al., 2020). The Netherlands, in particular, is facing freshwater scarcity, diminishing water quality and an increase in water consumption (van Oel et al., 2009; van Berkel et al., 2022). Nearly one third of the Netherlands lies below mean sea level, making it particularly vulnerable to flooding, saltwater intrusion, and seepage water, which can threaten current freshwater sources (Oude Essink et al., 2010). Additionally, changes in recharge by meteoric water and evapotranspiration patterns combined with sea-level rise will amplify stress on the groundwater system in coastal areas (Oude Essink et al., 2010). Therefore, the Netherlands must reduce consumption, increase water storage, reuse wastewater, and explore new freshwater sources in order to mitigate the impact of depleting and contaminated freshwater resources.

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However, freshwater availability in the Netherlands is not the only concern. Brouwer et al. (2020) found that 90% of their survey study participants thought Dutch tap water was safe. Despite this, nearly 50% of them also expressed worry about potential contamination of tap water regarding the presence of pharmaceuticals, pesticides, and Per and Polyfluoroalkyl Substances (PFAS), among other contaminants, in surface water bodies. Such perceptions, even if unfounded, can erode public trust in water quality and potentially lead to increased demand for alternative water sources, namely, an increase in groundwater use in place of surface water. Furthermore, nutrient pollution, particularly excess nitrogen, poses a significant threat to water quality and human health. Wiering et al. (2020) and Klages et al. (2020) have highlighted the prevalence of nutrient pollution in Dutch surface waters, which can lead to eutrophication, algal blooms, and the production of harmful substances. These factors underscore the need for a multifaceted approach to water resource management, including the exploration of alternative water sources.

In this study, it was investigated whether well water in houses in the inner-city of Middelburg could contribute at a local scale to alleviating water scarcity. Middelburg is a city in the Netherlands and the capital of the province of Zeeland. Within several residential properties exist wells of unknown water quality, and therefore, the water is currently not used but rather discharged. The aim of the research is to assess the feasibility of utilizing this well water, for graywater or even drinking purposes, depending on its alignment with the Netherlands' stringent drinking water standards. This initiative is especially relevant in Middelburg as most of Zeeland lies below the sea level (Figure 1) and, thus, is at risk of freshwater sources being contaminated by saltwater intrusion, and overall scarcity of freshwater. There are 36 known wells in Middelburg, although it is likely there are many more which are currently unknown. This study focuses on seven wells, distributed throughout the city. Figure 2 shows all known wells, in black, and wells participating in the study, in purple. The primary

goal of this study is to provide an initial indicator of whether this well water could be used for some purpose; however, a secondary goal is to determine the source(s) of the water, to establish how sustainable the use of this water could be.

Sampling sites

There are seven wells tested in this study. These wells were chosen due to the availability of the homeowners to participate and the location of the wells. The wells are spread across the city with Well 1 & 2 and Well 5 & 6 located very close to each other, in order to determine if there are similarities based on location. In Wells 3, 4, 5, and 7, rising water levels cause the water to be pumped out of the well and into the street. Though there are seasonal variations, the amount of water pumped out of wells 3, 5, and 7 is at least a hundred liters each per year. Well 4 sometimes has massive amounts of water flowing out of it, and some weeks almost 20,000 liters must be pumped out into the street gutters. Driven by concerns regarding potential health risks associated with unidentified contaminants, residents are choosing to remove this water through pumping, rather than using it for any purpose. However, this is a waste of water, and such large quantities could be extremely beneficial. This research aims to provide a preliminary insight into whether this well water can be used for drinking purposes. If the water does not meet the requirements laid out in the Drinkwaterbesluit [drinking water decree] (2024), then it will be assessed whether this water could be used as graywater. This graywater could be used for purposes such as watering gardens and plants, flushing toilets, car washing, mopping floors, or even as part of a cooling system in a residence. These could be excellent uses for the well water as these activities do not need the water to meet the strict requirements drinking water requires. If this well water is determined to be safe enough to use for these purposes, it will greatly reduce the amount of drinking water the residents need to use for activities that do not require it and help reduce water stress.

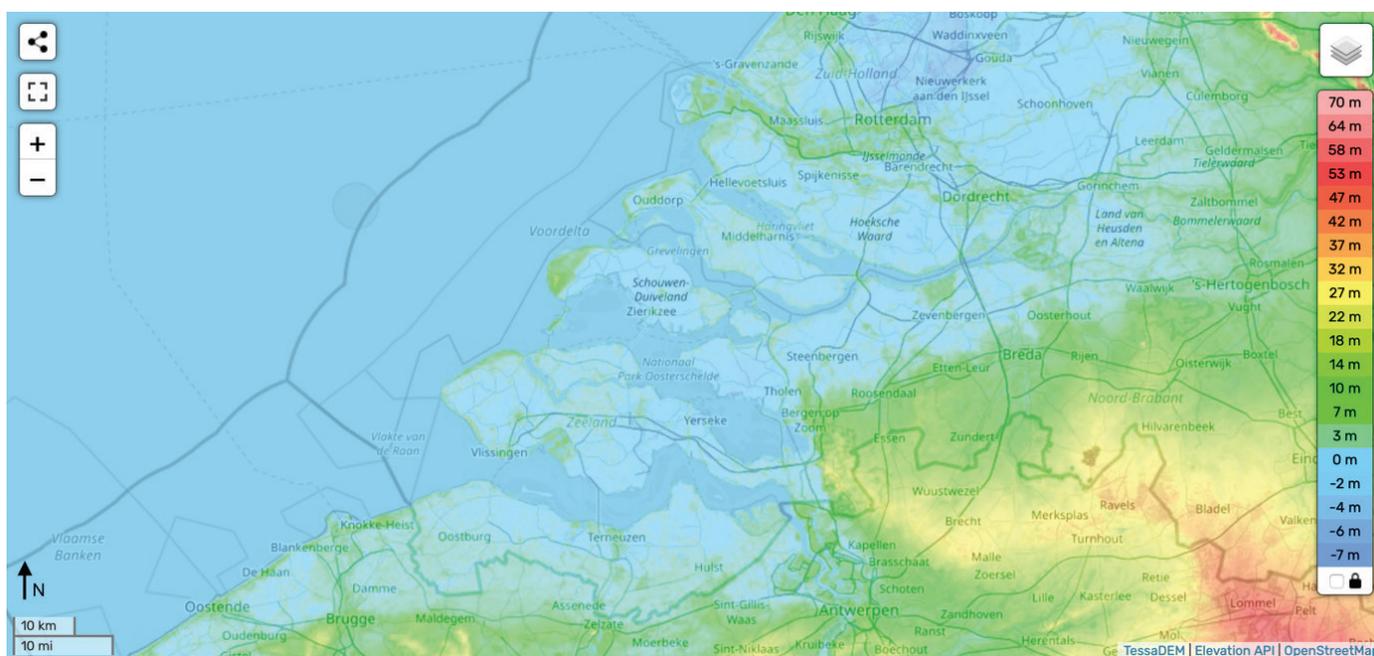


Figure 1. Elevation map of Walcheren (Topographic Maps, 2010).

The characteristics of each well can be seen in Table 1, and a sketch of each well can be seen in Figure 3. In Table 1, the information was provided by the homeowners or by observation during this research unless specified otherwise.

Methods and materials

Seven wells were tested from December 2023 to April 2024. The existence of the wells was revealed by a survey of Middelburg homeowners conducted by a coauthor whose

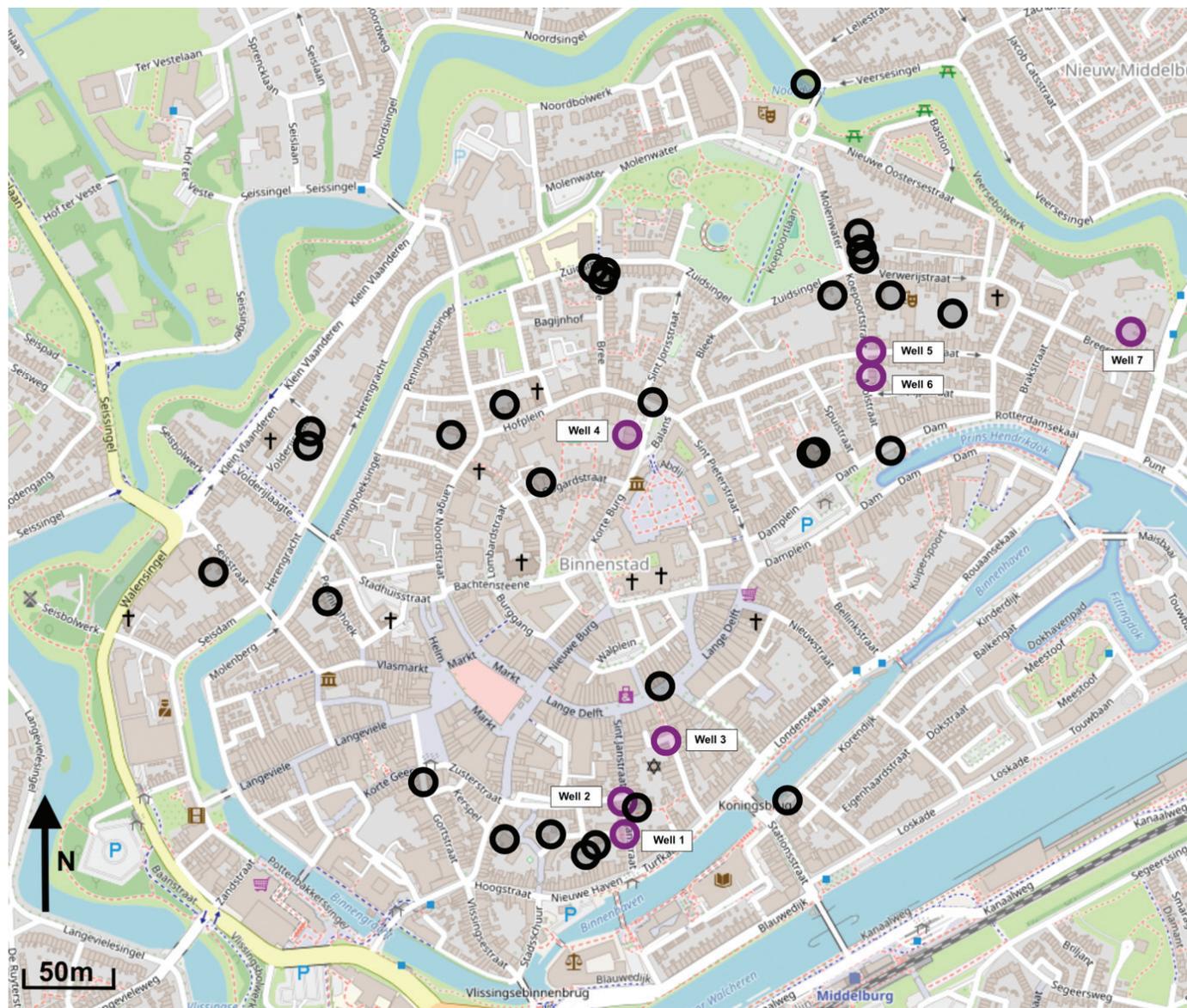


Figure 2. Map of wells in Middelburg (black) and wells in the study (purple). Made using RStudio R Version Elsbeth Geranium Leaflet Package (Cheng et al., 2024).

Table 1. Description of each well in the study

Well number	Location of the well	Date of construction	Water level fluctuation	Depth (m)	Approximate elevation (m above NAP, Gemeente Middelburg)
Well 1	Backyard	Front house built in 1485, back house built in 1610	No change	1.45	3.19
Well 2	Basement (outside)	~1796	No change	1.6	3.19
Well 3	Basement (inside)	1630	Rises with rain	~0.5	3.22
Well 4	Basement (inside)	~1600	Rises sporadically	~1.2	6.14
Well 5	Basement (outside)	~1660	Rises with and without rain	~0.15	1.1
Well 6	Basement (outside)	~1593	No change	0.07	1.1
Well 7	Backyard and basement	~1600	Rises with rain	~0.3	1.4

NAP, Normaal Amsterdams Peil.

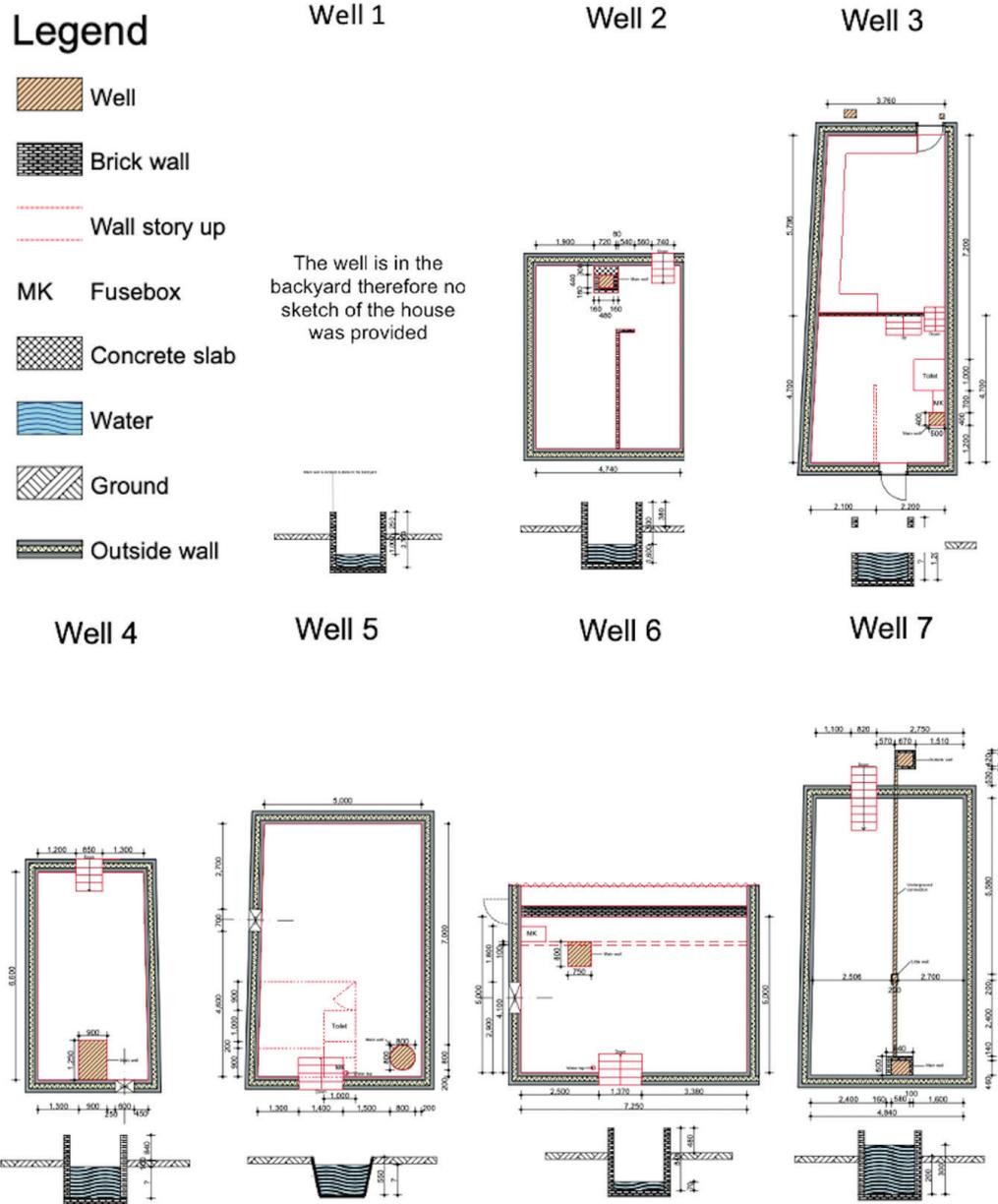


Figure 3. Sketch of each well in the study, created by Chris van Boven.

own well inspired this investigation and is included in this study. Diameter, height, width, and depth of the wells were measured with a measuring tape. A Pancellent™ Borescope for Android underwater camera with Light Emitting Diode (LED) lights was used to explore the interior of the well. Any pipes or other notable features of the well were noted, as well as the approximate amount and composition of sediment. The water in the wells was samples approximately once a month. Water samples were taken in polyurethane bottles. In some of the wells, the water level is too far below ground to be reached, and therefore, when taking samples, the bottles had to be attached to a pole in order to reach the water. pH, DO, conductivity, and temperature were tested on site, and phosphate, copper, lead, and Escherichia (E.) coli were determined in the laboratory as soon as possible after sampling. The method of testing for each parameter is shown in Table 2.

Table 2. Water quality parameters and the method of testing

Parameter	Method of testing
pH	Hicarer™ Universal pH Test Strip 0–14
Phosphate	Colorimetric assay, VWR PV4 Visible Spectrophotometer
Dissolved oxygen	WTW™ Oxi 3205 Dissolved Oxygen (D.O.) meter & Winkler titration
Conductivity	Eutech Instruments Cyberscan Con I I conductivity meter
Temperature	WTW™ Oxi 3205 Dissolved Oxygen (D.O.) meter
E. coli	3M Petrifilm™ Select E. coli Count Plates
Heavy metals	ThermoScientific iCap™ PRO Series ICP-OES

DO, Dissolved Oxygen; ICP-OES, Inductively Coupled Plasma Optical Emission Spectroscopy.

These parameters were chosen for the following reasons. pH was tested to determine if any inputs to the water that drastically changed pH were present, which would generally indicate an issue such as contamination from industrial runoff, decomposition of organic matter or ammonia-rich agricultural runoff. Phosphate was tested to get an indication of whether agricultural runoff full of phosphate-rich fertilizer was seeping into the well water. This is not dangerous for human health but rather would give an indication whether agricultural runoff was capable of seeping into this water. Dissolved oxygen is generally an indicator of ecosystem health as low dissolved oxygen levels cannot support aquatic life. However, in this case, it was tested to see if it changes over time, indicating algal blooms, decomposition of organic matter, or some manner of aeration. Conductivity was tested in order to determine the salinity of the water (Rusydi, 2018). Temperature was tested to determine if there was some input of water of drastically different temperature; deeper aquifers would have a more stable temperature fluctuation, while shallower waters would show greater seasonal variations. *E. coli* and heavy metals can be harmful to human health and cause serious issues if ingested.

Homeowners were engaged in testing the pH with a pH test strip and shown how to do this on a weekly basis by themselves. For the remainder of the visits, the homeowner was first asked if pH measurements were going well and if anything of note had happened with their well. This included if the water level had risen or dropped, and whether it coincided with rainfall. The residents were an essential contributor to this citizen-science project and provided key information regarding the elevation of the well, the location of the well, history of the well, and anything else they deemed pertinent.

A DO meter was used first so that the water was not disturbed and interfered with the next measurements. However, the numbers were unusually low, and therefore, a Winkler titration was also conducted in the lab to confirm whether the probe was malfunctioning, or the dissolved oxygen levels were simply very low. In a sterile polypropylene container, an *E. coli* sample was taken. This was immediately stored in a cold container and put in a refrigerator as soon as possible until the laboratory testing was done no more than 24 hours later. Another water sample was taken with a polyurethane bottle and stored at room temperature until further testing was done within a month.

E. coli was tested using count plates. A positive control was created by cultivating a known sample of *E. coli* and plating it at 1.24, 12.4, and 124 Colony Forming Units (CFU). A negative

control was created using pure H₂O. All samples as well as the positive and negative controls were applied to the count plates using the method provided by the manufacturer. A spreader was used to press each sample to fill the whole plate. Every sample was placed in a Memmert® UF75 incubator at 38°C for 48 hours. Once removed from the incubator, they were inspected using the 3M Petrifilm™ Interpretation Guide. The count plates required 1 mL of sample, and therefore, the CFU was counted per 1 mL. All chemicals used for testing were reagent grade.

Dissolved oxygen was tested using a DO meter, which was brought to each well during the visits. The Winkler titration was done with manganese (II) sulfate and potassium iodide. Conductivity was tested using a conductivity meter. The probe was placed in 50 mL of each sample for approximately 15 seconds, or until the reading was stable. Using this conductivity measurement, it was determined whether the water was fresh or saline (Rusydi, 2018).

Phosphate was tested using a colorimetric assay. Each sample and the standards were prepared for measurement by adding ammonium molybdate reagent (6.6M H₂SO₄, 0.018M ammonium molybdate tetrahydrate, and 0.003M potassium antimony tartrate) and 0.5M ascorbic acid and measured after 30 minutes at 880 nm. Only the first six wells were tested over time as Well 7 could only be sampled once.

Prior to Inductively Coupled Plasma (ICP) analysis for heavy metal content, samples were filtered through a 0.45 µm filter and acidified with HNO₃. The results of this ICP gave exact measurements for the concentration present in the samples of lead and copper.

Results and discussion

The average test results for DO, conductivity, coliform bacteria, copper, and lead are shown in Table 3.

The results of the Winkler titration showed much higher levels of dissolved oxygen than the DO meter, and therefore, the DO meter was compared against another one, which proved that it had a negative offset. Due to this, there was only one useable DO measurement from the Winkler titration, all other measurements were taken using the DO meter, and therefore, a systematic error was assumed. Well 1 and 2 were quite anoxic at 0.78 and 1.49 mg/L, respectively, Wells 5 and 6 were also low at 4.27 and 6.39 mg/L, respectively. Well 4 was within normal levels for freshwater at 8.85 mg/L (Bozorg-Haddad et al., 2021). Because this well had a high throughput,

Table 3. Results for DO, Conductivity in micro-Siemens (µS) as well as the standard deviation (SD), Coliform bacteria (not *E. coli*) as well as the SD, Copper and Lead

Well number	DO (mg/L)	Conductivity average, µS (SD)	Coliform bacteria average CFU (SD) per 1 mL	Copper (ppm)	Lead (ppm)
Well 1	0.78	686 (20.1)	4.5 (2.12)	0.287	0
Well 2	1.49	573.67 (13.32)	2 (2.83)	0.288	0
Well 3	-	511.33 (24.95)	15.5 (0.71)	0.286	0
Well 4	8.85	617.33 (32.35)	41.5 (13.4)	0.289	0
Well 5	4.27	861 (52.6)	9.5 (0.71)	0.295	0
Well 6	6.39	796 (63.65)	11 (4.24)	0.286	0
Well 7	-	856 (0)	-	0.293	0

this result is expected. If the hydraulic residence time underground is relatively short, there is less time for oxygen to be consumed (Mellor et al., 2013). The anoxic conditions of the other wells are also expected, as they are much more stagnant than Well 4, and therefore, they have more time for the oxygen to be consumed.

The dangerous *E. coli* was not present; however, other unidentified coliform bacteria were found with unknown implications for potential harmful effects. Well 4 had a similar amount of CFU per mL as all the other wells combined. It is possible that because of Well 4's high throughput, more organics are brought into the well that bacteria could feed on. Higher DO rates in groundwater also support aerobic microbial activity, and therefore, the combination of those two factors could explain the significantly higher CFU count (Mellor et al., 2013). All other wells had relatively low average CFU per mL, ranging from 0 to 15.5. These coliform bacteria could have many sources, potentially a contaminant somewhere before the water reaches the wells. However, the variability in coliform counts across wells suggests potential point-source contamination at the well sites, possibly due to open and exposed conditions. The presence of this unknown coliform bacteria in the well water samples exceeds drinking water standards (Drinkwaterbesluit, 2024). This contamination could pose a health risk, and therefore, this water is not safe for drinking purposes. However, water quality standards for non-potable gray water applications are less stringent, allowing up to 100 CFU per mL (Li et al., 2009). By these standards, Wells 1, 2, and 5 can be used for graywater purposes, Wells 3 and 6 are not much higher, and therefore, with some filtration may also be used.

Copper and lead were determined with ICP-OES as test strips indicated their presence. However, ICP-OES did not confirm that lead was present. Copper is present, but the highest amount was 0.295 ppm in Well 5, and the level set by the Drinkwaterbesluit (2024) is 2 ppm; therefore, this is not a concern. This shows that drawing conclusions from test strips used to determine water quality should be done with great caution, and that citizens when given such strips for citizen-science research projects may be unnecessarily alarmed about the water. The amount of copper present is consistent across all seven wells and indicates a shared source. This copper could be potentially related to historical or current anthropogenic activities such as copper pipes. It is not unusual to have low levels of copper in Dutch groundwater. It is commonly found in soil due to emissions from traffic, agriculture, and industry and often leaches into groundwater (De Vries et al., 2008; Comber et al., 2023).

Table 4 shows the Temperature in degrees Celsius (°C) and pH results over time. pH levels exhibited fluctuations across all wells, likely influenced by factors such as rainfall and potential contamination from agricultural runoff. Temperature measurements were consistent with atmospheric conditions, indicating no significant external heat sources.

Phosphate levels were monitored to assess potential agricultural runoff contamination. This phosphate could be reaching the well water by runoff from agricultural areas, which are plentiful across Walcheren, seeping through the soil into the sandy ridges. An increase in phosphate levels from December to April, coinciding with the fertilizer application period, was expected. This trend aligns with findings from Shang et al. (2021) and Rajmohan and Elango (2005). However, the observed increase in Middelburg occurred slightly later, possibly due to climatic differences between the regions. The seasonal variation in phosphate levels is further corroborated by Yaobin et al. (2024), who reported similar patterns in sediment phosphorus release.

All wells, except for Wells 1 and 3, exhibited consistent phosphate trends, suggesting a shared source of contamination (Figure 4). Well 3s data are limited, but the initial decrease in phosphate levels differs from the other wells. The drastic difference in Well 1 is unusual, and currently, the cause is unknown. Well 1 is within 20 m of Well 2, and they share similar characteristics in depth, stagnancy, and pH, indicating a unique source of contamination to Well 1. The elevated phosphate levels in all wells, particularly compared to literature values (Fadiran et al., 2008; Schilling et al., 2020), further support the hypothesis of agricultural runoff as a significant contributor. It is possible that the measured phosphate levels were affected as the samples were taken and stored for up to a month before being tested, and during this period of time, the coliform bacteria may have used some of the phosphate.

Conductivity values indicated that all wells were freshwater (300–800 μ S), with Wells 5 and 7 ever so slightly more saline, but still within range for normal water (500–3000 μ S) (Rusydi, 2018). The fact that these wells are freshwater is unexpected. Walcheren used to be an island, and freshwater was scarce; therefore, this freshwater has very few possible sources.

There are only two sources of water that could have been running through Middelburg when the wells were built, which was likely around the time the houses were built, in the early 17th century. The first is the old river Arne, which used to flow through Middelburg (Encyclopedie van Zeeland, 2020a). The river Arne has since silted up; however, it is possible that it still flows in some capacity underground, and this is the water that the wells are tapping into. However, the river Arne likely originated as a tidal creek as these were very common,

Table 4. pH and temperature (°C) in each well from November 2023 to April 2024

Wells	November		December		January		February		April	
	pH	Temp	pH	Temp	pH	Temp	pH	Temp	pH	Temp
1	5–6	14.9	7–8	14.2	7	12.7	7–8	11.3	7	12
2	-	-	6	14.1	6	12.1	7	10.9	6–7	11.3
3	7–8	15.3	6	14.6	6	13.1	7	11	-	12.2
4	7–8	12.1	6	10.7	6	8.6	7	7.4	7–8	8.1
5	6–7	15	6–7	13.9	7	11.4	7	9.8	7	10.4
6	6	15.4	6–7	14	7	12.3	6–7	10.3	6–7	11.8

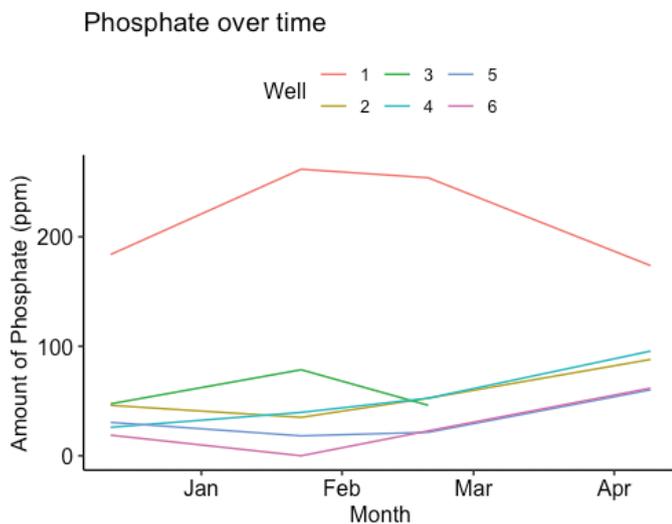


Figure 4. Parts per million (ppm) of phosphate in each well over time.

crisscrossing the island of Walcheren. Salt water flowed through these tidal creeks, coming inwards from the sea. Therefore, it is unknown how the river could be freshwater, ruling it out as a source of the freshwater that the wells could be accessing. Additionally, it is not known if the Arne ever ran through the old city of Middelburg, since historical records only indicate it flowing around the city in a canal (Encyclopedie van Zeeland, 2020b). Consequently, it is highly unlikely that the water of the former river Arne is the source of freshwater for the wells, as it would have had to change paths since silting up and become freshwater.

The second possible source is rainwater. Some of the wells are very connected to the rainwater, and the water levels rise within a few hours after rainfall. Other wells do not move at all, indicating they are connected to a more stable source with less fluctuations. This source could still be rainwater, albeit in a more secondary way. Therefore, another option is the remnants of tidal creeks, consisting of sandy deposits (Figure 5). These deposits can store freshwater from rain, especially if deposited over clay layers, which, in this deltaic environment, can be expected (Pauw et al., 2015).

Zeeland's geological history, primarily influenced by sea-level rise and sedimentation, has shaped a complex hydrogeological system. The region's subsurface is composed of a sequence of marine and fluvial deposits, including sands, clays, and organic-rich peat layers (Stafleu et al., 2011). The underlying Paleogene and Neogene strata, particularly the low-permeability Boom Clay, play a significant role in controlling groundwater flow and quality (Siemon et al., 2019). During the Holocene, sea-level rise led to the formation of a tidal basin, resulting in the deposition of marine and estuarine sediments (Siemon et al., 2019). Subsequently, as sea levels stabilized and the tidal basin transformed into a peat marsh, organic-rich deposits accumulated (Stafleu et al., 2011; Siemon et al., 2019). The eventual closure of tidal inlets and subsequent land reclamation efforts further shaped the region's hydrological landscape. The differential compaction of these deposits, particularly the organic-rich layers and the underlying sands and clays, has led to the formation of distinct topographical features, including sandy creek ridges (Vos, 2015; Siemon

et al., 2019). Middelburg was built on these elevated ridges and sits on top of an intersection of them (Silkens, 2022). These sandy ridges can be seen in soil maps of Walcheren, such as Figure 5.

These ridges are elevated, while the surrounding silt has since sunk. The elevation of Walcheren is visible in Figure 1. The lower level of peat that used to be the peat swamp that formed Walcheren has taken up lots of salt water and is now salty; however, the sandy ridges never took up salty water and remained uncontaminated. Therefore, when it rains, especially near the dunes, the water collects on the inland side of the dunes, percolating down and recharging the underground sandy ridges. The ridges then act as underground rivers, which carry the freshwater to Middelburg and other towns (Provincie Zeeland, 2024). The wells in Middelburg likely tap into this source of water, especially the deeper ones whose water level does not fluctuate as this flow is quite stable. However, this is simply the most likely source based on available literature. It is well documented that these sandy ridges contain freshwater, and Middelburg is located on top of some of them; however, whether the wells tap into this source is currently unknown (Vos, 2015; Provincie Zeeland, 2024). The former river Arne, while dismissed as being the source of the freshwater, was also a tidal creek, and therefore, once it silted up and the salt water no longer flowed, it could be used to carry freshwater. Once the source of this water has been verified, the potential consequences of withdrawing water from the wells can be identified. Groundwater withdrawal can have serious geochemical consequences, and since the wells are relatively close to the coastline, one major concern about withdrawing water is saltwater intrusion (Oude Essink et al., 2010). This could potentially contaminate this freshwater with saltwater and render it useless for many graywater purposes, significantly decreasing its usefulness as an alternative groundwater resource. Additionally, land subsidence, changes in water chemistry, and degradation of water quality are potential impacts of groundwater withdrawal (Tularam & Krishna, 2009), highlighting the importance of further research.

The sandy underground ridges that have been identified as a possible source of the groundwater could provide some explanation for the possible phosphate and copper contamination found in the results. The shallow depth of these ridges and the permeable nature of the overlying sediments make them susceptible to contamination from various sources, including agricultural runoff and industrial activities. Runoff and other contamination could find its way into the well water by permeating the soil above the ridges anywhere on Walcheren before the water reaches Middelburg. If this is the case, sources of contamination would have to be identified, and mitigation strategies would have to be implemented to ensure other contamination does not occur, especially if the water can be used for some graywater purpose.

The results of this study revealed unexpected water quality issues, particularly concerning the presence of coliform bacteria. While the water met drinking water standards for other parameters, the bacterial contamination renders it unsafe for consumption. However, in some of the wells, the water meets the criteria for graywater use, while the other

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Conflicting interests

The authors declare no conflict of interest.

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