Utrecht University

Water Scarcity: Exploring Offshore Groundwater and its Desalination as a Sustainable Solution

Joep van Lith (6571921)

Earth surface and Water, Utrecht University

Daniël Zamrsky & Rens van Beek

Abstract

Growing population and increased urbanization result in an increasing demand on the water supply. A substantial amount of the population lives within close proximity of coastlines and implications for water stress in these regions are significant. Sea level rise, decreasing water quality, waterborne diseases, storm surges are some of the many factors that play a role in the phenomenon of coastal groundwater squeeze. The UN is advocating for safe drinking water for the global population, however, if we do not find alternatives for our current groundwater sources reaching this goal is almost impossible without compromising on other issues.

One of the recent developments in finding alternative groundwater sources is offshore fresh groundwater. Located within close vicinity of coastal areas, this supply of submarine fresh groundwater could supply large population centers with ample amounts of drinking water. These alternative water supplies are found along coasts all over the world, mainly in the shallow seas at the edges of continental shelves. Groundwater modelling and where these reservoirs can be found are well known. What still misses is where and how we can extract this and if this new groundwater source is economically viable.

Via conceptual models, 3D interpretations of offshore aquifers located at the Bohai Sea, Pearl River Delta, and Yangtze River Delta, are made to get an idea of how water slowly gets more saline over time when fresh or brackish water is extracted. The volume of water that is brackish is sent to desalination plants for further treatment. Extraction, treatment, and infrastructure are the three main expenses involved in offshore fresh groundwater pumping. Notably, extracting the maximum fresh and brackish water volume emerges as the most cost-effective option across all regions. In the Bohai Sea, costs range from $0.345 to $0.412, undercutting the national average of $0.46. Conversely, the Pearl River Delta presents costs of $0.869 to $0.937, while the Yangtze River Delta ranges from $0.710 to $0.778, both exceeding the national average. Despite higher costs in the latter two regions, the investment in offshore fresh groundwater exploration appears economically viable in the long term, offering potential cost efficiencies and mitigating risks associated with continued reliance on onshore groundwater sources. Future research is needed to asses potential environmental issues or on groundwater table changes inland for aquifers that have onshore connections

Table of Contents

Introduction

Freshwater is a fundamental resource to human health and well-being, agricultural and industrial development, ecosystem support, and environmental stability. However, the convergence of climate change, population growth, urbanization, and declining water quality has heightened the global water crisis, threatening societies worldwide (Chen et al., 2015). Natural hazards, droughts and floods, in particular, pose a grave threat to the drinking water supply. As a global community it is important to find a good and safe solution to ensure a safe drinking water supply for the population.

The United Nations (UN) advocates the provision of safe and affordable drinking water worldwide, as outlined in the Sustainable Development Goals (SDG) report of 2023 (United Nations, n.d., United Nations Statistics Division, n.d.). Despite progress, significant challenges persist. In 2022, while 6 billion people had access to safely managed drinking-water services, 2.2 billion people still lacked such access. Furthermore, 4.2 billion individuals, half of the global population, lacked safely managed sanitation services, leading to nearly 300,000 deaths annually among children under the age of five due to waterborne diseases. Approximately two billion people reside in regions experiencing water stress, with four billion encountering water scarcity for at least one month each year (United Nations, n.d., World Health Organization: WHO, 2023). Water demand has surged at twice the rate of population growth over the past century, emphasizing the need for efficient water resource management. Most of the current measures to address drinking water scarcity is to supply people with substantial amounts of water, however, if this is done improper the quality of the water can degrade rapidly endangering even more people (Salehi, 2022). Moreover, the SDG 2 outlines that in 2030 there should be no hunger or malnutrition (World Health Organization: WHO, 2023). The already acute shortages of the freshwater supply do not help the UN to achieve this goal. The Mediterranean, West and South Asia are the regions where the largest percentage of agricultural land, arable and grazing land, is irrigated (Ritchie, 2017). India used a total of 700 billion cubic meters of water in 2010 for agriculture. These regions are also already experiencing medium to high water stress. Thus, finding freshwater reservoirs to support the rising demands is crucial for the food supply and the economic future of these countries.

Considering that a substantial portion of the global population lives within 100 kilometers of coastlines, the implications for water stress in these regions are significant (Maul & Duedall, 2021, Reimann et al., 2023). Pressures on coastal ecosystems increase, habitat conversion, land use change, and pollutants are among the most significant pressures. These pressures can lead to reduction in water quality, siltation, algal blooms, and threat to human health through waterborne diseases (Sellner et al., 2003, Funari et al., 2012). Finally, having large population centers in low-elevation coastal zones, elevations ranging between 1m and 20m above mean sea level (Barbier, 2015, NASA, 2016), increases a nation’s vulnerability to sea level rise and natural hazards such as storm surges.

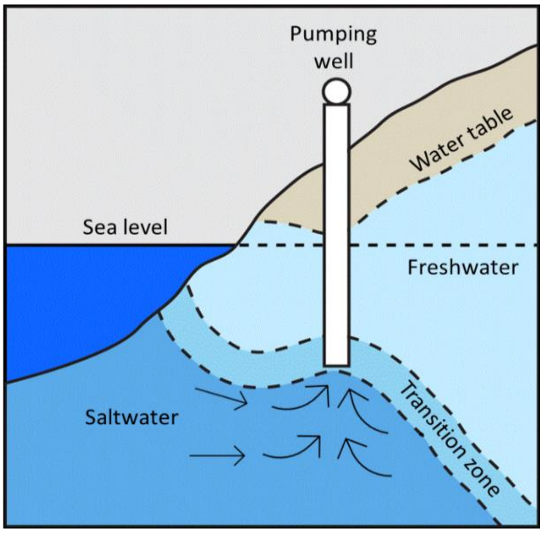


Figure 1 - Schematization of seawater intrusion, indicated by the arrows. Cone of upwelling is situated right underneath the well. Adapted from Climate Adaptation and Saltwater Intrusion (2023).

One pressing issue concerning groundwater, primarily in arid regions or developing countries, is the unauthorized extraction of groundwater by, mainly, farmers seeking to circumvent water costs (Llamas & Martínez-Santos 2005, Stefano & Lopez-Gunn, 2012). Excessive groundwater pumping lowers the piezometric head in an aquifer and causes substantial land subsidence, with rates reaching up to 18 centimeters per year in places like Jakarta, Indonesia (Chaussard et al., 2012, Erkens et al., 2015).

Especially in coastal areas, the unauthorized extraction of groundwater results in large problems. Besides land subsidence, the extraction of ground water creates a "cone of upwelling" around the pumping well drawing in saltwater from the sea (Figure 1) this is called seawater intrusion (SWI) (Werner et al., 2013).

These coastal aquifers face a dual threat: contamination from overpumping and seawater intrusion and pollutants introduced by agriculture, industries, urban sewage, and landfills. This multifaceted danger is often referred to as "coastal groundwater squeeze" (Figure 2) (Michael et al., 2017).

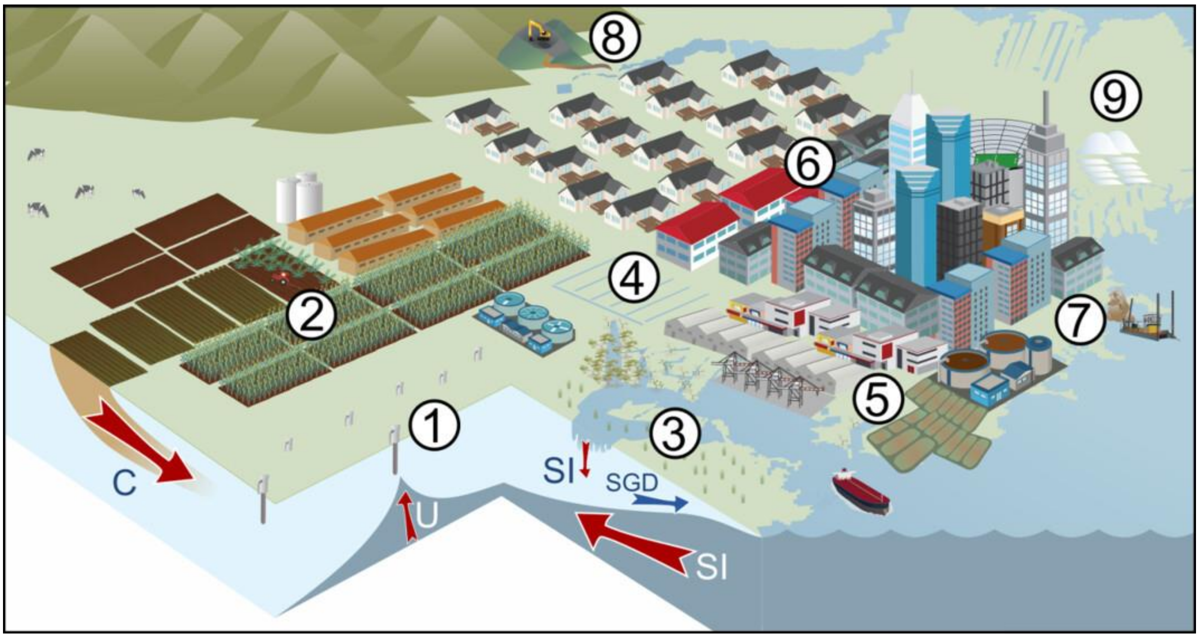


Figure 2 - Diagram showing contributors to the "coastal groundwater squeeze." (1) Excessive groundwater pumping results in a cone of upwelling around the well and in SWI, both reducing the submarine groundwater discharge; (2-9) contamination (C) due to agriculture, vertical SWI, land subsidence, urban expansion, dredging, and industries. From Michael et al., 2017.

Water stress around the world

There is physical water scarcity, that is when the supply of water is insufficient due to ecological conditions, and there is economic water scarcity, when the infrastructure to supply water is inadequate. Together they cause water stress which means that the demand for safe usable water in a given area exceeds the supply. Figure 3 shows areas around the globe with extremely high water stress that do not have thick layers of OFG available in the vicinity. However, the study by Zamrsky et al., 2021, shows that the same areas as those in Micallef et al., 2021 do have substantial amounts of OFG available (Figure 4). In this study the focus will be on three regions in China, where OFG availability is abundant, and water demand is high.

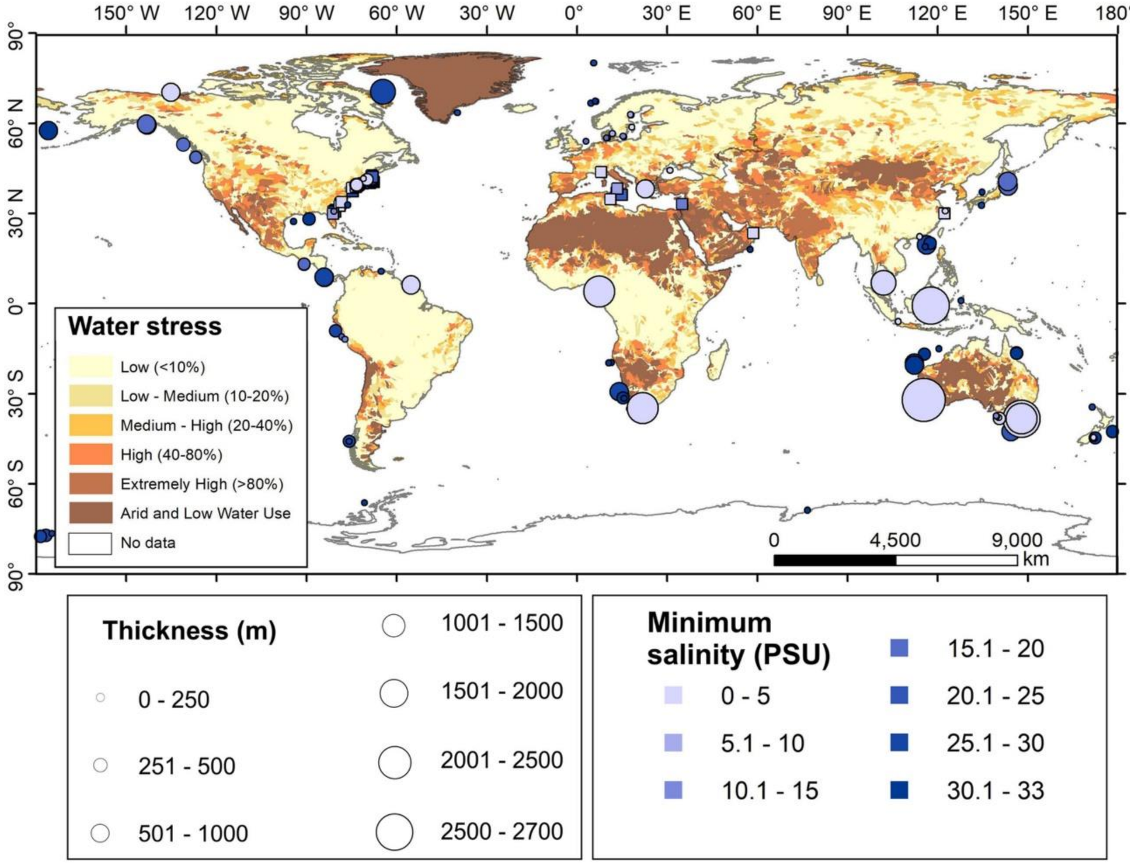


Figure 3 - OFG thickness and minimum salinity plotted on a global map of water stress. Square symbols denote sites where OFG thickness could not be determined. From Micallef et al., 2021.

The advantage of offshore fresh groundwater is that it can help relieve the stress on coastal aquifers and reduce the risk of SWI. It allows for implementation of measures aimed at SWI reduction and mitigation. Furthermore, the offshore groundwater could provide coastal communities with a long term, years to decades, source of freshwater, if managed correctly. The low salinity of the groundwater opens the door to additional advantages. In desalination processes it can be efficiently used offering a less energy-intensive and, consequently, cost-effective approach.

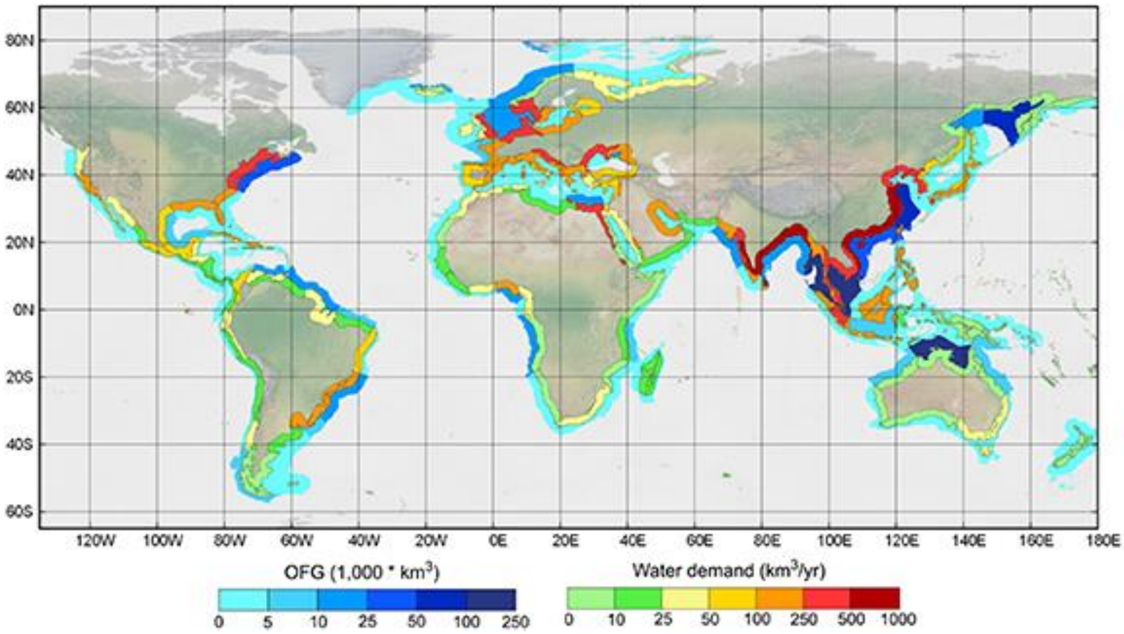


Figure 4 - Estimated regional OFG volumes (in 1000km^3) plotted with regional coastal current water demand (km^3 yr^{-1}) based on the global hydrological and water resources model PCR-GLOBWB. From Zamrsky et al., 2021.

Offshore fresh groundwater

The formation of offshore fresh groundwater (OFG) can be traced back to the last glacial maximum, 26,500 to 19,000 years ago (Clark et al., 2009), when vast ice sheets drastically lowered global sea levels by up to 130 meters. The large exposure of the continental shelf created an environment that is ideal for freshwater infiltration and accumulation (Figure 5). Unconsolidated sediments, such as sand and gravel, provided pathways for freshwater to flow and accumulate, when sea levels rose again the sediment deposited changed to silt and clay creating a sealing layer on top of the OFG reserves.

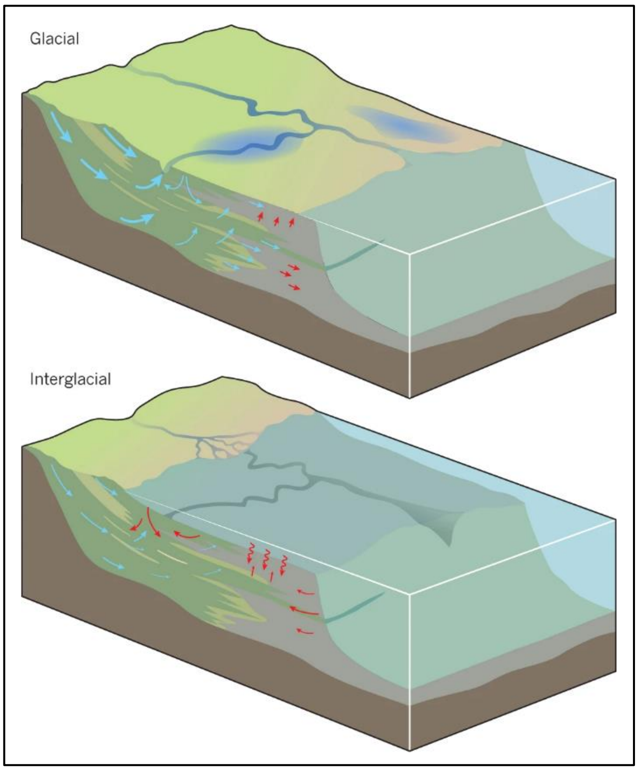


Figure 5 – Lower sea levels during glacial periods promote further penetration and recharge of groundwater below continental shelves, whereas incised rivers provide a driving force for topographic flow systems, and saline groundwater retreats seaward. When the shelves are flooded during interglacials, intruded seawater (red arrows) migrates landward as well as downward, while the flow of fresh water (blue arrows) stagnates. From Post et al., 2013

These aquifers can be found globally, extending along coastlines worldwide. Large occurrences of OFG have been documented in Eastern North America, the North Sea, and East-Asia/Oceania (Zamrsky et al., 2021).

Global estimates of OFG reserves vary, however recent studies (Cohen et al., 2009, Post et al., 2013, Zamrsky et al., 2021) suggest that these aquifers may hold substantial volumes of fresh or brackish water (10^5 km^3 to 10^6 km^3). This amounts to around 10% of the total terrestrial fresh groundwater, a significant potential source for water-stressed coastal regions.

OFG presents several advantages over traditional freshwater sources in coastal areas:

1. **Potential for long-term storage:** OFG reserves can be strategically managed to provide a reliable source of freshwater during periods of drought or increased demand. This long-term storage capacity is crucial for ensuring water security in coastal communities.
2. **Semi-renewable resource:** Close to coastal areas some OFG reserves are connected to inland groundwater table. This connection allows for recharge of freshwater into the OFG reserves. Offshore aquifers that are completely disconnected from any inland freshwater source are considered as a non-renewable source.

Despite its potential, the development of OFG as an alternative water supply also faces several challenges:

1. **Environmental considerations:** Offshore groundwater extraction may have ecological implications for marine ecosystems. Careful environmental assessments and mitigation measures are essential to minimize potential impacts on biodiversity and marine habitats.
2. **Groundwater table drop:** When extracting the water from offshore aquifers that have an inland connection there is a possibility that the groundwater table will lower, resulting in a worsening of the problem
3. **Economic feasibility:** The costs associated with developing and maintaining offshore groundwater extraction facilities may be higher than for traditional freshwater sources. Economic viability will depend on factors such as local water demand, energy costs, and government subsidies.

Using offshore groundwater

However, the quality of offshore groundwater varies, with some areas containing brackish water and others holding freshwater. Brackish water, with total dissolved solids (TDS) ranging from 1,000 to 10,000 mg/L, is not suitable for direct human consumption (Greenlee et al., 2009 and Stanton et al., 2017). To make it potable, different desalination techniques can be employed:

- **Reverse osmosis (RO)**, a membrane-based desalination process, stands out as the most widely used and efficient method for producing freshwater from brackish and seawater. RO membranes selectively allow water molecules to pass through while rejecting salts, effectively removing impurities and producing high-quality freshwater.
- **Multi-stage flash distillation (MSF)**, is a thermal desalination process that uses heat to evaporate seawater and then condense the vapor to produce freshwater. MSF is a mature technology that is relatively energy-efficient, but it can be expensive to operate and can produce brine with a high concentration of salt.
- **Multiple-effect distillation (MED)**, is a variation of MSF that uses multiple stages of evaporation and condensation to increase the efficiency of the process. MED is a more energy-efficient option than MSF, but it is also more expensive to build and operate.
- **Electrodialysis (ED)**, is a membrane-based desalination process that uses an electric field to separate ions from water. ED is a relatively modern technology, but it is becoming increasingly popular due to its low energy consumption.

The global installed capacity of desalination techniques is 5.37 x 10^6 m^3/day, of which RO occupies 68.7% (Curto et al., 2021). The energy consumption of RO desalination is directly related to the TDS concentration of the feedwater. Brackish water, with lower TDS levels, requires less energy to desalinate compared to seawater. This energy efficiency makes brackish water desalination an attractive and sustainable option.

For instance, while RO desalination of seawater typically requires pressures ranging from 90 to 138 bar, desalinating brackish water from offshore reservoirs can be achieved with pressures between 9 and 28 bar (Younos & Tulou, 2005). This significant reduction in pressure translates into lower energy consumption and a more cost-effective desalination process.

Effects of groundwater pumping

Groundwater pumping, whether onshore or offshore, has multiple consequential impacts on its surroundings.

- Land subsidence is a well-known effect of groundwater extraction on terrestrial aquifers (Poland & Davis, 1969). According to Bagheri-Gavkosh et al., (2021), almost 60% of land subsidence is caused by groundwater extraction. When water is extracted from the soil the pore pressure decreases and the hydraulic head declines. The decrease of pore pressure and the pore water removed results in air gaps in the soil. The stresses on the lithology increase without the support of groundwater resulting in the compaction of susceptible aquifer systems (Zektser et al., 2004, Galloway & Burbey, 2011). Land subsidence can be triggered dozens of kilometers away from the pumping well (Yu & Michael, 2019) affecting areas that do not even benefit from groundwater extraction.
- Coastal aquifers that are used for groundwater extraction often experience SWI. Here, again, the reason for the landward movement of seawater is the decline of the hydraulic head inside the aquifer (Zektser et al., 2004, Werner et al., 2013). Seawater intrusion causes a reservoir to be contaminated (Knight et al., 2018), the increase in TDS makes water unfit for drinking. To combat this injection wells can be installed to halt or push back intruding seawater, however, for this to work effectively fresh water has to be imported from elsewhere making this an expensive solution to combat SWI (Edwards & Evans, 2002, Allow, 2011).
- Soil is an important medium for plant growth and water filtration. The extensive use of fertilizers on the soil for agricultural use results in peaks of nitrogen, phosphorus, potassium, and heavy metals (e.g. lead, copper and zinc) in the surface- and groundwater (Rozemeijers & Broers, 2007, Adamu & Ngaje, 2010). Soil pollution is a great threat for humans as the drinking water gets contaminated and the quality of food diminishes. Other sources like industrial wastewater, seepage of landfills and septic tanks, or mining activities (Fried, 1975). The contamination of groundwater sources due to land use practices can significantly harm the quality and safety of these freshwater sources.

The stress that is put on the water supply by countries for agriculture, industry, and domestic use is getting more pressing each year. Groundwater pumping rates increase and the groundwater supply of countries is quickly running out, rising sea levels cause SWI, and other factors result in the degradation of water quantity and quality. Effects of climate change also cause higher water stress for certain regions. Drier and hotter summers mean more water use during this time, and less snowfall in mountains means there is less water runoff in the spring. Combine all this and the water supply cannot be resupplied sufficiently to sustain a country's annual usage.

Study Area

Figure 4 shows that the coastal regions in China have high water demand and abundant OFG available. Due to time constraints only three regions will be looked at (Figure 6).

Bohai Sea

The Bohai Sea, located in northern China, is a semi-enclosed sea surrounded by the Liaodong Peninsula and Shandong Peninsula. Economically, the Bohai Sea region is vital for industries like shipping, fishing, and oil exploration. In terms of water situation, the Bohai Sea faces challenges related to pollution and overexploitation, impacting marine life and ecosystem health (Du et al., 2015 and Liu et al., 2012).

Figure 6 - Location map of Bohai Sea (yellow), Yangtze River Delta (blue) and Pearl River Delta (silver).

Pearl River Delta

The Pearl River Delta, situated in Guangdong Province, is a highly urbanized and economically significant region in southern China. Known for its rapid urban expansion and industrial development, the Pearl River Delta is a major hub for manufacturing and trade. Water availability in the region is relatively high, with the Pearl River serving as a crucial water source for various sectors, although the area faces water shortages due to salt intrusion and increasing demand (Liu et al., 2012 and Zhang et al., 2022).

Yangtze River Delta

The Yangtze River Delta, encompassing Shanghai and surrounding provinces, is a key economic powerhouse in China. Characterized by advanced industries, commerce, and a dense population, the Yangtze River Delta is a major contributor to China's GDP. Water management in this region is crucial due to the high demand for water resources, leading to challenges such as pollution and water scarcity, necessitating sustainable water use practices to support the region's development (Yao, 2017).

The questions to be asked to find a solution to the afore mentioned issues are:

- Can OFG extraction be economically feasible?
- How does the OFG water price compare to the national average water price in China?
- What are the main difficulties in achieving feasible OFG extraction?

Methods

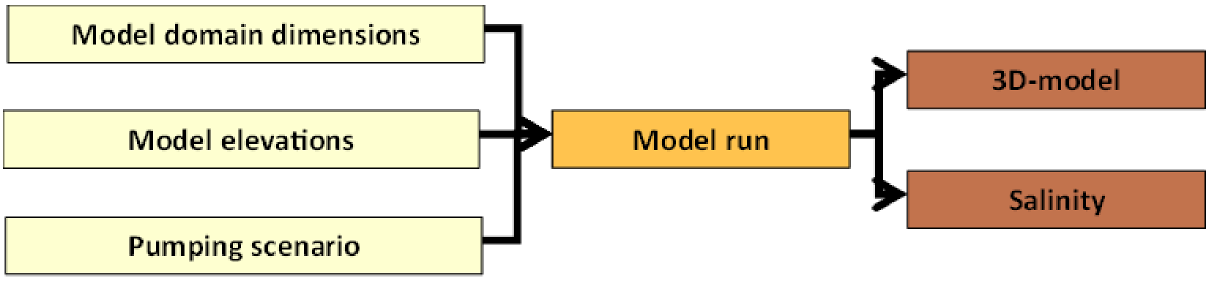
Groundwater model

Understanding the mechanisms and implications of offshore fresh groundwater pumping (OFGWP) involves a multifaceted approach. Firstly, we need to define how water behaves in an offshore aquifer and what the effect of SWI is on extracting the water. Secondly, an economic analysis is necessary to determine the feasibility of OFGWP as an alternative freshwater source in countries experiencing water scarcity. In this case a conceptualized model of an aquifer is made. The aquifer is only a fraction of what the total dimensions of the aquifer system could be, and the aquifer is modelled as a box-model.

For the groundwater modeling aspects of this study imod-wq and a Python library called FloPy are employed. SEAWAT represents a software program that combines the capabilities of MODFLOW for groundwater flow and MT3DMS for solute transport. It is tailored to simulate the intricate dynamics between freshwater and saltwater in coastal and offshore aquifers (Langevin et al., 2008). The primary use of SEAWAT is for modeling problems related to SWI in coastal aquifers, or in this case offshore aquifers. In utilizing these software tools, we aim to construct conceptual models of aquifers. Complementary to SEAWAT FloPy is employed, a Python library that can create, run, and post process models based on MODFLOW and SEAWAT.

Groundwater model flowchart

The flowchart below describes how the conceptual model works. The size and depth of the conceptual model have to be put in. The pumping scenario data is needed after the paleo reconstruction is completed. When the groundwater model has finished, the result is a 3D-model of the aquifer domain showing the salinities in each cell, besides an spreadsheet is created that has the exact groundwater salinity concentrations for each timestep at each pump



Each model contains 10 layers, thus in total the model calculates 600,000 cells per simulation. The 10 layers are sub-divided into one aquitard, four aquifer, one aquitard, and four aquifer layers. In these layers the proportional thickness of each sector (inland, shelf, slope) can be set as a percentage. Hydrogeological parameters involved in the model are kept constant. Hydraulic conductivity is set at 10 m/s in the aquifers and as 0.0001 m/s in the aquitard. The anisotropy for both the aquifers and aquitards is set at 0.1.

Extraction equations

When the paleo reconstruction is finished the model will run the pumping scenario. Initially there are two rows of five pumps in the model, if one of the scenarios has an extraction rate that exceeds the limits of a pump the number of pumps will be increased. Finally, the salinity level is measured at the location of the pump for each stress period, from here the volume of fresh and brackish water is calculated as:

$$Volume = Ext * t \tag{1}$$

Where, volume is either the fresh or brackish volume (depending on the salinity level) in m^3, Ext the extraction rate in m^3/d, and t the time in days.

Looking at the 'by source' tab in table 1 it shows that the amount of water originating from groundwater is 17.99% of the total freshwater withdrawals in China, this percentage is used to calculate how much water should be coming from a groundwater source. Using equation 6, the average cost of water annually in China is $195.50 per capita.

Table 1 - Table with the water withdrawal by sector and by source for China (FAO, 2011)

WATER WITHDRAWAL	Year	Value	Unit
By sector			
Agricultural	2015	385.2	km³
Municipal	2015	79.4	km³
Industrial	2015	133.5	km³
Total	2015	598.1	km³
Total water withdrawal per capita	2015	425	m³
By source			
Surface water withdrawal	2015	484.9	km³
Groundwater withdrawal	2015	106.9	km³
Total freshwater withdrawal	2015	594.2	km³

Note that the average water withdrawal per capita from the country is used to calculate the water use in a region. This, of course, varies from the actual water withdrawal per capita in the region, which would be higher than the average as the regions are densely populated and wealthy.

The calculations for the extraction rates for each of the five scenarios are done with Equation 2, 3, and 4. For each region the average water consumption of the country is multiplied by the regional population and the percentage of water sourced from groundwater. The total daily groundwater use is calculated as:

$$DGW_t = \frac{C_{avg} * Population}{365\ days} * GW\text{-}fraction \qquad (2)$$

Here, DGW_t is the total daily groundwater use of each region in m^3/day, C_{avg} is the average water consumption in the country in m^3/year, and GW-fraction represents the groundwater withdrawal percentage.

To adapt the daily groundwater use to the specific model domain area, a scaling factor is introduced. This factor adjusts the total daily groundwater use to reflect the dimension of interest within the model domain. This scaling factor is calculated as:

$$DGW_m = DGW_t * \frac{W_m}{W_d} \qquad (3)$$

Where, DGW_m is the daily groundwater use within the model domain in m^3/day, W_m is the width of the model domain (25 km), and W_d is the width of the total domain (500 km).

Various extraction rates are defined for each scenario to represent distinct levels of groundwater withdrawal intended to partially alleviate potential water shortages. These extraction rates are calculated as:

$$Ext = \frac{DGW_m * Fraction}{10\ pumps} \qquad (4)$$

Where, Ext is the extraction rate in m^3/day and Fraction the percentage of the total water demand intended to be replaced by groundwater extraction, which are set at 5%, 10%, 15%, 25%, 50%.

The division by 10 accounts for the fact that the model script defines the extraction rate as that of a single well. By varying the "Fraction" parameter, different scenarios with varying degrees of dependence on groundwater extraction are simulated. An overview of the extraction rates for each of the five scenarios is given below in Table 2. The full calculations for the extraction rates of each scenario for each region can be found in Appendix 1, 2, and 3.

Table 2 – Column 1: Location names, Column 2: this is the volume of water (in cubic meters) that originates from a groundwater source for each region, Column 3: this is the volume of water (in cubic meters) that would be accounted for over the width of the model domain of 25 km, Column 4-8: here the extraction rates are shown for the five different scenarios, where each percentage shows how much of the daily groundwater will be replaced with water from the offshore aquifer.

Location	**Total daily GW need (m^3)**	**Model daily GW need (m^3)**	**5% scenario (m^3/d)**	**10% scenario (m^3/d)**	**15% scenario (m^3/d)**	**25% scenario (m^3/d)**	**50% scenario (m^3/d)**
Bohai Sea	23,041,986	1,152,099	5,760	11,521	17,281	28,802	57,605
Pearl River	13,825,192	691,260	3,456	6,913	10,369	17,281	34,563
Yangtze Delta	50,273,425	2,513,671	12,568	25,137	37,705	62,842	125,684

Cost equations

The economic analysis that is made is divided into three parts: (i) the extraction costs of getting the water out of the aquifer, (ii) the desalination costs that are required when the extracted water is brackish, (iii) the one-time installation cost concerning infrastructure, maintenance, machinery, etc. Each section will contain detailed information on how the results are calculated. All results are then combined to get the final results for each of the three regions. The outcome of the regions is compared mutually and to the average water cost in China.

Over the year 2023 the average water cost in China was 3.25 CNY ($0.46) per cubic meter of water (Xie et al., 2023). This value will be used for all three regions, Bohai Sea, Pearl River, and Yangtze River delta. In figure 7 below the water withdrawal in China is shown from 2015.

The energy required for extracting water from the aquifer is determined by considering mass, gravitational acceleration, height, and a conversion factor. The energy calculation is given by:

$$Energy = \frac{m*g*h}{3{,}600{,}000} \quad (5)$$

Where, Energy is in kWh, the mass in kg, gravitational acceleration in m/s^2, height in meters, and 3,600,000 is a conversion factor to go from Joules to kWh.

The average annual cost for water in the region is calculated as:

$$Average\ water\ cost\ (\$) = Water\ withdrawal\ per\ capita\ (m^3) * Water\ cost(\$/m^3) \quad (6)$$

This value can be compared to the cost of drinking water that is extracted from the offshore aquifer when the cost for extracting and desalinating water is known.

The calculation of the final cost per cubic meter consists of three primary values: (i) the extraction cost, (ii) the desalination cost, and (iii) the installation cost.

Equation 1 gives a volume of fresh and brackish water. The sum of this is used to calculate the energy needed for extraction with equation 5. The next step is to calculate the extraction costs, this is calculated as:

$$C_{ext} = E_{lift} * C_{eng} \quad (7)$$

Where C_{ext} is the cost of extracting the water from the aquifer in $USD, E_{lift} is the energy required to pump the water to the surface in kWh/m^3 calculated in Equation 5, and C_{eng} the energy cost of the electricity used by the pumps in $USD.

Second, the cost involved for desalinating the brackish water that is extracted is calculated as:

$$C_{des} = E_{des} * C_{eng} \tag{8}$$

Where, C_{des} is the cost of desalinating a volume of brackish water in \$/m^3, E_{des} is the energy required to desalinate a volume of brackish water in kWh/m^3, and C_{eng} is the energy cost in $/kWh from four different energy sources.

Third, the installation costs encompass various elements such as pump costs, seafloor foundation costs, drilling costs, drilling-rig expenses, seafloor pipeline costs, and maintenance expenses. These costs are calculated based on specific parameters like pump lifetime, foundation installation frequency, drilling depths, rig rates, pipeline lengths, and maintenance intervals. The total installation cost (C_{inst}) is computed by summing up all these individual costs:

$$C_{inst} = Pump + Foundation + Drilling + Rig + Pipes + Maintenance \tag{9}$$

Finally, the results from Equation 7, 8, and 9 are the total cost of extracting the water. This has to be converted to a cost per cubic meter. This is calculated as:

$$Water\ cost = \frac{C_{ext} + C_{des} + C_{inst}}{Total\ volume} \tag{10}$$

Results

Study areas

Bohai Sea

Each scenario sees an increase in extraction rate which results in a larger volume of water that is extracted from the aquifer over 500 years. Using equation 10, we see that the larger the volume of water is, the smaller the water cost per volume will be (Figure 8). Each scenario started with extracting fresh water, going from 125 years in the 5% scenario to just 10 years in the 50% scenario. For each scenario most of the water has to be desalinated. The most cost effective scenario is the 50% scenario, which is discussed more thoroughly below.

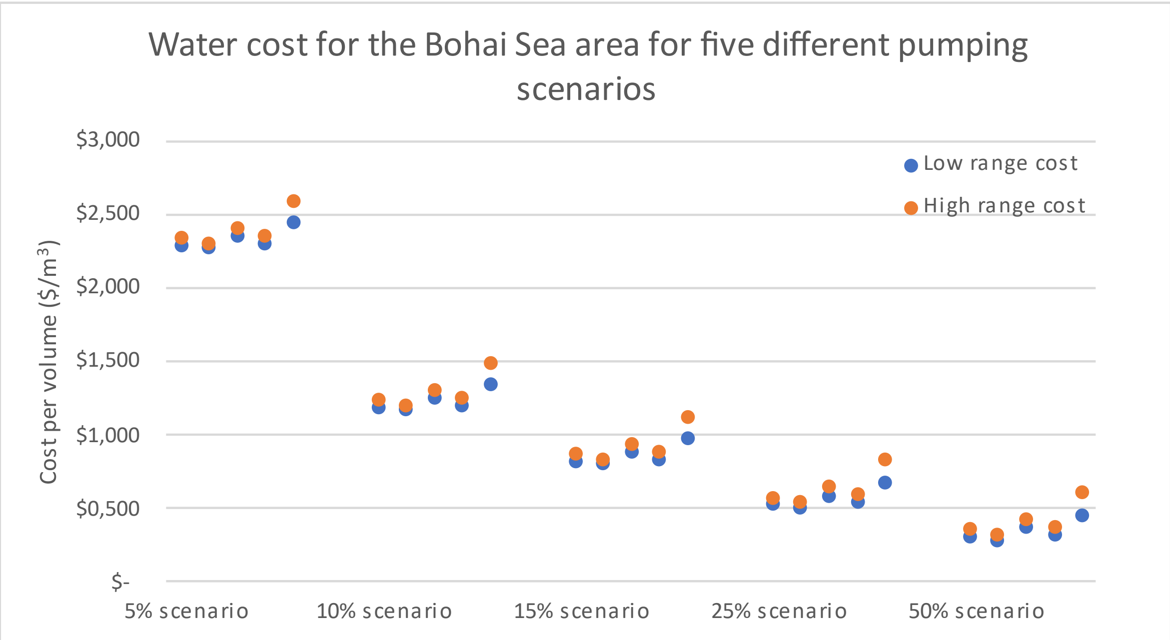


Figure 7 - The cost of water for each of the five pumping scenarios. The low range cost, in blue, assumes the lowest available cost for energy and desalination. The high range cost, in orange, assumes the highest available cost for energy and desalination. The five data points in each scenario represent the energy source used (f.l.t.r.: solar, onshore wind, offshore wind, fossil fuel low, fossil fuel high). The scenarios are in order of amount of groundwater substituted with an offshore source with increasing extraction rates, which can be found in Table 1.

The extraction cost for each scenario is the same, due to the fact that the energy cost increases proportionally with the volume extracted. For low range extraction the cost is $0.012, and the high range is $0.032. Bohai Sea sees the lowest amount of money needed for the installation cost at $2.3 billion, dividing this with total water volume the installation cost is $0.221 per cubic meter for the 50% scenario. Adding all this up gives a range of cost per cubic meter where the average cost per volume of the 50% scenario is $0.345 and $0.412 for the low and high range cost respectively. An overview of all costs involved of all five scenarios can be found in Appendix 2. If this is multiplied by the average water consumption in China the total water cost is $146.42 and $175.24, being 25% and 10% lower than the average water cost in China of $195.50.

The final groundwater salinity concentrations in the aquifer domain of the 50% scenario are shown in the 3D-plot in Figure 9-A. High salinity is found at the locations of the pumps and intruding from the shelf edge on the right. The layers of the aquifers are clearly visible and show different gradations of salinity. Intrusion occurs in both the top and bottom aquifer, the horizontal hydraulic conductivity is low, so intrusion does not reach far into the aquifer. Intrusion at the pumps happens from the top down into the aquifer, with a seawater salinity hotspot at the top layer.

The evolution of the aquifer salinity is depicted in Figure 9-B below. The horizontal red line indicates where the average salinity of the water extracted by the pumps reaches the threshold of brackish water. Only a small fraction of each scenario is below the threshold, thus most water has to be desalinated. For each scenario the salinity increases steadily with time.

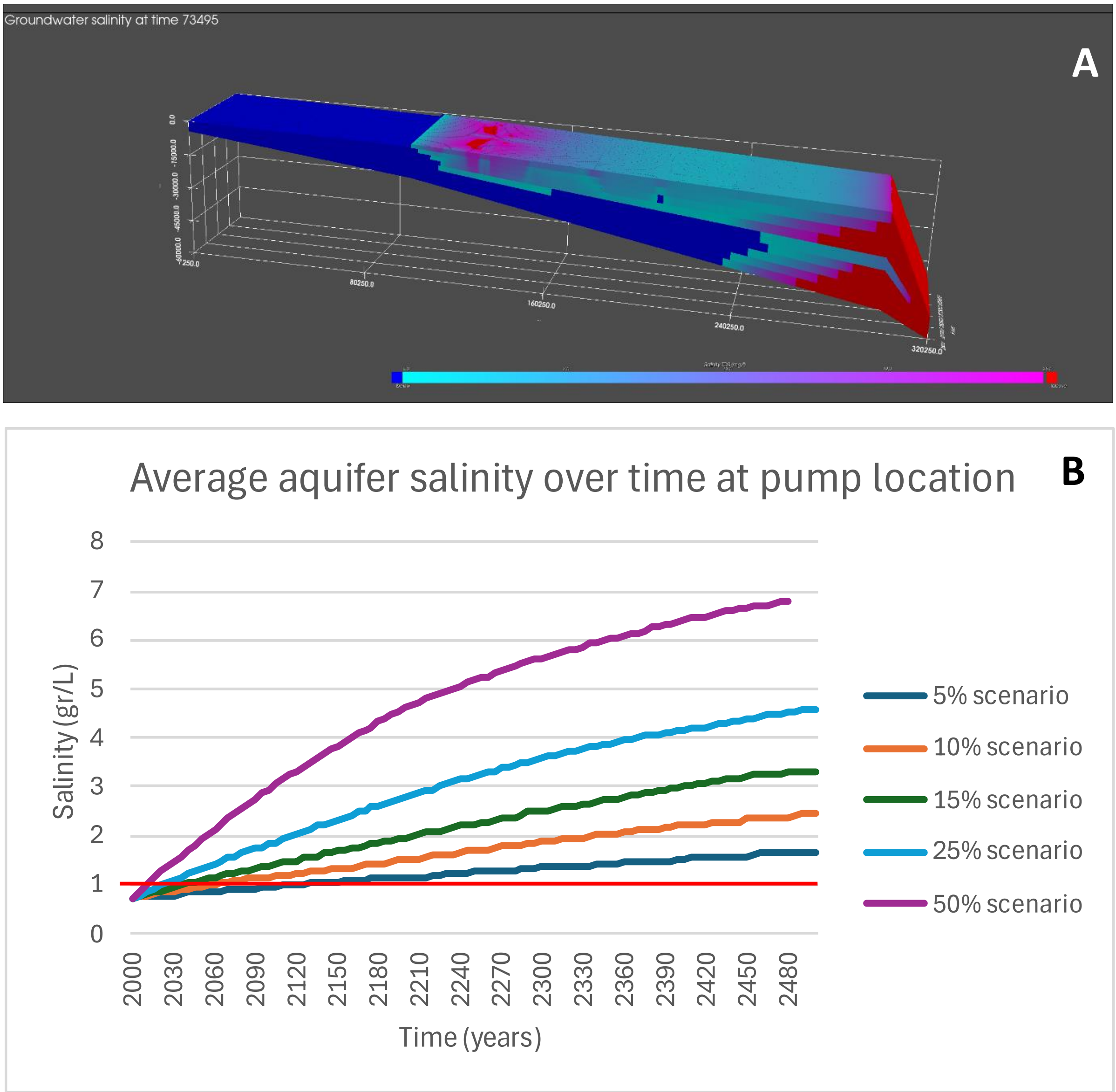


Figure 8 – (A) 3D-plot of the final timestep for pumping scenario five for the Bohai Sea area. Colors indicate the salinity within the modelled aquifer, fresh water is indicated in blue and highly saline water is indicated with red. (B) Line plot illustrating the course of the salinity levels inside the aquifer for each pumping scenario. The red line indicates the boundary value from fresh water to brackish water.

Pearl River Delta

The results here (Figure 10) show the same downward trend as the Bohai Sea region. The scenario where the largest amount of water is extracted gives the lowest water price. However, the base cost per volume is much higher due to this region needing less water in total. In this region the number of years that fresh water could be extracted ranged from 215 years in the 5% scenario to 20 years in the 50% scenario. So, again most water that is extracted has to be desalinated.

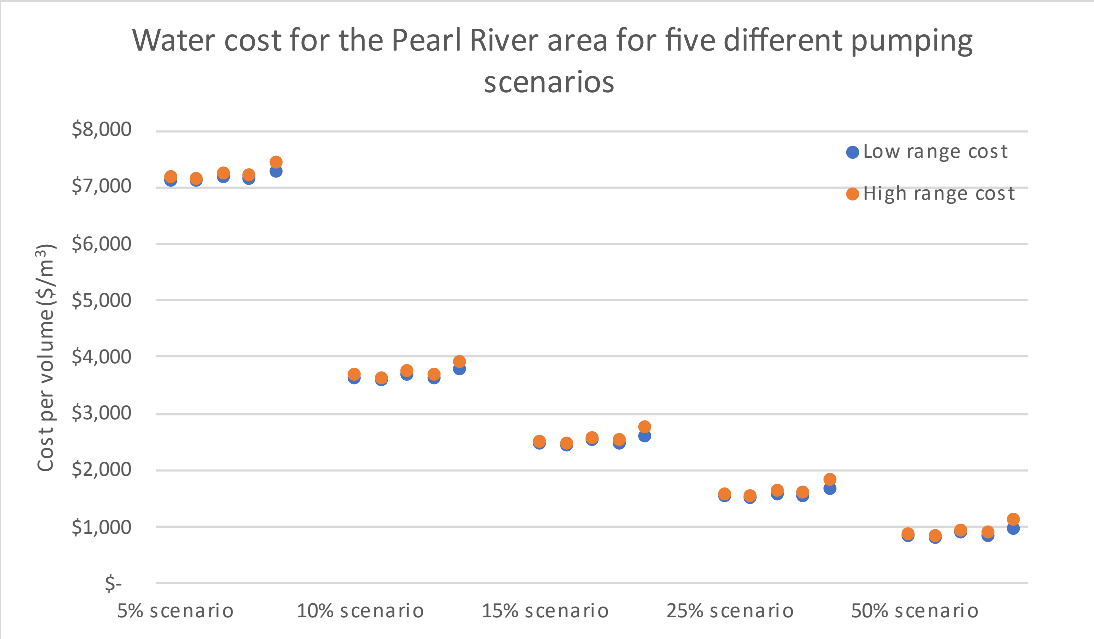


Figure 9 - The cost of water for each of the five pumping scenarios. The low range cost, in blue, assumes the lowest available cost for energy and desalination. The high range cost, in orange, assumes the highest available cost for energy and desalination. The five data points in each scenario represent the energy source used (f.l.t.r.: solar, onshore wind, offshore wind, fossil fuel low, fossil fuel high). The scenarios are in order of amount of groundwater substituted with an offshore source with increasing extraction rates, which can be found in Table 1.

The extraction cost for each scenario is the same, due to the fact that the energy cost increases proportionally with the volume extracted. For low range extraction the cost is $0.056, and the high range is $0.151. Pearl River sees the highest amount of money needed for the installation cost at $4.4 billion, the larger depth where the aquifer is situated in this region results in a large expense for the drilling rig and the drilling. Dividing this with the total water volume, the installation cost is $0.701 per cubic meter for the 50% scenario. Adding all this up gives a range of cost per cubic meter where the average cost per volume of the 50% scenario is $0.869 and $0.937 for the low and high range cost respectively. An overview of all costs involved for all five scenarios can be found in Appendix 4. If this is multiplied by the average water consumption in China the total water cost is $369.33 and $398.23, being 189% and 204% higher than the average water cost in China of $195.50.

The final salinity values for the 50% scenario are shown in Figure 11-A. Saline water is found at the top layers of the pump locations, however in the aquifer the average salinity is at the level of brackish water. Due to the lower water demand in this region the extraction rates are much lower and show a low rate of seawater intrusion. The seawater intrusion from the shelf edge on the right is similar to that of the Bohai Sea. Inside the layers of the model the difference in salinity can be seen. The average salinity from each aquifer layer at the pump locations stays below 10 gr/L.

The lower extraction rates also result in an overall lower salinity for each of the scenarios (Figure 11-B). A larger fraction of the scenarios lies below the threshold of brackish water, thus less water needs to be desalinated. The 5%, 10%, 15%, and 25% scenario increase almost linearly, with the 50% scenario showing a faster increase with a more curved plot.

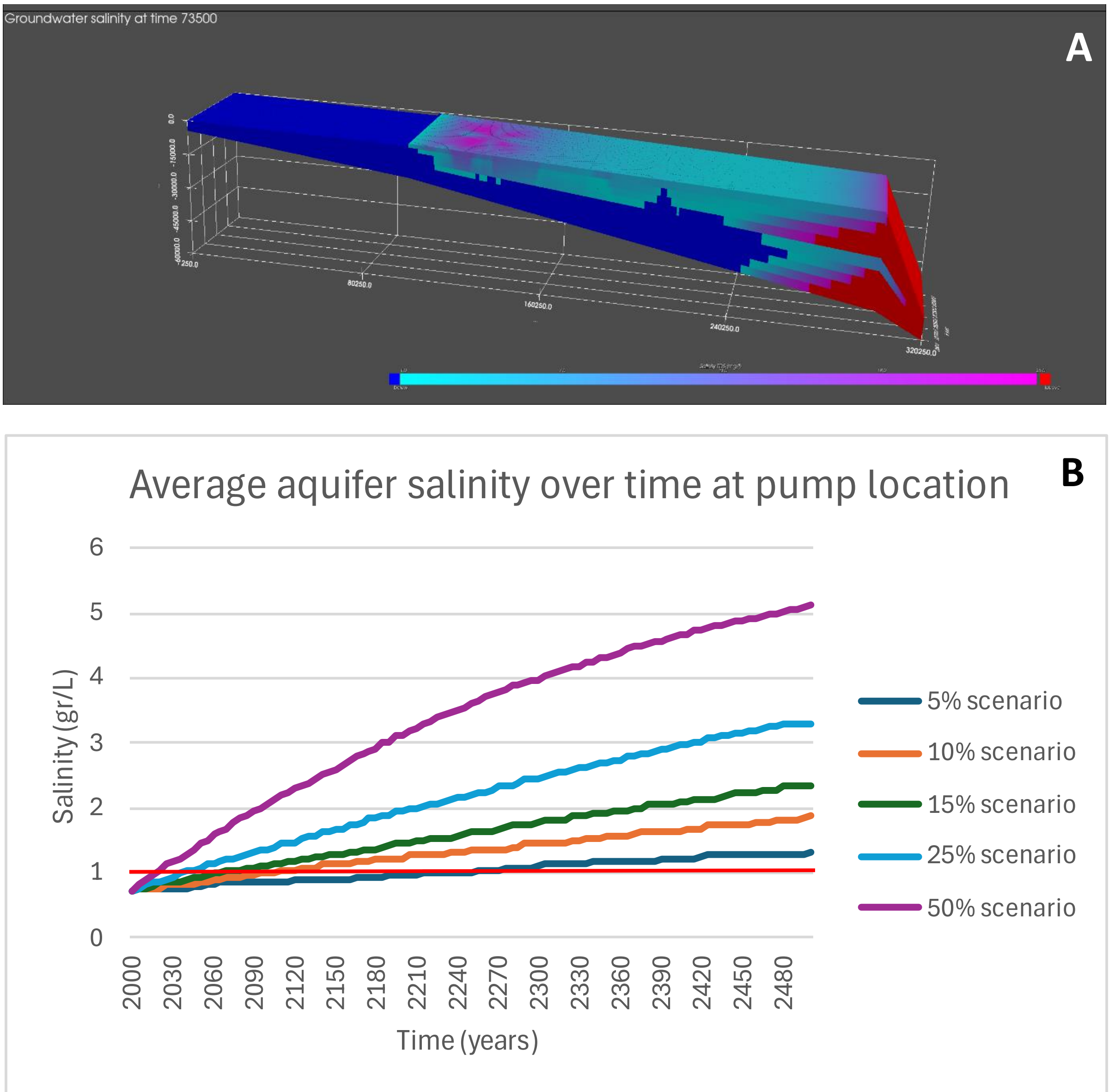


Figure 10 – (top) 3D-plot of the final timestep for pumping scenario five for the Pearl River Delta. Colors indicate the salinity within the modelled aquifer, fresh water is indicated in blue and highly saline water is indicated with red. (below) Line plot illustrating the course of the salinity levels inside the aquifer for each pumping scenario. The red line indicates the boundary value from fresh water to brackish water.

Yangtze River Delta

The Yangtze River Delta shows a more interesting result (Figure 12) as the previous two, as the lowest water prices are at the 15% scenario instead of the 50% scenario. From the start the water in this aquifer has an average salinity that is above 1 gr/L, thus brackish. All extracted water has to be desalinated. In the case of the 15% scenario the extraction is the most beneficial, as it is able to extract for 425 years resulting in the lowest cost for water, this is explained in more detail below. The 25% and 50% scenario extracted brackish water for 210 and 85 years respectively, despite their large extraction rates the total volume of brackish water extracted was not large enough that it results in lower costs when using equation 10.

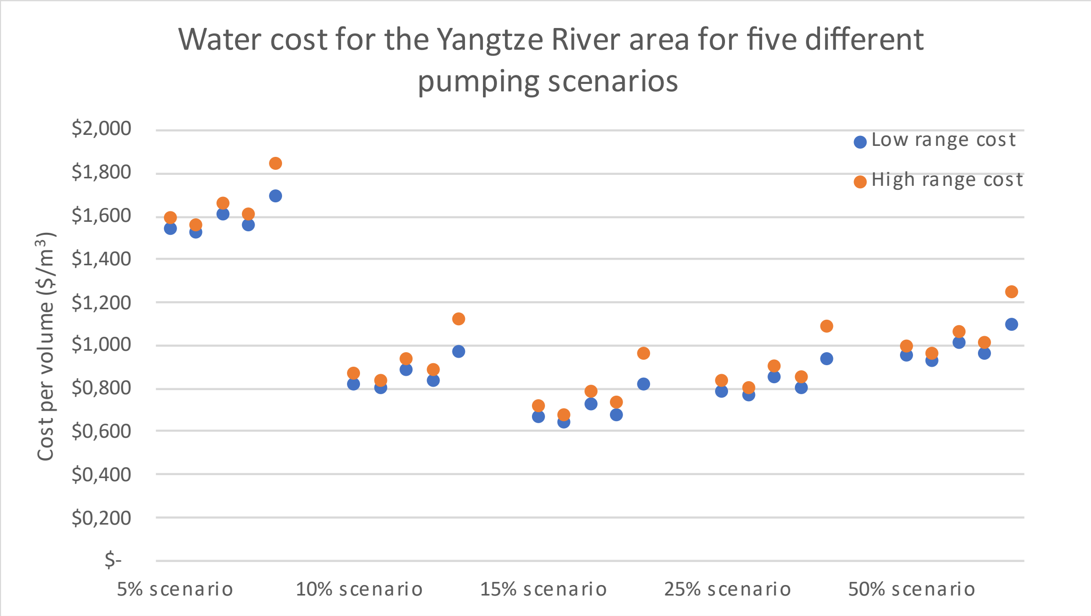


Figure 11 – The cost of water for each of the five pumping scenarios. The low range cost, in blue, assumes the lowest available cost for energy and desalination. The high range cost, in orange, assumes the highest available cost for energy and desalination. The five data points in each scenario represent the energy source used (f.l.t.r.: solar, onshore wind, offshore wind, fossil fuel low, fossil fuel high). The scenarios are in order of amount of groundwater substituted with an offshore source with increasing extraction rates, which can be found in Table 1.

The extraction cost for each scenario is the same, due to the fact that the energy cost increases proportionally with the volume extracted. For low range extraction the cost is $0.032 and the high range is $0.087. The desalination costs that are added for each energy source from Table 3 are already in $/m^3 so this can be added to the total directly. The Yangtze River Delta sees the medium amount of money needed for the installation cost at $3.3 billion, dividing this with total water volume the installation cost is $0.566 per cubic meter for the 15% scenario. Adding all this up gives a range of cost per cubic meter where the average cost per volume of the 15% scenario is $0.710 and $0.778 for the low and high range cost respectively. An overview of all costs involved of all five scenarios can be found in Appendix 6. If this is multiplied by the average water consumption in China the total water cost is $301.96 and $330.77, being 154% and 169% higher than the average water cost in China of $195.50.

The large extraction rate for the 50% scenario results in a highly saline aquifer at the end of the simulation as can be seen in Figure 13-A. Despite having the same hydraulic conductivity, the seawater intrusion from the shelf edge is much higher because of the large extraction rate. Average salinities reach much higher values throughout the whole aquifer. At the pump locations seawater reaches to the deepest layer in the top aquifer, making the extracted water unsuitable.

Figure 13-B clearly show that no water is ever fresh in this simulation (lower red line), and that for the 15%, 25%, and 50% scenario the water even breaches through the threshold of saline water, making the water unusable for the purpose of this study. The 5%, 10%, and 15% scenario still show an almost linear trend, where the 50% scenario clearly shows an exponential increase for the first quarter of timesteps, and steadily flattening out over the rest of the simulation.

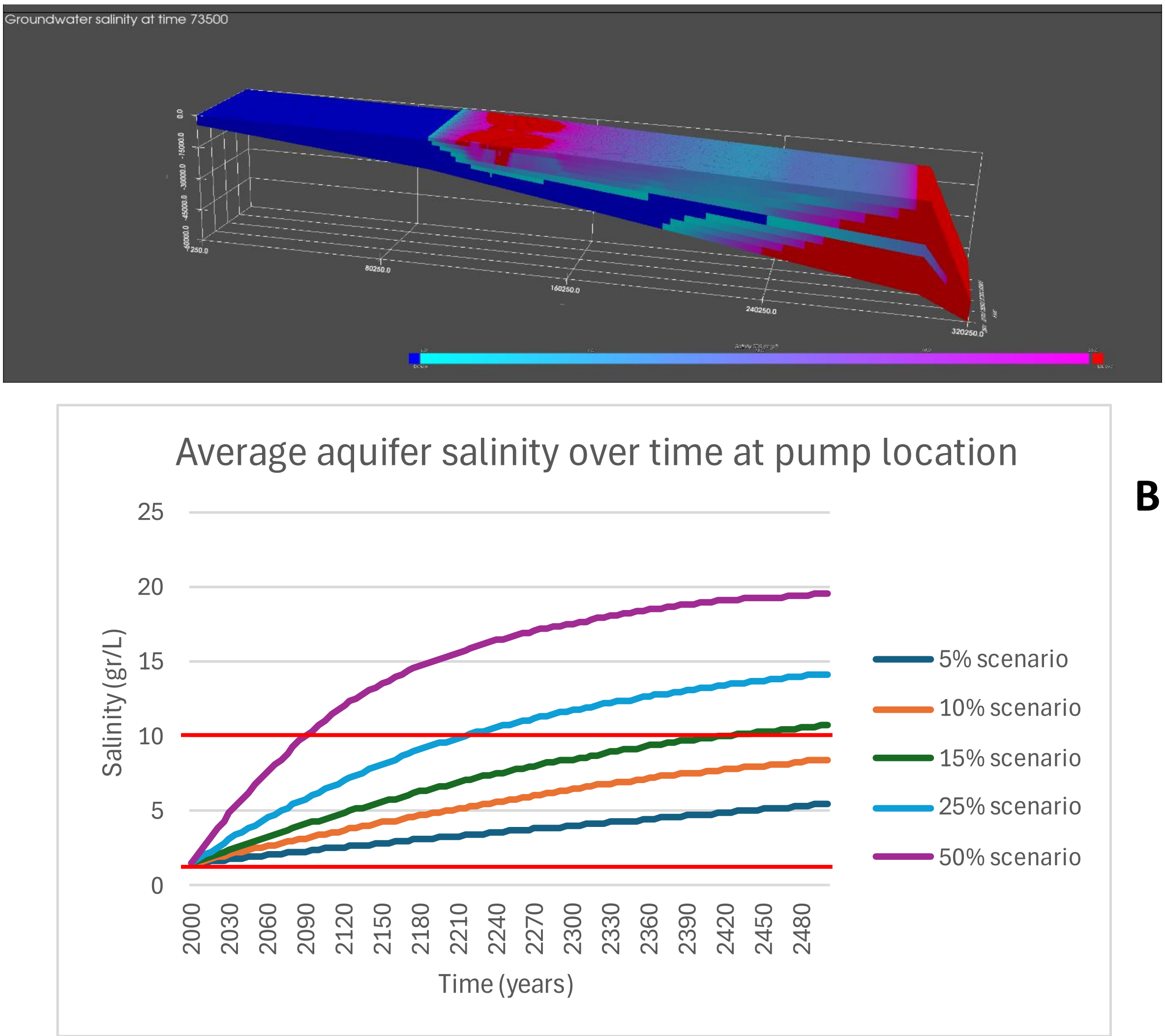


Figure 12 – (top) 3D-plot of the final timestep for pumping scenario five for the Yangtze River Delta. Colors indicate the salinity within the modelled aquifer, fresh water is indicated in blue and highly saline water is indicated with red. (below) Line plot illustrating the course of the salinity levels inside the aquifer for each pumping scenario. The lower red line indicates the boundary value from fresh water to brackish water and the upper line the boundary from brackish water to saline water.

Water extraction cost

According to Immerzeel et al., 2011 the global average cost of extracting water is 0.25 $/m^3$. With equation 10 our own estimated cost of extracting water can be calculated. The calculated cost and the global average will be compared to evaluate if the offshore groundwater is an economically viable option as a new freshwater resource.

Table 3 -Overview of the extraction costs for each of the five scenarios. Column 2, 4, 6: Extraction cost for the lower range electricity cost. Column 3, 5, 7: Extraction cost for the higher range electricity cost.

Scenario	**Bohai Sea**		**Pearl River**		**Yangtze River**	
5% scenario	$12.612.520	$33.939.146	$35.472.714	$95.453.850	$73.959.515	$199.018.332
10% scenario	$25.227.231	$67.884.185	$70.955.693	$190.935.320	$147.924.915	$398.052.500
15% scenario	$37.839.752	$101.823.332	$106.428.408	$286.389.171	$188.601.766	$507.510.207
25% scenario	$63.066.983	$169.707.518	$177.373.837	$477.296.872	$155.319.925	$417.951.799
50% scenario	$126.136.156	$339.420.929	$354.757.939	$954.621.365	$125.735.177	$338.341.933

Reverse osmosis cost

With the current technologies, the process of reverse osmosis has an energy consumption ranging from 3 to 8 kWh/m^3 for seawater desalination and a comparatively lower range of 1.5 to 2.5 kWh/m^3 for brackish water (Abdelkareem et al., 2017; Shahzad et al., 2017). According to estimates, the global cost of desalination stands at approximately 0.90 \$/m^3 for solar energy and 1.20 \$/m^3 for fossil fuel-based methods (Immerzeel et al., 2011). In this case, I try to calculate and compare the actual desalination costs against these global estimates, considering various energy sources including solar, offshore and onshore wind, and fossil fuels. The analysis encompasses both lower and upper limits of each energy source across brackish and seawater desalination scenarios.

Table 4 - Column 1: type of energy source, Column 2 and 3: cost of desalination per cubic meter of brackish water for the lower and upper range values, Column 4 and 5: cost of desalination per cubic meter of seawater for the lower and upper range values.

Energy source	Brackish lower limit (\$/m^3)	Brackish upper limit (\$/m^3)	Seawater lower limit (\$/m^3)	Seawater upper limit (\$/m^3)
Onshore wind	0.050	0.083	0.099	0.264
Offshore wind	0.113	0.188	0.225	0.600
Solar	0.072	0.120	0.144	0.384
Fossil fuel low	0.083	0.138	0.165	0.440
Fossil fuel high	0.222	0.370	0.444	1.184

Installation cost

Accessing comprehensive data regarding the preparation and installation of offshore subsea water pumps presents a challenge. To establish a preliminary understanding of associated costs, the expenditure for offshore wind farm installations is referenced, given their comparable depths and locations to those relevant in this study. The cost of a foundation is set at \$100,000 per unit (Wind Farm Costs – Guide to an Offshore Wind Farm, n.d.), it is projected that these foundations have a 25-year lifespan. Consequently, the replacement of ten foundations over twenty cycles has a cumulative cost of \$20 million.

Maintenance activities on offshore infrastructure pose logistical complexities, necessitating more frequent interventions than their onshore counterparts. The estimated maintenance cost stands at \$50,000 (Wind Farm Costs – Guide to an Offshore Wind Farm, n.d.). Assuming that maintenance is done every five years for ten pumps, cumulative maintenance operations total 100 over the simulation period, culminating in a total cost of \$50 million.

The expenses of the water pumps are estimated at \$100,000 per unit. The lifetime of a pump is set at 25 years, and over the course of the simulation, pumps have to be installed 20 times. In total 200 pumps have to be installed, costing a total of \$20 million.

Installing seafloor pipelines is an expensive operation, requiring specialized vessels and equipment to ensure placement is done safely in suitable zones with minimal ecological impact. The cost of installing pipelines is around \$2 million per kilometer (Kaiser, 2017), with the operational life of high-capacity pipelines estimated at 50 years (Kenny, 2018). In the model, pipelines extend 20 kilometers offshore in two rows with a total installation distance of 40 kilometers. Which is repeated ten times, thus totaling a cost of \$800 million.

The cost of drilling an injection well is \$68.8 million. In this study, we use the cost on a per meter basis, which is \$26,500 per meter for exploration and delineation (Kaiser, 2021). The lifespan of an offshore well is 20 years (Palkar & Markeset, 2012, and Life Cycle of a Well | Exploration | Well Abandonment | Reclamation, n.d.). Thus, wells have to be redrilled 25 times over the course of the simulation. The drilling costs in the Bohai Sea (80m), Pearl River (375m), and Yangtze Delta (215m) are $530 million, $2,484 million, and $1,424 million respectively.

The cost of drilling rigs depends heavily on the location of where a well should be drilled. Different seas are easier to navigate than others or have longer operating seasons. A jackup or a floater type of rig can be used to perform drilling operations. This comes with a price tag of $200,000 per day (Kaiser, 2009, and Kaiser & Snyder, 2013). The time it takes to drill a well and make it operable depends on the complexity of the project and can take between 15 days to 12 months (Offshore Drilling Basics | Deepwater Drilling | Diamond Offshore Drilling, n.d.). Utilizing the calculations in Kaiser (2009), drilling one well takes 18 days for the Bohai Sea, 21 days at the Pearl River, and 20 days for the Yangtze River. Considering a well's 20-year lifespan and the need for 25 deployments, operational costs for drilling rigs in the previously mentioned regions sum up to $900 million, $1,050 million, and $1,000 million respectively.

A comprehensive overview of the total installation costs over the simulation period of 500 years are depicted in Table 5 below.

Table 5 - Table containing all costs for each subject that adds to the total. Column 1: the names of the six main contributors and the total cost, Column 2-4: the three study regions with their respective costs for each contributor.

	Bohai Sea	**Pearl River**	**Yangtze River**
Foundation	$ 20.000.000,00	$ 20.000.000,00	$ 20.000.000,00
Maintenance	$ 50.000.000,00	$ 50.000.000,00	$ 50.000.000,00
Pipelines	$ 800.000.000,00	$ 800.000.000,00	$ 800.000.000,00
Pump	$ 20.000.000,00	$ 20.000.000,00	$ 20.000.000,00
Drilling rig/day	$ 900.000.000,00	$ 1.050.000.000,00	$ 1.000.000.000,00
Drilling cost/meter	$ 530.000.000,00	$ 2.484.375.000,00	$ 1.424.375.000,00
Total	$ 2.320.000.000,00	$ 4.424.375.000,00	$ 3.314.375.000,00

The comparison of water extraction scenarios in the three different regions reveals significant insights into cost-effectiveness and salinity concerns. Initially, all regions exhibit a uniform decrease in total cost corresponding to the rise in extraction rate. However, as the scenarios progress differences emerge. Most notably in the Yangtze River Delta, where extraction rates get so large the water becomes saline in a majority of the scenarios. In contrast, the Bohai Sea and Pearl River Delta maintain a balance between recharge and extraction, making sure that aquifer salinity remains within the optimal range of 1 to 10 gr/L.

Cost considerations further differentiate between the regions, with the Yangtze River Delta showcasing more favorable costs per cubic meter than the Pearl River Delta due to extensive brackish water extraction and lower installation costs distributed across the total water volume. Despite variations in extraction rates, the graph's shape remains consistent across scenarios for each region. The total water cost calculation incorporates desalination prices, which are fixed within a range for each energy source utilized. This addition consistently contributes to the overall cost structure, reflecting a distinct pattern in the graph. However, this contrast is less pronounced in the graph of the Pearl River Delta due to the overall high total costs and the minimal variations in the desalination prices, which mitigate the impact of cost fluctuations on the graph's shape.

Discussion

Modelling and data

In this study, the focus was on offshore aquifer systems in three regions in China. While there is extensive literature on inland aquifer systems in these areas, offshore data is scarce, requiring estimations for offshore aquifer dimensions. This approach resulted in a model that significantly deviates from the actual aquifer volume and hydrogeological properties.

Despite these limitations and given the novelty of this research area, the primary objective was to create a pathway to evaluate if using OFG as a new groundwater source would be economically viable. By understanding the costs associated with offshore groundwater extraction and desalination, this study lays the groundwork for a framework that cities and countries can utilize to assess the feasibility of alleviating pressure on their terrestrial fresh water resources.

Another consideration is the generalized nature of the data concerning energy sources and desalination costs. Relying on globally collected data for energy source costs, it is important to remember that these are averages. The actual cost of electricity can vary significantly depending on location, source (e.g. fossil fuels, solar), and even time of year. Different energy sources have inherent cost differences due to the technology and efficiency involved. Desalination, for example, is a developing technology that is expected to become cheaper and more efficient over time, like what happened with renewable energy sources already over the last two decades (Figure 15).

Obtaining reliable, regional data on water use can be challenging, particularly in a country like China. Concerning its political climate, China might be hesitant to share detailed information on their water consumption and other data. Even more, being such a large country China can lack comprehensive data collection, making it difficult to track water usage across different regions. Finally, relying solely on national averages can be misleading. Highly populated areas and economic zones typically consume more water than rural regions. This reliance does not accurately reflect localized water demands and consumption patterns.

Desalination and energy costs

Regarding the calculated desalination costs in this study, they range from $0.05 to $1.18 per cubic meter, which is broader than the global average reported by Immerzeel et al. (2011). However, my results show all but one cost estimate falling below $0.90 per cubic meter, which was found to be a global average for solar energy desalination. This difference can be primarily attributed to the use of more recent data (2017 for desalination energy use and 2021 for energy costs). As renewable energy prices have dropped significantly since 2010 (How Falling Costs Make Renewables a Cost-effective Investment, 2020)

Moreover, using Equation 5 offers only a simplified approach to calculating energy use for lifting mass, extracting water from aquifers involves a more complex connection of factors. Pump efficiency plays a significant role, as mechanical losses due to friction and other factors can significantly impact energy consumption. Similarly, friction within the piping network contributes to energy loss. Additionally, as the water level in the aquifer declines, the available head pressure decreases, leading to reduced well flow rates and potentially higher energy requirements to maintain extraction.

Furthermore, each scenario progressively replaces a larger portion of the water source with offshore aquifer water. Due to the limitations of Equation 5 (its simplified nature), the energy usage increases proportionally to the increase in aquifer water substitution. This implies that the extraction cost per cubic meter remains constant across all scenarios. Notably, the overall cost is influenced by two additional factors: desalination costs and installation costs, both of which wield significant influence over the economic feasibility of offshore groundwater usage.

Attempts to gather precise information on industrial water pump costs were unsuccessful, as companies either declined cooperation or failed to respond. Exact costs for borehole pumps were not found in any sources, therefor the expense for the water pumps was estimated at $100,000 per unit.

Infrastructure and installation

Additionally, the aging global offshore pipeline network poses further complexities, with infrastructure operating beyond its intended design life (Britton & Taylor, 2017). Most offshore piping that is installed has a design life of 20-30 years, and due to excessive cost of decommissioning and replacement, repairs are made to safe on cost, resulting in an aged and potentially compromised network. In light of this, the economic analysis adopts a conservative approach, considering only pipeline replacement over a 50-year lifespan.

On the subject of installation costs, most information is uncertain. The large scale offshore industry as is known today is around since the 1960's. Regarding knowledge on design life or lifespan of offshore infrastructure is small, and only now coming up to the end of their first life-cycles.

Finally, the potential investments that have to be made to address drinking water challenges pales in comparison to the extensive damage that is done by flooding and drought events. For example, expenses due to drought reached into the tens of billions already in 1988 in the USA and substantial job losses were reported across various sectors (Riebsame et al., 2019 and Ding et al., 2011). Similarly, a study highlighted the significant impact of drought on Australia's economy, revealing a 1.6% decline in GDP during the 2002-2003 period (Horridge et al., 2005). In contrast, the costs associated with implementing the proposed solutions for drinking water issues amount to a few billion US dollars spread over a 500-year timeframe. This comparison underscores the relatively modest investment required for sustainable water management solutions in contrast to substantial economic losses and societal impacts incurred due to recurrent flooding and drought events.

Summary and conclusion

In this study, the focus was on offshore aquifer systems in three regions in China, a new research topic that presents unique challenges. Deterioration of water quality, land subsidence, climate change, and groundwater overdraft are one of the main causes of water stress. The UN has been trying for a long time to find suitable solutions. Recently, developments in offshore aquifers containing fresh water show a suitable solution.

Water stress is an issue found all over the globe. In some areas this is the cause due to high water demand for agriculture or the energy industry, and in others it is due to their arid climates or both. Not all regions have had the conditions where offshore fresh groundwater could be formed. With large and shallow continental shelfs the seafloor is exposed to the elements during glacial periods when sea levels dropped significantly, allowing for freshwater to slowly infiltrate into the subsurface. Unfortunately, these conditions are not found globally, making the solution in this study not applicable everywhere.

A factor that needs to be taken into account is the economic feasibility of offshore groundwater extraction. With the use of 3D modelling conceptual models are made to simulate the groundwater flow and salinization of offshore aquifers. An economic analysis incorporating extraction, desalination, and infrastructure cost, is used to find the expenses involved in this solution. The Bohai Sea showed one scenario where the average water cost could potentially be lower than the national average

($146.42 and $175.24 instead of $195.50). All other scenarios were more expensive than the current price of water in China, however the largest increase in cost for the best scenarios is only twice as large as the current water prices. Making offshore fresh groundwater pumping an attractive solution to combat water scarcity.
The investment in this solution is probably worth its higher cost, potentially outweighing the economic damages that result from the continued use of inland water sources.

As a novel area of research, this study contributes valuable insights into offshore aquifer systems in China. While limitations exist in data availability and model accuracy, the findings provide a foundation for further research and policy development in water resource management. Future studies should aim to address data gaps, refine modeling techniques, and engage with industry partners to enhance the robustness of findings in this evolving field.

References

Adamu, C. I., & Nganje, T. N. (2010). Heavy metal contamination of surface soil in relationship to land use patterns: A case study of Benue State, Nigeria. Materials Sciences and Applications, 01(03), 127–134. https://doi.org/10.4236/msa.2010.13021

Allow, K. A. (2011). The use of injection wells and a subsurface barrier in the prevention of seawater intrusion: a modeling approach. Arabian Journal of Geosciences, 5(5), 1151–1161. https://doi.org/10.1007/s12517-011-0304-9

Aqueduct. (2023, October 17). World Resources Institute. https://www.wri.org/aqueduct

Bagheri-Gavkosh, M., Hosseini, S. M., Ataie-Ashtiani, B., Sohani, Y., Ebrahimian, H., Morovat, F., & Ashrafi, S. (2021). Land subsidence: A global challenge. Science of the Total Environment, 778, 146193. https://doi.org/10.1016/j.scitotenv.2021.146193

Barbier, E. B. (2015). Climate change impacts on rural poverty in low-elevation coastal zones. *Estuarine Coastal and Shelf Science*, *165*, A1–A13. https://doi.org/10.1016/j.ecss.2015.05.035

Britton, J., & Taylor, M. A. (2017). Advancements in Cathodic Protection of offshore structures. In *Elsevier eBooks* (pp. 593–612). https://doi.org/10.1016/b978-0-08-101105-8.00025-5

Centre for Research on the Epidemiology of Disasters [CRED]. (2023). 2022 Disaster in numbers. In *https://www.cred.be/publications*.

Chan, F. K. S., Adekola, O., Mitchell, G., Ng, C. N., & McDonald, A. (2013). TOWARDS SUSTAINABLE FLOOD RISK MANAGEMENT IN THE CHINESE COASTAL MEGACITIES. a CASE STUDY OF PRACTICE IN THE PEARL RIVER DELTA. *Irrigation and Drainage*, *62*(4), 501–509. https://doi.org/10.1002/ird.1733

Chaudhuri, S., & Roy, M. (2017). Drinking water sources in India: how safe is safe? *Current Science*, *113*(3), 393–402. http://www.jstor.org/stable/26293995

Chaussard, E., Amelung, F., & Abidin, H. Z. (2012, September). Sinking cities in Indonesia: Space-geodetic evidence of the rates and spatial distribution of land subsidence. In Proceedings of the FRINGE 2011 Workshop, Frascati, Italy (Vol. 19, p. 23).

Chen, Z., Ngo, H. H., Guo, W., & Eslamian, S. (2015). Water shortages. In *Urban Water Reuse Handbook* (1st ed., pp. 39–50). CRC press. https://doi.org/10.1201/b19646-6

Clark, P. U., Dyke, A. S., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., Mitrovica, J. X., Hostetler, S. W., & McCabe, A. (2009). The last glacial maximum. *Science*, *325*(5941), 710–714. https://doi.org/10.1126/science.1172873

Climate adaptation and saltwater intrusion. (2023, June 14). EPA. https://www.epa.gov/arc-x/climate-adaptation-and-saltwater-intrusion

Cohen, D., Person, M., Wang, P., Gable, C. W., Hutchinson, D. R., Marksamer, A., Dugan, B., Kooi, H., Groen, K., Lizarralde, D., Evans, R., Day-Lewis, F. D., & Lane, J. W. (2010). Origin and Extent of Fresh Paleowaters on the Atlantic Continental Shelf, USA. Groundwater, 48(1), 143–158. https://doi.org/10.1111/j.1745-6584.2009.00627.x

Curto, D., Franzitta, V., & Guercio, A. (2021). A review of the water desalination technologies. *Applied Sciences*, *11*(2), 670. https://doi.org/10.3390/app11020670

De Stefano, L., & López-Gunn, E. (2012). Unauthorized groundwater use: institutional, social and ethical considerations. *Water Policy*, *14*(S1), 147–160. https://doi.org/10.2166/wp.2012.101

Ding, Y., Hayes, M. J., & Widhalm, M. (2011). Measuring economic impacts of drought: a review and discussion. *Disaster Prevention and Management*, *20*(4), 434–446. https://doi.org/10.1108/09653561111161752

Du, X., Guo, H., Fan, X., Zhu, J., Yan, Z., & Zhan, Q. (2015). Vertical accuracy assessment of freely available digital elevation models over low-lying coastal plains. *International Journal of Digital Earth*, *9*(3), 252–271. https://doi.org/10.1080/17538947.2015.1026853

Edwards, B. D., & Evans, K. R. (2013). Saltwater intrusion in Los Angeles area coastal aquifers—The marine connection; USGS Fact Sheet 030–02.

Erkens, G., Bucx, T., Dam, R., De Lange, G., & Lambert, J. (2015). Sinking coastal cities. Proceedings of the International Association of Hydrological Sciences, 372(372), 189-198.

FAO. (2011). *Country fact Sheet - China*. Retrieved January 12, 2024, from https://www.fao.org/aquastat/en/countries-and-basins/country-profiles/country/CHN

Foley, J. (2015, May). *Fundamentals of energy use in water pumping*. cottoninfo.com.au. Retrieved February 26, 2024, from https://www.cottoninfo.com.au/sites/default/files/documents/Fundamentals%20EnergyFS_A_3a.pdf

Fried, J. J. (1975). Groundwater pollution. Elsevier.

Funari, E., Manganelli, M., & Sinisi, L. (2012). Impact of climate change on waterborne diseases. Annali dell'Istituto superiore di sanita, 48, 473-487.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., & Moulin, P. (2009). Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Research, 43(9), 2317–2348. https://doi.org/10.1016/j.watres.2009.03.010

Gupta, A. (2001). Challenges and opportunities for water resources management in southeast Asia. *Hydrological Sciences Journal*, *46*(6), 923–935. https://doi.org/10.1080/02626660109492886

Horridge, M., Madden, J. R., & Wittwer, G. (2005). The impact of the 2002–2003 drought on Australia. *Journal of Policy Modeling*, *27*(3), 285–308. https://doi.org/10.1016/j.jpolmod.2005.01.008

How falling costs make renewables a cost-effective investment. (2020, June 2). https://www.irena.org/news/articles/2020/Jun/How-Falling-Costs-Make-Renewables-a-Cost-effective-Investment

Immerzeel, W., Droogers, P., Terink, W., Hoogeveen, J., Hellegers, P. J. J. G., Bierkens, M., & Van Beek, R. (2011). Middle-east and northern Africa water outlook. *Report FutureWater*, *98*.

IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-452-3

Kaiser, M. J. (2009). Modeling the time and cost to drill an offshore well. *Energy*, *34*(9), 1097–1112. https://doi.org/10.1016/j.energy.2009.02.017

Kaiser, M. J. (2017). Offshore pipeline construction cost in the U.S. Gulf of Mexico. *Marine Policy*, *82*, 147–166. https://doi.org/10.1016/j.marpol.2017.05.003

Kaiser, M. J. (2021). A review of exploration, development, and production cost Offshore Newfoundland. *Natural Resources Research*, *30*(2), 1253–1290. https://doi.org/10.1007/s11053-020-09784-3

Kaiser, M. J., & Snyder, B. F. (2013). The five offshore drilling rig markets. *Marine Policy*, *39*, 201–214. https://doi.org/10.1016/j.marpol.2012.10.019

Kenny, S. (2018). Offshore Pipelines—Elements of Managing Risk. In *Methods in chemical process safety* (pp. 289–325). https://doi.org/10.1016/bs.mcps.2018.04.005

Klingbeil, R., & Al-Hamdi, M. I. (2010). Transboundary Water and Transboundary Aquifers in the Middle East: Opportunities for Sharing a Precious Resource. *ISARM*.

Langevin, C. D., Thorne, D. T., Dausman, A., Sukop, M. C., & Guo, W. (2008). SEAWAT Version 4: A computer program for simulation of Multi-Species solute and heat transport. Techniques and Methods. https://doi.org/10.3133/tm6a22

Lezzaik, K., & Milewski, A. (2017). A quantitative assessment of groundwater resources in the Middle East and North Africa region. *Hydrogeology Journal*, *26*(1), 251–266. https://doi.org/10.1007/s10040-017-1646-5

Life cycle of a well | exploration | well abandonment | reclamation. (n.d.). CAPP | a Unified Voice for Canada's Upstream Oil and Gas Industry. https://www.capp.ca/explore/life-cycle-of-a-well

Liu, Y., Lai, Z., Yu, H., Xu, X., Su, Q., Yao, J., Wang, X., & Shi, X. (2012). Chronologies of sedimentary changes in the south Bohai Sea, China: constraints from luminescence and radiocarbon dating. *Boreas*, *42*(2), 267–284. https://doi.org/10.1111/j.1502-3885.2012.00271.x

Llamas, M. R., & Martínez-Santos, P. (2005). Intensive groundwater use: silent revolution and potential source of social conflicts. Journal of Water Resources Planning and Management, 131(5), 337–341. https://doi.org/10.1061/(asce)0733-9496(2005)131:5(337)

Maul, G. A., & Duedall, I. W. (2019). Demography of coastal populations. In *Encyclopedia of earth sciences* (pp. 692–700). https://doi.org/10.1007/978-3-319-93806-6_115

Micallef, A., Person, M., Berndt, C., Bertoni, C., Cohen, D., Dugan, B., Evans, R., Haroon, A., Hensen, C., Jegen, M., Key, K., Kooi, H., Liebetrau, V., Lofi, J., Mailloux, B. J., Martin-Nagle, R., Michael, H. A., Müller, T. J., Schmidt, M., . . . Thomas, A. (2021). Offshore freshened groundwater in continental margins. *Reviews of Geophysics*, *59*(1). https://doi.org/10.1029/2020rg000706

Michael, H. A., Post, V., Wilson, A. M., & Werner, A. D. (2017). Science, society, and the coastal groundwater squeeze. Water Resources Research, 53(4), 2610–2617. https://doi.org/10.1002/2017wr020851

Mukherjee, A., Saha, D., Harvey, C. F., Taylor, R. G., Ahmed, K. M., & Bhanja, S. N. (2015). Groundwater systems of the Indian Sub-Continent. *Journal of Hydrology: Regional Studies*, *4*, 1–14. https://doi.org/10.1016/j.ejrh.2015.03.005

Mushtaq, A. Q., & Afzal, M. H. B. (2017). Arab Spring: Its Causes And Consequences. *JPUHS*, *30*(1). http://pu.edu.pk/images/journal/HistoryPStudies/PDF_Files/01_V-30-No1-Jun17.pdf

NASA. (2016, March). *Low-Elevation Coastal Zone (LECZ)*. CIESIN.

http://www.ciesin.org/documents/lecz-final.pdf

Palkar, S., & Markeset, T. (2012). Extending the service life span of ageing oil and gas offshore production facilities. In *IFIP advances in information and communication technology* (pp. 213–221). https://doi.org/10.1007/978-3-642-33980-6_25

Poland, J. F., & Davis, G. H. (1969). Land subsidence due to withdrawal of fluids. Reviews in engineering geology, 2, 187-270.

Post, V., Groen, J., Kooi, H., Person, M., Ge, S., & Edmunds, W. (2013). Offshore fresh groundwater reserves as a global phenomenon. Nature, 504(7478), 71–78. https://doi.org/10.1038/nature12858

Raghav, S., Painuli, R., & Kumar, D. (2018). Threats to water: Issues and challenges related to ground water and drinking water. In Springer eBooks (pp. 1–19). https://doi.org/10.1007/978-3-319-75484-0_1

Reimann, L., Vafeidis, A. T., & Honsel, L. E. (2023). Population development as a driver of coastal risk: Current trends and future pathways. *Cambridge Prisms Coastal Futures*, *1*. https://doi.org/10.1017/cft.2023.3

Riebsame, W. E., Changnon, S. A., & Karl, T. R. (2019). Drought and natural resources management in the United States. In *Routledge eBooks*. https://doi.org/10.4324/9780429045332

Ritchie, H. (2017, November 20). Water use and stress. Our World in Data. https://ourworldindata.org/water-use-stress

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, *460*(7258), 999–1002. https://doi.org/10.1038/nature08238

Rozemeijer, J., & Broers, H. P. (2007). The groundwater contribution to surface water contamination in a region with intensive agricultural land use (Noord-Brabant, The Netherlands). Environmental Pollution, 148(3), 695–706. https://doi.org/10.1016/j.envpol.2007.01.028

Salehi, M. (2022). Global water shortage and potable water safety; Today's concern and tomorrow's crisis. Environment International, 158, 106936. https://doi.org/10.1016/j.envint.2021.106936

Sellner, K. G., Doucette, G. J., & Kirkpatrick, G. J. (2003). Harmful algal blooms: causes, impacts and detection. *Journal of Industrial Microbiology & Biotechnology*, *30*(7), 383–406. https://doi.org/10.1007/s10295-003-0074-9

Stanton, J. S., Anning, D. W., Brown, C. J., Moore, R. B., McGuire, V. L., Qi, S. L., Harris, A. C., Dennehy, K. F., McMahon, P. B., Degnan, J. R., & Böhlke, J. K. (2017). Brackish groundwater in the United States. *U.S. Geological Survey Professional Paper*. https://doi.org/10.3133/pp1833

Stein, S., Yechieli, Y., Shalev, E., Kasher, R., & Sivan, O. (2019). The effect of pumping saline groundwater for desalination on the fresh–saline water interface dynamics. *Water Research*, *156*, 46–57. https://doi.org/10.1016/j.watres.2019.03.003

Tariq, A., & Mushtaq, A. (2023). Untreated wastewater reasons and causes: A review of most affected areas and cities. *Int. J. Chem. Biochem. Sci*, *23*, 121-143.

Total water use in the United States | U.S. Geological Survey. (2018, August 30). https://www.usgs.gov/special-topics/water-science-school/science/total-water-use-united-states#overview

United Nations. (n.d.). Water | United Nations. https://www.un.org/en/global-issues/water

United Nations Statistics Division. (n.d.). — SDG indicators. https://unstats.un.org/sdgs/report/2023/

Wang, T., Sun, D., Zhang, Q., & Zhang, Z. (2021). China's drinking water sanitation from 2007 to 2018: A systematic review. *Science of the Total Environment*, *757*, 143923. https://doi.org/10.1016/j.scitotenv.2020.143923

Warf, B. (2015). Corruption in the Middle East and North Africa: a geographic perspective. *The Arab World Geographer*, *18*, 1–18. https://doi.org/10.5555/1480-6800.18.1.1

"Water rates and services" Metropolitan Water Authority (MWA). Retrieved 18 January 2024. https://www.mwa.co.th/services/users-should-know/users-service-rate/service-rate/

Werner, A. D., Bakker, M., Post, V., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C. T., & Barry, D. A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources, 51, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004

Wind farm costs – Guide to an offshore wind farm. (n.d.). https://guidetoanoffshorewindfarm.com/wind-farm-costs

World Health Organization: WHO. (2023, September 13). Drinking-water. https://www.who.int/news-room/fact-sheets/detail/drinking-water

Xie, X. L., Tu, X., Zhu, J., Singh, V. P., & Chai, Y. (2023). Spatiotemporal variability and impact factors of domestic water prices in China. *Water*, *16*(1), 115. https://doi.org/10.3390/w16010115

Yao, M. (2017). *Water use in a heavily urbanized delta : scenarios and adaptation options for sectorial water use in the Pearl River Basin, China*. https://doi.org/10.18174/426923

Younos, T., & Tulou, K. E. (2005). Overview of desalination techniques. Journal of Contemporary Water Research & Education, 132(1), 3-10.

Zamrsky, D., Essink, G. O., Sutanudjaja, E. H., Van Beek, R., & Bierkens, M. F. (2021). Offshore fresh groundwater in coastal unconsolidated sediment systems as a potential fresh water source in the 21st century. Environmental Research Letters, 17(1), 014021. https://doi.org/10.1088/1748-9326/ac4073

Zektser, S., Loáiciga, H. A., & Wolf, J. (2004). Environmental impacts of groundwater overdraft: selected case studies in the southwestern United States. Environmental Geology, 47(3), 396–404. https://doi.org/10.1007/s00254-004-1164-3

Zhang, D., Gersberg, R. M., Wilhelm, C., & Voigt, M. (2009). Decentralized water management: rainwater harvesting and greywater reuse in an urban area of Beijing, China. *Urban Water Journal*, *6*(5), 375–385. https://doi.org/10.1080/15730620902934827

Zhang, X., Lin, J., Huang, H., Deng, J., & Chen, A. (2022). Analysis on the dynamics of coastline and reclamation in Pearl River Estuary in China for nearly last half century. *Water*, *14*(8), 1228. https://doi.org/10.3390/w14081228

Appendix 1. Extraction rate calculations Bohai Sea

Bohai Sea with the scenario where 5% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (110 * 10^6)}{365} * 17.99\% = 23{,}041{,}986$$

$$DGW_m = 23{,}041{,}986 * \frac{25}{500} = 1{,}152{,}099$$

$$E = \frac{1{,}152{,}099 * 5\%}{10} = 5{,}760$$

Bohai Sea with the scenario where 10% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (110 * 10^6)}{365} * 17.99\% = 23{,}041{,}986$$

$$DGW_m = 23{,}041{,}986 * \frac{25}{500} = 1{,}152{,}099$$

$$E = \frac{1{,}152{,}099 * 10\%}{10} = 11{,}521$$

Bohai Sea with the scenario where 15% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (110 * 10^6)}{365} * 17.99\% = 23{,}041{,}986$$

$$DGW_m = 23{,}041{,}986 * \frac{25}{500} = 1{,}152{,}099$$

$$E = \frac{1{,}152{,}099 * 15\%}{10} = 17{,}281$$

Bohai Sea with the scenario where 25% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (110 * 10^6)}{365} * 17.99\% = 23{,}041{,}986$$

$$DGW_m = 23{,}041{,}986 * \frac{25}{500} = 1{,}152{,}099$$

$$E = \frac{1{,}152{,}099 * 25\%}{10} = 28{,}802$$

Bohai Sea with the scenario where 50% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (110 * 10^6)}{365} * 17.99\% = 23{,}041{,}986$$

$$DGW_m = 23{,}041{,}986 * \frac{25}{500} = 1{,}152{,}099$$

$$E = \frac{1{,}152{,}099 * 50\%}{10} = 57{,}605$$

Appendix 2. Overview of volume and cost Bohai Sea

Below are five tables, one for each of the scenarios containing the most important data. Fresh, brackish, and total volume of water in cubic meters, the low and high range of the extraction cost, the one-time installation cost, and the combined total low and high range cost for each energy source used.

Bohai Sea, Scenario 1	**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
Fresh	262,980,000	$0.012	$0.032	$2.205	Solar	$2.289	$2.337
Brackish	788,940,000				Wind onshore	$2.267	$2.300
Total	1,051,192,000				Wind offshore	$2.350	$2.405
					Fossil fuel low	$2.300	$2.355
					Fossil fuel high	$2.439	$2.587

Bohai Sea, Scenario 2	**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
Fresh	252,482,715	$0.012	$0.032	$1.103	Solar	$1.187	$1.235
Brackish	1,851,539,910				Wind onshore	$1.165	$1.198
Total	2,104,022,625				Wind offshore	$1.248	$1.303
					Fossil fuel low	$1.198	$1.253
					Fossil fuel high	$1.337	$1.485

Bohai Sea, Scenario 3	**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
Fresh	252,475,410	$0.012	$0.032	$0.735	Solar	$0.819	$0.867
Brackish	2,903,467,215				Wind onshore	$0.797	$0.830
Total	3,155,942,625				Wind offshore	$0.880	$0.935
					Fossil fuel low	$0.830	$0.885
					Fossil fuel high	$0.969	$1.117

Bohai Sea, Scenario 4		**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
	Fresh	262,998,262	$0.012	$0.032	$0.441	Solar	$0.525	$0.573
	Brackish	4,996,966,988				Wind onshore	$0.503	$0.536
	Total	5,259,965,250				Wind offshore	$0.586	$0.641
						Fossil fuel low	$0.536	$0.591
						Fossil fuel high	$0.675	$0.823

Bohai Sea, Scenario 5		**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
	Fresh	210,402,262	$0.012	$0.032	$0.221	Solar	$0.305	$0.353
	Brackish	10,309,710,863				Wind onshore	$0.283	$0.316
	Total	10,520,113,125				Wind offshore	$0.366	$0.421
						Fossil fuel low	$0.316	$0.371
						Fossil fuel high	$0.455	$0.603

Appendix 3. Extraction rate calculations Pearl River Delta

Pearl river with the scenario where 5% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (66 * 10^6)}{365} * 17.99\% = 13{,}825{,}192$$

$$DGW_m = 13{,}825{,}192 * \frac{25}{500} = 691{,}260$$

$$E = \frac{691{,}260 * 5\%}{10} = 3{,}456$$

Pearl river with the scenario where 10% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (66 * 10^6)}{365} * 17.99\% = 13{,}825{,}192$$

$$DGW_m = 13{,}825{,}192 * \frac{25}{500} = 691{,}260$$

$$E = \frac{691{,}260 * 10\%}{10} = 6{,}913$$

Pearl river with the scenario where 15% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (66 * 10^6)}{365} * 17.99\% = 13{,}825{,}192$$

$$DGW_m = 13{,}825{,}192 * \frac{25}{500} = 691{,}260$$

$$E = \frac{691{,}260 * 15\%}{10} = 10{,}369$$

Pearl river with the scenario where 25% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (66 * 10^6)}{365} * 17.99\% = 13{,}825{,}192$$

$$DGW_m = 13{,}825{,}192 * \frac{25}{500} = 691{,}260$$

$$E = \frac{691{,}260 * 25\%}{10} = 17{,}281$$

Pearl river with the scenario where 50% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (66 * 10^6)}{365} * 17.99\% = 13{,}825{,}192$$

$$DGW_m = 13{,}825{,}192 * \frac{25}{500} = 691{,}260$$

$$E = \frac{691{,}260 * 50\%}{10} = 34{,}563$$

Appendix 4. Overview of volume and cost Pearl River Delta

Below are five tables, one for each of the scenarios containing the most important data. Fresh, brackish, and total volume of water in cubic meters, the low and high range of the extraction cost, the one-time installation cost, and the combined total low and high range cost for each energy source used.

Pearl River Delta, Scenario 1		**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
	Fresh	271,395,360	$0.056	$0.151	$7.010	Solar	$7.138	$7.186
	Brackish	359,756,640				Wind onshore	$7.116	$7.149
	Total	631,115,200				Wind offshore	$7.199	$7.254
						Fossil fuel low	$7.149	$7.204
						Fossil fuel high	$7.288	$7.436

Pearl River Delta, Scenario 2		**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
	Fresh	265,122,191	$0.056	$0.151	$3.504	Solar	$3.633	$3.681
	Brackish	997,364,433				Wind onshore	$3.611	$3.644
	Total	1,262,485,625				Wind offshore	$3.694	$3.749
						Fossil fuel low	$3.644	$3.699
						Fossil fuel high	$3.783	$3.931

Pearl River Delta, Scenario 3		**Water volume (m^3)**	**Extraction low**	**Extraction high**	**Installation**		**Total low**	**Total high**
	Fresh	265,109,407	$0.056	$0.151	$2.336	Solar	$2.465	$2.513
	Brackish	1,628,529,218				Wind onshore	$2.443	$2.476
	Total	1,893,638,625				Wind offshore	$2.526	$2.581
						Fossil fuel low	$2.476	$2.531
						Fossil fuel high	$2.615	$2.763

Pearl River Delta, Scenario 4		Water volume (m³)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	252,475,410	$0.056	$0.151	$1.402	Solar	$1.530	$1.578
	Brackish	2,903,467,215				Wind onshore	$1.508	$1.541
	Total	3,155,942,625				Wind offshore	$1.591	$1.646
						Fossil fuel low	$1.541	$1.596
						Fossil fuel high	$1.680	$1.828

Pearl River Delta, Scenario 5		Water volume (m³)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	252,482,715	$0.056	$0.151	$0.701	Solar	$0.829	$0.877
	Brackish	6,059,585,160				Wind onshore	$0.807	$0.840
	Total	6,312,067,875				Wind offshore	$0.890	$0.945
						Fossil fuel low	$0.840	$0.895
						Fossil fuel high	$0.979	$1.127

Appendix 5. Extraction rate calculations Yangtze River Delta

Yangtze river delta with the scenario where 5% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (240 * 10^6)}{365} * 17.99\% = 50{,}273{,}425$$

$$DGW_m = 50{,}273{,}425 * \frac{25}{500} = 2{,}513{,}671$$

$$E = \frac{2{,}513{,}671 * 5\%}{10} = 12{,}568$$

Yangtze river delta with the scenario where 10% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (240 * 10^6)}{365} * 17.99\% = 50{,}273{,}425$$

$$DGW_m = 50{,}273{,}425 * \frac{25}{500} = 2{,}513{,}671$$

$$E = \frac{2{,}513{,}671 * 10\%}{10} = 25{,}137$$

Yangtze river delta with the scenario where 15% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (240 * 10^6)}{365} * 17.99\% = 50{,}273{,}425$$

$$DGW_m = 50{,}273{,}425 * \frac{25}{500} = 2{,}513{,}671$$

$$E = \frac{2{,}513{,}671 * 15\%}{10} = 37{,}705$$

Yangtze river delta with the scenario where 25% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (240 * 10^6)}{365} * 17.99\% = 50{,}273{,}425$$

$$DGW_m = 50{,}273{,}425 * \frac{25}{500} = 2{,}513{,}671$$

$$E = \frac{2{,}513{,}671 * 25\%}{10} = 62{,}842$$

Yangtze river delta with the scenario where 50% of the total groundwater need is substituted by the water from an offshore aquifer.

$$DGW_t = \frac{425 * (240 * 10^6)}{365} * 17.99\% = 50{,}273{,}425$$

$$DGW_m = 50{,}273{,}425 * \frac{25}{500} = 2{,}513{,}671$$

$$E = \frac{2{,}513{,}671 * 50\%}{10} = 125{,}684$$

Appendix 6. Overview of volume and cost Yangtze River Delta

Below are five tables, one for each of the scenarios containing the most important data. Fresh, brackish, saline, and total volume of water in cubic meters, the low and high range of the extraction cost, the one-time installation cost, and the combined total low and high range cost for each energy source used.

Yangtze River Delta, Scenario 1		Water volume (m^3)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	0	$0.032	$0.087	$1.444	Solar	$1.548	$1.596
	Brackish	2,295,231,000				Wind onshore	$1.526	$1.559
	Total	2,295,231,000				Wind offshore	$1.609	$1.664
						Fossil fuel low	$1.559	$1.614
						Fossil fuel high	$1.698	$1.846

Yangtze River Delta, Scenario 2		Water volume (m^3)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	0	$0.032	$0.087	$0.722	Solar	$0.826	$0.874
	Brackish	4,590,644,625				Wind onshore	$0.804	$0.837
	Total	4,590,644,625				Wind offshore	$0.887	$0.942
						Fossil fuel low	$0.837	$0.892
						Fossil fuel high	$0.976	$1.124

Yangtze River Delta, Scenario 3		Water volume (m^3)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	0	$0.032	$0.087	$0.566	Solar	$0.670	$0.718
	Brackish	5,852,994,281				Wind onshore	$0.648	$0.681
	Saline	1,032,881,344				Wind offshore	$0.732	$0.786
	Total	6,885,875,625				Fossil fuel low	$0.681	$0.736
						Fossil fuel high	$0.820	$0.968

Yangtze River Delta, Scenario 4		Water volume (m³)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	0	$0.032	$0.087	$0.688	Solar	$0.792	$0.840
	Brackish	4,820,138,505				Wind onshore	$0.770	$0.803
	Saline	6,656,381,745				Wind offshore	$0.853	$0.908
	Total	11,476,520,250				Fossil fuel low	$0.803	$0.858
						Fossil fuel high	$0.942	$1.090

Yangtze River Delta, Scenario 5		Water volume (m³)	Extraction low	Extraction high	Installation		Total low	Total high
	Fresh	0	$0.032	$0.087	$0.849	Solar	$0.954	$1.002
	Brackish	3,902,016,885				Wind onshore	$0.932	$0.965
	Saline	19,051,023,615				Wind offshore	$1.015	$1.070
	Total	22,953,040,500				Fossil fuel low	$0.965	$1.020
						Fossil fuel high	$1.104	$1.252