Can Surface Water be an Alternative to Groundwater in Jakarta, Indonesia?

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ABSTRACT

Groundwater-induced land subsidence is experienced by many coastal cities around the world, including Jakarta. It is an issue occurs because of groundwater extraction that causes the porosity of sedimentary layers to reduce and compact causing the land to subside. Impacts of groundwater-induced land subsidence in Jakarta include flooding, damage to infrastructure, and the displacement of coastal communities. The government is currently deciding mitigation plans which include the movement of the capital city as well as the construction of a giant sea wall. However, many argue that these plans are only short-term solutions as it does not tackle the root source of the issue: groundwater extraction. Therefore, it is vital that the solution to this issue considers how the city can limit the amount of groundwater extracted. Surface water as an alternative source is a widely applied solution to the overextraction of groundwater which is why I ask whether there is enough surface water to sustainably meet the water demand of Jakarta, Indonesia's household, agricultural, and industrial activities. I will begin by (1) determining the water demand of Jakarta, Indonesia through calculated deductions of secondary data, (2) determining the surface water availability of Jakarta, Indonesia through using secondary data and the 'calculating watershed' tool on GIS and (3) determining the current water quality status of Jakarta, Indonesia's surface waters and its treatment potential through a case study. I found that there is enough surface water available to meet the current water demand of Jakarta, Indonesia but time and investment is needed to treat the surface water of Jakarta, Indonesia.

KEYWORDS

Groundwater-induced land subsidence, environmental flows, digital elevation model (DEM), two-stage membrane filtration system, dissolved oxygen (DO)

INTRODUCTION

Globally, many coastal cities around the world are experiencing increased vulnerability due to rapid sea level rise from climate change (Erkens et al. 2015). The global mean sea level has already risen 11-16 cm in the twentieth century and will rise at least 0.5m under a low emissions scenario, and up to another two meters or more by the end of the twenty-first century under a high emissions scenario (Kulp and Strauss 2019). The impacts that sea-level rise imposes on many coastal cities around the world are often exacerbated by groundwater-induced land subsidence that is leading to an increase in flooding and damage to infrastructure (Abidin et al. 2015). This risk occurs because when groundwater is extracted from below for commercial, agricultural, and industrial purposes due to its high quantities and relatively clean quality, the porosity of sedimentary layers is reduced and compacts causing the land to subside (Li et al. 2021). Land subsidence in these coastal cities combined with rising sea levels due to warmer temperatures speeds up the sinking of the lands and intensifies the environmental impacts. Coastal cities such as Tokyo, Japan, Mekong Delta, Vietnam and Jakarta, Indonesia, are current examples of the impacts of land subsidence and sea level rise. In Tokyo, the land has sunk to below sea level due to over abstraction of groundwater since the 1910s (Erkens et al. 2015). In Mekong Delta in Vietnam, land subsidence occurred at 1-4 cm/year in 2006-2010 (Taftazani et al. 2022). Lastly, Jakarta is at risk of experiencing increased flooding in an additional 110.5km^2 of the city, mainly caused by land subsidence (Cao et al. 2021). As the land subsides and the sea levels rise, many coastal communities are being displaced and environmental damages creep inland. Therefore, many coastal cities are put in a state of debate regarding the next steps necessary to mitigate the issue.

The city of Jakarta, Indonesia is already experiencing the effects of groundwater-induced land subsidence and sea level rise. Jakarta experiences subsidence rates of about 1-15 cm/year with a few locations reaching up to 20-28 cm/year (Abidin et al. 2011). In response, the Indonesian government has mitigated for groundwater-induced sea-level rise through projects such as the Great Sea Wall and the movement of the capital city, Jakarta, to Kalimantan (van der Wulp et al. 2016). However, these projects are challenged by critiques and the people of Jakarta because these “solutions” are only short-term and do not aim to solve the point source of the problem: groundwater extraction.

The main reasons for intensive groundwater extraction in Jakarta is due to highly contaminated surface waters as well as the lack and inadequacy of municipal piping infrastructure (Furlong and Kooy 2017). There are thirteen rivers that flow through Jakarta and Jakarta experiences a positive trend in rainfall exceeding 50 mm a day ("River water quality study in the vicinity of Jakarta" 1995). Although surface water is a good solution for meeting increasing demands for water resource in Jakarta due to its abundance, surface water contamination is a huge problem. Rivers in Jakarta receive a discharge of wastewater from more than 10 million residents combined with industrial, agricultural activities, and solid waste and leakage from septic tanks in which some are untreated (Luo et al. 2019). With the lack of adequate funding for piped water supply, environmental injustices occur as poor communities are unable to afford clean water, forcing them to rely on polluted river water, lakes, and shallow wells to meet their water needs (Luo et al. 2019). According to the World Health Organization, 525,000 children die worldwide a year in 2018 due to poor water quality, sanitation, and hygiene, mainly due to infectious diarrhea caused by E.coli bacteria (Jeon 2020). In addition, the lack of municipal piping infrastructure prevents the people of the city to access alternative sources such as surface water (Azevedo de Almeida and Mostafavi 2016). This means that many people rely on packaged drinking water (PDW) to access non=contaminated water, which many people cannot afford. Despite clear linkages, the relationship between groundwater extraction, land subsidence, and water quality is not fully understood and mitigation strategies that address these issues now and in an uncertain future remain undetermined. Therefore, there is a need to explore other methods of mitigation.

In this study, I aim to evaluate how surface water can be used to meet the water needs of Jakarta, Indonesia's household, agricultural, and industrial activities. I will determine this through: (1) evaluating the water demand of Jakarta, Indonesia (2) calculating surface water availability to see whether it can balance the water demand of Jakarta (3) and studying the water quality of surface waters and analyzing its treatment potential. To evaluate the water demand of Jakarta, I will use secondary data for water use in Jakarta and compare it with the surface water available which will be calculated through inputting secondary data in a formula. Lastly, I will conduct research on surface purification methods and conduct a case study to analyze whether Jakarta's surface water can be purified. I expect that surface water amount will be able to meet the water demand of the city. However, there will need to be high investment in the time and cost that is needed to treat the surface waters of Jakarta before surface water can be used an alternative source of water. In addition, although surface water will currently be able to meet the water demands of the city, the city continues to develop and grow leading to more uncertainty regarding whether surface water is a sustainable alternative.

METHODS

Study Site

Jakarta, Indonesia is the capital and largest city of Indonesia and it is located on the northwest coast of Java with an area of 662 km^2 (Luo et al. 2019). The city is home to over 10 million people ("The lost city of Jakarta?: Discovering Sustainability" n.d.). Jakarta has a tropical monsoon climate with rainy season that starts around November and lasts through June before entering the dry season. Rain is heaviest in the winter months between December and March (Martinez and Masron 2020)

Jakarta is vulnerable to the impacts of land subsidence because of intense groundwater extraction (Cao et al. 2021). The city's vulnerability to land subsidence is a largely a result of the environmental conditions of the land the city is built on which is swampy land due to the 13 rivers that flow through it. Furthermore, Jakarta lies on a low, flat alluvial plain with an average elevation of 8m above sea level ("Jakarta is slowing sinking into the Earth" n.d.). Because of the environment the city is located, it is prone to high rates of erosion and sedimentation making them susceptible to intensive flooding, an environmental outcome of the association between groundwater extraction-induced land subsidence and sea-level rise. As one of the main sources of water for the city is groundwater in addition to purified water from the Citarum River and areas outside of the city such as the Jatiluhur Dam, groundwater extraction is widely practiced around the city (Apip et al. 2015). The proposed solutions by the government such as the Great Garuda Sea Wall and the movement of the capital city are believed to be short-term solutions that do not tackle the root source of the issue. For these reasons, I have chosen Jakarta, Indonesia to be my site for studying land subsidence mitigation and proposing an alternative solution that utilizes alternative sources of water to reduce the demand of groundwater extraction in the city.

Although surface water is an alternative source to groundwater, it is important to take note of the issue of water contamination in Jakarta. In Jakarta, 75% of the waste water remains untreated and is released directly into rivers. The outcome is that more than 50% of the shallow wells in the city are contaminated by E. coli and more than 10% of them are also contaminated by iron and manganese (Apip et al. 2015). Most rivers in Jakarta are highly polluted and based on regularly monitoring, the rivers also has high BOD levels that comes from industrial waste water, solid waste, and domestic sewage. Despite the urgent issue of water contamination in Jakarta, there are existing sanitation practices in place that is divided into off-site and on-site sanitation. On-site sanitation is dominantly practices in residential and slum areas where waste water is treated using individual septic tanks before being released into sewerage (71%) while poorer areas (11% of the population) deliver their waste water into the river. On the other hand, off-site sanitation is dominantly practices by apartment, office buildings, and industrial buildings in Jakarta (16% of population) in which individual treatment plants (ITP) and advanced treatment processes (ATP) are used before the waste water was delivered into the rivers. Despite the existing sewerage system, improvements can still be made. The two septic tank waste treatment installations (IPLS) in the city has fell behind on technology making them ineffective and inefficient in treating waste water and is struggling to meet the needs of the population.

Jakarta's Water Demand

In this study, I first ask "what is the water demand of Jakarta, Indonesia?" To answer this, I aim to utilize secondary data to estimate the domestic, commercial, and agricultural water demand of the city.

Domestic Water Demand

I estimated domestic water data through finding secondary data on average water consumption per capita and population. To find domestic water demand, I multiplied average water consumption per capita to the population of the city.

Agricultural and Commercial Water Demand

For agricultural and commercial water demand, I acquired the data through secondary articles. Commercial water demand was acquired from PAM Jaya's 21 years of historical data while agricultural data was taken from the data published by the Ministry of Agriculture.

Water Demand Analysis

Once all the data is collected on domestic, agricultural and water demand on the variable, I can identify the Jakarta's total water demand through:

Total Water Demand = Domestic water demand + Commercial water demand + Agricultural water demand

Jakarta's Surface Water Availability

My next question is "how much surface water is available in Jakarta, Indonesia?" To answer this question, I collected secondary data on precipitation (P), evaporation [E], runoff [R], environmental flows (Ef), and human consumption (Hc) in which human consumption is the estimated number of water demand from sub question one.

Precipitation and Evaporation

Precipitation and evaporation data in Jakarta, Indonesia was taken from secondary sources.

Runoff

To calculate runoff, I will be utilizing the ArcGIS software. I will be creating a watershed model using the hydrology toolset. A watershed is a drainage basin in an area of land where all flowing surface water such as runoff converges to a point. Steps taken in ArcGIS software is as follows:

1. My first step was to use secondary data to find a digital elevation model layer (DEM) of Jakarta that I can load onto ArcGIS.
2. I accessed the hydrology toolbox on ArcGIS to create my watershed model. Before moving forward, I had to fill the sinks which are areas surrounded by higher elevation values in the DEM which is an error.
3. Using the flow direction tool, I created a flow direction raster
4. The flow accumulation tool calculates the accumulated flow to each raster cell. This created a color-coded map of the DEM model classified with a number. The different numbers classify a direction of flow with each color representing a direction of flow (N, S, E, W, etc.).
5. Next, I used the flow accumulation tool and input the flow direction layer created in the previous step to create a flow accumulation raster.
6. With the flow accumulation raster, I adjusted the symbology to break the height values into 2 classifications, one with low height values with low accumulation and one with high height value that has a high flow accumulation. This way, high flow accumulation will be visibly distinct compared to the low flow accumulation areas.
7. At this point, the map will depict lines where water flows. With the flow accumulation set, you can then identify the watershed locations in Jakarta on the map.
8. The following steps to complete the runoff calculation will require more research and time.

Environmental Flows

The last variable that I will be looking for is environmental flows. I reviewed published secondary articles that focus on estimating environmental flows. This will be done through conducting a case study of existing research on environmental flows of surface water. I will be taking the methods and values of these papers and comparing the situations to fit Jakarta’s environmental conditions. This will help me determine the environmental flows.

Surface Water Amount Analysis

Once all the variables are collected (P, E, Ro, Ef, Hc), I will then insert the data into an equation:

$$\mathbf{P - E - Ro - Ef = HC}$$

This equation will determine whether there is enough surface water available in Jakarta, Indonesia to meet the city's water demand.

Jakarta's Surface Water Contamination

To ensure the viability of using surface water as an alternative source of water to groundwater, my last question to ask is "how contaminated are the surface waters and how can it be treated?" I aimed to find the contamination levels of the surface waters in Jakarta, Indonesia while also looking for existing water treatment technologies or methods. This was done through conducting research on secondary data and performing a case study to find which treatment(s) is best fitting to tackle Jakarta's contaminated surface water. To measure the surface water conditions of rivers in Jakarta, I collected secondary data on temperature (T), pH, dissolved oxygen (DO), turbidity, E.Coli, and metal. evels of the 13 rivers. The different metal concentrations I collected data on are lead, cadmium, chromium, copper, mercury and nickel. Additionally, to determine the best surface water treatment method, I looked for different types of surface water treatment methods, efficacy, and cons. Through analyzing this in a case study, I will then propose a water treatment method/technology that Jakarta can utilize to treat its surface waters.

RESULTS

Water Demand of Jakarta

Residential Water Demand

As Jakarta is an urban city, residential water demand resulted is a high number when compared to commercial and agricultural and industrial water demand. The per capita water consumption of Jakarta is 174.2 liters per capita per day while the total population of the city is 11,249,000. Therefore, total domestic water demand is:

174.2L/capita/day x 11,249,000 people = **1,959,575,800 liters/day = 715,245,167,000 liters/year**

Agricultural and Commercial Water Demand

Data collected from a secondary article online stated that agricultural water demand amounted to 35,345,362,000 liters/year while commercial water demand amounted to 446,279,904,000 liters in a year.

Total Water Demand of Jakarta

To determine total water demand of Jakarta, I aggregated the total domestic, commercial, and agricultural water demand:

Domestic water demand + commercial water demand + agricultural water demand = 715,245,167,000 L/yr + 446,279,904,000 L/yr + 35,345,362,000 L/Yr = 1,197,000,000,000 L/Yr

Surface Water Amount

Precipitation and evaporation

Rainfall in Jakarta happens frequently as there were 169 rainy days in 2020. Rainfall in DKI Jakarta varies by month. February sees the highest amount of rainfall with around 1043.20 mm while July marks the lowest amount of rainfall.

According to 2019 data, two stations, Kemayoran Observation Station and Priok/Tanjung Priok observation station measured a total of 3229,7 mm^2 of rainfall. Rainfall measured by month in the two stations is in the table below.

Table 1. Measurement of Rainfall (mm^2) in Jakarta. Data reported by Kemayoran Observation Station and Priok/Tanjung Priok Observation Station.

Rainfall (mm^2)			
Month	Kemayoran Observation Station	Tanjung Priok Observation Station	TOTAL
January	383.9	365.5	749.4
February	270.1	216.9	487.0
March	327.3	332.1	659.4
April	194.6	132.5	327.1
May	47.8	24.7	72.5
June	23.1	5.0	28.1
July	0	0	0
August	0	0	0
September	1.0	0	1.0
October	1.0	1.0	2.0
November	50.1	80.0	130.1
December	263.8	509.3	773.1
TOTAL			**3229.7**

Evaporation

Secondary data on evaporation rates in Jakarta have not been estimated at the time. However, a study that estimated the evaporation rates of Bandung, a city neighboring Jakarta, showed average evaporation rates of 730mm per year.

Runoff

Through utilizing ArcGIS, runoff in Jakarta, Indonesia estimated to be [data still yet to be determined]

Environmental Flows

[Data still yet to be determined]

Surface Water Amount Analysis

With data on precipitation, evaporation, runoff, and environmental flows collected, the evaluated surface water amount of Jakarta, Indonesia is:

3229.7 (mm) – 730 (mm) – [Ro]- [Ef] = [number to be determined]

As surface water amount totals to [] and the city's domestic, agricultural and commercial water demand totals to [] as calculated in sub question one, it can be concluded that there is enough surface water to meet the water demands of the city.

Surface Water Treatment Potential

Through conducting the case study, several different treatment methods were discovered to be effective in treating surface waters. However, treatment methods could be narrowed done when considering how similar the conditions of treated surface waters were to the surface waters of Jakarta, Indonesia in terms of severity of contamination levels. Levels of surface water contamination in Jakarta differed for each river but all were intermediately or heavily polluted.

Table 2. Rivers of Jakarta and Water Quality Parameter Measurements. Listed are concentrations of temperature, pH, DO, Turbidity, and E.coli.

River	Temperature	pH	DO	Turbidity	E.coli
Cakung		6.5-8.0	1-5		$4x10^6$-9x10^6
Jati Kramat		7.0-7.7	1.0-2.5		
Buaran		6.5-8.0	1.0-6.0		$4x10^6$-$9x10^6$
Sunter		6.5-7.6	1.0-8.0		0-$3.5x10^6$
Cipinang		6.7-7.7	1.0-6.0		0 – $1x10^6$
Baru Timur		6.7-7.5	1.0-5.0		$1x10^6$-$3.5x10^6$
Ciliwung		6.5-8.0	1.0-7.0		0-$3.0x10^7$
Baru Barat		6.9-7.8	1.8-7.2		
Krukut		6.7-7.9	0.7-6.9		
Grogol		7.0-7.8	1.0-10.0		0-$3x10^7$

Pesanggrahan		6.7-7.6	2.0-4.2		0
Angke		6.5-7.5	0.5-5.4		0-1x10^{7}
Mookervart		6.7-7.4	0.5-5.0		0-7.0x10^{6}

Table 3. Metal Concentrations in the 13 rivers of Jakarta. Listed are concentrations of lead, cadmium, chromium, copper, mercury, and nickel.

Metals (mg/l)	Cakung	Jati Kramat	Buaran	Sunter	Cipinang	Baru Timur
Lead	0.02	0.02-0.08	0.02-0.03	0.02	0.02	0.02
Cadmium	<0.0005	<0.0005	<0.0005	0.006	0.006	0.006
Chromium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	0.02	0-0.3	0-0.33	0.01-0.02	0.01-0.02	0.01
Mercury	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Nickel	0.04	0.04	0.04	0.04	0.04	0.04

Table 4. Continued list of Metal Concentrations in the 13 Rivers of Jakarta.

Metals (mg/l)	Ciliwung	Baru Barat	Krukut	Grogol	Pesanggrahan	Angke	Mookervart
Lead	0.02	0.02	0.02	0.02	0.02	0.02	
Cadmium	0.006	0.006	0.006	0.006	0.06	0.006	
Chromium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
Copper	0.008-0.03	0.009	0.009-0.02	0.01-0.08	0.01-0.13	0.01-0.03	
Mercury	<0.001	<0.001	<0.001	<0.005	<0.005	<0.005	
Nickel				0.04	0.04	0.04	

Table 5. Surface Water Treatment Method, Treatment Time, and Treatment Cost, and Efficacy.

Surface Water Treatment	**Treatment Cost**	**Efficacy**	**Cons**

Low-pressure membranes (microfiltration & ultrafiltration)	Cost has decreased dramatically since the early 1990s	Highly capable of removing particulate matter (turbidity) and microorganisms.	Ineffective for the removal of DOM
High-pressure membrane systems (nanofiltration & reverse osmosis)	40-gpm, two-membrane system at $4/gpd	Considered as a TOC removal tech in surface water treatment	
Two-stage membrane filtration (MF/UF followed by NF/RO)	1.5 MGD = $200,000 Low pressure UV lamp costs about $500 Medium-pressure UV lamp costs about $5000	Low-pressure membranes highly effective for particulate removal while high pressure membranes are effective for dissolved matter removal (organic and inorganic)	High costs compared to conventional treatment methods.
Ultraviolet irradiation technology		UV disinfection systems are commonly used in large scale wastewater plants	Limited information on Giardia and Cryptosporidium inactivation capability No significant oxidation capability Operational issues with scale buildup

			Impaired by particulate matter that shield microorganisms from UV light Limited process reliability
Advanced Oxidation Technology – process that produces hydroxyl radicals (OH) for the oxidation or organic and inorganic water impurities		Efficient for color removal, taste-and-odor control, and/or disinfection process	Potential formation of bromate a possible human carcinogen, when the water being treated contains bromide
Ion Exchange Technology		Used to limit water softening (Ca^{2+} and Mg^{2+} removal)	
Biological Filtration			

As shown from the tables above, surface waters of Jakarta are highly polluted and will need a highly effective treatment method. [] as a treatment method has high costs yet reasonable treatment time and high efficacy while treatment [], [], and [] are not as effective with high costs. Therefore, it is suggested that [] be used for surface waters to be a viable alternative to groundwater.

DISCUSSION

Groundwater depletion poses a serious threat to the city of Jakarta as the land subsides and sea levels rise. At the rate that groundwater is being depleted, Jakarta is estimated to subside an additional 1800 (mm) by 2025 while already having subsided 2000 mm from 1900-2013 (Erkens et al. 2015). With this in mind, there must be action made to alleviate the subsidence issues in Jakarta through tackling the root source of the problem: groundwater depletion.

Therefore, this study aimed to evaluate how surface water can be an alternative source of water to reduce the groundwater extraction rates. I evaluated how surface water can be used to meet the needs of Jakarta, Indonesia's domestic, commercial, and agricultural water demand of the city.
The results indicate that the surface water availability of Jakarta can meet the total water demand of the domestic, commercial, and agricultural sector of the city. However, despite this information, water contamination remains an obstacle as surface waters are polluted and treatment methods will require high costs and significant time. This implies that although it is possible for surface water to become an alternative source of water for the city, implementation and action from the government to treat the surface waters will be needed alongside efficient treatment methods.

Jakarta's Water Demand

Water demand for low-income households amounted to [] while high-income households had a significant increase in water usage per household that amounted to []. However, due to income inequality in Jakarta being very prevalent, the aggregate water demand for low-income households is higher than the aggregate water demand for high-income households. Looking into the different water usage for each home appliance, clothes washer or hand-washing clothes used the highest amount of water for both low-income and high-income households, followed by the shower and toilet. Although my results of household water demand came from data from articles, there is concern over whether I considered all the household water appliances in the research as well as cultural influences over usage of water.

Moving onto the commercial water usage, I found that commercial water demand amounted to a number higher than the domestic water demand of the city. The commercial water demand is []. (I still need to find more data regarding commercial water demand to complete this paragraph.)

Lastly, agricultural water demand is the sector that uses the highest amount of water. When evaluating the main crops grown in the city of Jakarta, the rice crop used the highest amount of water that amounted to []. (More data also needed to complete this paragraph).

Although I found data to the best of my capabilities, a more accurate representation of agricultural water usage in Jakarta may be found by considering all the crops grown in Jakarta rather than choosing the main crops.

All in all, when aggregating the domestic, commercial, and agricultural water demand, it amounted to [].

Surface Water Availability

Surface water availability was determined by finding the data for the following variables: precipitation, evaporation, runoff and environmental flows, then adding the data altogether. I found that total surface water availability amounted to []. (More data needed to complete this paragraph). Despite finding the total surface water availability in Jakarta, a better number can be found through a better method of calculating environmental flows and more recent data found on precipitation and evaporation. Despite the limitations, it is visible from the results that surface water availability is enough to meet the water demand of the city as the total water demand is less than the surface water availability. Nonetheless, my study does not account for future changes in water demand as the city continues to grow and develop which might provide issues for the balance between surface water availability and water demand.

Treatment of Surface Water

Through conducting the case study on surface water treatment methods, [] seems to be the most effective treatment method to utilize. This is because it has lower treatment time with high efficacy despite the high costs that come with the treatment. Although there are high costs with [], the results in water quality were the highest with the method as it resulted in a [%] increase in water purity. This ensures clean drinking water for the people which is important as current health issues regarding water contamination is a severe problem in Jakarta. Furthermore, this treatment method has a relatively low treatment time despite it still needing several years for the treatment to produce surface waters that are clean enough to be used by the domestic sector.

Future Directions

Jakarta must begin to take action on how it may divert the use of groundwater as a source of water for the city to avoid the land from subsiding any further. Although surface water is a viable alternative to groundwater, it may not be the solution that the government decides to enact to prevent land subsidence issues. However, the future decision of the government must think of the long-term viability and sustainability of the method chosen if they want to see the city of Jakarta above sea-level in the coming future.

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