Exploiting Regional Topography and Macro-engineering to Transform Southeastern Jordanian Desert Into a Coastal Area

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ABSTRACT

Jordan has a very short coastline, which is reflected in limited and expensive coastal tourism, as well as limited marine life. Therefore, a technical proposal to transform part of the Jordanian desert into a coastal area is presented. The proposal is called: "Red Sea-Jafer Basin Pipeline (RSJBP)"; the idea is to create an artificial lake by filling Jafer Basin (JB), which is a large desert depression, with seawater pumped from Gulf of Aqaba (GoA), via a 140 km long pipeline, extending straight from GoA to JB. The design process starts by estimating the required water volume, which is 2,000 MCM and proceeds to sizing the required pipes and pumps, as well as computing flow pressure and pumping power. The results show that the project can be successfully developed and operated; the filling operation will take 3 years, at a flow rate of 51 m³/s, resulting in water depth of 8 m. In order to maintain this level, evaporated water must be compensated; it is estimated at 958 MCM/y as opposed to a recharge rate of only 23 MCM/y; therefore, every year, 935 MCM must be pumped into the Lake, at a rate of 30 m³/s. A steel pipe of 4 m diameter is found the most appropriate for this purpose. Annual pumping costs are recovered by deducting 22% from the forecasted annual revenue, resulting in an annual profit of 1.15 Billion US$. Moreover, the payback period is 3.4 years and the break-even point is 6.4 years. Indeed this macro-project will vastly impact the economy and enrich the domestic tourism scene.

KEYWORDS

Macro-engineering, Jordan desert, Land development, Artificial Lake, Gulf of Aqaba, Jafer Basin, Seawater pipeline, Seawater pumping.

INTRODUCTION

Jordan is at risk of rapid desertification due to little rainfall and climate change. Ongoing terrestrial degradation would decrease available farmland. The desert (Badia) area is the main region for livestock production, and many Badia dwellers; called "Bedouins" depend on the rangeland to make a living. Further land degradation would result in less arable land which will push the Bedouins to move to the cities. This would result in decreased food production [1]. [2] explained how the growing demand for water in the south Levant region can be met by seawater desalination as well as water recycling for agriculture. [3] suggested lowering water consumption in arid regions as a more sustainable approach than seawater conveyance. However, this approach is not feasible due to growing population.

This work proposes the creation of an artificial Lake in southeast Jordan, particularly in JB, which is part of Badia region, to stop and reverse land degradation in the area. [4] highlighted seven examples of historic hydraulic structures from different geographic contexts and connected their specifications to economic, social, political and environmental dimensions for good water governance. [5] indicated that a network of freshwater sites such as Wadi Gharandal oasis in southern Jordan had been visited by humans during migration from Africa to the Levant. [6] reviewed the potential of growing saline crops in desert areas for food, fodder and biofuels production to meet human demand. [7] assessed the characteristics of an artificial lake containing mixture of treated wastewater and rainwater to examine whether the nutrient loading is sufficient for fish culture. They also evaluated the suitability of the lake's water quality for irrigation after fish farming. The artificial lake proposed in this work will help establish saline agriculture.
The proposal includes preliminary engineering design calculations to help in assessing the technical feasibility of the project. In addition, the cost and economic viability of the project is addressed. The proposed project is called “Red sea-JB Pipeline (RSJBP)”. It involves a pipeline connecting the GoA at the Red Sea and JB in southeast Jordan. Seawater will be pumped from the Red Sea to JB via a 140 km long pipeline. In addition to the terrestrial restoration impact of the project, it is expected to have positive impact on biodiversity, landscape and socio-economy. A similar giant project that has been proposed is the Red Sea-Dead Sea Canal (RSDSC); however, this canal requires international cooperation which resulted in construction delays. [8] studied alternatives to increase water supply in the Jordan River Basin, including the Red-Dead Sea Conveyance and pipeline from Turkey. [9] tested scale mitigation in Desalination in the Red Sea-Jordan Water pipeline using nanofiltration and chemical addition.

A fundamental constraint to further development in Jordan is the limited available coastline. The southeastern region desperately needs development so as to encourage human settlement. Since the formed Lake will create new opportunities for tourism, fishery and industry, a more balanced distribution of the population can be realized [10]. The cost of the project includes pumping the seawater from the GoA on the Red Sea to JB as well as cost of pipes and installation. On the environmental aspect, evaporating water from the Lake will increase humidity which results in increasing rainfall. The area is very dry and having more humidity means more pastures for animals and more meat production which would reduce imports of virtual water. Eventually, this will lead to more food security as well as less water deficit.

The idea of transporting seawater from Aqaba is not new; it was implemented in the RSDSC project. This project consists of GoA intake, seawater pumping station at 100 MW, 830 GWh, and design flow of 60 m³/s, a 180 km canal and, tunnel, reverse osmosis (RO) desalination plant producing 27 m³/s, desalted water double pipeline of 200 km with 2.75 m diameter, nine pumping stations for the uplift of 1,500 m at 310 MW, and a 2,640 GWh, 570 MCM reject brine carrier. The project cost is 5×10¹⁴ US$ [11]. [12] investigated marine ecosystem and water quality at GoA. [13] evaluated the role of zero discharge policy at GoA in improving environmental conditions. [14] investigated the levels of 16 trace and heavy elements in seawater for the first time in the northern GoA.

An initial artificial Lake design has been presented by [15]; where they proposed to bring seawater to Lake Eyre in Australia. The study offered technical and economical details. The proposed water volume is 75 km³ with surface area of 9,920 km². They suggested the pipeline made of inexpensive waterproof textile. [16] studied the fluctuations in water levels at Bačina Lakes due to water evacuation through Krotuš tunnel, and Adriatic Sea. [17] investigated the formation of Lakes in Antarctica from Ocean flood events consisting from a mix of glacial meltwater and seawater. [18] studied the pollution in Lake Toba in Indonesia, where water quality at the lake was classified according to pollution status. [19] identified water contamination in Cempaka Lake due to residential activities, clinics, restaurants, and petrol stations. In an effort to solve the sand dunes expansion problem, [20] suggested bringing seawater from the ocean to the desert to fix the dunes by spraying them with seawater. This project requires building a seawater-conveying pipeline section across the African desert, through a distance of 265 km. Due to expected high pressure; they suggested the pipes be made from steel or composite fiber material. [21] evaluated the degree to which pumping wells at Moghra aquifer will attract seawater to the aquifer system in the Egypt Western Desert region under different pumping conditions.

An economic valuation study on small artificial lakes in Germany was presented by [22]. Those lakes are managed by recreational anglers, who strongly prefer to have certain elements in the lake such as boats, predatory fish, endangered fish and non-fish species. On the other hand, the same group opposed swimming at the lakes. Therefore, the study recommended that the lakes should be managed by spatial zoning in order to satisfy different groups. Hydropower RO desalination system using energy generated by flowing water from Disi (at 840 m ASL) to Aqaba at sea level, through a distance of 80 km was proposed by [23]. Input seawater of 2,130 MCM is to be brought from the Red Sea, at TDS of 40,000 mg/l (Mohsen, 2007), while output desalted water of 530 MCM at 500 mg/l is obtained. However, even though technically it sounds a good idea, the fossil water in Disi is not renewable; therefore, this proposal is unsustainable.

**PROJECT PLAN**

The general layout of the RSJBP project is shown in Figure 1. It consists of two basic components:
1) Seawater conveyance system including pumps and pipeline, with intake installed in Aqaba on the Red Sea (Point A) and discharge installed at JB (Point B). The length of the pipeline is 140 km.

2) The artificial Lake that will be formed inside the JB (The blue body above Point B). The area of the Lake is 250 km².

Figure 1. RSJBP plan with pipeline above the mountains

A schematic diagram of the RSJBP project alignment is shown in Figure 2; Water is pumped from the Red Sea (point 1), which is at sea level to Shara mountains (point 2) at 1,350 m above sea level (ASL). Then water will flow by gravity from point 2 to JB (point 3), at 850 m ASL, where the Lake is formed. Hydropower generators are installed in the downslope to take advantage of the potential energy. The seawater intake will be positioned in Aqaba at the shore of the Red Sea, while multiple pumps will be used to pump the water along the pipeline. The total length (air distance) of the pipeline is 140 km. However, the actual land distance will be more. Therefore, a factor of 5% is assumed for the extra pipe length needed, where the adjusted pipeline length becomes 147 km. This arrangement will provide steady pressure in the pipeline. The pipeline has to go up and down following the terrains, and having multiple pumping stations along the way would prevent back flow. The design of the RSJBP project will ensure that the energy consumed in operating the project will be minimized, especially with a down slope of 500 m from point 2 to point 3 as shown in Figure 2. However, there are unavoidable energy losses such as friction in the pipes, as well as pumping head required from point 1 to point 2. The project is divided into two phases; in phase I, the pipeline and pumping stations are constructed. While in phase II, the basin is filled up with seawater. According to preliminary calculations, phase II can take around 3 years.

Figure 2. Pipeline route above the mountains

PROJECT ANALYSIS AND COST

Lake Location

JB is a unique natural place located in the south-eastern part of Jordan, about 60 km from the city of Ma’an [24] and 6 km to the east of Jafer town [25]. It is a flat white basin which accumulates rain water from the surrounding
mountains. The current status of the basin supports a potential for car rally, horse race or camel race, since the floor of the basin is very hard and do not grow any vegetation [25]. A plan of the basin is shown in Figure 3, where the proposed Lake is supposed to occupy the enclosed area, which equals 250 km$^2$, while the perimeter is 105 km.

![Figure 3. Proposed Lake Area and perimeter](image)

In summer, this place is totally dry, whereas in winter, fresh water coming from the surrounding mountains fills up the basin. The annual amount of direct rainfall ($R_B$) on the basin is given by:

$$R_B = R_A \times A_B$$  \hspace{1cm} (1)

Where $R_A$ is the annual rate of rainfall in JB, equal to 32 mm/year [26], and $A_B$ is the basin area, equal to 250 km$^2$. The resulting $R_B$ amount is 8 million cubic meters per year (MCM/yr). The outer JB has a circular shape with a diameter of 100 km and a total area of 7,366 km$^2$. Inside the outer basin sits the JB itself, which has a mean elevation of 850 m ASL [27], as shown in Figure 3. The basin is mostly bare land consisting of bare rock, gravel, basalt, stone, boulder and hardpan areas. The area is characterized as a hyper-arid zone [28]. The groundwater recharge in JB takes place primarily in the outcrop area of the western highlands by direct and indirect infiltration of rainfall. Flood flow into JB in a wet year is 15 MCM/yr [29]. The total volume of water ($V_w$) needed to fill up the basin can be approximated by multiplying the area by the depth. The basin area ($A_B$) is 250 km$^2$ [27], and the basin depth ($D_B$) is 8 m [30]. Therefore, the water volume ($V$) is calculated as:

$$V_w = A_B \times D_B$$  \hspace{1cm} (2)

Applying eqn. (2), the required water volume to fill up the basin and create the Lake is calculated as 2,000 MCM. The main source of water used to fill up the Lake will be the seawater pumped from Gulf of Aqaba. The contribution of the fresh flood and rain water adds up only 23 MCM [29], [26]. After filling up the Lake, the nearby Jafer town and the airbase will be between 3 m and 19 m above the Lake water level. An important concern is the time needed to fill up the Lake; where a period of three years is assumed in this work. Based on this assumption, the water flow rate needed to maintain a constant water level in the Lake is calculated, as shown in Table 1. In addition, the depth of water at the end of each year is calculated and shown in the same table.

In order to accurately calculate the amount of seawater that needs to be pumped into the basin, due consideration should be given to evaporation. The high temperatures and low humidity in Jordan result in an extremely high evaporation rate. The long-term average evaporation rate is 80.2% of precipitation over the entire area of Jordan. Potential evaporation ranges from 1,600 mm/y in the northern highlands to more than 4,000 mm/y in the southern and eastern desert [31], [32] estimated an annual evaporation rate of 280 W/m$^2$ in the Gulf of Aqaba, which is equivalent to 1 cm/day of evaporation. The expected evaporation rate from the Lake can be estimated using the rate (4,000 mm/y) for fresh water in Ma’an near Jafer, and the rate (1 cm/day) for seawater in the Gulf of Aqaba. The expected rate should be less than the first figure because evaporation of seawater is less than fresh water. On the other hand, JB is located 850 m ASL and therefore, should have an evaporation rate greater than Aqaba at sea level, because of lower atmospheric pressure.

In view of the above, the evaporation rate of seawater in JB should be between the above two figures. Therefore, the average of 4,000 mm/y and 1 cm/day should be taken; where the 4,000 mm/y is converted to 4 m/y, while 1 cm/day is converted to 0.01 m/day which equals 3.65 m/y. The resulting average evaporation rate ($E_B$) is 3.83 m/y. The volume of the evaporated water is calculated by multiplying $E_B$ with the water surface area ($A_B = 250$}
km$^2$), which yields an annual amount of evaporation from the surface of the Lake of 958 MCM. Falling rain, which equals 8 MCM/y as well as incoming seasonal streams (15 MCM/y) are accounted for so as to prevent the level of the Lake from overflowing. In the fourth year and beyond, only 30 m$^3$/s must be pumped constantly to compensate for evaporation, as shown in Table 1.

**Table 1. Water pumping rate calculation**

<table>
<thead>
<tr>
<th>Description</th>
<th>Operation</th>
<th>Water volume</th>
<th>1st Year</th>
<th>2nd Year</th>
<th>3rd Year</th>
<th>4th Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of basin (MCM)</td>
<td>Add</td>
<td>2,000</td>
<td>667</td>
<td>667</td>
<td>667</td>
<td>0</td>
</tr>
<tr>
<td>Evaporation (MCM)</td>
<td>Add</td>
<td>958</td>
<td>958</td>
<td>958</td>
<td>958</td>
<td>958</td>
</tr>
<tr>
<td>Flooding streams (MCM)</td>
<td>Subtract</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Direct rain (MCM)</td>
<td>Subtract</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Pumping needed (MCM)</td>
<td>---</td>
<td>1,602</td>
<td>1,602</td>
<td>1,602</td>
<td>935</td>
<td></td>
</tr>
<tr>
<td>Net volume in the Lake (MCM)</td>
<td>---</td>
<td>667</td>
<td>1,333</td>
<td>2,000</td>
<td>2,000</td>
<td></td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>---</td>
<td>2.7</td>
<td>5.3</td>
<td>8.0</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Pumping rate needed (m$^3$/s)</td>
<td>---</td>
<td>51</td>
<td>51</td>
<td>51</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

**PUMPING AND CONVEYANCE**

The pumping and conveyance requirements can be assigned based on the proposed Lake capacity calculated in the previous section. The pumping station should be designed such that it can fill up the volume of the basin in a reasonable time frame. During the first three years of the project, 1,602 MCM must be pumped into the basin each year, as shown in Table 1. In each subsequent year, only 935 MCM must be pumped in order to compensate for evaporation. In all cases, the fresh water flooding from surrounding mountains as well as the direct rainfall on the Lake is accounted for. The pumping capacity should be designed based on the maximum required volume which equals 1,602 MCM/y. Assuming the time needed to fill up the basin is three years, which is not considered a long time compared to the size of the project. The design flow of seawater ($Q_{SW}$) can be calculated as:

\[
Q_{SW} = 1,602 \frac{\text{MCM}}{y} = 1,602 \times \frac{10^6 \text{m}^3}{y} \times \frac{y}{(365 \times 24 \times 3600 \text{s})} = 51 \text{ m}^3/\text{s}
\]  

(3)

The pumping capacity will be designed based on the required seawater flow rate given by eqn. (3). As for conveyance, due to existing difficult terrains along some portions of the pipeline route, it will be unpractical to dig a canal. Even if a zigzag route is established so as to avoid the mountains, the spread of seawater along the canal will increase the salinity of the arable land. Therefore, rigid or flexible pipes must be used. Since it is expected that pumping will be permanent due to evaporation losses from the Lake, the quality and reliability of the pipes and pumps should be good enough to endure long life spans. The pipeline design involves different parameters; including Length, Diameter, Thickness and Material. Different values of pipe diameters will be investigated; from 1 to 5 m. The wall thickness of the pipe is computed using the following equation [33]:

\[
\delta = \frac{pD_{pipe}}{2\sigma}
\]  

(4)

As a sample calculation, if water pressure ($p$) is 3 atm, pipe diameter ($D_{pipe}$) is 3 m, and wall safety tensile stress ($\sigma$) is 47 kg/mm$^2$, the pipe wall thickness ($\delta$) will be 1 mm. For reinforced concrete at 6% fiber volume fraction, the maximum tensile stress ($\sigma$) is 15 MPa [34]. With safety factor of 1.5, safety tensile stress ($\sigma_s$) would equal 10 MPa. As for the pipe material, there are different options available; such as steel, plastic, fabric, composite and concrete. In this work, the first three options will be investigated. The source of seawater for the Lake may be continuous or intermittent. The speed of the seawater in the pipe is calculated as [33]:

\[
w_{SW} = \frac{4Q_{SW}}{\pi D_{pipe}^2}
\]  

(5)

Where the water flow rate through the pipe is $Q_{SW}$. The conveyance system includes a series of pumps where their main parameter is pumping power $P_{pump}$, which can be drawn from the grid. The power required to impel seawater within the pipe is defined as [33]:

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\[ P_{\text{pump}} = g \rho_{SW} Q_{SW} H / \eta_p \]  

(6)

Where \( g \) is the gravitational acceleration (= 9.81 m/s\(^2\)), \( \rho_{SW} \) is the density of seawater (= 1.030 kg/m\(^3\)), \( H \) is the hydraulic head and \( \eta_p \) is the efficiency of the electric pump (= 0.75). The hydraulic head is obtained by summing the maximum elevation of the pipe above sea level \( H_{\text{pipe}} \) (=1.350 m, as shown in Fig. 2), with the lost pressure height \( \Delta H \) due to friction [33]:

\[ H = H_{\text{pipe}} + \Delta H \]

(7)

In this work, only linear pressure losses are considered, and the lost pressure height is [33]:

\[ \Delta H = \lambda \frac{L_{\text{pipe}} w_{SW}^2}{n_{\text{pipe}} \rho_{SW} g} \]

(8)

Where \( L_{\text{pipe}} \) is the pipe length and \( \lambda \) is coefficient of linear pressure loss, given by:

\[ \lambda = \begin{cases} 
\frac{1}{1800} & \text{for } Re < 10^5 \\
0.0032 + \frac{0.211}{Re^{0.237}} & \text{for } Re > 10^5
\end{cases} \]

(9)

Reynolds number is given by:

\[ Re = \frac{w_{SW} H_{\text{pipe}}}{\nu_{SW}} \]

(10)

Where \( \nu_{SW} \) is kinematic viscosity of seawater (=13×10\(^{-4}/\rho_{SW}\)) m\(^2\)/s. The pump specific power for a 1 m\(^3\)/s flow rate is given by:

\[ P_{\text{specific}} = \frac{P_{\text{pump}}}{Q_{SW}} = \frac{g \rho_{SW} H}{\eta_p} \]

(11)

The annual energy consumed with pumping \( E_{\text{pump,year}} \) (J/y) is obtained from [33]:

\[ E_{\text{pump,year}} = 365 \times 24 \times 3600 \times P_{\text{pump}} \]

(12)

The dependence of the pipe wall thickness on wall safety tensile stress for pipe diameter of 3 m and water pressure of 5 atm is shown in Figure 4. Figure 5 shows the dependence of the specific pumping power \( P_{\text{specific}} \) (MW) on water speed for a diameter of 3 m. The variation of Flow velocity, Pumping power and Annual pumping energy with Pipe diameter is shown in figures 6, 7 and 8, respectively. A clear conclusion is that using a large diameter pipe is much more energy efficient. Three years of pumping are required to fill up the Lake. Numerical results covering the first year are presented in Tables 2 to 5. They involve all the essential parameters, including input variables, multiple pipe diameters, water speeds, pumping power and pumping stations. By inspecting the results in these tables, a pipe diameter of 4 m is identified as best suited for this work. It should be noted that a pipe diameter of 1 m was not considered because the pressure was too extreme. It is further noted that the needed pumping decreases from 51 to 30 m\(^3\)/s starting from the fourth year. The later value is required to compensate for evaporation.

Figure 4. Pipe thickness vs. Safety stress
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Figure 5. Specific pumping power vs. Water speed

Figure 6. Flow velocity vs. Pipe diameter

Figure 7. Pumping power vs. Pipe diameter

Figure 8. Annual pumping energy vs. Pipe diameter
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Table 2. Pipeline input parameters for Year-1, Stage-I

<table>
<thead>
<tr>
<th>$Q_{SW}$ (m$^3$/s)</th>
<th>51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pipe length (km)</td>
<td>147</td>
</tr>
<tr>
<td>Start elevation (m)</td>
<td>0</td>
</tr>
<tr>
<td>End elevation (m)</td>
<td>1,350</td>
</tr>
<tr>
<td>$H_{pipe}$ (m)</td>
<td>+1,350</td>
</tr>
<tr>
<td>Start location</td>
<td>Aqaba</td>
</tr>
<tr>
<td>End location</td>
<td>Shara mountains</td>
</tr>
<tr>
<td>$L_{pipe}$ (m)</td>
<td>7.35×10$^4$</td>
</tr>
<tr>
<td>$\rho_{sw}$ (kg/m$^3$)</td>
<td>1,030</td>
</tr>
<tr>
<td>$v_{sw}$ (m$^2$/s)</td>
<td>1.26×10$^{-6}$</td>
</tr>
<tr>
<td>$\Delta p$ (atm)</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3. Pipeline output parameters for Year-1, Stage-I

<table>
<thead>
<tr>
<th>$D_{pipe}$ (m)</th>
<th>$w_{SW}$ (m/s)</th>
<th>$\Delta H$ (m)</th>
<th>Hydraulic Head ($H$) (m)</th>
<th>$P_{pump}$ (MW)</th>
<th>Number of stations</th>
<th>$P_{pump}$/Station (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>16</td>
<td>3,379</td>
<td>4,729</td>
<td>3.2×10$^3$</td>
<td>136</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>469</td>
<td>1,819</td>
<td>1.2×10$^3$</td>
<td>52</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>116</td>
<td>1,466</td>
<td>1.0×10$^3$</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>39</td>
<td>1,389</td>
<td>9.5×10$^2$</td>
<td>40</td>
<td>24</td>
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Table 4. Pipeline input parameters for Year-1, Stage-II

<table>
<thead>
<tr>
<th>$Q_{SW}$ (m$^3$/s)</th>
<th>51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pipe length (km)</td>
<td>147</td>
</tr>
<tr>
<td>Start elevation (m)</td>
<td>1,350</td>
</tr>
<tr>
<td>End elevation (m)</td>
<td>858</td>
</tr>
<tr>
<td>$H_{pipe}$ (m)</td>
<td>-492</td>
</tr>
<tr>
<td>Start location</td>
<td>Shara mountains</td>
</tr>
<tr>
<td>End location</td>
<td>JB</td>
</tr>
<tr>
<td>$L_{pipe}$ (m)</td>
<td>7.35×10$^4$</td>
</tr>
<tr>
<td>$\rho_{sw}$ (kg/m$^3$)</td>
<td>1,030</td>
</tr>
<tr>
<td>$v_{sw}$ (m$^2$/s)</td>
<td>1.26×10$^{-6}$</td>
</tr>
</tbody>
</table>

Table 5. Pipeline output parameters for Year-1, Stage-II

<table>
<thead>
<tr>
<th>$D_{pipe}$ (m)</th>
<th>$w_{SW}$ (m/s)</th>
<th>$\Delta H$ (m)</th>
<th>Hydraulic Head ($H$) (m)</th>
<th>$P_{pump}$ (MW)</th>
<th>Number of stations</th>
<th>$\Delta p$ (atm)</th>
<th>$P_{pump}$/Station (MW)</th>
<th>Power Direction</th>
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<tr>
<td>2</td>
<td>16</td>
<td>3,379</td>
<td>2,887</td>
<td>1,975</td>
<td>83</td>
<td>3</td>
<td>24</td>
<td>Power Consumption</td>
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<tr>
<td>3</td>
<td>7</td>
<td>469</td>
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<td>-257</td>
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<td>5</td>
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<td>39</td>
<td>-453</td>
<td>-309.9</td>
<td>1</td>
<td>-45</td>
<td>-310</td>
<td>Power Generation</td>
</tr>
</tbody>
</table>

Cost Estimation

For each of the macro-engineered components (i.e., pipes and pumps), there are two associated costs [34]:

1. Cost of construction, which is proportional to the quantity of each component. This cost refers to building the pipeline and pumping system.
2. Operational cost, which is proportional to the quantity of pumped seawater.
The pipe cost depends on pipe diameter as well as pipe material, with composed fabric the least expensive solution. The same applies for the cost of installing the pipe. The cost of pumping comprises the pumps and their installation. The cost of the pipes and the electric pumps enabling steady seawater flow are estimated. The cost $c_{\text{pipe}}$ of the conducting pipe is given by [34]:

$$c_{\text{pipe}} = c_{\text{pipe,1}}D_{\text{pipe}}$$

(13)

Where $c_{\text{pipe,1}}$ is the cost of unit length of pipe. Similarly, the cost of installing the pipe, $c_{\text{inst,pipe}}$ is defined as:

$$c_{\text{inst,pipe}} = c_{\text{inst,pipe,1}}D_{\text{pipe}}$$

(14)

Where $c_{\text{inst,pipe,1}}$ is the cost of installing a unit length of the pipe. The unitary costs depend on different factors; such as pipe diameter $D_{\text{pipe}}$ as well as pipe material. The cost of pumping installation, $C_{\text{pump}}$ is obtained as:

$$C_{\text{pump}} = P_{\text{pump}}c_{\text{pump,1}}$$

(15)

Where $c_{\text{pump,1}}$ is the cost of a pump unit power. An estimation of the investment costs of pipeline & pumping for Stage-I and Stage-II of the first year is summed up in Tables 6 and 7, respectively. Stage-I of the conveyance system transmits the seawater from point 1 to point 2 (1,350 m ASL), as shown in Figure 2, where point 2 is about half distance between Aqaba and Jafer. In the other half of the pipeline (Stage-II, from point 2 to point 3 in Figure 2), gravity flow from 1,350 m ASL to 850 m ASL with water column of 500 m helps seawater to flow down to JB. In addition, hydropower is generated during the flow. The mean speed of seawater in the pipe of diameter $D_{\text{pipe}}$ equals volumetric flow rate divided by pipe area. The cost of a pump of unit power $c_{\text{pump,1}}$ for an average pump quality is 800 US$/kW$ [34]. The cost of the energy consumed during one year, $c_{\text{year}}$ is given by [20]:

$$c_{\text{year}} = E_{\text{year}}c_{1}$$

(16)

Where $c_{1} = 0.1$US$/kWh$. The cost of energy for $N$ years, $c$, is obtained from:

$$c = Nc_{\text{year}}$$

(17)

Where $N$ is the total number of project service years. The initial investment cost $c_{\text{invest}}$ for pipe and pumping installations is given by [20]:

$$c_{\text{invest}} = c_{\text{pump}} + c_{\text{pipe}} + c_{\text{inst,pipe}}$$

(18)

The costs of pumping energy corresponding to different pipe diameters for the two stages of the second and third years are similar to the first year. However, in the fourth year, the pumping energy will cost less due to the less water volume needed. The total cost of RSIBP project using pipes made of steel is presented in Table 8.

### Table 6. Cost of pipeline & pumping for Year-I, Stage-I

<table>
<thead>
<tr>
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### Table 7. Cost of pipeline & pumping for Year-I, Stage-II

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<td>170</td>
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<td>-1.4</td>
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<td>2.5</td>
<td>9.9</td>
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</table>
Exploiting Regional Topography and Macro-engineering to Transform Southeastern Jordanian Desert Into a Coastal Area

<table>
<thead>
<tr>
<th>Up (0-1350 m)</th>
<th>Down (1350-858 m)</th>
<th>Total cost of pipes and pumping 1st year (10^6 US$)</th>
<th>Total cost of pumping energy 2nd year (10^6 US$)</th>
<th>Total cost of pumping energy 3rd year (10^6 US$)</th>
<th>Total cost of pumping energy 4th year (10^6 US$)</th>
<th>Total cost-3 years (10^9 US$)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>5.6</td>
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<td>3.1</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Many variables depend on the pipe diameter and can be expressed as a function of the pipe diameter; for example the cost of pumps and installation, annual pumping cost, pipe cost for different materials and initial investment cost for different pipe materials, are shown in figures 9, 10, 11 and 12, respectively. On the other hand, the projected cost dependence on the desired water quantity in the Lake is shown in Figure 13 for a 4 m pipe diameter.

**Figure 9. Cost of Pumps & Installation (Billion US$)**

**Figure 10. Pumping cost vs. pipe diameter**
As for the revenue, it should be calculated and compared to the cost. Assuming that steel pipe is selected, this determines the initial cost. In addition, as explained earlier, energy is continuously needed for pumping. In order to estimate the RSJBP project revenue, it is assumed that the adjacent area around the Lake which equals the area of the lake itself (250 km$^2$) will be subjected to zoning, development and investment. The current price of the land in the area is too low and can be assumed negligible compared to the expected price. After the completion of the Lake, the adjacent land is expected to cost between US$118,000 [35] and US$260,000 per dunam [36]. Therefore,
in order to calculate the total price of surrounding land, the area of 250 km$^2$ is converted to 250 × 10$^6$ m$^2$. Taking a Dunam as 1,000 m$^2$, the area will be 250,000 Dunams. After multiplying this area by the minimum price above, it will worth 29.5 Billion US$. Assuming this land is leased for an annual rate of 5% of the property value (Davies et al., 2007); an annual return on investment (ROI) of 1.5 Billion US$ is obtained, as opposed to 330 Million US$ annual pumping cost, as shown in Table 8. The annual pumping cost can be covered by deducting from the annual lease (about 22%). As shown in Table 9, the RSJBP project cost will be 3.9 Billion US$. With 1.5 Billion US$ annual ROI, the payback period will be 3.4 Years. On the other hand, sustainable annual profit will be 1.15 Billion US$. The distribution of cost and revenue in twelve years is shown in Fig. 14, while the cost and revenue timeline is shown in Table 9, where the break-even point is reached at 6.4 years.

![Figure 14. Distribution of cost and revenue](image)

<table>
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<th>Year</th>
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<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost (Billion US$)</td>
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<td>0.7</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>6.9</td>
</tr>
<tr>
<td>Revenue (Billion US$)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Balance (Billion US$)</td>
<td>-2.6</td>
<td>-3.2</td>
<td>-3.9</td>
<td>-2.8</td>
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<td>1.8</td>
<td>3.0</td>
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DISCUSSION AND CONCLUSION

This work introduces a macro-engineering project, RSJBP, aimed at developing abandoned land in Southeast Jordan and stimulating the economy. The RSJBP project is meant to create a major center for tourism, industry, agriculture and urban settlement in southeast Jordan. The project involves creating a Lake in JB by drawing seawater from the Gulf of Aqaba. The area has limited urbanization with wide potential for growth which may reduce congestion in major cities, as well as encourage industrial activities. In addition, the availability of seawater would encourage bio-saline agriculture, which can be a new source of income. On the environmental side, the Lake will enhance the local rainfall, which is badly needed, as well as enrich the flora and fauna. Moreover, this water reservoir will alter the surrounding climate making it more favorable for human settlement, where the creation of the Lake will improve the air quality by decreasing the blowing dust, which makes the area more inhabitable. The above factors combined will dramatically increase the land value around the basin.

In this work, the volume of the proposed Lake is estimated at 2,000 MCM to be filled in a period of three years. The corresponding water flow rate during this period is 51 m$^3$/s. Based on the flow rate and the pipeline route elevations, design parameters are calculated such as flow pressure and pumping power. Three different types of pipe materials are investigated, including steel, plastic and fiber. The steel is found the most expensive followed by plastic and fiber. Four different pipe diameters are investigated, where a diameter of four meters was found the most appropriate for the RSJBP project. The pipeline extends straight from the GoA to JB. It is mainly divided into two stages; Stage-I starts at the GoA(sea level) and ends at Shara mountains (1,350 m ASL). Stage-II starts at the Shara mountains and ends in JB (850 m ASL). The planned water volume in the Lake will result in 8 m
water depth, where 1,602 MCM is pumped during each of the first 3 years. It is noted that pumping power and energy decreases substantially for pipe diameters larger than 3 m. Since Stage-II is down slope, power can be generated using hydro-energy. This is especially true at high diameters. This power is used to reduce the high cost of pumping.

After three years, the desired water depth is reached. In order to maintain this level, the evaporated water should be compensated. It is estimated at 958 MCM/y as opposed to the much lower recharge rate of 23 MCM/y. Therefore, the salinity level of the Lake is expected to increase. In the meantime, the water surface level will decrease. In order to compensate for evaporation and maintain a constant water level, every year, 935 MCM must be pumped into the Lake, at a rate of 30 m³/s. However, since the evaporation rate will decrease as salinity increases, this means the required pumping will decrease with time, and this results in decreasing the running cost of the project in the long run. Another way to reduce the cost is to use photovoltaic (PV) cells. Since the sun radiation is high in the area, all or part of the power needed for pumping can be extracted from flexible PV membrane attached to the upper hemisphere of the pipeline. Moreover, the cost of the project can be further reduced by scheduling pumping during grid off-peak hours. An added advantage of the basin is the hard and completely flat floor, which is once covered with water, will result in constant water level. This unique feature may have benefits as opposed to varying level in other places. For example, it can support systematic or automated fish breeding using robots.

A brief cost and revenue estimate is performed in this work. Steel pipe and average quality pumps are selected. It is revealed that the annual pumping costs can be recovered by deducting 22% from the annual revenue, resulting in an annual profit of 1.15 Billion US$. Moreover, the payback period is calculated as 3.4 years and the break-even point is reached after 6.4 years. However, further research is needed to provide a broader perspective on the potentials of this huge project.

ACKNOWLEDGMENT

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REFERENCES


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