Macro-engineering Design for an Artificial Lake in Southeastern Jordan

OSAMA M. AL-HABAHBEH[1], ROMIL S. AL-ADWAN[1], MUSTAFA A. AL-KHAWALDEH[2]
[1]Mechatronics Engineering Department, The University of Jordan, Amman 11942, JORDAN
[2]Mechatronics Engineering Department, Philadelphia University, Amman-Jarash Road, JORDAN

Abstract: - Water situation in Jordan has become very critical. A feasible solution is to desalinate water drawn from Gulf of Aqaba (GoA). Another problem that Jordan faces is the very short coastline. These two problems can be solved by developing an artificial lake in south Jordan. The water from the lake can be desalinated while the lake itself provides a badly needed coastline. This work presents a macro-engineering design for the proposed lake; The proposed project is named "Red Sea-Jafer Basin Conduit (RSJBC)"; it involves a pipeline connecting GoA at the Red Sea with Jafer Basin (JB) in the south-eastern desert, where the topography of the region is exploited to develop an artificial Lake. Using multiple pumping stations, seawater will be pumped from GoA to JB though a 220 km long pipeline. After constructing the project, it will take three years to fill-up the Lake. Once it is filled, the pumping rate is reduced from 51 to 30 m^3/s. However, based on fresh water needs, a volume of up to 21 m^3/s can be desalinated. The suggested pipeline route has a curved path (CP) to avoid the mountains if it were to go straight path (SP). A comparison is conducted between CP and SP, where it was found that CP offers the lowest development cost for RSJBC, given fabric pipe is used. More specifically, a pipe diameter of 6 m enables total development cost of 2.74 B$, with corresponding annual operating cost of 306 M$.

Key-Words: - Artificial Lake, Jordan desert, Gulf of Aqaba, Jafer Basin, Water transport, Pumping station, Gravity flow, Seawater pipeline, Seawater pumping, Tourist attraction development.

Received: July 18, 2021. Revised: May 13, 2022. Accepted: June 4, 2022. Published: June 21, 2022.

1 Introduction

One of the major challenges facing Jordan is the insufficient water resources. A clear solution for this problem is desalination of seawater brought from GoA at the Red Sea. Another major challenge is the very short coastline, as it hinders the potential for growth of domestic tourism. These two challenges together can be overcome using Macro-engineering method, which is defined as the implementation of very large-scale engineering designs. This method is used to develop a design for an artificial lake in south Jordan, where part of the water from the lake can be desalinated and transported to cities, while the lake itself provides Jordan with extra coastline. The proposed design exploits JB, which is a unique but overlooked natural resource that contributes very little to the national economy. However, if the basin is converted into a lake, it will become a tool to attract investors, where many activities can be done to generate revenue. The cost of the project includes seawater pumping from GoA to JB as well as pipes and installation. The total cost of construction and operation will be estimated.

Large-scale water projects are important infrastructure elements. Since antiquity, these projects have been vital for development; Megdiche et al. [1] highlighted seven examples of historic hydraulic structures. Al-Saqarat et al. [2] indicated that a network of freshwater sites in Jordan had been visited by early humans. On the other hand, natural rivers and lakes are the main sources of fresh surface water. Therefore, they have received considerable attention in the literature; Bonacci et al. [3] studied the fluctuations in water levels at Baćina Lakes. Goodwin et al. [4] investigated the formation of Lakes in Antarctica from Ocean flood events. Lukman et al. [5] studied the pollution in Lake Toba in Indonesia. Abd Aziz et al. [6] identified water contamination in Cempaka Lake. The phenomenon of inter-basin water transfers was studied by Gupta and Zaag [7]. The restored ecosystem of Chilika lake in India was studied by Mohanty et al. [8]. Badescu and Cathcart [9] proposed a macro-engineering solution to raise the Aral Sea level by importing water from Caspian Sea. Stone [10] discussed the hydrolofical collapse of Lake Urmia in Iran.

Many water transport studies have been presented in the literature; an artificial lake design was presented by Badescu et al. [11]; where they proposed to bring seawater to lake Eyre in South Australia. In an effort to solve the sand dunes problem in the African desert, Badescu et al. [12] suggested conveying seawater from the ocean to the desert to fix the dunes by spraying them with water. Gomaa et al. [13] evaluated the degree to which pumping wells at Moghra aquifer in the Egypt western desert will attract seawater to the aquifer system.

Alleviating water shortage is an area of active research; Yazdandoost et al. [14] suggested lowering water consumption in arid regions as a more sustainable approach than seawater conveyance. However, due to the high water demand, this option is not feasible. Instead, desalination of seawater is often proposed as a practical solution; Greenbaum [15] explained how the growing demand for water in the south Levant region could be met by seawater desalination as well as water recycling for agriculture. In Jordan, desalination can be done using seawater from GoA, which is the only seaport in the country. Therefore, many researchers were interested in the environment at GoA; Al-Taani et al. [16] investigated marine ecosystem and water quality at GoA. Al Hseinat et al. [17] evaluated the role of zero discharge policy at GoA in improving environmental conditions. Al-Absi et al. [18] investigated the levels of 16 trace and heavy elements in seawater in the northern Gulf of Aqaba.

In Jordan, many water projects have been proposed, especially the idea of conveying seawater from GoA; this was planned in the Red Sea-Dead Sea conveyance (RSDSC) project [19]. Quba'a et al. [20] studied alternatives to increase water supply in Jordan River Basin including the Red Sea–Dead Sea Conveyance and pipeline from Turkey. Al-Maabreh et al. [21] tested scale mitigation in Disi-Amman water pipeline using nanofiltration and chemical addition. Akash et al. [22] proposed hydropower desalination system using energy generated by flowing water from Disi to Aqaba [23]. However, despite being a sound proposal, this idea relies on transporting fossil water, which is non-renewable; therefore, the proposal is unsustainable. The potential for laying a straight pipeline from the Red Sea to Jafer Basin in order to create an artificial lake was investigated by Al-Habahbeh [24]; however, this work proposes a more feasible solution, which is to construct a minimum gradient pipeline for water conveyance. Furthermore, the potential for excavating a descending tunnel to flow water by gravity from the Red Sea to Jafer Basin in order to create a sustainable lake was proposed by Al-Habahbeh [25]; however, the current proposal is much more affordable.

Among the benefits of artificial lake development is the flourishing agriculture. Holguin et al. [26] reviewed the potential of growing saline crops in desert areas for food and biofuel production. AbuDalo et al. [27] assessed the characteristics of an artificial lake containing a mixture of treated wastewater and rainwater to examine whether the nutrient loading is sufficient for fish culture.

From the above discussions, it is clear that the proposed artificial lake would solve two problems; firstly, it will expand the available coastline by multiple folds. Secondly, it will provide seawater for possible desalination in a location closer to the center of the country. The artificial lake design process starts with formulating the problem as shown in section 2. The problem solution is presented in secion-3; it consists of the reservoir design as well as water pumping and transporting. The cost of the project is estimated in the economic assessment section. Finally, a comparison between the curved and the straight paths of the pipeline is conducted.

2 Problem Formulation

The general plan of the RSJBC project is shown in Fig. 1. It consists of two major components; the first one is seawater transportation system, which includes pipes and pumps, with the intake installed at GoA (Point A) and the discharge installed at JB (Point B). The length of the pipeline is 220 km. The second component is the artificial lake that will be developed inside JB (The blue region above Point B). The proposed area of the Lake is 250 km^2.

It is noted in Fig. 1 that the pipeline is not straight, but rather curved towards the east side. The reason for that is to avoid crossing the Shara Mountains, which means climbing up to 1,350 m above sea level (ASL). A schematic diagram for the RSJBC project alignment is shown in Fig. 2, where seawater is pumped from Red Sea (point 1), at sea level to South eastern desert (point 2) at 894 m ASL. From point 2, water will flow by gravity to JB (point 3), at 850 m ASL, where the lake is formed. There is a possibility for hydro-energy generation in the downslope, which will be investigated.

For the water conveyance system, a pipeline is selected. The water intake will be placed in GoA, while multiple pumping stations will be deployed along the pipeline. This arrangement will result in steady pressure in the pipeline. The estimated total length of the pipeline is 220 km. The pipeline course has to go up and down following the terrains, and having multiple pumps along the way would prevent back flow. The RSJBC project is divided into two phases; in phase-I, the pipeline and pumps are constructed, while in phase-II, the basin is filled up with water. After the completion of Phase-II, it will be necessary to continue pumping a certain amount of water in order to compensate for evaporated water. In the meantime, an additional amount can be pumped and desalinated in order to fulfill the growing needs for fresh water in the area. The main steps of the lake development algorithm are shown in Fig. 3.

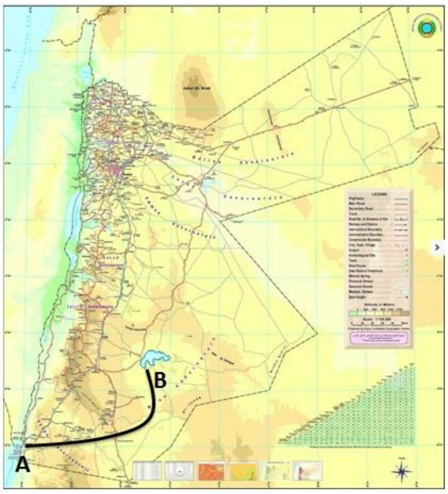

Fig. 1: RSJBC pipeline plan [28]

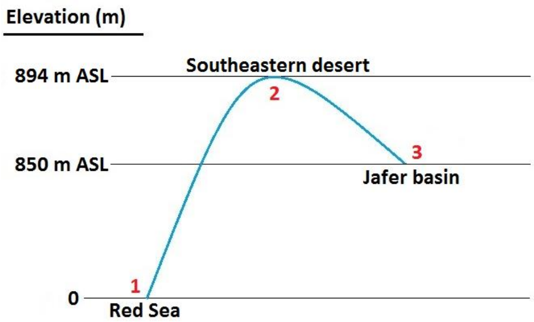

Fig. 2: Pipeline route around the mountains

3 Problem Solution

3.1 Reservoir Design

The proposed lake will be located in JB, which is a unique natural place. It is a dry and quiet dish-like area located in the south-eastern Jordanian desert, about 60 km from Ma'an [29] and 6 km to the east of Jafer town. It is a flat white basin which collects rain water from the surrounding mountains. Furthermore, the floor of the basin is very hard and do not grow any vegetation [30]. A schematic plan of the basin is shown in Fig. 4, where the Lake is designed to occupy the enclosed area, which equals 250 km^2, while the perimeter equals 105 km. In summer, this place is very dry, while in winter, fresh water flowing from the surrounding mountains accumulates in the basin. The annual direct rainfall (R_B) on the basin is given by:

$$R_B = R_A \times A_B \quad (1)$$

Where R_A is the annual rate of rainfall in the basin, equal to 32 mm/year [32], and A_B is the area of the basin, equal to 250 km^2. The resulting R_B is 8 million cubic meters per year (MCM/y). The outer JB has a circular shape with 100 km diameter and a total area of 7,366 km^2. JB is located inside the outer basin. It has a mean elevation of 850 m ASL [33], as shown in Fig. 4. JB region is characterized as a hyper-arid zone [34]. The rate of flood flow into the basin in a wet year is 15 MCM/y [35]. The total water volume (V_w) needed to fill up the basin can be calculated by multiplying the area by the depth. The area of the basin (A_B) is 250 km^2, and the average depth (D_B) is 8 m [36]. Therefore, the volume of the water (V) is calculated by:

$$V_W = A_B \times D_B \quad (2)$$

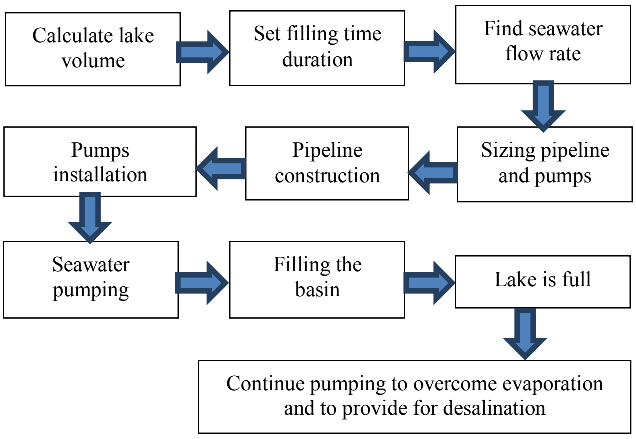

Fig. 3: Lake development algorithm

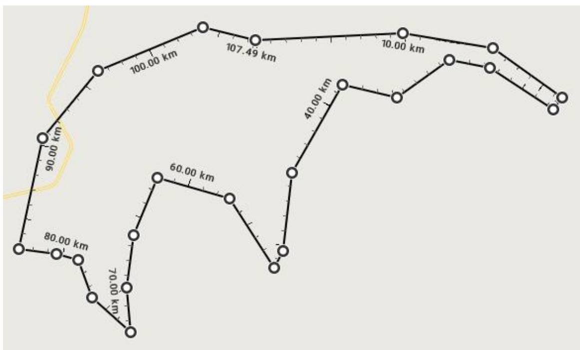

Fig. 4: Layout of the proposed lake [31]

Equation (2) is used to calculate the water volume needed to fill up the basin and create the lake; the resulting volume is 2,000 MCM. The main source of water used to fill up the lake is the seawater pumped from GoA. The contribution of fresh flood and rain water adds up to 23 MCM. It was confirmed that after filling up the lake, the nearby Jafer town and the airbase will still be 3 to 19 m above water level. In order to accurately calculate the volume of seawater that must be transported into the basin, due attention should be paid to evaporation. The combination of high temperatures and low humidity in the area results in an extremely high evaporation rate. The evaporation rate ranges between 1,600 mm/y in the northern Highlands and 4000 mm/y in the south eastern desert [37]. Assaf and Kessler [38] estimated an annual evaporation rate of 280 W/m^2 in GoA, which is equivalent to 1 cm/day of evaporation. Therefore, the expected evaporation rate from the lake (E_R) can be estimated using the above data as 3.83 m/y. The volume of evaporated water is calculated by multiplying E_R with the water surface area (A_B), which yields an annual evaporation rate of 958 MCM from the surface of the lake. In addition, the marginal amounts of falling rain (8 MCM/y) and incoming seasonal streams (15 MCM/y) are subtracted from the needed supply.

Seawater pumping requirements are assigned based on the proposed lake capacity calculated using eqn. (2), which equals 2,000 MCM. Pumping capacity should be designed such that it can fill up the basin in a reasonable time frame. It will be assumed that the time needed to fill up the lake is three years. This is considered a reasonable time for a project of this size. During each of the first three years of the project, 1,602 MCM must be pumped into the Lake, as shown in Table 1. However, starting from the fourth year, 935 MCM must be pumped annually in order to compensate for evaporation, and keep the water level constant. The pumping capacity must be designed based on the maximum required volume which is 1,602 MCM/y. Based on this assumption, the design flow of seawater (Q_{SW}) during the first three years is calculated as:

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

However, in the fourth year and beyond, a rate of 30 m^3/s must be continuously pumped to keep the level of water constant. The required pumping volumes are presented in Table 1. It is noted that the water depth at the end of the first, second, and third years is 2.7 m, 5.3 m and 8 m, respectively. An important outcome of the RSJBC project is the possibility of desalinating up to 21 m^3/s of seawater to fulfill the needs of the area. The 21 m^3/s represents the difference between the 51 m^3/s used for three years to fill up the lake, and the 30 m^3/s needed after that to keep the water level constant. Assuming a recovery rate of 45%, the rate of produced fresh water could reach 9.45 m^3/s, which amounts to 298 MCM/y.

Table 1. Basin filling plan

Description (Volumes in MCM)	1st Year	2nd Year	3rd Year	4th Year	Total	Operation
Water volume of the Lake	667	667	667	0	2,000	Add
Evaporation from the Lake	958	958	958	958	3,832	Add
Flooding streams into Lake	15	15	15	15	60	Subtract
Direct rain into Lake	8	8	8	8	32	Subtract
Pumping needed into Lake	1,602	1,602	1,602	935	5,741	---
Net volume in the Lake	667	1,333	2,000	2,000	---	---
Water depth in the Lake (m)	2.7	5.3	8.0	8.0	---	---
Pumping rate into Lake (m^3/s)	51	51	51	30	---	---

3.2 Pumping and Transporting

The pumping rate will be designed based on the required water flow rate given by eqn. (3). As for conveyance, rigid or flexible pipes must be utilized. Due to evaporation losses from the lake, it is expected that pumping will be permanent; therefore, the quality and reliability of the selected pipes and pumps should be good enough to endure long life cycles. The pipeline design includes several parameters, such as Length, Diameter, Thickness, and Material. Multiple values of the pipe diameter will be investigated; from 2-7 m. A pipe diameter of 1 m is not considered in this work because the pressure will be too high. The wall thickness of the pipe is calculated using the following equation [11]:

$$\delta = \frac{pD_{pipe}}{2\sigma} \qquad (4)$$

Where, p is Water pressure, D_{pipe} is Pipe diameter, σ is Wall safety tensile stress, and δ is Pipe wall thickness. The effect of material safety tensile stress on pipe wall thickness for pipe diameter of 3 m and pressure of 5 atm was checked to be safe. Considering pipe material selection, there are different options available; such as steel, plastic, fabric and composite. The mean water velocity in a pipe of diameter D_{pipe} is equal to volumetric flow rate divided by the pipe cross-sectional area, defined as:

$$w_{SW} = \frac{4Q_{SW}}{\pi D_{pipe}^2} \quad (5)$$

Where the seawater flow rate through the pipe is Q_{SW}. The transport system includes a series of pumps where their main parameter is the pumping power P_p, which can be obtained from the grid. The power required to impel the water within the pipe is given by:

$$P_{pump} = g\rho_{SW} Q_{SW} H/\eta_p \quad (6)$$

Where g is the gravitational acceleration (= 9.81 m/s^2), ρ_{SW} is the density of seawater (= 1,030 kg/m^3), H is the hydraulic head and η_p is the efficiency of the pump (= 0.75). The hydraulic head is obtained by adding the maximum elevation of the pipe above sea level H_{pipe} (= 894 m), as shown in Fig. 2, to the lost pressure height (ΔH) due to friction, which equals:

$$H = H_{pipe} + \Delta H \quad (7)$$

In this work, only linear pressure losses will be considered, and the lost pressure height will be:

$$\Delta H = \lambda \frac{L_{pipe}}{D_{pipe}} \frac{w_{sw}^2}{2g} \quad (8)$$

Where L_{pipe} is the pipe length and λ is the coefficient of linear pressure loss, given by:

$$\lambda = \begin{cases} \frac{1}{\sqrt[4]{100Re}} & for \;\; Re < 10^5 \\ 0.0032 + \frac{0.211}{Re^{0.237}} & for \;\; Re > 10^5 \end{cases} \quad (9)$$

The expression for Reynolds number is given by:

$$Re = \frac{w_{sw} D_{pipe}}{v_{sw}} \quad (10)$$

Where v_{sw} is the kinematic viscosity of seawater (=13×10^{-4}/ρ_{sw}) m^2/s.

Pump specific power for a 1 m^3/s flow rate is given by:

$$P_{specific} = \frac{P_{pump}}{Q_{SW}} = \frac{g\rho_{sw} H}{\eta_p} \quad (11)$$

A clear conclusion is that using a large diameter pipe combined with low pressure is much more energy efficient. The energy consumed with pumping $E_{pump,year}$ (J/year) is obtained from:

$$E_{pump,year} = 365 \times 24 \times 3600 \times P_{pump} \quad (12)$$

For analytical reasons, the pipeline route is divided into two sections, the first section measures two-thirds of the total length and extends from GoA to South eastern desert. It is designated as Stage-I. The second section measures one-third of the total length and continues from the South eastern desert to JB. It is designated as Stage-II. The basic parameters of Stage-I of the pipeline are shown in Table 2 for Year-1. Similarly, parameters for Stage-II of the pipeline are presented in Table 3 for Year-1. While pipeline results for different diameters and water speeds for Year-1 (Stage I & II) are presented in Table 4. After the 3 years needed to fill up the basin, pipeline results for Year-4 (Stage I & II) are shown in Table 5. It is noted that the data for the second and third years are identical to the first year. Considering the fourth year and beyond, the water flow rate will be lower, as shown in Table 5. Furthermore, if a diameter of 5 meters is used, it is possible to generate energy during Stage-II, which is a downslope. This fact is exploited in the calculations, and it will for sure reduce the power withdrawn from the grid.

The pumping flow speed as a function of pipe diameter is shown in Fig. 5. Furthermore, since the water flow rate needed after three years is less than the flow required during the first three years, it is reflected on the flow velocity as shown in Fig. 5. The effect of pipe diameter on pumping power is shown in Fig. 6. It is clear that employing a pipe diameter of more than 3 meters would greatly reduce the required pumping power. The same trend is noted in Fig. 9, where the annual pumping energy is plotted against the pipe diameter.

Table 2. Pipeline parameters, Year-1, Stage-I

Q_{SW} (m^3/s)	51
Total pipe length (km)	220
Start elevation (m)	0
End elevation (m)	894
H_{pipe} (m)	+894
Start location	Aqaba
End location	South eastern desert
L_{pipe} (m)	1.47×10^5
ρ_{sw} (kg/m^3)	1,030
v_{sw} (m^2/s)	1.26×10^{-6}
Δp (atm)	3

4 Economic Assessment

Due to their huge expenditure, it is essential to calculate the cost of macro-engineering projects. For the RSJBC project, each macro-engineered component such as pipes and pumps involves two associated costs; erection and operation. The erection cost is proportional to the quantity of each component. This cost refers to pipeline and pumping system construction, while the operation cost is proportional to the volume of pumped water, after installing the pipeline and pumps. In addition to the total length, the pipeline cost depends on its diameter and material, where the cost of pipe installation depends mainly on the diameter. In this section, the cost of the pipeline and the pumps enabling steady water shifting is calculated. The cost c_{pipe} of the conducting pipe is determined by [11]:

$$c_{pipe} = c_{pipe,1} L_{pipe} \tag{13}$$

Where $c_{pipe,1}$ is the cost of a unit length of the pipe.

Table 3. Pipeline parameters, Year-1, Stage-II

Q_{SW} (m^3/s)	51
Total pipe length (*km*)	220
Start elevation (*m*)	894
End elevation (*m*)	858
H_{pipe} (*m*)	-36
Start location	South eastern desert
End location	Jafer basin
L_{pipe} (*m*)	7.33×10^4
ρ_{sw} (kg/m^3)	1,030
v_{sw} (m^2/s)	1.26×10^{-6}

Table 4. Pipeline results, Year-1 (Stage I & II)

D_{pipe} (*m*)	w_{SW} (*m/s*)	ΔH (*m*)	Hydraulic Head (*H*) (*m*)	P_{pump} (*MW*)	Number of stations	Δp (*atm*)	P_{pump}/ Station (*MW*)
2	16	7,130	10,335	5,522	326	3	24
3	7	1,468	2,243	1,626	63	3	24
4	4	315	1,179	854	36	3	24
5	3	129	1,003	692	29	0.3	24

Table 5. Pipeline results, Year-4 (Stage I & II)

D_{pipe} (*m*)	w_{SW} (*m/s*)	ΔH (*m*)	Hydraulic Head (*H*) (*m*)	P_{pump} (*MW*)	Number of stations	P_{pump}/ Station (*MW*)
2	9	2,465	3,359	1,842	130	14
3	4	343	1,237	554	36	14
4	2	85	979	394	28	14
5	2	29	923	359	27	14

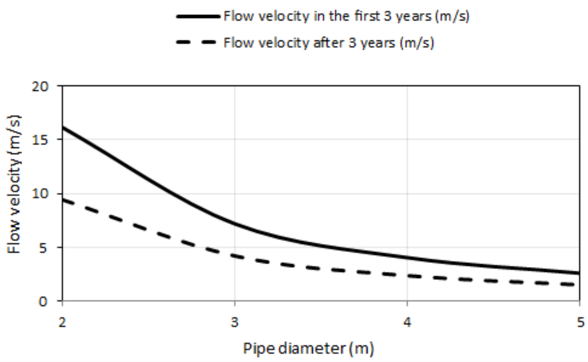

Fig. 5: Flow velocity vs. pipe diameter

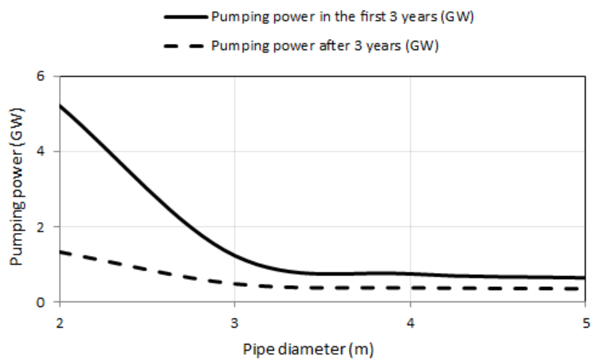

Fig. 6: Pumping power vs. pipe diameter

Similarly, the cost of pipe installation, $c_{inst,pipe}$ is given by:

$$c_{inst,pipe} = c_{inst,pipe,1} L_{pipe} \tag{14}$$

Where $c_{inst,pipe,1}$ is the cost of installing one unit length of the pipe. The unitary cost depends on different factors, such as pipe diameter D_{pipe} and material. The cost of pump mounting, C_{pump}, is determined by:

$$C_{pump} = P_{pump} c_{pump,1} \tag{15}$$

Where $c_{pump,1}$ is the cost of the pump unit power. In order to transform JB into a lake, a number of pumps must be installed along the pipeline as indicated in Tables 4 and 5. The first part of the water transport system (Stage-I) transmits the water to point 2 in Fig. 2, at an elevation of 894 m ASL. This point is located 147 km from GoA and 73 km from JB. After passing point 2 on the way to Jafer, the pipeline descends down from 984 m to 850 m, with 34 m water column. However, according to analysis, hydropower could be generated only after three years using a 5 m pipe diameter. Considering the cost of an average quality pump of unit power $c_{pump,1}$ as 800 \$/kW [11], the cost of energy consumed during one year, c_{year} is calculated as [12]:

$$c_{year} = E_{year} c_{year,1} \quad (16)$$

Where $c_{year,1}$ = 0.1$ k/Wh. For N years, the energy cost, c, is given by:

$$c = N c_{year} \quad (17)$$

Where N is the number of service years. The initial investment cost c_{invest} for the pipes and pumping installations is given by:

$$c_{invest} = c_{pump} + c_{pipe} + c_{inst,pipe} \quad (18)$$

After constructing the pipeline and pumping stations, it will take three years of pumping to fill up the basin. During that period, annual pumping cost will be constant. However, after filling up the lake, the pumping cost will decrease and stay constant. An estimation of the investment costs is presented in Tables 6 to 12; Table 6 depicts the annual operating cost for the SP pipeline for multiple diameters. Table 7 shows the pipeline cost of Stage-1 during the first year. Table 8 provides the pumping cost during the second year for both Stage-I and Stage-II. Table 9 shows the pumping cost during the fourth year for both stages. Table 10 depicts the sum of the initial cost and the pumping cost for steel pipes. The annual operating cost for CP pipeline for multiple diameters is shown in Table 11.

In order to decrease the cost of pumping, floating PV cells could be deployed on the surface of the Lake. Ikhennicheu et al. [39] presented three cases of floating solar PV farms, small, large and offshore. Furthermore, renewable resources had been proposed by Salem and Hudaib [40] to pump water via pipeline and excavated tunnel into Qattara Depression Reservoir. The cost of pipeline made of different materials versus pipe diameter is shown in Fig. 7. The highest is the steel and the lowest is the fabric. Fig. 8 shows the pumping cost for different pipe diameters. It is noted that energy and consequently cost decreases with pipe diameter, where there is a turning point at 4 meters diameter. The annual pumping energy for different pipe diameters is shown in Fig. 9. The energy decreases sharply from 2 m to 3 m diameter. The pumping cost variation with pipe diameter is plotted in Fig. 10. It is noted that the cost decrease tangibly after 4 m diameter.

From the previous results, it is noted that if fabric pipes are deployed, the development cost of the RSJBC project can be minimized. Within this option of pipe material, the minimum cost can be achieved using a 6 m diameter, which equals 2.74 B$. On the other hand, the total annual operating cost is equal to 306 M$.

Table 6. Annual operating cost (SP)

D_{pipe} (m)	Cost of pumping (M$)
3	421
4	330
5	310
6	304
7	302

Table 7. Cost of pipeline, Year-1, Stage-I

D_{pipe} (m)	Pumps (M$)	Pump Energy (M$)	Steel pipe & pump (B$)	Plastic pipe & pump (B$)	Fabric pipe & pump (B$)
2	4,227	4,628	9,32	9.18	8.98
3	1,010	1,106	2,82	2.61	2.32
4	623	678	2,23	1.95	1.56
5	535	585	2,29	1.94	1.45

Table 8. Cost of pumping, Year-2 (Stage I & II)

D_{pipe} (m)	Pumping Energy (M$)
2	6,651
3	1,368
4	726
5	587

Table 9. Cost of pumping, Year-4 (Stage I & II)

D_{pipe} (m)	Pumping Energy (M$)
2	1,594
3	481
4	345
5	315

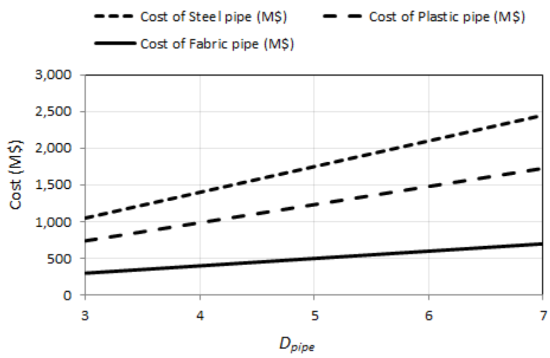

Fig. 7: Cost of pipeline vs. diameter

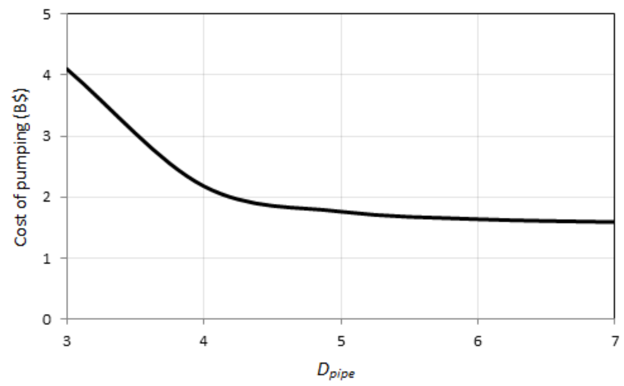

Fig. 8: Pumping cost vs. pipe diameter

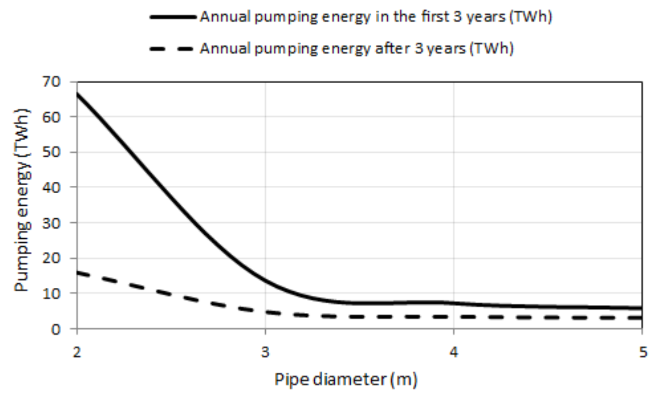

Fig. 9: Annual pumping energy vs. pipe diameter

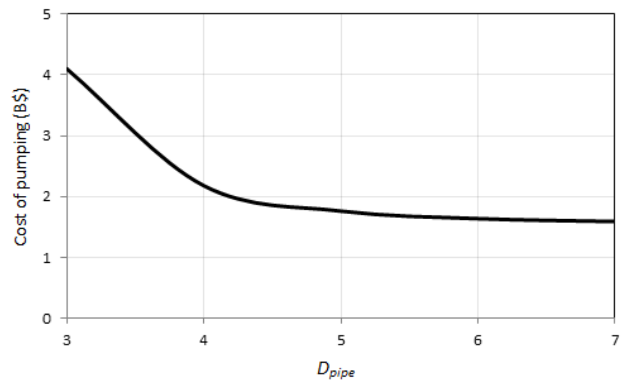

Fig. 10: Pumping cost vs. pipe diameter

Table 10. Initial & pumping costs for Steel pipes

D_{pipe} (m)	Pumps & pipes (B$)	Pumping Energy Y-1 (B$)	Pumping Energy Y-2 (B$)	Pumping Energy Y-3 (B$)	Total development (B$)
3	2.28	1.36	1.36	1.36	6.35
4	2.06	0.72	0.72	0.72	4.22
5	2.29	0.58	0.58	0.58	4.04
6	2.59	0.55	0.55	0.55	4.24

Table 11. Annual operating cost for CP

D_{pipe} (m)	Cost of pumping (M$)
3	480
4	345
5	315
6	306
7	303

5 Comparison between Curved Path (CP) and Straight Path (SP)

This section compares between two pipeline routes; the first route is the one described in this work and shown in Fig. 1. Because of its shape, it is called; "Curved Path (CP)". The second route connects points A and B in Fig. 1 by a straight line. This alternative route is called; "Straight Path (SP)". However, due to the en-route Mountains, this pipeline has to climb 1,350 m ASL, and then descend to 858 m ASL at point B in Fig. 1. Using the SP, the lowest total development cost of the RSJBC project can be obtained using fabric pipe. Within this pipe material option, a diameter of 6 m provides the minimum cost, standing at 3.01 B$, as opposed to 2.74 B$ for the CP. The corresponding annual operating cost is equal to 304 M$, versus 306 M$ for the CP. This means the CP provides the minimum possible development cost for the RSJBC project, even though the operating cost is slightly higher than SP. The total cost for different pipe diameters is shown in Fig. 11 for CP and SP. While the annual operating cost for different pipe diameters is shown in Fig. 12. The full comparison between CP and SP is shown in Table 12; it is noted that the pipe diameter has a large influence on the cost; for large diameters, CP is better than SP in terms of development cost and annual operating cost. The cost timeline for SP and CP both using Fabric pipe is shown in Fig. 13. One more point to consider is that CP extends through vacant desert, while SP extends over the mountains, where there are more human activities, which create more obstacles to the pipeline route.

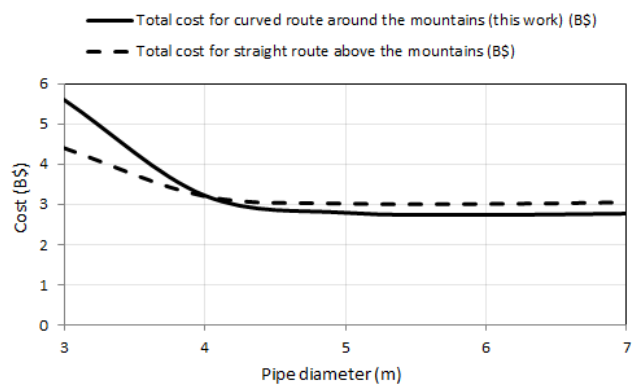

Fig. 11: Total cost vs. pipe diameter

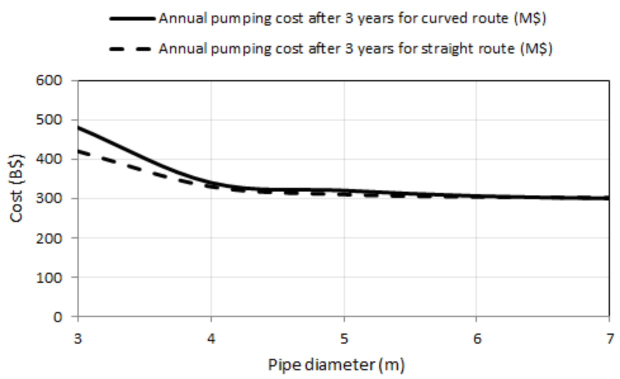

Fig. 12: Annual operating cost

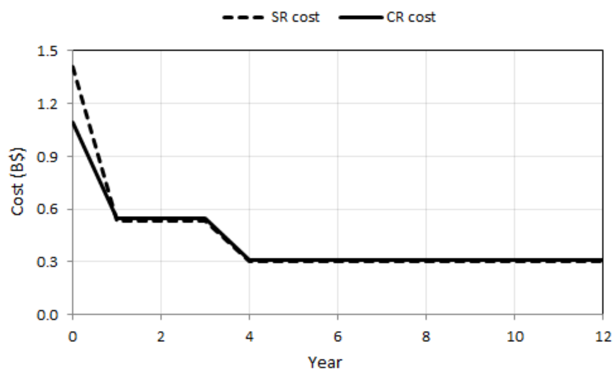

Fig. 13: Cost timeline for SP & CP (Fabric pipe)

Table 12. Annual operating cost for CP & SP

D_{pipe} (*m*)	CP		SP	
	Development cost (B$)	**Annual operating cost (B$)**	**Development cost (B$)**	**Annual operatin g cost (B$)**
3	5.60	0.48	4.4	0.42
4	3.22	0.34	3.2	0.33
5	2.79	0.32	3.02	0.31
6	2.74	0.306	3.01	0.304
7	2.77	0.30	3.05	0.302

6 Conclusion

This work presents a design of an innovative macro-engineering project; the proposed project is called RSJBC and involves a seawater pipeline extending from GoA to JB, where an artificial Lake is created. After the construction of the pipeline and the pumping stations is completed, and the project is commissioned, it will take three years to fill-up the basin. Once the Lake is filled-up, the pumping rate delivered to the Lake must be reduced from 51 m^3/s to 30 m^3/s, to keep the water level constant. The surplus flow of 21 m^3/s can be desalinated to fulfill the needs of the area. Assuming a recovery rate of 45%, the rate of produced fresh water could reach 9.45 m^3/s, which equals 298 MCM/y. The suggested pipeline route (CP) is curved so as to avoid high altitude mountains if it were to go straight (SP). However, to confirm the benefit of this approach, a comparison is conducted between CP and SP. It was revealed that using CP, the lowest development cost of RSJBC project can be realized, provided fabric pipe is selected. Specifically, a pipe diameter of 6 m provides a minimum development cost of 2.74 B$, with corresponding annual operating cost of 306 M$. There is a small difference between the operating costs for both designs, which can be neglected.

Furthermore, attention should be paid to the fact that CP extends through vacant desert while SP extends over the mountains where there is more human activity going on, which creates more obstacles to the pipeline route.

Since the floor of the basin is completely flat, once it is covered with water, the lake will have constant water depth. In this work, the main concern is the relatively high operating cost, which is due to evaporation process. Since evaporation rate is much higher than recharge rate, the salinity level of the lake is expected to rise. However, evaporation rate will decrease with increasing salinity. Future research is recommended on the ecological effects and sustainability of the lake; especially the salinity increase rate and the feasibility of mining and using the excess salt. On the cost aspect, one possible way to reduce the operating cost is to schedule pumping during grid off-peak hours. Another option is to invest in solar photovoltaic (PV) energy to power the continuous pumping needed. The PV modules can be conveniently positioned on the surface of the lake. In this case, the efficiency of the modules will be improved by the cooling provided by seawater.

References:

[1] Megdiche-Kharrat F., Zheng X. Y., Moussa M., Famin Z., Angelakis A. N., Historic hydraulic works: paradigms of traditional good water governance, integrity and sustainability, *Water Science and Technology: Water Supply*, Vol.20, No.7, 2020, pp. 2484-2498. https://doi.org/10.2166/ws.2020.146.

[2] Al-Saqarat B. S., Abbas M., Lai Z., Gong S., Alkuisi M. M., Abu Hamad A. M. B., Carling P. A., Jansen J. D., A wetland oasis at Wadi Gharandal spanning 125-70 ka on the human migration trail in southern Jordan, *Quaternary Research (United States)*, Vol.100, 2021, pp. 154-169. https://doi.org/10.1017/qua.2020.82.

[3] Roje-Bonacci T., Splitu S., Građevinarstva F., Geodezije A., The impact of hydrotechnical

interventions on the water regime of Baćina Lakes, *Hrvatske Vode,* Vol.28, No.114, 2020, pp. 277–290. https://hrcak.srce.hr/254511.

[4] Goodwin I. D., Roberts J. L., Etheridge D. M., Hellstrom J., Moy A. D., Ribo M., Smith A. M., Modern to Glacial age subglacial meltwater drainage at Law Dome, coastal East Antarctica from topography, sediments and jökulhlaup observations, *Geological Society Special Publication,* Vol.461, No.1, 2018, pp. 215–230. https://doi.org/10.1144/SP461.16.

[5] Lukman, Hidayat H., Subehi L., Dina R., Mayasari N., Melati I., Sudriani Y., Loads of Pollution to Lake Toba and Their Impacts, *International Journal on Advanced Science, Engineering and Information Technology*, Vol.11, No.3, 2021, pp. 930-936. https://doi.org/10.18517/ijaseit.11.3.12733.

[6] Abd Aziz N., Toriman M. E., Gasim M. B., Muftah S., Barggig A., Kamarudin M. K., Water Quality Deterioration in Artificial Lake: Their Impact and Sources, *International Journal on Advanced Science, Engineering and Informat-ion Technology*, Vol.7, No.1, 2017, pp. 49- 56. https://doi.org/10.18517/ijaseit.7.1.1012.

[7] Gupta J., Van der Zaag P., Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock, *Physics and Chemistry of the Earth, Parts A/B/C*, Vol.33, No.1–2, 2008, pp. 28-40.

[8] Mohanty R., Mohapatra A., Mohanty S., Assessment of the impacts of a new artificial lake mouth on the hydrobiology and fisheries of Chilika Lake, India, *Lakes and Reservoirs: Science, policy and management for sustainable use*, 2009. https://doi.org/10.1111/j.1440-1770. 2009.00406.x.

[9] Badescu V. and Cathcart, R.B., Aral Sea partial restoration. II. Simulation of time-dependent processes, *Int. J. Environment and Waste Management*, Vol.7, Nos.1/2, 2011, pp. 164-174.

[10] Stone R., After revival, Iran's great salt lake faces peril, *Science*, Vol.372, No.6541, 2021, pp. 444-445. https://doi.org/10.1126/science.372.6541.444.

[11] Badescu V., Cathcart R. B., Paulescu M., Gravila P., and Bolonkin A. A., Chapter 89 Geo-Engineering South Australia: The Case of Lake Eyre, Macro-Engineering Lake Eyre with imported Seawater. In: Badescu V., Cathcart R. B., (eds) Macro-Engineering seawater in unique environments. *Environmental science and Engineering (Environmental Engineering)*, Springer, Berlin, Heidelberg, 2010. https://doi.org/10.1007/978-90-481-9920-4_89.

[12] Badescu V., Cathcart R. B. and Bolonkin A. A., Sand dune fixation: a solar-powered Sahara seawater pipeline macro project, *Land Degrad. Develop.*, 2008. https://doi.org/10.1002/ldr.864.

[13] Gomaa S. M., Hassan T. M., Helal E., Assessm-ent of seawater intrusion under different pump-ing scenarios in Moghra aquifer, Egypt, *Science of the Total Environment*, Vol.781, 2021. https:// doi.org/10.1016/j.scitotenv.2021.146710.

[14] Yazdandoost F., Noruzi M. M., Yazdani S. A., Sustainability assessment approaches based on water-energy Nexus: Fictions and nonfictions about non-conventional water resources, *Science of the Total Environment*, Vol.758, 2021. https://doi.org/10.1016/j.scitotenv.2020. 143703.

[15] Greenbaum N., Hydrology and water management in Israel and the southern Levant, *Geographische Rundschau*, Vol.72, No.12, 2020, pp. 24–29.

[16] Al-Taani A. A., Rashdan M., Nazzal Y., Howari F., Iqbal J., Al-Rawabdeh A., Al Bsoul A., Khashashneh S., Evaluation of the gulf of Aqaba coastal water, Jordan, *Water (Switzerland)*, Vol.12, No.8, 2020. https://doi.org/10.3390/w12082125.

[17] Al Hseinat M., Rasheed M., Al-Rousan S., Long-term quality record (1996–2018) of coastal sediments at the complex industrial site along the Jordanian coast of the Gulf of Aqaba, *Environmental Monitoring and Assessment*, Vol.192, No.443, 2020. https://doi.org/10.1007/s10661-020-08390-3.

[18] Al-Absi E., Manasrah R., Abukashabeh A., Wahsha M., Assessment of heavy metal pollutants at various sites along the Jordanian coastline of the Gulf of Aqaba, Red Sea, *International Journal of Environmental Analytical Chemistry*, Vol.99, No.8, 2019, pp. 726-740. https://doi.org/10.1080/03067319.2019.160945 9.

[19] Beyth M., The Red Sea and the Mediterranean–Dead Sea canal project, *Desalination*, Vol.214, 2007, pp. 364–370.

[20] Quba'a R., El-Fadel M., Abou Najm M., Alameddine I., Comparative assessment of joint water development initiatives in the Jordan River Basin, *International Journal of River Basin Management*, Vol.15, No.1, 2017,

pp. 115-131. https://doi.org/10.1080/15715124.2016.1213272.

[21] Al-Maabreh A. M., Al-Rawajfeh A. E., Alshamaileh E., Al-Bazedi G. A., Mitigation of scale problem in the pumped Disi water to Amman, Jordan, *Environment Protection Engineering*, Vol.45, No.1, 2019, pp. 97–110. https://doi.org/10.5277/epe190108.

[22] Akash B. A., Al-Jayyousi O. R., Mohsen M. S., Multi-criteria analysis of non-conventional energy technologies for water desalination in Jordan, *Desalination*, Vol.114, 1997, pp. 1-12.

[23] Mohsen M. S., Water strategies and potential of desalination in Jordan, *Desalination*, Vol.203, 2007, pp. 27–46.

[24] Al-Habahbeh O. M., Exploiting regional topography and macro-engineering to transform southeastern Jordanian desert into a coastal area, *Journal of Mechanical Engineering Research and Developments*, Vol.44, No.10, 2021, pp. 251-265.

[25] Al-Habahbeh O. M., Sustainable design of an artificial lake in Jafer basin based on gravity flow, *Mathematical Modelling of Engineering Problems*, Vol.9, No.1, 2022, pp. 101-110.

[26] Holguin Pena R.J., Medina Hernandez D., Ghasemi M., Rueda Puente E. O., Salt tolerant plants as a valuable resource for sustainable food production in arid and saline coastal zones, *Acta Biologica Colombiana*, Vol.26, No.1, 2021, pp. 116–126. https://doi.org/10.15446/abc.v26n1.82412.

[27] AbuDalo M., El-khateeb M., Ayadi H., Al-Rahahleh B., Jaradat A., Guermazi W., First assessment of water quality of an artificial lake for fish culture and irrigation: A case study of water reuse in water shortage area across the Middle East, *Aquaculture Research*, Vol.52, No.3, 2021, pp. 1267–1281. https://doi.org/10.1111/are.14985.

[28] Royal Jordanian Geographic Center, 2020. http://rjgc.gov.jo/rjgc_site.

[29] Al-Rai Newspaper, 2016. http://alrai.com/article/1032053.

[30] Ad-Dustour Newspaper. https://www.addustour.com/articles/143047.

[31] Google maps: https://www.google.jo/maps/@32.0151601,35.8607108,15z?hl=en.

[32] Kumar A. and Mozar S., *500th Volume of LNEE*, ICCCE 2018, Proceedings of the International Conference on Communications and Cyber Physical Engineering, Springer, 2018.

[33] Aljazy A. D. and Al-Nasrat M. I., The History of Al-Jafer in Southern Jordan from the Earliest Times to the Establishment of Bedouin Settlement Project (500,000 BC to 1962 AD), *Jordan Journal for History and Archaeology (JJHA)*, 2017.

[34] Alzghoul M. and Al-husban Y., Topographic Characteristics and Estimation of the Quantity of Water Harvesting in Al-Jafer Depression, *JKAU/Arts and Humanities*, Vol.28, 2020, pp. 455-473. https://doi.org/10.4197/Art.28-2.18.

[35] Al Kuisi M. and El-Naqa A., GIS based Spatial Groundwater Recharge estimation in the Jafr basin, Jordan – Application of WetSpass models for arid regions, *Revista Mexicana de Ciencias Geológicas*, Vol.30, No.1, 2013, pp. 96-109.

[36] Vivid Planet Software GmbH, Salzburg/Austria, 2022. https://www.mapcoordinates.net/en.

[37] Water Resources Management Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, *Water Resources in Jordan: A Primer*, 2010.

[38] Assaf G. and Kessler J., Climate and Energy Exchange in the Gulf of Aqaba (Eilat), *Monthly Weather Review*, Vol.104, No.4, 1976, pp. 381–385.

[39] Ikhennicheu M., Danglade B., Pascal R., Arramounet V., Trebaol Q., Gorintin F., Analytical method for loads determination on floating solar farms in three typical environments, *Solar Energy*, Vol.219, 2021, pp. 34-41. https://doi.org/10.1016/j.solener.2020.11.078.

[40] Salem A. and Hudaib E., Evaluation of Al Qattara Depression Renewable Energy Potentials, *WSEAS Transactions on Environment and Development*, Vol.10, Art. #47, 2014, pp. 444-452.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Osama Al-Habahbeh performed the design and analysis.
Romil Al-Adwan performed the visualization.
Mustafa Al-Khawaldeh performed the validation.