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Design and Analysis of a Fish-Friendly Micro Gravitational Water Vortex Power Plant (GWVPP) on Zarqa River, Jordan

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ABSTRACT

The main water source of Zarqa River is the treated wastewater from As-Samra Wastewater Treatment Plant (As-Samra WWTP) which is located in Zarqa Governorate in Al-Hashimiyya on the eastern part of the river; this means year-round flowing water in the eastern part of the river. This hydro energy is wasted continuously without exploiting it to generate electricity, but when trying to implement traditional hydropower projects on the river the main problem faced is low water head and low water flow. Since a Gravitational Water Vortex Power Plant (GWVPP) is an in-stream hydropower technology that can be operated with a low hydraulic head of (0.7-5.0) m and a low flow rate of 0.5 m^3/s at least; this study proposed to install an on-grid GWVPP on Zarqa River by one of the manufacturing companies to exploit hydro energy and to serve the local community by providing farmers needs of electricity. The study also determines the appropriate site for establishing the GWVPP by collecting site data in terms of head, flow, and proximity to the grid and roads by Google Earth, site visits, and making site measurements. Then one of the GWVPP manufacturers contacted which is Turbulent Company, and then GWVPP has been designed. Environmental and economic feasibility analyses were performed by using RETScreen Expert software. As a result, the research indicates that installing a GWVPP on the Zarqa River is technically, economically, and ecologically viable.

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1. INTRODUCTION

Due to the intermittency and unpredictability of wind or solar power production, hydropower has increasingly been seen as one of the most attractive ways of harnessing energy. Hydropower is the largest renewable energy source where it contributes approximately 94% of the total renewable energy production and almost 20% of the total global energy requirements [1, 2]. However, there can be considerable environmental and economic issues associated with traditional hydropower such as large dams, high cost of civil works, large covered area, high operation and maintenance cost, and requires high head or high flow of water or both of them [3]. There has been a revolution in recent years in terms of Micro Hydro Power (MHP) technologies. However, it has been a challenge to create a solution for channels with low water head and flow at the same time. To solve this specific issue, many studies headed out to use appropriate techniques, one of these techniques are the Gravitational Water Vortex Power Plant (GWVPPs) which are emerging among various hydropower plants because of their simple design and installation. GWVPP is a hydropower technology that can be classified under the category of Mini, Micro, or Pico Hydropower which is capable of producing energy from a low hydraulic head and with a minimum flow rate where its works by vortex methodology based on the vortex motion of water [4–7].

In Jordan, hydropower sources are limited because surface water resources like rivers and waterfalls are almost negligible. One of the rivers is Zarqa River and the main water source of it is treated wastewater from As-Samra Wastewater Treatment Plant (As-Samra WWTP) which means year-round flowing water. This running water energy is wasted continuously without exploiting it to generate electricity but there are some problems that come in contact when trying to implement traditional hydropower projects on the river. The main problem faced is low water head and low water flow [8, 9].

Also, along Zarqa River, there are many farms where the owners of their need to pump water to their crops, but the high electrical energy cost in Jordan is a financial burden on them when using electric water pumps. And some of them use diesel pumps, especially in areas that are not close to the electrical network, and they suffer from the use of these pumps because they have a high operational and maintenance cost, in addition, to the air and sound pollution caused by these pumps [8, 9].

Service to the local community by covering farmers' electricity consumption that reduces the cost, and this avoids using diesel water pumps for the farmers. Thus, in this work, a design of an on-grid GWVPP on Zarqa River to exploit its running water energy is presented. An analysis of the techno, economic and environmental feasibility of the GWVPP installation is provided. Furthermore, this study aimed to reduce greenhouse gas (GHG) emissions from electricity generation in conventional electrical power plants that run on fossil fuels.

2. STUDY AREA

Zarqa River is consists of two main branches as shown in Figure 1:

1. Amman-Zarqa branch, the western part where thae length of this branch is approximately 30 km,
2. Wadi Dhuliel branch, the eastern part where the length of this branch is approximately 10 km.

The two branches converge at Al-Hassia Bridge and continue to King Talal Dam (KTD), in the Jordan Valle where the length of this main branch is approximately 40 km starting from Al-Hassia Bridge and ending with KTD [10, 11].

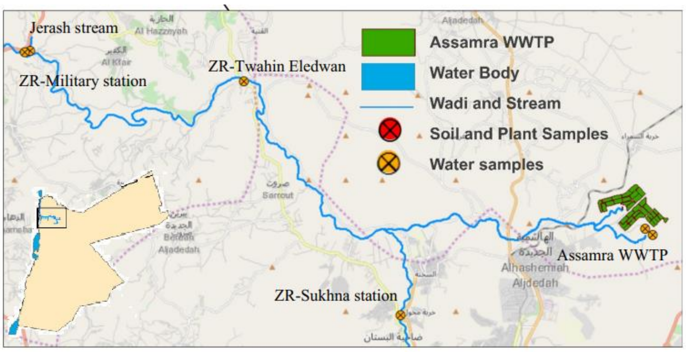


Figure 1. Location of the Zarqa River basin in Jordan [10].

As-Samra WWTP is the largest WWTP in Jordan and is located in Zarqa Governorate in Al-Hashimiyya Brigade on Wadi Dhuliel branch of Zarqa River. It designed to treat domestic wastewater emanation from Amman-Zarqa basin, which happens to include the country's most populated cities: Amman, Rusaifa, and Zarqa. Where in Amman-Zarqa basin live about 60% of the population of Jordan [10]. The total inlet flow per month (10^6 m^3/month) and the average daily inlet flow (10^6 m^3/day) in As-Samra WWTP during 2020 are presented in Figure 2.

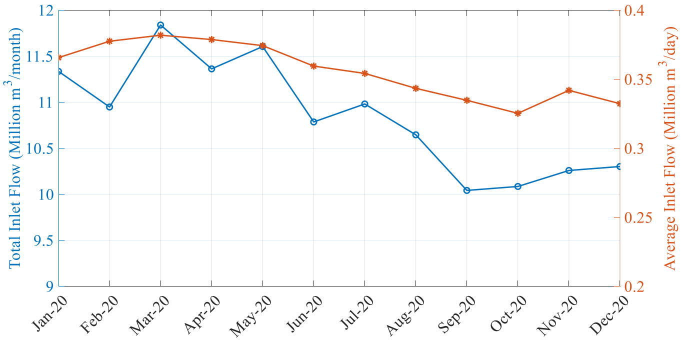


Figure 2. Inlet flow of As-Samra WWTP in 2020

3. GRAVITATIONAL WATER VORTEX POWER PLANT (GWVPP)

GWVPP is an emerging technology for sustainable & renewable energy resources to generate electrical energy which can be operated with a low hydraulic head and low flow rate. It is classified under a mini, micro, or pico ROR hydropower plant. The technology builds right next to a stream, based on a basin (circular, spiral, or conical) with a central outlet orifice, and inlet and outlet canals, where the water introduced into the basin tangentially which generates a stable water vortex above the outlet orifice then the vortex drives a water turbine which is positioned in the center of the water vortex at a suitable height.

The major components of the GWVPP include Mechanical components (Inlet gate (sluice gate), vortex turbine, turbine shaft, gearbox), civil components (Overflow dam, trash rack, inlet channel, outlet channel, vortex basin, basin protective mesh), and electrical components (generator, electrical cables, power electronics, and electrical control unit [12]), See Figure 3.

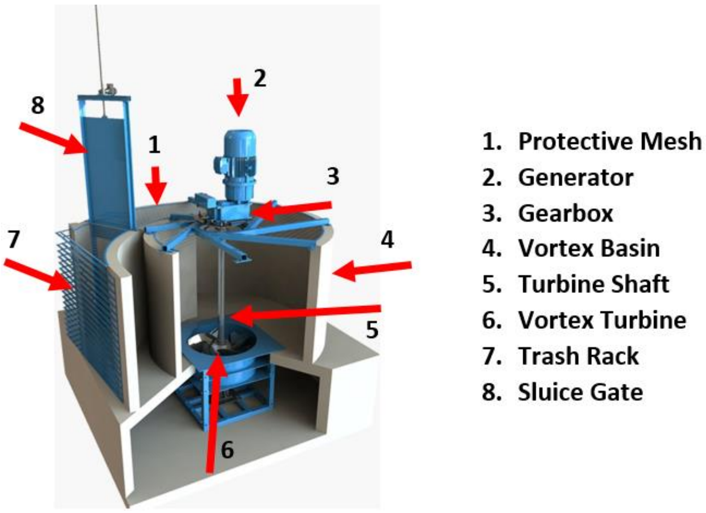


Figure 3. GWVPP main components [13].

3.1. GWVPPs Worldwide

Currently, different companies worldwide are commercializing different power rating of GWVPPs. The list of full-scale installations and location distribution of GWVPPs projects are summarized in Table 1.

The maximum power (P) obtained from the hydropower turbine can be calculated as follows [14, 15]:

$$P = \rho g Q H \tag{1}$$

Where ρ is the water density, g is the gravitation, Q is the water head, and H is the water flow rate passing through the turbine.

The efficiency of the turbine is calculated based on the ratio of the actual power (P_{actual}) from the turbine to the theoretical output power (P) [14, 15]:

$$\eta = \frac{P_{actual}}{P}\% \tag{2}$$

Further, the power density can be calculated as follows [14, 15]:

$$Power\ Density = \frac{P_{actual}}{flow\ rate} \tag{3}$$

Using (1) – (3), the actual power, power density, and efficiency were calculated for each installation projects as depicted in Table 1. Further, the relationship between the head and power density is plotted in Figure 4. As shown, the power density of the turbines rises as the head increases. Compared with result found in [15], GWVPPs have nearly double the power density, thus, GWVPPs would be able to produce twice as much power as a propeller turbine in the same head.

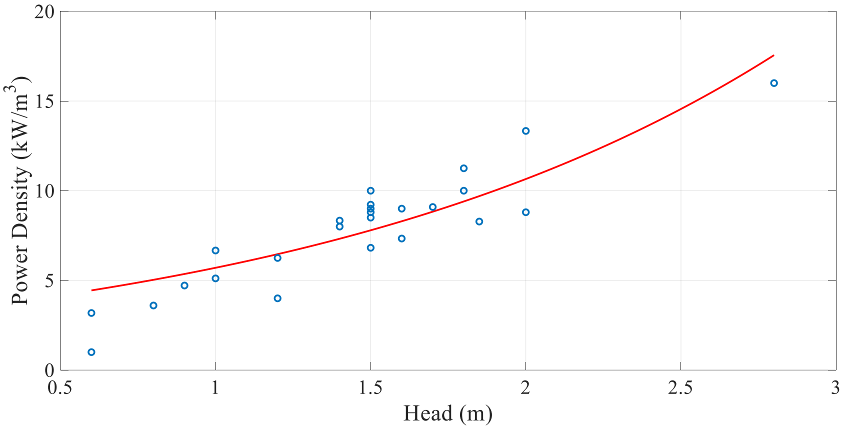


Figure 4. Head versus power density of the GWVPPs installation sites.

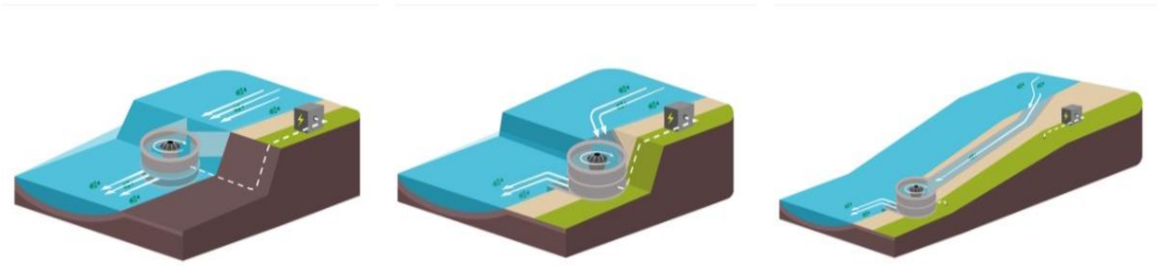
Table 1. List of the GWVPPs full-scale installation [5, 13–17].

#	Company/ Organization Involved	Location	Head (m)	Flow (m^3/s)	Actual Output Power (KW)	Theoretical Output Power (KW)	Efficiency (%)	Power Density*	Type**
1	Zotlöterer	Austria	1.5	0.9	8.3	13.5	61%	9.2	F
2			0.9	2x0.7	2x3.3	2x6.3	52%	4.7	F
3			1.5	0.5	4.4	7.5	59%	8.8	F
4			1.4	0.5	4	7	57%	8	F
5			2x1.4	0.5	2x4	2x7	57%	8.3	F
6			1.4	0.6	5	8.4	60%	8.1	F
7			1.5	1	8.5	15	57%	8.5	F
8			1.2	1.2	7.5	14.4	52%	6.25	F
9			1.8	1	10	18	56%	10	F
10			1.6	2	18	32	56%	9	F
11			1	0.9	4.6	9	51%	5.1	F
12			1.5	1	9	15	60%	9	F
13			1.8	0.8	9	14.4	63%	11.25	F
14	Turbulent***	Belgian	2	0.25	2.2	5	44%	8.8	F
15		Chile	1.7	1.65	15	28	53%	9.1	F
16		Indonesia	1.85	1.57	13	29	45%	8.3	F
17		Estonia	1.6	0.75	5.5	12	46%	7.3	F
18		France	3.2	0.7	5.5	22.4	25%	7.9	F
19	Kouris Centri-Turbine Generator (KCT)	Marysville, Australia	0.6	0.11	0.35	0.66	53%	3.2	S
20		Braeside, Australia	0.6	0.01	0.01	0.06	17%	1	S
21		Kalorama, Australia	0.8	0.05	0.18	0.4	45%	3.6	S
22	Wasserwirbelkraftwerke Schweiz	Wesenitz, Sachsen	1.2	1.5	6	18	33%	4	F
23		Suhre, Aargau	1.5	2.2	15	33	45%	6.8	F
24		Dabka, Nainital	2	1.5	20	30	67%	13.3	F
25	AquaZoom (previously known as Verde Renewables)	Technical University Dresden	1	0.75	5	7.5	67%	6.7	F
26		Kerala,India	1.5	2x1	2x10	2x15	67%	10	F

*Power density = output power/flow. **F = Flat based, C = Conical, S = Stepped inlet. ***According to Turbulent's website, there are five projects in progress.

3.2. Installation

A GWVPP system as installed either on-grid or off-grid or smart on/off-Grid can be built. The vortex basin can be installed in the river as shown in Figure 5-a or on land where the inlet channel is short with a sudden drop as shown in Figure 5-b or long with a long inclination as shown in Figure 5-c (for example height difference 5 meters over a distance of 100 meters), where the on-land install useful to protects the GWVPP components from floods and they are easy to access in cases of inspection and maintenance [13].



(a) (b) (c)

Figure 5. Types of GWVPP installation: a) In river, b) On land, short channel/sudden drop, c) On land, long channel [13]

It is possible to install multiple GWVPPs separate from each other along the stream as shown in Figure 6. Another configuration for GWVPPs is achievable which is a multiple arrangement scheme where in a multitude of turbines are placed in parallel or in series. A serial arrangement involves connecting the outlet of one vortex basin to the inlet of the subsequent basin and so on. On the other hand, a parallel arrangement involves connecting multiple vortex basins to the same inlet channel or headrace.

Figure 6. Multiple GWVPPs along canal or river [13].

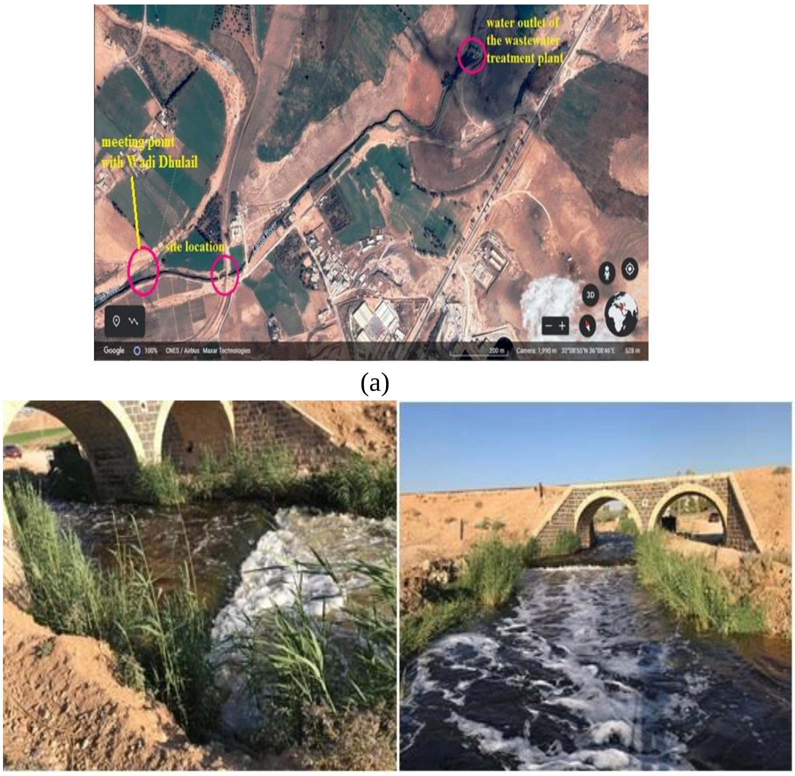
4. GWVPP AT ZARQA RIVER

4.1. GWVPP Location

The site is located specifically on Zarqa River in Zarqa Governorate in Al-Hashimiyya Brigade near As-Samra WWTP as shown in Figure 7-a, as it is located on an old bridge of a railway dating back to the days of the Ottoman Empire (see Figure 7-b). This site was chosen for several reasons:

1- Suitable water falling head caused by the bridge.
2- Reduces grid connection costs and transmission losses where the site located proximity to the low voltage local grid about 30 meters.
3- The site is close to paved roads, which means easy access to the site and transportation of materials and equipment to the site.
4- Reduce base construction civil work.
5- Width and depth of the river are regular at the bridge, which makes it easy to take site measurements.
6- It is close to As-Samra WWTP, where the distance between the site and the water outlet of As-Samra WWTP is about 1150 meters (the length of the stream) and the air distance is about 1040 meters. This

means the maximum benefit from the flow before it decreases as a result of drawing water from the river which means the output flow of the WWTP equal the input flow of the GWVPP.



(a)

(b)

Figure 7. GWVPP site location: a) Google Earth and b) the old railway bridge that is the site of the GWVPP (site visits).

4.2. Data Collection

For the selected site, the data was collected through Google Earth, site visits, site measurements, and visit As-Samra WWTP to obtain the outlet flow data. The data obtained from As-Samra WWTP are shown in Figure 8, which is the average flow rate /month (m^3/month) for the period from 01-01-2021 until 01-12-2021, see Figure 8, and the average daily outlet flow rate for different months, e.g. March 2021, June 2021, September 2021, and December 2021, see Figure 9. From different data, the minimum flow of As-Samra WWTP in 2021 was 5941 m^3/hour (1.65 m^3/s), the maximum flow in 2021 was 25874 m^3/hour (7.19 m^3/s), and the average flow in 2021 was 14880m^3/hour (4.13 m^3/s). The peak flow hours are 11 am - 9 pm and the lower flow hours are 1 am - 8 AMam

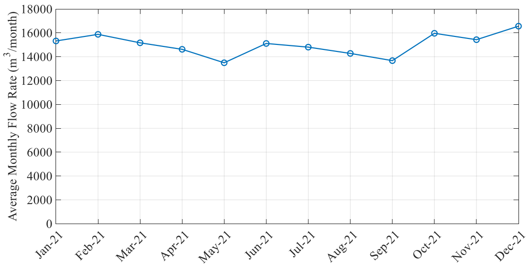


Figure 8. Average monthly flow rate of As-Samra WWTP in 2021

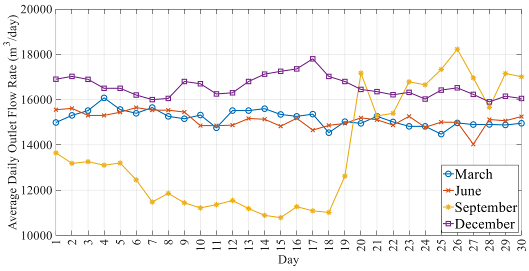


Figure 9. Average monthly flow rate of As-Samra WWTP in 2021

Further, the site measurements required is flow rate and head, the materials used in the determination are: Float (i.e. pieces of wood or plastic bottle), Measuring tape, Stopwatch, Rope, and Pegs. see Figure 10. The complete selected site measurements are tabulated in Table 2.

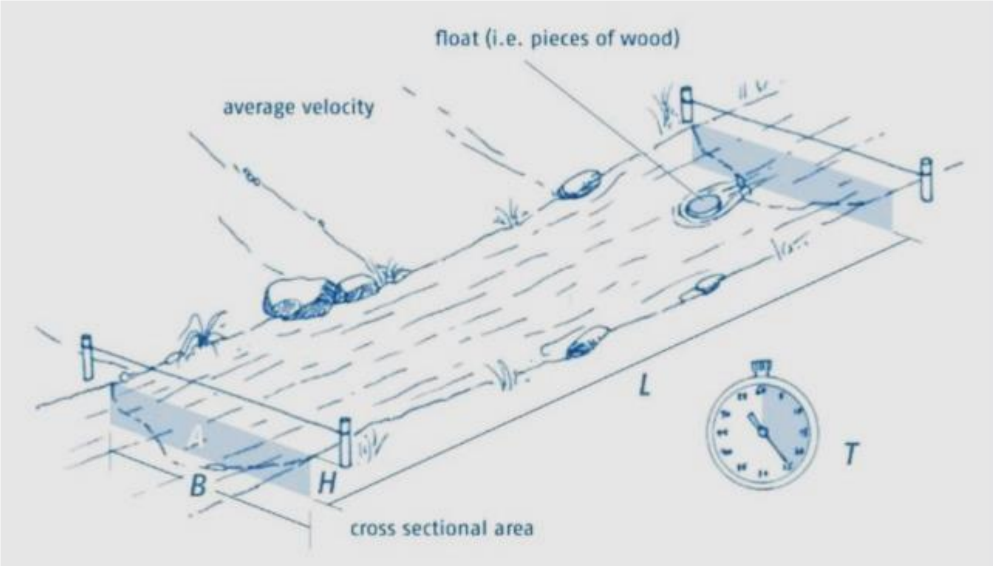


Figure 10. Site measurements [13].

Table 2. The selected site measurements.

Measurements	Value
Bridge width (B)	6 m
Bridge length (L)	4 m
Average depth (H)	0.5 m
Head of the waterfall (H_w)	1.45 m
Average travel time (T)	3.19 s
Cross-sectional Area (A)	= Total width × Average depth = (6 × 0.49) = 2.94 m^2
Velocity	= Length/Average travel time = L/T = 4/3.19 = 1.25 m/s
Flow rate	= Area (A) × Velocity (V) = 2.94 × 1.25 = 3.675 m^3/s

4.3. GWVPP Design

There are still no generic design approaches or manuals available that allow design and establish performance metrics for the GWVPP for a particular hydropower site. So far, anyone attempting to construct such a system has only learned about a basic inlet, a vortex basin with a central outlet orifice, and a coaxial turbine runner, which all have various sizes and shapes in practice. So according to the GWVPP companies, the most famous and successful commercial companies design and building GWVPP are Turbulent Company followed by Zotlöterer Company. In addition, GWVPP system for both companies is fish-friendly. The reduced speeds of the turbine and the big distance between blades ensure that fish and small debris can pass through the turbine without danger on fish and turbine. This makes these turbines fish-friendly. Therefore, in this study, one of these two companies' designs will be adopted.

Both two companies adopt the same design of the basin, which is a concrete flat-based cylindrical or spiral vortex basin with a concrete rectangular inlet channel connected tangentially to the basin with a guide plate at the basin inlet with a central outlet orifice with a turbine placed at the center of the basin on the outlet orifice where the system is located to the side of a stream with an overflow dam. But there are a few differences and the measurements vary between both designs.

Based on the flow data, site measurements, and site pictures that were submitted to the Turbulent Company, its response was: Designing a GWVPP system with a capacity of 40 KW for 4 m^3/s design flow and 1.5m hydraulic head. As shown in Figure 11 the system contains two parallel vortex basins with two turbines with a capacity of 20 kW for each turbine using PMSG generators connected directly to the grid with AC/DC/AC electrical power converter without transformer [2, 18, 19].

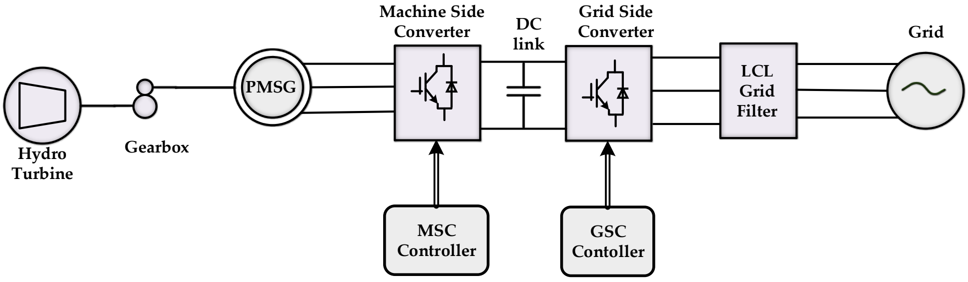


Figure 11. Electrical design of the GWVPP.

The design flow of the system is equal to the average flow of the river which is 4 m^3/s. If the available flow is more than or equal to the design flow of the plant excess water will flow over the dyke thus limiting and controlling the flow which inlet to the vortex basin, and if the available flow is less than the design flow of the plant, the turbine rpm will decrease, then the system generation will decrease. The turbine will shut down at 20% of the design flow thus will dos not produce any power at that point. Regarding grid connectivity; it is much simpler technically to use on-grid system and much more cost-effective where the payback period for grid interconnected systems is reasonable and avoid waste energy.

The technical design and equipment for GWVPP on Zarqa River is:

1- On land GWVPP.
2- Short inlet channel with sudden drop with overflow dam.
3- Concrete flat-based spiral basin with a rectangular inlet channel.
4- On-grid 40 KW GWVPP with 4 m^3/s design flow and 1.5 m hydraulic head contains two parallel vortex turbines with a capacity of 20 kW for each one.
5- Turbulent Company turbine.
6- The system is fish-friendly where fish can cross the turbine safely due to the design of the turbine, distances between blades, and the low speed of the turbine.
7- Three-phase non-submersible air-cooling PMSGs.
8- AC/DC/AC power converter which connecting to the low voltage local grid (400 V 3-phase voltage and 50 Hz frequency) without using transformer.
9- Electric Meter.

The civil structure design has been prepared approximate by Sketchup software as shown in Figure 12-a. By refer to the detailed specification of the GWVPP of the Turbulent Company on the website of the company (Appendix B); the design dimensions are as shown in Figure 12-b. Whereas, the dimensions are as in the column of the hydraulic head range of 1.5 - 3 m and the flow range of 1.85 - 3.7 m3/s; where dimensions are the same with the difference in the value of the head and the flow in these two ranges.

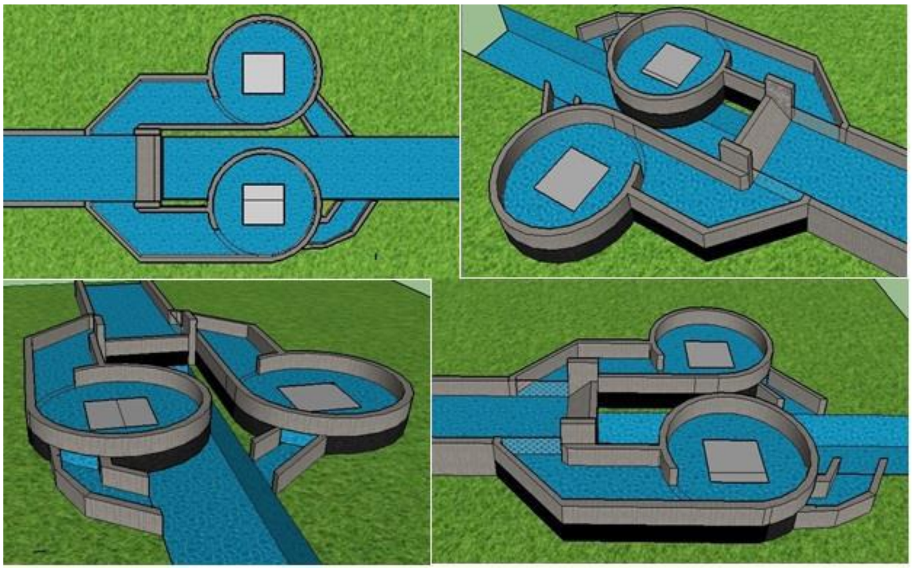


Figure 12-a. Approximate civil design of the GWVPP. [Prepared by using Sketchup software].

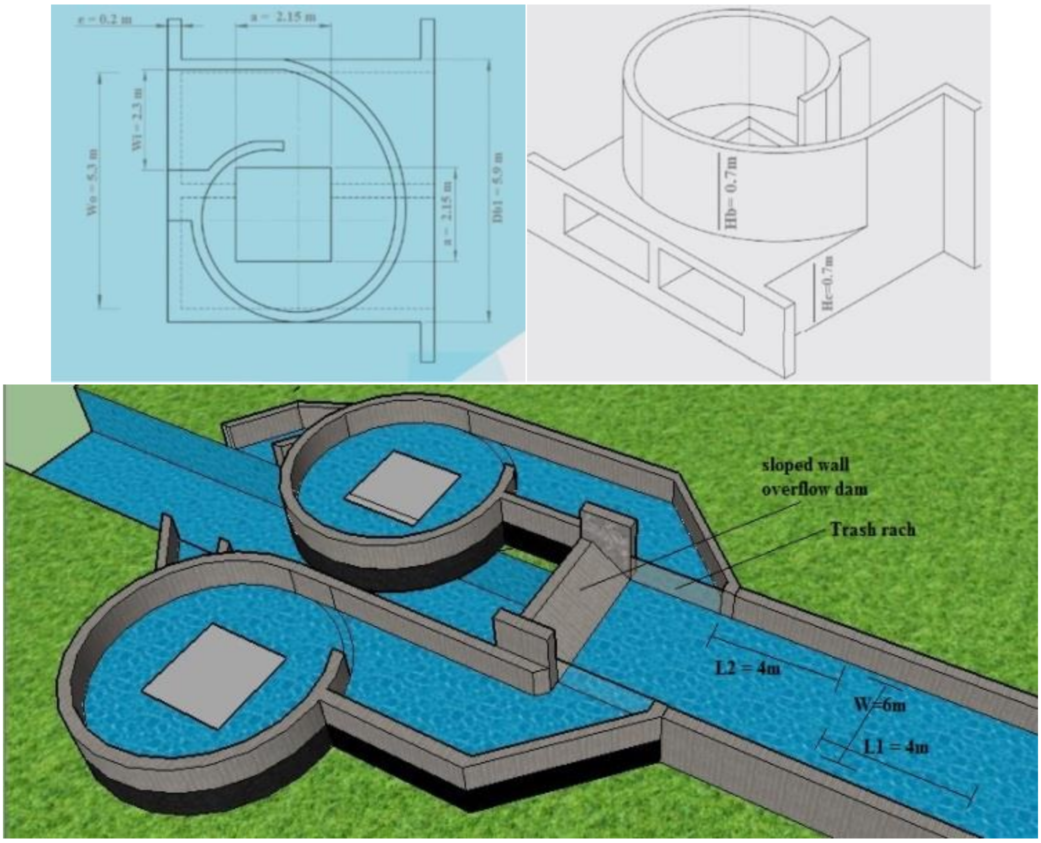


Figure 12-b. GWVPP civil design dimensions [Prepared by using Sketchup software].

Where: e: concrete walls thickness,
a: turbine pit width,
Db1: basin outer diameter,
Wi: inlet channel width,
Wo: basin inner diameter,
Hb: basin height,
Hc: outflow Height**,**
L1: length under the bridge,
L2: length after bridge until inlet channel,
W: width of the river under the bridge and thus the width of the design channel.

Table 3 compares experimental measurements and numerical calculations of the water height at inlet and outlet. Simulation and experiment show very good agreement between water heights at the inlet and outlet, with deviations below 4%.

Table 3. Comparison of experimental measurements and numerical calculations

Parameters	Simulation Results	Experimental Results	Relative Deviation %
Water hight at inlet point	0.87	0.83	4.8
Water hight at outlet point	0.75	0.79	5.1
Defferance between inlet and outlet	1.22	1.13	7.9

4.4 Cost Analysis

Cost analysis describes all the costs of investment in detail. The cost of GWVPP components has been estimated based on what was provided by Turbulent Company and estimating the cost of civil works and transportation. As Turbulent Company provided, the GWVPP cost is 4000 €/KW equal 160,000 € for 2 × 20 KW excluding the cost of civil works and transportation. Also, the yearly maintenance is 1.5% of the initial cost.

By the approximate design, as shown in Figure 12, the measurements of the design that will be constructed were determined approximately. And through providing the design measurements, site information, and the nature of the soil to a local contracting company, the cost of the civil work was roughly determined the design needs 80 m^3 of concrete, and 5 tons of reinforcing iron, and according to the prices of concrete and reinforced iron in Jordan on 25/11/2021: Concrete 50 JOD/m^3 and reinforced iron 650 JOD/ton. And the construction wages are calculated per square meter of concrete, where they were at a price of 80 JOD/m^3 as the local contracting company provided. Thus, the civil works cost is as follows: $80 \times 50 + 5 \times 650 + 80 \times 80 = 13650$ JOD. Table 4 summarized the cost of the GWVPP components.

Table 4. Cost analysis.

Type	Cost in Euro	Cost in JOD
Design		
Mechanical equipment	160,000	128,000
Electrical equipment		
Civil works	17,063	13,650
Total	177,063	141,650
Maintenance	0.015 × 177,063 = 2,656 €/year	2,125 JOD/year

5. GWVPP MODEL BY RETScreen® Expert SOFTWARE

The model parameter descriptions utilized in RETScreen® Expert software are as follows:

1- Benchmark: It the sale electricity price (Electricity export rate) paid to private developers or merchant power plants. In this study, the Benchmark is the electricity price paid by consumers (Farmers), which is 0.06 JOD/KWh regardless of the amount of consumption, as mentioned in section 4.2.
2- GWVPP power capacity: 40 KW
3- Gross head: 1.5 m.
4- Maximum tail water effect: It is the maximum reduction in available gross head that will occur during times of high flows in the river. At most sites, during high flows, the tail water level rises more than the level upstream of the intake and causes a reduction in the gross head. Consequently, during these periods, less power and energy are available. The tail water effect can be significant, especially for low-head sites. This value will be neglected (equal zero) due to the design of the GWVPP where the water outlet is in form of a channel that flows into the river and extends beyond the outlet of the vortex basin for several meters. Thus, there will be no effect from the high flows to reduce in the available head.
5- Residual flow: It is the flow must be left in the river throughout the year for environmental reasons. The residual flow is deducted from the available flow as part of the calculation of available energy. In the GWVPP design, the residual flow will be zero because the plant will be on the river and all flow of the river will enter through it without any environmental impacts, and if the entering flow is more than the design flow; the excess water will pass over the overflow dam, and if the flow is equal to or less than the design flow will be no residual flow. Thus there is no flow that must be left in the river.
6- Percent time firm flow available: The percentage of the time that the firm flow should be available. The minimum outlet flow of As-Samra WWTP is 1.65 m^3/s which equal 41.25% of the design flow where the turbine shutdown at 20% of the design flow (see section 4.3); this means the flow will be available all the time; so the value will be 100%.
7- Design flow: It is the maximum flow that can be used by the turbine(s). The selection of the design flow depends primarily on the available flow at the site. In GWVPP design, the design flow is (4 m^3/s), which is equaled or exceeded about 60% of the time.
8- Efficiency adjustment: It is an adjustment factor for the turbine efficiency. The adjustment, expressed as a percentage, applies to the entire efficiency curve. It will be considered zero in this design.
9- Flow-duration curve data: The flow-duration curve is a cumulative frequency curve that ordered from maximum to minimum flow shows the percent of time during which specified flow was equaled or exceeded in a given period. The Flow-duration curve data required in RETScreen is within 20 intervals (5%-10%-15%.........100% of time) and by Microsoft Excel software, these values for the available flow data calculated to be as shown in Figure 13.

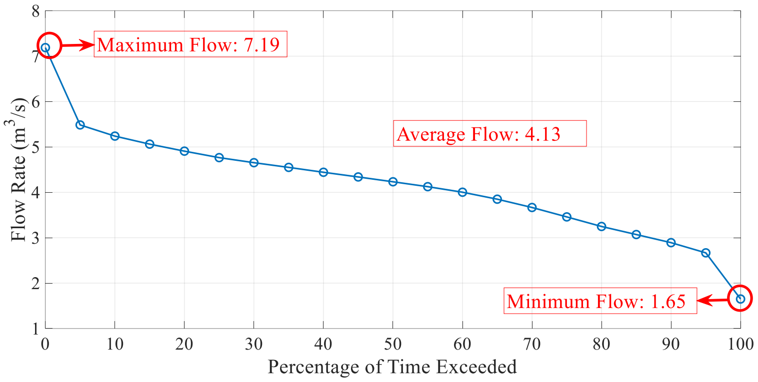


Figure 13. Flow-duration curve data.

10- Turbine efficiency curve data: The turbine efficiency curve data are provided by the manufacturer and the turbine efficiency curve is plotted as shown in Figure 14.

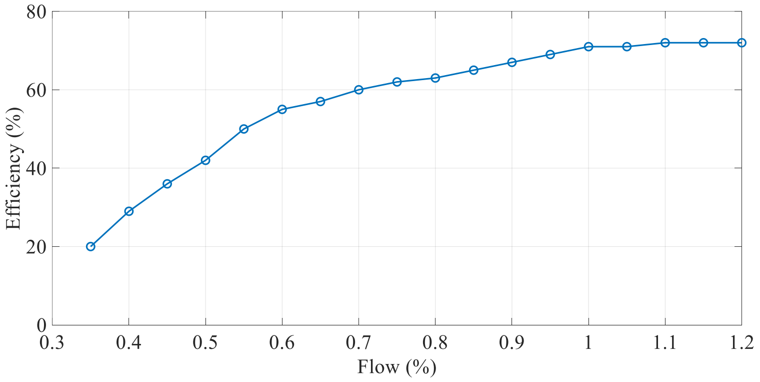


Figure 14. Turbulent company turbine efficiency curve.

11- Maximum hydraulic losses: It is a value that represents the estimated equivalent hydraulic losses (%) in the water passages. In a hydro plant, energy is lost as water flows through the water passages. A value of 2% is appropriate for low-head hydro plants with long water passages. The GWVPP in this study is with very short water passages; so the value will be 2%.

12- Miscellaneous losses: This value accounts for transformer losses, parasitic electricity losses, etc. In this study all miscellaneous losses will be considered as 2% of the power generated.

13- Generator efficiency: Generator efficiencies can range from 93% to 97%. In many hydro plants, a gearbox between the turbine and generator is required to match the ideal rotational speeds of each. A gearbox reduces the overall efficiency of the system. In this system, the generator efficiency will be considered 95%.

14- Availability: It is the percentage of the availability of the hydro plant, shutdown losses are a result of scheduled maintenance, hydro turbine failures, plant outage, and grid outage. This study assumed the shutdown hours include 182 hours/year due to very high flow during winter, 96 hours/year due to scheduled maintenance, and 365 hours/year due to electrical grid outage or the plant outage. Thus the availability percentage find by the following equation:

$$\text{Availability} = \left(1 - \frac{\text{Shutdown Time}}{8760}\right) \times 100 \quad (4)$$

$$= \left(1 - \frac{maintenance\ hours + turbine\ failures\ hours + plant\ outag\ hours + grid\ outage\ hours}{8760}\right) \times 100$$

$$= \left(1 - \frac{96+182+365}{8760}\right) \times 100 = 92.6\% \quad (5)$$

15- Available flow adjustment factor: The presence of the overflow dam and sluice gate in this system makes it easy to control the available flow. Thus, the value will be 1.

16- Initial costs: This value includes both equipment and installation costs. The total initial cost is mentioned in section 4.4 which equals 141,650 JOD.

17- Operation and maintenance costs: This value includes annual operating and maintenance costs. The total O&M cost is mentioned in section 4.4 which equals 2,125 JOD/year.

18- GHG emission factor: Table 5 shows the GHG emissions when using oil, diesel, and natural gas for electricity generation.

Table 5. GHG emissions of electricity generation.

Fuel type	GHG emission (g CO_2/KWh)
Oil	733
Diesel	456
Natural gas	715

Therefore, the electricity generation mix emits on average 635 g CO_2/KWh. Transmission and distribution losses were assumed at 7%.

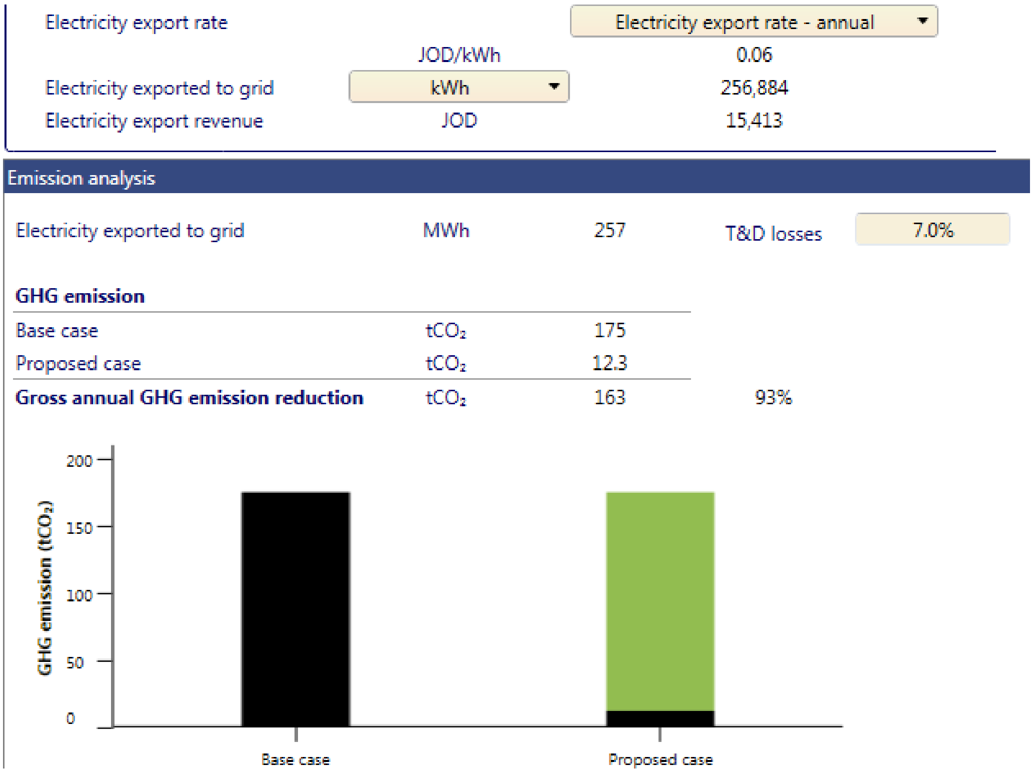
19- Inflation rate: It is the projected annual average rate of inflation over the life of the project. It considered 1% in this study.

20- Debt ratio: Two cases were assumed: The first case is without debts at 0% of the total initial cost. The second case with debt at 85% of the total initial cost with a debt interest rate of 7% with debt term 15 years.

21- Life Time: As provided by Turbulent Company the concrete and other support structures can keep operating for 100 years, and the turbine at least for 30 years. Other components like bearings and gearboxes will need periodic maintenance and change every 5 - 15 years. So the general lifetime is about 30 years.

6. RESULTS

The results and the financial analysis for 30 years project life are as shown in the following Figures, where Figure 15 represents the electricity exported to grid (KWh/year), electricity export revenue (JOD/year), and GHG reduction (tCO_2/year), Figure 16 represents the results in the case of without debts to finance the initial cost of the project, and Figure 17 represents the results in the case of debt at 80% of the total initial cost with a debt interest rate of 7% with debt term 15 years.



Electricity export rate		Electricity export rate - annual
	JOD/kWh	0.06
Electricity exported to grid	kWh	256,884
Electricity export revenue	JOD	15,413

Emission analysis

Electricity exported to grid	MWh	257	T&D losses	7.0%
GHG emission				
Base case	tCO_2	175		
Proposed case	tCO_2	12.3		
Gross annual GHG emission reduction	tCO_2	163	93%	

Figure 15. Electricity exported to grid, electricity export revenue, and GHG reduction per year.

RETScreen - Financial Analysis

Subscriber: Viewer

Financial parameters

General		
Fuel cost escalation rate		0%
Inflation rate	%	1%
Discount rate	%	0%
Reinvestment rate	%	0%
Project life	yr	30
Finance		
Incentives and grants	JOD	
Debt ratio	%	0%
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	MWh ▾	257
Electricity export rate	JOD/kWh ▾	0.06
Electricity export revenue	JOD	15,413
Electricity export escalation rate	%	0%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	163
Gross GHG reduction - 30 yrs	tCO_2	4,894
GHG reduction revenue	JOD	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	JOD	141,650
Total initial costs	**100%**	JOD	**141,650**
Yearly cash flows - Year 1			
Annual costs and debt payments			
O&M costs (savings)		JOD	2,125
Debt payments		JOD	0
Total annual costs		**JOD**	**2,125**
Annual savings and revenue			
Electricity export revenue		JOD	15,413
GHG reduction revenue		JOD	0
Other revenue (cost)		JOD	0
CE production revenue		JOD	0
Total annual savings and revenue		**JOD**	**15,413**
Net yearly cash flow - Year 1		**JOD**	**13,288**

Financial viability

Pre-tax IRR - equity	%	8.4%
Pre-tax MIRR - equity	%	3.4%
Pre-tax IRR - assets	%	8.4%
Pre-tax MIRR - assets	%	3.4%
Simple payback	yr	10.7
Equity payback	yr	10.8
Net Present Value (NPV)	JOD	246,084
Annual life cycle savings	JOD/yr	8,203
Benefit-Cost (B-C) ratio		2.7
Debt service coverage		No debt
GHG reduction cost	JOD/tCO_2	-50.29
Energy production cost	JOD/kWh ▾	0.028

Yearly cash flows

Year #	Pre-tax JOD	Cumulative JOD
0	-141,650	-141,650
1	13,267	-128,383
2	13,245	-115,138
3	13,224	-101,914
4	13,202	-88,712
5	13,180	-75,533
6	13,157	-62,376
7	13,135	-49,241
8	13,112	-36,129
9	13,089	-23,040
10	13,066	-9,974
11	13,042	3,068
12	13,019	16,087
13	12,995	29,081
14	12,970	42,052
15	12,946	54,998
16	12,921	67,919
17	12,896	80,815
18	12,871	93,687
19	12,846	106,532
20	12,820	119,353
21	12,794	132,147
22	12,768	144,915
23	12,742	157,656
24	12,715	170,371
25	12,688	183,059
26	12,661	195,720
27	12,633	208,353
28	12,605	220,958
29	12,577	233,535
30	12,549	246,084

Yearly cash flows

Figure 16. The results and the financial analysis without debts.

RETScreen - Financial Analysis

Subscriber: Viewer

Financial parameters

General		
Fuel cost escalation rate		0%
Inflation rate	%	1%
Discount rate	%	0%
Reinvestment rate	%	0%
Project life	yr	30
Finance		
Incentives and grants	JOD	
Debt ratio	%	80%
Debt	JOD	113320
Equity	JOD	28,330
Debt interest rate	%	7%
Debt term	yr	15
Debt payments	JOD/yr	12,442
Income tax analysis		☐

Annual revenue

Electricity export revenue		
Electricity exported to grid	MWh ▾	257
Electricity export rate	JOD/kWh ▾	0.06
Electricity export revenue	JOD	15,413
Electricity export escalation rate	%	0%
GHG reduction revenue		
Gross GHG reduction	tCO_2/yr	163
Gross GHG reduction - 30 yrs	tCO_2	4,894
GHG reduction revenue	JOD	0
Other revenue (cost)		☐
Clean Energy (CE) production revenue		☐

Costs | Savings | Revenue

Initial costs			
Initial cost	100%	JOD	141,650
Total initial costs	**100%**	JOD	**141,650**
Yearly cash flows - Year 1			
Annual costs and debt payments			
O&M costs (savings)		JOD	2,125
Debt payments - 15 yrs		JOD	12,442
Total annual costs		**JOD**	**14,567**
Annual savings and revenue			
Electricity export revenue		JOD	15,413
GHG reduction revenue		JOD	0
Other revenue (cost)		JOD	0
CE production revenue		JOD	0
Total annual savings and revenue		**JOD**	**15,413**
Net yearly cash flow - Year 1		**JOD**	**846**

Financial viability

Pre-tax IRR - equity	%	10.1%
Pre-tax MIRR - equity	%	6.8%
Pre-tax IRR - assets	%	1.6%
Pre-tax MIRR - assets	%	1.2%
Simple payback	yr	10.7
Equity payback	yr	16.4
Net Present Value (NPV)	JOD	172,775
Annual life cycle savings	JOD/yr	5,759
Benefit-Cost (B-C) ratio		7.1
Debt service coverage		1
GHG reduction cost	JOD/tCO_2	-50.29
Energy production cost	JOD/kWh ▾	0.038

Yearly cash flows

Year #	Pre-tax JOD	Cumulative JOD
0	-28,330	-28,330
1	825	-27,505
2	803	-26,702
3	782	-25,920
4	760	-25,160
5	738	-24,422
6	715	-23,707
7	693	-23,014
8	670	-22,344
9	647	-21,697
10	624	-21,073
11	600	-20,473
12	577	-19,896
13	553	-19,344
14	528	-18,815
15	504	-18,311
16	12,921	-5,390
17	12,896	7,506
18	12,871	20,378
19	12,846	33,224
20	12,820	46,044
21	12,794	58,838
22	12,768	71,606
23	12,742	84,347
24	12,715	97,062
25	12,688	109,750
26	12,661	122,411
27	12,633	135,044
28	12,605	147,649
29	12,577	160,226
30	12,549	172,775

Yearly cash flows

Figure 17. The results and the financial analysis with debts.

Table 6 summarizes the results obtained for the two cases.

Table 6. Results obtained for two cases.

Case	total initial costs (JOD)	Debts ratio (%)	initial paid required (JOD)	Debt interest rate (%)	Debt term (years)	total annual costs (JOD/year)
1	141,650	0	141,650	0	0	2,125
2	141,650	80	28,330	7	15	14,567

Case	Electricity exported to grid (KWh/year)	Electricity export revenue (JOD/year)	Payback period (years)	GHG reduction (tCO_2/year)	Net lifetime profit (JOD)	Benefit/Cost ratio	LCOE
1	256,884	15,413	10.8	163	246084	2.7	0.0281
2	256,884	15,413	16.4	163	172775	7.1	0.0376

In the first case the net lifetime profit is 246,084 JOD and in the second case is 172,775 JOD. In the second case by the yearly cash flows the project pays itself, where the initial paid required is 28,330 JOD and then the annual return covers the annual costs which include the debt payments and maintenance costs which equal 14,567 JOD, the total cost of the project with the debt interest is repaid in 15 years approximately. The Benefit/Cost ratio for the second case is much higher than for the first case; this indicates that it will be economically feasible for the farmers if they invest with borrowing 80% of the initial cost in the absence of support or capital. The energy production cost (LOCE) in both cases is (0.0281, 0.0376) JOD/KWh respectively which less than the cost of electricity consumed from the electrical grid by the farmers which is (0.06) JOD/KWh.

6.1. Environmental Impact and Social Impact

There are many advantages to establishing GWVPP, whether these advantages are on the social and environmental level. Social and environmental benefits of GWVPP summarized in Table 7.

Table 7. Socioeconomics and environmental advantages.

Socioeconomic advantages	Environmental advantages
• Reducing the cost to the farmers by covering farmers' electricity consumption which includes lighting, electrical appliances, and agricultural irrigation using electric pumps. And they dispose of diesel water pumps. • Increase renewable power generation capacities to the community. • Increasing the stability of energy price for the community instead of depending totally on fuel price. • Increasing the opportunity of agricultural activities surrounding Zarqa River.	• The water is not diverted and the natural course of the stream is maintained that's mean no impact at all on stream flow where the water circulates for a few seconds in the plant before moving downstream. • Preservation of wildlife where fish can cross it safely due to the low speed of the turbine and no large dams. • Effectively aerates the waterway. • Produce electricity without burning fossil fuel which contributes to reducing CO2 emission in Jordan, which reaches 189,269 kg/year when using GWVPP. • Reducing the sound and air pollution through using electric water pumps instead of diesel water pumps.

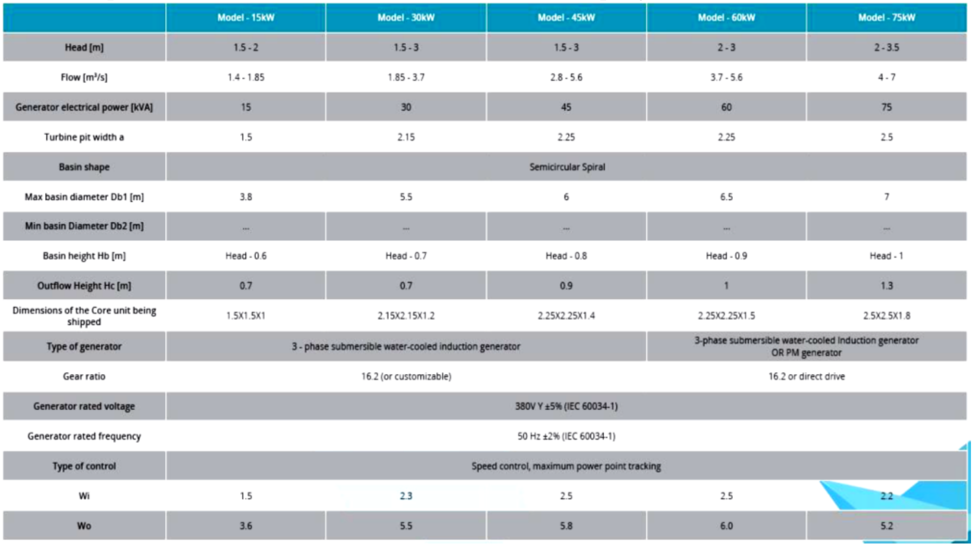
7. CONCLUSION

GWVPP is simple, environment-friendly, zero-emission technology, and economically viable as it is capable of generating power from a low hydraulic head and low flow rate by a simple vortex basin inside it a simple turbine based on vortex motion of water across the turbine with minimal civil works, low installation time, low installation cost, small covered area, no effect on wildlife where fish can pass safely, requires little maintenance, low maintenance cost, low operation cost, and continuous power source 24 hours a day.

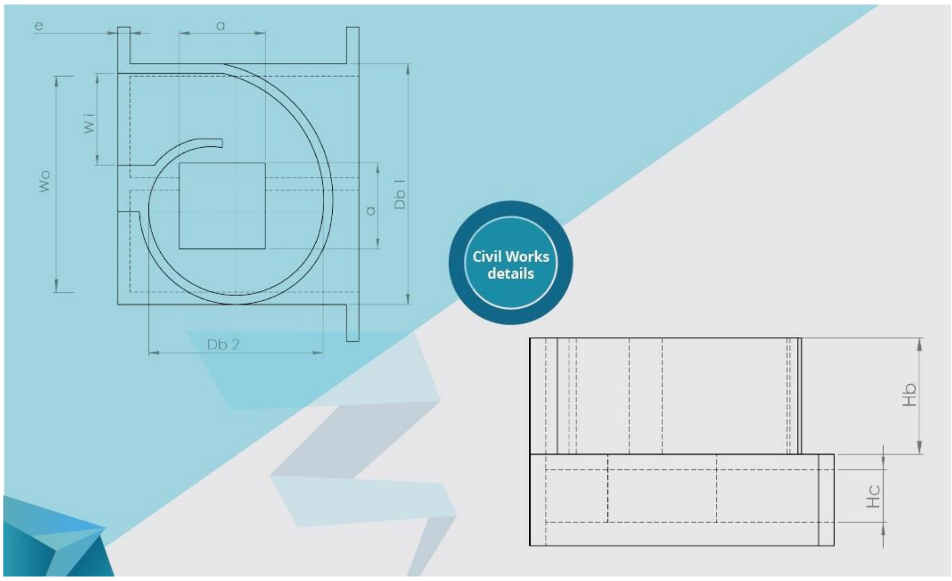
In the eastern part of Zarqa River, the treated waste water from As-Samra WWTP flows continuously throughout the year, and along the river, there is no high head along and the flow water rate is approximately low. Since these conditions fit with GWVPPs specifications; this study proposed to install an on-grid GWVPP, to exploit the energy of this running water to generate electricity and serve farmers on the river by providing electricity. And since there are still no generic design approaches or manuals available to design and build the GWVPP; one of the manufacturing companies was chosen to install the GWVPP on Zarqa River which is Turbulent Company and the location appropriate on the river for installing the plant was determined by collecting the site data in terms of head, flow, and proximity to the grid and roads. And then by providing Turbulent Company with the data, and pictures for the site; the company assumed the plant capacity, cost, and design. Then the initial total cost was calculated, and environmental and economic feasibility analyses were performed by using RETScreen Expert software. Thus, the study concludes that installation of a GWVPP on Zarqa River is technically feasible as well as economically and environmentally feasible.

8. APPENDIX:

The detailed specification of the GWVPP of Turbulent Company [13].



	Model - 15kW	Model - 30kW	Model - 45kW	Model - 60kW	Model - 75kW
Head [m]	1.5 - 2	1.5 - 3	1.5 - 3	2 - 3	2 - 3.5
Flow [m³/s]	1.4 - 1.85	1.85 - 3.7	2.8 - 5.6	3.7 - 5.6	4 - 7
Generator electrical power [kVA]	15	30	45	60	75
Turbine pit width a	1.5	2.15	2.25	2.25	2.5
Basin shape	Semicircular Spiral				
Max basin diameter Db1 [m]	3.8	5.5	6	6.5	7
Min basin Diameter Db2 [m]	...	...	...	...	...
Basin height Hb [m]	Head - 0.6	Head - 0.7	Head - 0.8	Head - 0.9	Head - 1
Outflow Height Hc [m]	0.7	0.7	0.9	1	1.3
Dimensions of the Core unit being shipped	1.5X1.5X1	2.15X2.15X1.2	2.25X2.25X1.4	2.25X2.25X1.5	2.5X2.5X1.8
Type of generator	3 - phase submersible water-cooled induction generator			3-phase submersible water-cooled Induction generator OR PM generator	
Gear ratio	16.2 (or customizable)			16.2 or direct drive	
Generator rated voltage	380V Y ±5% (IEC 60034-1)				
Generator rated frequency	50 Hz ±2% (IEC 60034-1)				
Type of control	Speed control, maximum power point tracking				
Wi	1.5	2.3	2.5	2.5	2.2
Wo	3.6	5.5	5.8	6.0	5.2



Vortex turbine models 5 to 70 kW	Value	Unit
Min Flow	0.7	m3/s
Max Flow	4	m3/s
Min Head	1	m
Max Head	4.4	m
Min. Speed	80	rpm
Blade tilt angle range	(-14) to 14	deg
Stainless steel type	304	-

Representative Models	5 kW	15 kW	30 kW	50 kW	70 kW	Unit
Turbine hydraulic output	5.8	17.4	34.9	56.8	79.5	kW
Electrical output	5	15	30	50	70	kW
Maximal Energy generation per year	40,000	120,000	240,000	400,000	560,000	kWh
Nominal flow	0.7	1.5	2.2	3.1	3.8	m³/s
Nominal head	1.6	2	2.8	3.25	3.7	m
Impeller Diameter	800	1140	1200	1300	1500	mm
Rotor Height	385	550	580	625	730	mm
Vortex turbine core weight	135	275	300	360	475	kg
Generator and gearbox weight	180	350	600	950	1200	kg
Electrical cabinet. weight	220	270	330	390	480	kg

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