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Assessment of mini and micro hydropower potential in Egypt: Multi-criteria analysis

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ABSTRACT

There is a common misconception that at least 95% of Egypt's potential hydropower has already been used, which does not reflect reality. Currently, only five hydropower plants operate along the river Nile, from Aswan high dam to Assiut barrage. The total installed capacity is around 2840 MW. However, Egypt has many main canals and Rayahat and an irrigation network system, including barrages, head regulators, and navigation locks, which enable 120 MW of clean electricity (equivalent to 4 times of Assiut power station generation) if used to generate electricity. This paper aims to assess mini and micro hydropower's potential in Egypt for the main grid areas. Eight sites have been selected and ranked as an application sample in this work based on their hydraulic data availability. The rank of the most suitable energy generation sites is determined with spatial maps' aid based on the flow duration curves, capacity factor, and multi-criteria analysis. The decision matrix developed to rank the selected locations, and the turbine efficiency curve is proposed in terms of the available flow to decide the suitable turbines. Also, the spatial maps give a clear vision to decision-makers of the possibility of exploiting different resources and the priority of implementation. The results obtained show a promising prospect of mini and micro hydropower in Egypt. The annual energy from the eight studied sites is estimated by 200 GWh according to the daily hydraulic data of the year 2017. Damietta barrage takes priority as the weight value of criteria is the highest value by 2.85, and its annual energy is estimated by 78.5 GWh. The eight sites are more suitable for peak load plants, but Damietta and Zefta are appropriate by less priority for baseload plants.

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1. Introduction

1.1. Background

Small-scale hydro plants (SHPs) provide an alternative solution to electric grid extension that serves widely scattered communities as an efficient power supplement in urban areas with few environmental problems, particularly for the areas that are still not connected to the primary grid (Tian et al., 2020; Ajanovic and Haas, 2019). The use of SHPs for energy generation by restraining the river's flow can be considered one of the popular renewable energy sources (Ghorbani et al., 2020).

Hydropower plants have many advantages such as high efficiency (greater than 60%), low operating and maintenance costs, long-life horizon, few to no pollution, or greenhouse gas emission (Hatata et al., 2019). They can be installed in different power ranges as large-scale (100 MW and above), medium-scale (10 MW up to 100 MW), small-scale (1 MW up to 10 MW), mini-type (100 kW up to 1 MW), micro-type (5 kW up to 100 kW), and pico-type (less than 5 kW) hydro plants (Paish, 2002). However, it should be noted that these divisions are arbitrary, and to date, there are no widely accepted divisions of degrees of the smallness of hydropower (Morales et al., 2015).

In this regard, Egypt is one of the African countries that address climate change impacts and enhance its climate change performance metrics. However, to-date, electricity in Egypt is mainly generated from thermal electric power plants. In the Egyptian energy sector, Egypt suffers from two main factors. The first factor is the high electricity generation cost, where fossil fuels are used in thermal power stations by around 94% of the total electricity generation (Egyptian Electricity Company Holding, 2018). The second factor is the increase in the amount of electricity required at peak load periods. These two factors affect national security, necessitating searching for other clean energy sources and enhancing the used sources' performance and efficiency (Abdel Aleem et al., 2015; Mousa et al., 2016).

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Abbreviations

AHP	Analytical hierarchy process
CF	Capacity factor in percent
CYM	Calendar-year method
FDC	Flow duration curve
GIS	Geographic information system
HMT	Hydro matrix turbine
IGDT	Information-gap decision theory
KML	Keyhole markup language
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision aid
MCDM	Multi-criteria decision making
PDC	Power duration curve
RS	Remote sensing
SAW	Simple additive weighting
SHPs	Small-scale hydro plants
TEC	Turbine efficiency curve
TPM	Total-period method
VLH	Very low head turbine

Nomenclature

c	Criterion under consideration
D_t	Diameter of the turbine (m)
E	Maximum energy generated annually (kWh)
h	Number of hours
H	Net head (m)
n	Number of events for the period of record
P	Rated power (kW)
P_m	Maximum power (kW)
Q_d	Maximum designed discharge rate (m^3/s)
Q_i	Daily discharge rate (m^3/s)
Q_j	Available flow in the river (m^3/s)
Q_k	Rated flow through the turbine (m^3/s)
R	Ranked position on the listing
s	Degree of the score
t	Time-horizon per year (8760 h)
val	Centroidal value
w	Weight factor
x	Expedience probability
η	Overall efficiency (%)
δ	Specific weight of water (kN/m^3)

Besides, CO_2 emissions from fossil fuel in Egypt have reached 219,377,350 tons, in which the share of electric power plants from this reached about 37% of the total share. This has caused several negative impacts on the environment and air pollution (Worldometer, 2020). It should be mentioned that the United Nations closed the 2019 UN Climate Action Summit by recommending a halt to increased emissions by 2020 and significantly reducing emissions to reach net-zero emissions by mid-century. It has allocated $10 billion for this purpose and has raised about $7.5 billion of this amount, which means global attention to the shift towards renewable energy (UN Climate Action, 2019). To encounter the increasing load growth and enable the utilization of higher levels of renewable electricity production, Egypt has established a promising energy strategy until 2035. This strategy includes diversifying the power generation mix among fossil fuel-based plants, nuclear, and renewables (Egyptian Strategic Energy Strategy, 2020).

1.2. Motivation

Applying renewable energy alternatives can potentially reduce CO_2 emissions ((Mousa et al., 2016)). One of Egypt's promoted renewable energy technologies is to use SHPS as Egypt has the river Nile to provide an excellent hydraulic energy source. There is a common misconception that at least 95% of Egypt's potential hydropower has already been used, which does not reflect reality. Currently, only five hydropower plants operate along the river Nile, from Aswan high dam to Assiut barrage. The total installed capacity is around 2840 MW. However, Egypt has a large number of main canals and Rayahat, in addition to an irrigation network system including barrages, head regulators, and navigation locks, which enable 120 MW of clean electricity (equivalent to 4 times of Assiut power station generation) if used to generate electricity, solve the peak load problem, improve the environment and reduce the CO_2 emission. Notably, the potentiality of small, mini, micro, and pico hydropower is very high in Egypt, as irrigation systems contain more than 1000 different hydraulic structures that can be used in the hydropower generation can participate in covering the peak load of electrical periods. Fig. 1 shows an illustrative map of the Nile river with some canals and the main barrages in Egypt. Egypt's hydropower generation participates by 5.1% in the total Egyptian generation (Egyptian Electricity Company Holding, 2018). However, the cost of generating 1 kW from hydropower is estimated by $0.15, equivalent to around 2.5 Egyptian pounds (Eshra and Abdelnaby, 2014). Accordingly, Egypt has to make use of its hydro potential effectively. The irrigation systems and their different types of hydraulic structures used in hydropower generation should be cost-effectively exploited.

1.3. Related works

Water is the fuel to operate the hydropower plant, so it is a significant parameter in the feasibility evaluations of power projects. This evaluation can be occurred by estimation of the link between hydrological characteristics and aspects of hydropower plant design using the flow duration curves (FDC) and capacity factor (CF) in designing run-of-river power plants (Liucci et al., 2014). Besides, the best sites for hydropower plants depend on a suitable head and a turbine site, which depends on the continuous flow of water and the acceptability of diverting water to the turbine (Couto and Olden, 2018; Okot, 2013).

Many research works have been conducted in the literature to assess the potential of rivers' hydroelectric power using conventionally complicated, time-consuming methods, and field inspection. Currently, remote sensing (RS) and geographic information systems (GIS) are being promoted to differentiate between the high potential hydropower locations spatially and find appropriate places in a comfortable, user-friendly, and time-effective way that enables powerful functionality in recording, storing, and analyzing numerous types of spatial and output geographic information (Tian et al., 2020).

GIS software has been used in many works to identify the potential of hydroelectric power stations. In Tian et al. (2020), an overview of various research works that promoted GIS use to assess the potential of sites for small-scale hydropower generation in different countries is presented. However, it was noticed in most of these studies that other critical performance metrics, such as social and environmental metrics, were not evaluated. This means that GIS-based methods should employ in conjunction with multi-criteria decision making (MCDM) based systems

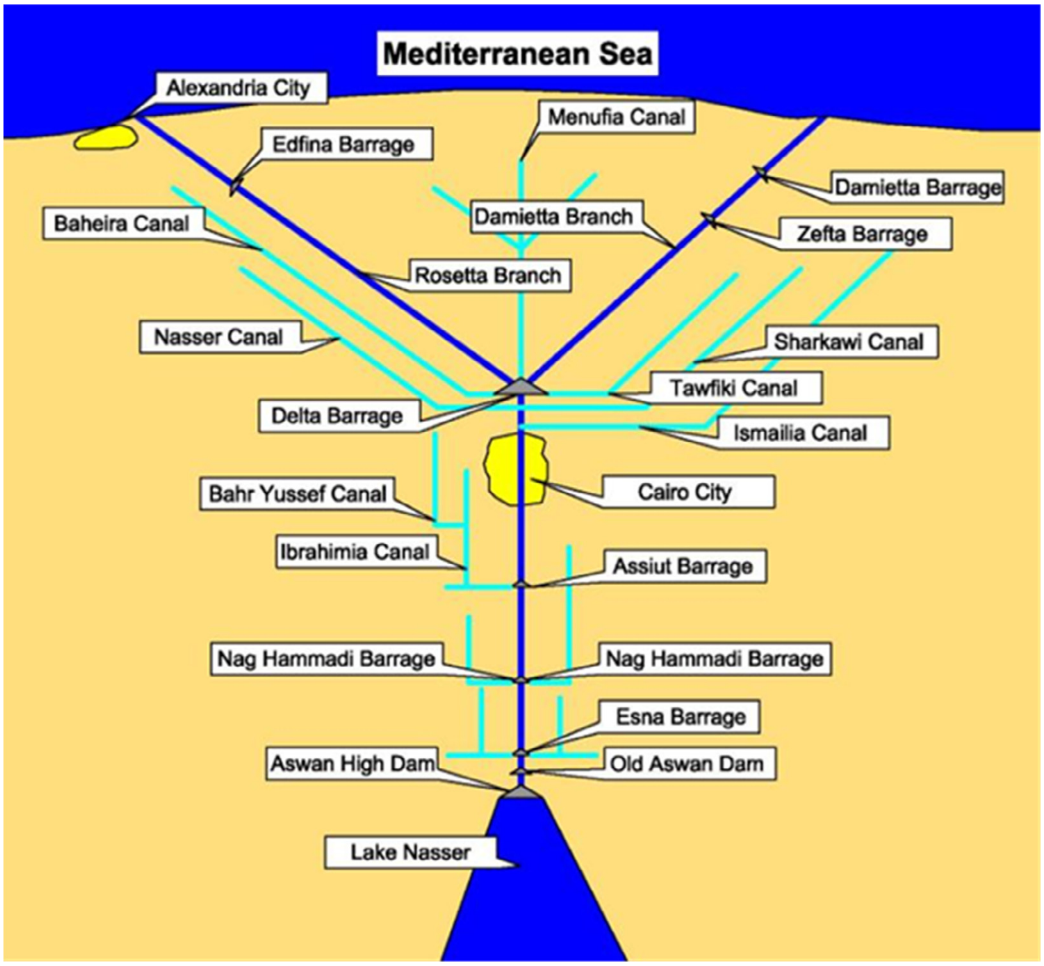

Fig. 1. Schematic diagram of the Nile river with some canals and the main barrages.

that enable the planner or the designer to quantify the other performance metrics such as the social and environmental metrics (Tian et al., 2020; Wu et al., 2020; Rikalovic et al., 2014; Zobaa et al., 2018). In this regard, MCDM methods are used to support decision making in case of problems where conflicting economic, environmental, societal, technical, and aesthetic objectives are involved. Multi-criteria analysis (MCA) is generally structured in two macro-phases. The first one consists of the construction and compilation, referring to the evaluation problem in question, of the evaluation matrix, which consists of the different alternatives and their performance, based on the various criteria and sub-criteria (and their weightings), plus their indicators of assessment. The second regards the processing of the data in the evaluation matrix used to evaluate the alternatives, based on the objectives to be reached. Besides, the second phase involves processing (or aggregating) data via various procedures, depending on which method is being used, considering that each technique comes with its application procedures. When selecting the best-suited manner to meet the evaluation's objectives, it is necessary to consider the assessment context and give rise to many different decision-making problems attached to the settlement process phases. Guidelines to MCDM users for choosing the method that best suits the decision-making problem's requirements at hand are presented in (Montis et al., 2000; Guarini et al., 2018).

The most common and straightforward MCA methods, the simple additive weighting (SAW) method, also known as the weighted summing method, is used to find the weighted sum of performance ratings on each alternative for all attributes. The SAW method requires normalizing the decision matrix to a scale comparable to all existing alternative ratings (Setiawan et al., 2018). The second widely-known method is the analytical hierarchy process (AHP), which generates weighted factors to divide the decision-making procedure into simple pairwise comparison steps (Abdel Aleem et al., 2015; Mahdy and Bahaj, 2018; Elbasuony et al., 2018). Besides, many research works have been conducted in the literature to promote increasing the penetration of renewable energy resources using various MCDM methods, multi-objective optimization, and uncertainty analysis techniques. For instance, the information-gap decision theory (IGDT) based robust approach is presented in (Mirzaei et al., 2019) to address the uncertainty caused by wind power's intrinsic nature for coordinated electricity and natural gas systems. Multi-objective techno-economic-environmental optimization of an electric vehicle for energy services is presented in (Das et al., 2020). The electrical/thermal optimum generated power values such that the generation resources' profit becomes maximum is presented in (Marzband et al., 2018). Also, solving a multi-objective two-stage stochastic problem for integrated power and gas systems with high penetration of wind energy is presented in (Nazari-Heris et al., 2020), and a hierarchical energy management system for multiple home energy hubs in the neighborhood grid is presented in (Gholinejad et al., 2020).

1.4. Novelty and contribution

This paper aims to assess the potential of mini and micro hydropower in Egypt for the areas that are still outside the main grid, in which a new approach that depends on a MCA, FDCs, CF, and GIS is integrated to assess and rank eight different locations in Egypt to evaluate their potential for small-scale hydropower generation. In the current study, SAW is used, in which the tests are carried out by ranking the different sites while assessing the multi-dimensional options to set-up a direct decision matrix. Several technical and non-technical criteria have been investigated and scored according to the evaluation scores. The criteria considered in this work are the condition of the barrage, access to the site, plant layout, grid connection, environmental and social aspects, actual head, actual discharge, days of energy generation, and amount of the energy generated. The spatial maps are used to give a clear vision of the possibility of exploiting various resources and the priority of implementation.

The main contributions of the work are outlined as follows:

1. This work shows that Egypt has many main canals and Rayahat and an irrigation network system, including barrages, head regulators, and navigation locks, which enable clean electricity if used to generate electricity.
2. FDC, MCA, and CF are used in this study to assess and rank the priorities of the studied hydraulic structure for small hydropower generation using the simple additive weighting (SAW) method while considering multi-dimensional options to set-up a direct decision matrix. Further, the spatial maps are produced for the selected sites.
3. Several technical and non-technical criteria have been investigated and scored according to the evaluation scores to supplement the evaluation. The criteria considered in this work are the condition of the barrage, access to the site, plant layout, grid connection, environmental and social aspects, actual head, actual discharge, days of energy generation, and amount of the energy generated.
4. The spatial maps for the eight locations were created based on FDCs and PDCs.
5. The results obtained validate the promising prospect of mini and micro hydropower in Egypt, in which the annual energy from the selected sites is estimated by 200 GWh according to the considered data.

1.5. Organization

The paper is organized as follows. Section 2 presents the methodology proposed in this work in detail, in which FDCs, power availability, turbine selection, specification of sites, and their collected data, and analysis of data are presented and discussed. Section 3 presents the results obtained and their discussion. Finally, Section 4 presents the conclusions and recommendations drawn from this work and the possible future works.

2. Methodology

FDC, MCA or multi-criteria decision aid (MCDA), and CF are used in this study to assess and rank the priorities of the studied hydraulic structure for small hydropower generation and the spatial maps produced for the selected sites using the GIS software. In what follows, FDC for every hydraulic system, classification of these structures, and the value of hydropower potential (power duration curve (PDC)) are estimated based on the available technical data of the different canals, main barrages, and head regulators.

Table 1
Scores used and their explanation.

Score	Explanation of difficulties	Value
0	Very severe difficulties	Insufficient
1	Severe difficulties	Substandard
2	Average difficulties	Acceptable
3	Few to no difficulties	Good

2.1. Multi Cariteria Analysis (MCA)

In this study, Simple Additive Weighting (SAW) method which known as the weighted summing method is used. The basic concept of the SAW method is to find the weighted sum of performance ratings on each alternative on all attributes. The SAW method requires the process of normalizing the decision matrix (X) to a scale comparable to all existing alternative ratings, (Setiawan et al., 2018). SAW is used, in which the tests are carried out by ranking the different sites while assessing the multi-dimensional options to set-up a direct decision matrix. Several technical and non-technical criteria have been investigated and scored according to the evaluation scores presented in Table 1 (Mostafa et al., 2016). The criteria considered in this work are the condition of the barrage, access to the site, plant layout, grid connection, environmental and social aspects, actual head, actual discharge, days of energy generation, and amount of the energy generated. The effects of the barrage's different operation factors and the boundary and operating conditions are investigated while considering that the barrages' surrounding environment is not the same.

Besides, the weight factor, w, of each criterion is introduced in order of importance. The degrees of the scores, s, are multiplied with w of the related criterion, c. The resulting values of each criterion are then summed to get a centroidal value, val, that results in the rank of the different potential project sites, as formulated in Eq. (1). Further, GIS is used to establish a spatial map for the various hydraulic structures selected and ranked by the implementation priority. Fig. 2 shows the flow chart of the criteria processing.

$$val = \frac{\sum s \times w}{\sum w} \tag{1}$$

2.2. Flow duration curve (FDC)

FDC is a cumulative frequency curve that illustrates the historical variation observed of flow over a given period with the percentage of time resolution to show the percent of time specified discharges were equaled or exceeded (Searcy, 1969; Owolabi et al., 2020), in which the time horizon is the mean daily, weekly, monthly or seasonal discharge (Hordon, 2005). FDC helps select a suitable turbine. Besides, the FDC shape affects the time unit used (Murdock and Gulliver, 1993). The capacity factor of run-of-river power plants uses to measure the performance of hydropower plants. The calendar-year method (CYM) and the total-period method (TPM) are commonly used to construct FDCs. In CYM, the discharges for one year are ranked according to the daily magnitude (Liucci et al., 2014). However, in TPM, all discharges are placed in classes according to their magnitudes. In this work, the CYM is used. FDC is constructed based on the following steps (Oregon State University, 2002):

Step 1: Calculate the average daily discharges for a period of record sorting from the most considerable value to the smallest value, involving a total of n values, where n denotes the number of events for the period of record (taken as 365 in this study).

Step 2: Rearrange each discharge value, where (R) denotes the ranked position on the listing, starting with 1 for the most considerable daily discharge value.

Step 3: Calculate expedience probability (x), the likelihood that a given flow will be equaled or exceeded in percent of the time, as follows:

$$x = 100\left(\frac{R}{n+1}\right) \tag{2}$$

2.3. Power availability and capacity factor (CF) calculation

Capacity factor (CF) is the ratio between what a generation unit can generate at the maximum output versus the unit's actual generation output over a while. These two variables can be significantly different. Many generators do not operate at their full capacity all the time. CF is a crucial parameter in designing a hydropower plant to measure the proposed plant's performance. Its calculation needs to specify the rated power and annual energy.

The actual power available from mini- or micro-hydropower plants depends on the available discharge, in which the flow-dependent hydraulic losses and tailrace reduction are taken into account. Hydraulic data of the year 2017 with a series of the mean daily discharges and related heads are available. All discharges are used for power generation and pass the new hydropower plant and head losses in the waterway system. They are estimated as 5% of the mean gross head, and the amount is estimated at 0.15 m.

The turbine, generator, and transformer efficiencies are considered 90%, 98%, and 99%, respectively. Thus, the overall efficiency considered in the analysis amounts to 87% (Liucci et al., 2014; Prado and Berg, 2012).

The following equations are used to estimate CF in percent.

$$CF = 100\left(\frac{E}{P \times h}\right) \tag{3}$$

where E is the maximum energy generated annually at a specific time interval (kWh), P is the rated power (kW), and h is the number of hours in the same time interval. Thus;

$$E = P_m \times t \tag{4}$$

where P_m is the maximum power and t is the time-horizon per year (8760 h). Hence, one can calculate P_m as follows:

$$P_m = Q_d \times H \times \eta \times \delta \tag{5}$$

where H is the net head (m), Q_d denotes the maximum designed discharge (m^3/s), η represents the overall efficiency (i.e., η =87% considering the efficiencies of the different components in the plant) and δ is the specific weight of water ($\delta = 9.807$ kN/m^3).

Besides, one can calculate P as follows:

$$P = \frac{\sum_{i=1}^{365}(Q_i \times H \times \eta \times \delta)}{365} \tag{6}$$

where Q_i represents the daily discharge (m^3/s).

Thus, CF is finally formulated as follows:

$$CF = 100 \times \frac{\sum_{i=1}^{365} Q_i}{365 \times Q_d} \tag{7}$$

2.4. Turbine selection

The selection of the turbines depends on their technologies, conventional or non-conventional types. For the traditional types, the turbine efficiency curve (TEC) is the main key factor to select a suitable turbine (Adejumobi and Shobayo, 2015), in which it is studied according to the relationship between the rated flow through the turbine (Q_k) and the available flow in the river (Q_j). There are other factors in the selection process, such as the head, depth of the turbines, and costs.

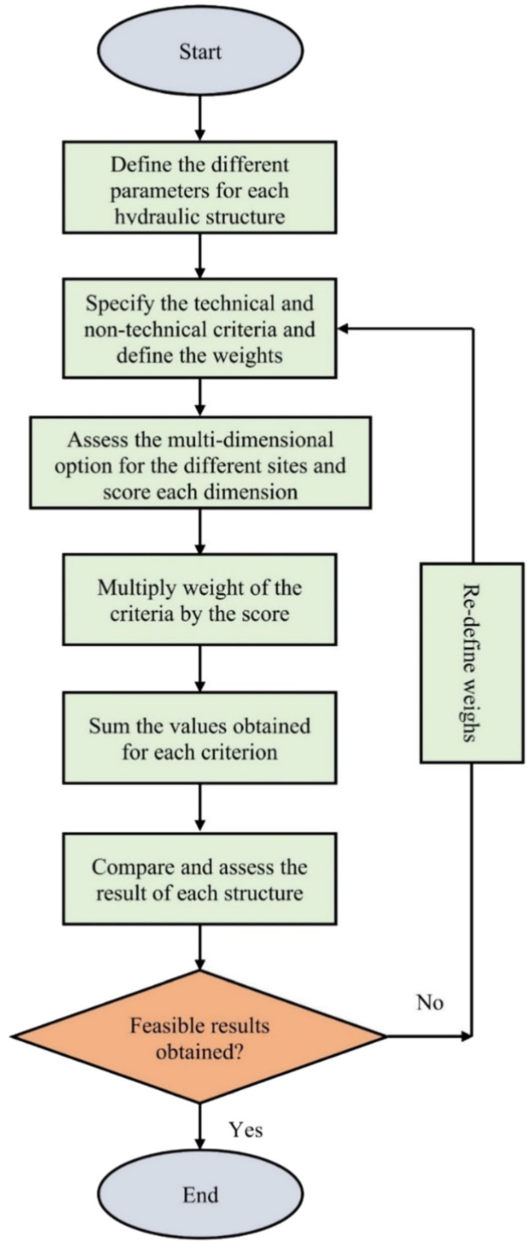

Fig. 2. Flow chart of the ranking procedure of the different sites.

Conventional hydropower turbines are categorized into two common types: impulse and reaction. Each of them is suitable for different types of discharge and head. Other non-conventional types (i.e., the types used in micro- and pico-turbines) are classified as a new version of impulse types as hydro matrix turbine (HMT) and reaction types as the very low head (VLH) and stream driver (Voith) turbines (Eshra, 2019).

Fig. 3 shows the TEC of different turbines as Kaplan, Propeller, Francis, Crossflow, Pelton, and Turgo in which the studies have established formulae to determine their relative efficiencies under different conditions of the head and flow (Adejumobi and Shobayo, 2015; Natural Resources Canada, 2005; Clean Energy Australia Report, 2019).

In this work, in the conventional turbines, the percent of flows (Q_j/Q_k) is assumed to range from 70% (with losses considered) to 100% (with no losses considered). Besides, Table 2 presents some non-conventional types of turbines that were nominated to be used depending on their characteristics.

Table 2
Main characteristics of different non-conventional types of turbines.

Voith			HMT			VLH		
D_t (m)	Q (m^3/s)	H (m)	D_t (m)	Q (m^3/s)	H (m)	D_t (m)	Q (m^3/s)	H (m)
0.79–1.30	2–12	1.5–6.5	1.2–1.3	5–12	2–20	3.1–5	3.1–10	1.4–3.4

D_t represents the diameter of the turbine (m), and Q is the discharge through the turbine (m^3/s).

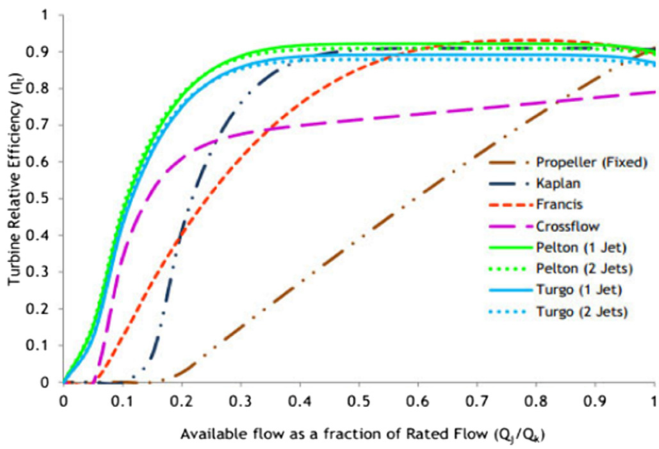

Fig. 3. Relative efficiencies for different turbine types versus the available flow as a fraction of rated flow (Adejumobi and Shobayo, 2015).

Fig. 4. Overview of the delta barrage: Damietta and Rosetta (Google Earth, 2020).

2.5. Specification of sites and data collected

The sites selected are diversified in terms of usage and technical characteristics. Eight sites have been grouped according to their characteristics, namely barrages, head regulators, and three drainage sites at Fayoum Oasis. The barrages are Damietta, Rosetta, and Zefta. The head regulators are El-Menofi and EL-Tawfeki. The three drainage sites at Fayoum are El-Azab, Tamia, and Mokhtalat. Table 3 presents some of the technical data of the eight selected sites. A variety of data such as discharges, related head for the year 2017, bathymetric surveys, more general information such as detailed studies on structure's stability and feasibility of rehabilitation measures have been collected for the studied sites. Also, Table 3 presents the hydraulic data of the eight sites.

The analysis of selected locations data and various relevant critical points in mini and micro hydropower preparation from the beginning of processing to many other processes are presented. The different processing of analysis has been conducted on a single-site (Damietta barrage) as a study sample, where the same processing can be done for the other sites.

2.6. Data analysis and criteria applicability

Damietta barrage is taken as a sample to represent the proposed methodology's applicability, as described below.

2.6.1. General description and technical data

Damietta barrage is a part of the delta barrages 20 km north-west of Cairo in El-Qanater El-Khayreya, in which the Nile river is separated into two branches, the Rosetta branch running to the north-west and the Damietta branch running to the north-east. The barrage is formed of one head-pond to control the discharges and enhance irrigation in the Nile delta. Fig. 4 shows an overview of the delta barrages; Damietta and Rosetta. The analysis reveals a mean discharge at Damietta barrage of 353 m^3/s and a total discharge volume of 11.14 billion cubic meters per year with an average gross head of 3.09 m.

Many factors should be considered to achieve the power plant's best design while applying the different criteria and determine the proper weights. The following points represent these essential factors.

2.6.2. Damietta power plant proposed

The flexibility in the layout design is one of the essential criteria for mini-hydropower plants. In this regard, different concepts have to be considered, such as:

- New civil structures and the suitable turbine: this means the in-barrage structure whereby many vents would be converted for the power intake or the powerhouse, locally replacing the ancient barrage structures. Alternatively, a new powerhouse may be erected somewhat downstream of the existing structures to maintain them untouched. Another alternative can be used by a bypass structure adjacent to the existing barrier structures with a separate headrace and tailrace channel and a new powerhouse. These plants would preferably be equipped with conventional turbines for the given site conditions. The *CF* calculated by Eq. (7) equals 88%. The conventional turbines expected to be suitable are the Bulb and Kaplan turbines, where the plant discharge is between 100 m^3/s and 700 m^3/s and the gross head is between 2.5 m and 3.5 m.
- Integration of generation equipment in the existing structure and the suitable turbine: pre-assembled small propeller turbine-generator units are installed at the existing gate structures using the available vents, with no new civil structures' addition. Presently four types are classified as non-conventional types that have been successfully developed, installed, and operated: HMT, VLH, Dive, and stream diver turbines. For a given head of approximately 3.0 m, the HMT accepts a maximum discharge of 10.5 m^3/s resulting in an installed capacity of about 0.25 MW for each unit. The same assessment for the stream diver turbine reveals a maximum discharge of 8.5 m^3/s using the SD 13.10 module. This will result in an installed capacity of 0.21 MW per unit and an overall 9.9 MW. As the discharge capacity of

Table 3
Technical data of the eight selected sites.

Site	Average/Design head (m)		Average/Design discharge (m^3/s)		Number of vents	Width of the vent (m)
Barrages: real data						
Damietta	3.06	NA[a]	353.08	402.0	34	8
Rosetta	3.40	3.2	181.20	209.0	46	8
Zefta	3.42	NA	129.20	170.2	50	5
Head regulators: real data						
El-Menofi	1.995	2.1	119.78	99.6	9	5
EL-Tawfeki	2.410	2.0	108.58	135	6	5
Other sites at Fayoum oasis: field data						
El-Azab	5.5	5.5	NA	NA	NA	NA
Tamia	6.0	6.0	22.0	22.0	NA	NA
Mokthalat	12.0	12.0	5.0	5.0	NA	NA

[a]NA denotes not available or unknown.

Table 4
Net head and the flow for the selected sites.

Site	Net head range (m)	Flow (m^3/s)		
		High-period	Mid-period	Low-period
Damietta	2.5–3.5	700 to 500 m^3/s for 90 days	500 to 300 m^3/s for 60 days	300 to 150 m^3/s for the rest of the year
Rosetta	2.5–3.75	700 to 300 m^3/s for 30 days	300 to 100 m^3/s for 240 days	100 to 40 m^3/s for the rest of the year
Zefta	2.5–4.35	231.5 to 150 m^3/s for 150 days	150 to 100 m^3/s for 80 days	100 to 50 m^3/s for the rest of the year
EL-Tawfeki	1.2–3.6	185 to 160 m^3/s for 90 days	160 to 100 m^3/s for 60 days	100 to 40 m^3/s for the rest of the year
El-Menofi	1.0–3.5	196 to 160 m^3/s for 80 days	160 to 110 m^3/s for 60 days	110 to 20 m^3/s for the rest of the year

the StreamDiver is somewhat less than that for the Hydromatrix, i.e., additional numbers of units are required. It is expected that 47 units have to be placed in 16 vents for passing the design discharge.

- Access: the power station's concerned area is easily accessible from El-Qanater by road (Kafr Al-Fokaha–El-Qanater Kheireya) and a navigable waterway (port at Damietta barrage). It should be noted that the existing road is directly crossing Damietta barrage.
- Grid interconnection: the nearest substation for feed-in is at a distance of about 1 km in El-Qanater.

3. Results and their analysis

The study presents an approach to assess and rank mini and micro hydropower potential based on MCA, FDCs, CFs, and TECs for eight selected sites. Damietta barrage is taken as a sample to represent data analysis and the methodology proposed for mini-hydro power stations.

3.1. Flow and power duration curves for the selected sites

Five FDCs have been developed depending on the daily data available for Damietta, Rosetta, and Zefta barrages, as well as El-Tawfeki and El-Menofi head regulators. Table 4 shows the net head and the flows for the five hydraulic structures. Besides, Fig. 5 shows the FDCs versus heads for the sites considered.

FDCs of Damietta barrage, as well as Zefta barrage, are characterized by a non-uniform flow distribution over the year; however, the slopes are not steep, which is more suitable for the peak load operation mode. Yet, it can also be used in base load founded on the continuous flow rate annually to meet the electrical load demand. The shape of the FDCs shows three different flow rates annually. For Damietta, a flow rate of 200 m^3/s has been exceeded about 90% of the time. Another flow rate of 300 m^3/s has been exceeded about 50% of the time, and a flow rate of 600 m^3/s has been exceeded about 20% of the time. It is worth noting that the maximum flow reaches 700 m^3/s, and the minimum flow is 100 m^3/s. On the other hand, the three flow rates of Zefta barrage are: a flow rate of 80 m^3/s has been exceeded about 90% of the time, another flow rate of 100 m^3/s has been exceeded about 50% of the time, and a flow rate of 200 m^3/s has been exceeded about 10% of the time, in which the maximum flow rate is 232 m^3/s, and the minimum is 62 m^3/s.

Table 5
Hydroelectric power generation proposed from the different hydraulic structures and their characteristics.

Site	Expected power (MW)			Annual energy (GWh)
	Maximum	Minimum	Average	
Barrages				
Damietta	17.00	3.42	9.0	78.5
Rosetta	21.18	1.15	5.3	46.4
Zefta	6.44	1.15	3.53	30.7
Head regulators				
El-Menofi	2.36	0.95	1.83	16.0
EL-Tawfeki	2.58	1.07	2.02	17.7
Other sites at Fayoum oasis				
El-Azab	NA	NA	0.8	3.15
Tamia	NA	NA	1.1	5.30
Mokthalat	NA	NA	0.5	2.41

The FDC of Rosetta barrage is characterized by a steep slope and a non-uniform distribution. Its FDC shows a flow rate of 200 m^3/s that has been exceeded about 90% of the time, another flow rate of 300 m^3/s has been exceeded about 50% of the time, and a flow rate of 600 m^3/s has been exceeded about 20% of the time, in which the maximum flow reaches 700 m^3/s and the minimum flow is 100 m^3/s. According to the FDCs of EL-Tawfeki and El-Menofi regulators, they are characterized by a non-uniform distribution, and their slopes are variable so that they will be more suitable for peak load operation. The EL-Tawfeki regulator's FDC slope is steep at 20%, and the remaining percentage is inclined to a semi-flat slope. The slope of the FDC of El-Menofi winds between steep and semi-flat.

PDC of the studied sites depends on the shape of their FDCs. Table 5 and Fig. 6 illustrate the expected energy generation in detail and the power potential from the sites, in which it is

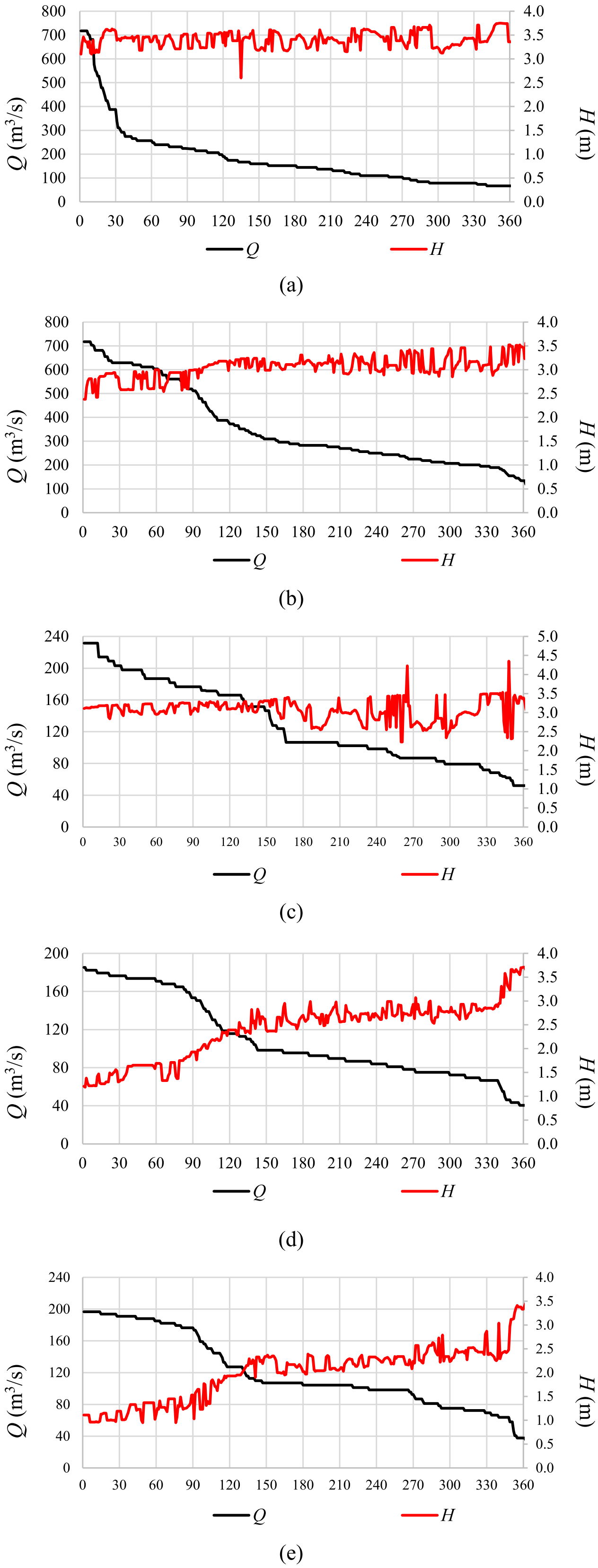

Fig. 5. FDC versus heads for the sites considered: (a) Damietta, (b) Rossetta, (c) Zefta (d) El-Tawfeki, and (e) El-Menofi.

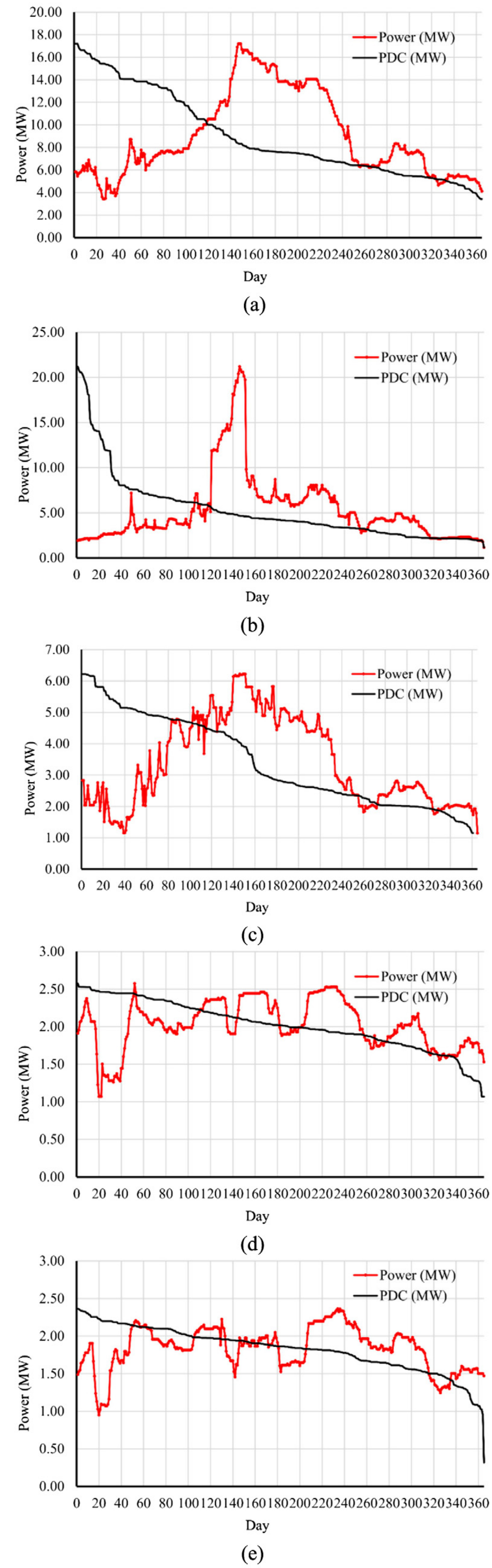

Fig. 6. PDC and power-time variation for the sites considered: (a) Damietta, (b) Rossetta, (c) Zefta (d) El-Tawfeki, and (e) El-Menofi.

evident that the hydrographs of power for the five locations in the irrigation systems are variable to a great extent.

Table 6
Proposed turbines: Conventional and non-conventional types.

Site	Number of vents used	Vent width (m)	Selected turbines	
			Conventional types, name, and efficiency (%)	Non-conventional types
Damietta	30	8	Pelton 1, 2 jets,	
Rosetta	40	8	$\eta = 90\%$	Hydro-matrix and Stream-driver are
Zefta	45	5	Turgo 1and, 2 jets,	more applicable provided that
EL-Tawfeki	5	5	$\eta = 90\%$	consideration is given to the
El-Menofi	7	5	Frances &	available flow, and the used number
Tamia	NA	NA	Kaplan η=90%	of turbines depends on the turbines'
Azab	NA	NA	Propeller, $\eta = 80\%$	diameter and width of the vent
Mohktalat	NA	NA	Crossflow, $\eta = 70\%$	

Table 7
Decision matrix for the barrage structures.

Criteria	Damietta			Rosetta			Zefta		
	w_i	s_i	$w_i s_i$	w_i	s_i	$w_i s_i$	w_i	s_i	$w_i s_i$
Condition of barrage	Acceptable: little Refurbishment			Acceptable: Refurbishment			Acceptable: Refurbishment		
	15	2	30	15	1	15	15	2	30
Access to site	Direct: Paved road			Direct: Paved road			Direct: Paved road		
	10	3	30	10	3	30	10	3	30
Plant layout	Easy or in the barrage			Easy or in the barrage			Easy or in the barrage		
	15	3	45	15	3	45	15	3	45
Grid connection	Short distance < 1 km			Short distance < 1 km			Short distance < 2 km		
	5	3	15	5	3	15	5	3	15
Environmental and social aspects	Existing barrage			Existing barrage			Existing barrage		
	5	3	15	5	3	15	5	3	15
Actual head (m)	5	3	15	5	3	15	5	3	15
Actual discharge (m^3/s)	10	3	30	10	3	30	10	3	30
Days of energy generation	All the year			All the year			All the year		
	15	3	45	15	3	45	15	3	45
Energy generated (GWh)	20	3	60	20	2	40	20	1	20
Total	100	$\sum w_i s_i = 285$		100	$\sum w_i s_i = 250$		100	$\sum w_i s_i = 245$	
R	1			2			3		
val	2.85			2.50			2.45		

3.2. TEC curve and turbines types suggested for the selected sites

Hydraulic structures in the Egyptian irrigation system depend on several vents to control the passage of flow. Based on a proposal of use, some of these vents act as the housing of the turbine. The percentage of available flow rates in 2017 for the five sites in the irrigation system to the rated flow rates of turbines (Q_j /Q_k) is performed to select suitable turbines for SHPs, in which a suitable turbine for every site is specified. Fig. 7 shows the number of vents used from every location and the selected turbines' efficiency. Also, Table 6 presents the conventional and non-conventional turbines chosen in this work.

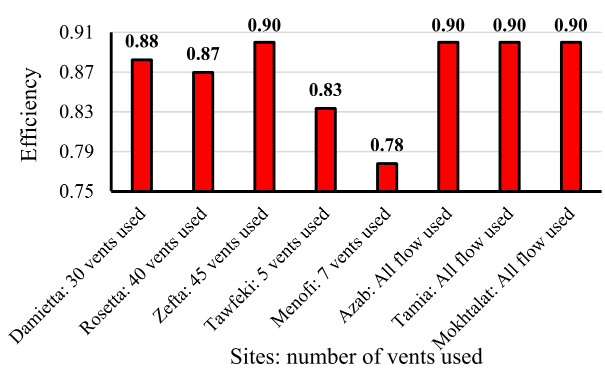

Fig. 7. Number of vents that can be used per site and the turbine's efficiency according to the available flow.

3.3. Decision matrix and ranking of the hydraulic structures

For all sites, sufficient discharge (current values) is paired with acceptable head values that are available throughout the entire year, and they have guaranteed adequate energy generation. Furthermore, additional electricity generation is available, and more benefits can be gained if the other head at the tailrace pond at the three sites is exploited. Besides, access is excellent as all barrages are directly connected to the road network. The connection to the transmission network can be quickly established with short power connections. The environmental and social impacts are negligible as the new hydropower plant will be either located entirely within the river channel or on the ground directly owned by the owners of the existing barrages. Table 7 presents the decision matrix for the barrage structures.

From Table 7, the Damietta barrage is the most promising because of its allowable energy generation potential and advantageous conditions for ease of implementation. The other two sites, Rosetta and Zefta barrages, come in the following order.

Table 8 presents the decision matrix for the head regulator structures. The second comparison is related to the head regulators. The El-Menofi head regulator (R = 1) and EL-Tawfeki

Table 8
Decision matrix for the head regulator structures.

Criteria	El-Menofi			El-Tawfeki		
	w_i	s_i	$w_i s_i$	w_i	s_i	$w_i s_i$
Condition of barrage	Good 15	3	45	Good 15	3	45
Access to site	Direct: Paved road 10	3	30	Direct: Paved road 10	3	30
Plant layout	Easy or in the barrage 15	3	45	Easy or in the barrage 15	3	45
Grid connection	Short distance < 1 km 5	3	15	Short distance < 1 km 5	3	15
Environmental and social aspects	Existing barrage 5	3	15	Existing barrage 5	3	15
Actual head (m)	5	1	5	5	1	5
Actual discharge (m^3/s)	10	1	10	10	1	10
Days of energy generation	All the year 15	1	15	All the year 15	2	30
Energy generated (GWh)	20	2	40	20	2	40
Total	100	$\sum w_i s_i = 220$		100	$\sum w_i s_i = 235$	
R	2			1		
val	2.20			2.35		

Table 9
Decision matrix for the sites at Fayoum oasis.

Criteria	Tamia			El-Azab			EL-Mohktalat		
	w_i	s_i	$w_i s_i$	w_i	s_i	$w_i s_i$	w_i	s_i	$w_i s_i$
Condition of barrage	Acceptable: Refurbishment 15	3	45	Acceptable: Refurbishment 15	3	45	Not exist 15	0	0
Access to site	Direct: Paved road 10	3	30	Direct: Paved road 10	3	30	Direct: Paved road 10	3	30
Plant layout	Easy or in the barrage 15	3	45	Easy or in the barrage 15	3	45	Easy or in the barrage 15	2	30
Grid connection	Short distance < 1 km 5	3	15	Short distance < 1 km 5	3	15	Short distance < 2 km 5	3	45
Environmental and social aspects	Existing barrage 5	3	15	Existing barrage 5	3	15	Existing barrage 5	3	15
Actual head (m)	5	3	15	5	3	15	5	3	15
Actual discharge (m^3/s)	10	3	30	10	3	30	10	3	30
Days of energy generation	All the year 15	2	30	All the year 15	2	30	All the year 15	1	15
Energy generated (GWh)	20	1	20	20	1	20	20	1	20
Total	100	$\sum w_i s_i = 245$		100	$\sum w_i s_i = 245$		100	$\sum w_i s_i = 190$	
R	1			2			3		
val	2.45			2.45			1.9		

head regulator ($R = 2$) are the most attractive sites for further development. Their evaluation is given in detail in Table 8. The remaining two head regulators have different boundary conditions. In general, technical feasibility can be confirmed for both. The two weir constructions have been recently renewed, and the overall condition of the civil structures is deemed satisfactory.

The available head is slightly above the threshold, but for El-Menofi, it drops below 1 m of the head for nearly eleven days throughout the year. These days could be used as a maintenance period. EL-Tawfeki provides much better head conditions. Access is also excellent as the head regulators belong to the Delta barrages and are located near Damietta and Rosetta barrages; therefore, they can be directly connected to the road. Also, the connection to the transmission network is easy because of the short distance. Also, environmental or social impacts will be negligible as the new hydropower plant will be either located entirely within the river channel or on the ground directly owned by the existing head regulators.

The third set of potential sites is located at Fayoum oasis and consists of a mixture of sites with different characteristics, e.g., in drainage canals instead of irrigation canals, ancient but abandoned hydropower plants. The civil structure condition criterion has only been used for the ponding structure to establish comparability with the above classes of barrages and head regulators.

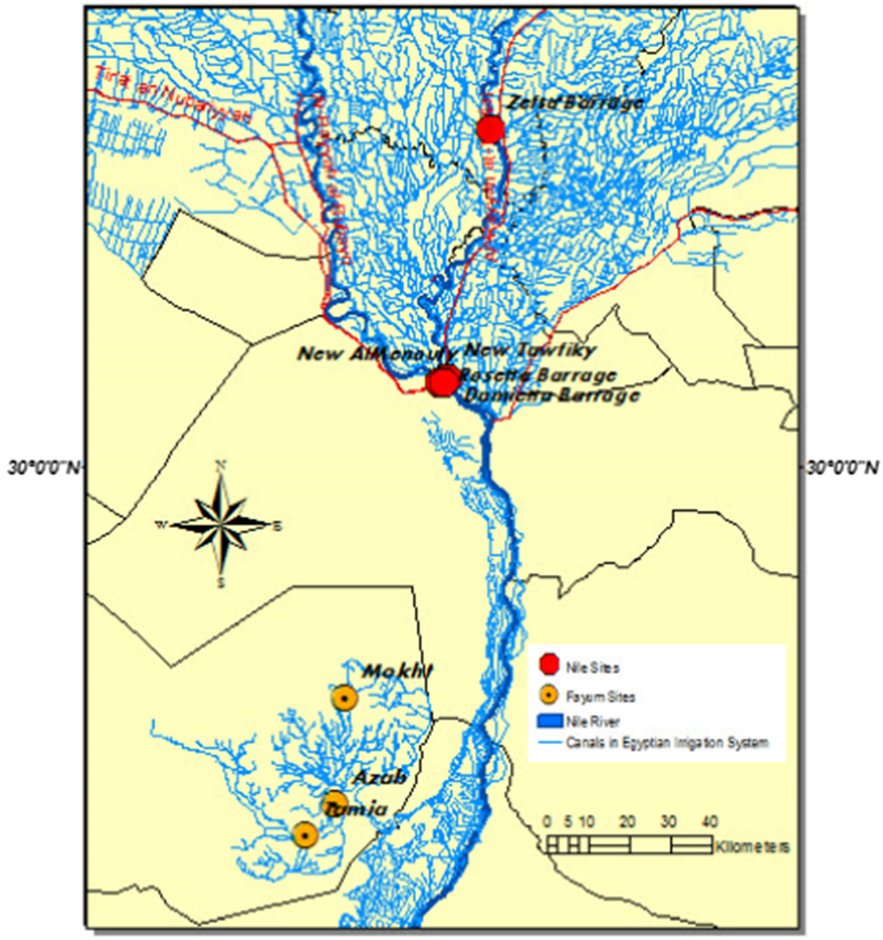

Fig. 8. Spatial map for the sites considered in this study.

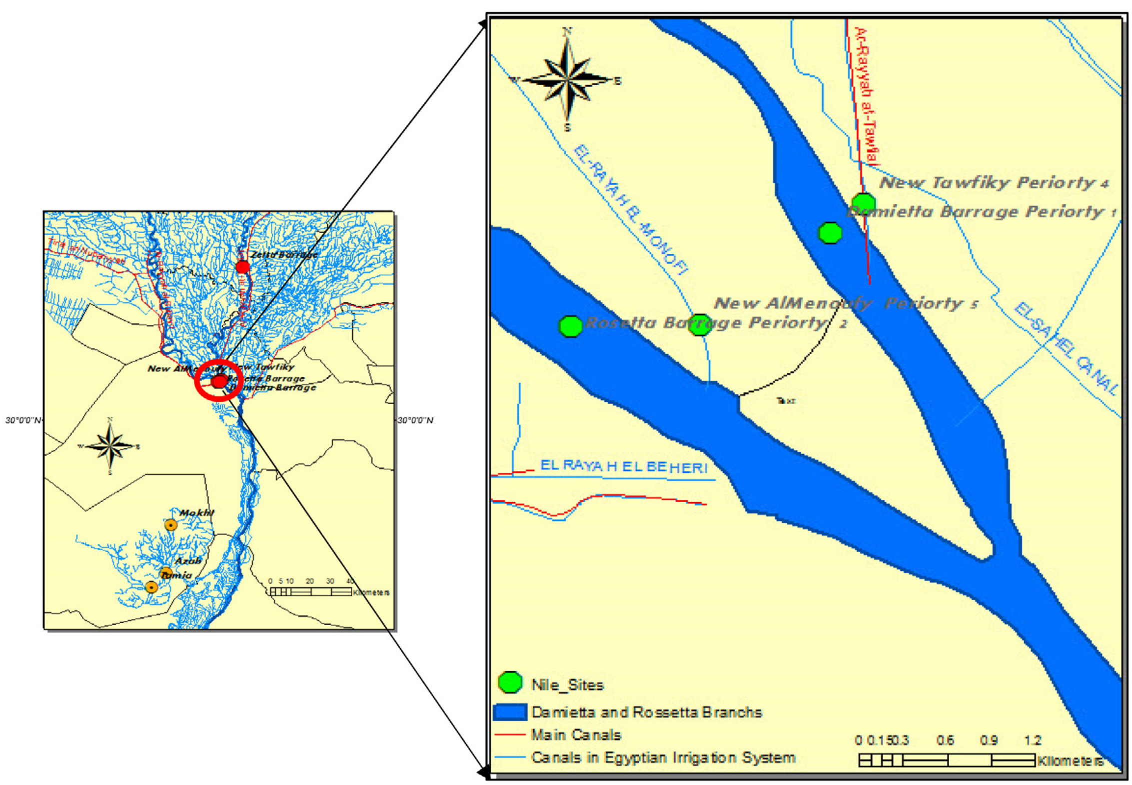

Fig. 9. Spatial map for Damietta, Rosetta, El-Tawfekei, and El-Menofi (implementation priorities: 1, 2, 6, and 7, respectively).

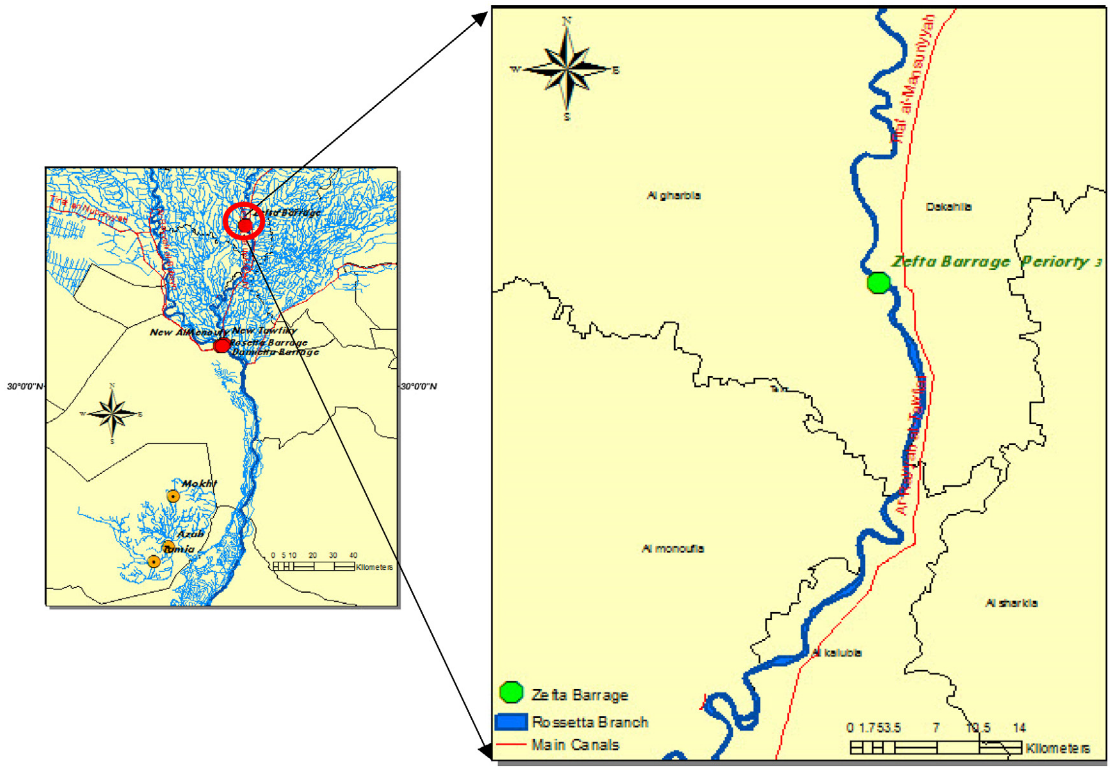

Fig. 10. Spatial map for Zefta barrage (implementation priority: 3).

Table 10
Proposed sites ranking and expected energy generation.

Site	*val*	Annual energy (GWh)	*CF* (%)	*R*
Damietta	2.85	78.5	87.83	1
Rosetta	2.50	46.4	87.50	2
Zefta	2.45	30.7	75.80	3
Tamia	2.45	5.30	NA	4
El-Azab	2.45	3.15	NA	5
EL-Tawfeki	2.35	17.6	58.60	6
El-Menofi	2.20	16.0	61.00	7
EL-Mohktalat	1.90	2.41	NA	8

It should be mentioned that a hydropower plant does not exist, and only the barrage or weirdo exists. The results are presented in Table 9.

3.4. Spatial maps

Three spatial maps for the eight sites are created to give the decision-makers a clear vision about the different areas using GIS software. Nowadays, GIS is used for the analysis of numerous types of spatial and geographic data to help select suitable locations for SHPs or renewable energy resources in general while considering technical, economic, and environmental criteria (Gandoman et al., 2020; Vaissi and Sharifi, 2019; Doorga et al., 2019; Mahdy and Bahaj, 2018).

The spatial maps for the eight sites were created based on FDCs and PDCs. Table 10 shows the average weighted value (*val*), CF, and the annual energy capacity (GWh) used in deciding the final ranking (*R*) and priority of implementation of the eight sites.

Four layers are developed and integrated. The first layer represents the river Nile, the second layer represents the irrigation canals, the third layer includes the spatial locations for the selected studied sites, and the fourth one represents the governorates of Egypt. These layers are integrated to accomplish the spatial map. Eight Points are gathered as keyhole mark-up language (KML) files obtained from Google Earth (Google Earth, 2020). Five of these points represent selected sites' locations on the irrigation canals system, in which two points are on the Damietta branch (Damietta and Zefta barrages). One point is on the Rosetta branch (Rosetta barrage), another point is on El-Rayah El-Tawfeki (New Tawfeki head regulator), and the last point is on El-Rayah El-Menofi (New Menofi head regulator). The three other points are at the Fayoum governorate, but their exact locations are not determined. These points are converted into shapefiles and projected as UTM; WGS_1984_UTM_Zone_36N. The generated spatial maps of the selected sites are shown in Figs. 8–11, respectively.

4. Conclusions

The potential of mini and micro-hydropower in Egypt is very promising. The annual energy from the eight studied sites is estimated by 200 GWh according to the daily hydraulic data of the year 2017. Damietta barrage takes priority as the weight value of criteria is the highest value by 2.85, and its annual energy is estimated by 78.5 GWh. The eight sites are more suitable for peak load plants, but Damietta and Zefta are appropriate by less priority for baseload plants. The study introduces a new approach to assess the potential of mini and micro hydropower in Egypt, depending on MCA, FDCs, and CFs of the proposed plants.

Eight sites in different locations are selected to be studied. These sites can be classified into three groups: barrages group for Damietta and Rosetta, head regulators group, El-Tawfeki, and El-Menofi. The third group is the three sites on the irrigation drainage network at Fayoum Oasis, including Tamia, El-Azab, and EL-Mohktalat.

The ranking of sites supported by spatial maps of their locations is proposed. The spatial maps are used to give a clear vision of the possibility of exploiting different resources and the priority

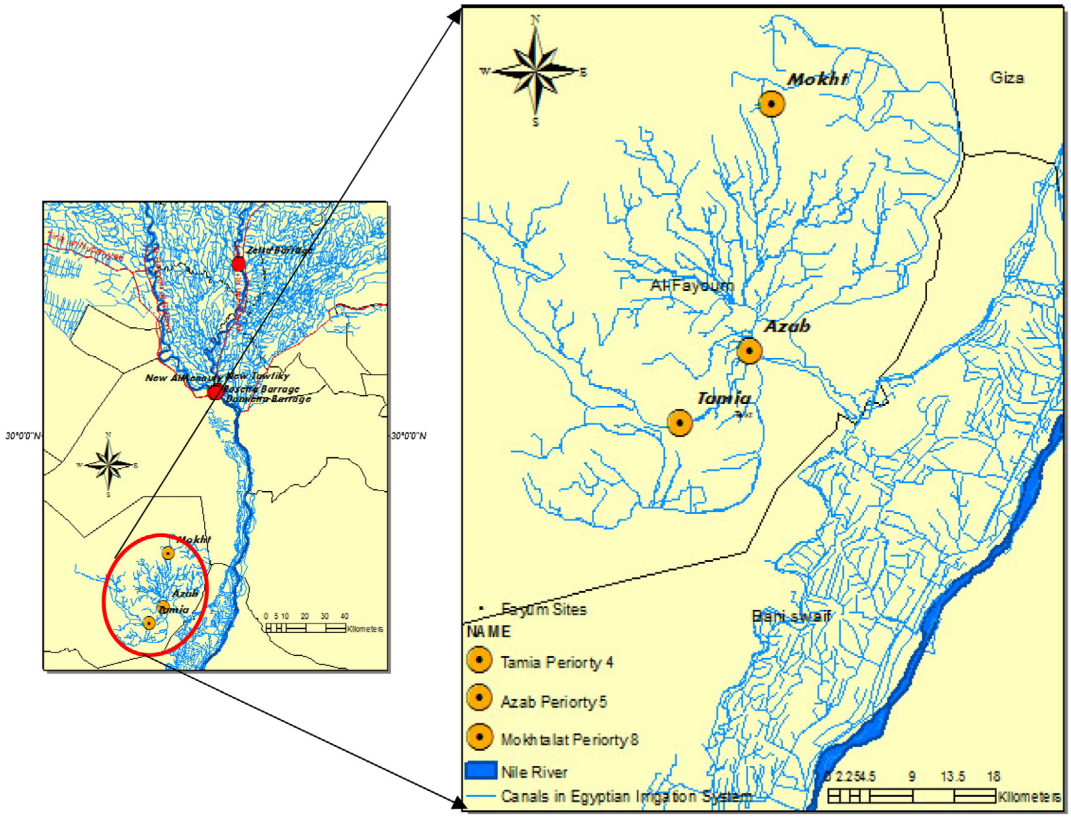

Fig. 11. Spatial map for the three sites at Fayoum oasis (implementation priorities 4, 5, and 8, respectively).

of implementation. The suitable turbines from the conventional and non-conventional types for every site are proposed, and their efficiencies are estimated. Applicability of the proposed turbines under various operating conditions will be investigated in the future works to evaluate their accurate performance with an analysis of uncertainty.

CRediT authorship contribution statement

Nadia M. Eshra: Conceptualization, Investigation, Writing - original draft, Methodology, Formal analysis. **Ahmed F. Zobaa:** Methodology, Validation, Final editing. **Shady H.E. Abdel Aleem:** Methodology, Analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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