Renewable Energy 172 (2021) 633–650

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Finding the most suitable existing irrigation dams for small hydropower development in Turkey: A GIS-Fuzzy logic tool

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ARTICLE INFO

Article history:
Received 6 October 2020
Received in revised form
27 February 2021
Accepted 11 March 2021
Available online 13 March 2021

Keywords:
Irrigation dams
Small hydropower
GIS
Fuzzy multi-criteria decision making
Turkey

ABSTRACT

This paper enables a screening of existing irrigation dams in order to assess and rank potential sites for small hydropower development by using a Geographic Information System (GIS)-fuzzy logic multi-criteria scoring technique. The following criteria are evaluated: dam characteristics (reservoir normal level, reservoir capacity, dam purpose, dam ageing), and grid connection spatial characteristics. The proposed method estimates the suitability degree of each criterion separately and then aggregates them into a Site Suitability Index (SSI). Existing irrigation dams in Turkey are assessed in order to be utilized for hydropower development. The overall score of each candidate site is obtained and, their performance is compared for different strategies. One of the most suitable dams, Karadere, was chosen as a case study. By using the daily continuous monitored data, we showed that flow and head is highly variable during the irrigation season. Accordingly, we evaluated an innovative compact medium-head hydro turbine that can capture those fluctuations with its operational flexibility and minimal civil works. Moreover, an optimal path methodology was applied to find the best grid connection route from the dam to its nearest substation considering the site land use characteristics in order to minimize land expropriation.

1. Introduction

Nowadays, the interest in the development of small hydropower, which is a renewable source of energy, is growing. However, such developments have to cope with multiple, sometimes contradictory, political, economic and environmental requirements and constraints [1]. In addition, the construction of dams or weirs, which necessarily causes some alteration of natural environment, may lead to some opposition by local stakeholders [2]. For instance, the House of Representatives of the Federation of Bosnia and Herzegovina passed a declaration on the protection of rivers and voted to completely ban the construction of small hydropower plants in June 2020 [3]. Also, the construction of the associated dams or weirs can often constitute a large percentage of the total investment cost. Concerning the development of small hydropower in such complex context (Fig. 1), existing irrigation dams represent a convenient potential of energy recovery.

In many regions of the world there are numerous existing irrigation dams which so far have not been used to generate electricity. Instead the potential energy of the water is lost as it flows over existing height differences or has to be dissipated by specially designed energy dissipators [2]. It is thus beneficial, where opportunities exist, to take advantage of installing hydropower at existing irrigation dams. It is possible to equip the bottom outlet of irrigation dams with hydro turbines (Fig. 2) and there is no need for the installation of gates [5]. The benefits and simplifications of these facilities compared to river-type hydropower plants could be summarized as follows: (i) all infrastructure access are present, which will reduce the investment cost and risk considerably, (ii) the facility has a guaranteed discharge through the irrigation season, (iii) the generated electricity can be used at the infrastructure system and the excess power can be sold on the grid, (iv) there is no significant operating costs (v) dam components as-built drawings (i.e. plan layout), and dam characteristics information (i.e. bottom outlet rating curve) are present, (vi) the continuous monitoring data (time series) of the reservoir water level and the discharge are available [6–8]. As a result of these benefits mentioned-above and others, many countries and companies are planning to develop small hydropower facilities at existing irrigation dams and networks.

European Small Hydropower Association (ESHA) [9] reported

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https://doi.org/10.1016/j.renene.2021.03.049
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Nomenclature

List of Symbols

A	Fuzzy Set
C_{ij}	Suitability Score of the Criterion j for the Dam i
E	Annual Electricity Generation (kWh/year)
g	Acceleration Due to Gravity (m/s^2)
H	Gross Head (m)
i	Dam Number
IC	Investment Cost (EUR)
j	Criterion Number
n	Total Number of Selected Dams
O & MC	Annual Operation and Maintenance Costs (EUR/year)
Q	Discharge (m^3/s)
P	Installed Capacity of a Hydropower Plant (kW)
R	Annual Revenue (EUR/year)
r	Total Number of the Criteria
Pr	Electricity Sale Price
SSI	Site Suitability Index
W_j	Weight of the Criterion j
ΔH	Total Head Loss (m)
η	Overall Efficiency of the Turbine, Generator, and Inverter Efficiency
μ	Fuzzy Logic Membership Function
ρ	Density of Water (kg/m^3)

Abbreviations

DSI	State Hydraulics Works of Turkey
ESHA	European Small Hydropower Association
GIS	Geographic Information System
ICOLD	International Commission on Large Dams
IEA	International Energy Agency
JICA	Japan International Cooperation Agency
SHP	Small Hydropower Plant

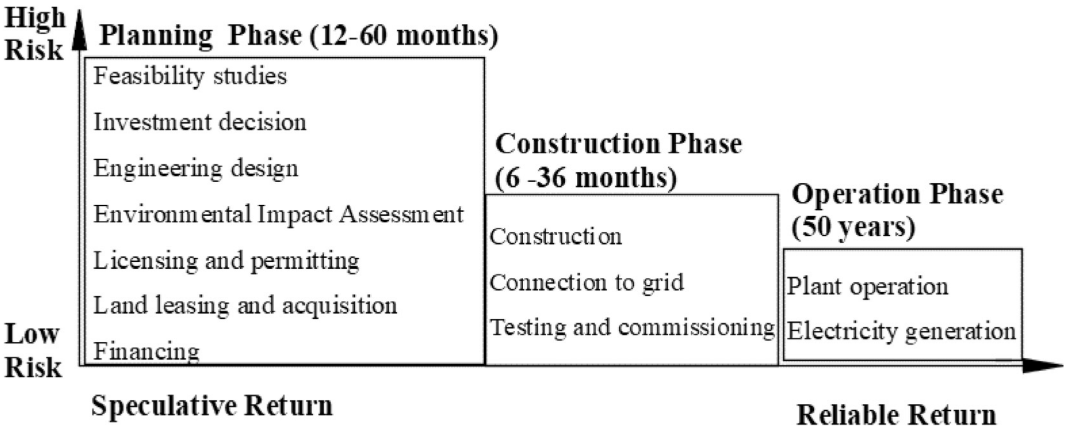

Fig. 1. The Phases of small hydropower projects life cycle. Adapted from Lawrence and Dickson [4].

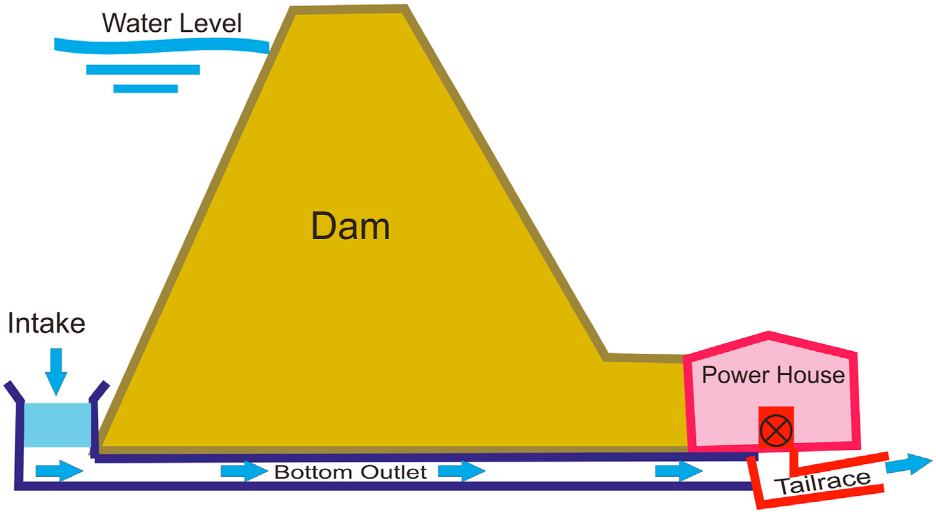

Fig. 2. Sketch of hydropower development at the outlets of irrigation dams with conventional hydro turbines. Adapted from European Small Hydropower Association (ESHA) [5].

that the limited number of operating sites at existing wet infrastructure is mainly due the lack of information on the possibility of recover energy and the lack of simple administrative procedures adapted to small hydropower. International Energy Agency (IEA) Hydro proposed the Hidden Hydro Opportunities initiative which has set an overall objective to provide a framework to enable and support increased development of hidden hydro opportunities globally [10]. Hidden hydro is defined as hydropower that was originally not considered during development of dams and water infrastructure, or potential that was not technically feasible, but could be with new technologies, innovative approaches or market changes [10]. Accordingly, multiple studies have been conducted in recent years to identify the remaining potential to develop hidden hydropower resources on existing water resources infrastructure [11–18]. In the ICOLD World Register of Dams, 29,163 dams are registered as non-powered per 2019, representing about 50% of the dams in the database [19]. These dams and their corresponding reservoirs provide both available water and a height difference potentially exploitable for hydropower production. For instance, O'Connor [20] reported that 12 GW of hydropower potential exists at dams without power, and up to 2 GW of potential may reside in U.S. irrigation canals and water supply conduits. Moreover, Pongtepupathum [21] stated that there are more than 4000 existing irrigation dams in Thailand and there has been an ongoing project for hydropower development at 8 irrigation dams. Pongtepupathum [21] reported the unforeseen technical problems during operation of these hydropower plants are the low quality of electromechanical equipment due to the bid evaluation stage of the project and the unit pulsation (power swing and over limit vibration). Murashige [22] pointed out the key issues and barriers for the hydropower development on existing water resources infrastructure in Japan as follows: (i) installing electro-mechanical (hydropower) equipment and obtaining access to the site, (ii) hydropower development is restricted by utilization of existing facilities, (iii) issues in the related regulations, and (iv) issues of grid interconnection. Furthermore, Frosio et al. [23] and Aschenbrenner et al. [24] stressed the importance of the plan layout and boundary conditions for the success of those kinds of projects.

In the literature most of the studies focused on the development of the hydropower potential at irrigation networks and canals [25–32] rather than at the outlet of the irrigation dams. Table 1 presents the characteristics of the some of the small hydropower plants developed at irrigation canal networks in Europe.

There are some limited studies that assessed the existing irrigation dams for energy recovery [33–35]. But, those studies did not take into account the daily monitoring data of the reservoir level and the discharge for irrigation purpose. Also, those studies ignored the variability of the head and discharge and considered the hydro turbines peak efficiencies in their economic feasibility analysis. But, due to wide flow range in irrigation canals the peak efficiency were rarely achieved and annual electric generation is generally lower than the estimated, and O&M costs are generally higher than expected due to cost for erosion repairs in conventional turbines [31]. Also, neither of those studies [33–35] considered the potential site grid connection characteristics. For instance, Fitzgerald et al. [36] developed a Geographic Information System (GIS) based model to identify the most suitable dam reservoirs for pumped-storage development, but the authors ignored the grid connection distance L_g, which is crucial factor for the feasibility of a hydropower project. Catrinu et al. [37] noted that the electric transmission lines and market conditions are the crucial factors for hydropower investments. For example, a potential site with favorable characteristics (e.g. high head and high storage capacity) but which is located far from the electrical grid infrastructure will not be suitable because of the significant cost generated [38]. We think that there is a clear gap in the literature about the assessment of the hydropower development at existing irrigation dams considering the dam attributes and grid connection spatial characteristics. Accordingly, this study aims to find most suitable existing irrigation dams for hydropower development by using a GIS-fuzzy logic multi-criteria scoring technique in an integrated approach. The proposed method was applied to existing irrigation dams in Turkey. The main contribution of this paper to the existing literature can be summarized as: (i) irrigation dams grid connection spatial characteristics and dam ageing factors are taken into account, (ii) a multi-criteria fuzzy logic tool, which deals with uncertainties, is employed, (iii) in the case study analysis daily variability of head and discharge is considered, and (iv) an innovative compact turbine that has an operational flexibility is evaluated for the economic analysis.

2. Irrigation dams and electric infrastructure in Turkey

Irrigation is the artificial application of the water to the land or soil. It is used to assist in the growing of agricultural crops in dry areas and during period of inadequate rainfall. Most of large dams in the world have been built for irrigation purpose and it is very important for the water-energy-food nexus [54]. According to the International Commission on Large Dams (ICOLD) Register (status March 2015) there are 38,452 large dams in the world with their purposes described, among which 26% are multipurpose reservoirs. There are 14,003 (36%) of large dams in the world have only for irrigation purpose [39]. Fig. 3a presents these purposes for single and multi-purpose dams around the Word. The share of irrigation dams is higher in Turkey (Fig. 3b) compared to around the Word. According to the database of the General Directorate of State Hydraulic Works of Turkey (DSI) (status December 2019) there are 629 (65%) of large dams in the country only for irrigation purpose. The establishment of dams and reservoirs has enabled Turkey to save the water from its brief seasons of rainfall to be used throughout the year [40].

Turkey has a semi-arid climate and the rivers often have irregular regimes. In the country, annual water consumption is about 54 billion (m^3), of which 74% is used for agriculture by 2017 [40]. The total land resources of Turkey are 78 million ha and almost one third of this, 28 million ha, can be classified as arable land. Recent

Table 1
Characteristics of the some small hydropower projects developed at the existing irrigation networks in Europe. Data source: ESHA [10].

Plant Name and Location	Gross Head (m)	Nominal Discharge (m^3/s)	Installed capacity (P) and electrical generation (E)	Investment Cost (EUR)	Turbine
Armary, Switzerland	105	0.08	P = 68 (kW), E = 454 (MWh)/year	400,000	The 2-nozzle Pelton turbine
Marchfeldkanal, Austria	2	6	P = 70 kW, E = 500 MWh/year	–	2 Kaplan tubular turbines
Petiva, Italy	5.9	18.5	P = 875 kW, E = 5000 MWh/year	2,500,000	3 Kaplan tubines
Esanta, Italy	24	4.5	P = 860 kW, E = 4300 MWh/year	1,535,000	Kaplan turbine
Rino, Italy	446	0.780	P = 2800 kW, E = 14,000 MWh/year	3,945,000	2 horizontal-axis Pelton turbines

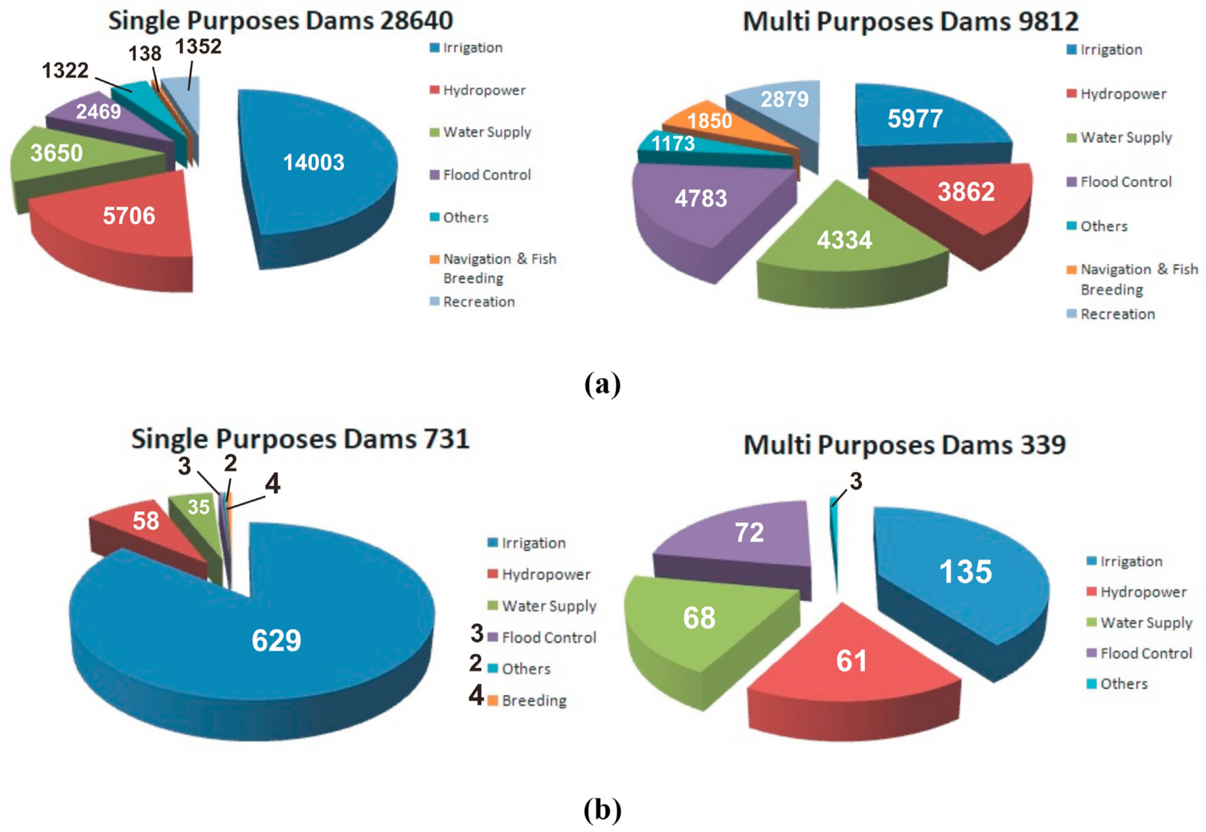

Fig. 3. (a) The use of dam reservoirs by purpose around the World by 2015 [39], (b) The use of dam reservoirs by purpose in Turkey by 2019.

studies indicate that 8.5 million ha is economically irrigable with the available technology. Altınbilek and Hatipoglu [40] reported that presently about 6.5 million ha of irrigation infrastructure has been developed and 4.21 million ha of this amount has been equipped with irrigation infrastructure by the General Directorate of the State Hydraulic Works (DSI). The inefficient use of water in agriculture results in over-abstraction of water from both surface and groundwater in several river basins. The majority of irrigation is realized as gravity irrigation, which leads to low water efficiency. Currently, water delivery systems in irrigation schemes are comprised of open channels (77%) and pipe flows (23%), and water losses due to leakage and evaporation in open channels is high compared to that in closed systems. In Turkey, 75% of the irrigation systems are depended on dam reservoirs and 25% are depended on groundwater reserves [40]. Distribution of 711 irrigation large dams (including single and multi-purpose dams) over 81 provinces in Turkey by 2019 is shown in Fig. 4; whereas, projection of 692 substations over 81 provinces in Turkey by 2019 is shown in Fig. 5. In the present study, the Turkish irrigation dam dataset and the electric substation dataset are merged in order to assess the potential irrigation dam suitability factors for small hydropower development.

3. Methodology

The installed capacity P (kW) of a hydropower plant is calculated from Ref. [41]:

$$P = \rho \times g \times Q \times (H - \varDelta H) \times \eta \quad (1)$$

ere ρ is the density (kg/m^3) of water, g is the acceleration due to gravity (m/s^2), Q (m^3/s) is the discharge, H is the gross head in meters (m), ΔH is the total head loss in meters, η is the overall efficiency of the turbine, generator, and inverter efficiency [41]. The gross head is defined by the difference in levels between the upstream water level at the reservoir and the downstream water level at the tailwater (Fig. 6). The design discharge depends on the flow duration curve of the site, as to optimize the production all over the years. The basic layout of a storage type hydropower plant is shown in Fig. 6. Water is drawn from an upstream reservoir and then flows down to the tailwater, driving the hydro turbine. The net head available to the turbine can be calculated from the gross head minus losses occurring in the inlet, outlet, and the penstock.

Revenue generated from a hydro energy project is computed from Ref. [42]:

$$R(i) = \Pr(i) \times E(i) \quad (2)$$

where i is the period, $R(i)$ is the revenue in period i, $Pr(i)$ is the electricity sale price in period i, and $E(i)$ is the amount of electricity generation in period i. One of the most important economic indicators is the payback period which is calculated from Ref. [42]:

$$Paybackperiod = \frac{IC}{R - O\&MC} \quad (3)$$

where IC is the investment cost, R is the annual revenue, O & MC is the annual operation and maintenance costs. It is a simple benefit/cost calculation without debt contracting. Payback period, which is a measure of the number of years it takes for a project to return the total investment, is the most important indicator of Small Hydropower Plant (SHP) feasibility [9]. Utilizing existing irrigation dam reservoirs for hydropower development is expected to be cost-efficient and to have low environmental impacts since there is

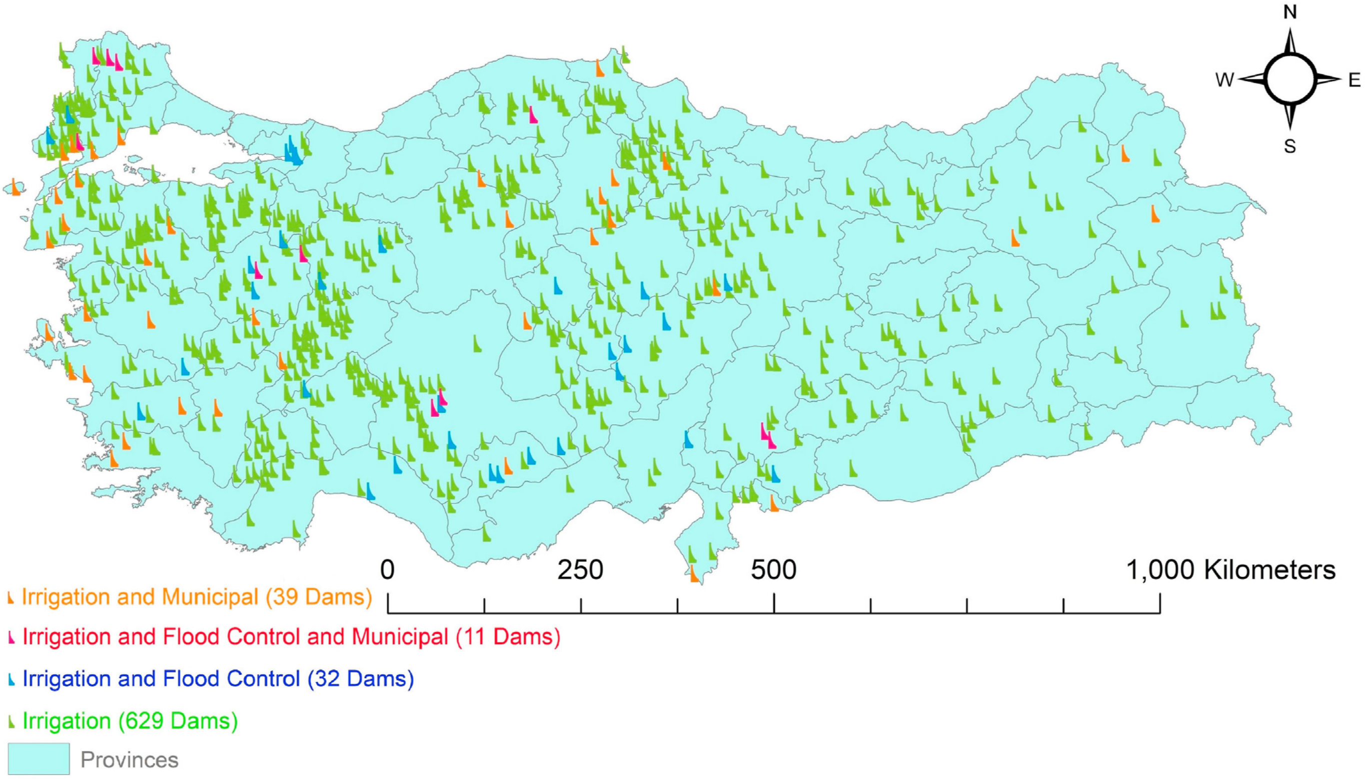

Fig. 4. Distribution of 711 irrigation dams classified by purpose over 81 provinces in Turkey by 2019 (including multi-purpose dams).

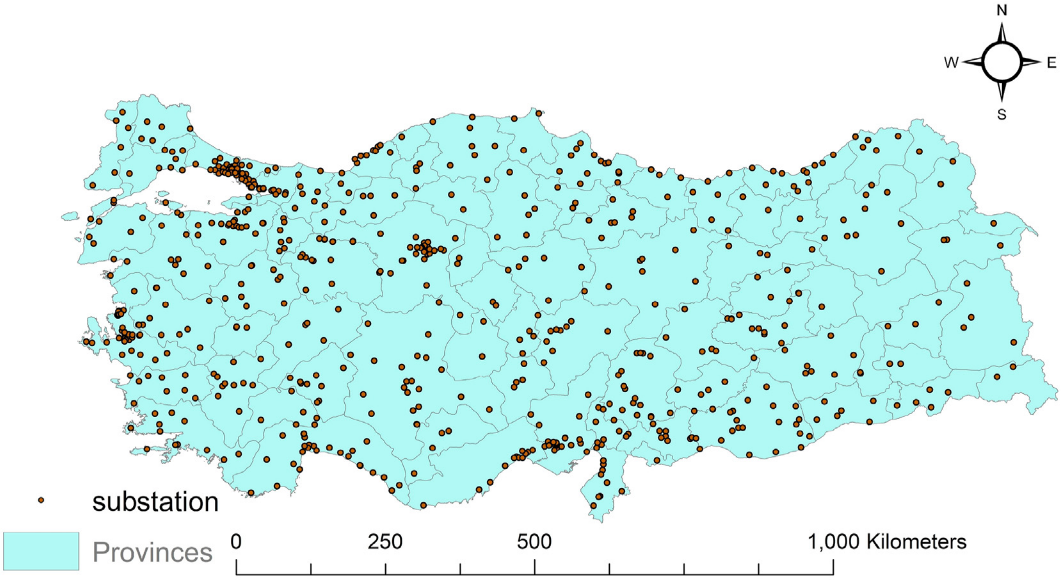

Fig. 5. Distribution of 692 power substations over 81 provinces in Turkey by 2019.

already transportation infrastructure in place and there is no need to build dam.

In the proposed tool, a fuzzy logic multi-criteria scoring method is used to find most favorable existing irrigation dams to develop hydropower. An important component of the proposed methodology includes converting site characteristics into a common scale, and these scales express preferences for one site over another [43]. The suitability degree was computed for each dam considering all the criteria. The scoring of selected parameters is based on fuzzy logic membership functions.

3.1. Multi-criteria decision making with fuzzy logic

Fuzzy logic was firstly introduced by Zadeh [44] and it has

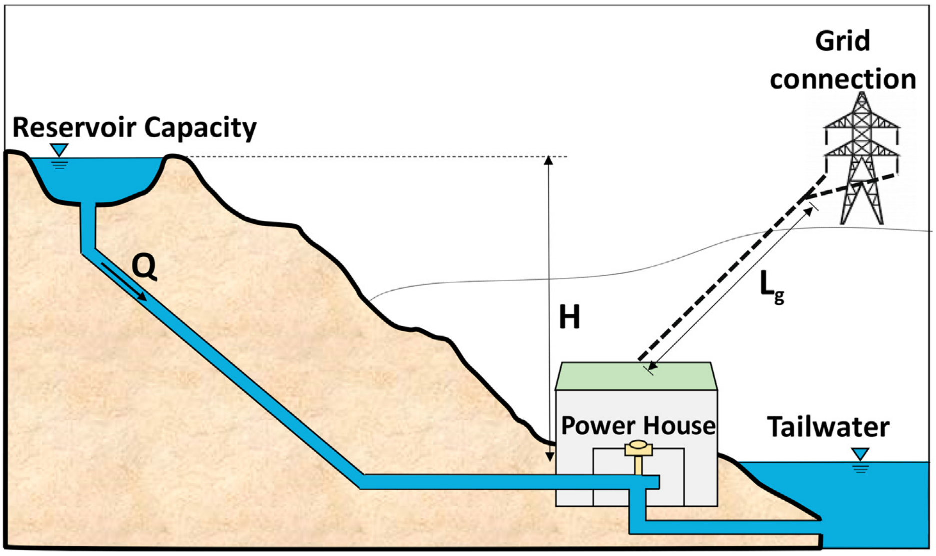

Fig. 6. Basic layout with main parameters of the storage type hydropower plant.

become an important tool for a number of different applications ranging from the control of engineering systems to business [45,46]. Fuzzy logic method depends on a systematic use of linguistic expressions to describe the values of variables in which expert judgements are crucial [47]. The advantage of this methodology lies on the ability to mimic the human thinking and reasoning. Thus, it can capture dynamic system behaviors including uncertainties. The fuzzy set A can be defined in the form as

$$A = \{(x_1, \mu_1); (x_2, \mu_2); (x_3, \mu_3)....\} \tag{4}$$

where A is fuzzy set, x is the numeric value and μ is the membership function varies in the range from 0 to 1. As an example, let the values of temperature be under consideration between 0 and 40 °C. Then hot can be defined by a fuzzy set as follows

$$Hot = \{(0, 0); (15, 0.5); (40, 1)\} \tag{5}$$

This fuzzy set reflects the point of view that 0 °C is not hot at all, 15 °C is somewhat hot, and 40 °C is indeed hot. One can think of membership functions as a technique to formalize empirical problem solving that is based on experience rather than the knowledge of theory [48]. A multi-criteria fuzzy decision-making tool was developed within the scope of this study in order to evaluate the suitability degree of irrigation dams for small hydropower development.

The suitability degree (score) for each dam could be aggregated in many different ways, such as a linear method of aggregation based on multiplication of the set of weights by the degrees of suitability memberships [49], as shown in Equation (6).

$$\mathrm{SSI} = \sum \mathrm{W}_{\mathrm{j}*}\mathrm{C}_{\mathrm{ij}} \quad \mathrm{i} = 1,2, \ldots,\mathrm{n} \quad \mathrm{j} = 1,2, \ldots,\mathrm{r} \tag{6}$$

Where i is the dam number, j is the criterion number, n = 265 is the total selected dams, r = 6 is the total number of the criteria, Wj is the weight of the criterion j, Cij is the suitability score of the criterion j for the dam i and SSI is the site suitability score of the dam i. Suggested scales in the proposed methodology range from 0 to 1, with 0 being the least preferable and 1 being the most preferable. The scores are assigned based on measured data and reported values. Then, the Site Suitability Index (SSI) is calculated and a 3-grade evaluation system is established as follows: SSI<0.5 low suitability, 0.5≤SSI<0.75 medium suitability, and SSI≥0.75 high suitability.

3.2. Geodatabase query of dams and grid connection criteria

The main criteria used to evaluate potential irrigation dam reservoirs are: normal water level, reservoir capacity, dam purpose, dam years of operation, distance to grid connection, Environmental Impact Assessment (EIA) requirement. The evaluation criteria are driving factors to select the most appropriate irrigation dams for small hydropower development. All those criteria play an important role on the economic viability of the project and those criteria are associated with a benefit/cost. However, especially for small hydropower plants it is important to consider these aspects in order to ensure the feasibility of the project. Accordingly, threshold values are defined for the each criterion on the basis of the expert judgements: dam height from foundation ≥15 m and reservoir capacity ≥3 cubic hectare meter (hm^3) which are the definitions of the ICOLD for large dams [50], dam years of operation ≤ 60 year which is related with the economic life of a dam, and maximum grid connection distance ≤ 40 km which is a criterion of Japan International Cooperation Agency (JICA) [51]. So, candidate irrigation dams need to meet the minimum geometrical requirements and lie outside of environmentally protected areas. By applying geodatabase queries based on the technical criteria for the dams and substations and the spatial criterion of nearest substation distance using ArcGIS v.10.2.2 spatial analyst tools [4th], the following results were obtained (Fig. 7): (i) 265 suitable irrigation dams for hydropower development were identified, (ii) a total of 183 nearest substations located within 40 km of the selected 265 dams were selected by assigning the nearest substation to each candidate dam, (some of these substations were near to more than one dam), (iii) the straight-line distance was calculated from each candidate dam to its nearest substation. This result means that 478 irrigation dams in Turkey did not meet one of the above-mentioned criteria (dam height from foundation ≥ 15 m, reservoir capacity ≥ 3 hm^3, dam years of operation ≤ 60 year) and those dams were excluded from the analysis. For the grid connection spatial analysis, step-up transmission substations in operation with a voltage of 154 (kV) and higher were selected. As a result of applying database query filtering to all 692 substations using the ArcMap v.10.2.2, the

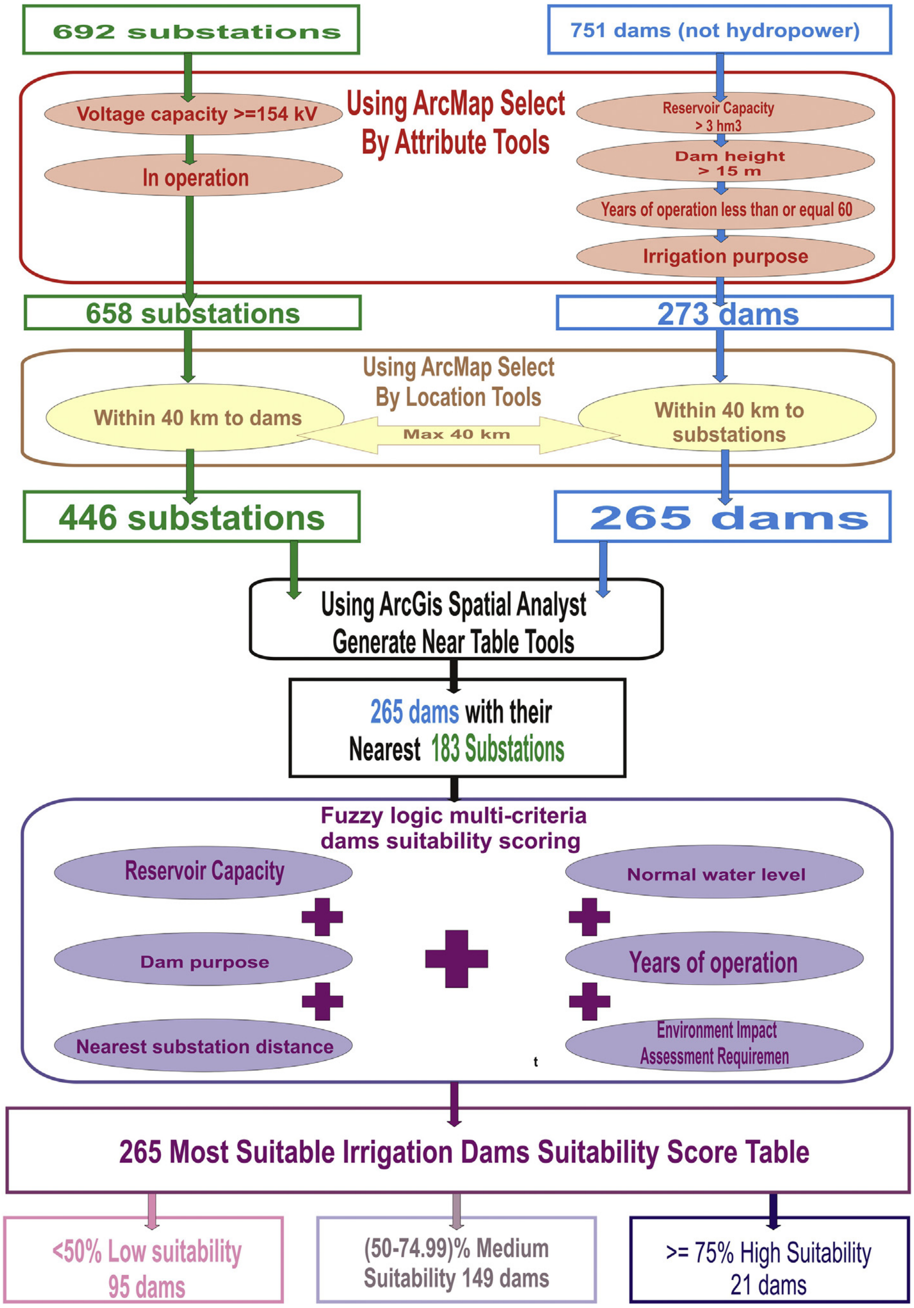

Fig. 7. The framework of determining the suitability of the irrigation dams in Turkey for hydropower development.

number of substations was reduced to 658. This means that 34 substations in operation status did not meet the criteria of voltage ≥154 kV and those substations were excluded from the analysis.

The attributes of the selected 265 irrigation dams are given in Table 2. For the selected dams, the average dam height form the foundation is 48 m, and most of the selected 265 dams have heights from foundations between 20 and 70 m. The average reservoir capacity for the selected dams is 43 hm^3 and most of the selected 265 dams have a reservoir capacity between 3 and 90 hm^3. The average distance to the nearest substation for the selected dams

Table 2
Attributes of the selected 265 irrigation dams in Turkey.

	Dam height from thalweg (m)	Reservoir capacity (hm^3)	Years in operation	Irrigated Area (hm^2)	Normal Water Level (m)	Near substation distance (km)
Minimum	11.2	3	1	53	10	0.72
Median	37.2	18.5	20	2062	33.5	16.55
Average	40.3	43	22	4913	36	17.29
Maximum	100	717.7	60	97015	98	38.20

was 17.29 km, and the selected 265 dams had a normal distribution around the average value for this criterion. The average value for the years of operation of the selected dams was 22 years, and most of the selected 265 dams were built after 1980. The irrigated area is strongly related to reservoir capacity, since a high reservoir capacity indicates reliable supply of water for irrigation (Table 2). The average value for the irrigated area for the selected dams was 4913 he, and around 200 of the selected 265 dams had irrigated areas of less than 10,000 he. There is a clear relationship between the dam normal water level and the dam height (Table 2). The average value of the normal water level for the selected dams was 36 m, and most of the selected 265 dams had a normal water level between 10 and 60 m. From the selected 265 dams, there are 201 dams that are only operated for irrigation purpose; while, there are 33 dams operated for irrigation and municipal water supply purposes. Fig. 8 shows the distributions of the selected 265 irrigation dams and nearest 183 substations within 40 km grid connection grid connection distance.

Linear fuzzy-logic functions are defined for the scoring of dam characteristics. The boundaries of the linear fuzzy logic functions are specific to Turkey and they are derived from the medium, median and maximum values of the selected 265 irrigation dams. Moreover, a threshold value is defined for the criterion of Environmental Impact Assessment (EIA) requirement. Detailed information for the selected criteria is given below.

Normal Water Level: It is the highest water level in the reservoir active storage zone. Maximum head is calculated from the difference between the normal water level in the reservoir and the tailwater (Fig. 9). The higher heads will decrease the turbine costs [52]. In this respect, higher heads represent preferable site conditions and they have higher scores (Fig. 10). For reservoir capacity and the normal water level, the suitability degree was calculated by Q_{50} method (above and under the median) which give each criterion a suitability degree (membership) between 0 and 1 [53]. The maximum normal water level of the selected irrigation dams is 98 m, the median value is 33.5, and the minimum value is 10 m The fuzzy set for normal water level is established based on these values (Fig. 10).

Reservoir Capacity: It includes the active and dead storage (sedimentation part) capacity of reservoir. Higher reservoir capacities will provide continuous reliable discharge for hydropower generation. The maximum reservoir capacity of the selected irrigation dams is 717.7 hm^3, median value is 18.5 hm^3 the minimum reservoir capacity is 3 hm^3. The fuzzy logic membership function for reservoir capacity is established based on these values (Fig. 11).

Dam Purpose: Dam reservoirs are designed and/or operated to provide services such municipal water supply, flood control, drought mitigation, irrigation, navigation services, and recreation [39]. The multipurpose uses of reservoir usually imply multi-users and these reservoir purposes can conflict at times. A major challenge with multi-purpose reservoirs is sharing water amongst competing users. Accordingly, if the dam has a single purpose, it has the highest score. Because single purpose dams have fewer constraints compared to multipurpose dams. The suitability degree was determined as follows: If the dam is used for irrigation purpose only (single purpose), then the suitability degree of this criterion is 1; if the dam is used for irrigation and municipal or irrigation and flood control purposes (two purposes), then the suitability degree of this condition is 0.66. If the dam is used for irrigation, municipal and flood control purposes (three purposes) then the suitability degree of this condition is 0.33 (Fig. 12).

Dam Years in Operation: This criterion is related with the age of the dam, and is an especially important parameter regarding to the sedimentation status of the reservoir. It also has an inverse linear relationship with the suitability degree, since as the age of the dam (years in operation) increases, the number of possible future years of operation decreases (Fig. 13). Generally economic life of dam is estimated to be 50–70 years depending on the dead storage capacity of the reservoir and annual sediment yield of the river basin [54]. For instance Cubuk-I Dam, which began operation in 1936 in Turkey to supply municipal water to the Ankara, completed its economic life in 1993 due the reservoir sedimentation.

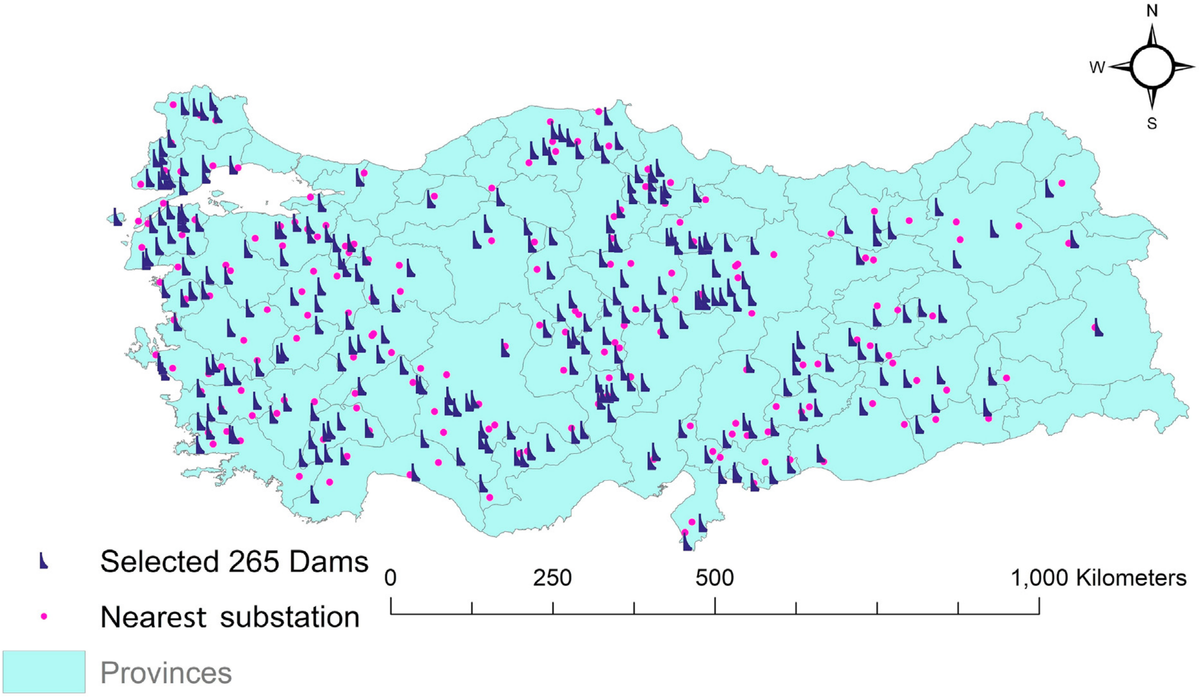

Fig. 8. Map of Turkey showing the locations of the selected 265 irrigation dams and their selected nearest 183 substations within 40 km distance.

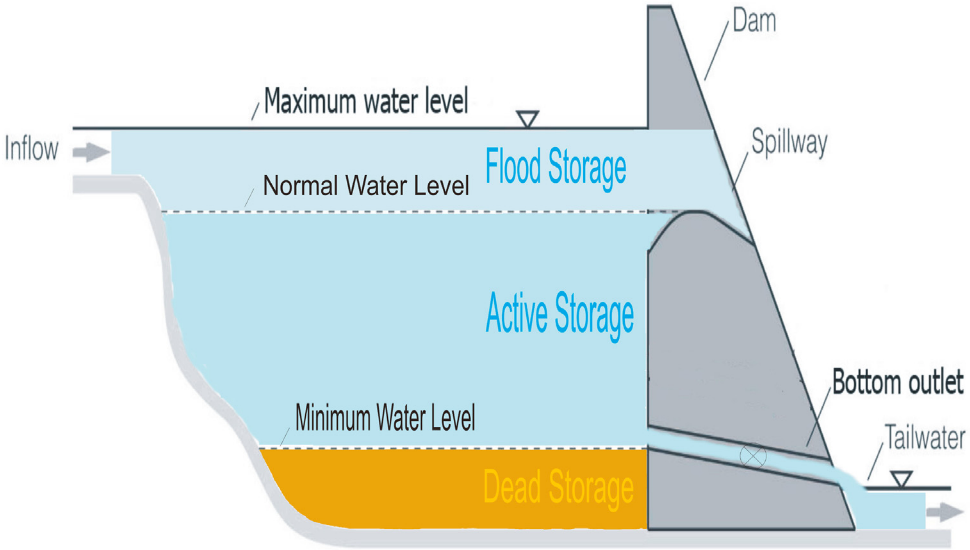

Fig. 9. Schematic representation of reservoir subdivisions and water levels. Reservoir active water level range is between the normal and the minimum of the water level. Adapted from Ref. [54].

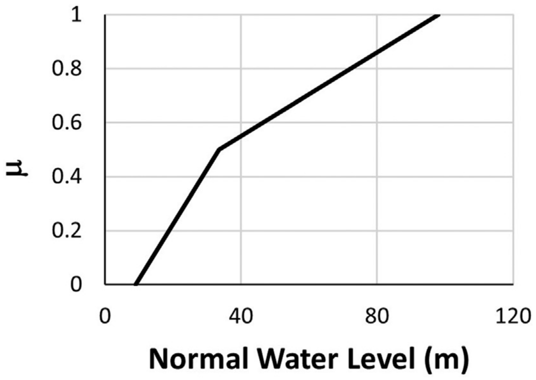

Fig. 10. Suitability function for the criterion of normal water level (maximum head).

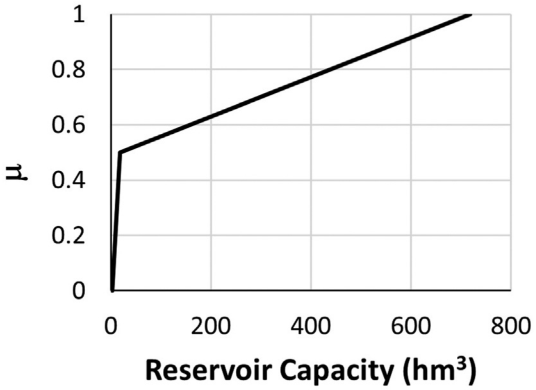

Fig. 11. Suitability function for the criterion of reservoir capacity.

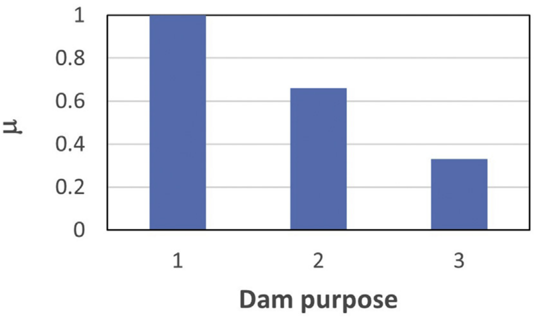

Fig. 12. Suitability function for the criterion of dams purpose.

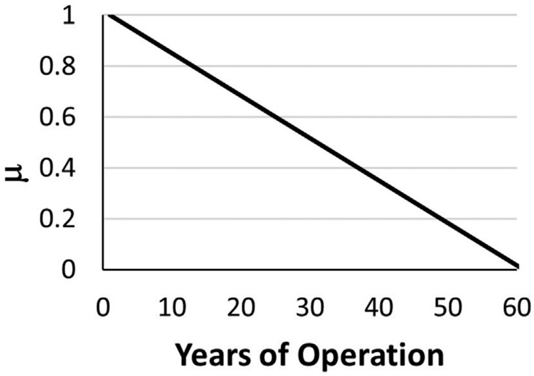

Fig. 13. Suitability function for the criterion of dam years in operation.

Distance to grid connection: Construction of a new transmission line is costly and could be complicate since it involves obtaining appropriate permits and may also require land acquisition and expropriation [43]. Therefore, the closer the dam is located the existing transmission lines, the lower costs of integration to the grid will be. So, the distance to the grid connection should be short, and the score is inversely proportional with the grid connection distance (Fig. 14). Accordingly, the distance to the nearest substation and the suitability degree has an inverse linear relationship. When the distance to the nearest substation decreases, suitability degree increases, due to the decrease in costs and increase in power efficiency. The minimum and maximum distances between the selected irrigation dams and their nearest substations are 0.7 and

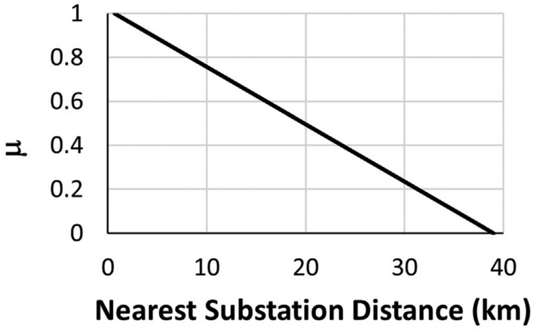

Fig. 14. Suitability function for the criterion of nearest substation distance.

38.2 km, respectively.

For power lines routing, it is possible to find the best grid connection path from any of the most suitable dams to its nearest substation using the multi-criteria GIS spatial analyst, where the following spatial criteria were selected: shortest distance, suitable elevation, least slope, near to the rivers, the existing roads and the power lines considering the land expropriation issues [37]. Certain types of public and private property, natural reserves and large water surfaces, and crossing some types of lands are avoided during the route selection.

Environmental Impact Assessment (EIA) Requirement: According to the EIA regulation in Turkey, which was published in the official gazette on November 25th, 2014, any grid connection distance higher than 15 km is required to have an EIA report. However, if the grid connection is less than 15 km, the project is exempted from the EIA. For Turkey, there will therefore be a threshold distance of 15 km, where any distance less than this will give a suitability degree of one, and a distance equal to or greater than this will have a score of zero (Fig. 15).

4. Application of the proposed methodology to the irrigation dams in Turkey

After the technical and spatial criteria were applied to the irrigation dams in Turkey, 265 irrigation dams were identified that were technically feasible for hydropower development, within the maximum of 40 km distance from the nearest substation for connection to the power grid. Although all of these dams are appropriate for hydropower development, it is important to determine their suitability level. The project developers and investors aim to choose dams that meet the criteria to the fullest extent (i.e. highest energy generation and benefit/cost ratio, and shortest grid connection), especially in view of the variation in the preference of the criteria for the selected dams. For example, the dam with the highest preference for the criterion of distance to the nearest substation, which is 720 m, had low preferences in relation to its other criteria where the reservoir capacity was 3.7 hm^3. Therefore, the selected dams were arranged according to their overall suitability score (Fig. 16). The dams have been classified according to theirs suitability score as follows: (i) 21 dams have a site suitability score of between 75% and 87% and they are classified as high suitability (Table 3), (ii) 149 dams have a site suitability score of between 50% and 74.99% and they are classified as medium suitability; and (iii) 95 dams have a suitability score of between 27% and 49.99% and they are classified as low suitability (Fig. 16).

Fig. 15. Suitability function for the criterion of EIA requirement.

The most suitable dams for hydropower development are those in the high suitability class that they have a reservoir capacities in the range of 10.9–220.5 hm^3. In those dams, normal the water level has a range of 36–98 m, the irrigated area ranged between 1580 and 31918 he and nearest substation distance ranged from 2.1 to 14 km. The dam which has the maximum height from the thalweg is Aktaş with a value of 100 m which is considered to be a high preference for hydropower development. Aktaş dam has also suitable values due to its preferences of the other criteria (Table 2). All the dams in the high suitability class are thought to be economically feasible for hydropower development (Table 4). In Table 4, scores of the each criterion of the most suitable irrigation dams are presented. The scores are assigned objectively considering site reported and measured characteristics by using defined fuzzy logic membership functions (Figs. 10–15). A score of 0 denotes the lowest level of suitability; while a score of 1 denotes the highest. Also, Site Suitability Indexes (SSI) are computed from Equation (6) for different strategies as follows: (i) equal weights of all criteria, (ii) only grid connection characteristics are considered (grid connection priority), and (iii) only dam characteristics are considered (dam characteristics priority). Accordingly, the existing irrigation dams are assessed and potential sites for hydropower development are ranked. For the most suitable dams, the results are given in Tables 3–4

5. Case study: Karadere Dam

The analysis was applied to a real case study of Karadere Dam (Rank 8, Table 3) during two irrigation seasons (2017–2018). It should be noted that case study assessment plays an important role in the framework of the IEA Hidden Hydro initiative [10]. Also, the advantage of case study as a method, in comparison to other numerical methods, is its ability to reveal of causal relationships providing a clear and deeper understanding of a specific concept or phenomenon [55].

For Karadere Dam, technical and spatial criteria are evaluated and the potential energy recovery and economic benefits are estimated. Karadere Dam is situated on the northwest of Turkey in Kastamonu (Fig. 17). The dam has been in operation since 2007 for irrigation and flood control purposes. The height of the dam from the thalweg is 70 m, it has a normal water level of 64 m and it has a reservoir storage capacity of 26.08 hm^3. The dam reservoir has a catchment area of 198.8 km^2 with an annual flow rate of 35.29 hm^3/year. Karadere Dam provides the irrigation water need of the 6449 ha area of the Taşköprü province with a rate of 0.55 L/s/ha. The main crops in the province are: sugar beet (29%), wheat (19%), barley (9%), zucchini (8%). hemp (3%), garlic (3%), beans (3%), clover (3%) potato (2%), and corn (%1). The State Hydraulics Works (DSI) is responsible from the operation of the dam and from the irrigation water supply system. Fig. 17a shows the photo of the Karadere Dam during bottom outlet is in operation. The water intake is placed on the left side of the upstream face of the dam which can be seen from the plan layout of the dam (Fig. 17b). The reservoir operation

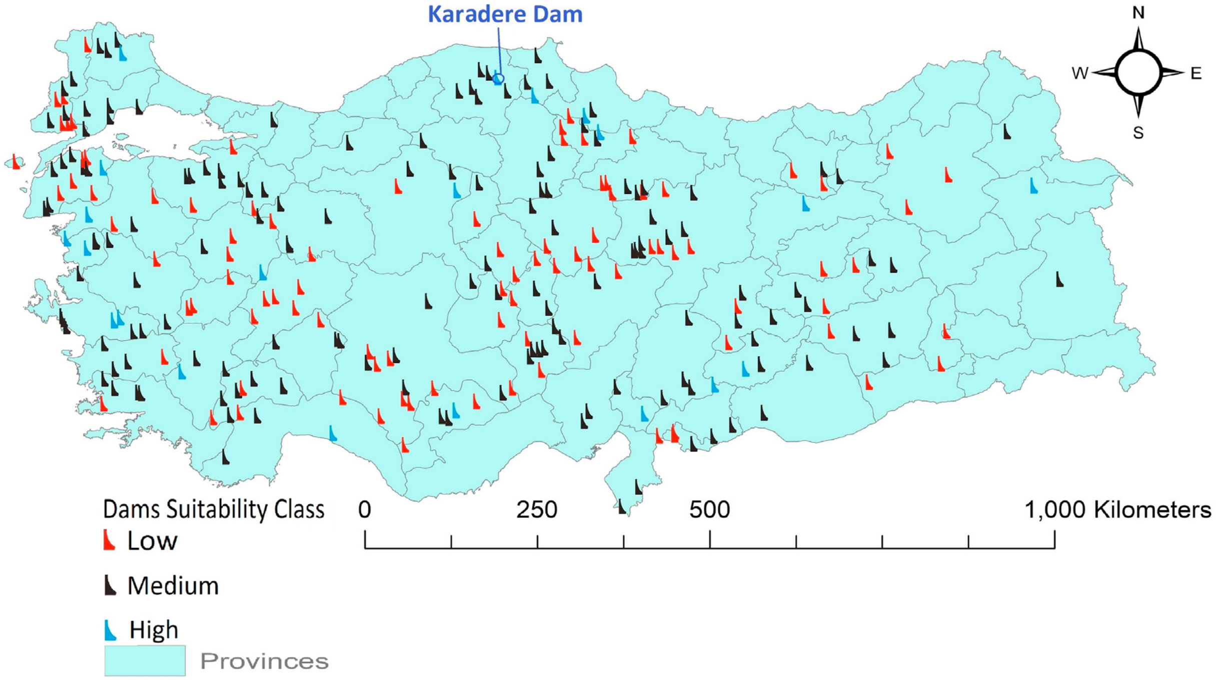

Fig. 16. The distribution of the selected most suitable 265 irrigation dams for hydropower development according to their suitability classes. The location of the Karadere Dam, which is investigated as a case study, is also shown on the map.

Table 3
Characteristics of the irrigation dams in Turkey that have high Site Suitability Index for hydropower development. The reservoir capacity includes active and dead storage capacity.

Rank	Dam Name	Start of Operation	Province	Purpose	Reservoir Capacity (hm^3)	Dam Height (m)	Maximum Head (m)	Irrigated Area (hm^2)	Nearest Substation Distance (km)	Substation Name	Site Suitability Index (SSI)
1	Aktaş	2017	Izmir	I	43.8	100.0	98	1580	9.9	Ödemiş	0.871
2	Burgaz	2013	Izmir	I	33.0	84.5	81.5	3009	11.9	Tire	0.829
3	Çayirdere	2017	Kirklareli	I	28.3	58.5	57.5	2583	10.6	Pinarhisar	0.814
4	Taşoluk	2009	Çanakkale	I	79.4	65.0	63	9606	8.9	Biga	0.813
5	Yenidere	2010	Denizli	I	65.4	43.0	40	3304	5.1	Tavaş	0.801
6	Havran	2010	Balikesir	I	66.5	63.5	60.5	3330	12.8	Edremit	0.794
7	Vezirköprü	2005	Samsun	I	51.5	73.5	67.5	10994	11.4	Vezirköprü	0.794
8	Madra	1998	Balikesir	I	79.4	87.0	84	7872	13.8	Ayvalik	0.789
9	Karadere	2007	Kastamonu	I	26.1	70.0	64	6852	12.1	Tasköprü	0.789
10	Derinöz	2002	Amasya	I	18.9	74.0	70	4990	11.0	Ladik	0.787
11	Beşkariş	2012	Kütahya	I	75.6	52.4	48.35	9093	13.0	Altintaş Tm	0.784
12	Yazici	2008	Ağri	IM	220.6	83.5	78.5	31918	11.4	Ağri Tm	0.780
13	Saraydüzü	2011	Sinop	I	36.3	58.5	50.5	4109	14.3	Boyabat	0.774
14	Kestel	1989	Izmir	I	37.4	58.0	53	4077	2.1	Bergama	0.769
15	Çamgazi	1998	Adiyaman	I	53.1	39.0	36	8000	3.5	Adicim	0.768
16	Kalecik	1985	Osamniye	I	31.3	77.0	75	4395	7.7	Bahce	0.763
17	Kalecik	2016	Ankara	IM	16.3	53.0	50	2455	4.0	Kalecik	0.762
18	Ibrala	2012	Karaman	IM	134.0	49.0	45	8700	6.4	Karaman_Osb	0.758
19	Naras	2016	Antalya	IF	36.2	68.0	56	7142	9.9	Gundogdu	0.757
20	Erzincan	1997	Erzincan	I	11.5	74.5	73.5	5406	8.6	Erzincan_Osb	0.757
21	Ardil	2017	Gaziantep	I	11.0	49.0	44	2126	12.7	Ps5 Tm	0.753

levels varied in the range of 37.60–64.60 m above the thalweg (Fig. 18). The water is carried from the reservoir to the irrigation channel with a 1.2 m diameter steel pipe. The possible location of the hydropower plant is at the outlet of the pipeline before the inlet of the irrigation channel. During the irrigation season, from April to September, the water demand was very high, increasing from May until August and then decreasing subsequently until September (Fig. 19). In the irrigation channel inlet, the head and discharge are highly variable during the irrigation season (Fig. 19). The head is calculated from the difference between the reservoir water level and enegy dissipator bottom level.

The daily measured discharge data make it possible to analyse the probability of exceedance of a certain flow. This information is critical for the design of the turbine, and it is shown in the flow duration curves. Flow duration curve is a conceptually simple but highly informative way to summarize the temporal variability of streamflow at given location. The average head loss was estimated as 1 m. The average flow during the irrigation season was 1.40 m^3/s, with maximum value of 2.05 m^3/s in August, and minimum value of 0.65 m^3/s in June. For the estimation of the annual electrical energy generation during the irrigation season time-averaged discharge (Q_{avr} = 1.40 m^3/s) and time-averaged net head (H_{avr} = 22.65 m)

Table 4
Assessment of the most suitable irrigation dam for hydropower development by assigning scores.

Dam name	Maximum head	Reservoir capacity	Grid connection	Dam purpose	EIA requirement	Start of operation	SSI Equal Weight	SSI Grid Connection Priority	SSI Dam Characteristics Priority
Aktaş	1.00	0.52	0.75	1.00	1.00	0.98	0.87	0.87	0.88
Burgaz zeytinova	0.87	0.51	0.69	1.00	1.00	0.92	0.83	0.85	0.83
Çayirdere	0.69	0.51	0.73	1.00	1.00	0.98	0.81	0.86	0.79
Taşoluk	0.73	0.54	0.77	1.00	1.00	0.85	0.81	0.89	0.78
Yenidere	0.55	0.53	0.87	1.00	1.00	0.87	0.80	0.93	0.74
Havran	0.71	0.53	0.67	1.00	1.00	0.87	0.79	0.84	0.78
Vezirköprü	0.76	0.52	0.71	1.00	1.00	0.79	0.79	0.85	0.77
Madra	0.89	0.54	0.65	1.00	1.00	0.67	0.79	0.82	0.78
Karadere	0.74	0.51	0.69	1.00	1.00	0.82	0.79	0.85	0.77
Derinöz	0.78	0.50	0.72	1.00	1.00	0.74	0.79	0.86	0.76
Beşkariş	0.62	0.54	0.67	1.00	1.00	0.90	0.78	0.83	0.76
Yazici	0.85	0.64	0.71	0.66	1.00	0.84	0.78	0.85	0.75
Saraydüzü	0.63	0.51	0.63	1.00	1.00	0.89	0.77	0.82	0.76
Kestel	0.65	0.51	0.95	1.00	1.00	0.52	0.77	0.97	0.67
Çamgazi	0.52	0.52	0.91	1.00	1.00	0.67	0.77	0.96	0.68
Kalecik	0.82	0.51	0.80	1.00	1.00	0.46	0.76	0.90	0.70
Kalecik	0.63	0.44	0.90	0.66	1.00	0.97	0.76	0.95	0.67
Ibrala	0.59	0.58	0.84	0.66	1.00	0.90	0.76	0.92	0.68
Naras	0.67	0.51	0.75	0.66	1.00	0.97	0.76	0.87	0.70
Erzincan	0.81	0.31	0.78	1.00	1.00	0.66	0.76	0.89	0.69
Ardil	0.58	0.30	0.67	1.00	1.00	0.98	0.75	0.84	0.72

values are used. Those values are shown in the duration curves of flow and head (Fig. 20). Considering the operation conditions of the Karadere Dam, the design discharge and design head were selected as 2.35 m^3/s and 29 m, respectively for the unit power output (Table 5). Thus, the conventional medium-head hydro turbine that best matched the flow and available head at this particular location is a Francis turbine. However, for the given flow situation, there is usually a high discharge fluctuation from 0% up to 100% and high head fluctuation from 20% up to 100%. Francis turbine has inadequate operational flexibility and it will not operate over the full range of available flows [24]. Also, Francis turbine will see a high risk of cavitation at this wide head variation. Therefore, a double regulated half-axial turbine (DIVE-HAX-Turbine) [56] better matches the operating requirement and this turbine is selected for the economics analysis. It can be operated with high efficiencies at different operating points related to its double regulation (Table 5). As a consequence, from this operation flexibility and high efficiencies, the average annual production of a DIVE-HAX-Turbine is expected to be higher than a one-turbine-solution with a classical Francis turbine [56].

Moreover, due to the cavitation free design of the DIVE-HAX-Turbine, basically a bigger and slower turbine, the turbine can be installed above the tail water level. Therefore, only a minimal excavation is necessary for the tail water canal. Also, it is not necessary to have fast closing emergency valve, the guide vanes will be closed slowly and it is guaranteed that no pressure surge/water hammer on the old equipment occurs. It is not necessary to have a complex pressure release by-pass plus and emergency closing gate. Therefore, it is not necessary to build any complex powerhouse around the turbine-generator-unit, only the draft tube foundation is necessary [56]. As a consequence, the investments costs for civil works and piping are expected to be minimal [57]. Furthermore, dam bottom outlet flows have high suspended sediment concentrations. The geometry, fluid mechanics and the materials of the DIVE-HAX turbine have a significantly higher resistance against abrasion due to sediments. Therefore the DIVE-HAX-Turbine can handle bigger particles compared to a Francis-Turbine and the turbine abrasion risks are less critical [56]. The efficiencies of the proposed turbine for different operational conditions are presented in Table 5. The hydropower plant installed capacity was calculated as 549 kW and the system is expected to generate 816 MWh/year electricity. The primary purpose of the power generated is for pumping use by the operator. This provides strong economic benefits and avoids the purchase of the retail electricity. Only excess power can be sold on the grid. The proposed hydropower plant will cover the electric consumption of the irrigation pumps ($P = 540$ kW) which has a payback period of 10.2 year (Table 6).

By applying the methodology for finding the optimal path for grid connection to nearest substation, the grid connection distance was calculated as 12.8 km for the Karadere Dam. In Fig. 21, the electric transmission line route was identified taking into account the site land use characteristics. The grid connection route passed close to the rivers, the existing roads and the power lines (Fig. 21), which are thought to be ideal locations for energy corridors. Also, special attention was given for avoiding power line passing through private properties (agricultural or residential land) and environmental protection areas to minimize land acquisition and expropriation administrative procedures and risks.

6. Discussion

Multi-criteria decision making is important in hydropower investments as it provides an added element of insight into the project being evaluated. In the present study, irrigation dams in Turkey were assessed and ranked for hydropower development by coupling GIS with fuzzy multi-criteria scoring technique. The model incorporates project stakeholder expertise to analyse technical, economic, and environmental performance of irrigation dams. This approach fosters the best possible opportunity of success for the developer. The proposed tool quantifies each criterion separately and then aggregates them by calculating the Site Suitability Index. In the literature there have been many studies that were conducted in Europe [38], Germany [58], and Switzerland [59] that have successfully identified several potential sites for hydropower development by using GIS tools based on different criteria. Besides, there are some studies that have successfully evaluated the criteria for power lines routing for grid connection in Turkey [60] and in Spain [61]. Unlike those studies, in the present study modern GIS tools and fuzzy logic approach are used together to achieve the objectives by combining grid connection and dam criteria. A second

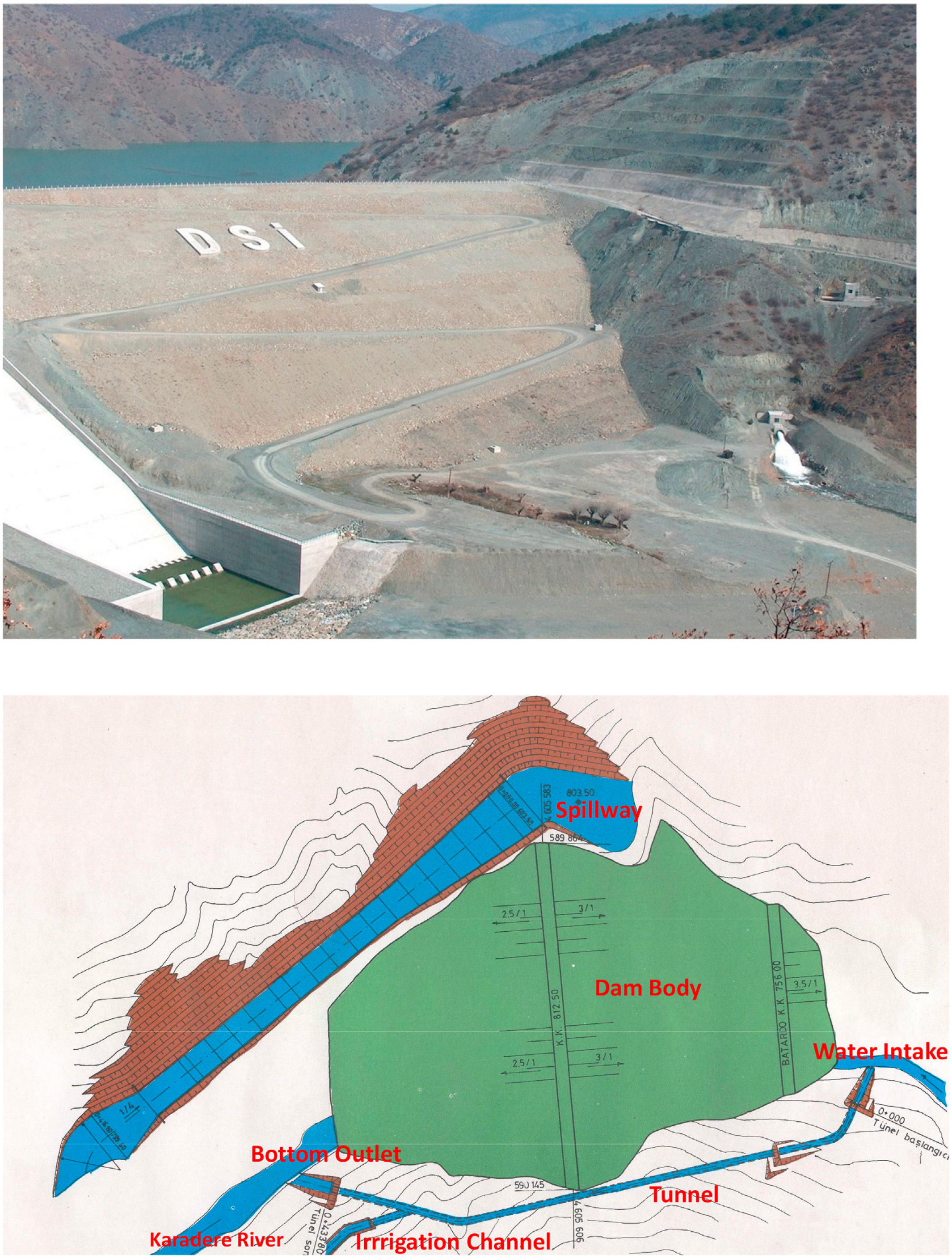

Fig. 17. (a) Karadere Dam during bottom outlet is in operation; (b) Layout sketch of the Karadere Dam.

step of spatial analysis is about electric route line optimization between the dam and the substation to avoid unbalanced results as in some energy projects where the cost of grid connection exceeded the benefits of generated power [62].

In the literature existing studies on hydropower development at irrigation dams in operation [15–18,33,35] ignored the grid connection spatial characteristics and ageing of the dams which were crucial factors for the success of those projects. Also, some of those studies used simulated time-averaged flows and did not consider the variability of the head for the economic feasibility analysis. Furthermore, continuous measured flow data and evaluation criteria to determine all cost drivers are not part of the existing studies in the literature. On the other hand, in this work continuous daily monitoring data of the discharge and reservoir levels were used and variability was considered. The annual energy generation and economic benefits are estimated with the implementation of an innovative medium-head hydro turbine and levelized cost of electricity is calculated (Table 6). However, existing studies [15–18,33,35] evaluated the conventional hydro turbines performance and did not explain how they dealt with the uncertainties during the evaluation of existing irrigation dams for hydropower development. In the present study the uncertainty of

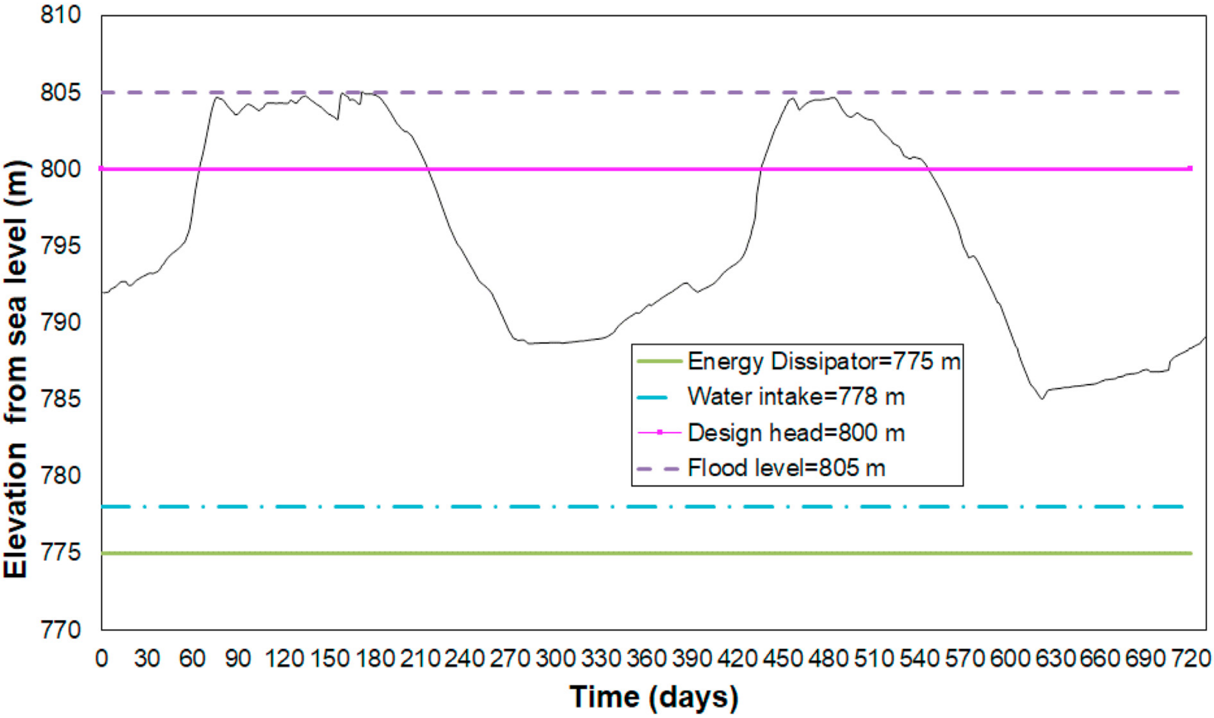

Fig. 18. The water level variations in Karadere Dam reservoir during 2017 and 2018. The Time-averaged water level in the reservoir during the irrigation season is 798 m.

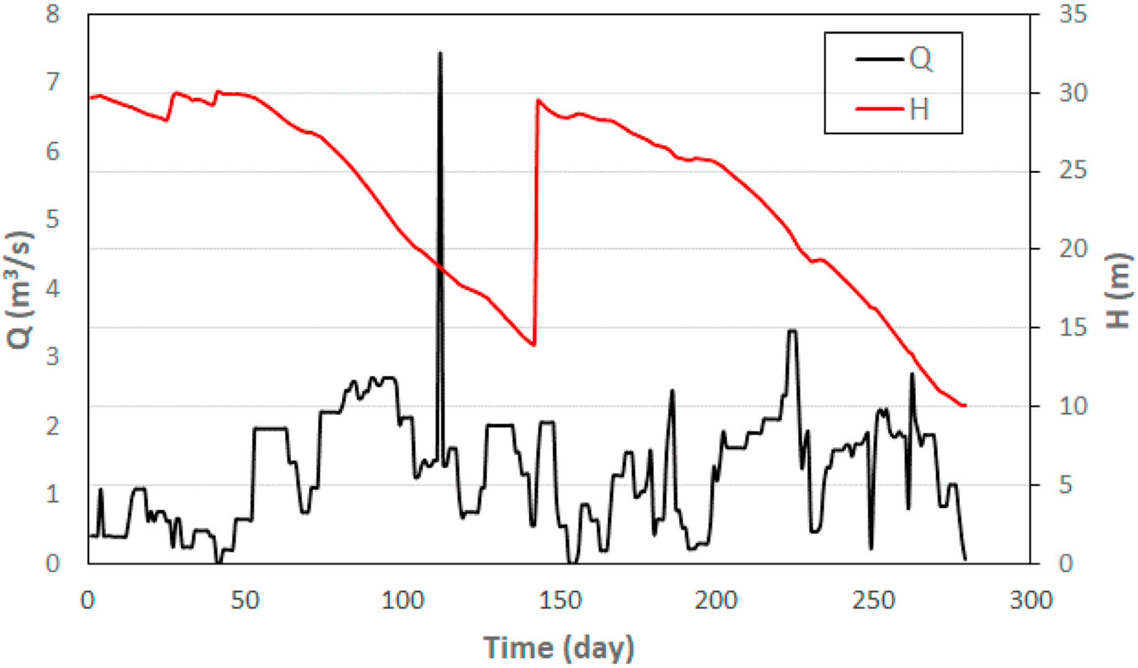

Fig. 19. Variation of irrigation discharge and head at the outlet of the Karadere dam during the irrigation season (May–September) between 2017 and 2018. Head is calculated from the difference between the reservoir water level and enegy dissipator bottom level which is 775 m.

the site suitability assessment is aimed to be minimized by: (i) analyzing the monitoring data, maps, and technical drawings of irrigations dams (ii) conducting technical visits to the irrigation dams, (iii) making discussions with the operational staff, and (iv) using fuzzy sets for attaining score for each criterion. For instance, Mermet and Gehant [63] stated that the statistical treatment of data cannot replace the expert judgments in the operational risk management process of hydropower plants.

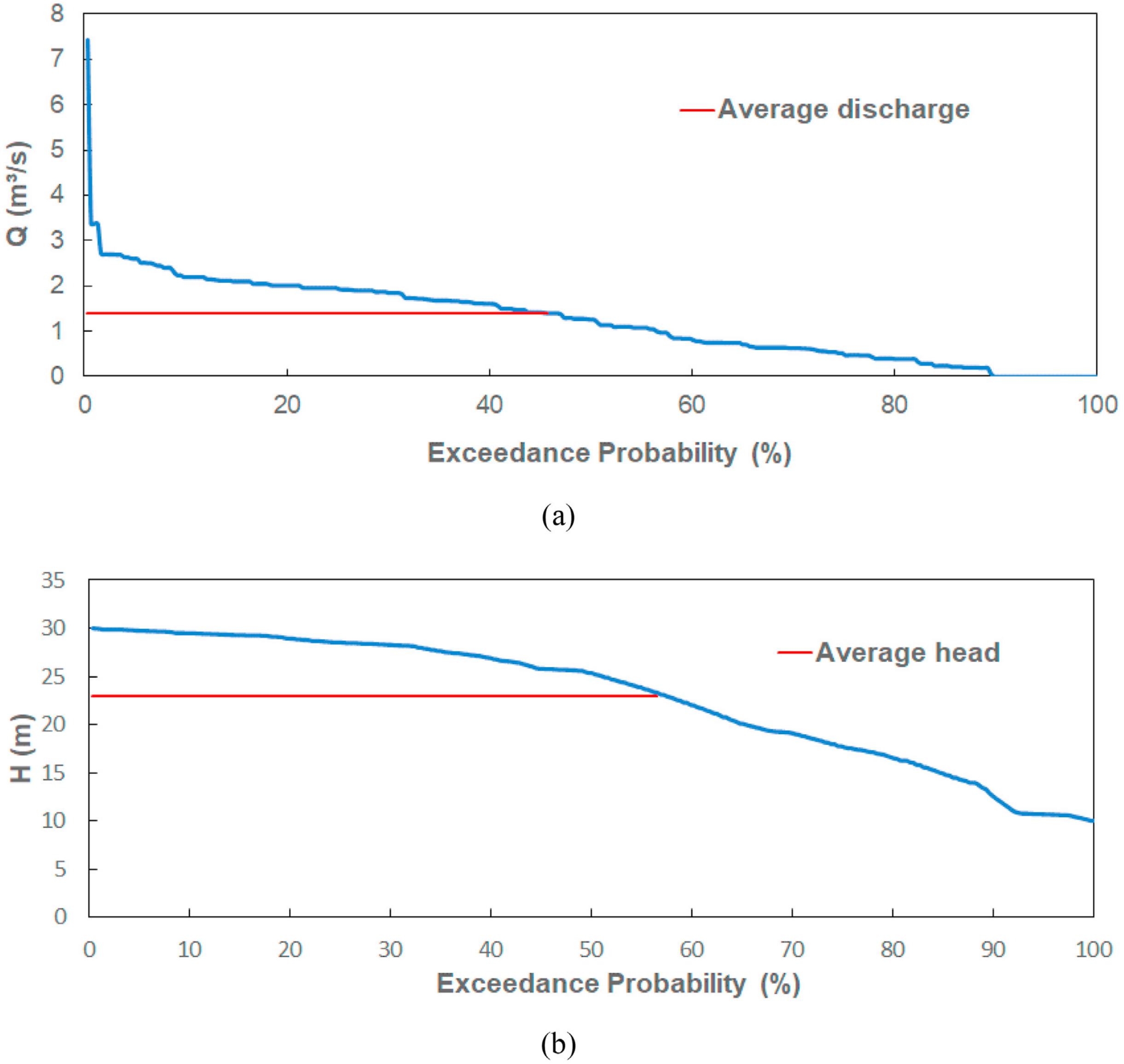

Fig. 20. (a) Flow and (b) head duration curves of Karadere Dam irrigation outlet. The discharge and head data are based on the measurements covering the period of 2017–2018 in the irrigation season.

Table 5
Performance of the DIVE-HAX turbine for different operational conditions at the Karadere Dam outlet.

Operation	Q	Q Runner	Net Head	Efficiency Turbine	Mechanical power Turbine	Overall efficiency[a]	Overall Power[a]	Estimated Annual Produciton
Point	(m^3/s)	(%)	(m)	(%)	(kW)	(%)	(kW)	(MWh/a)
1	0.24	10%	29.99	22.6%	16	20.2%	14	
2	0.47	20%	29.96	57.9%	80	52.1%	72	
3	0.71	30%	29.91	75.6%	156	69.3%	143	
4	0.94	40%	29.84	83.1%	229	76.4%	210	
5	1.18	50%	29.75	86.4%	296	80.0%	274	
6	1.41	60%	29.64	88.9%	365	82.6%	339	
7	1.65	70%	29.51	91.6%	436	85.3%	406	
8	1.88	80%	29.36	93.0%	504	86.8%	470	
9	2.12	90%	29.19	91.6%	555	85.8%	519	
10_P_{max}	2.35	100%	29.00	88.3%	590	82.2%	549	
11_H_{min}&Q_{max}	2.35	100%	20.00	85.2%	393	79.3%	366	
12_Average Value	1.40	60%	22.65	86.1%	268	79.8%	248	816

[a] The overall efficiency of the DIVE-Turbine is equivalent to the net efficiency of the Turbine-Generator-Unit including all losses from Turbine, Generator and Inverter. The efficiencies and performance data shall be in accordance with the IEC-standard Publ. 60041.

Table 6
Economic analysis of the Hydropower development at the Karadere Irrigation Dam.

Design discharge (m^3/s)	2.35
Gross Head (m)	30.0
Net Head (m)	29
Turbine efficiency	0.883
Generator efficiency	0.975
Transformer efficiency	0.955
Overall efficiency	0.822
Installed Capacity (kW)	549
The hours in operation (h)	4037
Annual Energy (kWh/year)	816,000
Cost of the plant (EUR)	1,000,050
Levelized Cost of Electricity (EUR/MWh)	20
Unit Energy Price (EUR/MWh)	140
Annual Benefit (EUR)	269,517
Payback period (year)	10.2

In Turkey, for medium-head (20–120 m) applications in irrigation dams, we found the most appropriate hydro turbine as double regulated half-axial turbine (DIVE-HAX-Turbine); whereas, for low-head (2–19 m) applications we recommended DIVE-Turbine. The reason of this turbine selection can be explained as follows: (i) DIVE-HAX-Turbine is a compact, mature, and cost-efficient technology, (ii) higher energy generation performance due to its operation range from 5% to 100% of its nominal discharge at a wide range of head variations, (iii) benefit gained in relation to cost drivers like powerhouse civil works (50–80% lower as necessary for a classical Francis turbine) and shorter construction duration, (iv) cavitation free design and absence of water hammer risk, and (v) higher resistance against abrasion due to sediments considering high suspended sediment concentrations in bottom outlet flows. The recommended small hydro turbine meets the several desired design features [64] and economic requirements [8].

7. Conclusions

Recently many regions in the world are challenging the climate changes especially in terms of floods and droughts. In the coming decades, due to climate change, the heavy rain events causing floods periods getting even more extreme. As a consequence, dams getting more and more important to manage the extreme flows of the rivers. Globally there are already thousands of existing dams, build for irrigation and flood management purpose. The outlet of those dams is ideal locations for efficient and reliable hydro energy generation with minimal civil works and operation costs. In this context, the existing irrigation dams in Turkey are assessed in order to develop small hydropower by applying a GIS-multi-criteria scoring technique in an integrated approach. The candidate irrigation are classified low suitable, medium suitable, and high (most) suitable based on their Site Suitability Index (SSI) values. The results reveal that Turkey has suitable irrigation dams and reservoirs for developing small hydropower. The most favorable irrigation reservoirs have high heads and storage capacities and they are close to the substations. Currently the country has legal and market framework for the development of small hydropower at existing irrigation dams. The development of this hidden hydropower potential thought to be beneficial for water-energy-food nexus.

By applying the proposed Site Suitability Index and least cost grid connection path approach, the responsible government agencies and project developers can assign priority ranks on the candidate sites and they can make a comparison between the alternatives. Additionally, project developers and investors can gain competitive advantage in the field of small hydropower deployment at irrigation dams and they can develop a strategy in project planning stage to cope with the unforeseen project risks and complex permitting procedure. For now, the investigated sites cover Turkish irrigation dams. However, the developed tool can be applied to other irrigation dams worldwide by adjusting the relevant parameters. The main advantages of the proposed methodology are replicability, modeling flexibility, and potential for the integration with other techniques.

The case study demonstrated that project makes use of an existing dam, impounding a lake that stores water for an irrigation channel. The flow into this channel can now be used to create additional electricity. Within the regulated half-axial turbine concept, it is possible construct the hydropower plant without influencing the operation of the existing system. Although, it mainly be suited to medium head sites, where Francis turbine is alternative, as demonstrated by the case study. Implementing the concepts described here, it is possible to generate hydroelectricity from many irrigation dams that may otherwise have been deemed unfeasible for development.

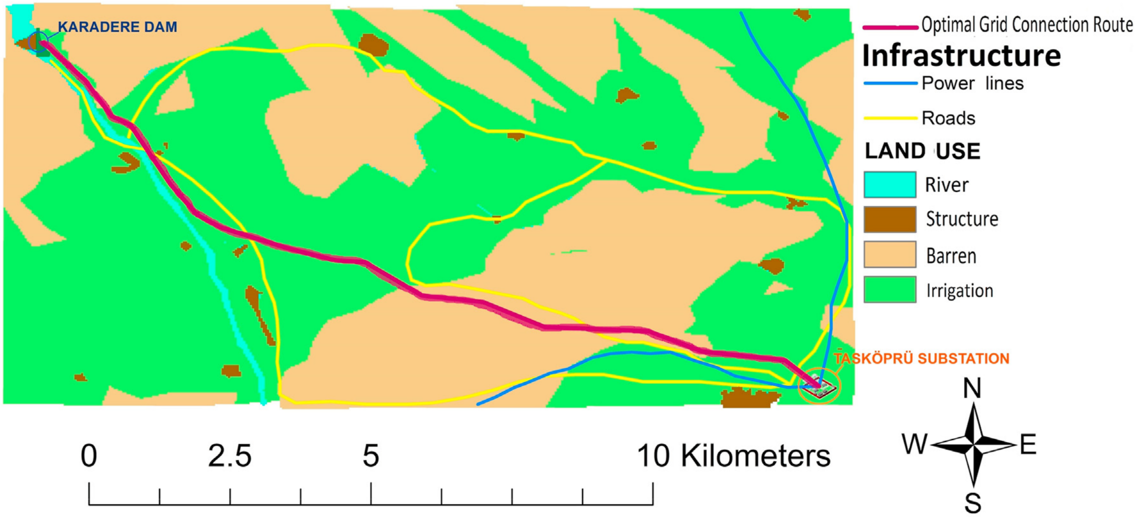

Fig. 21. Optimal grid connection path between Karadere Dam and Taşköprü Substation. Gird connection distance = 12.8 km.

CRediT authorship contribution statement

Serhat Kucukali: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Omar Al Bayatı:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **H. Hakan Maraş:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft.

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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