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Algorithm for calculation and selection of micro hydropower plant taking into account hydrological parameters of small watercourses mountain rivers of Central Asia☆

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ABSTRACT

Tajikistan and Kyrgyzstan are the two countries in Central Asia that have a huge reserve of hydro resources of the region. It is important to recognize the significance of the part played by the micro-hydropower plants (HPP) in the electric power generation in Tajikistan and Kyrgyzstan from the point of view of sustainable economic development. After all, the construction of micro-HPPs in mountainous areas will reliably ensure the development of small and medium-sized enterprises in the field of agriculture and livestock, industry, tourism, improve the social conditions of the population, as well as ensure the production of "green" hydrogen, which will contribute to the development of an environmentally friendly transport system in the regions. Micro HPPs gained recognition as a good alternative to traditional power generation for many developing countries around the world.

This study presents a structural model and methodology of choice of a feasible type of micro HPP using the developed algorithm for calculation of hydro turbines' characteristics based on the hydrological characteristics of small and shallow watercourses located in Central Asian countries, such as Kyrgyzstan and Tajikistan. Based on this model, the software "Calculation and choosing the type of hydro turbines for micro HPPs" has been developed. Depending on the load, a consumer can choose one of the suggested types of micro-hydroelectric power plants to meet his requirements. When choosing the type of micro-hydroelectric power station, a consumer should also take into account the factor of the seasonality of the water level, the constancy and speed of the water, and the volume of river water, since in some places the water freezes in winter.

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List of symbols	
HPP	hydropower plant
CM	computational module
CE	computational element
ADHEC	autonomous distributed hybrid energy complexes
CAD	computer-aided design
Nomenclature	
N	potential capacity, kW
Q	water flow, m^3/s
H	drop of the level (head), m
i	longitudinal slope of the watercourse
L	length, km
s	slope of the watercourse, %
W	energy, kWh/km
S	mapping
A	set
K	set
R	set
I	set of natural numbers
x, y	position of point
C	set of color numbers in the palette
$c_{x,y}$	is the color number of the (x, y) point of the screen
n	finite number of a series of natural numbers (power of a set)
m	finite number of a series of natural numbers (power of a set)
b	gauging station width, m
h	water depth, m
v	water flow rate, m/s
d	half the width of the tract, m
U	voltage, V
ω	angular frequency, radian/s
f	frequency, Hz
z	cost, y.e.
r	relative price per kWh
F	functional mapping
Superscripts and subscripts	
riv	river
tr	tract
hyd	hydro
HPP	hydroelectric power plant
tur	turbine
sect	section
b	beginning
e	end
i	ordinal number
j	ordinal number
x, y	position of point
k	finite number of a series of natural numbers
n	finite number of a series of natural numbers
η	efficiency,%
T	turbine
Mathematical operators	
Σ	amount
{...}	many
|...|	cardinality of a set
∈	element belonging to the set
⊂	strict inclusion symbol
×	cartesian product of sets
∪	union of sets
∀	community quotient

Introduction

Hydroelectricity production has several advantages over fossil fuels or nuclear power, the biggest of which is that it does not pollute the environment. In mountainous areas, small and micro-hydropower plants that can be installed on small rivers or streams with minimal or negligible impact on the environment are widely used [1–4].

It is known that the Kyrgyz Republic and the Republic of Tajikistan have a huge hydropower potential, with hundreds of small and shallow watercourses on their territory. The energy potential of small hydropower energetics in these countries exceeds the potential of all other renewable energy sources combined [5–13]. As a result of the analysis, it was found that given the hydro resources available in these regions, micro-hydropower plants are an optimal choice as compared to other autonomous sources.

In Kyrgyzstan, rivers have high concentrated potential reserves of hydropower resources: Naryn, Sary-Jaz, Kekemeren, Chatkal, Tar, Chu, Kara Daryya, and Chon-Naryn, with an average specific capacity of 2227 to 5322 kW/km. About 90% of the potential energy of small watercourses is concentrated in the upper and middle riverbed areas, where many dispersed energy consumers are located [7–9].

In Tajikistan, the potential of small hydropower energetics is more than 18 billion kWh per year. In the Kalai-Khumbsky, Vanch, and Rushan districts (Western Pamir), it is possible to build more than 20 small hydropower plants. In Central Tajikistan, there are good conditions for the development of small hydropower energetics, it is possible to build more than 100 micro and mini-hydropower plants. Technical and economic calculations for 14 promising small hydroelectric power plants show that their average annual electricity generation can reach 348 million kWh. The use of the energy of small rivers can cover 50–70% and more of the energy demand of remote regions [10–13].

Thus, the construction of micro-HPPs in mountainous areas will reliably ensure the development of small and medium-sized enterprises in the field of agriculture and animal husbandry, industry, tourism, improve the social and domestic conditions of the population, organize seasonal processing of agricultural raw materials, production of building materials, as well as production of green hydrogen, which will contribute to the development of an environmentally friendly transport system in the regions, since green hydrogen can be used as fuel for cars, buses, trucks, forklifts and more. It can also be used in various industries where hydrogen is required for fossil energy sources or other purposes. Finally, excess electricity from renewable energy sources can be stored as hydrogen and then burned to generate electricity when needed.

To make a rational choice of the type of micro-hydroelectric power station with the required consumer capacity, it is necessary to study and define the specifics of changes in the hydrological parameters of shallow mountain streams, depending on the slope, water content, the nature of the waterbed, etc. [14–21]. The knowledge of these values allows us to develop a scientifically grounded method for calculating the power of micro-hydroelectric power plants.

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For the general averaged assessment of the watercourse capacity, the linear calculation method, which includes the potential energy and the flow capacity, is of the greatest practical interest [22].

To calculate hydropower resources for this category, the method of continuous channel water flow counting, or the so-called linear counting method, can be applied [22].

According to this approach, the potential capacity of the watercourse section can be calculated as follows:

$$N_{sect} = 9,81\frac{Q_b + Q_e}{2}H; \tag{1}$$

where Q_b is water flow at the beginning of the section, m^3/s; Q_e - water flow at the end of the section, m^3/s; H -drop of the level, m.

Then, the potential capacity of the entire watercourse can be defined as the sum of the capacities of its sections:

$$N = 9,81\sum_{i=1}^{n}\frac{Q_{bi} + Q_{ei}}{2}H_i. \tag{2}$$

The resulting formula shows that to determine the average annual capacity of a watercourse, it is necessary, first of all, to know its water content. Therefore, the characteristics of the average flow-off are the most important when calculating hydropower resources.

In most cases, small and shallow watercourses are short in length, and, as a rule, only the capacity of the section of the watercourse at the location of an autonomous economic facility is of a certain interest. As shown by the studies, the length of such sections is just a few hundred meters. In such cases, it can be assumed that there will be practically no difference between the water flow rates Q at the beginning and end of the section, and therefore any given value of Q can be applied in the obtained formulas. When determining the water pressure in the selected section, it should be remembered that due to the small length of the section, no more than two portable micro-hydroelectric power plants can be installed on it, and therefore, the value of H should be taken as the average drop (elevation difference) of a section with a length of 100 m.

To compare and analyze the hydropower value of individual streams and their sections, let us compare the absolute values of energy resources using specific indicators representing the average capacity of a stream for a given section per 1 km of section length [23]:

$$\Delta N = \frac{N_{sect}}{L_{sect}}, \quad \text{kW/km}. \tag{3}$$

Similarly, the value of kilometric energy can be calculated as:

$$\Delta W = \frac{W_{sect}}{L_{sect}}, \quad \text{kWh/km}, \tag{4}$$

where N_{sect}, W_{sect} - the power and energy of the entire section of the watercourse, respectively; L_{sect} - total length of the watercourse section, km.

Using these indicators, it is possible to study the degree of concentration of hydropower in individual sections of the watercourse and identify the most valuable of them.

If we input the values of N_{sect} from (1) into (3), we get:

$$\Delta N = \frac{9,81 \cdot Q_{sect} \cdot H_{sect}}{L_{sect}}. \tag{5}$$

This indicator can be expressed through the value of the longitudinal slope of the watercourse $s = \frac{H_{sect}}{L_{sect}}$, then:

$$\Delta N = 9,81 \cdot Q_{sect} \cdot s, \quad \text{kW/km}. \tag{6}$$

Hence, it follows that a very important qualitative linear indicator of the hydropower resources of small watercourses is the longitudinal slope of the watercourse or its sections - s. The value of the longitudinal slope, firstly, plays a significant role in preliminary calculations when classifying a watercourse into energy levels and when choosing the most economically justified type of hydroelectric power station. Secondly, the value of the longitudinal slope can serve as an indirect technical and economic indicator when comparing the energy value of watercourse sections with slopes greater than 0.01, i.e. the ones that are the most promising from the point of view of the installation of micro-hydroelectric power plants.

In this paper, we address the task of calculating the potential capacity of watercourses in river sections and substantiate the choice of various types of hydro turbines for micro-HPPs.

To solve this task, the following data is used:

- geometric parameters of gauging stations of the river sections;
- hydrological characteristics of the river sections at gauging stations;
- types of hydraulic turbines in use, and their technical characteristics;
- types of micro-HPPs known in practice.

Below we describe a structural model of the task solution algorithm that served as a basis for the development of the "Calculation and selection of the type of hydraulic turbines for micro-HPPs" software and provide some examples for demonstration.

Structural model of the algorithm for solving the task of calculating

Structural model of the algorithm for solving the task of calculating the potential capacity of watercourses of river sections and justification of the choice of various types of hydro turbines for micro-HPPs, which includes the following interrelated functional modules:

- module for forming a database on rivers;
- a module for the formation of a database on the hydrological characteristics of river sections in the corresponding natural boundaries;
- module for creating a database on existing types of micro-hydroelectric power plants;
- a module for calculating the potential capacities of some selected rivers of Kyrgyzstan in the corresponding sections of the rivers for different types of hydraulic turbines;

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- module for choosing the best types from a variety of micro-hydroelectric power plants.

1) Structural model of the computational module (CM_1) for forming a database on rivers (see Fig. 1).

This module provides for forming a database on the rivers of Kyrgyzstan in the form of geographical maps, the model of which is described by the following (Fig. 1):

a) mapping S^{riv}, which associates each river with a specific map:

$$S^{riv} : A^{riv} \to K^{riv}, \tag{7}$$

$$A^{riv} = \left\{A_i^{riv} | i \in I_{riv}\right\}, I_{riv} = \{1, 2, \ldots, n_{riv}\},$$

$$K^{riv} = \left\{K_i^{riv} | i \in I_{riv}\right\},$$

$$S^{riv} = \left\{\left(A_i^{riv},\ K_i^{riv}\right) | i \in I_{riv}\right\} \subset A^{riv} \times K^{riv},$$

$$|A^{riv}| = |K^{riv}| = \left|S^{riv}\right| = n_{riv};$$

where A^{riv} is a set of rivers; K^{riv} - a set of geographical maps of rivers; S^{riv} - unambiguous mapping (7) that constitutes a set of pairs $(A_i^{riv},\ K_i^{riv})$, $\forall i \in I_{riv}$; A_i^{riv} - the name of the i-th river; K_i^{riv} - map of the i-th river.

b) display K_i^{riv}, which assigns some specific color to each point of the screen:

$$K_i^{riv} : X \times Y \to C,\ \forall i \in I_{riv}, \tag{8}$$

$$X = \{n'_x, n'_x + 1, \ldots, n''_x\}, |X| = n_x,$$

$$Y = \left\{n'_y, n'_y + 1, \ldots, n''_y\right\}, |Y| = n_y,$$

$$C = \{c_1,\ c_2,\ \ldots,\ c_m\}\ , |C| = m,$$

$$K_i^{riv} = \{((x,\ y), c_{x,y}) | x \in X, y \in Y\},$$

$$c_{x,y} \in C, |K_i^{riv}| = n_x \cdot n_y,$$

where K_i^{riv} is, in turn, an unambiguous mapping (8) that constitutes a set of triads $((x,\ y),\ c_{x,y})$, $\forall x \in X$, $\forall y \in Y$, $c_{x,y} \in C$; X - set of coordinates along the x-axis of the screen; Y - set of coordinates along the y-axis of the screen; C - set of color numbers in the palette; (x, y) is the coordinate of the point of the screen, and $c_{x,y}$ is the color number of the (x, y) point of the screen.

2) Structural model of the computational module (CM_2) for the formation of a database on the hydrological characteristics of river sections at the corresponding tracts (Figs. 1 and 2) with an indication of their coordinates (x, y) on the map of the rivers under consideration.

a) mapping K^{tr}, which assigns to each i-th tract A_i^{tr} from the set A^{tr} a specific point $(x_i, y_i) \in X \times Y$ of the river map on the screen (see the table in Fig. 2):

$$K^{tr} : A^{tr} \to X \times Y, \tag{9}$$

$$A^{tr} = \{A_i^{tr} | i \in I_{tr}\}, I_{tr} = \{1,\ 2,\ \ldots,\ n_{tr}\},$$

$$K^{tr} = \{K_i^{tr} = (A_i^{tr},\ (x_i, y_i)) | i \in I_{tr}\} \subset (A^{tr} \times X \times Y),$$

$$K^{tr}(A_i^{tr}) = \{(x_i,\ y_i) | i \in I_{tr}\},$$

$$K^{tr}(A_i^{tr}) = (x_i,\ y_i),$$

$$A_i^{tr} \in A_{tr}, x_i \in X, y_i \in Y, (x_i, y_i) \in X \times Y,$$

$$|A^{tr}| = |K^{tr}| = n\_tr;$$

b) mapping S^{tr}, which assigns to each tract $A_i^{tr} \in A^{tr}$, $\forall i \in I_{tr}$ with given coordinates $(x_i, y_i) \in X \times Y$ on the map, some specific data $(b_i,\ h_i,\ v_i,\ H_i)$ on the hydrological characteristics of river sections at the corresponding natural boundaries (see table in Fig. 2):

$$S^{tr} : K^{tr} \to R_b \times R_h \times R_v \times R_H, \tag{10}$$

$$S^{tr} = \{S_i^{tr} = ((A_i^{tr}, (x_i, y_i)), (b_i, h_i, v_i, H_i)) | i \in I_{tr}\} \subset$$

$$\subset (K^{tr} \times (R_b \times R_h \times R_v \times R_H)),$$

$$S^{tr}(K^{tr}) = \{(b_i, h_i, v_i, H_i) | i \in I_{tr}\},$$

$$S^{tr}(K_i^{tr}) = (b_i, h_i, v_i, H_i),$$

$$(A_i^{tr}, (x_i, y_i)) \in K^{tr}, b_i \in R_b, h_i \in R_h, v_i \in R_v, H_i \in R_H$$

$$(b_i, h_i, v_i, H_i) \in R_b \times R_h \times R_v \times R_H;$$

where b_i - gauging station width; h_i - water depth; v_i - water flow rate; H_i - pressure.

c) the computational element CE_2 (Fig. 2) tracks the coordinates (x_k, y_k) of the mouse cursor, corresponding to the newly introduced tract A_k^{tr}; adds a new k-th record S_k^{tr} to the end of the database S^{tr}, i.e. $S^{tr} \cup \{S_k^{tr}\}$, and records the coordinates (x_k, y_k);

d) the computational element CE_1 (Fig. 2) tracks the coordinates $(x'),(y')$ of the mouse cursor corresponding to the selected i-th tract A_i^{tr} for further processing (deletion or carrying out computational work); the i-th tract A_i^{tr} is considered selected if the following condition is met:

$$(x_i - d \le x' \le x_i + d) \& (y_i - d \le y' \le y_i + d).$$

e) computational element CE3 (Fig. 2) updates the current screen window after deleting or adding new tracts: clears the screen window; Displays the map K_i^{riv} of the current river A_i^{riv} (see (7)–(8)); Displays the legend of all tracts A_j, $\forall j = 1,\ 2, \ldots,\ k$ in the form of rectangles with the coordinates of the upper left corner $(x_j - d,\ y_j - d)$, $\forall j = 1,\ 2, \ldots,\ k$ and the lower right corner $((x_j + d,\ y_j + d)$ $\forall j = 1,\ 2, \ldots,\ k$ (Fig. 1).

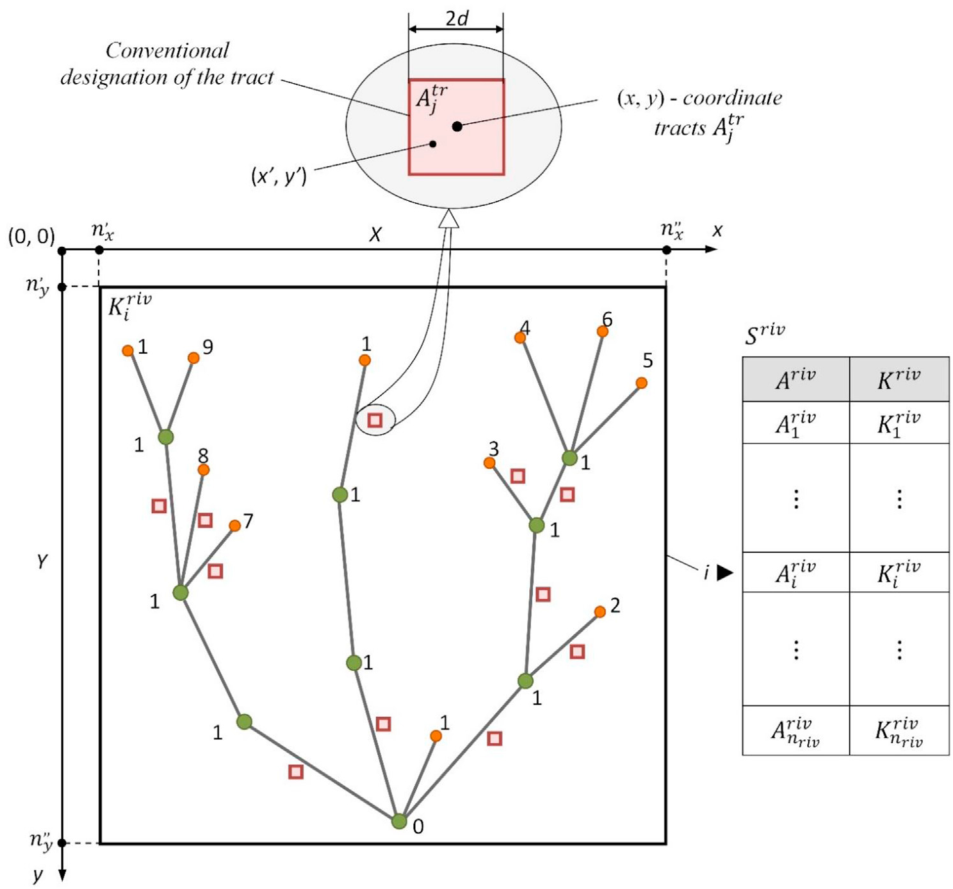

Fig. 1 – Geographic map K_i^{riv} of a random river A_i^{riv} with a tree-like structure, with the following symbol meanings: □- tract; ●- river flow (glacier); ●- junctions of individual sections of the river.

3) Structural model of the module (CM_3) for the formation of a database on the existing types of micro-HPP.

The model of this module is as follows:

a) display S^{hyd}, which links each j-th micro-HPP A_j^{HPP} from the set A^{HPP} to the specific hydraulic data (H_j^{HPP}, Q_j^{HPP}):

$$S^{hyd} : A^{HPP} \rightarrow R_H \times R_Q, \tag{11}$$

$$A^{HPP} = \left\{ A_j^{HPP} \middle| j \in I_{HPP} \right\}, I_{HPP} = \{1, 2, \ldots, n_{HPP}\},$$

$$S^{hyd} = \left\{ S_j^{hyd} = \left(A_j^{HPP}, \left(H_j^{HPP}, Q_j^{HPP} \right) \right) \middle| j \in I_{HPP} \right\} \subset A^{HPP} \times R_H \times R_Q,$$

$$S^{hyd}(A^{HPP}) = \left\{ \left(H_j^{HPP}, Q_j^{HPP} \right) \middle| j \in I_{HPP} \right\},$$

$$S^{hyd}\left(A_j^{HPP}\right) = \left(H_j^{HPP}, Q_j^{HPP}\right),$$

$$A_j^{HPP} \in A^{HPP}, H_j^{HPP} \in R_H, Q_j^{HPP} \in R_Q, \left(H_j^{HPP}, Q_j^{HPP}\right) \in R_H \times R_Q.$$

b) display S^{HPP}, which links each j-th micro-HPP $A_j^{HPP} \in A^{HPP}$ with given hydraulic data (H_j^{HPP}, Q_j^{HPP}) to the specific data (N_j^{HPP}, u_j, w_j) about the electrical characteristics and data $(z_j, r_j, \ldots)$ about economic and other characteristics:

$$S^{HPP} : S^{hyd} \rightarrow (R_N \times R_U \times R_\omega) \times (R_z \times R_r \times \ldots) \tag{12}$$

$$S^{HPP} = \left\{ S_j^{HPP} = \right.$$

$$= \left(\left(A_j^{HPP}, \left(H_j^{HPP}, Q_j^{HPP} \right) \right), (N_j, U_j, \omega_j), (z_j, r_j, \ldots) \right) \middle| j \in I_{HPP} \left. \right\} \subset$$

$$\subset \left(S^{hyd} \times (R_N \times R_U \times R_\omega) \times (R_z \times R_r \times \ldots) \right);$$

where N_j^{HPP} - power; U_j - voltage; ω_j - frequency; z_j - cost; r_j - relative price per kWh.

a) Structural model of the computational module (CM_4) for calculating potential capacities in the corresponding river sections for different types of hydraulic turbines.

The model of this module is shown in (Fig. 3):

a) mapping S^{tur}, which links each j-th type of turbine A_j^{tur} from the set A^{tur} to a specific model F_j^{tur} from the library (set) of models of various types of turbines:

$$S^{tur} : A^{tur} \rightarrow F^{tur}, \tag{13}$$

$$A^{tur} = \left\{ A_j^{tur} \middle| j \in I_{tur} \right\}, I_{tur} = \{1, 2, \ldots, n_{tur}\},$$

$$F^{tur} = \left\{ F_j^{tur} \middle| j \in I_{tur} \right\},$$

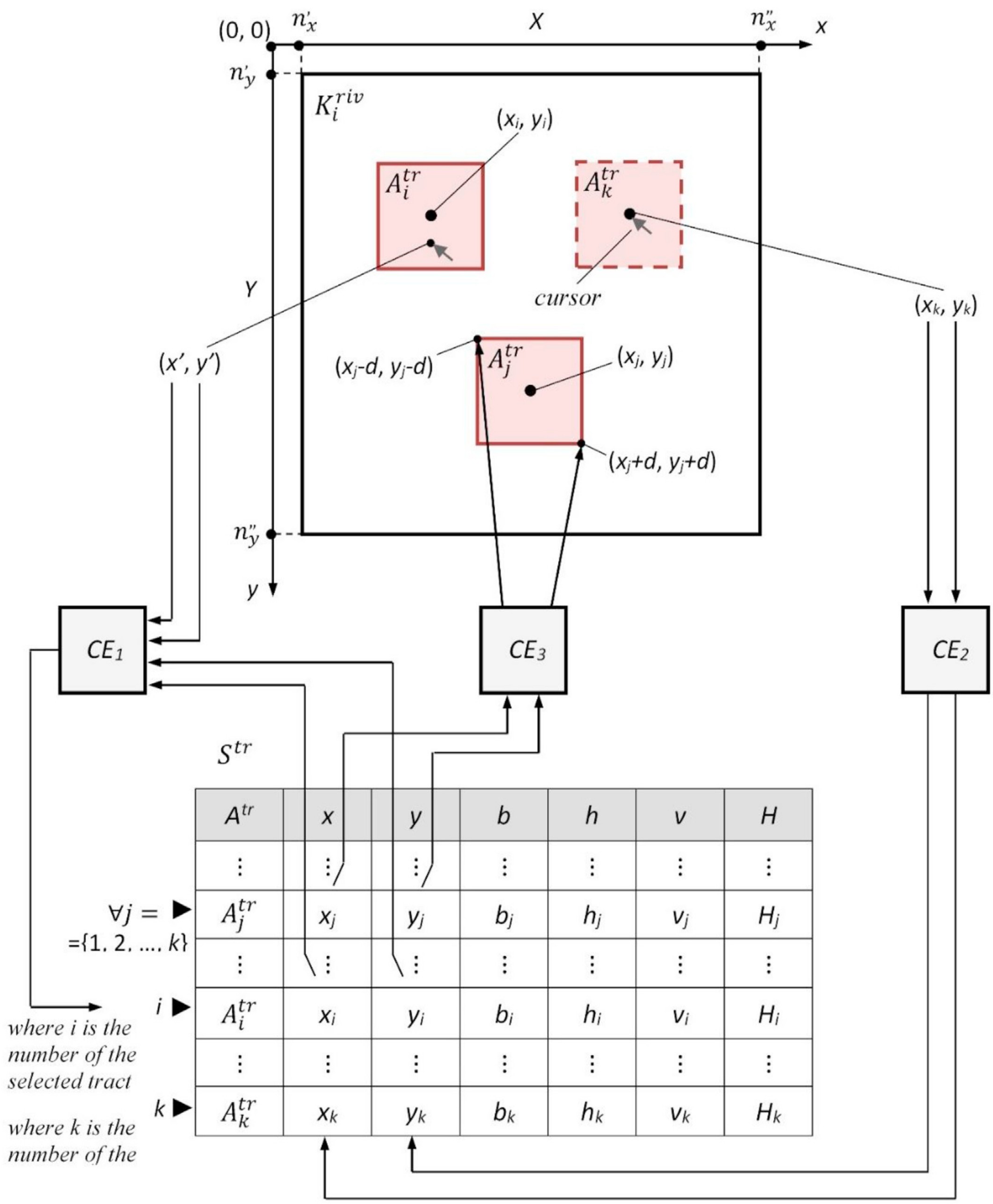

Fig. 2 – Explanation of the computing module CM$_2$.

$$S^{tur} = \left\{ \left(A_j^{tur}, F_j^{tur} \right) \middle| j \in I_{tur} \right\},$$

$$S^{tur}\left(A^{tur}\right) = \left\{ F_j^{tur} \middle| j \in I_{tur} \right\},$$

$$S^{tur}\left(A_j^{tur}\right) = F_j^{tur},\ \left|A^{tur}\right| = \left|F^{tur}\right| = \left|S^{tur}\right| = n_{tur}.$$

b) functional mapping F_j^{tur}, $j \in I_{tur}$, describing the structure of the model of each j-th type of turbine

$$F_j^{tur} : S^{tr}\left(K^{tr}\right) \rightarrow N_j^{tur},\ \forall j \in I_{tur}, \tag{14}$$

where N_j^{tur} is a set of different power values corresponding to the j-th type of turbine; $S^{tr}(K^{tr})$ is the set described in (10).

Based on (14), taking into account the formula $S^{tr}(K^{tr})$ from (10), we obtain a library (set) of models for calculating potential capacities for each i-th section of the rivers using various types of turbines A_j^{tur}, $\forall j \in I_{tur}$:

$$\left\{ N_{j,i} = F_j(b_i,\ h_i,\ v_i,\ H_i) \middle| j \in I_{tur} \right\},\ \forall i \in I_{tr}. \tag{15}$$

5) Structural model of the computational module (CM$_5$) for choosing the best types from a variety of micro-HPPs (see Fig. 4). The selection model can be described by the following:

$$S_{A_i^{tr}}^{HPP} = \left\{ S_j^{HPP} \in S^{HPP} \middle| \left(H_j^{HPP} \le H_i \right) \& \left(Q_j^{HPP} \le 0,6 \cdot b_i \cdot h_i \cdot v_i \right) \right\}, \tag{16}$$

where $S_{A_i^{tr}}^{HPP} \subset S^{HPP}$ - the set of the best types of micro-hydroelectric power plants for the i-th tract A_i^{tr}, $i \in I_{tr}$.

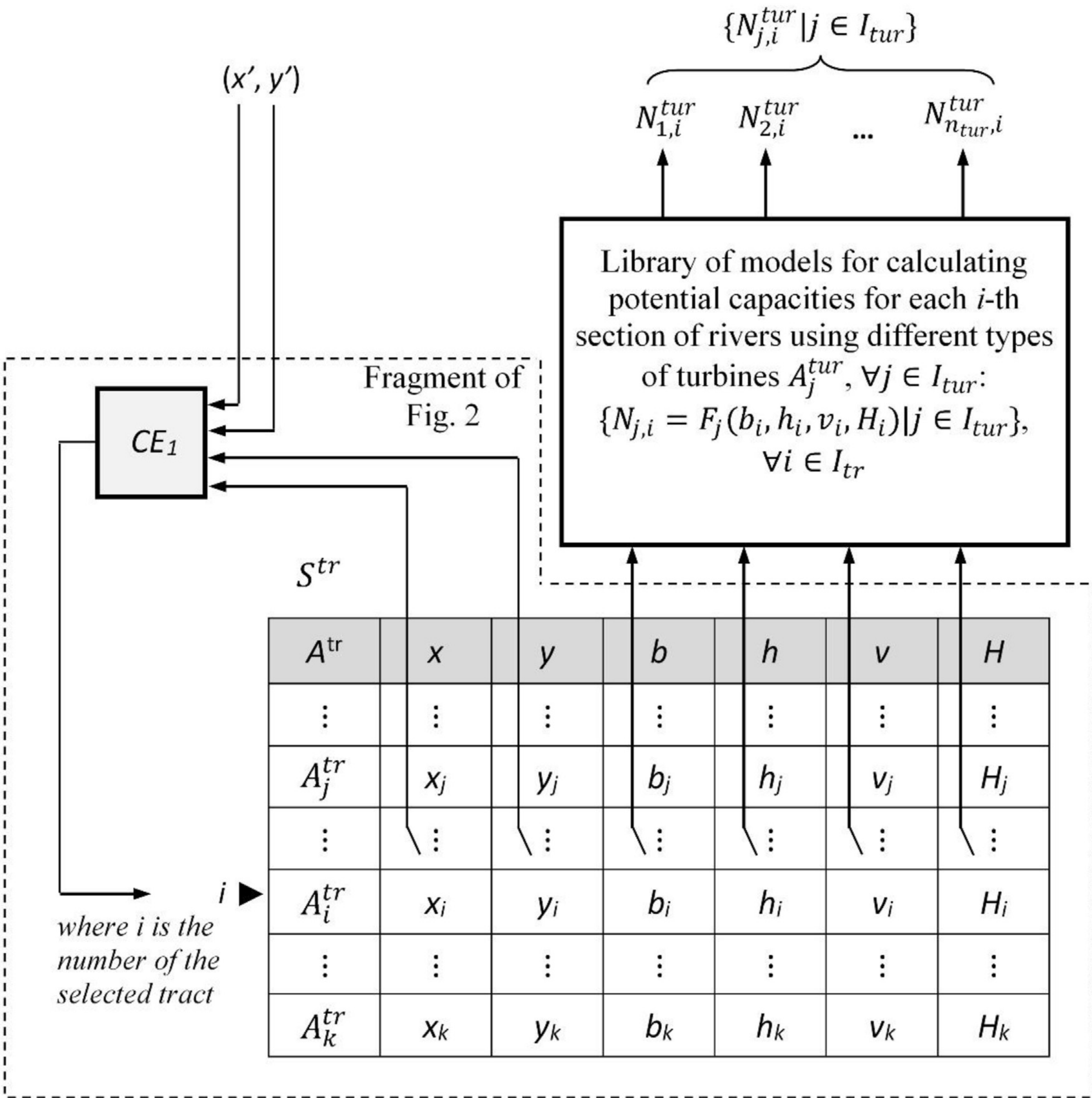

Fig. 3 – Explanations for the computing module CM_4.

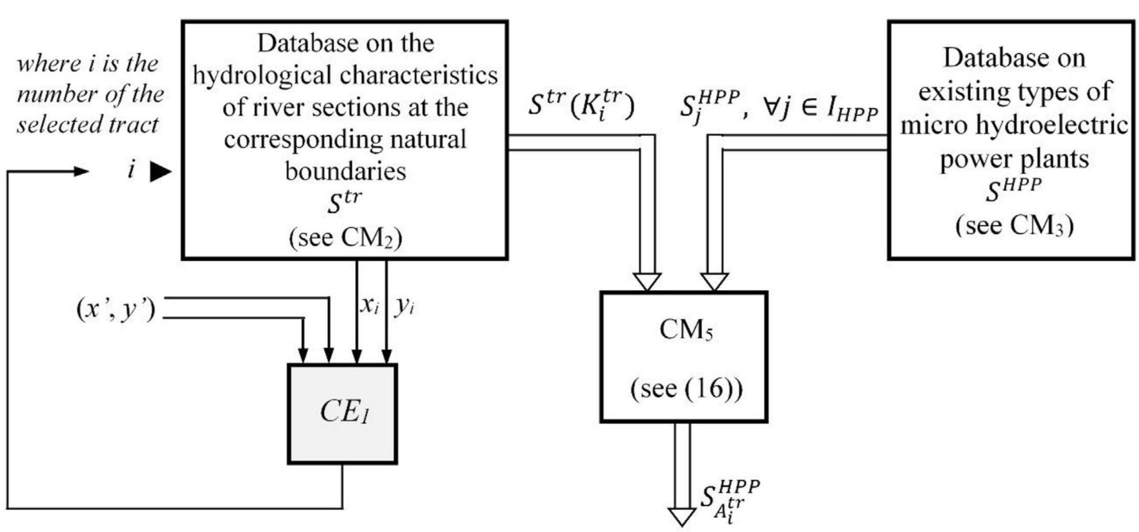

Fig. 4 – Explanation of the computational module CM_5.

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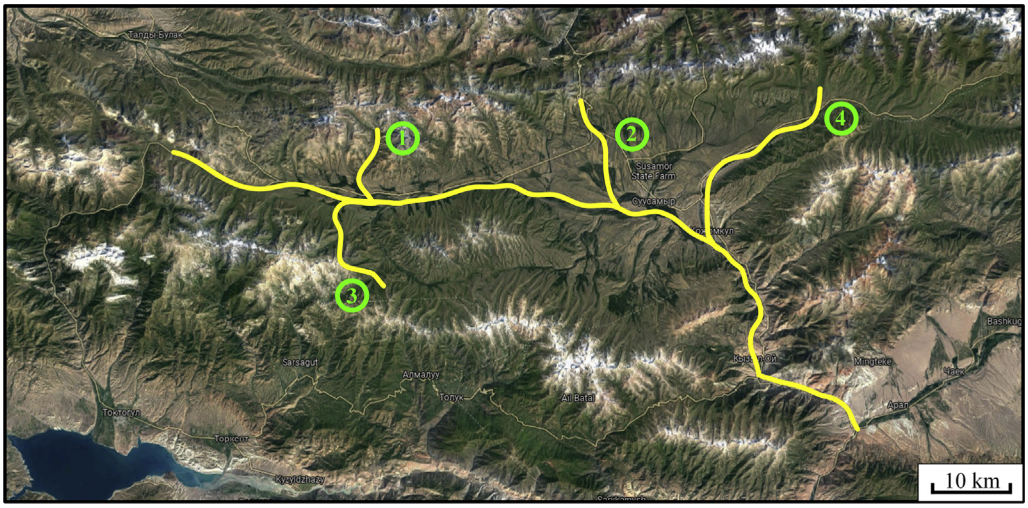

Fig. 5 – Map showing rivers: 1 – river A_1^{riv} = 'Korumdu'; 2 - river A_2^{riv} = 'Kara-Bulak'; 3 - river A_3^{riv} = 'Aram-Suu Vost.'; 4 - river A_4^{riv} = 'Oy-Kaying', all these rivers flow into the Suusamyr river.

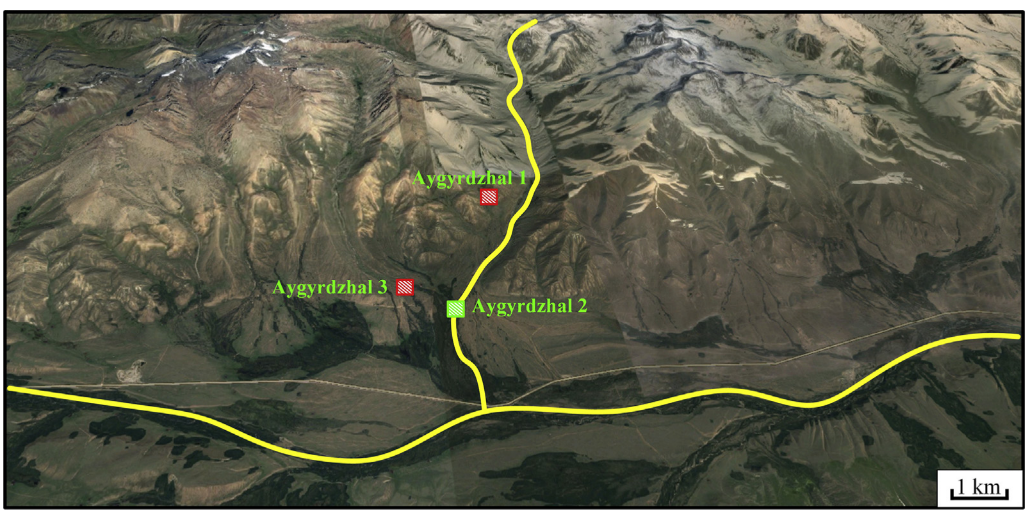

Fig. 6 – Map K_1^{riv} river A_1^{riv} = 'Korumdu'.

Software environment and demos

Based on the above model, a universal software environment "Calculation and selection of the type of hydraulic turbines for micro-HPPs" has been developed [24].

1) An example to explain the structural model of the computational module (CM_1), (see (7), (8)).

The set of rivers $A^{riv} = \{A_1^{riv}, A_2^{riv}, A_3^{riv}, A_4^{riv}\}$ (Fig. 5), where A_1^{riv} = 'Korumdu', which corresponds to a map named K_1^{riv} (Fig. 6); A_2^{riv} = 'Kara-Bulak', which corresponds to the map named K_2^{riv} (Table 1); A_3^{riv} = 'Aram-Suu Vost.', which corresponds to the map with the name K_3^{riv}; A_4^{riv} = 'Oy-Kaying', which corresponds to a map named K_4^{riv} (Table 1).

Table 1 – Display of.S^{riv}

i	A^{riv}	K^{riv}
1	Korumdu	K_1^{riv}
2	Kara-Bulak	K_2^{riv}
3	Aram-Suu Vost.	K_3^{riv}
4	Oy-Kaying	K_4^{riv}

Table 2 – Display.S^{tr}

i	A^{tr}	x	Y	b	h	υ	H
1	Aygyrdzhal 1	665	325	2,0	0,48	0,18	11
2	Aygyrdzhal 2	594	450	2,8	0,6	0,84	9
3	Aygyrdzhal 3	544	436	2,4	0,6	0,28	12

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Table 3 – Parameters of micro-HPP.

j	A^{HPP}	H^{HPP}	Q^{HPP}	N	U	f	z	r
1	Luch –1	5	0,04	1	220	50	75600	3,7
2	Luch - 2	6,5	0,05	2	220	50	136050	3,4
3	Luch –4	8,5	0,085	4	380	50	259350	3,2
4	Luch –10	10	0,145	10	380	50	585000	2,9
5	Micro HPP 10Pr	10,0	0,21	10,0	230	50	712500	3,5
6	Micro HPP 15Pr	12,0	0,30	15,0	400	50	787500	2,6
7	Inversiya 7,5 PR	4,5	0,21	7.5	230	50	420000	2,8
8	Micro HPP 50Pr	10,0	0,9	50,0	400	50	3,750,000	3,7
9	Micro HPP 100Pr	18,0	1,2	100,0	400	50	6,900,000	3,4
10	Micro HPP 20PrD	18	0,17	20	400	50	812600	2,0
11	Micro HPP 50D	25	0,26	50	230, 400	50	3,823,000	3,8
12	Shar-Bulak 1,0	4	0,009	1,0	220	50	45600	2,2
13	Shar-Bulak 1,7	7	0,02	1,7	220	50	72000	2,1
14	Shar-Bulak 5	8	0,03	5,0	220/380	50	105600	1,1
15	Micro HPP PR5-G-20	5	0,16	5,0	220/380	50	72000	0,7
16	Inversiya 10 PR	10	0,215	10	230	50	465000	2,3
17	Inversiya 22 PR	4.5	0,81	20	230	50	870000	2,2
18	Inversiya 50 PR	10	0,9	50	230	50	1,878,000	1,8
19	Inversiya 90 PR	10	1,22	90	230	50	2,991,000	1,6

The display of S^{riv} is presented in the form of a Table 1.

2) *An example to explain the structural model of the computational module (CM_2), (see (9), (10))*. As an example, let us pick the river A_1^{riv} = 'Korumdu' (Fig. 6). On the map K_1^{riv} of the river under consideration A_1^{riv} = 'Korumdu', the tracts are shown in the form of .

A set of tracts $A^{tr} = \{A_1^{tr}, A_2^{tr}, A_3^{tr}\}$, where A_1^{tr} = 'Aygyrdzhal 1′, on the map K_1^{riv} is shown in the form of a rectangle with coordinates $x = 665$, $y = 325$; A_2^{tr} = 'Aygyrdzhal 2′, on the map K_1^{riv} is shown in the form of a rectangle with coordinates $x = 594$, $y = 450$; A_3^{tr} = 'Aygyrdzhal 3′, on the map K_1^{riv} are shown in the form of a rectangle with coordinates $x = 544$, $y = 436$.

The display of S^{tr} is presented in the form of a Table 2.

3) An example to explain the structural model of the module for forming a database on the existing types of micro-HPP (CM_3), (see (11), (12)). The structural model described using expressions (11), (12) is presented in the form of a Table 3.

4) An example to explain the structural model of the computational module (CM_4).

Table 4 – Hydrological parameters of the watercourse.

i	A^{tr}	x	y	b	h	v	H
1	Kara-Bulak	541	503	2,1	0,42	0,56	9

The structural model for calculating potential capacities in the corresponding river crossings for different types of hydraulic turbines described using formulas (13) - (15), provided for a library (set) of models for calculating potential capacities for each i-th river crossing with different types of turbines A_j^{tur}, $\forall j \in I_{tur}$: let us explain how to define the capacity in example A_2^{riv} = 'Kara-Bulak', which corresponds to a map named K_2^{riv}. We aim to define the potential capacity of the watercourse on the condition of the installation of n micro HPPs. The hydrological parameters are shown in Table 4.

The calculation results for determining the power for different types of turbines of the Kara-Bulak river are given in Table 5.

5) An example to explain the structural model of the computational module (CM_5).

This module CM_5 (see (16)), selects the best type from a variety of micro-HPPs based on the databases S^{tr} ((see CM_2, (9), (10)) and S^{HPP} ((see CM_3, (11), (12)).

For the given section $i = 1$ of the river A_2^{riv} = 'Kara-Bulak', there were selected the best turbines matching the water pressure and water discharge. Fig. 7 shows the screen image of the given section $i = 1$ of the river A_2^{riv} = 'Kara-Bulak', which shows the list of micro-HPPs suitable for this section and their technical characteristics.

Of the variety of micro-hydroelectric power plants, the following micro-hydroelectric power plants suit the given

Table 5 – Power of micro-HPPs with different types of hydro turbines.

j	A^{tur}	Calculation formulas, kW $N_{j,i} = F_j(b_i, h_i, v_i, H_i)$	Calculation results, kW
1	Micro-HPP with a "Banki" type turbine	$N_{1,1} = 9,81 \cdot Q \cdot H \cdot \eta_T$ $\eta_T = 0,7$	$N_{1,1} = 9,81 \cdot 0,29 \cdot 9 \cdot$ $\cdot 0,7 = 18,31$; $Q = 0,29$
2	Micro-HPP with a propeller turbine	$N_{2,1} = 9,81 \cdot Q \cdot H \cdot \eta_T$ $\eta_T = 0,84$	$N_{2,1} = 9,81 \cdot 0,29 \cdot 9 \cdot$ $\cdot 0,84 = 21,97$
3	Micro-HPP with a diagonal turbine	$N_{3,1} = 9,81 \cdot Q \cdot H \cdot \eta_T$ $\eta_T = 0,86$	$N_{3,1} = 9,81 \cdot 0,29 \cdot 9 \cdot$ $\cdot 086 = 22,5$

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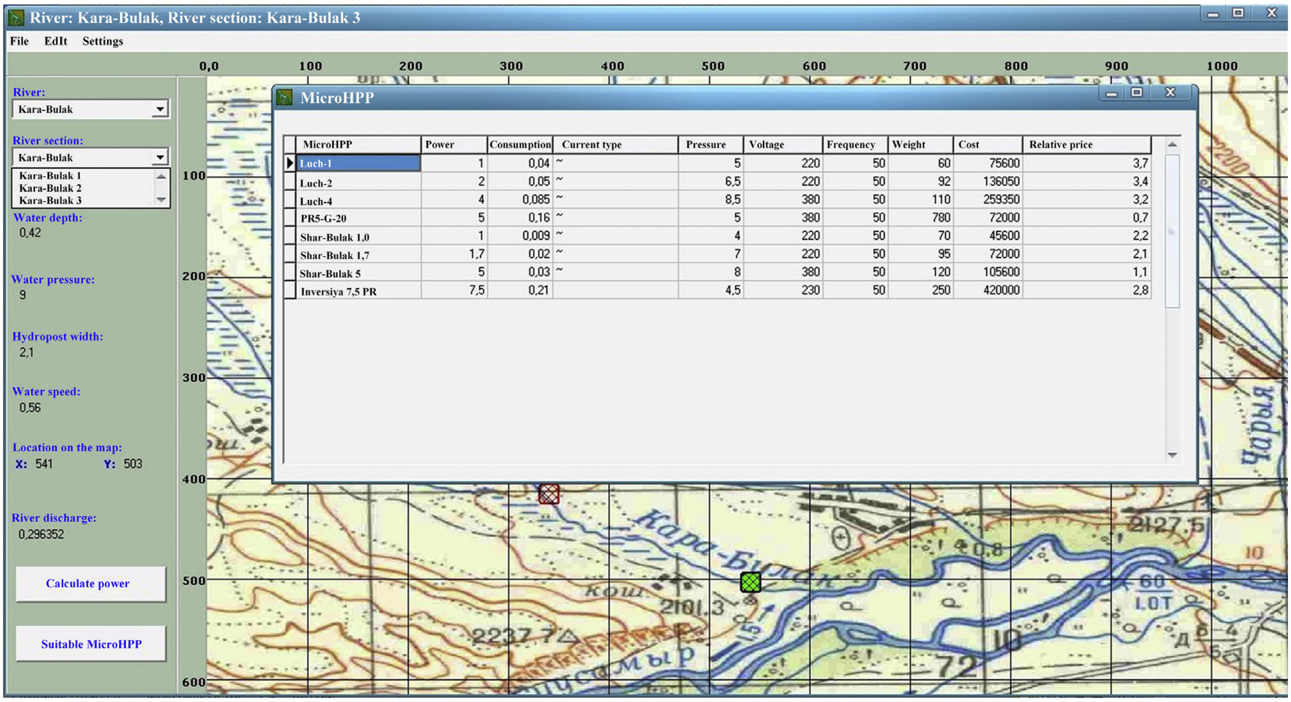

Fig. 7 – A screen of the software environment showing the suggested types. of micro-HPPs for the Kara-Bulak River (Kyrgyzstan).

section of the Kara-Bulak river (Fig. 7): Luch –1, Luch - 2, Luch –4, PR5-G-20, Shar-Bulak 1.0, Shar-Bulak 1.7, Shar-Bulak 5, and Inversion 7.5 PR. Depending on his load, a consumer can choose one of the suggested types of micro-HPP that will meet his requirements. Also, when choosing a micro-HPP, a consumer should take into account the factor of the seasonality of the water level, the constancy, and speed of the water, the volume of water, since in some places the water freezes in winter.

Conclusion

The aforesaid formulas (7) - (16) describe the structural model of the algorithm for solving the task of calculation of the potential capacities of small and shallow mountain rivers and the choice of the best types of micro-hydroelectric power plants for the given river sections. Based on this model, there has been developed a universal software environment “Calculation and selection of the type of hydraulic turbines for micro-HPPs” [24]. The operation of this software is shown on the example of the rivers Korumdu, Kara-Bulak, etc., and the Aigyrdzhal tract of the Kyrgyz Republic.

Further development. Another computational module will be added to this model to provide for modeling of the mountain rivers with a tree-like structure under the given hydrological parameters of their flows. This model will be used to create a universal computer-aided design (CAD) system for the optimal structure of autonomous distributed hybrid energy complexes (ADHEC) running on renewable (non-traditional) energy sources, whose power facilities are scattered land wise and are of varying nature. The main mathematical apparatus in the development of CAD systems for ADHEC is the theory of computational Petri nets [[25,26]], which is a further development of the classical theory of Petri nets.

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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