Hydropower potential implementation as an important stage of the environmental and economic frames formation in the mountain valleys

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Abstract. The hydrographic network within the mountain-piedmont zone is characterized. The necessity of the revaluation of the economically feasible rivers’ energy potential is grounded. The main hydrological elements of river basins applied to the research topic have been identified. A landscape assessment of the mountain valleys specificity considering the creating hydropower facilities issue has been carried out. The most preferred for the development watercourses are designated and described, considering statistical materials on their water flow dynamics. The method of compensation for deficient statistical materials on the water flow dynamics is represented. The features of the high-mountain zone hydropower potential are highlighted. A comparative analysis of the energy reserves of the main mountain rivers is given. The role of ice-free feeding minor rivers in a hydroelectric project is determined. The method of determining the water flow security is described, the corresponding coefficients are determined. 16 topographically convenient mountain-valley extensions were identified as potential cisterns for reservoirs. Dam and lake methods for regulating effluent are evaluated on the acceptability. An algorithm for determining the mountain streams’ channel energy potential of is given. A comparative analysis of the specific power of the rivers in relation to their different sections has been carried out. The most important limiting factors for the hydropower projects implementation have been identified. A working hypothesis for the use of environmentally friendly hydro energy has been formulated. In the first approximation, a scheme for selecting favorable landscapes for the hydropower facilities construction has been drawn up, and the corresponding map chart has been made. Criteria for selecting the power and type of power plants adequate to the natural base are indicated. The forecast of hydropower development is formulated in conjunction with the expected levels for electricity demand in the future.

1. Problem Statement

Kabardino-Balkaria mountain zone is one of the republican disadvantaged regions in terms of the hydropower competitive advantages realization. Meanwhile, by the beginning of the Second World War, every large mountain village had its own hydroelectric power plants (HPP): 20 plants of different capacities functioned in the mountains; another 22 objects were under installation. The production of own electricity was reasonably estimated as a guarantor for the sustainable provision of population with it, a real factor in reducing the cost of production and services [1].

Given the current trend of growth in the business projects cost structure, the electricity cost and inadequate tariff burden on low-income mountain dwellers, the feasibility of involving the unsold hydropower potential of the zone has only increased. In addition, there is always the growing relevance of using renewable energy on the global agenda.
Therefore, the hydropower resources reassessment under the transformation of the rivers nourishment nature and their flow regime on the background of global climate change; hydropower devices placement, proportional to the watercourses natural potential, remains strategic for the modernization of the economic and social infrastructure in the mountains. The designated priority harmoniously fits into the project proposed by the authors for constructing balanced ecological-economic zones in the main mountain valleys of the Republic.

2. Research Questions
Potential carriers of the hydropower resources of the Kabardino-Balkaria mountain areas are the basins of the Malka, Baksan, Cherek Rivers.

3. Purpose of the Study
Assessment of the current conditions for the involvement in the economy of the mountain rivers’ hydropower potential, the identification of optimal areas for the use watercourses, the choice of sites for the priority hydroelectric power plants placement.

4. Research Methods
On the expeditionary study basis, a research was conducted on the Lochskii canyon in order to regulate the river Malka flow. Based on archival statistical materials of past years, a working hypothesis was formulated for the use of mountain rivers’ hydropower. The comparative-geographical method was used in assessing the hydro-morphological parameters of watercourses. The mathematical method was used to identify the average long-term flow of rivers and their potential energy capacity.

5. Findings
Physical and geographical features of the study area led to the formation of three river basins’ types: high mountain, main mountain and foothill [2]. They differ in the nature of the nourishment, the structure of the basin and the longitudinal profile, as well as the potential power of rivers’ different sections.

Depending on the nature of nourishment, in the following river basins elements are highlighted:
1. The nourishing high-mountain fan of river tributaries of the 1st, 2nd, 3rd and higher orders (area of glacier flow), whose water content has increased by about 10% in recent decades (Table 1);
2. The nourishing system of the foothill rivers with mostly snow and rain feed;
3. Separate sources of groundwater;
4. The main mountain valleys that collect the waters of all influx types and divert them outside the mountain areas.

In accordance with the designated hydrological elements of the basins, zonal demarcation was carried out relating to the hydropower resources distribution:
I – the zone of the mountain rivers’ main valleys (Terek, Malka, Baksan, Urukh, Cherek, Chegem);
II – zone of high mountain runoff (Donguz-Orun, Iusengi, Adyl-su, Irik, Adyr-su, etc.);
III – zone of minor rivers of ice-free nourishing (Nalchik, Kich-Malka, Shalushka, etc.). The hydropower resources of each zone have specific features.

When analyzing the potential of hydropower resources zones, achieve materials were not enough to characterize the intensity of the increase in river flow along the length. Therefore, the assessment of potential channel capacity, in some cases, is carried out by known water flow rates and a schematic typical longitudinal profile, in others, by a known longitudinal profile and water flow rates, adopted by analogy with adjacent basins. In isolated cases, interpolation and extrapolation were hampered by a sharp differentiation of high-altitude microclimates and the lack of reliable data on the level of correlation between river runoff dynamics and global climate change, therefore approximate generalizations of their energy characteristics were made.

Table 1. Mountain-foothill areas hydrographic network characteristics [3]
To assess potential hydropower resources, the water flows workload associated with gravity has been identified. The method of continuous channel accounting was based on the rivers breakdown into sections with approximately equal slopes [4]. The work of the watercourse is calculated by the difference in water levels at the beginning and end of the selected part of the river using the formula:

\[ N = g \sum_{H_s}^{H_e} \frac{Q_1 + Q_2}{2} \Delta H, \]

where \( g \) – gravitational acceleration, m/s; \( Q_1 \) and \( Q_2 \) – water consumption in m\(^3\)/s at the beginning and at the end of the section, having a fall \( \Delta H \); \( H_s \) and \( H_e \) – absolute heights of the source and entry in meters; \( N \) – water flow.

The analysis allows conducting a hydropower assessment in the context of the 3 designated zones. The high mountain runoff zone covers the hydropower resources of high-mountain small rivers, mainly with glacier nourishing, which are main mountain rivers’ influxes. The zone can also include small rivers that have lost their glacial nourishing, but which geomorphological features indicate their postglacial sources, which formed the typical longitudinal profile. Due to the alpine snow nourishing, the seasonal distribution of the latter is similar to glacial rivers. The peculiarity of the high-mountain rivers’ hydropower resources is a high specific power with small runoff volumes and high pressures at their steep (downfall) source sections [5].

Valleys are included in the main mountain rivers space, crossing both the zone of high-mountainous areas and the underlying watercourses that do not have ice nourishing. The main part of hydropower resources is concentrated in the middle course of the zone, since runoff from both mountainous areas and ice-free nourishing rivers [6] rolls down into the mountain rivers’ valleys. This rivers’ group has a flatter parabolic longitudinal profile and maximum power in the middle course. Downstream, the power density decreases in line with the decrease in the channel slope, despite the increasing gross flow.

The secondary rivers zone of glacial-free nourishing is partly mountainous and the entire foothill area. Foothill rivers are energetically less significant, with a steep parabolic profile and diminishing downstream power. Maximum power within the zone is in the upper or in their middle parts.

Due to the high variability of water consumption, the full involvement of the indicated capacities is possible only under the condition of seasonal, even better – year-round regulation. Unregulated stock cannot be used highly efficiently [7]. The part of the water resources, which are suitable for development without flow regulation, is determined by the authors according to the high-availability water consumption. At the same time, the provision ratio is conditional and identified as the ratio of the water flow of this provision to the value of the average long-term water flow. The rates of transition from average annual water consumption to annual water consumption (100 %), nine-month (75 %) and six-month (50 %) provision are shown in Table 2.

**Table 2.** Average annual water provision of the main KBR rivers

| Main River | 1st order influxes | 2nd order influxes | 3rd order influxes | Basin area, km\(^2\) | River length, km | Fall of the river, m | Average slope, % | Average annual water consumption, m\(^3\)/s |
|------------|-------------------|-------------------|-------------------|---------------------|-------------------|-------------------|----------------|-----------------------------------|
| Malka      | —                 | —                 | —                 | 9819                | 201               | 2879              | 14.3           | 112.4                             |
| Baksan     | —                 | —                 | —                 | 6822                | 161               | 2154              | 13.4           | 102.2                             |
| —          | —                 | —                 | —                 | 3031                | 119               | 1840              | 15.5           | 52.3                              |
| —          | —                 | —                 | Cherek-Khulamskii| 640                 | 46                | 1358              | 29.5           | 13.9                              |
| —          | Chegem            | —                 | —                 | 923                 | 102               | 1975              | 19.4           | 13.9                              |
| —          | Gundelen          | —                 | —                 | 579                 | 56                | 2223              | 40.0           | 5.2                               |
| Urakh      | —                 | —                 | —                 | 1256                | 251               | 2601              | 10.4           | 27.4                              |
The flow utilization efficiency is maximizing the energy resources were preserved glacier nourishing is favorable: it is quite high, which is due to their extremely steep fall, caused by over-deepening of the erosion base under glacial landscapes [10]. At the same time, the energy values of some mountain rivers are limited by certain circumstances. In the mountains, there are alternative (lake) regulation. The most preferable object for lake regulation with respect to the energy and economic parameters of Baksan is the Syltran-Su, Gundelen. These reservoirs also have the most favorable starting characteristics for erecting hydro-accumulating stations on them; therefore they can become top-priority energy facilities.

| Name of the river | Average annual water consumption, m³/s | 100 % provision water flow, m³/s | 100 % provision coefficient | 75 % provision water flow, m³/s | 75 % provision coefficient | 50 % provision water flow, m³/s | 50 % provision coefficient | Potential annual average power (MW) |
|-------------------|----------------------------------------|---------------------------------|-----------------------------|---------------------------------|-----------------------------|---------------------------------|-----------------------------|----------------------------------|
| Malka             | 13.5                                   | 5.0                             | 0.37                        | 7.5                             | 0.55                        | 10.8                            | 0.80                        | 196                              |
| Baksan            | 33.9                                   | 9.0                             | 0.26                        | 12.0                            | 0.35                        | 19.0                            | 0.59                        | 394                              |
| Cherek            | 40.5                                   | 9.0                             | 0.22                        | 11.0                            | 0.27                        | 17.0                            | 0.47                        | 564                              |
| Chegem            | 12.6                                   | 3.0                             | 0.24                        | 3.6                             | 0.28                        | 6.3                             | 0.50                        | 174                              |
| Terek             | 147.2                                  | 57.0                            | 0.39                        | 70.0                            | 0.48                        | 111.                            | 0.76                        | 168                              |
| Urukh             | 24.2                                   | 3.9                             | 0.16                        | 5.7                             | 0.24                        | 7.0                             | 0.54                        | 72                               |

Table 2 suggests that the water consumption of year-round provision for most watercourses varies within 16-26 % of the average annual water flow and only for rivers Malka and Terek – close to 40 %. If we start from the minimum and installed capacity of hydroelectric power plants as 1: 2, the estimated water consumption for rivers with glacier nourishing is close to nine months provision (75 %), and the flow is used only by 25–30%. For mountain rivers with non-glacial nourishing under the same conditions, water consumption is approximately six months provision (50 %), and runoff is used at 50–60 %. Consequently, the flow of rivers with glacier nourishing is used less efficiently.

Thus, the vast majority of hydropower resources in the mountains must be regulated [8]. The morphology of mountain valleys, in general, is favorable for the construction of regulatory objects. In relation to them, 16 topographically convenient mine-valley extensions were previously identified, they are: 2 – on the Malka River, 5 – on the Baksan River, 2 – on the Cherek River, 1 – on the Cherek-Khulamskii River, 2 – on the Chegem River, 4 – on the small influxes of the Baksan (Danguz-Orun, Iussengi, Syltran-Su, Gundelen).

In the mountains, there are alternative (lake) regulation. The most preferable object for lake regulation with respect to the energy and economic parameters of Baksan is the Syltran-Su limnosystem located in the Kyrtky River at an altitude of 1700m north-west from Upper Baksan Village. It is more expedient to regulate the Cherek River by the Giybaskel Lake, which is localized southwest of the Upper Balkaria village [2]. These reservoirs also have the most favorable starting natural characteristics for erecting hydro-accumulating stations on them; therefore they can become top-priority energy facilities.

There are no functionally significant lakes in the Malka River basin, therefore here we can only consider the weir way of influence on the flow dynamics. A more preferable variant of its regulation is the creation of a reservoir on the Lochansky canyon basis. It has more acceptable topographical and geological conditions. With a dam height of 105–110 m, the useful volume of the reservoir will be about 80 million m³, which is sufficient to regulate the entire main river flow.

An important lever for increasing the river flow utilization efficiency is maximizing the energy involvement of the entire river fall [9]. In the process of studying this property, the hydropower channel potential was estimated by dividing the water courses into sections. The boundaries of the sites were selected on a topographic map at the fractures points of the rivers longitudinal profiles and in the entry of the most significant influxes (the yield of at least 5 % of the main river flow was taken as the criterion of significance).

Proceeding from the above, the Cherek and Baksan rivers have the largest specific power, the Malka –the smallest. In them, the energy capacities decrease in the entry areas and have maxima in the upper or middle third of their length. The hydropower potential of the entry of small high-mountain rivers with preserved glacier nourishing is favorable: it is quite high, which is due to their extremely steep fall, caused by over-deepening of the erosion base under glacial landscapes [10].

At the same time, the energy values of some mountain rivers are limited by certain circumstances. End moraine soils and fluvial-glacial deposits are the limiting factor for the implementation of
hydropower projects in the upper reaches of the Chegem River, since they are not a reliable basis for dams. The upper parts of Adyr-Su do not have applied significance, which means they except from the general river fall.

The involvement of high-mountain rivers in their average flow is problematic; debris flows and mountain landslides often clutter the valleys, creating gradations of longitudinal profiles and significant elevation differences with increased specific power of the watercourse in short sections [11]. Geological conditions may also become blocking development factors: karst landscapes of valleys confined to limestone and shale zones (Tiubele Kamyk Bylymskoe landtype associations on the Baksan River; Cherek gorges) are not a reliable basis for the construction of dams.

Thus, the distribution of hydropower resources reserves in the mountains in the first approximation can be estimated as follows: for high-altitude watercourses – 18 %, main mountain rivers – 76 %, foothill – 6 % of potential. Taking into account the cumulative properties of river systems, a schematic map has been compiled as one of the options for locating hydraulic systems and their combinations in river basins (Figure 1).

Figure 1. Approximate scheme of involvement of the mountain-piedmont zone hydropower potential

The choice of power plants’ power and type is important. It should be determined considering the nature of the valleys occupancy, the intensity of economic activity, the formalized priorities of the region’s development for the long term [12]. 6 climbing camps and one hotel are already functioning in the small Adyl-Su basin. In the foreseeable future, we predict a further expansion of the recreational economy, the beginning of industrial production and drinking water bottling, scientific institutions revitalization, rescue structures consolidation, and therefore the construction of mini hydroelectric facilities will be in demand. Low volume of construction and installation works; acceptability of small-sized power plants spatially combined with decentralized power consumers; insignificant specific capital investments level the limiting non-critical physical-geographical factors.

The further involvement of Baksan hydropower resources should take into account federal projects for the Elbrus ski infrastructure modernization, for the restitution of mining environmental management on the Tyrnayauskogo field basis with a wider range of commercial products, limestone building materials production [9].

Due to the particularly high specific power of water in the middle reaches of the main mountain rivers, relatively large (more than 25 MW) water installations should be selected for them. In their lower course, the power density decreases; the valleys slopes, the morphology and geology of the valleys do
not allow concentrating high water heads. Covered with a thick layer of sediment, disintegrating in the river branches are unfavorable for the construction of hydropower facilities. In addition, the density of power grids is quite high there, so consumers can choose the best connection option for themselves [10]. The experience of past construction in the republic shows that hydropower does not make major negative changes in the natural environment. The construction of hydropower plants will allow attracting a part of the unemployed both in the sphere of construction and its maintenance, and the subsequent operation of hydroelectric power plants. The industry will give a new impetus to the economic development of the mountain zone and, importantly, it will remain a permanent factor in motivating its economy development.

6. Conclusion
1. Landscape-climatic features, hydrographic parameters of mountain streams and their hydropower potential can be the basis of a profitable, annually renewable hydraulic energy source.
2. The main carriers of the Kabardino-Balkaria mountain zone hydropower resources are the basins of the rivers Malka, Baksan, Cherek.
3. High annual variability of water flow necessitates regulation of mountain river flow.
4. Flow regulation through the construction of large valley reservoirs is limited by a sharp differentiation of physiographic conditions, an increase in environmental risk, a large amount of construction and installation work, and their significant capital intensity.
5. The most expedient way to mountain rivers is the construction of low-capacity pumping stations on the natural mountain lakes base, which can simultaneously perform regulatory and energy-producing functions.
6. The most preferable for the construction of pumped storage stations are the karst lake Giibashkel (to regulate the flow of the Cherek River), the lake Syltrankel (to regulate the flow of the Baksan River). It is more expedient to transform the Malki River runoff by erecting a dam with the maximum use of favorable topographic and geological properties of the Lokhranskii canyon.
7. The distribution of hydropower resources in the mountains is as follows: for high-altitude watercourses –18 %, main mountain rivers – 76 %, foothill – 6 % of potential.
8. The Cherek and Baksan rivers have the largest specific power, the Malka River has the smallest. In them, the energy capacities decrease in the entry areas and have maxima in the upper or middle third of their length.
9. Phased involvement of the hydro potential cost-effective part in the power system, including autonomous supply, will reduce the cost of current and future business projects and the electricity costs for mountain people.
10. In case of the optimistic scenario for the renewable energy development, Kabardino-Balkaria will have the prospect of electric power cooperation with the regions of the South of Russia and the Transcaucasian states depending on the balance situation of the resource in the power systems.

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