Construction of Flow Control Structures as an Essential Condition for Increasing the Efficiency of Hydropower Facilities in Mountainous Regions

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Abstract. The hydropower industry of the Kabardino-Balkarian Republic (KBR) is weakened by the absence of flow control structures. Due to the extremely weak flow control of the mountain rivers utilized by hydropower structures, the total production and economic effect of the operating power units is rather low. This circumstance determines the highest seasonal variability of the annual flow — compared to summer months, the capacity of power plants is reduced in winter by almost 5–6 times.

It is obvious that it is almost impossible to utilize the entire capacity of river flows. At the same time, it is unacceptable when no more than 20% of the flow capacity is actually used, which leads to extremely low efficiency of expensive power units.

The objective of this research is to study the engineering and economical feasibility of controlling the flow of mountain rivers of KBR, to study the possibility of creating an optimal water pressure by constructing water storage facilities, to assess mountain-valley landscapes and select specific cross-sections for the construction of priority flow control facilities.

To achieve this objective, the following tasks were solved:
- study the conditions of water flow control for glacier-fed mountain rivers;
- formulate preliminary flow control schemes within the selected cross-sections;
- assess natural properties of watercourses and their relevance for the construction of flow control facilities; search high-mountain lakes suitable for river flow accumulation in the first approximation;
- substantiate a suitable sequence of construction of flow control facilities;
- assess the approaches to seasonal and long-term water flow rate forecasting as an essential condition for optimizing the operation of hydropower units.

1. Introduction
The energy of glacier-fed mountain rivers cannot be used efficiently without controlling the natural watercourse flow. The pronounced unevenness of the capacity of the functioning hydropower units...
during different seasons of the year necessitates the study of the natural properties of mountain valleys to equalize the annual water flow rate [1].

However, water storage facilities can not be constructed on all rivers of KBR — the soils of the terminal glacial moraine widespread in the highlands are not reliable enough for flow control facilities, while a number of gorges have unfavorable topographic or difficult geological conditions.

In this regard, valleys shall be found that are relatively favorable for the construction of water storage facilities, as well as a technical and economic assessment of the natural properties of the identified cross-sections shall be made related to dam construction.

2. Results
The preliminary results of the analysis of prospects for controlling river flow in KBR showed that valley slopes in the high-mountainous zone are most often composed of bedrock that allows the construction of dams. At the same time, the angles of longitudinal slopes of gorges are so big that even with wide sections present, they will not allow creating reservoirs with a volume sufficient for water accumulation.

In the middle reaches of the rivers, the geological properties of gorge slopes are more complicated — the latter are formed by sedimentary rocks (limestone, less often — shale), and therefore they have a large amount of karsts (for example, Bylymsk gorge of the Baksan river); the bottom of other valleys is littered with a thick layer of debris and talus (Cherek gorge). Side slopes of Su-Auzu valley of the Chegem river basin are saturated with groundwater, making them unreliable as dam support. In certain cases, the sources of high-mountain rivers are covered with a thick layer of fluvial-glacial deposits (Yusengi, Adyr-Su, Chegem rivers), which complicates the possibility of construction of hydropower facilities [2].

Considering the abovementioned limiting factors, only 5 stretches have been selected from the set of initially convenient stretches of mountain valleys, in which water storage facilities can be safely constructed in the first approximation. Watercourses within the selected gorges have an approximately similar hydrological regime due to the same runoff character. The preliminary parameters of the cross-sections of mountain gorges are given in Table 1.

| Name of river and control facility | Power, MW | Power output, mln kWh | Volume of reservoir, mln m³ | Type and length of diversion system, km | Height of dam, m | Geological conditions of preferable cross-section |
|-----------------------------------|-----------|------------------------|-----------------------------|-----------------------------------------|-----------------|-----------------------------------------------|
| Lahran stretch of Malka river     | 25        | 125                    | 80                          | Tunnel 6.0                              | 105             | Elvans                                        |
| Itkol cross-section of Baksan river | 49        | 135                    | 36                          | Tunnel (5.8 km)                         | 100             | Crystalline shist                             |
| Gizhgit stretch of Baksan river   | 49        | 146                    | 130                         | Without diversion system                | 100             | Crystalline shist                             |
| Zayukov cross-section of Baksan river | 33        | 164                    | 170                         | Tunnel (1.5 km)                         | 75              | Limestone                                     |
| Syltran-Su river                  | 30        | 128                    | 22                          | Tunnel (2 km) + pipeline (2.7 km)       | 38              | Granodiorites                                 |
Based on the average annual flow rate and predicted water pressure, the Gizhgit and Itkol cross-sections demonstrate the greatest capacity (Table 1). The latter cross-section has such flow control capabilities because it is located at the highest altitude level compared to other selected cross-sections, i.e., in the head of the proposed cascade of hydroelectric power stations on Baksan river. Receiving the runoff of small Azau and Donguz-Orun rivers, the potential flow control structure will be able to somewhat equalize the pressure for the power units downstream. At the same time, runoff from only 6 percent of the river basin area will pass through this cross-section in total, meaning that its regulating effect will be insignificant [3].

The Gizhgit cross-section also receives runoff from the Kryz-Kam and Chaalmala gorges, as well as the entire slope runoff. However, its altitude position is lower than the previously mentioned cross-section, therefore, it will able to control the Baksan flow only partially. Furthermore, the Gizhgit stretch development is highly likely to be associated with an obvious high capital intensity of construction and installation works, therefore, this option is unlikely to be in demand in the short and medium term [4].

Considering the current state of the hydropower industry in the mountainous region, the Zayukov option seems to be the most preferred flow control facility. Hydrometric parameters of the Zayukov cross-section are shown in Figure 1.

![Figure 1](image.png)

**Figure 1.** Regime parameters of the Baksan river flow related to its power generation function.

Figure 1 shows a graph of the average monthly water flow rate, characterizing the mountain river as glacier-fed. However, hydrograph values are not enough for hydropower calculations — the volume...
of water that can pass through the cross-section at each moment of time shall be known as well. It is difficult to do this based on the dynamics of average monthly flow rates, therefore the integral flow rate curve has been built. The figure indicates that the total water flow rate has a stable growth trend. Inflections in the flow rate curve correspond to the extreme on the hydrograph. If the horizontal axis is drawn to scale, then the perpendicular from the curve to the horizontal line will show the water flow rate at any time moment.

The proposed location of the station — at the mouth of the Gundelen river, 2 km above the water intake dam of the operating Baksan HPP — can be considered a competitive advantage of the Zayukovsky cross-section. The reservoir, which may cover almost the entire catchment area of the Baksan basin, will allow to efficiently control flow fluctuations. A serious advantage of this stretch is a likely high specific volume per 1 m$^3$ of the dam body volume, as well as a more convenient transport infrastructure at the period of active construction of the facility. This solution to the problem is more preferable as well, as the construction site can be directly powered (without losses) from Baksan HPP.

For the Zayukov hydropower unit, it is more convenient to place the dam and the building of the hydroelectric power station 1.5 km downstream of the Baksan river, at the end of the diversion pressure tunnel. Placing the hydroelectric power station building near the dam can be also considered, which can be connected to the water storage facility with a short pipeline embedded in the tunnel. The dam of the Zayukov water storage facility should be constructed 75–80 m higher than the current low-water level of the river, which will provide a safe flow rate of 90–100 m$^3$/sec during flood period. The inclusion of a tower-type water intake in the power plant design will allow to use part of the "dead" volume of the reservoir to equalize the water flow in the first years of its operation.

At the same time, the geological conditions of the considered cross-section are not yet clear enough. The presence of Jurassic limestones on the stretch will inevitably require additional investment for cementation of the valley base and its right slope. The overheads may increase due to the need to conduct exploratory drilling, assess the filtration coefficient of slopes and the future foundation of the dam, and study the suitability of local building materials for the dam body. These surveys will give the final answer to the authors' proposal on the technical and economic feasibility of the construction of Zayukov HPP.

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Simultaneously with the hydropower system construction, the Baksan HPP dam crest should be slightly raised to obtain additional volume, which will be safe from mud filling from the Zayukov pool, and allow more efficient use of the flow.

The search for the optimal alternative of flow control necessitates the study of non-valley methods of influencing the water flow rate [5]. The most feasible reservoir alternative to be used as a water storage function is Syltran-Kel lake. Schematically, the proposal can be formulated as follows: raising the reservoir shore by means of a 30-meter dam will create a solid 1700-meter head on the hydroelectric power station turbines; the accumulation of the total runoff of the Kyrtys river and its tributary, Syltran-Su, in the basin of the Syltran-Kel high-mountain karst lake will ensure uniform water supply to the working surfaces of the unit [6]. This engineering approach will ensure the concentration of the entire high-mountainous runoff of the region in the lake basin, which will allow to obtain a highly efficient flow control system at a much lower unit cost compared to a hydropower unit with a valley reservoir. This calculation is based on a high predicted value of the specific pressure per 1 km of the diversion system, which length can reach 4000 m — a 2 km tunnel and a pressure pipeline with a length of 2.7 km.

The considered flow control system design is relatively complex, which dictates the need for phased commissioning of individual elements of the hydropower system. The first commissioning stage of the hydroelectric power station can use the waters of only the Syltran-Su river accumulated in the basin of Syltran-Kel. At the second stage, construction and installation work should be aimed at a consistent increase of the hydroelectric power station power output by staged collection and transfer of runoff from the adjacent basins of small rivers Mkyara, Mukal and Su-Bashi to the lake basin. The runoff of the mentioned rivers can be concentrated by a system of drainage channels and transferred by a kilometer tunnel into a lake with forced water pumping. This technical solution would
allow to maintain an almost year-round pressure in the system. The power supply needed to raise the runoff of small rivers into the reservoir can be obtained from Syltran HPP during the summer months, when there is excess capacity in the energy system.

A similar regulating hydroelectric power station, presumably, can be designed on the Giy-Bash-Kelkarst lake. It is located between the basins of the Cherek-Balkarsky and Cherek-Bezengiysky rivers. However, the authors have not yet succeeded in formulating an acceptable solution for incorporating the reservoir in the hydropower industry of KBR.

It is less problematic to control the flow of the Malka river, which has a relatively uniform water flow rate. The pronounced natural stabilization of the river's flow is due to strong groundwater supply. This aspect, among other things, makes the Lakhran gorge located below a vast basin with a strong groundwater supply a perfect cross-section for creating a water storage facility.

Taking into account the coefficient of natural regulation of the Malka river (0.2–0.25), i.e., the reservoir volume required for the full annual water flow control as a percentage of the annual river flow, the reservoir can become the head one for the proposed cascade of hydroelectric power stations at Malka. This will allow to control the entire river flow and consistently equalize the potential generation of electricity by all hydropower plants on the watercourse.

The estimated volume of 80 million m$^3$ of water required to stabilize the river flow can be roughly concentrated in a reservoir with a 100-meter dam. It can be built on dense serpentinites that make up the bottom of the gorge. The Lahran plant can have a dam-diversion system with a diversion tunnel length of about 6 km and an installed capacity of 25 MW.

Other cross-sections of the mountainous region not included in the five preferable ones have various limiting factors, such as unfavorable topographic or difficult geological conditions. For example, the cross-section of the Chegem river valley upstream of the Basmaly-Su river mouth (between the Su-Auzu gorge and the Nizhniy Chegem village) requires additional study. In a first approximation, using this gorge for hydropower construction would allow to supply the controlled flow of the Chegem river to the adjacent Baksan basin (to the Buru-Kol river mouth) and to the upper pool of the Baksan hydroelectric power station, which will likely lead to an increase in the capacity of the latter.

Before constructing the water storage facilities, the seasonal and long-term runoff of glacier-fed mountain rivers shall be forecasted, means for establishing a guaranteed water level shall be created in the upper and lower pools of the proposed water control structures, as well as measures to prevent ice phenomena [7].

The greatest technical and economic effect is expected from advance forecasts of seasonal (partial seasonal) runoff, which can be used to establish the volume of pre-flood water drawdown. The capacity of a hydroelectric power station with seasonal river flow control is determined by values of flow rates and heads depending on the reservoir water volume. The water volume can be calculated by the formula:

$$V_t + \Delta t = V_t + (\Delta W - Q \cdot \Delta t)$$ [8], where

- $V_t + \Delta t$ – water volume at the moment $t + \Delta t$;
- $V_t$ – water volume at the moment $t$;
- $Q$ – water flow rate through the hydroelectric system.

For the Malka River, a flow rate of 23–24 m$^3$/s can be considered as such, which is observed in April in most cases; the flow rate of pre-flood drawdown at Baksan water (near Zayukovo village) is within 30 m$^3$/s, which is stabilized a little later — in May due to more pronounced glacial feeding of the river (Table 2).

Calculations of water flow rates for the seasons, when the runoff from the melting snow and glaciers accumulated during the winter plays the main role in the river feeding, can be carried out using the ratio:
\[ Q_s = Q \frac{S_x}{S}, \text{ where} \]

\[ Q, \text{ and } Q \text{ – water flow rates in the desired and initial cross-sections, } m^3/s; \]
\[ S, \text{ and } S \text{ – areas of ice formation above these cross-sections, } km^2. \]

During the spring-summer season, the correlation between water flow rate and glacier areas is almost linear.

The basis for an unbiased long-term forecast is a reliable estimate of the volume of solid precipitation accumulated over the winter. If the forecast shows that the river flow rate is expected to be higher than the norm, then a drawdown shall be made to a lower horizon and a large free volume shall be prepared for receiving additional flood water volumes. If the flow rate is expected to be lower than the average long-term norm, then the water level in the water storage reservoir shall be purposefully raised to avoid the risk of operation of hydroelectric power stations with excessively low heads. Underproduction of energy by hydroelectric power plants can lead to the following social and economic consequences: at best — electricity being purchased in neighboring regions, at worst — temporary restrictions on electricity consumption for the population and business entities [1].

At the same time, this approach does not fully factor in the current, often abundant precipitation, which can lead to underestimation of the expected flow rate values. In such a case, the anticipatory idle water discharges are unfulfilled, which may threaten the safety of power plants and settlements.

Forecasts of water flow rate are of practical importance not only for operation, but also for the construction of hydroengineering structures [9]. Critical economic consequences can be caused by an error in the assessment of the optimal estimated flow rate during the construction of a hydroelectric power station. Flow rate forecasts are extremely important during the preparation for river damming — the minimum water flow rate and the specified dates of its occurrence shall be known, as well as the amount of material required for back filling and dumping into the passage, etc.

**Table 2.** Long-term values of water flow rate of some rivers within the mountainous zone of KBR [6].

| Rivers          | Metering station              | Catchment area km² | Average monthly water flow rate | Annu al water flow rate, m³/s |
|-----------------|-------------------------------|--------------------|---------------------------------|-------------------------------|
| Malka           | Kamenno-mostskoe village      | 1540               | 7. 6. 7.                       | 23 33 39 46 52 80 20 14 11 19 |
| Baksan          | Tegenkli village              | 180                | 2. 2. 2.                       | 3. 8. 20 31 28 13 6. 5 4 3.4 10 |
| Baksan          | Zayukovo village              | 2100               | 10 9. 9. 9. 14 30 61 91 84 45 23 16 12 34 |
| Cherek          | Kashkhatau settlement         | 1350               | 10 9. 9. 9. 9 7 35 70 112 107 54 25 16 12 39 |
| Cherek-Balkarsky | Babugent settlement           | 695                | 6. 6. 6. 9. 9 6 23 46 73 70 38 16 10 7.9 26 |
| Uurkh           | Tashly-Tala village           | 1150               | 3. 4. 4. 12 19 24 25 21 15 12 9. 7 7.9 14 |
| Chegem          | Chegem town                   | 739                | 3. 3. 3. 3. 2 24 39 37 19 8. 5. 3.9 13 |
| Nalchik         | White river                   | 140                | 8 8 2. 2 3. 2 8 8 2. 1. 8 2 1. 0. 2.1 |

In no forecasts are available (or neglected), an alternative approach to flow rate optimization can be a constant volume of drawdowns, calculated for the average multiyear flow rate during the flood.
period. For Baksan, this period coincides with July-August with values of 91.2 and 84.3 m³/s, respectively. The maximum Malka flow rate is most often observed in August-September (Table 2). If the actual runoff volume turns out to be higher than the forecasted value, then idle water discharges may be required in order to free up a part of the storage reservoir for flood waters; if the runoff values is lower than the forecasted, then by the end of the flood (the end of September for Malka, the end of August for Baksan), the flow control facilities may have water volumes lower than the normal headwater elevation. Consequently, HPPs will have to operate at a reduced head during a certain period, i.e., the plant will generate less power at the same water flow rate. In the first case, the power losses will be proportional to the volume of idle water discharges, in the second — the loss of a part of the water head during the time required to restore the normal headwater elevation [2].

Thus, well-grounded forecasts of water flow rate will allow to select the optimal mode of pre-flood drawdown of water reserves in water storage facilities. Flow rate forecasts, reduction of idle discharges and the time when hydroelectric power stations operate with a reduced head will allow to significantly increase the stability of the hydropower industry operation in the mountainous zone will. The higher the predictability of river flow rates, the higher the total power generation and the economic effect from considering the reasonable forecasts. The economic effect of forecasts over a number of years will be expressed by the difference between the total gain from successful forecasts and the total damage from unsuccessful ones. Collecting complete information about the actual reserves of solid precipitation in the mountains of KBR, as well as the extensive information on river flow rates, may serve as a strong base for successful forecasts, which will most likely lead to the optimal combination of reliability and economic efficiency of the power units being built [3].

3. Conclusions
The main production and economic risks of the hydroelectric power plants operating in KBR are associated with the extremely weak control of their capacity due to the seasonal flow variability of mostly glacier-fed mountain rivers. Meanwhile, the authors assume that year-round control is possible only in exceptional cases.

The cross-section in the Lakhran gorge was determined as the optimal location for a flow control facility on the Malka river, and it should also become the primary power unit on the watercourse. The reservoir will stabilize the seasonal water flow rate and capacity for all the prospective river stretches downstream — Khabaz, Kamennomostsky, Sarmakovskiy. Without the construction of the Lahran power unit, the prospective diversion systems will only be able to control daily flow rate fluctuations and be characterized by high fluctuations in their capacity.

Out of the 3 indicated preferable cross-sections in the Baksan river basin, Zayukov flow control facility shall be built in the first turn. The water storage reservoir to accommodate almost all the Baksan water flow will allow to efficiently control the fluctuations of the glacial runoff.

Along with the conventional flow control by means of a valley reservoir, the Baksan river flow rate can be alternatively equalized by accumulating the river flow from adjacent basins in the basins of Syltran-Kel and Giy-Bash-Kel lakes.

The power generated by hydropower units is a function of both water head and water flow rate. Ultimately, the required HPP capacity can be achieved by predicting the natural water flow. A reasonable water head is created by controlling the flow, as well as the energy system design adapted to the natural landscape specifics. Only by having the optimal combination of the flow rate and water head control, the required power of the hydroelectric power station and highly profitable electricity production can be achieved.

Thus, regulating the flow of glacier-fed mountain rivers is an essential condition for increasing the production stability and economic efficiency of hydroelectric power generation in the mountainous regions. New hydropower plants with flow control capabilities will provide KBR with new capacities and increase the sustainability and efficiency of already operating hydropower plants.
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