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Artificial mountain glaciers for water supply in the eastern Ciscaucasia

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ABSTRACT The paper deals with a method of reducing the need for water transportation and water scarcity in the BRICS countries using the example of the eastern Ciscaucasia of Russia, where reservoirs are losing a large amount of water through evaporation. It is proposed to take in a supply of water for agriculture, urban and transport infrastructure by reducing the rate of spring melting of high-altitude snow by building large ice pools at the sources of mountain rivers. Pools are horizontal platforms with a cold base, where the rate of melting of winter snow is minimal. They will reduce the intensity of spring floods which cause mudslides, water loss, and destruction of transport infrastructure. Ice pools are built by building a cascade of prefabricated lightweight wooden barriers that are assembled on site without heavy machinery. The cascade of barriers ensures that ice pools grow in winter and accumulated ice is preserved in summer without changing the flow of the river. The cascade is periodically made taller, contributing to the growth of the ice basin up to the formation of a new mountain glacier with up to 3 million tonnes of water over 8–10 years of construction.

KEYWORDS: water supply to agricultural lands; transport infrastructure of the Ciscaucasia; slowing down the melting of mountain snow; restoration of mountain glaciers; hydraulic engineering; accumulation of water in ice basins; control of mudflows

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Научная статья

Искусственные горные ледники для водообеспечения Восточного Предкавказья и снижение потребности в транспортировке воды

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АННОТАЦИЯ Рассмотрен способ снижения потребности в транспортировке воды и водного дефицита в странах БРИКС на примере восточного Предкавказья России, где в водохранилищах наблюдают большие потери воды на испарение. Воду для сельского хозяйства, городской и транспортной инфраструктуры предлагается запасать, сокращая скорость весеннего таяния высокогорных снегов строительством больших ледовых бассейнов в истоках горных рек. Бассейны представляют собой горизонтальные площадки с холодным основанием, где скорость таяния зимних снегов минимальна. Они снизят интенсивность весеннего половодья, вызывающего сходы селей, потери воды, разрушение объектов транспортной инфраструктуры. Ледовые бассейны возводятся строительством каскада легких деревянных заграждений, изготовленных в заводских условиях и собираемых на месте без тяжелой техники. Каскад заграждений обеспечивает рост ледовых бассейнов зимой и сохранение накопленного льда летом без изменения стока реки. Каскад периодически надстраивается, обеспечивая рост ледового бассейна вплоть до образования нового горного ледника массой до 3 млн тонн воды за 8–10 лет строительства.

КЛЮЧЕВЫЕ СЛОВА: водообеспечение сельскохозяйственных угодий; транспортная инфраструктура Предкавказья; замедление таяния горных снегов; восстановление горных ледников; гидротехническое строительство; аккумулирование воды в ледовых бассейнах; борьба с селями

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INTRODUCTION

Like many BRICS countries, the regions in the South-East of Russia, including the Eastern Ciscaucasia, are facing an acute shortage of fresh water.

The risk of desertification in these areas is reduced by slowing down the spring melting of snow in the mountains. It is proposed to store water in high-altitude ice pools rather than on farmlands where reservoirs occupy useable areas and lose a large amount of water through evaporation [1]. The idea has been already implemented by an Indian civil engineer Chewang Norphel from Ladakh (the western Tibetan Plateau, India) [2], who built 12 ice pools. Water was accumulated in the pools in autumn, while in winter, the pools froze to the bottom, and in spring the ice melted turning back to water which ran off to fields, just in time for the season of sprout development.

Norphel's pools turned out to be expensive structures. They were designed for watering fields with an area of 10–15 hectares each in summer, while building them required a large amount of manual work.

The Ciscaucasia is the main breadbasket region of Russia, and its eastern part has been facing a shortage of fresh water, which is rapidly growing. The method used by Chewang Norphel to accumulate water in the form of ice should be seen as a successful approach, but in the North Caucasian Federal District of the Russian Federation, the idea could be developed even further, to the extent of the recreation of retreating glaciers where the reserves of ice could reach as high as several millions of tonnes. Moreover, the construction can be completed with minimum consumption of material supplies, manual work and construction materials.

OVERALL SITUATION IN THE NORTH CAUCASUS

The Russian section of the Caucasus lies on the border between the moderate and subtropical climate belts, with the heat flux of solar radiation getting to the ground being on average 1.20 KW/m^2. About 85 % of the area of the flat lands in the Ciscaucasia is accounted for by plough lands which require a large amount of water in summer. More than 25 % of that is provided by rivers that are formed by the melting of high-altitude snow and glaciers [3].

With every 100 meters up, the annual average air temperature drops by 0.7 °C; and in the Caucasus Mountains, the permanent snow area starts at a height of about 2,800 metres. At a height of about 2,000 metres, winter temperatures reach as low as minus 20 °C to minus 25 °C. Days are hot in summer, while nights are almost cold; and in mid-autumn, the air cools down to temperatures below zero in the daytime.

In Russia, the Great Caucasus currently has 1,498 glaciers with a total area of 993.6 km^2; all of them are retreating, their lengths getting shorter by 30–40 metres every year[1].

The main rivers in the Ciscaucasia that flow to the Caspian Sea — Baksan Malka and Terek — form a chain. Their characteristics are listed in *Table 1*.

All these rivers are essential in terms of water management. They have reservoirs for feeding agricultural lands in the Ciscaucasia, but in the summer season,

Table 1

Characteristics of the main rivers in the Ciscaucasia [4]

River	Length, km	Basin, km^2	Source	Mouth	Water flow at the mouth in summer, m^3/s
Kuban	900	61,500	Elbrus	Sea of Azov	425
Baksan	173	6,800		Malka River	33.6
Malka	210	10,000		Terek River	97.8
Terek	623	43,200	Zilga-Khokh	Caspian Sea	305

[1] Ciscaucasia. The Great Russian Encyclopedia. 01.12.2023. URL: https://bigenc.ru/c/predkavkaz-e-ab07fe

when water evaporates intensely, water losses may exceed 40–50 % of the original amount[2].

The transport sector is one of the leading ones in the economy of the North Caucasian Federal District. Water supply to the transport sector is key to the quality of life and work of residents in the region.

The district lies at the intersection of major freight flows that connect Russia and foreign markets; therefore the transport sector accounts for more than 10 % of the total Gross Regional Product. The total length of railways in the North Caucasian Federal District is about 3,000 km; however, the dominating transport mode in the region is road transport. The length of motor roads in the North Caucasian Federal District is 24,788 km, including 2,577 km of federal roads and 22,211 km[1] of regional roads.

The Makhachkala Commercial Seaport is one of the key links in the system of transport services on the Caspian Sea. It is part of major plans for the development of the North – South transport corridor which is created with the involvement of BRICS countries. The corridor is a global project aimed to integrate Russia into the global freight traffic system, which is intended to reduce two times the distances and costs of transportation and provide access to transport systems in the Caspian countries of Middle Asia, Iran and the Gulf countries.

Difficulties and drawbacks in transport and logistics services in the North Caucasian Federal District are largely due to the region's terrain.

There is a risk of long-term failure in the operation of roads if affected by mudflows from numerous mountain gorges. Statistics show that boulders usually account for 33 to 46 % in a mudflow centre and 43 to 80 % in mudflow cones on road surfaces [3].

Each mudslide occurrence blocks traffic on the affected road for a long period of time, and repair works may take a few weeks due to difficulties with delivering heavy road machinery. Losses from unscheduled suspensions in the operation of roads may reach as high as hundreds of millions of roubles.

The challenges of improving the provision with water in the eastern part of the North Caucasian Federal District and control of mud and rock slides are addressed on a comprehensive basis. In this paper, we will consider ways to address these challenges by assessing the water regime for just one river — the Baksan River. It is the first section in the net of the rivers Baksan, Malka and Terek.

In addition to numerous creeks, the Baksan River is supplied by eleven smaller rivers that have similar characteristics[2]. It is enough for us to consider only its first tributary which joins the Baksan River 15 km away from its source. The tributary is the 12.8-kilometre long and about 30-metre wide Adyl-Su River with the bed slope ranging from 0.003 to 0.02, and the average slope of 0.01.

ACCUMULATION OF ICE FOR WATER SUPPLY OF PIEDMONT AREAS IN SUMMER

Let us consider the physical properties of water that ensure the accumulation of eternal snow high in the mountains. These are listed in *Table 2* [5–7].

Ice and snow have a very high albedo of solar radiation and high heat of phase transition; water has a high specific thermal capacity; and snow has a low thermal conductivity. Therefore when the ice is covered with snow it is difficult to turn it into water with the heat of solar radiation. It is also problematic to turn liquid water into ice when it is under a layer of ice and snow in a water body [8].

The anchor ice at the bottom of a water body maintains its state throughout the summer when it is sunny and the air is warm [9], and water under the surface ice on rivers and water bodies remain liquid throughout the winter even when frosts are severe. At the same time, water freezes very quickly when there is a large area of heat and mass exchange with the cold atmospheric air [10, 11].

Table 2

Physical properties of snow, ice and liquid water

State of water	Solar reflectance (albedo) at normal incidence	Thermal conductivity λ, W/m·K	Specific thermal capacity *C*, kJ/kg·K	Heat of phase transition *r*, kJ/kg	
				melting–solidification	evaporation–condensation
Ice	0.90	2.21	2.2	336	2352
Snow	0.93–0.95	0.1–0.35	2.2		
Liquid water	0.1–0.2	0.586	4.2		
Soil, granite	0.12–0.15	2.3–2.9	0.96–1.24	–	–

[2] The scheme of comprehensive use and protection of water bodies in the Terek River basin (Russian part of the basin). *Appendix to Order of the West Caspian Basin Water Authority dated November 10, 2014 No. 62-P. Appendix 2*. Consolidated Explanatory Note.

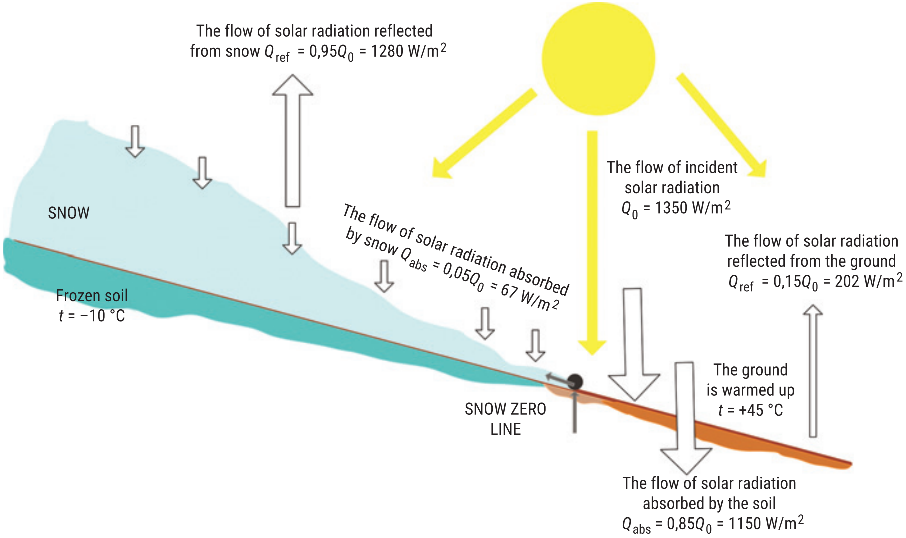

Fig. 1. Distribution of heat flows from solar radiation on a mountain slope at the snow zero line level

Ice is a good construction material for building engineering structures on site and operating them during the winter season. While easily cut with metal drills, it can withstand significant mechanical loads from pile fields placed on it for building various structures [12, 13].

Ice features fluidity and can spontaneously slide down a mountain slope [14, 15]. Therefore the melting rate of snow and glaciers in the mountains depends not only on their exposure to the sunlight, but also on the steepness of the mountain slopes. When sliding down along abrupt sections of a slope, a glacier cracks under its own weight — a phenomenon known as ablation. Cracks from ablation are about 1 metre wide and more than 70 metres deep. In summer, the walls of cracks in the ice melt in the warm atmospheric air and streams of meltwater are formed under the base of a glacier [16]. The glacier becomes a feeder for the river which forms below it.

The rates of snow melting on mountain slopes in spring are high, which is also explained by differences in the physical properties of ice and soils that become exposed on the mountain slope. The moving lower boundary of a snow cap on a mountain is referred to as the “snow zero line”; it moves down to the foot of the mountain in winter and goes up in spring [15, 16].

Figure 1 shows the components of the heat flow from the Sun. On a mountain slope, the density of a heat flow that heats the soil under the snow zero line is Q_{absorb} ≈ 1,150 Wt/m^2, and the soil temperature can exceed +50 °C. Featuring high thermal conductivity values $\lambda_{granite}$ = 2.91 Wt/m·K and λ_{graund} = 3.66 Wt/m·K, granite and soil transfer heat under the lower edge of the snow cap. Snow melts on the heated soil and water flows down the slope without absorbing thermal energy for heating or evaporation. The soil and granite dry out and heat up, causing the snow zero line to quickly move upward.

The rapid snow melting creates torrential streams that race along gorges in the form of mudflows [3]. They flood the flat-bottomed areas and destroy infrastructure facilities, causing huge losses of water which is so valuable in the summer season. By slowing down the rapid melting of snow in the mountains, this water could be preserved in the form of ice in the mountains and then rationally used to feed reservoirs in the summer.

Ice slides down and water flows down a mountain slope, and the steeper the slope, the faster. But on a horizontal high-altitude site with a cold base, the snow cap can lie throughout a sunny day reflecting up to 95 % of the energy of incident solar radiation. A small portion of snow melts, but water does not flow down, but instead soaks the lower layers of snow that freeze down during cold nights. This equilibrium may continue as long as throughout summer and autumn, and in winter, the weight of the snow cap on the mountain will grow from snowfalls.

As a result, growing snow caps are formed on horizontal high-altitude platforms and turn into glaciers over time; therefore creating an artificial glacier exceeding one million tonnes in weight requires vast ice pools of several hundred square metres with a horizontal surface to be located as a cascade over a mountain river somewhat below the glaciers that feeds it.

STEPS FOR BUILDING AN ARTIFICIAL GLACIER IN A NARROW GORGE

Let us return to the construction of a large, about 2-kilometres long ice pool, taking the high-altitude site of the Adyl-Su River as an example. The glacier that

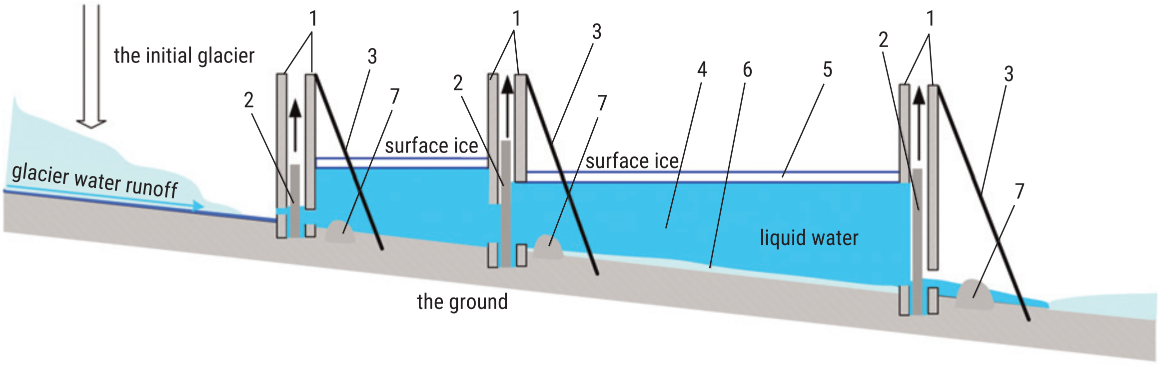

Fig. 2. Scheme of hydraulic structures to be built in a narrow gorge on a mountain river bed for the creation of an artificial glacier [17]

feeds it is located in a canyon where a cascade of cheap wooden barriers can be installed for short-term use.

High in the mountains, it is impossible to use heavy-duty construction machinery; therefore only structures made of easily transportable elements, such as rectangular timber, prefabricated metal screw piles and mounting hardware, should be assembled at the construction site. However, ice that forms at the site during the construction period should be used as the main construction material.

Wooden barriers on piles are consumables. As the glacier grows, they become frozen into the ice and, if necessary, are removed at the stage of construction and replaced with new ones; some of them can be reused.

The structural layout is shown in *Fig. 2* [17]. Assume that the cascade is formed of ten barriers *1*, each of which has a discharge gate *2* that can be moved vertically. Barriers *2* are provided with inclined supports *3* which make them stable.

Small reservoirs filled with water *4* are formed between the barriers. When it is frosty they are covered with a layer of surface ice *5* that provides thermal insulation of the water *4* from the cold air [8]. As the cascade is operated, masses of bottom ice *6* will accumulate on the bottoms of reservoirs. A water drain *7* is an auxiliary component — the water stream going through the discharge gate *2* flows over this lateral barrier.

If with the width of the canyon $L \approx 60$ m, a channel slope $k \approx 0{,}01$, and a barrier height $h_1 \approx 2.5$ m, the distance between the barriers is $l_3 \approx 200–300$ m, then the difference in height between their bases will be $h_2 \sim 2–3$ m. The average depth of the reservoir will be $l_2 \approx 1.8$ m, its area will be $S \approx 1500$ m^2, and its volume will be $V \approx 37{,}000$ m^3. The total amount of water in the cascade will reach ~0.33 mln m^3.

Let us assume that the construction begins in the late autumn when the river at the feeding glacier has a small runoff with a narrow channel of 2–3 m.

Small indentations about 0.5 m deep are made in the ground at open sections of the canyon under the feeding glacier for the installation of metal piles that two workers can move by hand [17, 18].

Once the piles are secured, rectangular timbers are attached to them to build a barrier with a height of $h \approx 2–2.5$ m across the river bed and a discharge gate *2* for releasing water to the reservoir downstream.

In the original state, the gates *2* are closed at all barriers except for barrier *1*. A cascade of small reservoirs of 2 to 2.5 m is formed between the barriers. These are filled with water that flows through the canyon from under the feeding glacier above the cascade.

In winter, the flow rate in the feeding glacier drops to the minimum level and each reservoir will have still water. In frosty weather it will freeze on the surface to form surface ice.

The lower reservoir of the cascade with the open gate *2* freezes down to the bottom to form an "ice bed" — a horizontal platform with a cold base. When it is formed, the discharge gate *2* at the lower reservoir is closed. Then the gate at the second reservoir is opened to let the water from it be discharged intermittently, with long pauses, onto the ice bed of the first reservoir where it freezes quickly.

In two or three days, the second reservoir is gradually discharged into the first one to turn it completely into an ice pool. In the second reservoir, the surface ice descends to fall upon the ground and freeze to stones forming an ice bed in the second reservoir which is consolidated with the ice bed in the first reservoir. The same pattern with waiting for the water to fully freeze on ice beds of upstream reservoirs is followed to discharge water from the reservoirs of the entire cascade, thereby turning all of its reservoirs into a large ice pool [19].

When the spring comes, the discharge from the feeding glacier increases and cold water of about plus 2–3 °C runs off from it down along the gorge across the cascade of ice pools. The ice in the reservoirs will turn into anchor ice. Protected against solar radiation and the warm atmosphere by the layer of flowing cold water, the anchor ice will retain its mass throughout the summer. The flow rate in the river will be maintained at the original level.

By the following autumn, works on the cascade will be resumed to add new pile fields connected between each other with light partitions to all of the barriers. New barriers will be installed on a bulky smooth surface ice bed which is approximately 2 km long with a maximum thickness of about 20 m in its lower portion.

By the end of the first winter, a large horizontal platform will be formed high in the mountains, on which a mountain glacier will grow from winter snowfalls over the next 8 to 10 years.

The reduction of the river bed slope to zero on horizontal platforms along the gorge will prevent the emergence of mudslides on them.

Approximately in 10 years, a new glacier can reach as high as ~60 m, 2–3 km in length, and have up to 3 million tonnes of ice.

As the glacier ablates, deep cracks will appear, and the melting of ice on the walls of cracks will increase the flow of the Adyl-Su River.

The new glacier will make the glacier that currently feeds the Adyl-Su River 2 to 3 km longer, thereby making up for its retreat over the last 80 to 100 years.

Upon the completion of construction, all of the timber elements of hydraulic structures will be dismantled and removed. The recreational area for the tributaries of the Baksan River will remain unaffected.

Glaciers to be recreated in the upper reaches of all the eleven small tributaries of the Baksan River alone can increase its summer runoff to the existing reservoirs in the eastern Ciscaucasia almost 8.5 times.

CONCLUSION

The paper proposes a comprehensive method for improving water supply in arid areas in the Ciscaucasia, while reducing the risk of large-scale mudslides during spring floods, which make it difficult to operate road infrastructure facilities in the region.

The method relies on slowing down the melting of snow in high-altitude mountain areas by creating large ice pools in areas with low annual average air temperatures which usually entail intense snowfall. Ice pools are planned to be built in the upper reaches of small mountain rivers that are fed by existing glaciers.

The physical properties of water, snow and ice allow for accumulating water in winter in the form of ice that forms on the cascade of smaller pools built according to temporary process flow diagrams using light barriers in a gorge along the river bed at its mouth under the feeding glacier.

In summer, ice accumulated in winter is transformed into anchor ice which is protected against solar radiation and atmospheric air by a layer of cold water received from the feeding glacier that flows on top of the ice. Ice will accumulate for several years before a new glacier is formed from the ice pools. With a weight of about 3 million tonnes, it will make up for the degradation of the original feeding glacier. Ablation of new glaciers will increase the runoff of rivers that belong to the basin of the Terek River which feeds water reservoirs on agricultural lands in arid regions of the eastern Ciscaucasia.

The method is very simple to implement and does not require any large capital investment. It contributes to the development of transport infrastructure in the region and can be a promising focus area for may BRICS countries that are facing shortages of water in land use. The method will improve the quality of living for residents in the region and can be a starting point in combating global warming of the climate on the Earth.

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