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# The Experimental Research of Ablation of Adishi Glacier Tongue

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**Abstract**

The study of glacier mass balance is gaining significant interest worldwide against modern global climate change. Using Drone gave good results in glacier mass balance studies. There is a sizeable difference between the values obtained by the modern and previous used methods, which is primarily because of the shortcomings of the old one. We believe the results obtained cause the revision of the old data of the mass balance ablation component. Therefore, it became essential to restore the observation series and determine the compatibility of the data obtained by the old, traditional methods with the data obtained using new, modern technologies. The study aimed to compare the results obtained by standard ablation studies (ablation stake) and modern aerial photogrammetric methods based on actual observations in the Adishi glacier tongue.

**Keywords**: Ablation, Glaciers, Mass Balance

## Introduction

Glaciological studies are of great importance in the context of global climate change. The urgency of the study is determined because glaciers are the best natural fixer for climate change. At the same time, glaciers are the largest reservoirs of freshwater. Glaciology requires interdisciplinary researches, requires climatologists, hydrologists, geomorphologists, tourism specialists, etc. joint studies and vision. At present glaciers are melting faster resulted in water balance change. Along with environmental problems, this will lead to natural disasters.

The studies of glacier mass balance on the southern slope of the Caucasus have not been conducted for the last 30 years. Semi-stationary (ablation period) combined glacial-hydro-meteorological observations on the Glaciers in the river Enguri, Rioni and Tergi basins have been performed by the Vakhushti Bagrationi Institute of Geography since the 1950s, many materials on glacier mass balance, motion dynamics, glacial zone microclimate, river runoff of glacial feeding, etc. have been collecting. The Tbilisa Glacier (Central Caucasus, Rioni Basin) was selected as the sample for the most extended, 22-year continuous observation series. The monograph reflected the observation results [1, 2]. Due to well-known events (1990s), those observations were terminated. Scientists of the Institute have recently updated studies conducted using modern technologies. The measuring method of the glacier consumption (ablation) has been significantly changed.

## Study Area

The Adishi glacier is located in the Samegrelo-Zemo Svaneti region of Georgia. A southwestern exposure on the southern slope of the Central Caucasus represents it. Its area is equal to 9.50 km$^2$, and its length is 9.46 km.

The firn of glacier basin is located at an altitude of 3800 meters. It has a 1200-meter icefall, and the tongue of the glacier descends to 2442 meters [2]. According to the scientific research program of the Institute of Geography, it has been determined to update glaciological studies. For this purpose, during June-September 2019 period, field observations were conducted on the Adishi Glacier using both traditional and modern technologies.

## Methods and Materials

### Stake method

Generally, the surface ablation accuracy calculated by this method greatly depends on the frequency of the stake net. The stake quantity is defined according to the study area and pollution degree of the glacier tongue surface. This network must cover the entire range of the glacier tongue and, as far as possible, the sharply outlined characteristic points - pure ice and surface covered with a layer of moraine material of different thicknesses. Usually, the systematic periodic observations are carried out in the morning or in the evening, which involves the data fixation on the stake and new drilling, so while

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determining the optimal number of the stakes, the technical factor must be considered - the number of observers and the speed of drilling. Before the beginning of fieldwork, the network of ablation stakes must be formed in advance using satellite images and be specified directly in the field.

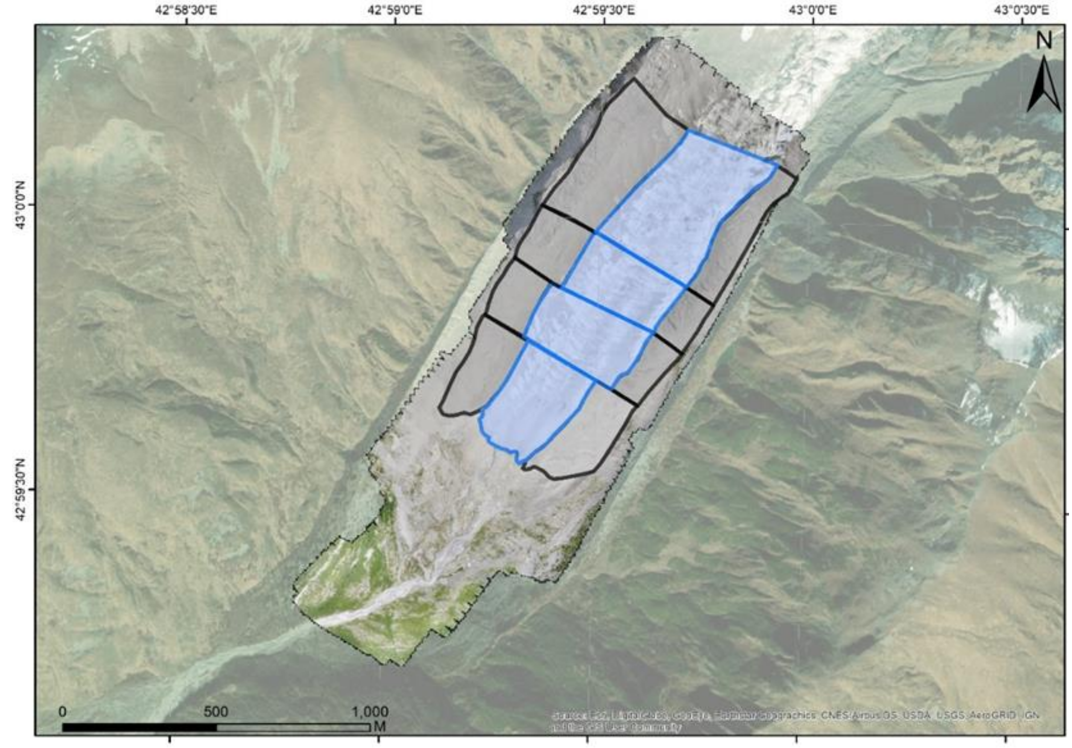


*Figure 1. Zoning of glacier tongue*

In our case, the Adishi glacier tongue has been divided into four zones (fig. 1). It allocated three characteristic surfaces in each zone: pure ice (central part), weak moraine cover (left part), and moraine-covered ice (right part). The melted volumes of the glacier in each zone are determined by the sum of the weighted volumes of the ice and moraine-covered ice surfaces and the melted volume of the entire tongue - by the sum of the volumes calculated according to the zones. The ice drill was used to drill the glacier's surface, and the 20 mm diameter and 4m length plastic pipes were used as stakes.

For the calculation of glacier surface ablation, the accuracy of the measurement of the glacier tongue and the areas of its characteristic zones is of great importance in terms of the reliability of the final results. We should note that prior to the application of the high-resolution satellite images in glaciological studies, topographic maps were mainly used, which have been updated by multi-year periods. We have realized the transfer of the area data taken from topographic maps to actual ones considering the angle of inclination of the glacier tongue [3, 4]. Besides, the surface of the glacier tongue drawn on a topographic map represents a less flat area than the actual relief area. Naturally, the accuracy of the surface melting calculated from such measured area data would not have been high in the conditions of the dynamic processes activated in the glacial zone in the last decades. Moreover, drawing the contours of the glacial surface covered by the moraine through satellite images is also associated with factual errors and requires correction in conducting direct observations in the field.

Here we will focus on another problem related to calculating the moraine-covered glacier surface ablation. It is known that, compared to the pure ice surface, the intensity of surface ablation covered with a certain amount of thin moraine material increases because of the heating of the latter by the effect of additional heat transfer to the ice surface. As the moraine capacity increases, the impact of surface heat energy on the ice melting weakens and ceases completely. There are universal curves that reflect the relationship between glacier surface melting and moraine strength, which is the basis for many experimental field studies [2]. However, they cannot wholly reflect the full range of the process, as the drilling of ablation stakes on the ice surface covered with thick moraine material or the area arrangement of runoff in such sites is associated with difficulties. In addition, using this type of data for the entire surface of the glacial tongue gives errors because the process of contamination of the glacial tongue with moraine material is dynamical and poorly studied.

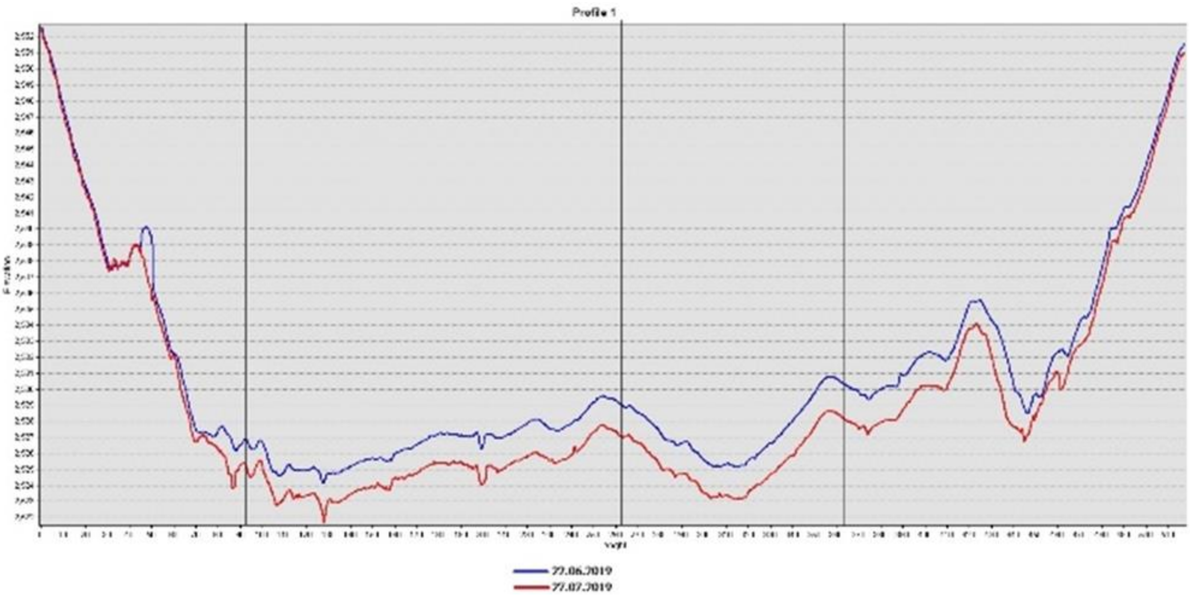


*Figure 2. Transverse profiles of Adishi glacier tongue in June and July, 2019 according to Zone I (Blue-June, red-July); Vertical lines indicate the locations of the ablation stakes*

To solve these problems, we used data obtained using drones. In particular, during each repetitive drone session, the data expresses the descent of the glacier tongue and, consequently, the static state of non-glacial surfaces at the edges. In this way, the Drone data allows us to assign the area contour involved in the glacier's ablation tongue with high accuracy.

*Table 1. Areas and average heights according to the zoning*

| Zones | Avg. elevation, m. | Area, $m^2$ | | |
|---|---|---|---|---|
| | | Total | Moraine covered | Pure ice |
| I | 2490 | 95930 | 36422 | 59508 |
| II | 2570 | 129728 | 75782 | 53946 |
| III | 2600 | 126213 | 66275 | 59938 |
| IV | 2645 | 294607 | 141958 | 152650 |

The case study (fig. 2) shows the transverse profiles of the glacier tongue and the ablation stakes with data from the Drone footage of June and July 2019.

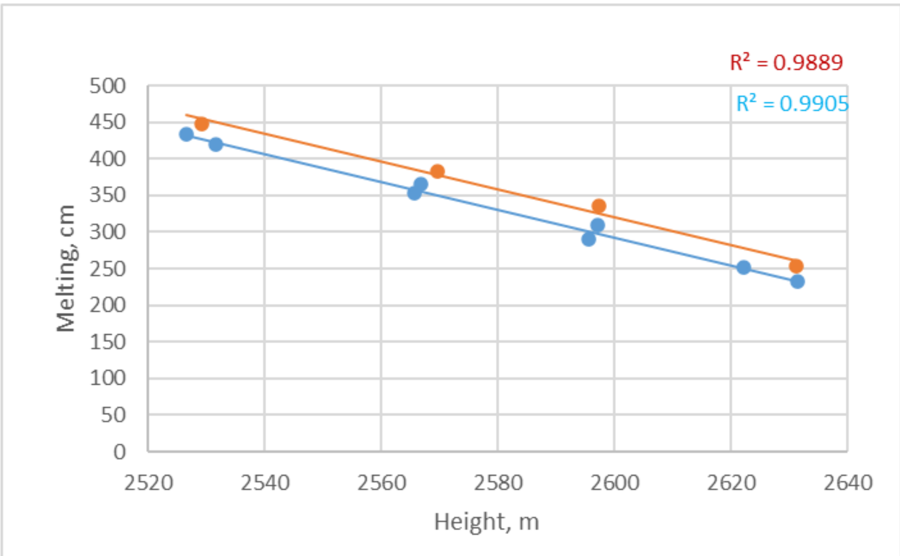


*Figure 3. Correlation between site heights and melting measured by ablation bars during the observation period*
▪ pure glacier surface ▪ moraine-covered glacier surface

It can be seen from the fig.2 that the separation of glacial and non-glacial (profile junction points) surfaces at the edge of the glacier tongue is not tricky.

In addition, these profiles directly represent the effect of the moraine power on the melting and complete cessation of the glacier, allowing data to be averaged.

The Adishi glacier separated zone areas, and the zones' average heights considering the above are given in Table 1.

The correlation was established between the site heights and the melting measured by ablation stakes according to the entire observation period and individual months (fig. 3).

The melting volumes were calculated using the melted data at average elevation for each zone, considering the clear and moraine-covered glacier areas (Table 2).

*Table 2. Surface melting of the Adishi glacial tongue during the observation period*

| Zones | Avg. height, m. | Pure ice area, $m^2$ | Moraine covered ice area, $m^2$ | Total area, $m^2$ | Avg. melting on ice, m | Avg. melting on moraine covered area, $m^2$ | Volume of pure ice, $m^3$ | Volume of moraine covered ice, $m^3$ | Total volume, $m^3$ |
|---|---|---|---|---|---|---|---|---|---|
| | | 36422 | 59508 | 95930 | 6.60 | 6.60 | 240384 | 196377 | 436761 |
| II | 2570 | 75782 | 53946 | 129728 | 4.53 | 4.30 | 343292 | 115984 | 459276 |
| III | 2600 | 66275 | 59938 | 126213 | 3.76 | 3.43 | 249194 | 102794 | 351988 |
| IV | 2645 | 141958 | 152650 | 294607 | 2.60 | 2.14 | 369090 | 163335 | 532425 |
| Sum | | 80528 | 15549 | 96077 | | | 1201960 | 578490 | 1780450 |

## The Drone method

In parallel with the above-mentioned stake method to study the ablation of the Adish glacial tongue, the modern, innovative method was used, which involves aerophotogrammetric scanning of the glacier surface using Drones.

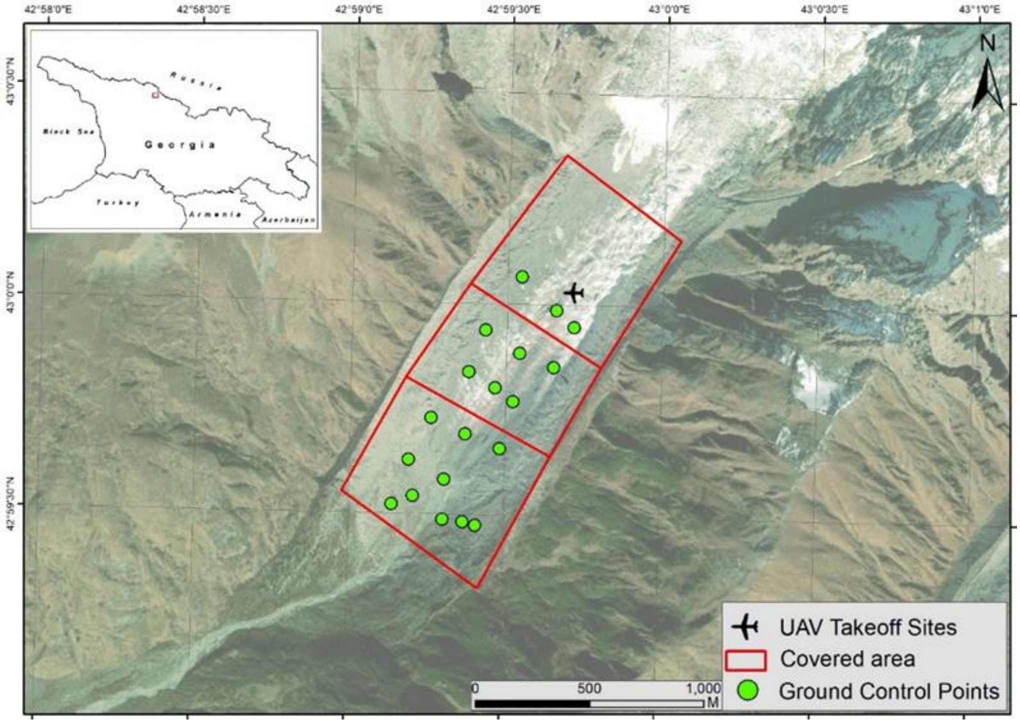


*Figure 4. The location of DGPS control points*

In scientific articles published in recent years [5-9], the perspective of unmanned aerial vehicles in glaciological studies is highlighted. It allows appropriate monitoring to be carried out promptly, with high accuracy and significant human and financial resources savings.

The resolution of the digital elevation model (DEM) and orthophoto depends on many factors, such as the quality of the aircraft camera and the altitude of the Drone. We used a portable DJI Phantom 4 Pro flying machine tested for complex terrain. It is essential to measure the DGPS control points on the glacier surface when performing aerial photogrammetric imaging. 19 control GPS points were located on the tongue of Adishi Glacier and its surrounding area (Fig. 4), and the footage area was divided into three polygons depending on the flight time and challenging terrain.

For the study, the altitude of the Drone flight was determined to be 100 meters to obtain high-resolution digital images. The aerial footage was carried out using the mission launch method for which the Pix4Dmapper software package was used. Before the aerial filming, 12 of the 19 reference points selected at the study site have been located on the glacier surface, and seven at the edge of the glacier tongue on the non-glacial surface. The points were scaled by the DGPS Stonex S9 III + RTK GNSS, with a vertical error of 2 cm during field measurements and a 1.5 cm horizontal error.

Field data, up to 1200 GPS coordinates of aerial and control points were processed in Agisoft Metashape Professional software package, from which the high-resolution orthophotos (orthomosaic-2 cm), digital elevation model (DEM-10 cm) and 3D relief were generated.

High-resolution images have been integrated into Geographic Information Systems (GIS) software package ArcMap 10.4.1. GIS gave the possibility to perform glacier tongue ablation calculations up the centimetre accuracy. Using the digital model of the terrain obtained from aerial photogrammetric imaging and the Cut Fill function of ArcMap 10.4.1, the change in the ice volume from June to September was calculated.

## Results and Discussion

As mentioned above, the comparative analysis of the surface ablation volumes of the Adishi Glacier, calculated by two methods, covers all four zones in July and the entire period of the first zone. The staking method was used to calculate the July surface melting volumes by zones (Tab. 3).

*Table 3. Surface melting of Adishi glacier tongue calculated by the stake method in July*

| Zones | Avg. elevation, m | Pure ice area $m^2$ | Moraine covered ice area $m^2$ | Total area $m^2$ | Ave. melting on ice m | Ave. melting on moraine covered area $m^2$ | Volume of pure ice, $m^3$ | Volume of moraine covered ice $m^3$ | Total volume, $m^3$ |
|---|---|---|---|---|---|---|---|---|---|
| I | 2490 | 36422 | 59508 | 95930 | 2.28 | 2.22 | 83092 | 66053 | 149144 |
| II | 2570 | 75782 | 53946 | 129728 | 1.81 | 1.74 | 137196 | 46941 | 184137 |
| III | 2600 | 66275 | 59938 | 126213 | 1.63 | 1.56 | 108280 | 46764 | 155044 |
| IV | 2645 | 141958 | 152650 | 294607 | 1.37 | 1.29 | 194324 | 98503 | 292827 |
| Sum | | 80528 | 15549 | 96077 | | | 522892 | 258260 | 781152 |

The surface ablation data of the glacier tongue measured by photogrammetric and stake methods in July are given in Table 4.

*Table 4. Adishi glacier surface ablation data by photogrammetric and stake methods*

| Zones | Photogrammetric method | | | Stake method | | |
|---|---|---|---|---|---|---|
| | Area, $m^2$ | Total volume, $m^3$ | Avg. melting, m | Area, $m^2$ | Total volume, $m^3$ | Avg. melting, m |
| I | 106287 | 179643 | 1.69 | 95930 | 149144 | 1.55 |
| II | 139179 | 201834 | 1.45 | 129728 | 184137 | 1.42 |
| III | 135791 | 174735 | 1.29 | 126213 | 155044 | 1.23 |
| IV | 321229 | 349666 | 1.09 | 294607 | 292827 | 0.99 |
| Sum | 702487 | 905879 | | 646479 | 781152 | |

The July surface ablation volumes calculated using two methods by zones are shown in Fig.5.

The ablation volume calculated by the stake method in July is 83% of the volume calculated by the photogrammetric method.

It should be noted that the result obtained by us is consistent with the ablation data measured by two methods of glacier Fontaine (New York State) in 2016: total melting, measured over a 3-day on the study area (0.185 km2), 0.170 m water equivalent was recorded by the Drone, and interpolation of ablation measured by the stake showed the water equivalent of 0.144 m, which is 85% of the volume calculated by the photogrammetric method [8].

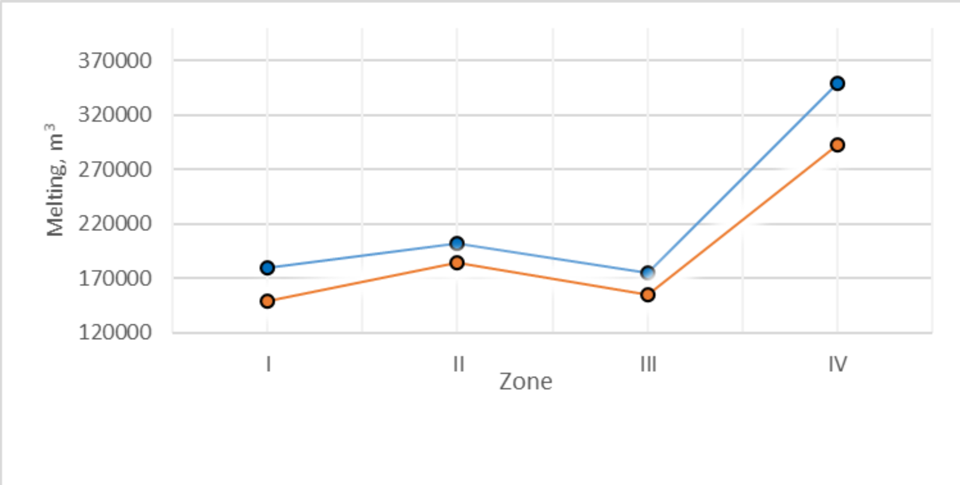


*Figure 5. The average surface melting of Adishi glacier tongue by zones using photogrammetric and stake methods in July*

*Photogrammetric method* *Stake method*

Data from actual observations make it possible to compare surface ablation measured by two methods in Zone I by months (Table 5).

*Table 5. Surface ablation data of Adishi Glacier I zone by photogrammetric (I) and stake (II) methods*

| Month | Ablation, m³ | | % |
|---|---|---|---|
| | Stake method | The Drone | |
| July | 149144 | 179643 | 83% |
| August | 158925 | 195443 | 81% |
| September | 62228 | 77805 | 80% |
| Sum | 370297 | 452891 | 82% |

The dynamics of surface ablation in zone I by months is graphically depicted on Fig. 6

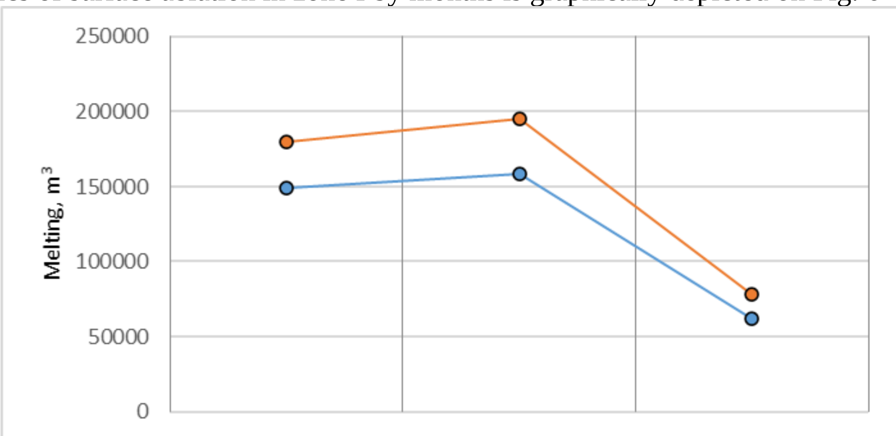


*Figure 6. Surface ablation of Zone I of Adishi glacier by months (July, August, September)*

*Photogrammetric method* Stake method

As we have seen, the quantity of ablation measured by the photogrammetric method, both in the whole range of the glacier tongue (July) and in the individual zone (July-September), is higher than the quantity of the ablation measured by the stake method, by 17 and 17-20%, respectively. Fig. 5and 6 show that we are dealing with a system error of the method (almost parallel curves).

As mentioned above, the stake method has some drawbacks. In particular:

· The melting is measured at the point of drilling of the ablation zone, and the data is generalized over a particular area;

· The accuracy of the measurement of the surface ablation of moraine-covered ice depends on the frequency of the network of ablation stakes, and the degree of data generalization is high too;

· The surface drawn through a topographic map of the glacier tongue and its distinct zones is a plane with less than the actual terrain area.

Let us consider the relief area accuracy as the critical factor of the system error of the method. In the presented article, we deliberately do not use the topographic map to calculate ablation, as the last topographic survey taken during the 1980s is disabled to reflect the current state of the glacier fully, and therefore the survey results cannot be compared. The glacier tongue data and the 2D area of the individual zones in the ablation calculations with the stake method are obtained using a digital map from the Drone footage.

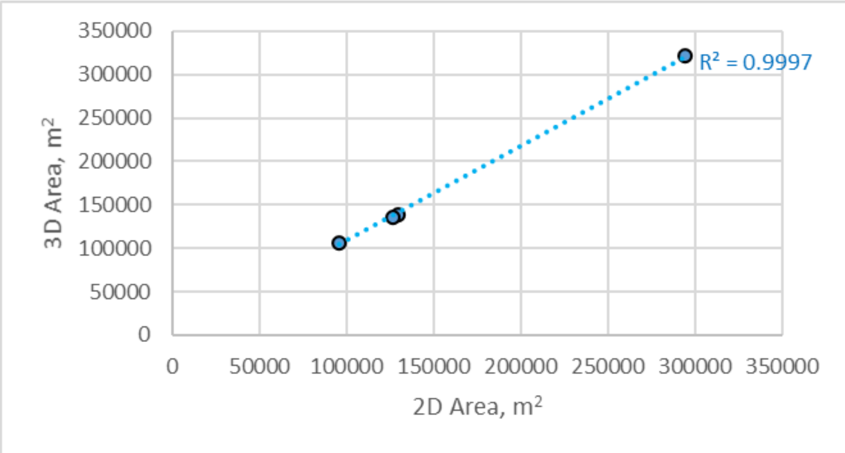


*Figure 7. Correlation between real and plane areas of the Adishi glacier tongue surface by zones*

Naturally, the degree of correlation between the relief and plane areas is high (Fig. 7). However, as shown in Table 6, the surface area of the Adishi glacier tongue used in the calculations is 92% of the actual area, and the areas of its zones range within 90.3-93.2%, respectively.

*Table 6. Adishi glacier tongue surface areas by zones in 2D and 3D formats*

| Zone | 2D Area, m$^2$ | 3D Area, m$^2$ | % |
|---|---|---|---|
| I | 95930 | 106287 | 90.3 |
| II | 129728 | 139179 | 93.2 |
| III | 126213 | 135791 | 92.9 |
| IV | 294708 | 321229 | 91.7 |
| Sum | 646579 | 702487 | 92.0 |

This can be explained by analysing the longitudinal profile of the central part of the Adishi glacier tongue presented in Figure 8. In particular, a significant deviation in zone I is related to the steep surface of the glacier at the end of the tongue, zones II and III are approximately homogeneous, and zone IV is distinguished from the rest by significant surface irregularities.

Based on the conducted analysis, it can be concluded that the 8% from 17% of July surface ablation error of Adishi glacier tongue calculated by the stake method and the 10% from 18% of the surface ablation errors calculated for the first zone by months are conditioned mainly due to the area size error.

The remained 8-9%, in our opinion, should be caused by mechanical and under-glacial ablation, the measuring of which was not considered in the present study. However, in this regard, we have a specific suggestion based on the analysis of profiles obtained by periodic photogrammetric images along with the ablation stakes (Fig. 9).

Fig. 9 presents the surface ablation profiles of the Adishi glacier tongue in the I zone along with the ablation stakes by months. It is clear from the figure that the glacier surface is relatively smooth in July, and in the following months, the negative peaks are gradually increasing and widening. This is caused by the impact of surface melted water streams of glacier tongue during the ablation period, which gradually deepens and widens the basins and cause the surface to sag. Then the streams are lost in the cracks, pass through the glacier body and emerge on the subsurface.

*Figure 8. Longitudinal profile of Adishi glacier tongue by zones*

In Fig. 9, the vertical lines mark the location points of the ablation stakes. While looking, no cracks and crevices are observed in the vicinity of these natural points because the places of drilling of the ablation stakes are also chosen from the viewpoint that to ensure the continuity of the observations, they will not be mechanically injured frequently replaced. Consequently, the stake method cannot reflect the mechanical melting process in the ablation calculation.

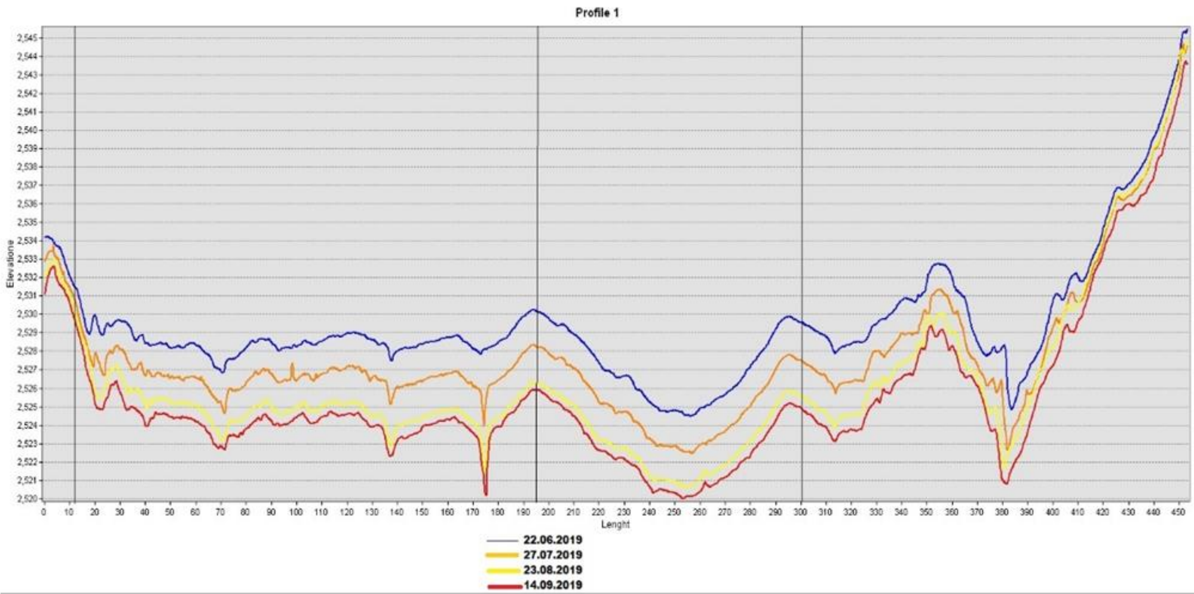


*Figure 9. Surface ablation profiles of the Adishi glacier tongue in I zone along the ablation stakes by months*

The scale of the mechanical melting is indicated by the glacial lake recorded from the photogrammetric method in the fourth zone (June) and then vanished (July), which left a concave of 18 m depth (Fig. 10).

From the given analysis, it can be concluded that the ablation value calculated by the photogrammetric method includes the component caused by ice surface melting and also the mechanical losses of ice.

As for under-glacier ablation, observation materials on this component of glacial ablation are scarce. It is known that the glacier melting at the contact point with the subsurface is caused by the mechanical and thermal impact of surface melting flows on the glacier subsurface through the Earth's heat and cracks.

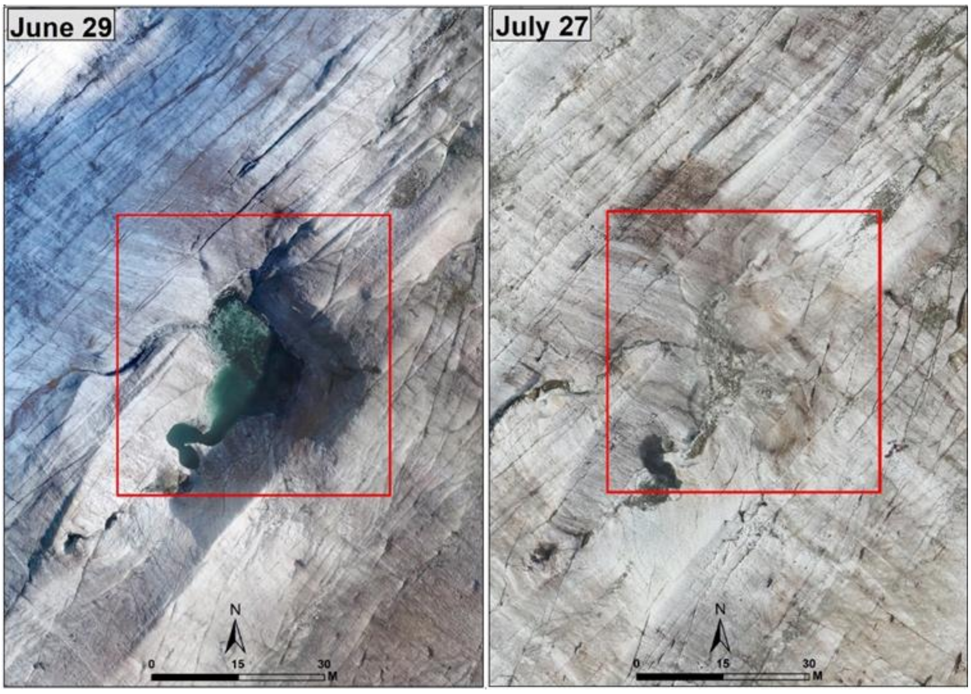


*Figure 10. Emerged and then vanished glacial lake (June) on the Adishi glacier tongue*

As a result of under-glacial ablation, by the pressure of a large mass of ice, the glacier experiences a periodic fall, which can be said to "fit", which is naturally described with the photogrammetric method. The staking method cannot fix this process for obvious reasons.

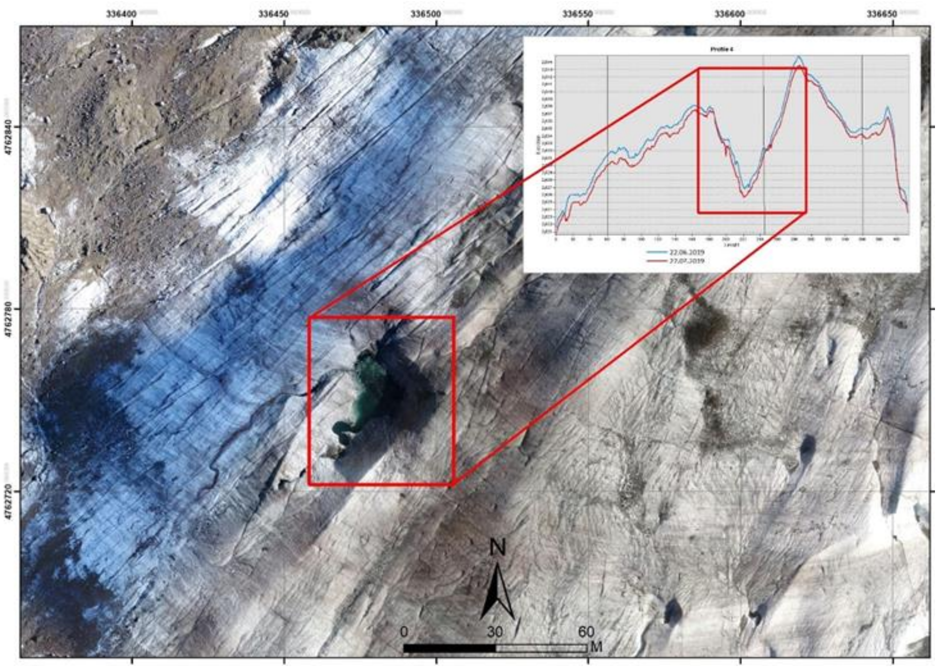


*Figure 11. Glacial lake and transverse profile*

In the case of an Adishi glacier, the manifestation of under glacial ablation is the last part of the tongue where all the melted water gathers and then flows in a single stream from the grotto. As a result, a large mass of ice is lowered by about 8-10 meters. Based on the above, it can be concluded that the ablation quantity calculated by the photogrammetric method also includes the under-glacial component.

## Conclusion

- The method of aerial photogrammetric is quite innovative, and it allows us to obtain a surface height digital model (DSM), orthophoto image (Orthomosaic) and three-dimensional model (3D) at a minimal cost. At the same time, it provides pretty high quality (accuracy) digital information of the terrain.
- The data obtained from the Drone allow us to allocate the contour of the area involved in the ablation of the glacier tongue with high accuracy.
- The quantity of ablation measured by the aerial photogrammetric method is greater than the quantity of ablation measured by the stake method (in our case, the difference was 17-20%). Data analysis showed that we are dealing with a systematic error of the stake method.
- 8% from 17% of Adishi glacier tongue the surface ablation error in July calculated by stake method, and 10% from 10% of the surface ablation error calculated by month mainly falls on the area value error.
- The ablation quantity calculated by the aerial photogrammetric method includes components caused by both surface ice melting and mechanical ice losses, and in the long run, by under-glacial ablation.
- There is a significant difference between the values obtained from modern and previous recording methods, primarily due to the shortcomings of the previous records method. We believe that the results obtained necessitate the revision of the old data of the mass balance ablation component.

## Competing interests

The authors declare that they have no competing interests.

## Authors' contribution

All authors contributed to the final version of the manuscript. Karalashvili T. - conceived the idea; wrote the paper. Bolashvili N. - worked out almost all of the technical details, was involved in planning the work. Geladze V. - supervised the findings of this work. Imnadze G. - performed the measurements, collected the data.

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