REMOTE DETECTION OF WATERFALLS AND CASCADES IN THE UPPER BASIN OF BASHIBOSKA RIVER USING DIGITAL MODELS AND AUTOMATED ALGORITHMS

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ABSTRACT

The upper basin of the Bashiboska River is situated on the southwestern slopes of the Belasica mountain, east of the town of Valandovo in the Republic of Macedonia. Bashiboska River is a continuation of Anska River, a left tributary of the Vardar River. The basin contains several waterfalls, including the renowned Kochuli Waterfalls. Until today, only the waterfalls near the Kochuli village are known due to the challenging terrain, leaving much of the upper basin unexplored. With the advancement of LiDAR technology, especially in creating high-resolution digital terrain models, remote sensing allows the discovery and registration of waterfalls. In our case, LiDAR data with a resolution of 1m x 1m was used, enabling the detection of areas where the river bed precipitously drops. For the detection of waterfalls, an automated process called "Model Builder" from the ArcGIS software package was used. It involved entering several predefined rules and criteria, leading to the detection of all potential locations of waterfalls. In our research, we identified 104 locations where waterfalls and cascades higher than 2m with a slope greater than 45° could be found. Among them, we can confirm with certainty that 12 locations have waterfalls, as they have been thoroughly investigated.

Keywords: Waterfall, cascade, digital terrain model, LiDAR, ArcGIS, Model Builder, Belasica, Republic of Macedonia

INTRODUCTION

A waterfall is defined as a steep, often vertical, rocky section of a river bed over which the flow of the river descends (Kolchakovski, 2006). Unlike a waterfall, a cascade is a steep drop in the river bed over which water falls in a stepped or cascading manner over several small rocky sections. Based on their formation, waterfalls and cascades can be classified as tectonic, erosive, and accumulative (Kolchakovski, 2006). Tectonic waterfalls occur at a fault between two tectonic blocks. Erosive waterfalls are formed through erosion, i.e., undercutting of the softer rocks found in the lower layers, over which more resistant rocks lie, then through vertical cutting of the main river in relation to its tributaries and by the main glacier in the trough valleys relative to the side valleys. Accumulative waterfalls are created in karst terrains where calcium carbonate (Limescale) deposits accumulate in the river beds (Kolchakovski, 2006). In the Republic of Macedonia, there are mostly tectonic and erosive waterfalls. The majority of tectonic waterfalls are found in the area of the Belasica mountain. Belasica is a classic example of a horst morphostructure formed by a series of contrasting faults (Kolchakovski, 2022). Hence, it is not

coincidental that some of the most famous waterfalls in the Republic of Macedonia are located on this mountain, such as: Smolari Waterfalls, Koleshino Waterfalls, Gabrovo Waterfalls, Kochuli Waterfalls, etc.

Although a large number of waterfalls have been explored in the Republic of Macedonia, there are still hard-to-reach and inaccessible locations where new waterfalls can be found and discovered. In recent years, technological advancements have made it possible to register waterfalls on various satellite images and digital models. In this context, drones can be used as a means of waterfall detection, allowing waterfalls to be seen and photographed from heights inaccessible to humans. The process of remote detection of waterfalls has been accelerated by the creation of high-resolution digital models capable of detecting even the smallest drop in the river bed, thereby registering all locations where waterfalls and cascades exist. Examples of waterfall detection using digital models and satellite images are provided by Alexey V. Kutuzov from the Russian Academy of Sciences, who explored the areas of the high-mountainous Jinbar waterfall and the low-mountainous waterfalls of the Blue Nile River in Ethiopia (Kutuzov, 2021). The same author used topographic maps, SRTM, Aster GDEM and ETOPO2 digital models, as well as satellite images from the Sentinel-2 program. Similar examples of waterfall detection are mentioned by adventurers and GIS experts Christopher Ryan Cockfield and Mark Oleg Ozboyd from the USA, who use LiDAR digital models and high-resolution data (1m x 1m) as a means of waterfall detection. Christopher Ryan Cockfield focuses on the state of South Carolina (https://waterfalladventurer.weebly.com/lidar.html), while Mark Oleg Ozboyd explores the state of Georgia (Ozboyd, 2024).

In the Republic of Macedonia, the path for remote detection of waterfalls is being paved by the Agency for Real Estate Cadastre, which conducted LiDAR surveys of the territory of Republic of Macedonia with the support of the Norwegian Mapping Authority – NMA (Jakir et al., 2022). The LiDAR surveying was carried out between 2019 and 2022, completed in two phases. The first phase was conducted by the MGGP AERO company from Poland, and the second phase was carried out by the PRIMUL MERIDIAN company from Romania. During the first phase, the Riegl VQ-780i laser standard was used, flying at a height of 1450m above the ground. The second phase was recorded with the Riegl VQ-1560i laser standard, flying at 2585m above the ground (MGGPAERO, 2019). The products from the LiDAR recordings have a resolution of 1m x 1m. During their processing, two types of LiDAR specifications were used: LiDAR B with a density of 5 points per m^2 and LiDAR C with a density of 2 points per m^2. The processing of LiDAR data produced a cloud of points (Point of Cloud) in LAZ and zLAS formats, as well as a digital terrain model (DTM) and a digital surface model (DSM). These LiDAR data have a vertical accuracy of ±0.10m, while the tolerance for horizontal accuracy is ±0.30m (AGENCY FOR REAL ESTATE CADASTRE, 2018).

STUDY AREA

The upper basin of the Bashiboska River is located on the southwestern slopes of the Belasica mountain. The basin stretches between the peak of Unka Tepe in the east, the ridge of Bajrambos in the south, the peak of Tarla Bash in the west, and the northwestern Belasica ridge in the north (Dzilvidziev, 2015). The easternmost point of the upper basin of the Bashiboska

River is the peak of Unka Tepe (1368 m), while the westernmost point is near the peak of Korubash (353 m). The northernmost point is near the peak of Dzami Kran (1198 m), while the southernmost point is the confluence of the Elez Dere river into the Bashiboska River. The distance between the easternmost and westernmost points is 7.52 km, while the distance between the northernmost and southernmost points is 6.38 km. The highest point in the upper basin of the Bashiboska River is the peak of Unka Tepe (1368 m), and the lowest point is the confluence of Elez Dere into the Bashiboska River (235 m). The elevation difference between these two points is 1133 m. Within the previously described boundaries, the upper basin of the Bashiboska River covers an area of 21.36 km². The basin consists of 46 constant and periodic rivers. Of these, 14 rivers are longer than 1 km, and 7 rivers extend more than 2 km. The longest watercourse is the Bashiboska River (2.8 km) – Kaldrma Dere (7.72 km) with a total length of 10.52 km.

Table 1. Hydrographic characteristics of the largest watercourses in the upper basin of Bashiboska River.

RIVER	Bashiboska River	Kaldrma Dere	Ark Dere	Chamdash Dere	Bashiboska River – Kaldrma Dere
Left/right tributary	/	/	Right	Right	/
Constant/periodic watercourse	Constant	Constant	Periodic	Constant	Constant
Stream order (Strahler)	5	4	4	4	5
First point (m)	363	1280	925	1199	1280
Last point (m)	235	363	328	363	235
Total decline (m)	128	917	597	836	1045
Average decline (m/km)	45.7	118.3	120.1	132	99.3
Length (km)	2.80	7.72	4.97	6.33	10.52
Minimum Length (km)	1.97	5.17	3.92	4.42	7.02
Basin Area (km²)	1.99	6.53	6.12	6.72	21.35
Total Watercourses in Basin	5	15	15	11	46

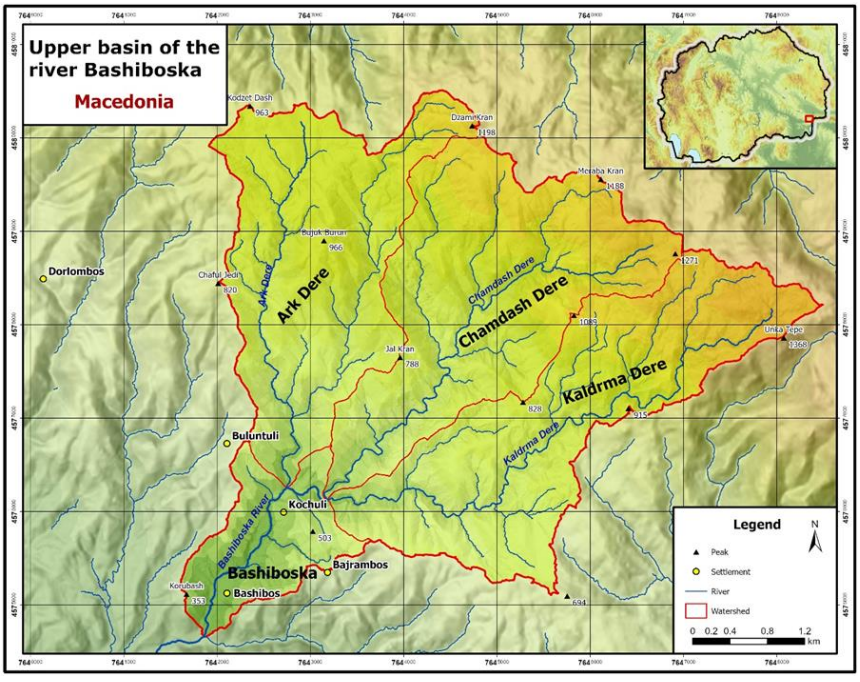

Figure 1. Geographic position of the upper basin of Bashiboska River

MATERIALS AND METHODS

This study includes LiDAR data obtained from the LiDAR portal of the Agency for Real Estate Cadastre (AREC). In this context, data in the format of a Digital Terrain Model (DTM) with a resolution of 1 meter were used. These data enable conversions that show elevation, a shaded model of the Earth (Hillshade), and a slope model. With the help of these converted data, it is easy to observe the decline in the river bed, thereby detecting potential waterfalls and cascades.

For the purposes of this research, the ArcGIS software package with desktop applications ArcMap and ArcGIS Pro was used. With these software tools, conversions of DTM data were performed and more relevant data were obtained, such as: points with elevation, points with slope, basins with area, and rivers with stream order and length. All these data were used as input parameters in an automated process called "Model Builder". Model Builder is a powerful tool that allows for the execution of multiple predefined analyses and automated processes at once. In this context, a Model Builder was created in the ArcGIS Pro software package, which automatically detected all potential waterfalls and cascades in the upper basin of the Bashiboska River. Before the analysis and detection of waterfalls and cascades were carried out, a set of detection rules was created. This set contains several rules, including restrictions regarding the points with slope and elevation and their intersection with watercourses, rules on rivers including stream order, length, and basin area. In the detection rulebook integrated into the automated Model Builder process, rivers with a stream order of second category and higher were included, as well as all rivers longer than 500 meters, and with a larger basin area than 0.5 km^2. Furthermore, the detection rulebook included a rule to detect all locations intersecting with the river bed, having a height greater than 2 meters, and a slope greater than 45 degrees. In this way, all potential waterfalls and cascades were detected, which were then manually verified with the elevation and slope data, removing any results that deviated from the river beds of the watercourses.

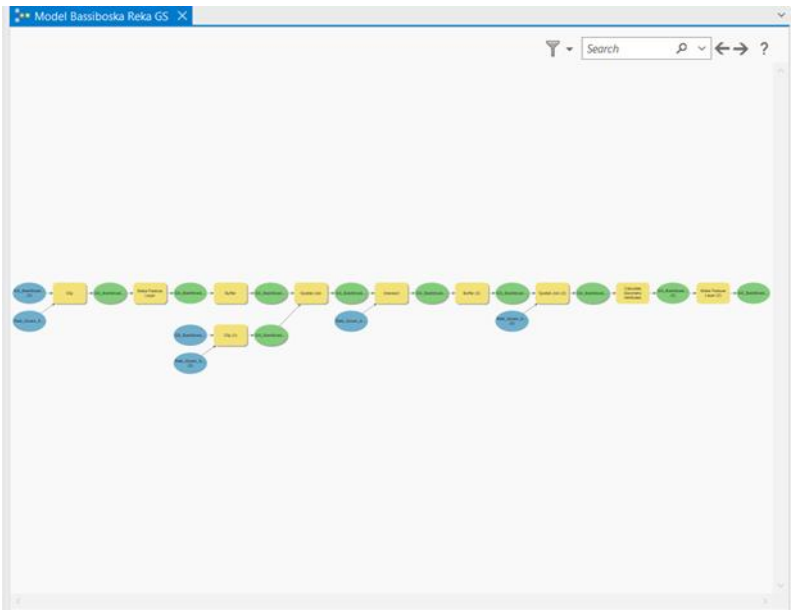

Figure 2. Visual representation of the automated Model Builder process, with blue marking the input data, yellow indicating the tools used, and green representing the output data, i.e., the results

RESULTS

With the aid of the automated Model Builder process and all previously defined procedures, 166 polygons (locations) representing potential waterfalls and cascades were identified. These locations were manually verified using maps with contour lines, hillshade and slope models, which led to the identification of two types of errors: polygons that are part of a single waterfall or cascade but do not intersect, and polygons that are vertical sections along the banks of watercourses without a direct decline in the river bed. After correcting the aforementioned errors, the number of potential waterfalls and cascades was reduced to 101 locations. Further examination of the river valleys identified an additional 3 locations not registered by the automated Model Builder process, yet meeting the criteria for potential waterfalls and cascades according to the predefined rules. Thus, a total of 104 locations where waterfalls and cascades might be found were registered in the upper basin of the Bashiboska River.

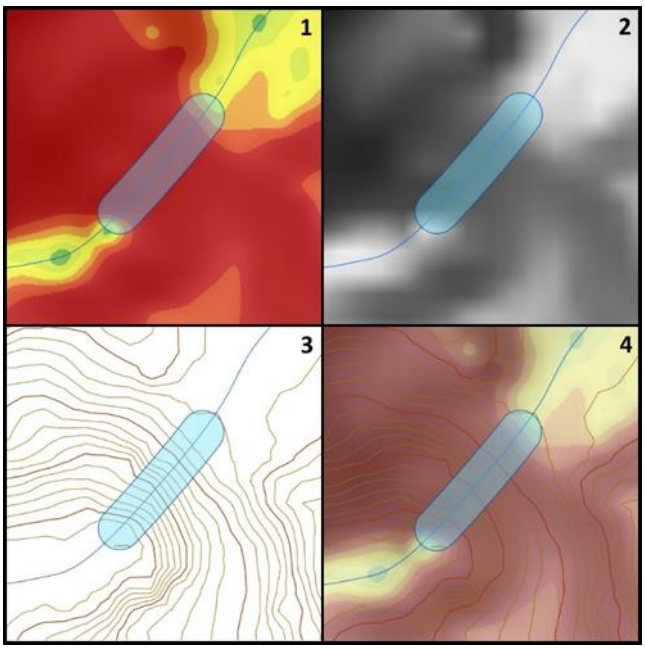

Figure 3. Detection of waterfalls using a digital slope model – Slope (1), digital shaded model – Hillshade (2), contour lines model (3), and a combined model of contour lines, digital hillshade and digital slope model (4).

Similar methods for remote detection of waterfalls are used by Christopher Ryan Cockfield and Mark Oleg Ozboyd from the USA, who detect waterfalls using high-resolution LiDAR data of 1m x 1m. These researchers convert LiDAR data to obtain a digital hillshade model, digital slope model, and a contour line model. Combining these methods, Christopher Ryan Cockfield in South Carolina (USA) detected over 300 waterfalls higher than 2m (https://waterfalladventurer.weebly.com/lidar.html), while Mark Oleg Ozboyd in Georgia (USA) detected over 500 waterfalls higher than 2 meters (Ozboyd, 2024). Both researchers and GIS experts indicate that using a combination of these three models is necessary to avoid false detection. Christopher Ryan Cockfield mentions that sometimes remote detection with LiDAR data can be incorrect. He notes an instance where digital analysis suggested a waterfall 12 m in height, which did not exist in reality (https://waterfalladventurer.weebly.com/lidar.html). One of the main reasons

for obtaining incorrect results, according to this author, is the presence of small gorges or narrow beds with high vertical banks, where LiDAR technology may fail to provide accurate data (https://waterfalladventurer.weebly.com/lidar.html). Nonetheless, Christopher Ryan Cockfield claims that LiDAR technology is a significantly better method for remote detection of waterfalls compared to traditional methods and the use of topographic maps.

Unlike previous authors, Alexey V. Kutuzov uses several examples for the detection of waterfalls, such as: satellite images from EarthExplorer and Sentinel-2 programs (10 m/pixel resolution), slope models obtained from SRTM and Aster GDEM and topographic maps. With the help of satellite images, Alexey V. Kutuzov detects all the bright surfaces that are located in the river beds that represent waterfalls and rapids. Also, this author uses slope models with which he notes all the slopes of the river bed that deviate and have a large drop.

Previously, the waterfalls in the upper basin of the Bashiboska River or Kochulski waterfalls were explored by Dzilvidziev G. and Stojcheski D., who during field research in the lower course of the Ark Dere, Chamdash Dere, and Kaldrma Dere stream recorded 14 waterfalls and cascades higher than 2 meters. With the automated Model Builder process for detecting waterfalls, as well as with the aid of LiDAR data, 12 waterfalls were registered, matching the waterfalls previously explored in the field. The detection did not include only two small cascades which, according to field measurements, are 2 to 3 meters in height and do not meet the slope criterion, i.e., they have a slope less than 45°.

Table 2. Overview of waterfalls previously recorded in the field, compared to the results obtained with LiDAR data through the automated Model Builder process

Waterfall	River	Top Elevation (amsl)	Bottom Elevation (amsl)	Height (m)	Average Length Top-Bottom (m)	Length of Longitudinal Profile – Field Measurements (m)
Akr Dere – 2	Akr Dere	428.31	422.65	5.66	8.03	7
Akr Dere – 3	Akr Dere	450.96	441.33	9.63	12.2	13.5
Akr Dere – 5	Akr Dere	505.99	496.68	9.31	9.78	9
Akr Dere – 8	Akr Dere	531.54	520.98	10.56	14.54	10.5
Akr Dere – 9	Akr Dere	549.73	536.44	13.29	18	13
Chamdash Dere – 1	Chamdash Dere	487.73	485.48	2.25	4.58	3.5
Chamdash Dere – 2	Chamdash Dere	511.28	505.16	6.12	9.14	10
Chamdash Dere – 3	Chamdash Dere	532.75	522.17	10.58	15.33	10
Chamdash Dere – 4	Chamdash Dere	547.96	543.22	4.74	5.83	6
Kaldrma Dere – 1	Kaldrma Dere	407.18	403.75	3.43	8.47	10.5
Kaldrma Dere – 2	Kaldrma Dere	422.62	408.01	14.61	15.97	17
Kaldrma Dere - 3	Kaldrma Dere	426.59	423.74	2.85	5.75	5

It is important to note that during 2015, Dzilvidziev and Stojcheski measured the length of the longitudinal profile of the waterfalls in the field. Table 2 provides a comparison of these field measurements against those obtained from LiDAR data with a 1-meter resolution. For most of the waterfalls, deviations of ±1 meter in the length of the longitudinal profile compared to the average length can be observed.

In this study, besides the location of the waterfalls obtained digitally, the following data were also gathered: coordinates of the waterfall, elevation at the top of the waterfall, elevation at the bottom of the waterfall, height of the waterfall, average length of the waterfall, maximum slope, and average slope of the waterfall. The height of the waterfall was determined by the difference between the elevation at the top and the bottom of the waterfall. The average length was calculated using the 3D distance between the top and bottom elevations, while the distance was calculated using the Pythagorean theorem ($a^2+b^2=c^2$), where "a" represents the height, "b" represents the horizontal (shortest) distance between the top and bottom elevations of the waterfall, and side "c" is the average length of the waterfall. The maximum slope of the waterfall was obtained from the automated "Model Builder" process, while the average slope was calculated using the mathematical formula:

$$\angle\alpha = \arcsin(\frac{a}{c})$$

Where "$\angle\alpha$" represents the angle, i.e., the slope of elevation of side "c" in relation to side "b", which is a horizontal line.

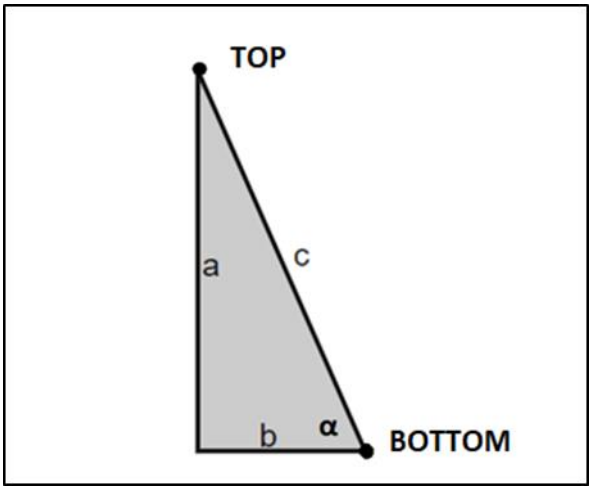

Figure 4. Shows the method for calculating the dimensions (sides) of a waterfall, where: side "a" is the height of the waterfall; side "b" is the shortest horizontal distance between the top and bottom elevations of the waterfall; side "c" is the average length of the waterfall; and the angle α represents the average slope of the waterfall.

Waterfalls and cascades identified using 1m DTM LiDAR data can be divided into four height categories: waterfalls under 5 meters (2-5 meters), waterfalls from 5 to 10 meters, waterfalls from 10 to 15 meters and waterfalls over 15 meters. There are 59 waterfalls in the first group of waterfalls up to 5 meters, accounting for 56.73% of the potential waterfall and cascade locations. The second group, from 5 to 10 meters, consists of 31 locations with potential waterfalls and cascades. The third group, with waterfalls ranging from 10 to 15 meters in height, includes 11 potential waterfalls and cascades. In the last group, or the group of waterfalls higher than 15 meters, there are 3 potential waterfalls and cascades. According to the height, the highest waterfall recorded in the upper basin of the Bashiboska River is the location "KD-P2-3" or waterfall 3 from tributary 2 of the Kaldrma Dere river, which is approximately 24 meters high according to LiDAR 1m DTM.

Regarding the slope, all locations (waterfalls) where the maximum slope exceeds 45° have been registered. Based on the slope, the locations of potential waterfalls and cascades are categorized into three groups: waterfalls with a slope of 45° to 55°, waterfalls with a slope of 55° to 65°, and waterfalls with a slope greater than 65°. The first group (45°- 55°) consists of 64 waterfalls and cascades. The second group (55°- 65°) includes 28 waterfalls, while the third group has 12 waterfalls with a slope greater than 65°. The absolute steepest slope was observed at the waterfall "Ark Dere-8" or Waterfall 8 on the Ark Dere river, which has a slope of 75° according to LiDAR data.

Regarding the hypsometry, there is a varied distribution of waterfalls. Five hypsometric zones have been identified: 400-600, 600-800, 800-1000, 1000-1200, and above 1200 meters. Most waterfalls are registered in the elevation zone from 400 to 600 meters, and only 3 waterfalls are located at an altitude greater than 1200 meters.

Table 3. Overview of waterfalls by hypsometric (elevation) zone

Elevation Zone (amsl)	400 - 600	600 - 800	800 - 1000	1000 - 1200	Over 1200
Number of waterfalls	34	18	23	26	3

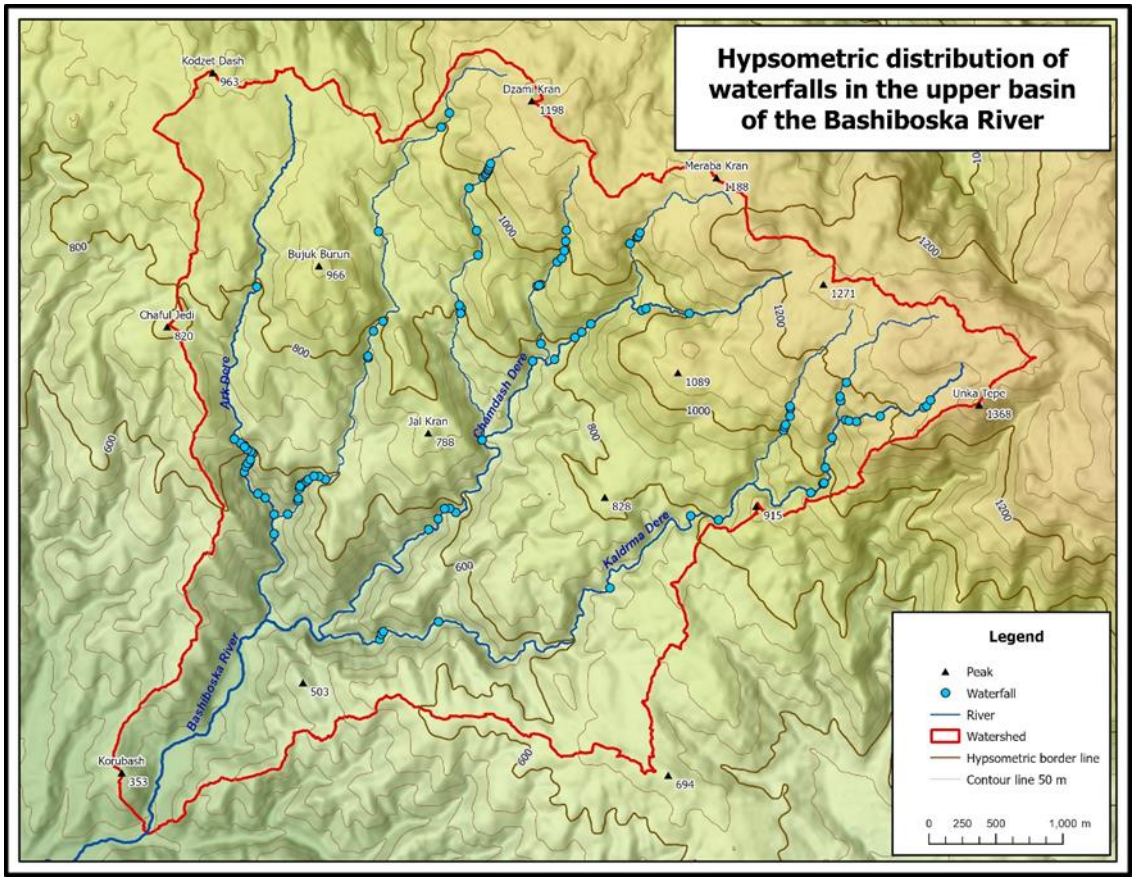

Figure 5. Hypsometric distribution of waterfalls in the upper basin of the Bashiboska River.

Among the river basins, the highest number of waterfalls is observed in the basin of the Chamdash Dere river (40 waterfalls), followed by Ark Dere (36 waterfalls) and Kaldrma Dere (28 waterfalls). Regarding larger watercourses, the Kaldrma Dere river has the most waterfalls and

cascades (19 waterfalls and cascades), along with the Galash Jedi Dere, i.e., tributary 9 from the Ark Dere basin (19 waterfalls and cascades).

Table 4. Waterfalls and cascades according to the river and river basin.

River	Number of waterfalls	Total waterfalls in the basin
Ark Dere	17	36
Galash Jedi Dere (tributary 9 of the Arc Dere)	19	/
Chamdash Dere	14	40
Chamdash Dere - (tributary 4)	4	/
Chamdash Dere - (tributary 5)	9	/
Chamdash Dere - (tributary 7)	13	/
Kaldrma Dere	19	28
Kaldrma Dere - (tributary 1)	3	/
Kaldrma Dere - (tributary 2)	6	/

The highest waterfall in the Ark Dere river basin is "Waterfall 8" (AD-T9-8), located on the Galash Jedi Dere river (tributary 8 of Ark Dere). According to LiDAR data and analyses, this waterfall has a height of 13.59 m. In the Ark Dere basin, the most famous and attractive waterfall is the Kazan Waterfall (Ark Dere -3), which is 9.6 m high. This waterfall is known for its whirlpool or giant pot resembling a cauldron, from which the waterfall's name is derived.

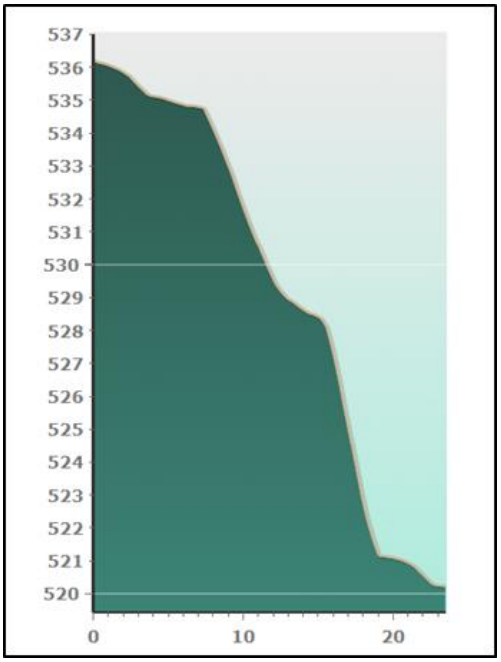

Figure 6. Profile of Galash Jedi Dere Waterfall 8 (AD-P9-8)

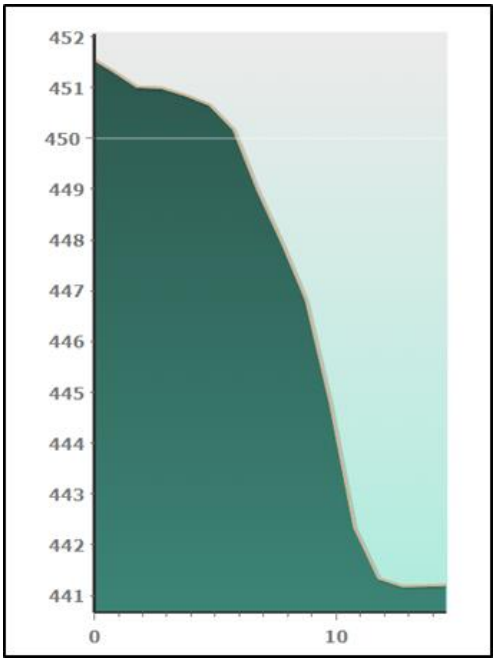

Figure 7. Profile of Kazan Waterfall (Ark Dere 3)



Figure 8. Kazan Waterfall (Ark Dere 3)



Figure 9. 3D Profile of Kazan Waterfall

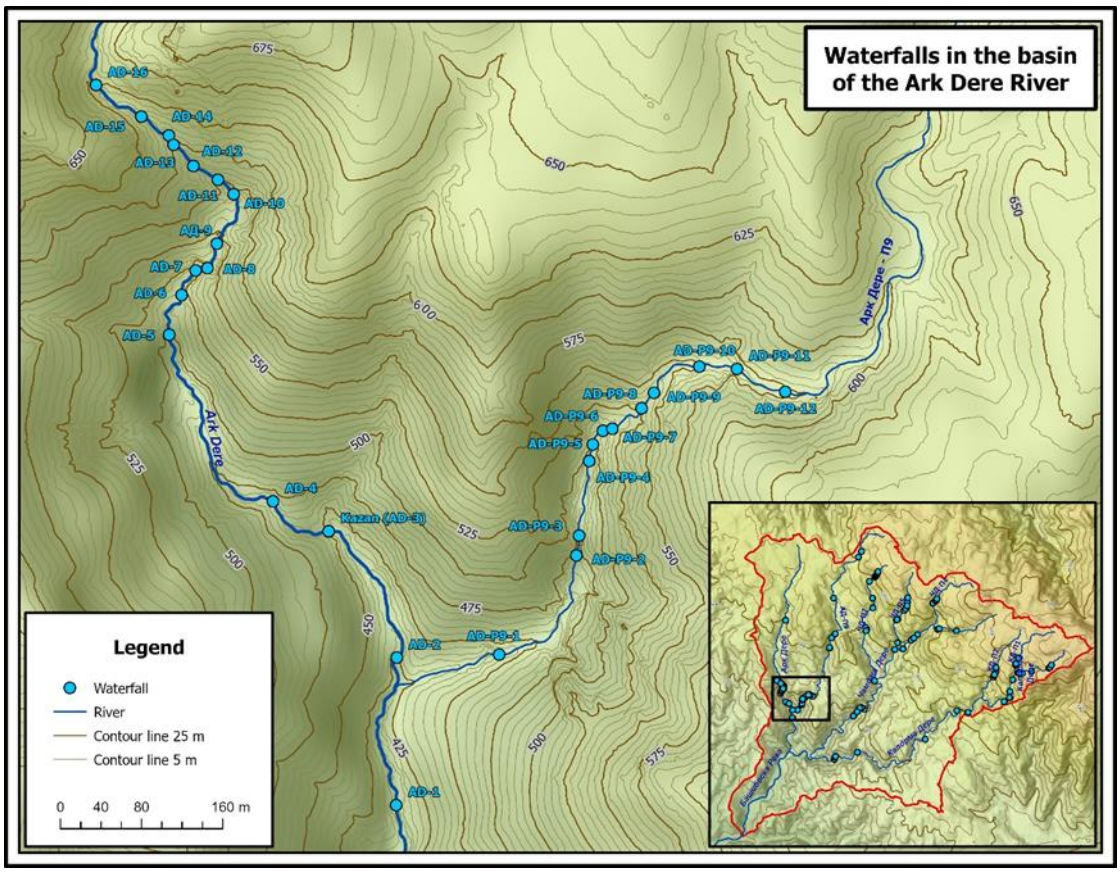

Figure 10. Display of waterfalls and cascades in the lower basin of the Ark Dere River

In the basin of Chamdash Dere river, 40 waterfalls and cascades have been detected. The highest waterfall is Waterfall 9 (CD-T7-9) located on tributary 7 of the Chamdash Dere basin. According to LiDAR 1m DTM, this waterfall is 15.5 m high. So far, 5 waterfalls and cascades have been recorded and confirmed in the field within the Chamdash Dere basin. Of these, the

"Zavesa" (“Curtain”) Waterfall (Chamdash Dere 3) standing at 6.1 m and the “Razigran” ("Playful") Waterfall or Chamdash Dere 3, which is 10.5 m high, are particularly attractive.

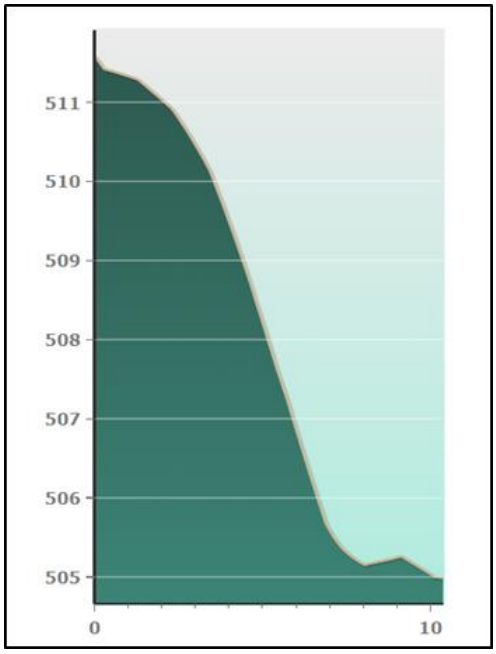

Figure 11. Profile of the "Zavesa Waterfall (Chamdash Dere 2)

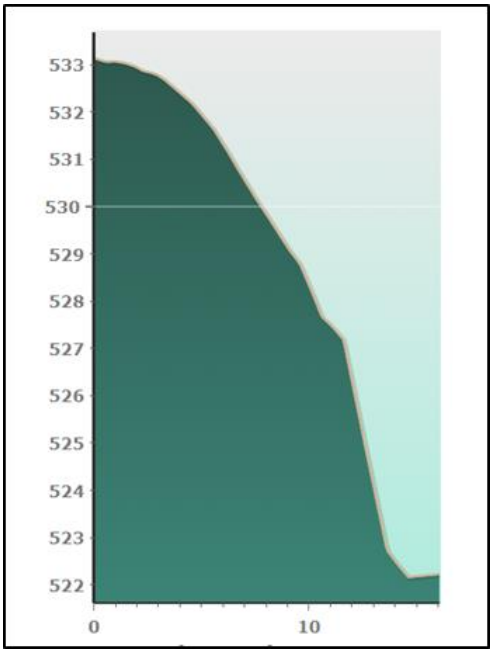

Figure 12. Profile of the "Razigran" Waterfall (Chamdash Dere 3)



Figure 13. The "Zavesa" Waterfall



Figure 14. The "Razigran" Waterfall

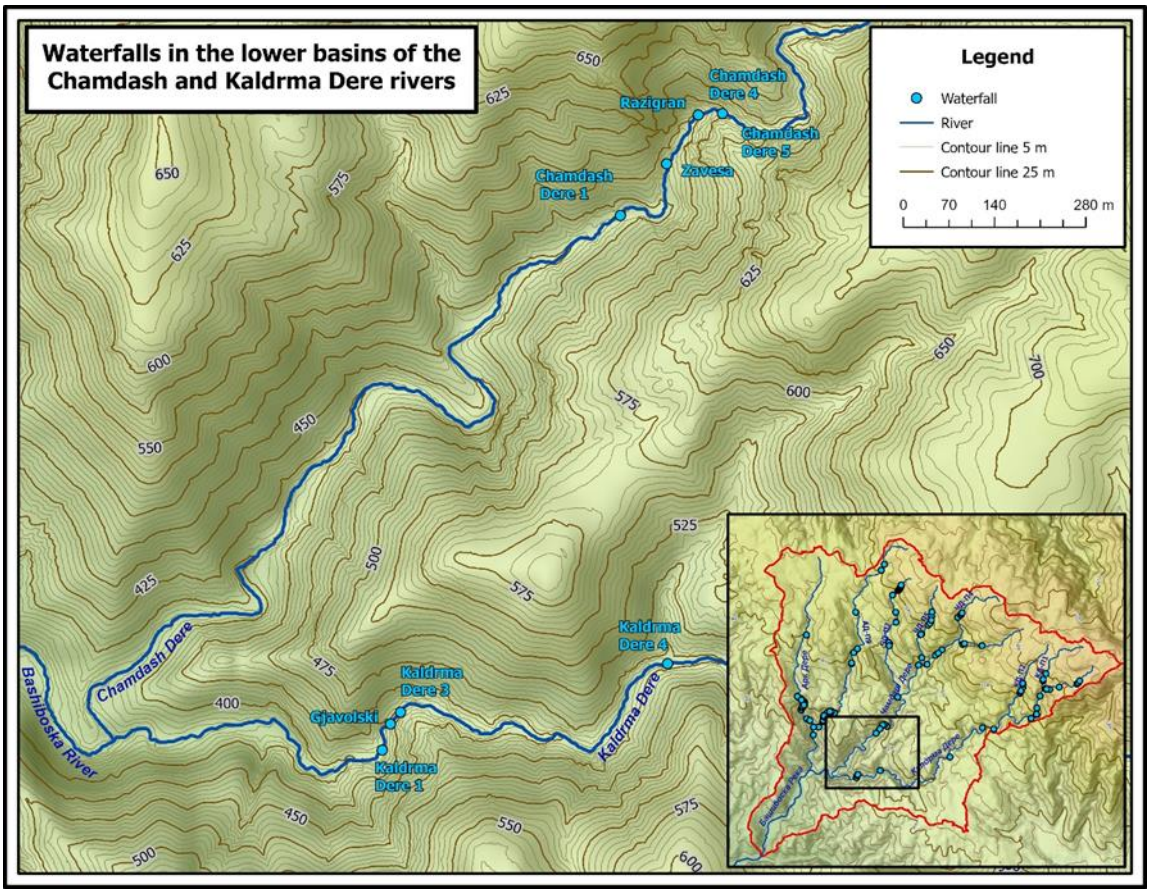

Figure 15. . Display of waterfalls and cascades in the lower basins of the Chamdash and Kaldrma Dere rivers

According to the results obtained from the detection using LiDAR 1m DTM, fewer waterfalls are observed in the Kaldrma Dere basin compared to the other two basins. The highest waterfall in this basin is "Waterfall 2" from tributary 2 of Kaldrma Dere, referred to in the study as "KD-T2-2." This waterfall has a height of 24.2 m. In the Kaldrma Dere basin, only three waterfalls located in the lower basin of the river have been explored in the field. The most attractive and famous waterfall in this basin, and indeed in the entire Bashiboska River basin, is the Gjavolski (Devil's) Waterfall, also known as the Kochulski Waterfall or Kaldrma Dere 2. This waterfall has a height of 14.6 m, and its profile shows a drop of 71.26°.

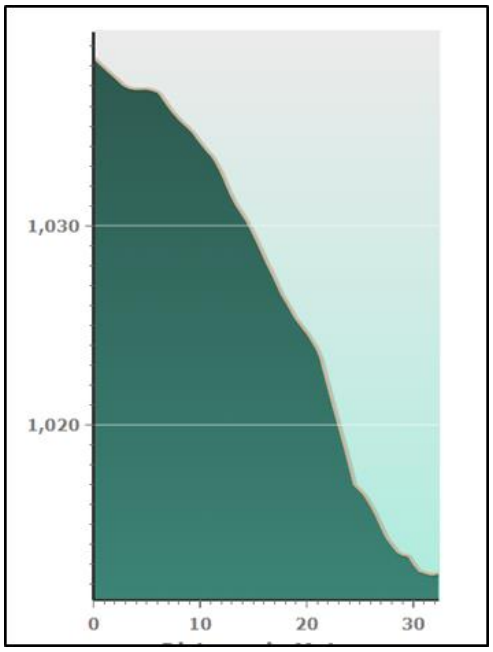

Figure 16. Waterfall 2" from tributary 2 of Kaldrma Dere (KD-T2-2)

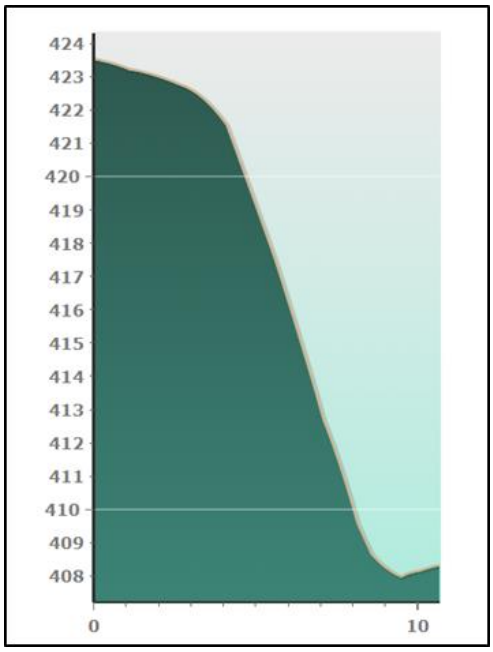

Figure 17. Figure 17. Profile of the Glavolski Waterfall or Kochulski Waterfall (Kaldrma Dere 2)



Figure 18. Gjavolski Waterfall



Figure 19. 3D Profile of the Gjavolski Waterfall

CONCLUSION

The upper basin of the Bashiboska River, situated on the southwestern slopes of the Belasica mountain, encompasses 46 constant and periodic rivers. Of these, 14 rivers are longer than 1 km, and 7 rivers extend more than 2 km. The longest watercourse is the Bashiboska River (2.8 km) – Kaldrma Dere (7.72 km) with a total length of 10.52 km. In 2015, the waterfalls of the Bashiboska River, or the Kochulski waterfalls, were explored by Dzilvidziev G. and Stojcheski

D., who recorded 14 waterfalls and cascades higher than 2 meters during field research in the lower course of the Ark Dere, Chamdash Dere, and Kaldrma Dere rivers. With the development of LiDAR technology and high-resolution digital models, the detection and discovery of waterfalls via remote detection have been enabled. For the purposes of this study, an automated process in ArcGIS Pro software called Model Builder was developed and applied. Using this process, which incorporated data from 1m LiDAR DTM, all river bed locations with a drop greater than 2 meters and a slope greater than 45° were detected. Following the automated Model Builder process, a manual digital check was performed to eliminate any potential errors, resulting in 104 locations where waterfalls and cascades could be found. The digital detection confirmed 12 of the previously explored waterfalls and cascades. The detection did not include only two cascades from field research that have a slope less than 45°. According to the basin, the most waterfalls were registered in the basins of the Chamdash Dere river (40 waterfalls), Ark Dere (36 waterfalls), and Kaldrma Dere (28 waterfalls). According to 1m LiDAR DTM, the tallest waterfall in the upper basin of the Bashiboska River is "Waterfall 2" from tributary 2 of Kaldrma Dere, referred to in the study as "KD-T2-2", with a height of 24.2 meters.

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