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Morphological Evolution of the Krasnodar Reservoir Bed (2006-2021): Insights from Geomorphometric Analysis and Benthic Form Transformations

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Abstract: In the Krasnodar region of the Russian Federation, a water reservoir was established along the Kuban River in 1973 and has undergone gradual siltation and significant morphological changes over the years. This study employs geomorphometry to examine the reservoir's bathymetry and categorize its mesoscale landforms, drawing on multiple bathymetric surveys. By utilizing Digital Benthic Models (DBM) and geospatial analysis, we examine the morphological evolution from 2016 to 2021. The results reveal notable transformations in benthic forms, including the disappearance of U-shaped valleys and their transition into canyons and plains. Spatial correspondence analysis and quantitative assessments offer insights into the consistency and changes within the reservoir's landscape. These findings not only contribute to a deeper understanding of sedimentation processes and reservoir morphometry but also have practical implications for reservoir management and environmental conservation.

Keywords: Bathymetry, Benthic Forms, Sedimentation, Geographic Information System, Digital Benthic Models, Geospatial Analysis

INTRODUCTION

The morphological study of the Krasnodar reservoir bed, which has undergone gradual siltation since its inauguration in 1973 on the Kuban River, is categorized as a large reservoir (Avakyan et al., 1987). The bottom of the reservoir encompasses level expanses of a submerged alluvial plain, characterized by predominant slopes ranging approximately from 0.2° to 0.4°. These areas are intersected by river channels originating from lower-order tributaries (Pogorelov et al., 2022).

Measuring bathymetry stands as one of the most widely used and accurate techniques for assessing sedimentation rates. Sediment accumulation at the base of reservoirs carries significant consequences for water supply, agricultural output, power generation, and the expenses associated with reservoir maintenance (Gao et al., 2016). It poses environmental risks by compromising water quality and diminishing biodiversity (Xu et al., 2017). Implementation of soil and sediment management strategies, both within and upstream of impounded reservoirs, has demonstrated effectiveness in mitigating sedimentation issues (Gonzalez Rodriguez).

Changes in land use represent the primary driver behind the escalation of sedimentation rates, followed by the combined influence of land-related activities and climate shifts. Recent research has highlighted an increase in sedimentation rates across numerous reservoirs attributed to heightened soil erosion resulting from land-use changes and intensified rainfall patterns (Schiefer et al., 2013). Conversely, certain reservoirs have witnessed reduced

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sedimentation rates due to human interventions and climatic factors (Chen et al., 2019; Darama et al., 2019). Factors like rainfall frequency and intensity exert direct influences on runoff, flood occurrences, and sediment deposition rates.

This geomorphometry study aims to elucidate the morphological characteristics of bathymetry and to derive a classification of mesoscale landforms of the reservoir. The established morphometric parameters for reservoirs, as adopted in hydrometry, encompass factors such as the type, shape, elevation, dimensions, and volume of water contained in the reservoir bed. Understanding the geomorphological attributes and the evolution of the reservoir proves pivotal in comprehending sedimentation processes and predicting morphometric characteristics.

The utilization of Digital Benthic Models (DBM) and geospatial analysis tools have elevated the benthic analysis of the reservoir bed to a new technical threshold (Kalinin et al., 2018; Florinsky, 2021). A chronological analysis spanning from 1973 to 2021 reveals significant changes in the reservoir's dimensions. The reservoir's useful volume decreased from 2160 million m³ to 1270 million m³ due to siltation. Concurrently, the water surface area decreased from 400 km² to 224 km² (Pogorelov et al., 2022).

The phenomenon of siltation within the reservoir arises from ongoing alterations in the underwater topography, propelled by interlinked geomorphological and hydrological dynamics. These include sediment deposition and fluctuations in local current structures, among other factors.

During the reservoir's existence, the benthic forms and morphometric attributes have undergone transformation due to the influence of fluvial processes stemming from the Kuban, Psekups, and Pshish rivers (as illustrated in Figure 1b). Comprehensive studies conducted by Laguta and Pogorelov (2019) and Pogorelov et al. (2021) have contributed to a deeper understanding of these evolutionary trends.

The morphological attributes of the Krasnodar reservoir bed have hitherto remained unstudied and are intriguing from the perspective of its long-term transformative changes. This study embarks on these objectives:

1. To elucidate the morphological traits of the reservoir bed using geomorphometric methodologies, identify the primary benthic forms within the reservoir basin and construct corresponding maps.
2. To determine the enduring morphometric alterations resulting from the reconfiguration of benthic forms and to assess deformations within the reservoir bed.
3. To pinpoint the predominant processes of morphogenesis, unveil patterns of sedimentation, and characterize their manifestations in the bed's relief.

Through the V-measure method, our study aims to address queries such as "How distinct are the benthic forms of the Krasnodar Reservoir in 2016 compared to those in 2021?"

During the interim between the latest bathymetric surveys of the Krasnodar Reservoir, the average volume of siltation from 2016 to 2021 was documented at 4.93 million cubic meters (Pogorelov et al., 2022). This information underscores the dynamic nature of sedimentation within the reservoir over this period. How different are the benthic forms of 2016 and 2021? Is there a relation between them?

MATERIALS AND METHODS

Krasnodar reservoirs, located within the Russian Federation along the Kuban River, share borders with the Krasnodar region and the Republic of Adygea (as depicted in Figure 1a). This reservoir serves two primary functions: flood control and irrigation. Its establishment dates back to 1973, resulting in the inundation of an expansive 400 km² area and accommodating an approximate total volume of 3 km³. Falling under the category of a valley-type reservoir, it features an elongated shape. The Kuban River, spanning 46 km in length, forms the reservoir's backbone, with a maximum width of 11 km and the greatest depth recorded at 24.7 m, as reported by Lurie et al. (2005).

The Kuban River notably boasts the highest turbidity level, measured at 0.68 kg/m³. According to Alekseevsky et al.. (2012), a substantial percentage of sediment brought by the river, ranging from 95% to 98%, is deposited within the reservoir.

Employing a comprehensive bathymetric survey methodology for the Krasnodar Reservoir as outlined in Laguta and Pogorelov (2018) and Pogorelov et al. (2021), a substantial number of bathymetric points were meticulously surveyed, amounting to 1.4 million and 1.0 million for the years 2016 and 2021, respectively.

Utilizing the data from these surveys, to build two distinct Digital Bathymetric Models, labeled as DBM-2016 and DBM-2021, with a spatial resolution of 50 meters, which proves to be sufficiently detailed for analyzing morphometric attributes of the reservoir bed, encompassing features like channels, ridges, and pits.

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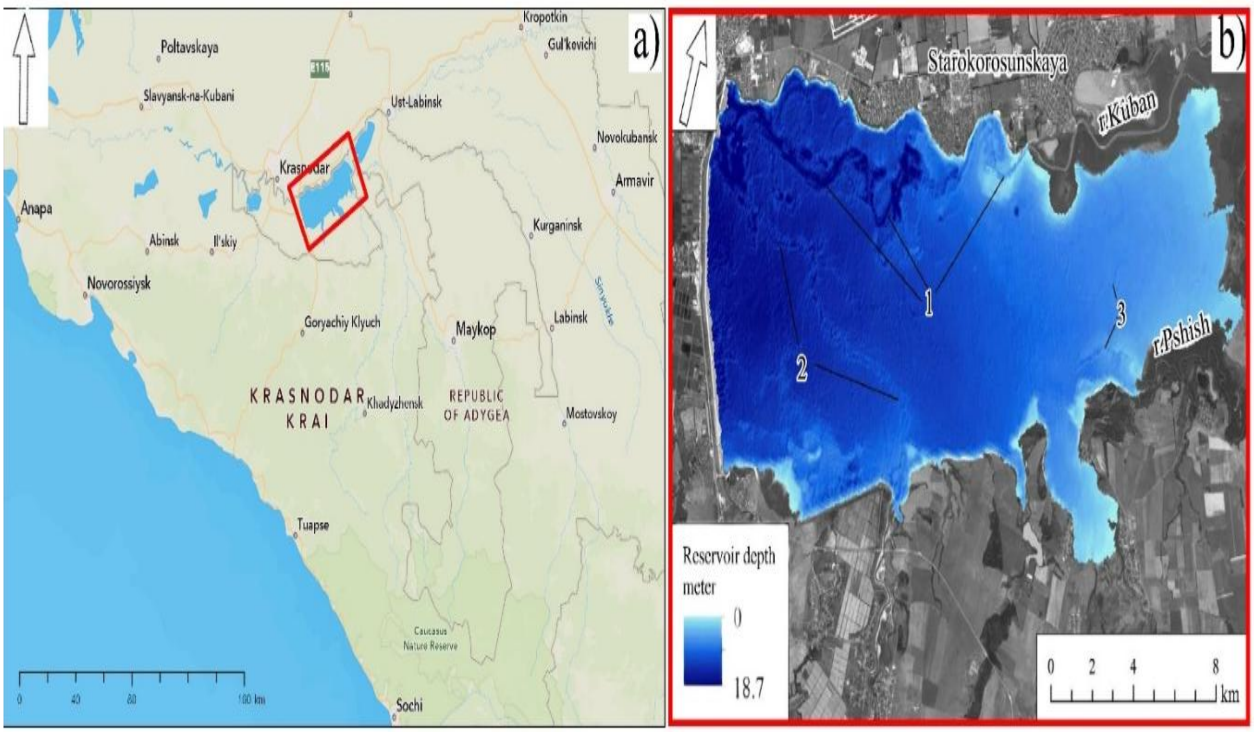
The classification of benthic forms within the Krasnodar reservoir bed was established through the utilization of the Bathymetric Position Index (BPI) method. This method entails the calculation of the second-order derivative (derived from the first derivative, i.e., slope) of the bathymetry. The foundation of this approach can be traced back to the topographic position index (TPI) as initially defined by Weiss (2001) and Iampietro and Kvitek (2002).

Figure 1

Location and Depth map Krasnodar Reservoir in Krasnodar region



Note. a) Krasnodar reservoir location in Krasnodar region. b) Depth map of Krasnodar reservoir at a normal backwater level (2021). The numbers indicate the rivers flowing into the reservoir: Kuban (1), Psekups (2), and Pshish (3). (After Pogorelov et al.2022)

The BPI index operates on a multi-scale basis, engendering the creation of both "rough" (Broad-BPI) and detailed (Fine-BPI) raster images. The BPI index is determined by the disparity between the absolute height of a point (represented by cells within a raster layer) and the average height of points within a buffer surrounding the reference point. Positive values of the BPI index correspond to surface convexities, while negative values denote concave features. Values approaching zero indicate a nearly flat surface.

After creating BPI data sets at both fine and broad scales, the next step in the benthic terrain classification process involves standardizing the values of these raster data sets. Bathymetric data exhibits spatial autocorrelation, meaning that locations closer together are more related than those farther apart (Weiss 2001). The range of BPI values increases with scale.

For instance, when working with broad (small-scale) BPI data sets, the BPI values are smaller due to the utilization of a larger analysis neighborhood. This smooths out small variations in the terrain. Conversely, fine (large scale) BPI data sets yield larger BPI values because of a smaller analysis neighborhood, which enables the detection of smaller, localized terrain variations. Standardizing the raw BPI values enables the classification of BPI data sets at nearly any scale (Weiss 2001).

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To create the standardized output data set, the following algorithm is applied:

BPI <scale factor>_std = int ((((BPI <scale factor>—mean)/std dev) * 100) + 0.5)

Where:

SCALE FACTOR = outer radius in map units * input bathymetric data set resolution (cell size)

MEAN = mean cell value across the BPI data set

STD DEV = standard deviation of cell values across the BPI data set.

This revised version clarifies the process of standardization and the associated parameters for creating the standardized output data set. The selection of neighborhood sizes for the fine BPI involves a radius of 250 m, five times larger than the cell size of the Digital Bathymetric Model (DBM). Conversely, the neighborhood size for the broad BPI is set at 1250 m. By leveraging two BPI grids at distinct scales (fine and broad), the landscape can be classified into ten morphological classes:

1. Canyons, deeply incised streams
2. Mid-slope drainages, shallow valleys
3. Upland drainages, headwaters
4. U-shaped valleys
5. Plains
6. Open slopes
7. Upper slopes, mesas
8. Local ridges, hills in valleys
9. Mid-slope ridges, small hills in plains
10. Mountain tops, high ridges

For the assessment of spatial associations between benthic forms and to achieve a quantitative understanding of changes over time (from 2016 to 2021), the V-measure method (Nowosad & Stepinski, 2018) was adopted. This approach facilitates comparisons, associations, and the derivation of sediment forms.

Leveraging the Spatial Association Between Zones tool within ArcGIS Pro, it becomes possible to identify correspondences and discrepancies between zones on two maps. This tool enables the quantification of changes across the designated time frame. Questions like "How different are the benthic forms of 2016 compared to those in 2021?" can be systematically addressed by evaluating spatial associations. This methodology allows for a more nuanced understanding of the shifts within the reservoir's landscape.

RESULTS AND DISCUSSIONS

The classification of the reservoir bed yielded nine distinct morphological elements, categorized into three surface types: flat, concave, and convex (as documented in Table 2 and represented in Figure 2). The open slopes or hills in valley forms were not identified in either the 2016 or 2021 benthic forms.

Based on the survey data from 2021, the plain terrain occupied 84.1% of the area, characterized by predominant slopes ranging from 0.1 to 0.4 °. The plateau concept aptly captures the essential attribute of this landform, which is primarily flat.

Figures 2a and 2b vividly display the benthic forms observed within the Krasnodar reservoir in the years 2016 and 2021, respectively. The evident diversity in these forms can be attributed to the dynamic processes of sedimentation, accumulation, and deposition across the reservoir floor. The juxtaposition of the benthic forms of 2016 and 2021 in Figure 2 is a visual testament to the ongoing evolution of the reservoir's landscape because of these sedimentary dynamics.

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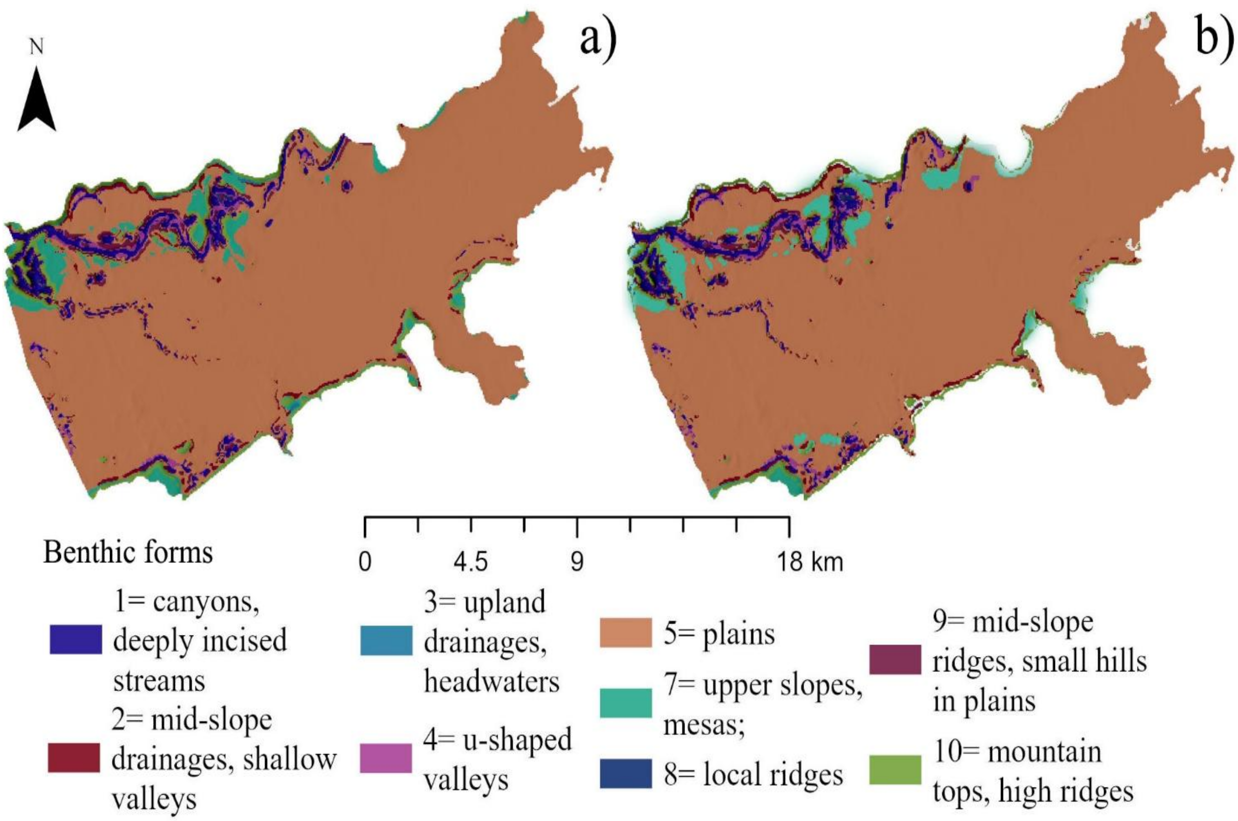
Negative forms, including shallow channels and depressions (classified as 1= Canyons, deeply incised streams), occupy 3.5% and 3.3% of the area, respectively. These depressions have diverse origins; some correspond to flooded riverbeds, while others stem from the concave foothills of alongshore accumulative forms like swells. Older channels, undergoing silting and flattening processes, transform in a sequence of "depression—hollow—plateau." Conversely, newly formed channels, such as those in the Pshish River delta, induce depressions during their incision.

Positive elements of floor morphology encompass a group of convex forms, further divided into three elementary categories: local ridges, slope ridges, and mountain tops. The origin of these convex forms, along with the ramparts that belong to the group of negative landforms, is genetically influenced by accumulative (fluvial) and abrasion processes. Figure 2 depicts the positioning of genetically homogeneous elementary landforms.

Figure 2

Comparison of the Benthic Forms of 2016 and 2021



Note. a) Benthic forms of 2016, b) Benthic forms of 2021

Accumulative forms emerged due to sediment translocation influenced by coastal swells' lateral movement. These forms manifest as ridges and frontal (marine) slopes of swells and hollows separating coastal swells from the underlying plateau. Rear facing (towards the coast) slopes are not discernible due to the spatial resolution constraints of the survey. The influx of sediment-laden tributaries alters the conditions for coastal ridge formation, helping to generate new generations of small ridges due to wave action.

In the deeper portion of the reservoir bed, riverbanks from submerged channels have been retained. This form is found sporadically along the flooded channel of the Kuban River. Examining the evolution of the bottom terrain over the analyzed period (2016–2021), significant morphological changes occurred among the elementary landforms.

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Approximately 34.1 km2, or around 15% of the analyzed area, experienced these transformations. Table 1 summarizes the diverse nature of these morphological shifts.

Concave forms of the reservoir floor underwent alterations, with the area of depressions (1 Canyon, deeply incised streams) decreasing and the area of hollows (10 Mountain tops, high ridges) expanding (as illustrated in Table 1). The number of depressions, although reduced in size, slightly increased, indicating fragmentation. The phenomenon of depressions "self-liquidating" due to siltation is exemplified by the former riverbeds of Psekups and Pshish, which are nearly absent in the 2021 data (as shown in Figure 2). Some depressions have transformed into hollows.

Table 1

Benthic form numbers and percentages of areas

Benthic forms	2016		2021		2021 vs. 2016	
	Numbers	Area %	Numbers	Area %	Difference in area %	Difference in numbers
1= Canyons, deeply incised streams;	134	3.5	143	3.3	-0.25	9
2= Mid-slope drainages, shallow valleys;	295	1.8	251	1.7	-0.04	-44
3 Upland drainages, headwaters;	20	0.1	33	0.1	-0.03	13
4= U-shaped valleys;	362	1.2	281	1.3	0.09	-81
5= Plains;	453	83.7	332	84.1	0.41	-121
6= Open slopes; hills in valleys;	-	-	-	-	-	-
7= Upper slopes, mesas;	284	3.8	262	4.1	0.25	-22
8= Local ridges;	67	0.2	53	0.2	-0.04	-14
9= Mid-slope ridges, small hills in plains;	353	2.1	287	1.6	-0.49	-66
10= Mountain tops, high ridges;	144	3.5	266	3.6	0.13	122

Simultaneously, new concave forms emerged within the previous plateau region (constituting about 40% of their total area). This is attributed to the incision of emerging channels, giving rise to hollows within the accumulative parts of shallows and underwater slopes. The total area occupied by concave forms decreased during the study period from 1559 ha to 1357 ha, primarily due to siltation.

To gain deeper insights into the evolution of benthic forms between 2016 and 2021, a spatial correspondence analysis was conducted. This analysis aims to highlight benthic forms with varying degrees of shape modifications—low, moderate, and high.

The analysis juxtaposed the benthic forms from the 2021 survey with the benthic forms from 2016. The association is highest when each benthic form from the 2016 survey closely aligns with a corresponding form in the 2021 data (as demonstrated in Figure 3).

The outcomes of this spatial association analysis are expressed through a single numerical value ranging from 0 (indicating no correspondence) to 1 (representing perfect spatial alignment of zones). The regions identified in the first regionalization are called input zones, while those in the second regionalization are termed overlay zones. This methodology allows for a comprehensive assessment of the changes and associations between different morphological zones within the reservoir bed over the specified time frame.

This figure visually depicts the relationship and correspondence between these forms within the reservoir's landscape.

The spatial association analysis visually emphasizes how much the benthic forms observed in 2016 align with those witnessed in 2021. Areas of significant spatial alignments are visually conveyed through the level of overlap between the forms from both periods, indicating regions where the morphology has remained consistent. Conversely, regions with lower overlap suggest areas where morphological alterations have transpired between the two-time points.

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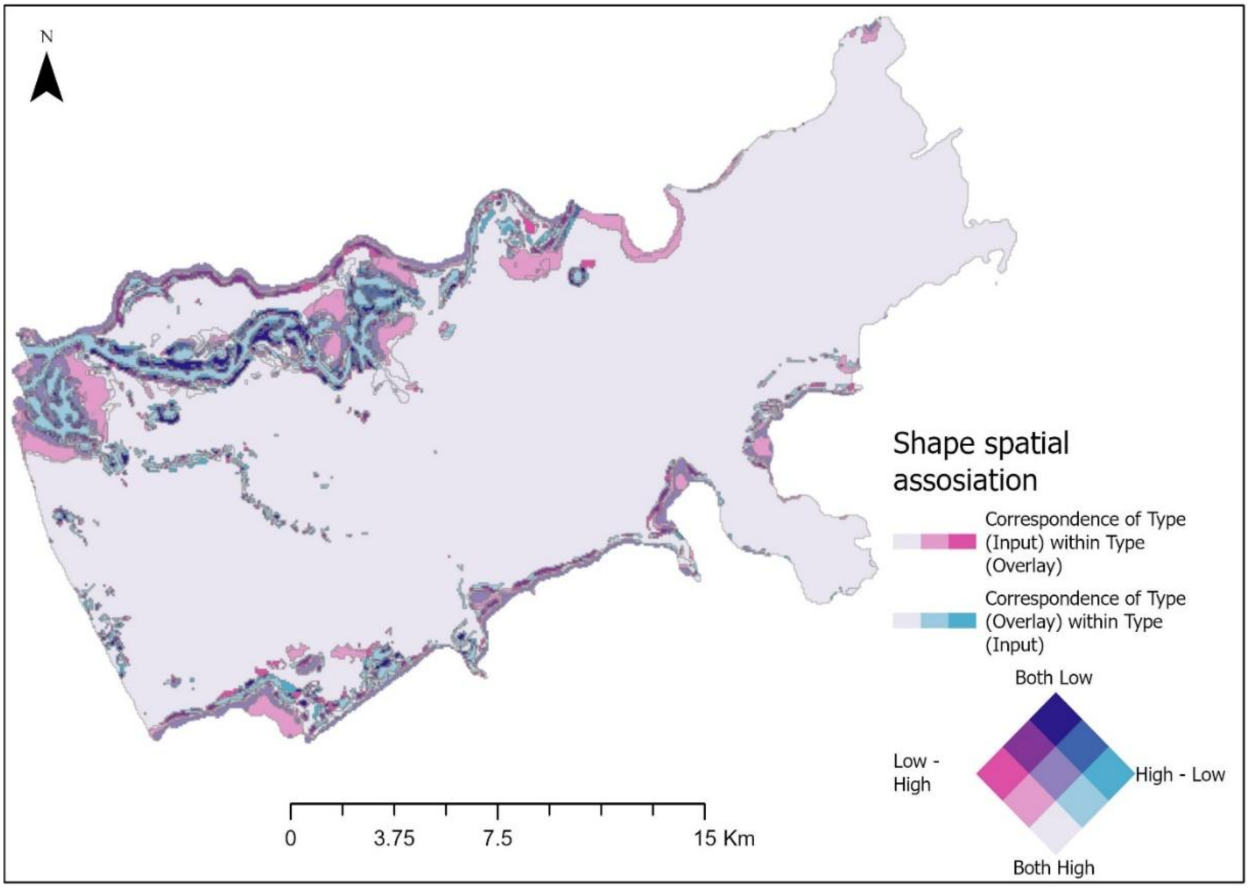
Figure 3

Illustration of the spatial association existing between the benthic forms of 2016, designated as an overlay type, and the benthic forms of 2021, categorized as input types.



This analysis enhances our comprehension of the reservoir bed's evolution by effectively presenting where the benthic forms have retained their characteristics and where modifications or shifts have taken place. The graphical representation depicted in Figure 3 concisely summarizes the spatial associations between these two sets of benthic forms, thus aiding in the quantitative understanding of the changes and consistency within the morphological features of the reservoir.

The association between the two regionalizations is intricately tied to the area overlap observed between the benthic forms of 2016 and 2021 Figure 3. This concept of association is at its peak when each zone within one regionalization closely corresponds to a corresponding zone within the other regionalization. An exemplary case of this phenomenon is the plain landform, which has remained unchanged in shape since 2016 with the spatial association being notably high in this scenario.

Conversely, the spatial association is minimized when the zones of one regionalization exhibit substantial overlap with numerous different zones from the other regionalization, this situation arises when multiple morphological forms from one period closely align with diverse forms from the other period.

The visual representation in Figure 3 of the benthic forms from both 2016 and 2021, each represented by distinct zones, when two corresponding zones display a high level of overlap, the spatial association is strong.

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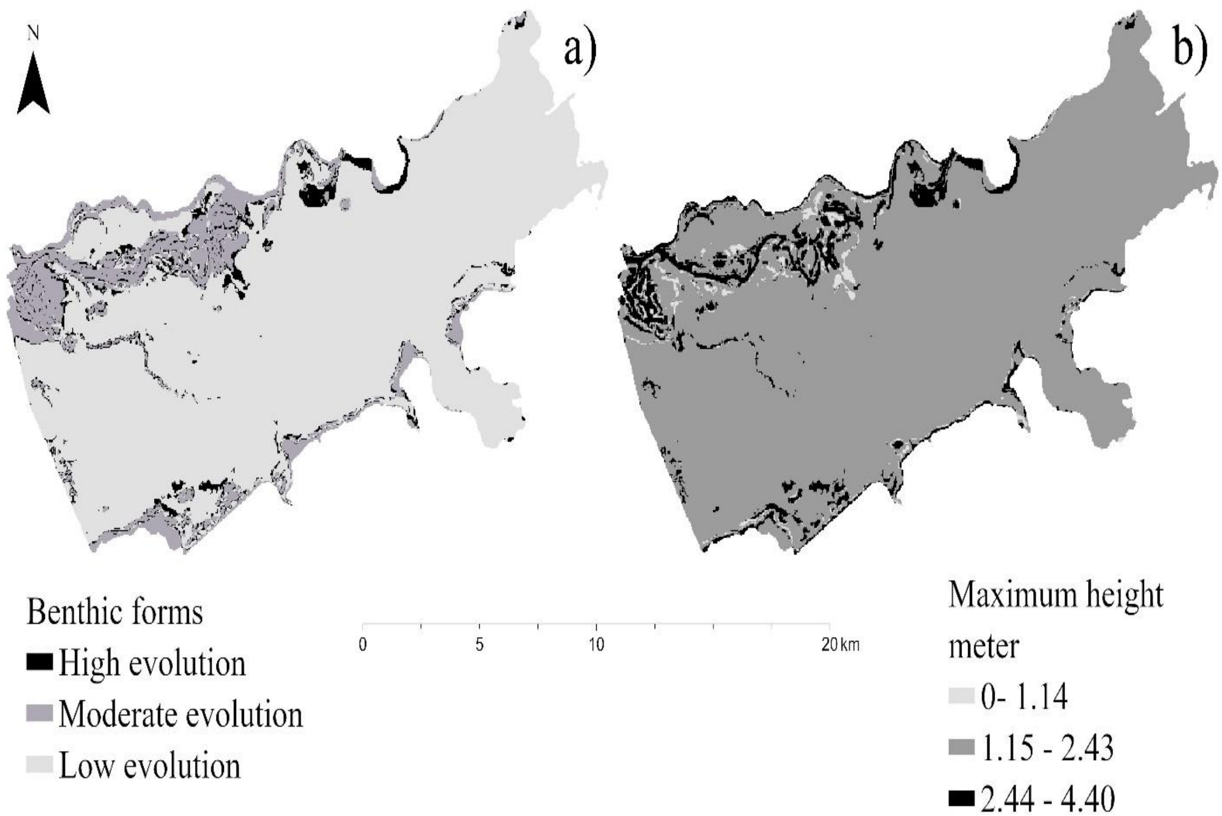
Conversely, if zones from one year's data set intersect with a range of zones from the other year's data set, the spatial association between these two data sets is diminished.

This approach allows for a quantitative assessment of the changes and consistency between benthic forms over the specified time frame, providing valuable insights into the reservoir's benthic form evolutions.

In Figure 4a, we observe significant changes in the morphology of benthic forms represented in black color at the boundaries of the reservoir when sedimentation is occurring, resulting in elevated formations. A more moderate transformation is observed in elongated shapes resembling deep erosion networks within the river streams on the reservoir bed.

Figure 4

Benthic Evolution and Sedimentation



Note. a) Benthic form evolution, b) sedimentation height in each benthic form

Both high and moderate evolved forms are present within the sedimentation height range of 2.44-4.440, as illustrated in Figure 4b.

The plateau of the reservoir remains unchanged in shape but experiences an evolution in height within the range of 1.15 to 2.43 meters, giving rise to a new sedimentation layer.

Forms with lower sedimentation heights, ranging from 0 to 1.14, are on elevated bathymetry areas resembling small hills.

To better comprehend the evolution of benthic forms from 2016 to 2021, Table 2 provides a spatial quantitative analysis detailing the changes in shape. This analysis includes information on the evolution area, the number of distinct shapes, and the minimum, maximum, and mean sedimentation thickness.

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The most notable evolution occurred in an area of 2.47 square kilometers, transitioning from the plains to the upper slope, with an average sedimentation thickness of 1.39 meters. Conversely, a transformation of 2.22 square kilometers from the upper slopes to the plains was observed, with an average sedimentation thickness of 0.49 meters.

Table 2

Minimum, maximum, and mean sedimentation thickness in each benthic form.

Shape evolution				Sedimentation thickness		
Benthic forms in 2016	Evolute in 2021	AREA/km^2	COUNT	MIN	MAX	MEAN
1 canyons, deeply incised streams	5= plains	1.11	387	0	3.32	1.66
2= mid-slope drainages, shallow valleys	5= plains	1.54	592	0	1.89	0.95
4= u-shaped valleys	1 canyons, deeply incised streams	0.71	215	0	1.94	0.97
4= u-shaped valleys	5= plains	0.6	222	0	2.58	1.29
4= u-shaped valleys	10= mountain tops, high ridges	0.06	14	0	3.3	1.65
5= plains	1 canyons, deeply incised streams	0.83	272	0	1.32	0.66
5= plains	7= upper slopes, mesas	2.47	972	0	2.78	1.39
5= plains	9= mid-slope ridges, small hills in plains	0.79	286	0	1.81	0.91
5= plains	10= mountain tops, high ridges	0.93	353	0	3.2	1.6
7= upper slopes, mesas;	5= plains	2.22	906	0	0.97	0.49
9= mid-slope ridges, small hills in plains	1 canyons, deeply incised streams	0.19	24	0	1.02	0.51
9= mid-slope ridges, small hills in plains	7= upper slopes, mesas	0.09	40	0	2.15	1.08

Table 2 reveals that the benthic forms in the plains underwent the most significant evolution compared to other areas. In 2021, U-shaped valleys vanished and transformed into canyons, plains, and even high ridges, particularly in areas of accumulation.

The evolution between the plains and upper slopes, and between upper slopes and plains, resulted in a substantial increase in the number of distinct shapes or forms.

CONCLUSION

The morphological study of the Krasnodar reservoir bed spanning from its inception in 1973 to the year 2021 has unveiled significant insights into its evolving landscape. Over this period, the reservoir has experienced substantial changes in its dimensions and benthic forms due to ongoing siltation and geomorphological dynamics influenced by the Kuban, Psekups, and Pshish rivers.

Our comprehensive analysis, utilizing geomorphometric methodologies and Digital Benthic Models, has allowed us to classify and quantify these morphological alterations. We observed the transformation of U-shaped valleys into canyons and plains, indicating the dynamic nature of the reservoir's sedimentary processes.

Spatial correspondence analysis and quantitative assessments have further elucidated the spatial associations and changes between benthic forms from 2016 to 2021. These findings provide valuable insights into the reservoir's morphological evolution, enhancing our understanding of sedimentation processes and reservoir morphometry.

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This study underscores the importance of continued monitoring and analysis of reservoir morphology, especially in long-term transformative changes. Such research is vital for managing water resources, flood control, and irrigation in the Krasnodar region.

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