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Assessment of the Vulnerability of the Coast of Lake Alakol to Modern Geomorphological Processes of Relief Formation

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Abstract: Over the last few decades, increasing water levels of Lake Alakol have led to the activation of processes of modern relief formation of the coastal territory. This study will make it possible to assess the vulnerability of the lake shore to modern relief-forming processes, which pose a threat to the economic and infrastructural development of the coast. Through a combination of field research methods, analysis of the archival materials and satellite images, GIS mapping, as well as the application of the Coastal Vulnerability Index, developed by Gornitz, a map of the modern relief of the coast of Lake Alakol was created, where 13 geomorphological types of relief were identified, and a map of relief-forming processes and leading exogenous processes were identified. The values of the assessment of the degree of vulnerability of the coast to dangerous processes by the Gornitz method were obtained, where a high vulnerability covers 67.4% of the coast, an average vulnerability covers 2.9%, a weak vulnerability covers 13.3%, and low vulnerability occupies 16.4% of the coast. The degree of vulnerability of types of relief in the study area, the coast of Lake Alakol, was determined. High degree occupies 42.8% of the study area, medium—30.7%, weak—25.4%, and low 1.1%. A map of the complex assessment of the degree of vulnerability of the coast of Lake Alakol was created. It was revealed that low accumulative types of relief of the northwest and northeast coasts and alluvial-proluvial types of relief are highly vulnerable due to waterlogging and the intensity of abrasion processes. Identified natural features of the relief formation of the coast of Lake Alakol are recommended as a basis for making decisions on the planning and implementation of any economic activities on the coast, including infrastructure development of the coast and strengthening of the shores.

Keywords: coast of Lake Alakol; relief types; exogenous processes; vulnerability assessment

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1. Introduction

The coastal zone is a dynamic environment, constantly changing due to the influence of a number of geomorphological processes [1], and is vulnerable to numerous hazards (e.g., flooding, sea level rise, erosion) and the normal functioning of infrastructure facilities [2,3]. With anthropogenic impacts on the coasts in recent years and the adverse effects of regional climate change impacts, the issue of assessing coastal vulnerability under current conditions becomes relevant. Continental lakes of closed basins are particularly susceptible to climate change and increasing anthropogenic impacts [4,5]. The degree of the negative impact of human activities on the coastal territories of endorheic lakes, which is an important area of activity in agriculture [6], fishing [7], and tourism [8], is increasing. The problem of instability of shores and coastal ecosystems in the water bodies of the closed basins of Kazakhstan can be exacerbated by the impact of climate change [9]. The shore/coastline is a dynamic geographical feature that is constantly changing under the influence of natural erosion, water interactions such as flooding, and anthropogenic factors [10].

Lake Alakol is characterized by secular and intra-secular cyclical (periodic) water-level variations due to seasonal changes, primarily from snowmelt runoff [11]. Wind, waves, and surges lead to shore erosion and the coastal degradation of beaches and wetland ecosystems [12]. These water-level fluctuations represent a key process that affects the structure and functioning of ecosystems in lakes [13]. Bai et al. determined that Alakol Lake's surface area showed an increased trend after 1990 (1990–2007) [14]. The study by Klein et al. showed that the surface areas of the Alakol–Sassykkol lake system remained very stable over the observed time period from 1986 to 2012 [15]. According to Valeyev et al., the dynamics of abrasion processing on the southwestern and eastern shores of Lake Alakol reached 3.8 m per year [16]. Valeyev et al. determined the flooding dynamics of the northeastern coast of Alakol Lake over a 28-year period, which ranged from 200 to 1000 m [17]. The low and deltaic northeastern and northwestern coasts of Lake Alakol are the most prone areas to flooding. The rise in the water level turns the wetlands into open-water lakes and turns dryland into wetlands [18].

The first comprehensive physical and geographical studies of the Alakol–Sasykkol lake system were conducted in 1960–1963, which included the study of geomorphology and relief formation processes of the shores of Lake Alakol [12]. The study of geology and relief formation of shores in the Anthropogenic period was conducted by Dzhurkashev T.N. [19]. The study of the natural and recreational potential of Lake Alakol was conducted by S.R. Yerdavletov, A.S. Aktymbaeva, and others—scientists who published a scientific and educational atlas: "*Journey to the Alakol*" [20,21]. Geo-ecological assessment of the tourist and recreational potential of the Alakol region was performed by A.S. Aktymbaeva and M.T. Taukebaeva [22]. The assessment of the anthropogenic impact on landscapes of the Alakol Lake basin was carried out by Mukaev J.T. and Ozgeldinova J.O. [8]. Kurochkina L.Ya. carried out ecological zoning by the degree of disturbance of ecosystems in the territory of the Sasykkol–Alakol depression [23]. Nusupov D.K. and Tursunov E.A. developed methods of coastal protection from abrasion processes on the southwestern coast of Lake Alakol [24,25]. These conducted studies are excellent indicators, showing a high degree of development of the processes in the zone of interaction between water and land. Obviously, these processes predetermine the degree of vulnerability of different shores. However, studies on the vulnerability of the shores of inland Lake Alakol have not yet been conducted. Therefore, the scientific and practical relevance of this study will aim to fill the gaps in the study of the degree of vulnerability of the lake shore.

Lake Alakol is an important lake in Kazakhstan, with a high recreation value and unique ecology. The wetlands of Alakol are the largest in Kazakhstan and are of particular importance, as they are located on the Central Asian-Indian bird migration route [26]. The coastline of Lake Alakol is becoming more affected by human activities every year. Only 1000 m from the southwestern shore lies the railway of the "Western Europe-Western China" corridor, and parallel to it is a highway and the Atasu-Alashankou oil pipeline. Recreational activities are intensively developed on the southwestern coast (Akshi and Koktuma villages) and the eastern coast of Kabanbay village [22].

Lake Alakol is an important tourist destination with considerable recreational potential. The last decade has witnessed an increase in infrastructure and transportation development along the shoreline. This has had a very positive effect on improving the economic situation of the local population, job creation, and the overall development of the region; however, coastal economic development may take place without careful consideration of the continuous natural processes occurring on the shores of Lake Alakol.

This study is therefore aimed at studying the relief of the lake shore as a base on which natural processes and anthropogenic development take place, the results of which will allow designation and preventive measures for rational land use of the coastal zone of Lake Alakol.

Due to the intensive involvement of the coast in infrastructure development and the development of a regional tourism destination, without taking into account the vulnerability of the shores in some parts of the coast, unfavorable conditions have already emerged on the southwestern and eastern shores of the lake. The destruction of structures and infrastructure as a result of the abrasion process forces owners to undertake shore protection engineering measures with their own resources. These mitigation measures are commonly expensive to construct because of the use of reinforced concrete structures [27]. In addition to the negative impact of the natural factors on the coast, wastewater discharge from the pools into the water area of the lake by land users of the first line are located close to the coast. Rapid population growth in many countries will eventually affect the provision of basic utilities and may lead to problems regarding sanitary conditions on the shore [28]. Significant growth of holiday homes and resorts along the coast, without regard to local natural conditions, and the lack of a central wastewater collection system also put pressure on maintaining the natural ecological balance of the lakeshore.

The lack of modern basic information about the relief of the coast and about the exogenous processes that form the coast is the reason for the increased negative impact on the infrastructure of the coast. Therefore, the purpose of this study is to assess the vulnerability of the lake shore to modern relief-forming processes that pose a threat to the economic and infrastructural development of the coast.

Assessment of coastal vulnerability is one of the most important tools for decision-making and providing effective management solutions to reduce the adverse socioeconomic impacts of multiple environmental hazards on the associated socio-ecological systems of coastal areas [29]. A vulnerability assessment is critical to coastal hazard management [30]. The degree of vulnerability is determined by the susceptibility and resilience of the coastal system to hazards [31]. At the same time, coastal processes influence the evolution and current state of the coasts [32]. Geomorphology determines the erodibility of different types of relief, which is especially important for coastal vulnerability [33]. The vulnerability of coastal habitats, populations, and infrastructure will change as coastal geomorphological characteristics change [34]. Therefore, in this study, based on a detailed analysis of geomorphological conditions, relief-forming processes, and components of the coastal vulnerability index, a comprehensive study of the degree of vulnerability of the Lake Alakol coast was determined.

Study Area

Lake Alakol occupies the central part of the Alakol inter-mountain depression, located in the southeastern part of the Republic of Kazakhstan, between the Tarbagatai and Zhetysu Alatau Mountains. Lake Alakol is the largest lake of the Alakol–Sasykkol lake system, which includes the large lakes of Sassykol, Koshkarkol, and Zhalanashkol. It occupies the lowest mark of absolute heights in the Alakol–Sasykkol lake system at a level of 349 m. Alakol Lake is a tectonic and endorheic lake with surface and groundwater inputs [4,19].

The climate of the study area is arid and sharply continental. The average annual air temperature is within 6–7 °C, and the average monthly temperature in July is from 24.0 °C to −14.8 °C in January. The annual precipitation varies from 200 to 350 mm, depending on the terrain, wind conditions, and the influence of large lakes. The average annual wind speed varies from 3.8 to 7.0 m/s. Local hurricane winds are observed: southeastern Eby, up to 50–70 m/s, and northwestern Saikan, up to 50–60 m/s [35].

The area of the lake is just over 3000 sq. km, with a maximum depth of 54 m. Several mountain rivers, such as the Zhamanty, Yrgaity, Katynsu, Urzhar, and the transboundary river Emel, flow into the lake. The lower shores of the lake, including river deltas, are included in the list of wetlands of international importance. The southwestern and eastern coasts are actively used for the development of beach and swimming tourism (Figure 1).

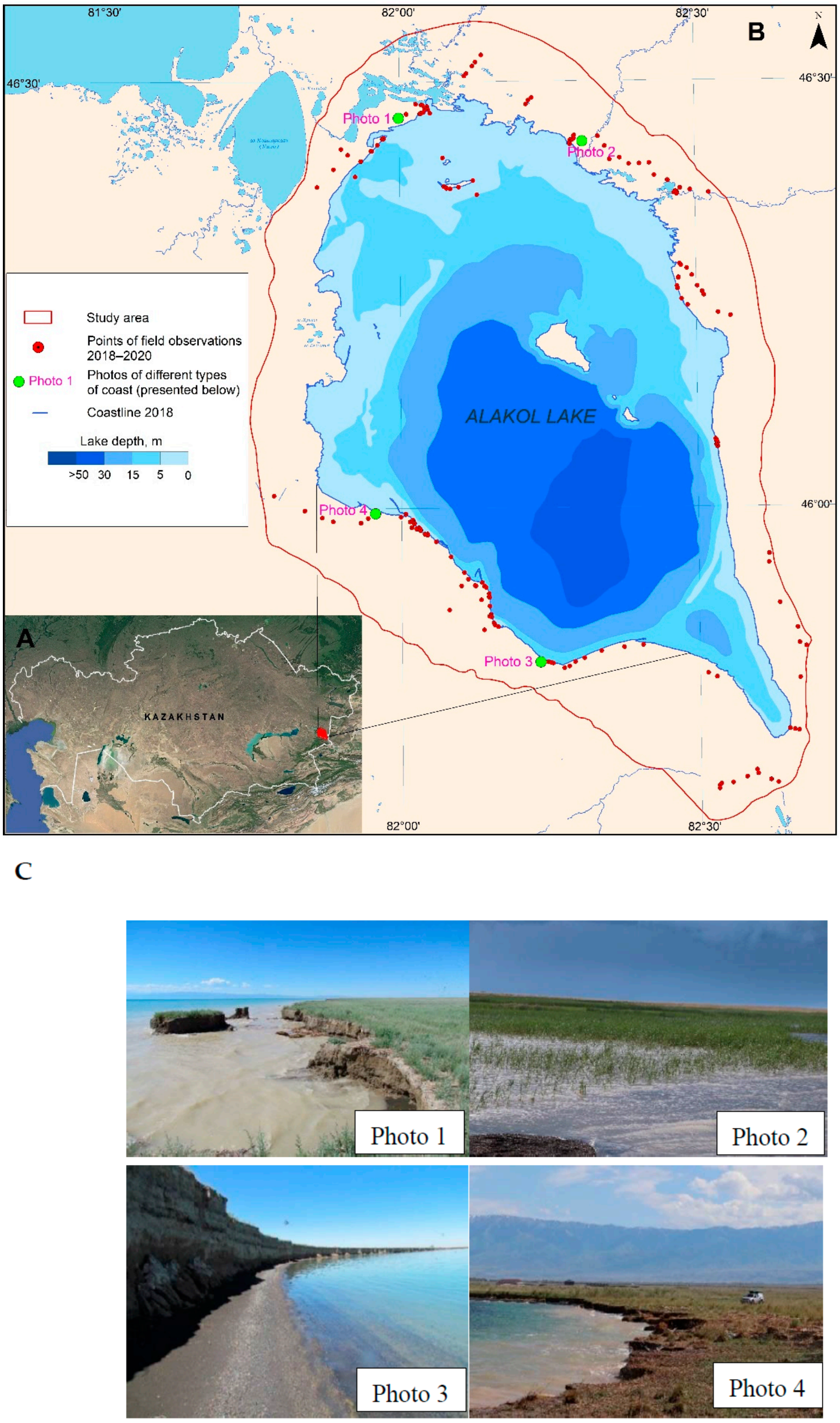

Figure 1. Coastal zone of Lake Alakol: sector (**A**)—satellite image of Kazakhstan territory, red color marks the study area, blue color, the lake; sector (**B**)—study area; sector (**C**)—photos taken by the authors, as examples of different coastal types. Location of sites on the map (sector (**B**)): photo 1—abrasion northwest coast; photo 2—low-lying accumulative coast near the Katynsu River delta; photo 3—abrasion-accumulative coast type; photo 4—abrasion southwest coast.

2. Methods

This research was developed based on an integrated approach to studying the relief environment of the coast of Lake Alakol. The research stages are based on a literature review and analysis, cartographic and archival materials collection, and remote sensing data by processing and analyzing collected data and materials and allocating the research area, as well as conducting a field observation to obtain the monitoring data and clarify the geospatial boundaries of the thematic layers. In the first stage, it was necessary to study the shores and relief of the coast of the study area, as well as to identify and obtain the variables involved in the assessment of coastal vulnerability. Thus, the types of coasts and their distribution, geomorphology and relief-forming processes of the coast are defined. Based on the variables: the relief of the coast, coastal geology, landform, cliff abrasion, leading process, and tidal range Coastal Vulnerability Index of Alakol Lakeshore were determined. Using maps of geomorphology, modern relief-forming processes, and coastal vulnerability (Gornitz) based on an expert approach, the degree of vulnerability of the coast of Lake Alakol to modern relief-forming processes was assessed (Figure 2) [36].

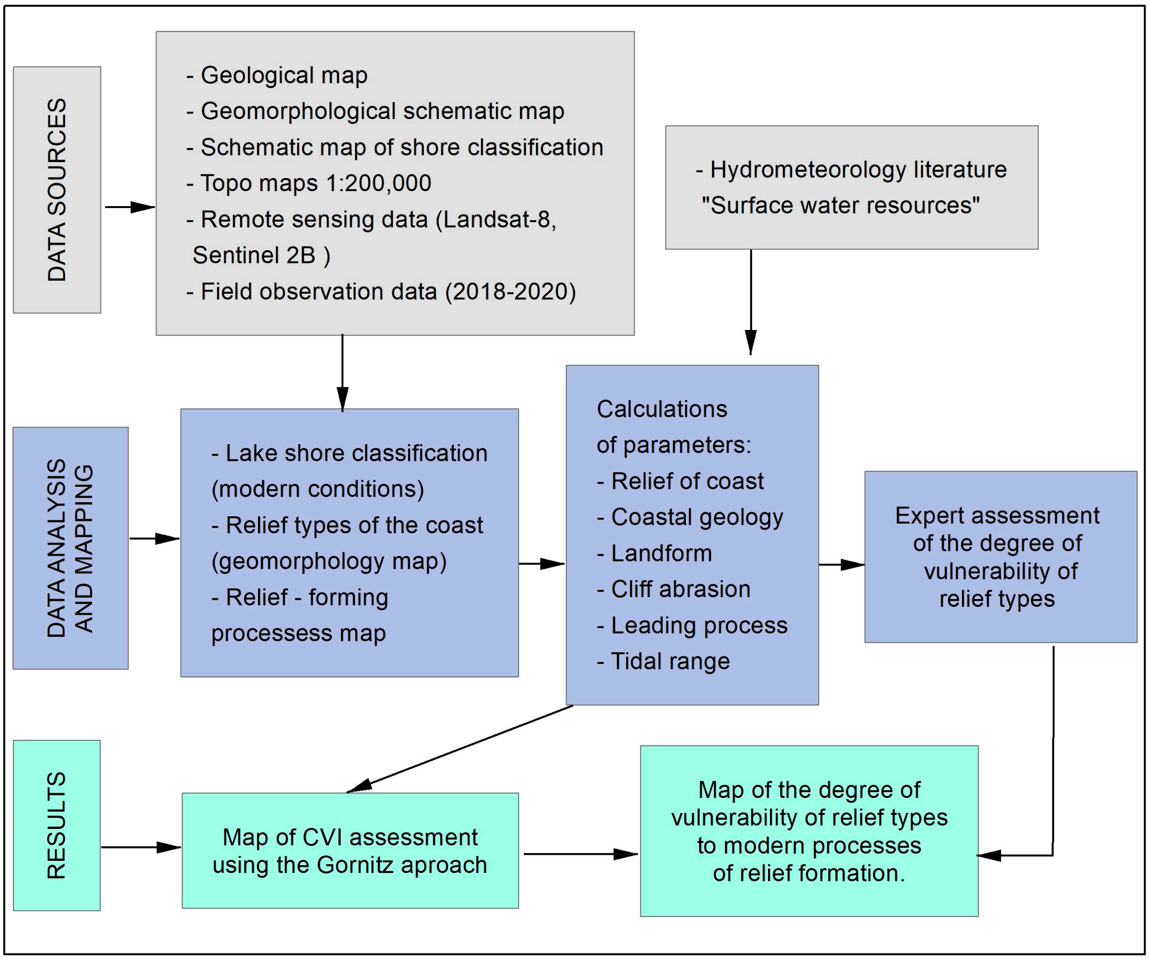

Figure 2. Flow chart of the research process used for this research.

2.1. Existing Cartographic Materials and Mapping

To determine the types of relief of the territory of the coast of Lake Alakol, it was necessary to create modern maps of geomorphology and relief-forming processes on a scale of 1:200,000. To create the maps, we used:

- Geological maps of the USSR, scale 1:200,000, Dzhungarskaya Series [37–40];

- Geomorphological maps-schemes from the explanatory note of the Geological Map of the USSR, scale 1:200,000, Dzhungarskaya Series. The Ministry of Geology and Subsoil Protection of the USSR [37–40];
- Map of the classification scheme of the shores of Lake Alakol [12];
- Topographic maps, 1:200,000 scale (editions 1976, 1990, 1992).

On the basis of the stock materials, morphological classification of the shores of Lake Alakol was conducted. Mapping was carried out using the ArcMAP 10.5 software.

2.2. Satellite Images

The use of geospatial technology remains an effective tool for terrain analysis [41]. Remote sensing data were used to refine the details of the spatial locations of various types of shores, determine their geomorphological types, and extract the lake's modern area and the coastline's location. These are pre-processed multispectral satellite images of Landsat-8 (2018), as well as Sentinel 2B (2018) and the Google Earth Pro application. This made it possible to correct the location and forms of geomorphological types of shores to create a modern map of the geomorphological conditions and relief-forming processes of the coast of Lake Alakol. The water surface was extracted from the Landsat-8 satellite image using the MNDWI index [17].

For Landsat 5™ and 7 (ETM+) Figure 1, the *MNDWI* index can be calculated as follows:

$$MNDWI = \frac{band\ 2\ (G) - band\ 5\ (MIR)}{band\ 2\ (G) + band\ 5\ (MIR)}$$

For Landsat-8 (OLI) Figure 2, the *MNDWI* index can be calculated as follows:

$$MNDWI = \frac{band\ 3\ (G) - band\ 6\ (MIR)}{band\ 3\ (G) + band\ 6\ (MIR)} \quad (1)$$

where G is green, and MIR is the mid-infrared.

A sufficiently high resolution of the Sentinel 2B images (10 m), as well as the Google Earth Pro application (from 15 m to 15 cm) [42], made it possible to correct the previously digitized contours of coast types, which were received as a result of processing the stock materials. The calculation of the *MNDWI* index, the correction of layers based on satellite images, and mapping were carried out using the ArcMAP 10.5 software.

2.3. Fieldwork

The field monitoring surveys were conducted from 1 June to 20 June 2018–2020 around Lake Alakol. The verification of different types of coastal relief and clarifying the boundaries between them were obtained from satellite imagery and archival data. Prevailing exogenous processes developed in different types of coastal relief, and the adverse effects on recreational, road, and residential infrastructure were determined in situ.

Eight monitoring sites were organized at key sites on the southwestern, eastern, and northern coasts. Three to four benchmarks were installed at each site, with concrete iron bars at a distance of 50 m from the ledge edge. Annual instrumental measurements comprised the dynamics of shoreline retreat along the cross-sections from the installed benchmark to the scarp edge. On two key areas of the southwest shoreline, we performed annual three-dimensional imaging of the lake shore with a 3D Scanner RIGEL-VZ4000 laser scanner. We also used the GNSS device's Trimble R8 module 4 to determine the absolute height of the water level of Lake Alakol [16].

2.4. Coastal Vulnerability Index

In the study of a quantitative assessment of the vulnerability of the coast of Lake Alakol to modern geomorphological processes of relief formation, the most comprehensive approach to the study of coastal vulnerability, the coastal vulnerability index, developed by Gornitz, was used.

The CVI is considered the best method in vulnerability assessment because of the combination of many influencing factors [43]. Obligatory variables for the assessment are the parameters of geomorphological conditions—relative elevation, landforms [36], coastal embayment, beach shape [44], and coastal geomorphology [45]. Geology-coastal vulnerability is geologically dependent and requires regional assessments [33], including contemporary exogenous processes, such as shoreline displacement [36], lithodynamic beach elements [44], geomorphological processes [46], coastal processes [47], and erosion vulnerability assessment in delta [30]. Also, combinations of physical vulnerability index and socioeconomic vulnerability index are used to estimate CVI [48].

The formula for calculating the CVI is the square root of the parameters characterizing the condition of one type of coastal relief and is divided by the number of input parameters:

$$CVI = \frac{\sqrt{a \times b \times c \times d \times e \times f}}{6}$$

where a is the relief of the coast, b is the coastal geology, c is the landform, d is the cliff abrasion, e is the unfavorable process, and f is the surge phenomena (Table 1).

Table 1. Lake coastal zone parameters for coastal vulnerability assessment.

Parameters	Coastal Vulnerability			
	Low—1	**Weak—2**	**Moderate—3**	**High—4**
Relief of coast (m)	Mountain (above 10 m)	Foothill (2–9 m)	Flat (0.5–2 m)	Lowland (less than 0.5 m)
Coastal geology	Rocky coast	Gravel and pebble	Sands	Sediments (loams)
Landform	Rocky, cliff coast	Sedimentary berm (cliff)	Spit and coastal beach	Lake-marsh, estuaries, reed thickets
Cliff abrasion (m/y)	Less than 1	1–3	3–5	More than 5
Process	Salinization	Waterlogging	- Alongshore transport of sedimentary material	- Abrasion and inundation
Tidal range m (mean)	0.1–0.2	0.2–0.4	0.4–0.7	0.7–1

The parameters for the CVI estimation were determined based on field observations and environmental factor analysis. A list of parameters (Table 1) was used to calculate the CVI of the coast of Lake Alakol. The results of the mathematical calculation are classified according to the vulnerability status (low, weak, moderate, high). The parameters do not use data on the hydrometeorological conditions involved in coastal development, such as the wave height, direction, and duration of waves, and parameters of storm activity, etc., due to the lack of an appropriate series of measurements at the only weather station of Lake Alakol. The available wave data for Lake Alakol, at wind speeds of 20 m/s and 30 m/s, as well as for the northwest, east, and southeast winds, are calculations. The data were obtained more than 50 years ago [35]. Due to possible significant errors, we did not use them to calculate the index. However, we used the data of the increase of the relative level of the lake during the surge phenomena, which occurred as a result of the strongest winds, with gusts of up to 60–70 m/s [35]. At the same time, scientists recommend covering all aspects of coastal zone evolution when choosing the input parameters for a CVI estimation [44]. To determine the relief of coast parameter data, 1:200,000 scale topographic maps, 1:200,000 scale geomorphological maps of the Alakol Lake coast, and 5 m interval horizons extracted from the SRTM digital elevation model were used. This made it possible to determine the parameters of the coast of each type of relief in the study area. The geological map of the USSR, scale 1:200,000, was used to analyze the parameters of the coastal geology of the study area.

Landform data were obtained by creating an updated geomorphological map at a scale of 1:200,000. Dynamics of coastal cliff abrasion occurs only on the denudation shores of the south-western, eastern and northern parts of Lake Alakol according to Valeyev et al., 2019 [17]. Data from the Lake Alakol 1:200,000 scale Contemporary Exogenic Coastal Processes map were used to determine unfavorable process data. Tidal range m (mean) data were obtained from USSR Surface Water Resources [35] (Table 1). From 2013 to 2020, instrumental measurements of the annual dynamics of lake abrasion shore recycling were conducted on the denudation shores of Lake Alakol [16]. These data formed the basis of the cliff abrasion parameters.

3. Results and Discussion

3.1. Classification of the Shore and Relief Types of the Coast of Lake Alakol

According to the morphological classification proposed by Zenkovich V.P. [49], the shores of Lake Alakol are classified into accumulative, abrasion-accumulative, and abrasion shores (Table 2). Accumulative shores are found around Lake Alakol and occupy 395 km. They include low-lying shores with aquatic vegetation, wetlands, aeolian, pebble beaches and spits, and river deltas. Abrasion-accumulative shores occupy only 29 km. These shores comprise a coastal escarpment composed of sedimentary rocks and a pebble beach. The abrasion shores of Lake Alakol occupy 46.5 km. These shores have a coastal escarpment composed of crystalline and sedimentary rocks with no beach at the base. Identification of the types of shores was carried out on the basis of field studies of the entire lake coast, as well as the use of the geological map of the USSR, scale 1:200,000, and the Google Earth Pro application.

Table 2. Classification of the shores of Lake Alakol.

Types of Shores	Distribution Areas
Accumulative	Shubartubek tract, west coast
	Plots in the northeast, south, and west shores of Lake Alakol
	Kishi Alakol Bay, east coast
	The periphery of proluvial fans on the west coast
	Alluvial fans and river terraces on the east coast
	Deltas of the rivers Urzhar, Katynsu, Emel, Zhamanty
	Alluvial fans and continental deltas (northeast coast)
	Kosayshagyl sand massif, east coast
Abrasion-accumulative	Fans (southwest coast)
	Kamyskala village, northwest coast
	Ulken Araltobe Island
Abrasion	The islands of Ulken Araltobe, Kishi Araltobe, Sands, sections of the northwest coast

The pattern of shoreline configuration changes depends on the type of shore [17]. The formation of the lake shores occurs on different types of shoreline relief. Based on the geomorphological schematic maps from the explanatory note of the Geological map of the USSR on a scale of 1:200,000, the processing of Landsat-8 and Sentinel 2B space images, as well as field studies, the map "Relief types of the Lake Alakol coast" on a scale of 1:200,000, was created (Figure 3). The coastal relief types around Lake Alakol are heterogeneous. Thirteen relief types of Lake Alakol shore relief were identified, which belong to the denudational, erosional, and accumulative relief groups (Table 3).

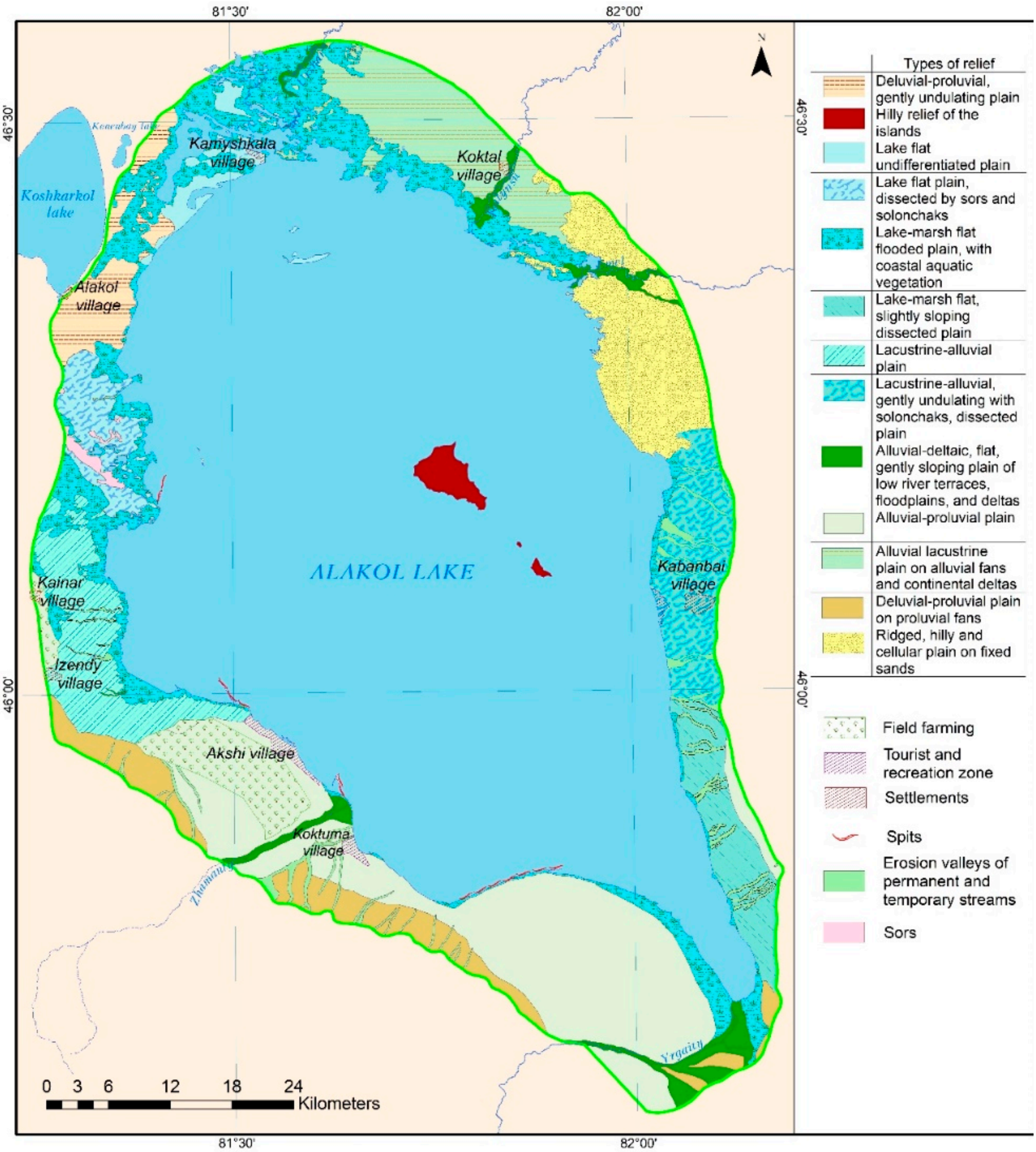

Figure 3. Types of relief of the coast of Lake Alakol.

Flat denudational and accumulative reliefs are represented by lowland plains spread in the western, northwestern, northern, and northeastern coasts of Lake Alakol. They include denudational, lake, lake-marsh, lake-alluvial, alluvial-delta, alluvial-proluvial and alluvial-lake plains. The modern rise in the lake level, continuing for the last 30 years, exposes the mentioned territories to unfavorable processes related to the rise in the water level.

Table 3. Lake Alakol lakeside terrain types.

Relief Group	Types of Relief
Denudational	Gently undulating plain
Erosion	Ulken Araltobe and Kishi Araltobe Islands
Accumulative	Lake flat undifferentiated plain
	Lake flat plain, dissected by sors and solonchaks
	Lake-marsh flat flooded plain, with coastal aquatic vegetation
	Lake-marsh flat, slightly sloping dissected plain
	Lacustrine-alluvial, gently undulating with solonchaks, dissected plain
	Lacustrine-alluvial plain
	Alluvial-deltaic, flat, gently sloping plain of low river terraces, floodplains, and deltas
	Alluvial-proluvial plain
	Alluvial lacustrine plain on alluvial fans and continental deltas
	Deluvial-proluvial plain on proluvial fans
	Ridged, hilly and cellular plain on fixed sands

The sloping foothill accumulative relief is represented by alluvial-proluvial, deluvial-proluvial, lacustrine-alluvial, and lacustrine-swampy plains on the southwestern, southern, and eastern shores of the lake. These coastal areas include both an accumulative low-lying coast and an abrasion-accumulation coast with a sheer abrasion coastal ledge from 1 to 9.5 m. From the right and left sides of the Zhamanty River, the plain on the southwestern coast cuts in sections to the lake with a steep coastal ledge. From the base of the delta of the Zhamanty River in the northwestern direction, the abrasion-accumulative coast, with a height of the coastal ledge of up to 6.3 m, extends for 10 km to the base of the Belkudyk spit. To the southeast of the right side of the Zhamanty River is an abrasion-accumulative section of the plain, with a coastal ledge height of 9–9.5 m and a length of more than 11 km. The lacustrine-alluvial plain of the east coast within the recreational zone of the village of Kabanbay breaks off with a 1–2 m loamy ledge [16]. The territory is adversely affected by the consequences of rising water levels and the abrasion of the territory. The presence of abrasion ledges confirms the activity of exogenous processes in modern bank formation. Additionally, the impact of anthropogenic factors, such as irrigated agriculture on alluvial fans and alluvial-proluvial plains, and the development of tourist and transport infrastructure on the abrasion-accumulation coast are increasing.

On the northeastern shore is the Kossayshagyl sand massif, which forms a ridgy and hilly plain on consolidated sands. The modern raising of the water level in the lake also has an adverse effect on the sandy ridge shoreline. The inter-ridge depressions of the shore are flooded, and the ridges are eroded.

The erosion type of relief on the islands Ulken Araltobe (95 m), Kishi Araltobe (150 m), and Orta (65 m) are the most resistant to the modern processes of relief formation. The geological structure of the relief of the islands from the parent rocks allows the islands to remain resistant to various types of impact.

The classification of the lake shores by genesis, Table 2, made it possible to determine the spatial location of accumulative, abrasion-accumulative and abrasion shores. The identification of shore types and distribution areas provided overview information about the lake shores. Obtaining this basic information about the types of shores and the coastal relief provided the basis for studying the relief-forming exogenous processes of the territory and their impact and for determining the parameters of the coastal landform abrasion leading process used for the assessment of the shore vulnerability.

3.2. Modern Relief-Forming Processes of the Coast of Lake Alakol

The leading relief-forming processes on different types of coastal relief have been determined. On denudation and accumulative types of relief occupying the western, northwestern, northern and northeastern coasts, the processes of waterlogging of low-lying coastal areas, surge events, soil salinisation, as well as abrasion on coastal ledges prevail (Figure 4a). On the lake-marsh plain, with coastal aquatic vegetation, the dynamics of waterlogging ranged from 200 to 1000 m landward from 1990 to 2018 [17].

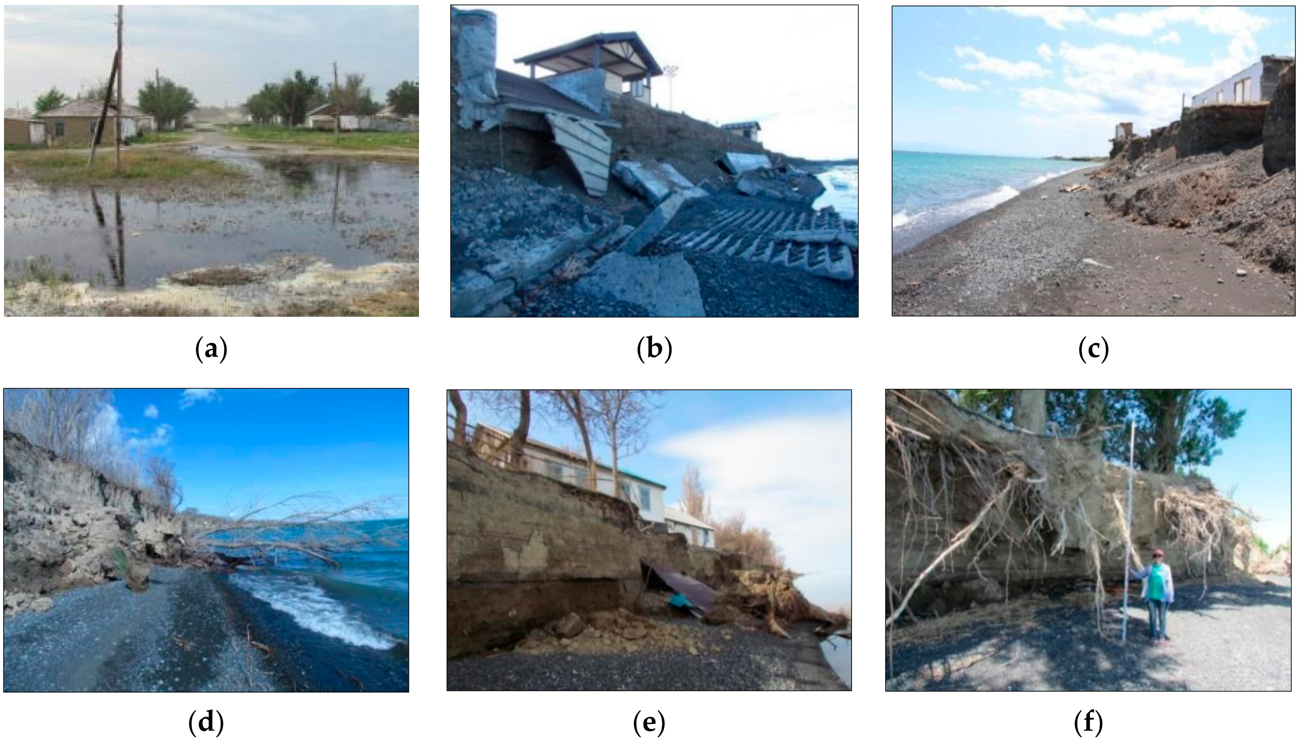

Figure 4. Modern relief-forming processes on different types of coastline of Lake Alakol: (**a**) flooding of Kamyskala village residential areas as a result of increased water level during filtration through the dam; (**b**,**c**) consequences of bank processing, which caused the destructive impact of recreational infrastructure on the coast of Akshi recreation area; (**d**) bank processing of Koktuma village; (**e**,**f**) coastal erosion impact on residential structures of Koktuma village.

On the sloping foothill accumulative relief of the southwestern, southern, and eastern coasts, the leading processes of relief formation are planar washout, linear erosion, coastal retreat processing along the peripheral part, as well as increased transport and tourist development of the territory. The leading process of relief formation of the alluvial-proluvial plain on the fans of the Tentek, Zhamanty, and Yrgaity rivers is a planar washout, as well as linear erosion. Linear erosion is enhanced by deflation during agricultural cultivation of irrigated lands on the plains of the Tentek River and the middle part of the alluvial fan of the river. Zhamants is where anthropogenically transformed landforms formed. In the coastal zone of the deluvial-proluvial plain, proluvial fans are dominated by linear erosion and coastal retreat. In this territory, there are lands of settlements (Figure 4d–f) and recreational areas, which are subject to the adverse effects of abrasion processes (Figure 4b,c). According to field studies, the average dynamics of the abrasion process ranges from 3 to 5 m per year, with a cliff height of 2 to 9 m [16]. The process of the coastal retreat has significant material damage to the land users of the first line of the coast, who are forced to renew the construction of the coast's protection every year, restore the coastal infrastructure, and leave the inhabited houses that are under threat of collapse.

On the eastern coast of Kishi Alakol Bay, on the lake marsh, slightly sloping plain wedges, and among numerous groundwater sources, swamping and salinization processes are widespread.

On the ridgy, hilly, and cellular plains on the fixed sands, the area adjacent to the shore has waterlogged inter-ridge depressions, where waterlogging is the leading process. The deflation process prevails on the mainland part of the plain; generally, the sands are fixed with vegetation, but there are small scattered areas.

Based on the results of E.A. Kazanskaya's [12] research on the geomorphological map of the Alakol Lakeshore and field monitoring studies conducted from 2013 to 2020, modern relief-forming processes on different types of terrains of the Alakol Lake shore relief were determined (Table 4). Based on the results, the map "Modern relief-forming processes of the Alakol Lakeshore" was created at a scale of 1:200,000 (Figure 5).

Table 4. Modern relief-forming processes on different types of relief of the Alakol Lake coast (Figure 4).

No	Types of Relief	Landforming Processes
1	Gently undulating plain	Flooding, inundation, abrasion
2	Lake flat undifferentiated plain	Flooding, abrasion
3	Lake flat plain, dissected by sors and solonchaks	Flooding, salinization, sor formation
4	Lake-marsh flat flooded plain, with coastal aquatic vegetation	Flooding
5	Lake-marsh flat, slightly sloping dissected plain	Waterlogging, salinization
6	Alluvial-proluvial plain on river fans	Planar washout, linear erosion, abrasion, deflation
7	Lacustrine-alluvial, gently undulating with solonchaks, dissected plain	Planar washout, development of salt marshes, abrasion in the area of the Kabanbay recreational zone
8	Lacustrine-alluvial plain	Flooding Mudflow processes in riverbeds
9	Alluvial lacustrine plain on alluvial fans and continental deltas	Waterlogging, flooding
10	Alluvial-deltaic, flat, gently sloping plain of low river terraces, floodplains, and deltas	Flooding and waterlogging in river deltas
11	Deluvial-proluvial plain on proluvial fans	Planar washout, linear erosion, abrasion, gully erosion
12	Ridged, hilly and cellular plain on fixed sands	Deflation, flooding and swamping in inter-ridge depressions
13	Ulken Araltobe and Kishi Araltobe Islands	Abrasion

3.3. Assessment of Input Parameters of CVI:

3.3.1. Relief of Coast and Coastal Geology

The vulnerability of the coast depends on the level of relative height between the water level and the land. The relief of the coast of the islands of Ulken Araltobe (h—95 m), Kishi Araltobe (h—150 m), and Orta (h—65 m) are classified with a low degree of vulnerability since the shores of the islands have steep bedrock ledges.

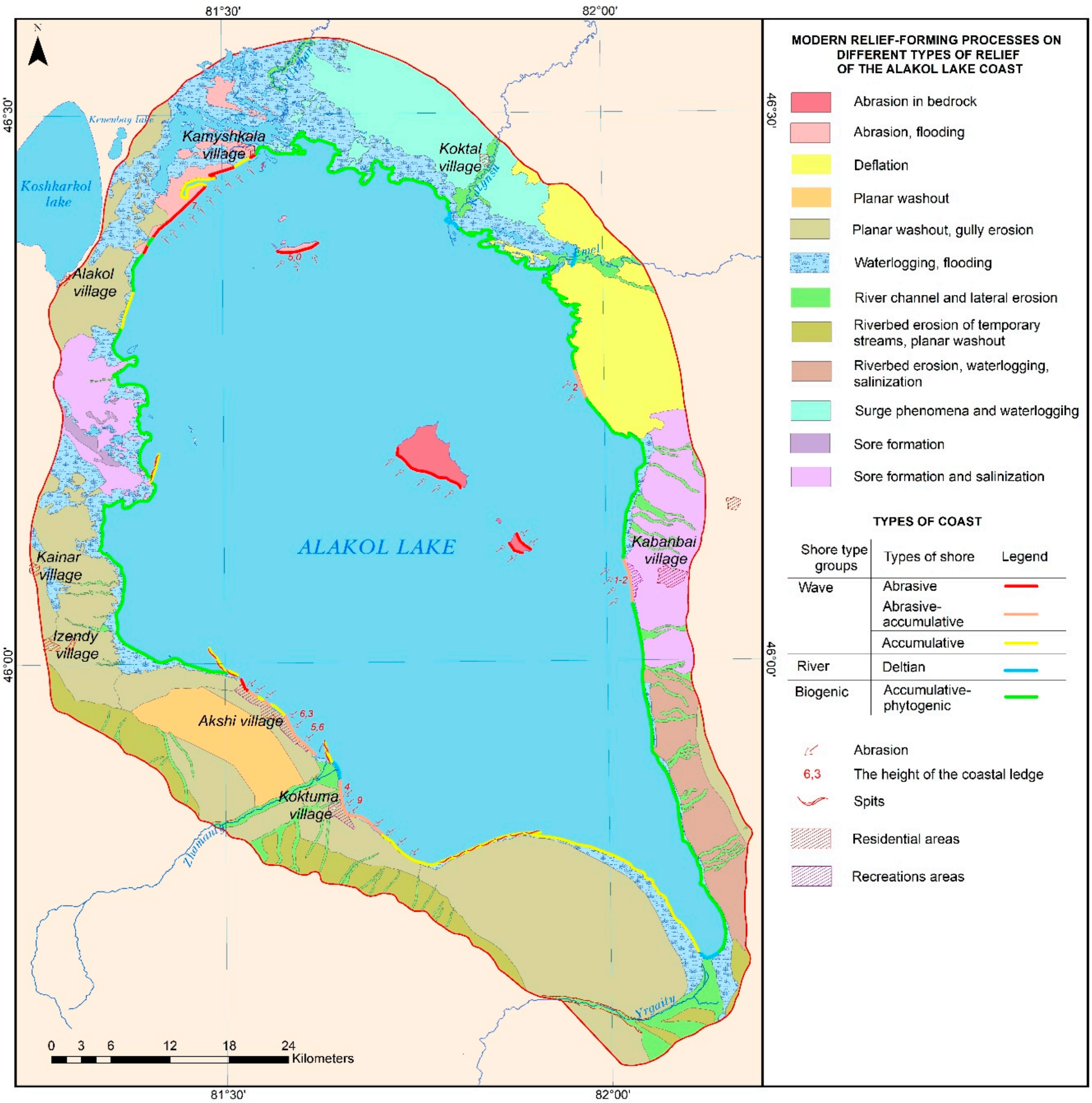

Figure 5. Modern relief-forming processes of the coast of Lake Alakol.

The vulnerability of the abrasion-accumulative shores of the southwestern coast is assessed as weak. The relative heights of the coastal ledge are 1 to 9 m above the beach. The pebble beach's width and the presence of spits play a stabilizing role in some parts of the coast.

The accumulative type of shores of the northwestern, southern, eastern, and western coasts of the plains have a modern pebble beach (h—0.5–1 m). The relief is practically flat, gradually rising towards the land. Under stormy conditions, the shores can be flooded, the level of groundwater rises in depressions, and waterlogging and salinization of the coastal territory occur. The vulnerability of accumulative shores is medium.

The low-lying, accumulative relief of the northeastern coast is vulnerable to extensive flooding and swamping. These shores are distinguished by a significant change in the position of the coastline as a result of the increase in the water level in the lake in recent years [50]. The shores are low-lying, the increase in absolute heights from the water's edge occurs gradually and extends over long distances, and therefore the vulnerability of the relief of low-lying accumulative shores is assessed as strong. The vulnerability of the northwestern coast is characterized as strong; flooding and abrasion are widespread in depressions. Coastal relief indicators are shown in Figure 6a (upper left corner).

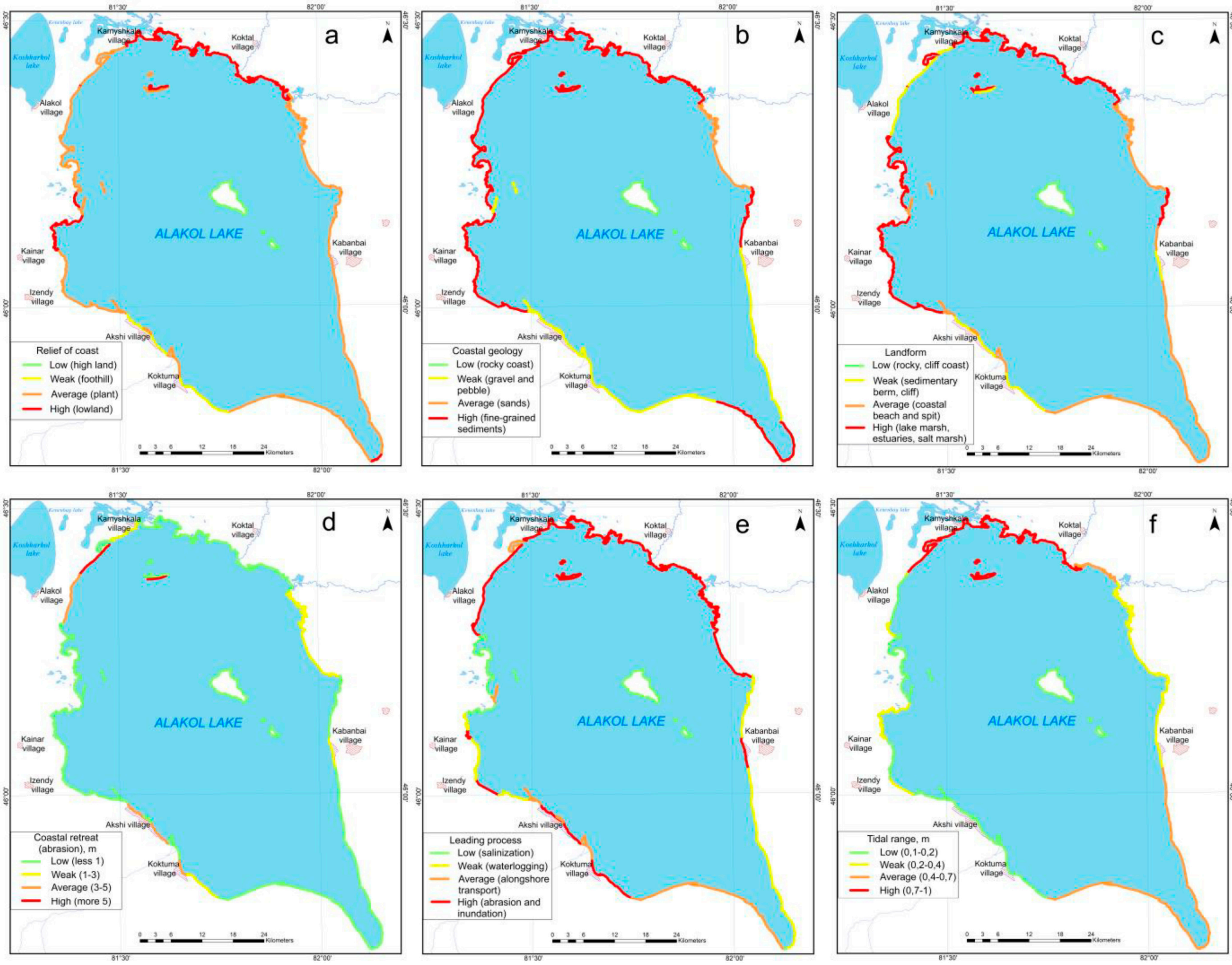

Figure 6. Values of different coastal vulnerability parameters: (**a**) relief of coast; (**b**) coastal geology; (**c**) landform; (**d**) cliff abrasion; (**e**) leading process; (**f**) tidal range, m.

The islands of Ulken Araltobe and Kishi Araltobe are outcrops of the longitudinal axis of the Paleozoic (Carboniferous, Devonian) horst-anticlinal uplift [19]. The shores, composed of crystalline rocks, are of low vulnerability. The southwestern and eastern shores represent a gravel-pebble beach with a width of 7 to 15 m and five gravel-pebble spits extending from the beach. Field studies have shown that although beaches and spits have a stabilizing effect from external influences and are in constant alongshore movement, the degree of vulnerability is weak.

The sandy massif of Kosayshagyl, located on the eastern shore of the lake, belongs to a medium degree of vulnerability. The shore of the ridge sandy massif is subject to abrasion and flooding of depressions between ridges. Easily eroded sedimentary fine-grained rocks (sandy loam, loam) are highly vulnerable to water processes. These shores occupy 58% of the entire coast of Lake Alakol and are located western, northwestern, northern, northeastern, and southern coasts of the lake. The coastal geology vulnerability assessment is shown in Figure 6b.

3.3.2. Landform and Cliff Abrasion

The rocky and steep landforms of the shores of the islands of Ulken Araltobe and Kishi Araltobe belong to a low degree of vulnerability. Coastal ledges of sedimentary rocks (h 1–9 m) are found on the southwestern, northwestern, and eastern coasts, as well as on the southern coast of the Peski Island. Such landforms with a total length of 56 km are of weak vulnerability. The landform coastal beaches and spits are of medium vulnerability. They occupy the southern, eastern, and partially southwestern shores of the lake, with a total length of more than 150 km. Landforms, such as lacustrine swamp plains, estuaries (deltas), and reed beds, are highly vulnerable to hazardous processes. They are located on the northeast, east, and west coasts, with a total length of 190 km. The landform parameters are shown in Figure 6c.

Abrasion-accumulative shores, with a steep coastal ledge composed of sedimentary rocks, occupy more than 11% of the coast of Lake Alakol. The vulnerability of coastal ledge retreatment is determined by the dynamics of abrasion in one year. A weak degree of vulnerability corresponds to values of 1–3 m of cliff abrasion per year [16]. The parameter was determined on the northern coast, near the village of Kamyskala, on the southwestern coast, south of the village of Koktuma, on the eastern coast near the Kabanbay recreational zone, as well as on the coast of the ridged Kosaishagyl sandy massif. The average degree of vulnerability, abrasion within 3–5 m per year, is determined on the coastal ledges of the northwestern coast and southwestern coast (Akshi and Koktuma villages). The dynamics of the processing of the coastal ledge of more than 5 m per year are a high degree of vulnerability. They are located on the northern coast of the lake and on the southern coast of the Peski Island. The rest of the coast is classified as low vulnerability, with an indicator of less than 1 m per year. Figure 6d shows the spatial distribution of the cliff abrasion vulnerability.

3.3.3. Leading Process and Tidal Range

The shores of the Ulken and Kishi Araltobe islands are assigned to a low degree of vulnerability from the activities of exogenous processes. The geological structure of the islands is resistant to the activity of relief-forming processes. This category also includes the predominant processes of salinization and the development of solonchaks developed on the western coast. Swamping processes are developed on the eastern and partly on the western coasts of the lake. These coasts are classified as weak vulnerabilities. We attributed the influence of the processes of alongshore transport of sedimentary material to a medium degree of vulnerability. These coasts are located on the southwest and south coasts. A high degree of vulnerability has been identified for the leading processes of abrasion and flooding. These are sections of the southwestern coast, northwestern, northern, and northeastern coasts of Lake Alakol. The characteristics of the leading process vulnerability assessment on the coast are shown in Figure 6e.

The location of Lake Alakol in the inter-mountain depression causes significant wind and wave phenomena that affect the coast in the form of surge processes [11]. Coastal vulnerability is ranked by the height of surge events in meters, thus low (0.1–0.2), weak (0.2–0.4), medium (0.4–0.7), and high (0.7–1). The low level was determined in the areas of the western coast, southwestern, and on the coast of the islands of Ulken and Kishi Araltobe. A weak degree of vulnerability has been established in the low-lying areas of the western and eastern coasts. Medium vulnerability is common on the south and east coasts. A high degree of vulnerability is observed on the northern and northeastern coasts. The tidal range parameters are shown in Figure 6f.

3.3.4. The Total CVI of the Alakol Lake Coast

The overall vulnerability index of the Alakol Lakeshore was estimated using the Gornitz formula [36]. In total, the coast of Lake Alakol consists of 13 geomorphological types of relief. For each individual type of coastal relief, a set of parameters was determined and ranked according to four classes of coastal vulnerability: the low range was rated at

1 point; weak at 2 points; medium at 3 points; and high at 4 points. For example, the CVI for a section of the coast of the alluvial-industrial plain on the cones of the removal of the Tentek, Zhamanthy, and Yrgaity rivers (southwestern coast) was designed according to the scheme $\sqrt{(2 \times 2 \times 2 \times 3 \times 4 \times 1)/6}$, and amounted to 4 points. After applying the Gornitz formula, the numerical value of coastal vulnerability was divided into four categories depending on the natural discontinuities by the method provided by the ArcGIS software [44]. Based on the results, a map was built. Then an assessment of the degree of vulnerability of the coast of Lake Alakol using the Gornitz method was conducted (Figure 7).

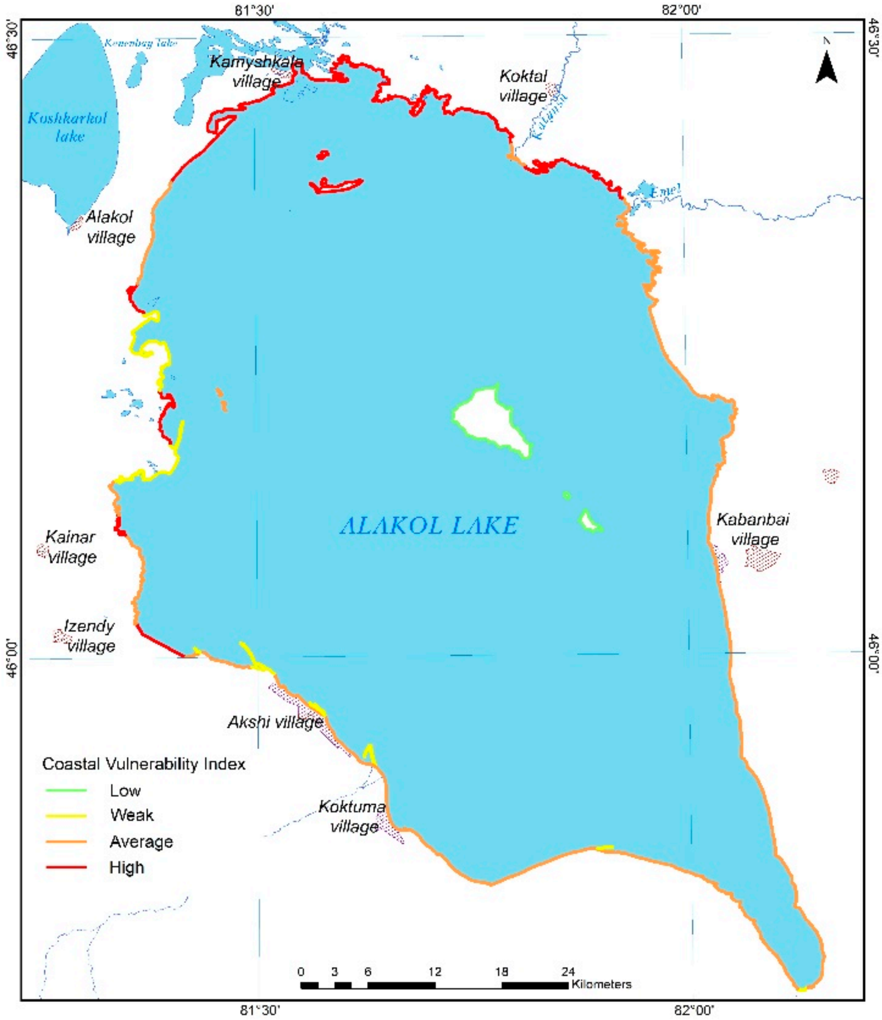

Figure 7. Assessment of the degree of vulnerability of the coast of Lake Alakol using the Gornitz method (Gornitz, 1991).

The shores of Lake Alakol have a large length with an average vulnerability to hazardous processes (47.4% of the total length of the coast). They occupy the northwestern, southwestern, and all southern and eastern coasts. Shores with a high degree of vulnerability account for 30.9%. They are located in the northern and northeastern parts of the lake, as well as fragments on the lake's western coast. Weak vulnerability is determined as fragmentary on the western banks and the Kishi and Ulken Balgyn spits; they occupy 14.4%. A low vulnerability was determined on 7.3% of the shores of the lake on the islands of Ulken Araltobe, Kishi Araltobe, and Orta Araltobe (Figure 7).

3.4. Assessment of the Degree of Vulnerability of Relief Types on the Coast of Lake Alakol

By the method of expert evaluation, based on the CVI results and taking into account anthropogenic load, the map "Comprehensive assessment of the degree of vulnerability of the coast of Lake Alakol to modern processes of relief formation", with a 1:200,000 scale, was created (Figure 8). The area is immediately adjacent to the lake on the northern, northwestern, northeastern, and southwestern coasts and has a high degree of vulnerability; 18.6% in total. The average level of vulnerability occupies 33.8% of the territory. It is marked on an alluvial-proluvial gently sloping plain; deluvial-proluvial gently sloping plain; lake flat plain; aeolian churlish plain along the lake; and a lake-alluvial sloping undisturbed plain. These mainly occupy the northeastern, northwestern, and western coastal areas. The territory with weak vulnerability occupies 30.7%; it includes the sand massifs, Barmakkum and Kosayshagyl; lake-alluvial semi-swampy plains with solonchaks; lake-marsh flats, slightly sloping; and deluvial-proluvial semi-swampy plains. They are located in the western and eastern parts of the study area. The Ulken Araltobe and Kishi Araltobe islands and alluvial-proluvial gently sloping plain on the fans of the Yrgaity River, with an area of 16.9%, belong to the low vulnerability degree. The analysis of the anthropogenic impact on natural and economic systems is given in Table 5.

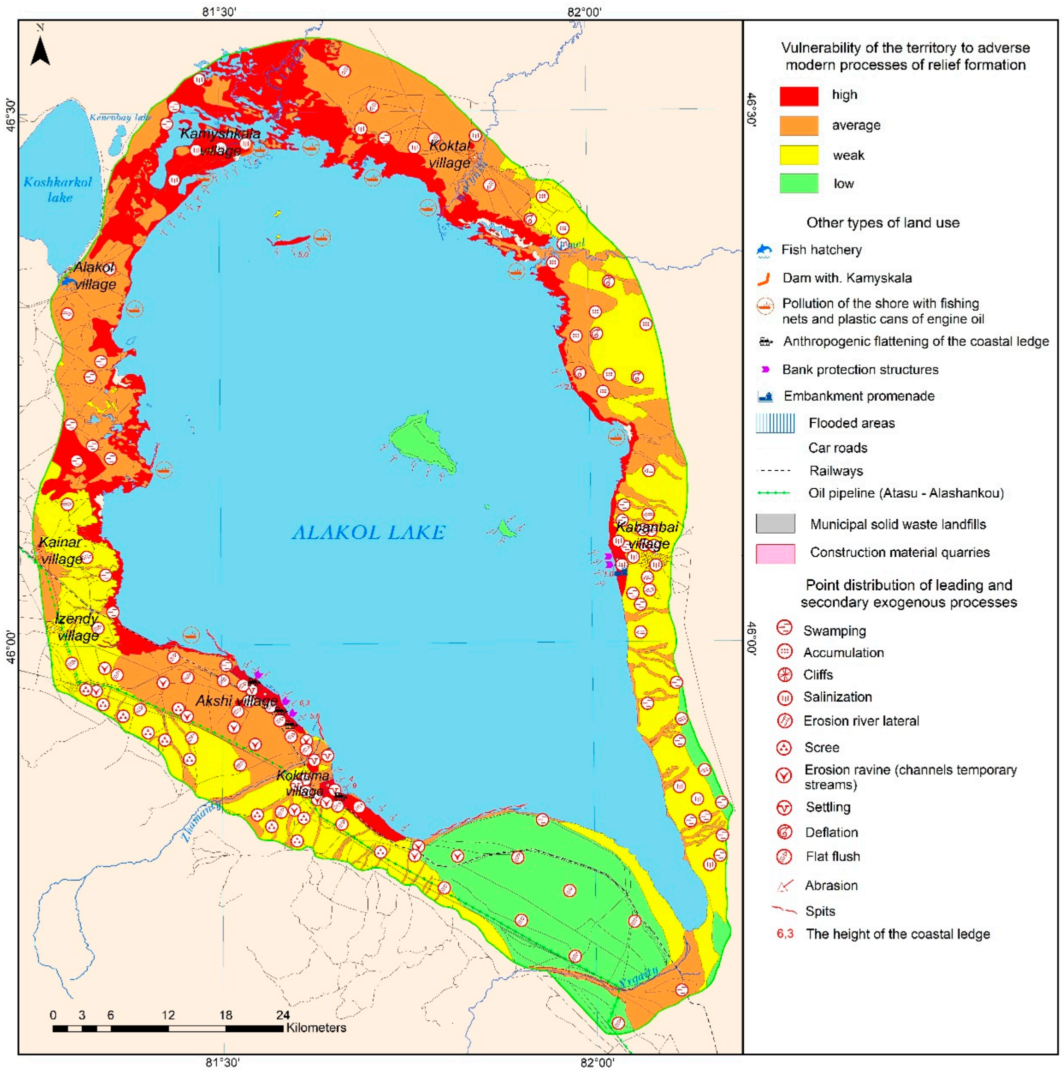

Figure 8. Comprehensive assessment of the degree of vulnerability of the coast of Lake Alakol to modern processes of relief formation.

Table 5. Analysis of the anthropogenic impact on the natural and economic systems of the coast of Lake Alakol, which form the ecological and geomorphological conditions.

Type of Nature Management	Adverse Impact on the Natural Environment	Measures Aimed at Ensuring the Safety of Natural and Economic Objects
Recreational	- Violation of the natural morphometric conditions of the relief (backfilling of wetlands, leveling the beds of temporary streams)	- Design and construction of recreational facilities, taking into account morphometric conditions (diversion of watercourses, drainage of wetlands, etc.)
	- Changes in the natural forms of the shore - Increase in the intensity of coastal retreat - Planar washout and linear erosion over the entire area of the artificial slope - Abrasion of the peripheral part of the artificial slope	- Development of shore protection measures - Observance of the boundaries of water protection zones
	- Disturbance of longshore and cross-shore sediment transport - Activation of abrasion processes - Disturbance of the natural shape of the shore	- Application of effective, science-based integrated coastal protection measures
Residential	- Water filtration - Swamping of residential areas	- Flood protection dam (Kamyskala village) - Drainages
	- Pollution with solid household waste (plastic, cellophane) of the natural environment as a result of wind development, smoke with acrid smoke, soil pollution	- Fencing of solid waste landfills - Organization of collection and processing of solid household waste
Transport	- Violation of the natural catchment area - Violation of natural morphometric conditions - Swamping and flooding - Deflation	- The design of engineering linear structures should be carried out, taking into account the morphometry of the territory, including drainage systems and drainage systems - Phytomelioration
Industrial	- Change in natural landforms - Vegetation degradation - Activation of landslide-talus, erosion, and deflationary processes, as well as waterlogging	- Monitoring and banning the extraction of construction inert material in unauthorized areas - Reclamation of quarries after mining
Agricultural (pastoralism)	- Activation of deflationary processes in the Kosayshagyl sand massif	- Regulation of livestock pasture management (in grazing and stabling areas) - Phytomelioration and mechanical protection of eroded areas
Agricultural (irrigated cropland)	- Increased linear erosion, planar washout and waterlogging	- Drainage water drainage - Application of water-saving technologies in agriculture
Fishing	- Pollution of the shore with fishing nets and plastic canisters from motor oil	- Strengthening requirements and providing conditions for the development of commercial fisheries

4. Conclusions

An assessment of the vulnerability of the coast of Lake Alakol is necessary for the rational use of land resources and planning for the effective and sustainable economic development of the shore.

The vulnerability of the Lake Alakol shoreline to modern landforming processes depends on a number of natural conditions, including the level rise, geology, topography, and coastal processes. The coastline of Lake Alakol is becoming more and more involved in intensive economical use every year. At the same time, 67% of the shore is classified as high vulnerability according to the Gornitsa approach. The high degree of vulnerability of the relief types of the study area is 42.8% of the whole area.

The study of the vulnerability of the lake shores becomes relevant after the mass development of tourism and infrastructural development of the coast without taking into account the natural conditions of the coast. The consequences of coastal vulnerability are manifested in the negative impact on residential and tourist facilities and transport infrastructure.

The implementation of this study will contribute to a practical solution for land use issues of vulnerable shores. The country's water code defines the concepts and standards for water protection zones of water bodies, while land users in the tourism industry are trying to develop areas close to the shore. In the future, the results of this survey may provide a scientific basis for adhering to the Water Code's rules and regulations governing the development of the shores of large endorheic water bodies. The cartographic results provide illustrative material for the development and implementation of sustainable coastal land management mechanisms; for example, by taking into account the vulnerability of coasts during tourist development, as well as factors of modern relief-forming processes during the construction of the second branch of the Aktogay-Dostyk railway (border with China). The results of the coastal vulnerability assessment can be used in the development and implementation of shore protection measures, as well as the planning and construction of communal infrastructure on the lakeshore. The inevitable involvement of the lake shore potential in economic activities as a basic approach to rational land use is proposed to take into account the results of the Lake Alalkol shore vulnerability assessment.

An assessment of the vulnerability of the shores of Lake Alakol is of scientific value in the study of the shores of the world's endorheic lakes. Most work focuses on the shores of seas and oceans; however, similar problems may occur on the shores of large inland lakes, including those in Central Asia. In addition to the vulnerability of the coastline itself, we consider it important to assess the vulnerability of coastal relief types. This is because, given the ongoing climatic variability and possible adverse impacts of increasing human activity, efforts should be directed toward the sustainable use of coastal topography as the underlying habitat.

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