An integrated coastal vulnerability index for sustainable development of coastal ecosystems: a case study of Issyk-Kul lake

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Abstract

In this paper, the coastal vulnerability of Lake Issyk-Kul has been defined through the Integrated Coastal Vulnerability Index (ICVI) using the Coastal Vulnerability Index (CVI) and the Socio-Economic Vulnerability Index (SVI). Lake Issyk-Kul is an important object of this kind of research due to the presence of both pristine, little modified by man, and significantly transformed coastlines allows to evaluate the different degrees of vulnerability of coastal ecosystems. The results of the study emphasize the importance of reassessing the vulnerability of coastal ecosystems depending on the specific natural, climatic, and socio-economic conditions of each area using the ICVI index. The Integrated Coastal Vulnerability Index provides an integrated assessment and state of coastal ecosystems and can be used to assess such fragile ecosystems that are affected by the entire watershed. The identification of vulnerability using this index allows for proactive planning adapted by the relevant authorities and management, which can be scaled up to increase the resilience of coastal zones to changing conditions.

Key words: Issyk-Kul lake, integrated vulnerability index, coastal areas, sustainable development, anthropogenic impact

1. Introduction

The intensive growth of urbanization leads to the shrinking of natural ecosystems. A significant proportion of which are coastal ecosystems [1- 2]. They are characterized by a high population density and accelerated socioeconomic growth and provide ecosystem services on a global and a local scale [3-10]. There are many studies of ecological risks, their consequences and protection measures of ecosystems harmed by human activities [11-12]. Recently, significant attention has also been paid to the study of environmental risks for coastal areas affected by human activities [13]. In this regard, the importance of integrated approaches in assessing the vulnerability of ecosystems is noted [14-16]. Thus, ecosystems of water bodies and the factors influencing them require detailed study.

Lakes and various types of watersheds are vulnerable to human impacts. Different natural and climatic conditions and rapidly growing socio-economic development of coasts lead to spatial pollution of water body [17]. Ecological assessment of the water quality of large lakes was carried out without taking into account its spatial heterogeneity [13]. Regional zoning of lakes can reflect changes in water quality and thus can be used to manage the entire watershed [13], since the spatial heterogeneity of possible pollution will be taken into account. Most studies on analyzing lake water quality have been conducted using qualitative methods, and there are few studies on quantitative analysis [11-12], which also causes uncertainties in planning the Lake Watershed Management Plan and its sustainable management. Therefore, Lake Issyk-Kul, which is one of the largest lakes in the world and has a wide range of natural, climatic and socio-economic conditions for the development of its shores, allows for a broad assessment of the vulnerability of various coastlines. Thus, it shows the importance of using an integrated approach in assessing the vulnerability of not only the coastline but also the entire watershed. The uniqueness of its study also is that a significant part of the coast of Lake Issyk-Kul is untouched, the other part is in the early stages of transformation, and another part is a tourist area with its own environmental problems.

Coastal zones of Issyk-Kul lake are important due to their natural and social characteristics: obtain vital ecosystem services and help to protect transformation of contaminants to the water body of endorheic mountain lake. Lake Issyk-Kul is located in Issyk-Kul region of Kyrgyz Republic and is the fifth deepest lake in the world (Figure1). The catchment area of the lake is about 21.900 km^2 and water volume is approximately 1.730 km^3. The lake is surrounded by two mountain ranges: Kungei Ala Too and Terskei Ala Too [18]. In 1998, the entire territory of region 43.144 km^2 (including the surface area of Lake Issyk-Kul - 6280 km^2) was declared the Issyk-Kul Biosphere Territory, recognized by UNESCO and included in the World Network of Biosphere Reserves.

The Issyk-Kul region includes 5 districts and 3 cities, almost all districts and cities are located around the lake. The population in the region is 501.9 thousand people [19]. In Issyk-Kul region, the coastal zones concentrate more than 40% of the population and the main infrastructures. In recent years, the coastal zone has become increasingly transformed and reduced due to urbanization, agriculture and intensive land use. As a result, the coastal two-kilometer zone was reduced to five hundred meters. Lake Issyk-Kul is a closed lake with more than 80 rivers flowing into it; therefore, there is a high risk of pollution entering the lake.

In recent years many authors have assessed the pollution vulnerability of Lake Issyk-Kul using various indices [20-23], but there has been no tendency to use the index regarding the vulnerability of its coastal zone. Despite of the impact of these factors on the coastal environment, no studies were undertaken to evaluate the vulnerability of the Issyk-Kul coastal area. This is the first time that a quantitative assessment of a coastal vulnerability is performed along the Issyk-Kul coastline using integrated vulnerability index.

The aim of this study is to assess the vulnerability index of the Issyk-Kul coastal zone by combining socio-economic factors and coastal vulnerability factors. The index derived from socio-economic and coastal vulnerability factors computation provides a quantification of their respective weight in the coastal vulnerability. The results will facilitate selecting the appropriate adaptation method for the increasing of the resilience of this coastal area.

2. Materials and Methods

2.1 Study area

Lake Issyk-Kul is an endorheic mountain lake located at 1608 m above sea level, in the northern Tien Shan ranges, in the Republic of Kyrgyzstan, Central Asia (Figure 1). Lake area - 6247 km^2, depth - 668 m, length - 177 km, width - 60 km. Up to 80 large and relatively small tributaries flow into the endorheic lake. The largest of them are Jergalan and Tyup flowing from the east. The feeding of the rivers in the lake basin is mixed, with a predominance of melt runoff - snow and glacial [24-26]. The lake is surrounded by a plain, the narrow shoreline is covered with sand, less often with pebbles, in some places it is composed of cemented sandstone, and in some areas it is swampy.

The climate of Issyk-Kul is continental. Constant evaporation from the water surface creates increased air humidity in the coastal zone. The average air temperature in January varies from +2 to -3°C. Summer on the coast of Issyk-Kul is moderately warm. The average temperature in July and August is about 16-17°C. In the highland part of the basin the average temperature in January drops to –8-10°C. The distribution of precipitation across the Issyk-Kul basin is uneven due to the general circulation of the atmosphere and the occurrence of downward air currents in the west and upward air currents in the east. On the western coast of the lake, only 115 mm falls [27-28] and their amount increases from west to east. Precipitation occurs mainly during the warm period of the year. May-August accounts for 50% of their annual amount, December-February – 10%. In the western part, maximum precipitation is observed in June-July, minimum – from December to February. Average monthly values of relative air humidity on the western and southern coasts are 54-64%, on the northern coast - 62-73%, on the slopes of the basin - 60-74%.

To determine the vulnerability index of the coastal zone of Issyk-Kul, five administrative-territorial districts were considered: Ak-Suu, Jeti-Oguz, Issyk-Kul, Ton, Tyup and two (Figure 2). There are 3 cities and 2 urban-type settlements, 61 ayil aimaks and 178 rural settlements in the region. In general, the coastal zone of Lake Issyk-Kul is a strip with a width of 2 to 15–20 km, formed by river fans and terraces, where populated areas and tracts of agricultural land are concentrated. Its territory is located at absolute altitudes from 1607 to 7439 m above sea level.

Ak-Suu district is located in the eastern part of the Issyk-Kul basin. The area of the district is 9917 km^2. On the territory of the district is located the city of regional subordination Karakol. The hydrography of the area is represented by the rivers Karakol, Jyrgalan (maximum flow 70 m^3/sec) and Sary-Jaz (258 m^3/sec) and numerous mountain rivers.

Jeti-Oguz district is located in the southeastern part of the Issyk-Kul basin. The area of the district is 14499 km^2. The administrative center is the village of Kyzyl-Suu. The Jeti-Oguz gorge is famous for its picturesque cliffs and a resort near thermal springs and waterfalls.

The Issyk-Kul region is located in the northwestern part of the Issyk-Kul basin. The area of the district is 3603 km^2. The Issyk-Kul region includes the resort town of Cholpon-Ata.

Ton district is located in the southwestern part of the Issyk-Kul basin. The area of the district is 7230 km^2. On the territory of the district is the city of Balykchy, a large transport and industrial hub of the country. The area of the city of Balykchy is the driest place in the Issyk-Kul basin. Average annual precipitation is about 120 mm, evaporation is about 1050 mm [29].

2.2 Methods

Coastal vulnerability Index (CVI) [30]. In order to quantify the CVI for each coastal section the physical factors (shoreline type, rivers, distance of agriculture land and pasture behind the shoreline, transformation of agricultural land for the construction of household facilities, degree of groundwater protection according) have been classified as new variables ranged between 1 and 5 which could illustrate the degree of vulnerability (Table 1). The annual CVI is computed for each district according to the following equation [31]:

$$CVI = \left(\frac{1}{N} \prod_{i=1}^{N} X_i \right)^{\frac{1}{2}} \quad (1)$$

where N = 3 is the number of load parameters; X_1 coastline type, X_2 rivers and X_3 degree of groundwater protection.

Socio-Economic Vulnerability Index (SVI) In order to quantify the SVI for each coastal section, the qualitative (airport, road, harbor, land use and protected area) and quantitative (coastal population density) factors have been classified as new variables ranged between 1 and 5 which could illustrate the degree of vulnerability (Table 2), in accordance with [32]. The annual SVI is computed for each district according to the following equation [31]:

$$SVI = \left(\frac{1}{N} \prod_{i=1}^{N} v_i \right)^{\frac{1}{2}} \quad (2)$$

where N =10 is the number of socio-economic parameters; v_1, v_2, v_3, v_4, v_5, v_6, v_7, v_8, v_9 and v_{10} represent population density, airport, road, harbor, land use, amount of recreational and industrial facilities protected area agriculture and pastures respectively

Integrated Coastal Vulnerability Index (ICVI) The integrated coastal vulnerability index illustrates the degree of exposure of coastal areas to the impacts of coastal vulnerability and socio-economic factors. The approach of the coastal vulnerability index called integrated coastal vulnerability index (ICVI) computed in this study can be expressed by the Equation (3) as follows in accordance with [30]:

$$ICVI = \frac{\alpha \times SVI + \beta \times CVI}{\alpha + \beta}; \alpha = \beta = \frac{1}{2} \quad (3)$$

Finally, each coastal zone could then be classified as low, moderate, high or very high-risk categories vulnerability according Table 3.

3. Results and Discussion

3.1 Influence of Socio-Economic Factors on Issyk-Kul Coastline

The impact of human activities on the Issyk-Kul coastal area is quantified by computing the SVI of this area. SVI illustrates the degree to which coastal areas are threatened by socio-economic factors. This analysis is undertaken by creating a SVI for each administrative territorial districts of Issyk-Kul region (Table 4).

The Issyk-Kul region is one of the economically promising territories of Kyrgyzstan due to the high diversity of landscapes, which determines its uniqueness. As a result, the tourism industry in this region is growing every year and plays a significant role in the socio-economic development of the country as a whole [33]. According to the Table 4, the degree of vulnerability associated to amount of recreational facilities around the lake Issyk-Kul is the highest for all districts except Tyup. Thus the best sandy beaches are located on the northern, eastern and southern coasts. There are 132 boarding houses, resorts, children's sanatoriums, and 212 travel agencies and other recreational facilities in Issyk-Kul region. The main territory of the Issyk-Kul region is mountainous, and most of the population lives on the coastal strip around lake. The highest population density is concentrated in two cities of regional significance – Karakol, Balykchy and one city of regional significance and the main base of the Issyk-Kul sanatorium-resort complex - Cholpon-Ata (Figure 3). Most of the socio-economic factors have a high degree of vulnerability in Ak-Suu, Ton and Issyk-Kul districts. As for the Karakol, Balykchy and Cholpon-Ata cities are densely populated, the very high presence of industrial, commercial (airport) and urban infrastructures justify its very high degree of vulnerability.

According to Table 4, the degree of vulnerability associated with land use is high for all areas. The total land area of the Issyk-Kul region is 4467.5 thousand hectares. Agricultural lands occupy only 1645.9 thousand hectares or 36.8% of the total area of the region, and their structure is dominated by pastures (Figure 4). The optimal land use areas are the coastal strip of Lake Issyk-Kul. The area of cultivated land is 12.6% of all agricultural land. Local residents mainly grow crops such as wheat, barley and potatoes and engage in livestock farming. Intensive farming in the coastal zone leads to the transformation of the natural landscape of the coast.

Anthropogenic impact - urbanization of the territory, development of industry, transport, grazing, irrigation of land are negative factors that threaten the environmental safety of the Issyk-Kul region. Contaminated sites associated with the results of the mining industry pose a high risk in terms of environmental consequences. The activities of the Kumtor mining production which located in Jety-Oguz district create a significant risk for the region under study from a risk perspective. Transshipment base of Kumtor Operating Company. It is located within the city of Balykchy, 1500 m from the shore of Lake Issyk-Kul. The base is intended for short-term storage of chemical reagents. However, there is a possibility that the base area will be exposed to mudflows, which could result in the removal of chemical reagents to the western part of the city and the adjacent water area of the lake Issyk-Kul. The tailings of waste from the processing of uranium ores from Kajy-Sai which located in Ton district, are causing concern. The possibility cannot be ruled out that if natural phenomena such as earthquakes become more active, radioactive contamination may enter both the lake and underground sources.

In the socioeconomic vulnerability we note that the very SVI values are ranged as follow: Issyk-Kul (237,2) > Ton (158,1) > Ak-Suu (125,0) > Tyup (42,43) > Jety-Oguz (24,49). Tyup and Jety-Oguz districts have the weaker degree of vulnerability because of the low population density, lack of modern infrastructures and industries (Figure 5). According the pairwise comparison of the socioeconomic variable the population density, coastal land-use and amount of recreational and industrial facilities are priority parameters. Unfortunately, the status of specially protected areas along the shore of Lake Issyk-Kul does not fully cope with its obligations to ensure the protection of protected areas.

3.2. Influence of Coastal Factors on Issyk-Kul Coastline

Considering the three variables (coastline type, rivers and degree of groundwater protection) affecting coastal vulnerability of the study area CVI is presented in Table 5. The value of the Coastal Vulnerability Index or CVI ranges from 5.0 to 15,49. In the coastal vulnerability we note that the CVI values are ranged as follow: Issyk-Kul (15,49) > Ton (15,49) > Jety-Oguz (8,66) > Tyup (7,75) > Ak-Suu (5,0) (Figure 6).

The coastal zones of the Issyk-Kul and Ton regions have a high level of vulnerability, since behind the coastal zones there are many buildings of tourist sites, but there is a lot of protective vegetation, for example, sea buckthorn shrubs, which play a very important role in reducing the abrasion/erosion process, especially during extreme events, have also been reduced [34].

The total length of the coast of Lake Issyk-Kul is 688 km. The length of the beach area is 600 km, of which more than 120 km are natural beaches of the 1st and 2nd categories. The total area of beaches reaches 9.5 million m^2. The best sandy beaches are located on the large peninsulas of the northern, eastern and southern coasts. They are bordered by bushes, the total area of which is three times the area of the beaches. More than half the length of the beach area is occupied by accumulative, leveled shores, composed of sand, small and medium-sized (0.5-0.1 mm) pebbles, and, to a lesser extent, boulders. About twenty large beach areas are located in the areas of Issyk-Kul and Ton districts. Sandy and pebble ridges are developed along the coastline, reaching their greatest size near river mouths, where fresh river waters mix with brackish lake waters and solid river sediment accumulates. The eastern part (Ak-Su and Tyup districts) of the coast is the most indented. It is characterized by deep bays that extend far into the land. The largest of them - Jergalan and Tyup - are separated by the Sukhoi Ridge peninsula. The eastern and partially southern shores are composed of rather loose sandy deposits. The lakeside plain ranges from several hundred meters to 12-20 km: northern – 1-10 km, eastern – 40-50 km, western – 10-15 km, south – narrow.

The lake is endorheic; up to 80 relatively small tributaries flow into it. The rivers are full in late spring and summer. Of these, the largest are Tyup and Jergalan, flowing from the east. All rivers flowing into the lake pass between villages and populated areas. The location of agricultural and arable land around the lake increases the risk of nutrients entering due to the wash-off of used nitrogen and phosphorus fertilizers from the fields. The coastal zones contain azonal and intrazonal soils resulting from sedimentation and waterlogging, while the settlements around the lake are characterized mainly by lowland and foothill soils, namely gray sandy soils with gravel inclusions, with high permeability, low retention potential and low organic content. As a result, it is possible that a certain amount of pollutants accumulates in the lake.

3.3. The Issyk-Kul Lake Integrated Coastal Vulnerability Index

As can be seen from Figure 7, the ratio of data obtained from the calculated coastal vulnerability index, socio-economic vulnerability index and integrated coastal vulnerability index can be used as integrated indicators of sustainable development of coastal territories and as a system of indicators of anthropogenic transformation of territories to determine the priority of measures for sustainable development of coastal territories.

Figure 8 shows the spatial variability of the Issyk-Kul Lake integrated coastal vulnerability derived from the combination of physical and socio-economic factors.

Jety-Oguz district (16,12) in low-risk category. Ak-Suu (65,0) and Tyup (25,55) are characterized by moderate degree of vulnerability. Ton district (86,80) fall in high risk-category. Finally, Issyk-Kul districts (126,33) represent the most vulnerable coastal cite. The Integrated Coastal Vulnerability Index (ICVI) computed for each zone shows that the vulnerability of the different sections depends both physical and socio-economic factors.

3.3. Conclusion

This article assesses the vulnerability of the coastal zone of Lake Issyk-Kul using the Integrated Coastal Vulnerability Index, determined by both physical and socio-economic factors. The ICVI calculated for each coastal zone of Lake Issyk-Kul indicate that the vulnerability of different sites depends on both physical and socio-economic factors. The results of the Socio-Economic Vulnerability Index (SVI) point out that the two main areas with the most developed infrastructure, located directly on the lake shore, experience particularly strong anthropogenic pressure. The Coastal Vulnerability Index (CVI) did not reveal particularly high vulnerability of the study areas, which were divided into moderate and low vulnerability zone, which is probably due to the high self-healing natural potential of the lake. The integral vulnerability index (ICVI) make obvious the most realistic picture of coastal zone vulnerability. Thus, to assess the environmental risks of particularly vulnerable coastal ecosystems, taking into account the integral vulnerability index is relevant and allows us to take into account the entire range of possible negative impacts and vulnerability of coastal zones. The main directions of environmentally-oriented land use planning in the designed coastal area assume a spatial relationship between the parameters of the socio-economic development of the territory and the environmental potential within the framework of long-term sustainable development. Consequently, one of the main tasks is to ensure the balanced development of natural and socio-economic systems that are in constant interaction.

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Appendix A

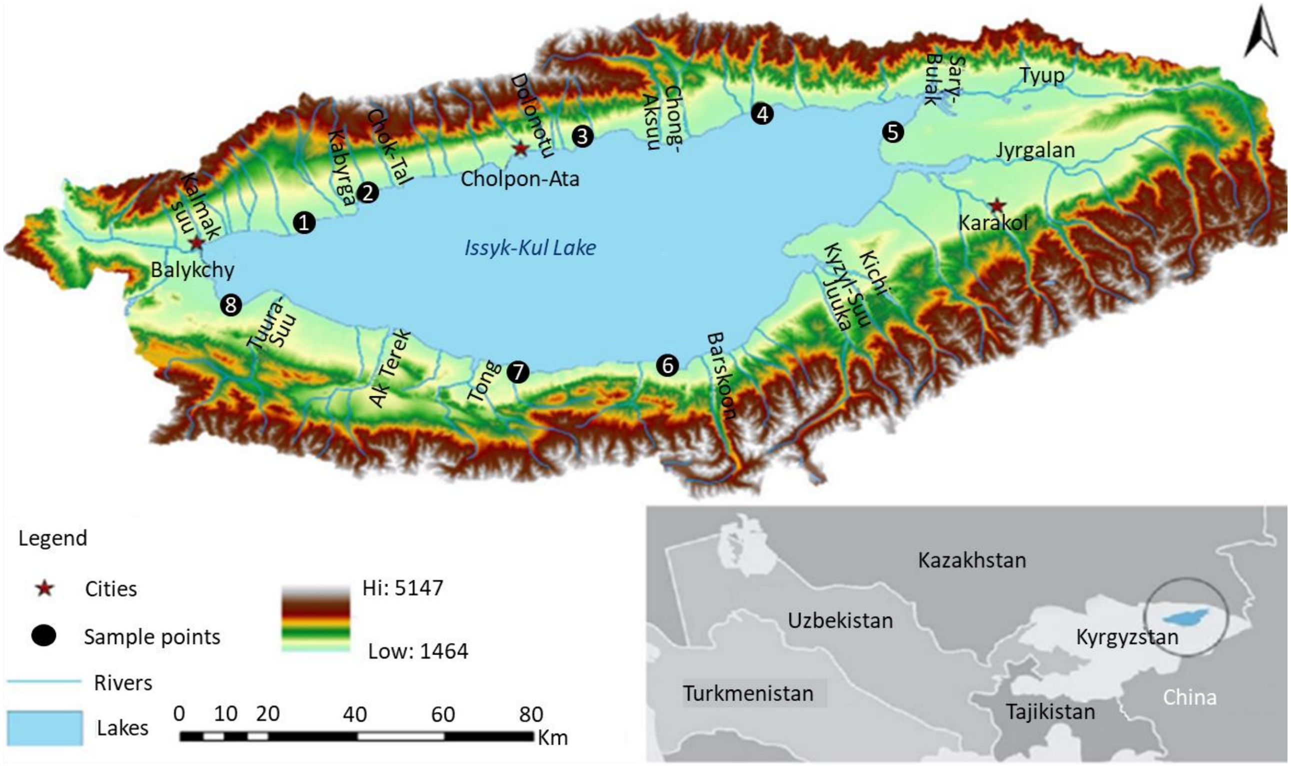

Figure1. Issyk-Kul Lake

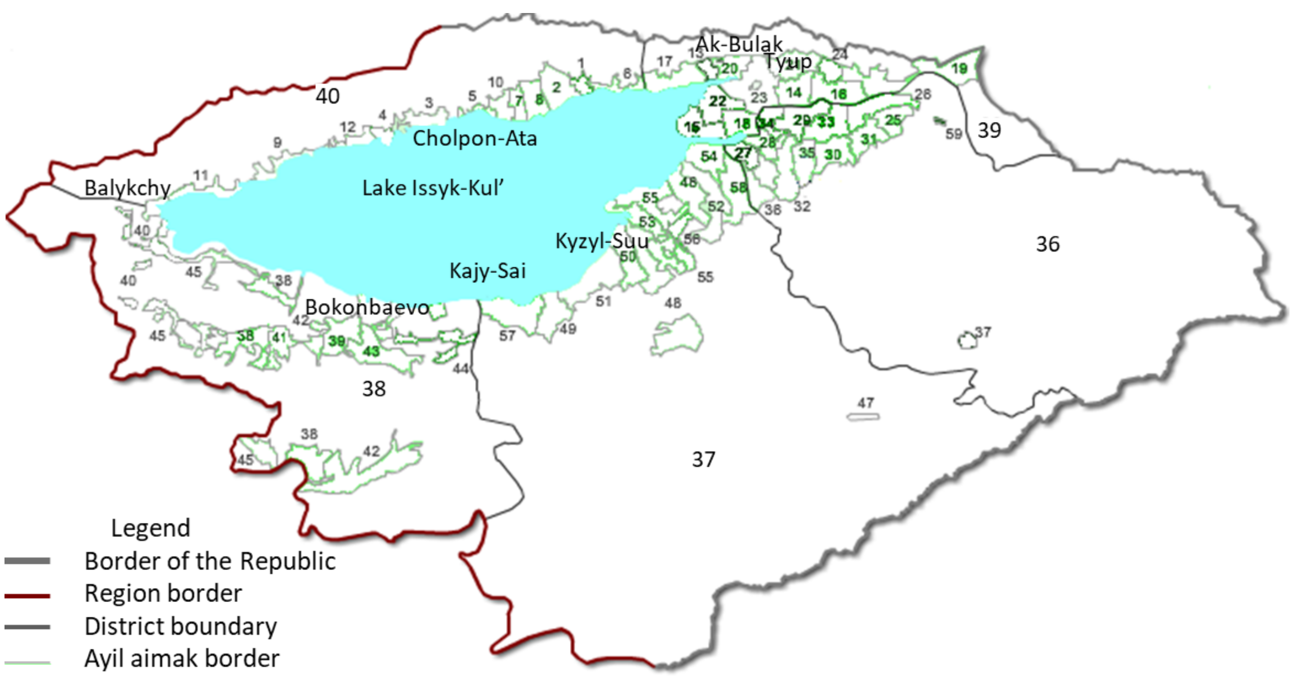

Figure 2. Administrative-territorial districts of Issyk-Kul region: 36- Ak-Suu, 37- Jeti-Oguz, 38- Ton, 39- Tyup, 40- Issyk-Kul.

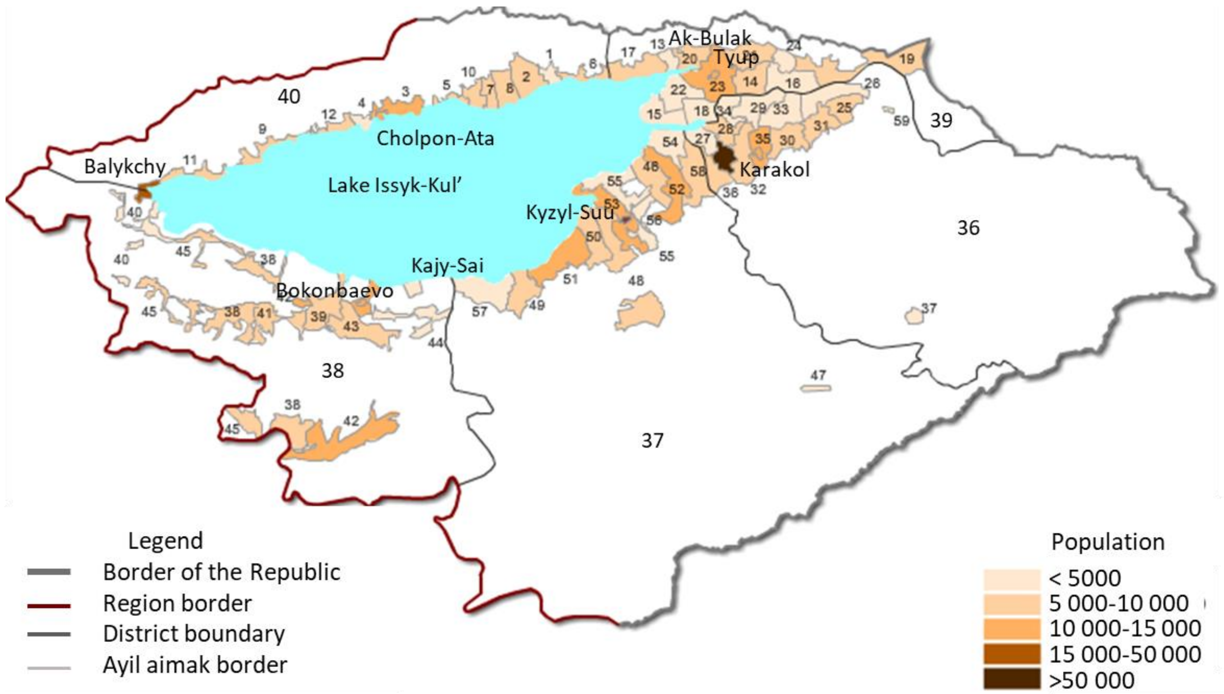

Figure 3. Territorial development structure of Issyk-Kul region

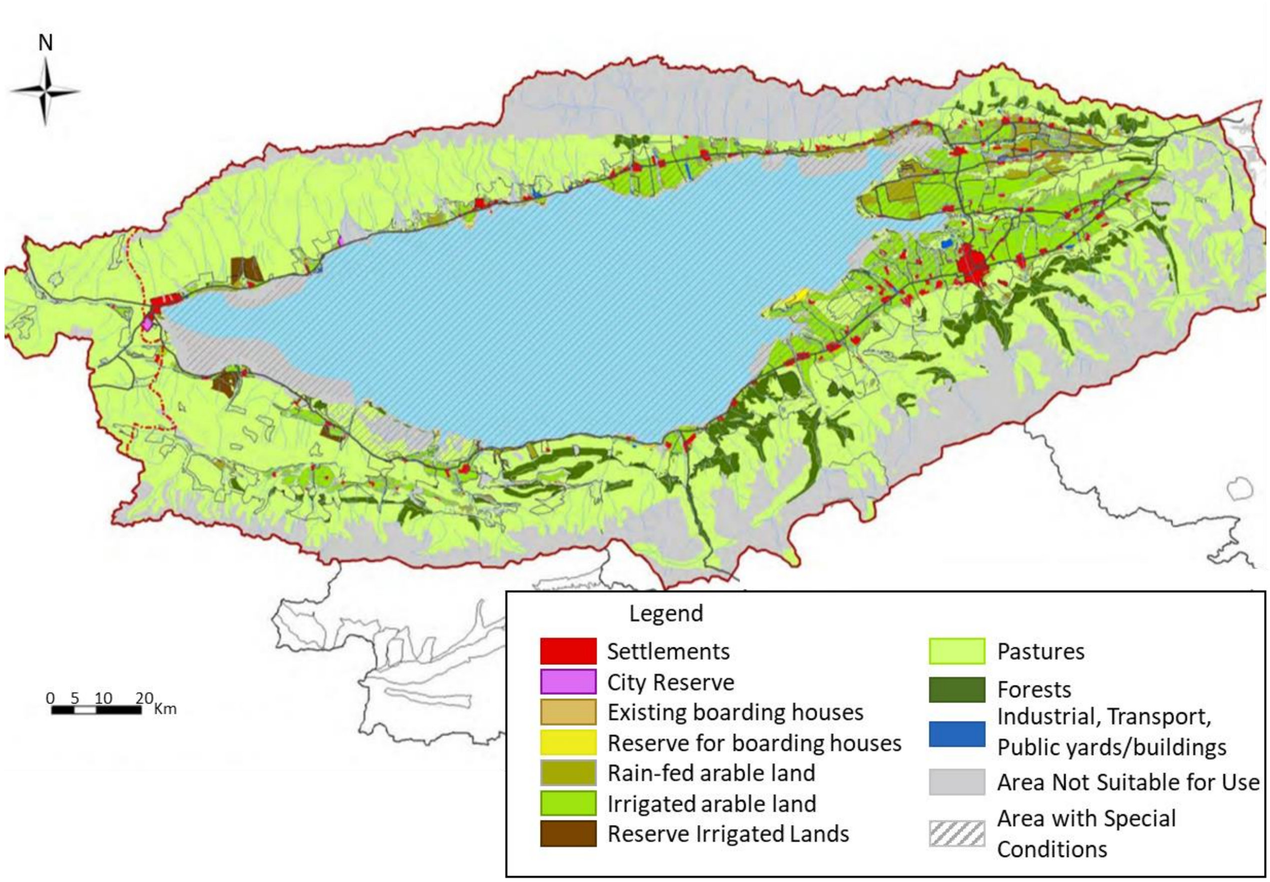

Figure 4. Land use in Issyk-Kul region

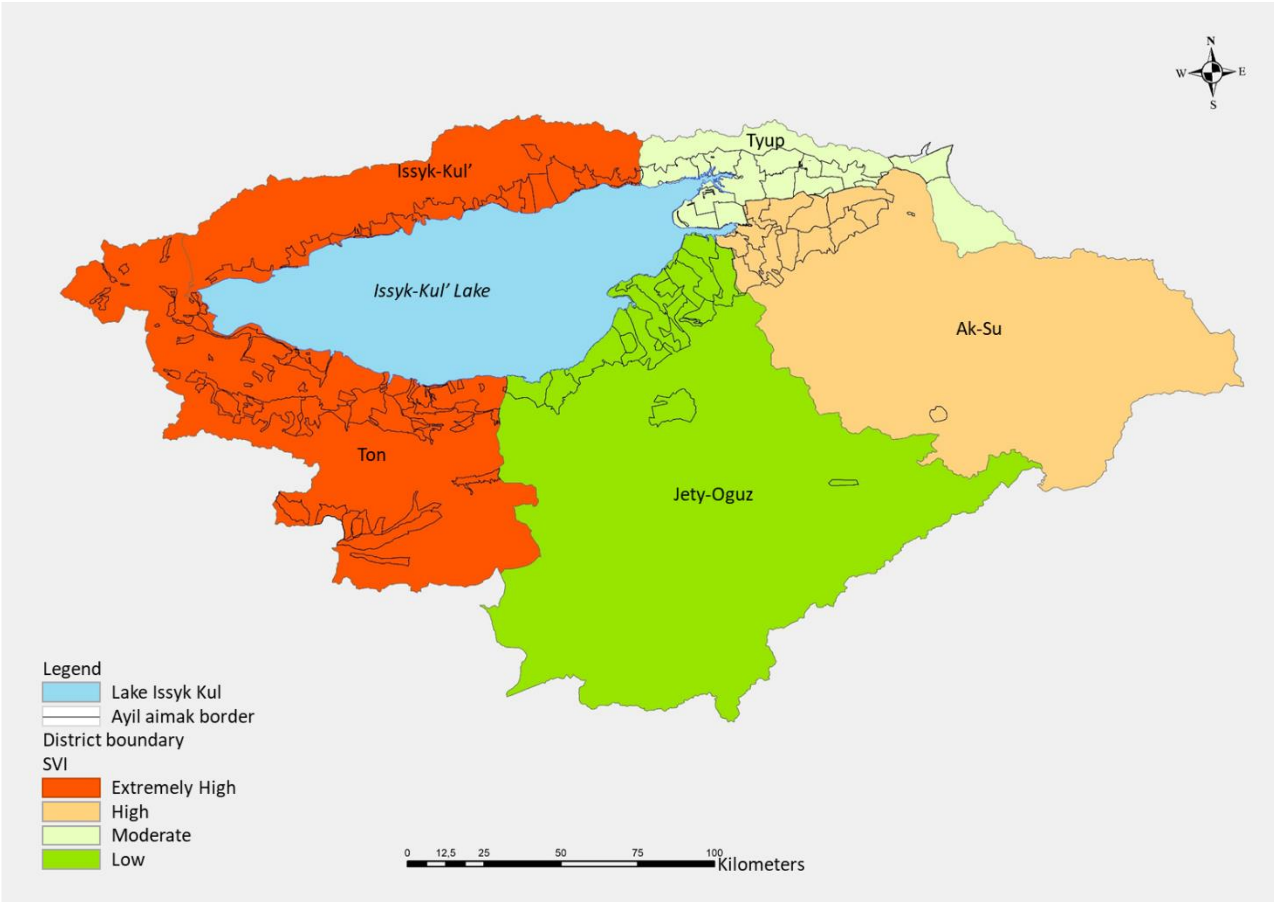

Figure 5. Spatial variability of socioeconomic vulnerability index (SVI) of Issyk-Kul coastline

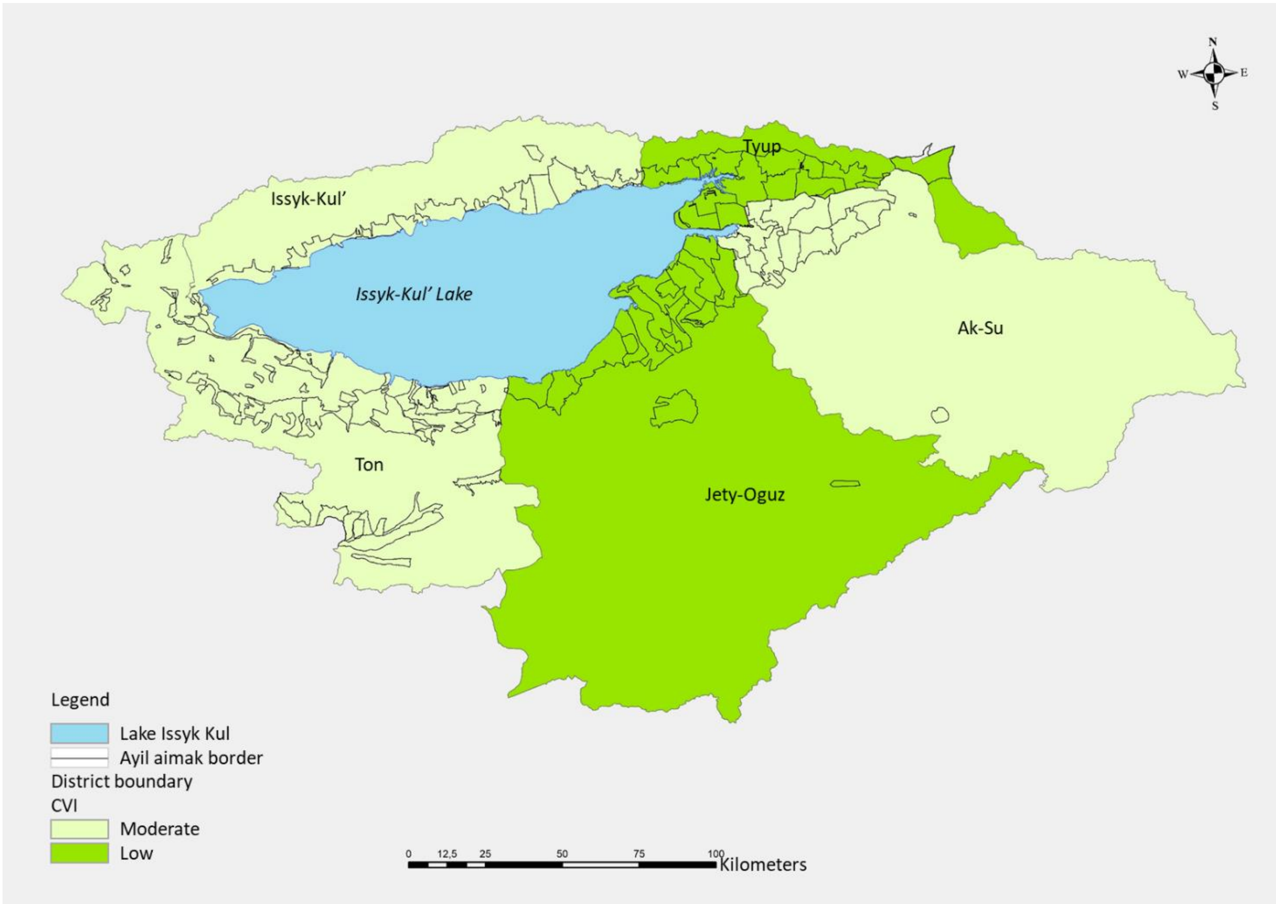

Figure 6. Spatial variability of coastal vulnerability index (CVI) of Issyk-Kul coastline

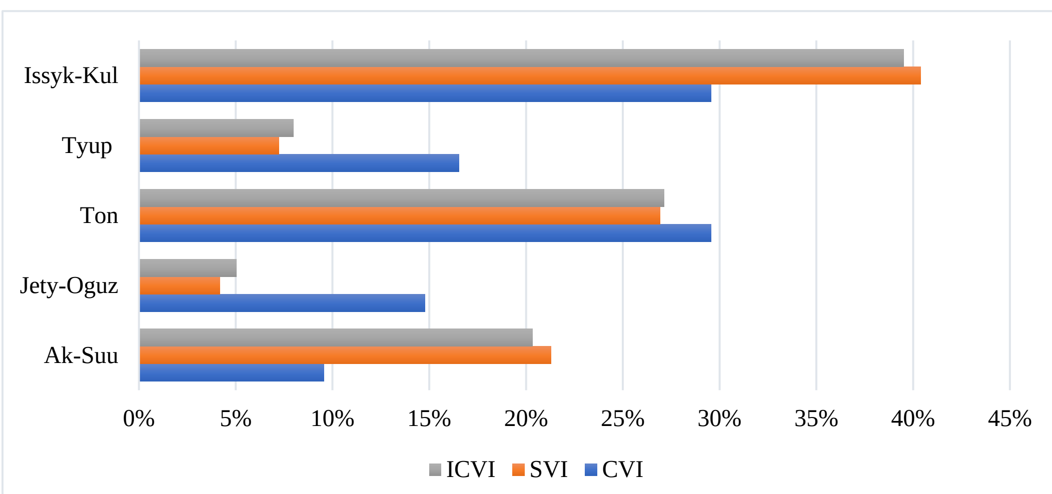

Figure 7. Vulnerability level rating CVI, SVI and ICVI

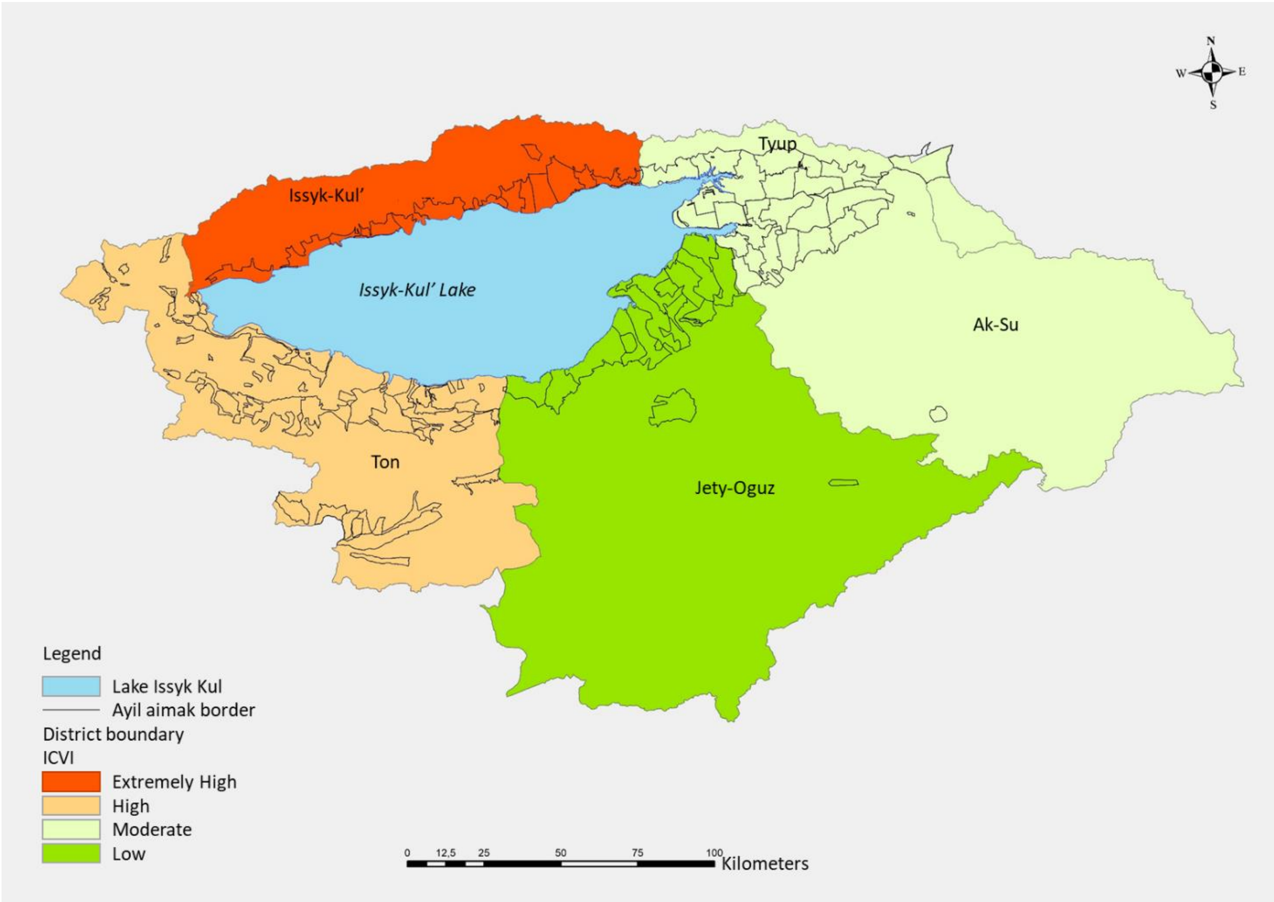

Figure 8. Spatial variability of integrated coastal vulnerability index (ICVI) of Issyk-Kul coastline

Table 1. Physical parameter ratings associated with different levels of vulnerability

Degree of vulnerability	**Very low**	**Low**	**Moderate**	**High**	**Very high**
Variable	1	2	3	4	5
Coastline type	High cliff (40+ m)	Medium cliff (20 to 40 m)	Low cliff (10 to 20 m)	Shingle ridge/bar	Sand beach/dune
Rivers	Absent	Stream	Small river	Medium river	Large river
Degree of groundwater protection	High protection	Protected	Moderate protected	Low protected	Unprotected

Table 2. Ranking of relative risk factors relative to population density, airport, road, harbor, land use, protected area and amount of recreational facilities, pastures and agricultural land close to shoreline. Empty box corresponds to no risk factor.

Degree of vulnerability	**Very low**	**Low**	**Moderate**	**High**	**Very high**
Variable	1	2	3	4	5
Population density (hbt/km^2)	<100	100-200	200-400	400-600	>600
Airport	Absent	Aerodrome	Regional airport		International airport
Road	absent		A'Class		Motorway Dual carriageway
Harbor	Absent				Present
Land use	Forest	Cleared vegetation	Natural grasslands	Agriculture	Urban and industrial infastructure
Protected area	Present				Absent
Amount of recreational facilities (hotel, rest house, sanatorium, guest house)	1-5		6-10		Over 11
Amount of industrial fagilities	Absent	1	2-5	6-10	More 10
Agriculture	Absent	>1000m from coastline	>5000m from coastline	100-500 from coastline	In 500 m from coastline

Pastures	Absent	>1000m from coastline	>5000m from coastline	100-500 from coastline	In 500 m from coastline

Table 3. Vulnerability level ratings

Persentiles	**Vulnerability**
<20	Low
20-40	Moderate
40-60	High
>60	Extremely High

Table 4. Socio-economic or human pressure vulnerability matrix

Coastal administrative territorial district	**Ak-Suu**	**Jety-Oguz**	**Ton**	**Tuyp**	**Issyk-Kul**
Population density (hdts/km^2)	5	1	5	2	3
Aiport	1	1	1	2	5
Road	5	3	5	3	5
Harbor	1	1	1	1	1
Land use	5	4	5	5	5
Protected area	5	1	5	1	5
Amount of recreational facilities	5	5	5	3	5

Amount of industrial facilities	5	5	4	5	3
Agriculture	5	5	5	5	5
Pasture	2	4	4	4	4

Table 5 Coast vulnerability matrix

Coastal administrative territorial district	**Coastal type**	**Rivers**	**Degree of groundwater protection**		
			Presence of RF in the area where groundwater is unprotected from pollution	Presence of RF in the area where groundwater is poorly from pollution	Presence of RF in the area where groundwater is moderately from pollution
Ak-Suu	5	5	5	1	1
Jety-Oguz	5	4	5	1	3
Ton	5	4	5	4	3
Tuyp	5	5	5	1	3
Issyk-Kul	5	4	5	4	3

Appendix B

Assoc.Prof.Dr. Nurzat Totubaeva received her Doctorate (Ph.D.) from the Institute of Soil and Biology National Academy of KR . She is currently an Assoc. Prof. Dr. at the Kyrgyz-Turkey Manas University, Bishkek, where she leads projects focused on assessment of water quality, particular of Issyk-Kul lake . Dr. Totubaeva has authored over 30 publications in international and local scientific journals. Her research interests include environmental protection, ecological microbiology, eco-monitoring, soil ecology, sustainable development of ecosystem.

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Rakhat Abdykadyrova is currently pursuing a PhD in Environmental Engineering. She has published several articles on the assessment of water quality and is involved as a researcher in a project focusing on this topic. In addition to her research, she works as an assistant at Manas University in the Department of Environmental Engineering, where she contributes to both teaching and research efforts in the field of water resource management.