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Revisiting Kazakhstan's Hydraulic Structures: A GIS-Based Approach to Dam Design and Allocation Considering Climate Change and Land Use Scenarios

Abstract. *This article discusses the importance of hydraulic structures, particularly dams, in Kazakhstan's economy due to water scarcity in many regions. The article highlights the need for a comprehensive approach to the location and design of dams considering climate change and land use scenarios. The article also emphasizes the need to update the design parameters and characteristics of dams to consider changes in land use and climate. The Samarkand reservoir hydrosystem is used as an example to discuss the potential hazards of the new spillway and the need for technical upgrading. The article suggests that the development of an integrated GIS-based approach to survey works, location, and design of dams could improve the quality of design and survey works and lead to the modernization of design and operation of reservoirs. The study proposes the use of modern research methods, including space methods, to provide more flexible and safe management of river flow with consideration of environmental and economic interests. The article concludes that the comprehensive GIS-based methodology for the location and design of dams, considering potential changes in river flow characteristics and the impact of changes in land use and climatic scenarios, can improve efficiency and optimize the work of hydraulic engineers.*
Keywords: *embankments, dams, GIS, DEM, Landsat, land cover*.

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Introduction

During the Soviet period in the 1940s to 1960s, Kazakhstan underwent industrialization, which included the construction of numerous hydraulic structures such as large river reservoirs and water intake reservoirs [1]. These structures continue to play a vital role in the economy of the country as the majority of Kazakhstan experiences water scarcity, with annual precipitation in some areas ranging from 250-500 mm. While some river basins such as Yertis and Balkash-Alakol have sufficient resources of surface and groundwater, others such as Nura-Sarysu, Yessil, Tobol-Torgay, Zhaik-Caspian, Aral-Syrdarya experience deficits in both [2]. This scarcity of water leads to dry vegetation and watercourses during summer months, and the need for irrigation of crops using water from artificially created reservoirs. Irrigated farming is the largest consumer of fresh water, accounting for 65% of intake. However, the needs of industry, urban and rural utilities, and irrigated agriculture are covered during low-water periods by the operation of hydraulic structures. Despite this, many regions still experience water deficits, and a comprehensive approach to the location and design of dams is required, considering climate change and land use scenarios in river basins that are subject to urbanization [3-4].

The calculated parameters and characteristics of dams during their design in the 1940s to 1960s require updating, and the existing methodological approach to their determination needs to be revised. The main factors that have undergone significant changes since the time of dam design are land use and climate change. These changes can completely alter the characteristics of river flows, which can, in turn, affect the location and design of the structure, and ultimately the stability and performance of dams. Therefore, it is crucial to calculate and design predicted parameters of river flow under the influence of changes in land use and climatic scenarios during the design of new dams or the reconstruction of existing hydraulic structures [5].

The Samarkand reservoir, located on the Nura River in the eastern region of Temirtau city in the Karaganda district, was constructed in 1939 to regulate the flow of the Nura River and provide water supply to the Karaganda industrial district . Between 1974 and 1988, the spillway structures of the hydrosystem were reconstructed due to changes in the system's functions, an increase in the capital class of its structures, and the unsatisfactory technical condition of the former spillway. The current hydroscheme is partially operational and has a total volume of 253.70 million m^3 at the normal supporting level of 490.17 m and a useful volume of 100.2 mln m^3 with level fluctuations of 1.5 m. The hydroscheme comprises a supply canal, a new spillway, a diversion canal, an earthen dam, an old spillway, a temporary earth cofferdam, and a siphon spillway. The new spillway is potentially hazardous and requires reconstruction and technical upgrading [6].

Hydrologists and hydraulic engineers closely involved in the task of analyzing the current state of design, construction, and operation of dams provided their opinions. The research in this direction is expected to be novel since modern space methods are rarely used in Kazakhstan. The primary objective is to develop an integrated GIS-based approach to survey works, location, and design of dams, taking into account changes in the Earth's surface and climatic scenarios in the river catchment areas under conditions of urbanization. This study is of significant importance in practice, as the low-quality construction and reconstruction projects are often due to imperfect methodology and incomplete implementation of survey works and incomplete consideration of factors affecting the regime of rivers and reservoir operation [7–10]. The above-mentioned approach can improve the quality of design and survey works, which can lead to the modernization of design and operation of reservoirs. It is expected that the use of modern research methods, including space methods, can provide more flexible and safe management of river flow with consideration of environmental and economic interests. This will enable correct zoning and effective use of new irrigated lands, leading to increased profitability [11].

However, some experts suggest that the design, filling, and operation of reservoirs require large-scale research works, whereas only exploration works are currently being carried out. They propose that to improve the situation in basins of regulated rivers, all technological links of design, preparation, and operation of reservoirs must be improved, and the concept of rational use of reservoirs must be implemented under increasing anthropogenic water [12].

The present study aims to develop a comprehensive GIS-based methodology for the location and design of dams, considering the potential changes in river flow characteristics and the impact of changes in land use and climatic scenarios, using the SCS-Curve Number method for modeling river flows. The application of the SCS-Curve Number method based on ArcGIS PC is expected to optimize the work of hydraulic engineers and improve efficiency. The object of the study is the Samarkand reservoir hydrosystem, including its location, history, construction details, and current condition. This study also highlights the need for reconstruction and technical upgrading of the system, as well as the use of digital terrain models and GIS-based methodology for the location and design of dams, considering potential changes in river flow characteristics and the impact of changes in land use and climatic scenarios [13].

Materials and methods

To collect climatic data for the study area, the nearest local weather station was located using a web service [14]. Historical data from the archives of the local weather station in Karaganda, Kazakhstan were collected, which had a latitude of 49.80, a longitude of 73.15, and an elevation of 553 m above sea level. The Institute of Geography and Water Security in Kazakhstan created a map to identify areas affected by significant climate change, which was used in the study. Soil maps and soil characteristics in the study area were obtained from the FAO-UNESCO Soil Map of the World and the Unified State Register of Soil Resources of the Russian Federation, as domestic libraries were insufficient [15]. The level of urbanization and location of buildings were determined using a topographic map of Kazakhstan, which was also used in the study [16]. Open web resources of DEM space images libraries were analyzed, and appropriate software for DEM space image processing was selected for data processing in GIS [17–22]. The study team identified individuals within government agencies who could provide data in an official capacity. However, it was discovered that there is no unified national database of climatic indicators, and data were collected manually for 30 years by searching each day, month, and year on several web services containing climatic data libraries. Commercial [23–27] and free software tools [28–32] were utilized for data processing in GIS.

A crucial component in GIS analysis is the Digital Elevation Model (DEM), which contains information about elevation without considering objects on the terrain surface. It is important to differentiate DEMs from Digital Surface Models (DSMs), which include information about elevation marks along with objects on the terrain surface. DEMs are derived from satellite or airborne imagery, and their quality is determined by their vertical and horizontal resolutions. In GIS, the vertical resolution of the DEM is critical for identifying watershed boundaries, which refers to the difference in height between modeled or detected elevations and the actual elevations of the terrain surface. DEMs with resolutions of 10 m, 30 m, and 90 m are widely available for free. For research purposes, more accurate DEMs with resolutions of less than 1 m can be obtained through an official request to authorized bodies, but their cost is typically high. DEMs are typically available in formats such as .tif, .shp, and others [33–35].

The relief of a territory plays a critical role in natural processes and environmental differentiation, particularly in the distribution of water and solar radiation. Accurate information on the relief is essential for efficient water resource management, planning, forecasting, ecological modeling, and design. One common approach for catchment area calculation involves the following algorithm: first, prepare a digital elevation model (DEM), such as the Shuttle Radar Topography Mission (SRTM) DEM, which can be downloaded from free sources. Next, spatially bind the image to a relevant coordinate system, such as the WGS_1984_UTM_Zone_43N (Figure 1).

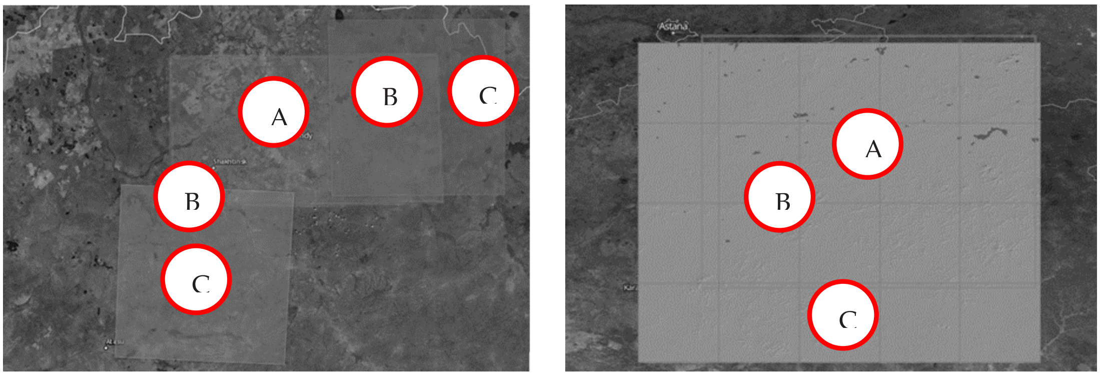

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Figure 1. Examples of inconsistencies in the boundaries and dimensions of the DEM and the study area: a) the study area; b) the intersection area of the study area with the image area; c) the image area outside the study area

To determine the catchment area of a pilot site, utilize horizons and elevations of scale 1:25000 and topographic surveys to produce a DEM with a relatively even and topologically correct relief, with a resolution of 10 meters per image pixel (Figure 2). Finally, apply the Catchment Polygon Processing tool in Arc Hydro Tools to transform the input watershed grid into a class of watershed polygon objects. For the Samarkand reservoir, the catchment area is defined in the plain part and has no sharp differences in elevation, with a maximum height of 1500 m. The coordinates of the research object are latitude 50° and longitude 73°.

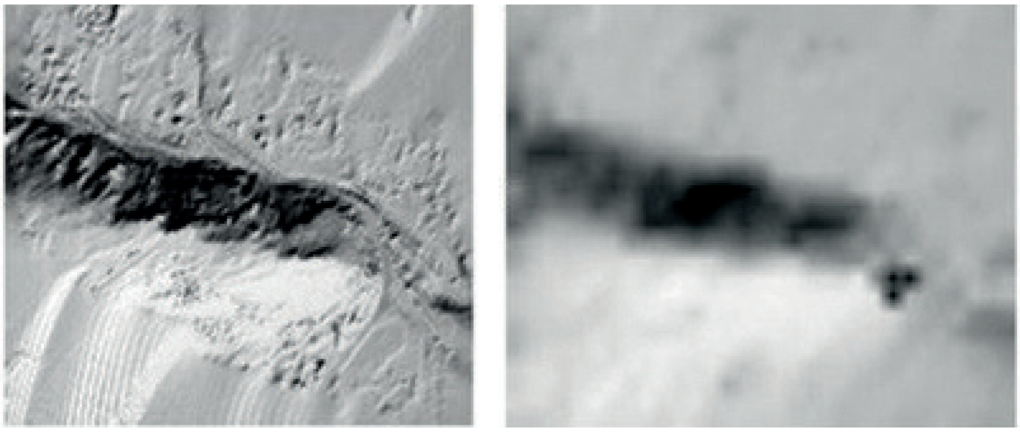

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Figure 2. Examples of DEMs with different resolutions: a) 5 m; b) 30 m

In order to simulate the movement of water volume along the slope, a scientific approach was employed using the Flow Accumulation tool. This tool applies a similar methodology to the previously used Flow Direction tool, but instead of determining the direction of flow, it identifies the volume of water flow. The resulting pixel values are then filled, with the flow volume receiving a value of 0 and the surrounding terrain taking a value of 1. This technique is essential for accurately modeling the flow of water along a slope and predicting potential issues such as erosion or flooding. By using this method, scientists and engineers can better understand the behavior of water in a given area and make informed decisions about land use, infrastructure development, and other important factors.

The formation of drainage basins is a crucial step in delineating catchment boundaries for the Samarkand reservoir. This process involves converting the raster dataset into polygons using the Raster to Polygon tool, which utilizes the size of similar contained cells to identify the drainage basin area and differentiate it with a distinct color from other boundaries outside the study catchment area. The final processing step involves cutting out a fragment of one feature class using one or more objects of another class, specifically clipping the DEM along the watershed boundary from the resulting polygon using the Clip tool.

The selection of image processing software was based on the ArcGIS Desktop software, which is produced by ESRI (USA) and has a high demand rating of 97% among programs of this type. ArcMap software enables full manipulation of raster data and processing of various images. Alternatively, the QGIS software of second or third generation was considered as another option, with the second version being free and open for private use and implementation of custom tools.

The determination of watershed boundaries was a complex process that involved several steps, each utilizing different tools of the ArcMap software. The aim of this analysis was to provide a representation of the qualitative composition and spatial distribution of land use and land cover across the entire watershed area. To achieve this, three basic flow calculation algorithms were employed (Figure 3).

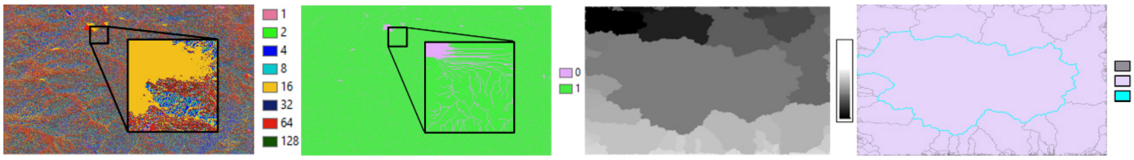

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Figure 3. Flow calculation of DEMs: a) directing threads according to pixel value; b) accumulation of pixels into one common stream; c) all drainage basins; d) boundary of the allocated catchment

To supplement the available information on domestic resources, the world soil map developed by the Food and Agriculture Organization of the United Nations (FAO) was used. This map contains all necessary data for all continents and countries, providing a valuable resource for this type of analysis (Figure 4).

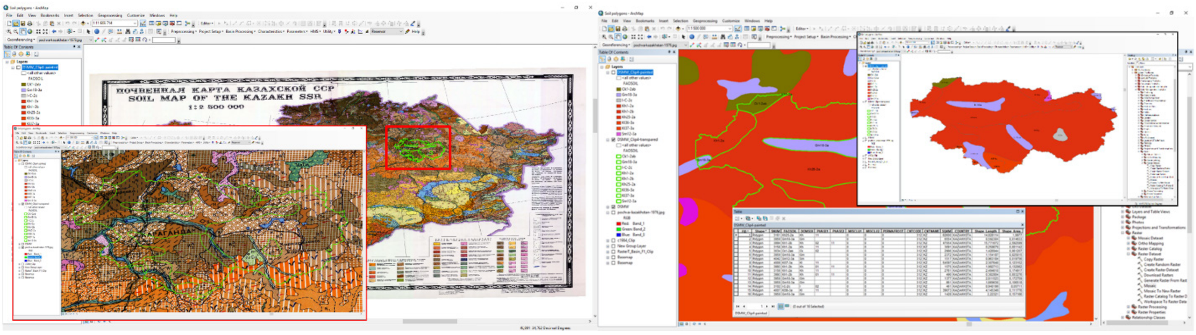

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Figure 4. Overlaying catchment boundaries: a) the world soil map; b) the national soil map

The Food and Agriculture Organization of the United Nations (FAO) provides a comprehensive system for the classification of soil types worldwide. In this system, the Republic of Kazakhstan (RK) is assigned a unique number or CNTCODE, which is registered as No. 312. The names of the main soil types found in the catchment area were deciphered, and their areas were calculated and presented in the table 1.

Table 1. Name of soils and their occupied area in the territory of Samarkand reservoir

№	№ FAO	Abbreviation and full name of the main soil on the FAO map			Total area for types of landfills, km²
1	3034	Ck1-2ab	Ck	Calcic Chernozems	2 966
2	3959	Gm18-3a	Gm	Mollic Gleysols	12 592
3	3102	I-C-2c	I	LITHOSOLS	461
4	3156	Kh1-2a	Kh	Haplic Kastanozems	5 852
5	3994	Kh1-2b	Kh	Haplic Kastanozems	49 119
6	3161	Kh25-2a	Kh	Haplic Kastanozems	62 600
7	4007	Kl36-3a	Kl	Luvic Kastanozems	39 073
8	4008	Kl37-3a	Kl	Luvic Kastanozems	54 597
9	4042	Sm12-3a	Sm	Mollic Solonetz	1 517

Results

Through the implementation of multi-step processes on Digital Elevation Model (DEM) data, the boundary of the Nura-Sarysu basin was generated and its corresponding area and boundary length were quantified to be 22877 km^2 and 1118 km, respectively. The resulting .shp file can be utilized to perform geographic overlays with other types of spatial data, enabling the selective emphasis or exclusion of information within or outside the hydrological catchment.

The hydrological catchment boundary was established and computational algorithms were applied to simulate water volume flows along the slopes, based on the analysis of pixel values.

Subsequently, a DEM of the Nura-Sarysu watershed was generated in raster format, which can be employed in conjunction with other ArcGIS software tools to facilitate a comprehensive analysis of the hydrological basin (Figure 5).

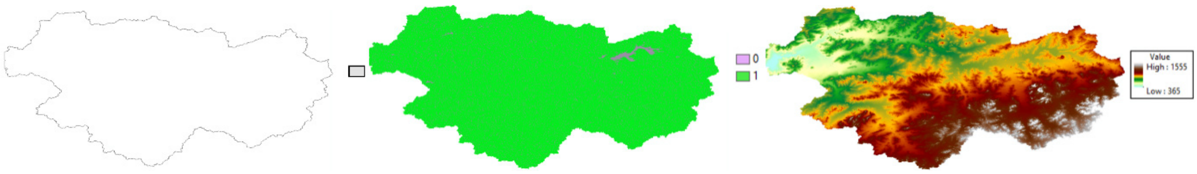

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Figure 5. Flow processing of Samarkand reservoir: a) watershed boundaries; b) Catchment boundary with directional flows; c) Catchment boundary with processed raster data

The methodology evaluated in this research has increasing practical relevance in contemporary Geotechnical Systems (GTS) design principles. There have been widespread discussions at conferences and in numerous articles concerning the incorporation of Geographic Information Systems (GIS) into the design and construction of GTS. For instance, the first imagery acquired from the Kazakhstani remote sensing satellite, KazEOSat-1, was used to forecast floods in the Zhabai River basin, a frequent phenomenon in the Central Kazakhstan region. The study's focus was to model and predict flood frequency using the obtained DEM in combination with data obtained from the hydrometeorological service, Kazgidromet. Furthermore, another area where GIS is extensively applied is in the processing of forest resources in Kazakhstan. The resulting model enables the identification of forest areas that have been subjected to alterations such as logging and fires. Overall, the application of GIS techniques has the potential to solve numerous global strategic tasks, given the availability of high-resolution satellite imagery and powerful technical equipment for efficient data processing.

Due to the nonlinearity of hydrometeorological processes and the various feedback mechanisms involved, natural oscillations with distinct time scales are stimulated in the climate system. In order to comprehend and anticipate the behavior of such a complex system under the influence of external forces (both anthropogenic and natural), it is essential to employ statistical and physical-mathematical models of the climate system that provide an adequate degree of reliability and detail in describing the processes within the specified media. The construction of a climate model starts with defining a system of equations, which serve as a mathematical representation of the physical laws governing the climate system. However, solving the corresponding partial differential equations analytically is challenging, and thus, computational methods are frequently utilized. Despite the rapid advancement in computational technology, the need for regional climate models to provide spatially detailed assessments of future climate change, beyond what global models can offer, persists. In such models, the values obtained from global models at the borders of the region are inputted and recalculated with higher spatial resolution. Hence, this study adopts a regional approach to climate modeling in key regions of the Nura River basin.

The input data used for the calculations comprise statistical long-term climate data, such as annual average precipitation, maximum daily precipitation, and air temperature obtained from the Karaganda meteorological station.

The simulation of excess precipitation schedules is based on the amount of precipitation available for direct surface runoff, which is known as excess precipitation. The graphs below depict the entire volume of precipitation minus any absorption processes, such as interception, storage in depressions, and infiltration, showing a clear increase in excess precipitation (Figure 6).

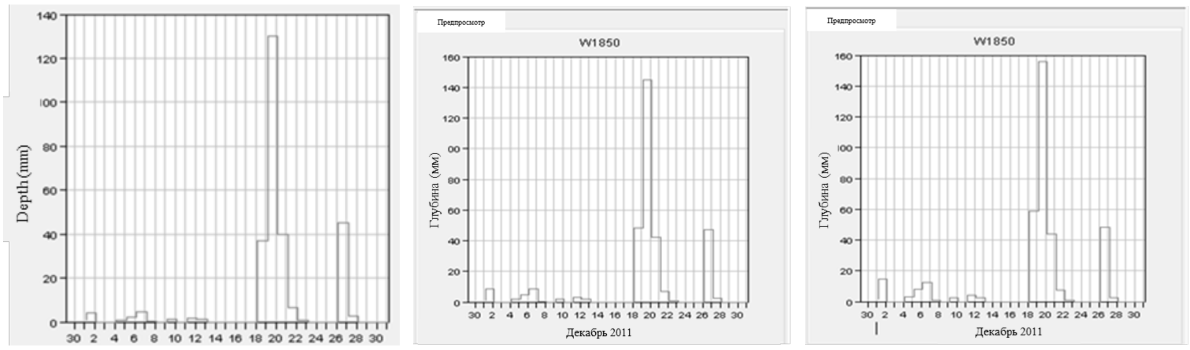

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Figure 6. Simulated graphs of excess precipitation by years for December 2011:
a) W3540-1998; b) W1850-2009; c) W1850-2018

The modeling of excess cumulative precipitation plots is a crucial aspect of this study. Similar to cumulative precipitation plots, excess cumulative precipitation plots exhibit a considerable surge due to the December 20 severe event, as illustrated in the figures below (Figure 7).

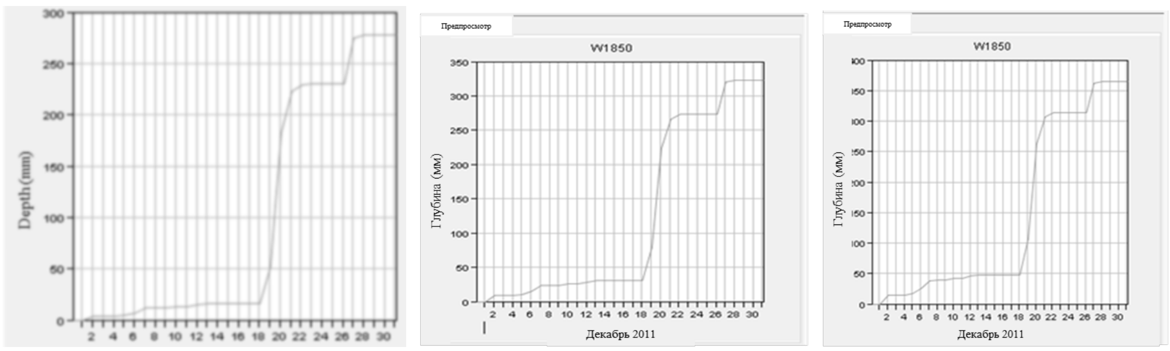

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Figure 7. Simulated graphs of cumulative excess precipitation by years for December 2011:
a) W3540-1998; b) W1850-2009; c) W1850-2018

The modeling of precipitation loss plots is a key aspect of this research. Precipitation loss occurs due to various factors such as interception, evaporation, transpiration, accumulation in depressions, and infiltration. The results indicate that there is a decreasing trend in precipitation loss from 1998 to 2018, which can be attributed to the changes in land use (Figure 8).

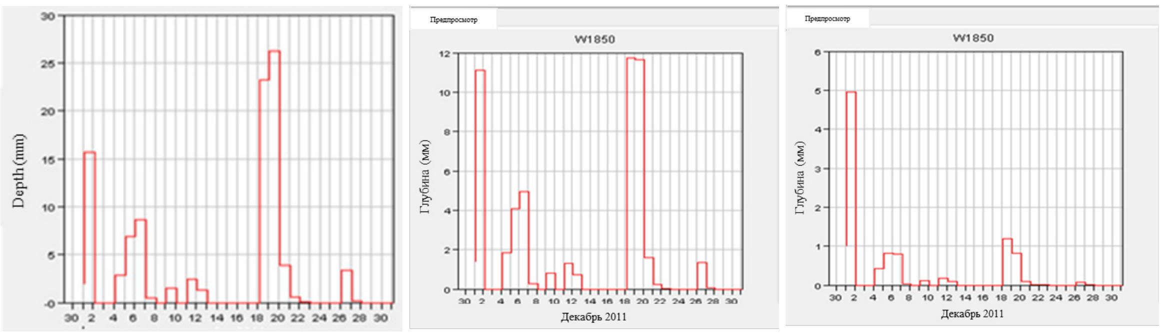

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Figure 8. Simulated graphs of precipitation losses by years for December 2011:
a) W3540-1998; b) W1850-2009; c) W1850-2018

The simulation plots of cumulative precipitation loss hold immense significance in the domain of water resource planning and management. These plots present a comprehensive view of the cumulative precipitation loss over a period of time and enable the identification of peak water flows. In the present study, the cumulative precipitation loss graphs portray a significant surge owing to the December 20 exceptional event. This information can be valuable for making informed decisions, such as for assessing flood risks or devising water flow plans during a drought (Figure 9).

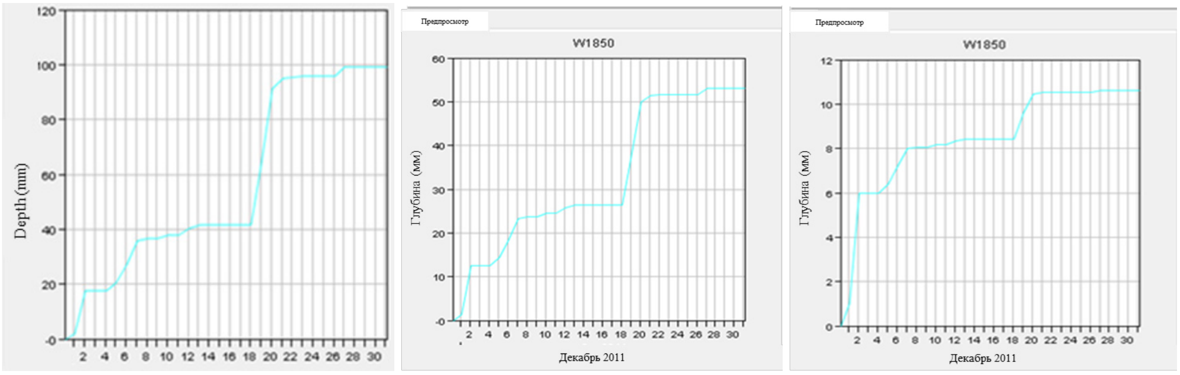

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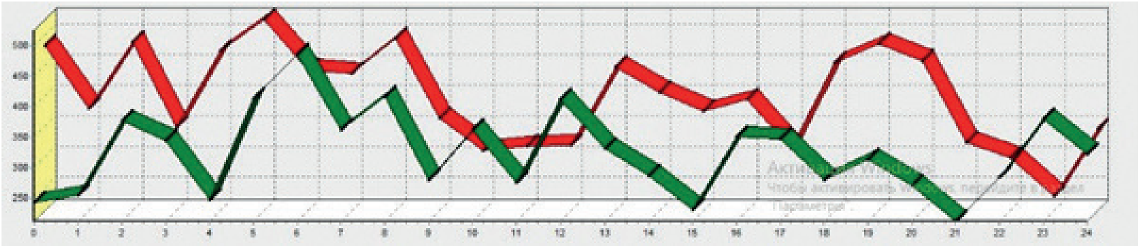
Figure 9. Simulated graphs of cumulative precipitation loss by years for December 2011:
a) W3540-1998; b) W1850-2009; c) W1850-2018

The meteorological time series for the selected weather station spans over 50 years, meeting the minimum requirement for stationary meteorological observations. The coefficient of variability (Cv) ranges from 1.1 to 1.4, which is generally considered high, indicating a significant level of variability in the observed data. A low variability is classified as Cv < 0.05, medium as Cv between 0.05 and 0.10, and high as Cv > 0.10.

To calculate the security curve, theoretical parameters Q0, Cv, Cs, and kp% were utilized through the Foster-Rybkin method. The resulting probability curves were constructed using monthly and annual mean water discharges. A summary table was compiled, specifying the meteorological parameters for the 4%, 20%, 50%, 75%, and 95% probability levels.

Homogeneity of the long-term meteorological series was analyzed using statistical criteria, including Fisher's, Student's, and Wilcoxon's tests in the Stockstat program. Two out of three criteria indicated homogeneity between the compared samples at a significance level of 0.05. Empirical probability curves were then constructed to visualize the results, indicating the percentage of the year in which a particular amount of precipitation occurs. These curves are based on the stationary observations from the Karaganda meteorological station and were calculated using a grouped series for homogeneous populations. The probability curves can provide useful information for planning water-related activities and analyzing climate changes in the region (Figure 10).



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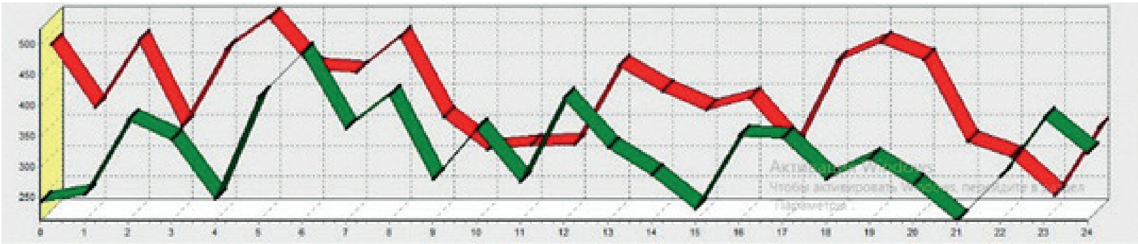

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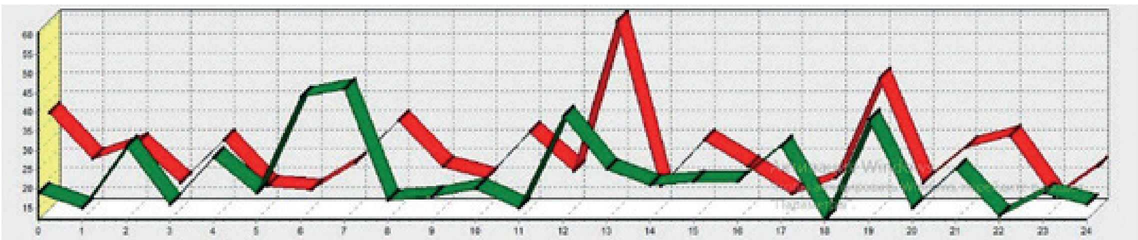

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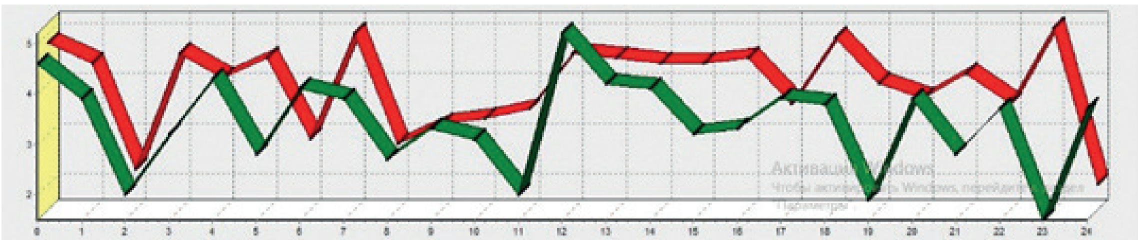

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Figure 10. Assessment of homogeneity: a) multiyear meteorological series - sum of mean annual precipitation; b) total annual precipitation; c) total daily maximum amount of precipitation; d) mean annual air temperature

It is important to highlight that the region under consideration experiences an annual total precipitation of 298 mm in dry years with 75% security, while in the most favorable years with 4% security, the annual total precipitation reaches 494 mm. Furthermore, the maximum daily precipitation during years with 4% probability of high precipitation over a multi-year period is 46 mm per day, whereas during dry periods it is 18 mm per day, which is less than twice as much.

This study presents a geoprocessing toolkit that offers a comprehensive framework for handling geographic and related data. The toolkit is equipped with an array of geoprocessing tools that enable automated spatial analysis and management of geographic information system

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data. By utilizing a digital elevation model, a trimmed shapefile comprising land use/land cover polygons, and a CNLookup table, the proposed geoprocessing program can perform watershed delineation and create a grid of curved numbers simultaneously. Developed using the Python programming language, the geoprocessing program integrates multiple procedures into a single entity (Figure 11).

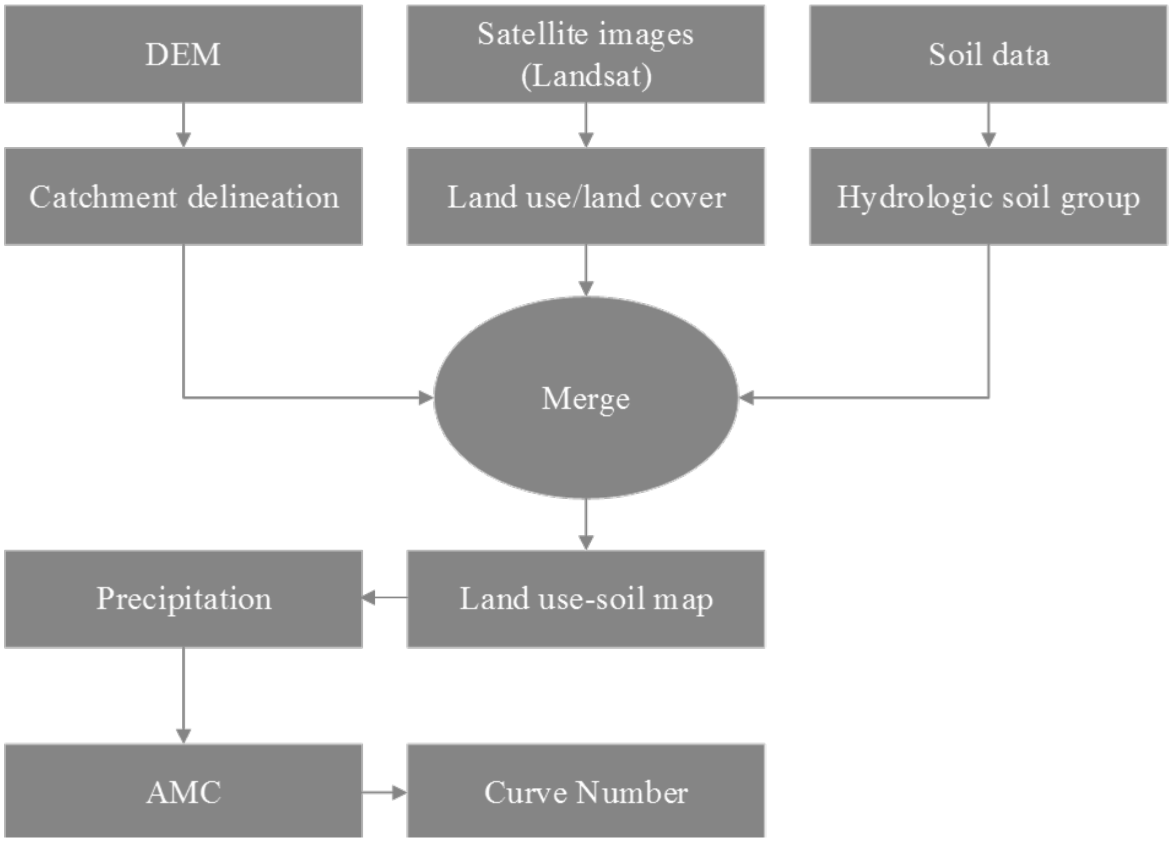

Figure 11. Geoprocessing toolset

Watershed delineation is crucial for identifying surface water characteristics within a watershed and comprehending downstream effects when planning and implementing measures to protect and mitigate water quality and quantity. While some dams worldwide can be appropriately represented in a single basin, others require division into several sub-basins. The rainfall flow mechanism employed and a range of hydrologic characteristics influences the size and definition of sub-basins.

Curve numbers are widely utilized in hydrologic modeling, including rainfall-runoff models for predicting runoff volume and peak flows. The curve numbers serve to approximate the infiltration, interception, and storage capacity of various land covers and are determined based on soil cover and soil type.

Currently, determining catchment boundaries and obtaining curve numbers are complicated and time-consuming procedures. However, the developed geoprocessing program offers a simpler approach to calculate catchment boundaries and a grid of curve numbers.

Conclusion

The results of this study have significant implications for the development of the construction sector in Kazakhstan. The developed integrated approach for the location and design of dams, taking into account climate change and land use scenarios in river basins affected by urbanization, represents an effective domestic solution for hydrological monitoring. The approach can lead to more precise and reliable monitoring of water resources in these river basins, ensuring safer and more efficient construction of dams, and enabling the effective management of water resources in these areas.

Moreover, the developed approach can contribute to the sustainable development of the country, ensuring the proper management and conservation of water resources, while also promoting the economic development of the region. By taking into account the impacts of climate change and urbanization, the approach can help to mitigate the risks of flood and drought, and ensure the long-term sustainability of the water resources.

In conclusion, the developed integrated approach for the location and design of dams, taking into account climate change and land use scenarios in river basins affected by urbanization, represents a valuable contribution to the field of hydrological monitoring and the construction sector in Kazakhstan. The approach can ensure the sustainable development of the country by promoting the efficient management of water resources, mitigating the risks of flood and drought, and ensuring the economic development of the region.

Acknowledgments

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Қазақстанның гидротехникалық құрылыстарын қайта қарау: ГАЖ арқылы климаттың өзгеруі мен жерді пайдалану сценарийлерін ескере отырып, бөгеттерді жобалау мен орналастыру әдісі

Андатпа. Бұл мақалада көптеген өңірлердегі су тапшылығына байланысты Қазақстан экономикасындағы гидротехникалық құрылыстардың, атап айтқанда бөгеттердің маңыздылығы қарастырылады. Мақалада климаттың өзгеруі мен жерді пайдалану сценарийлерін ескере отырып, бөгеттерді орналастыру мен жобалауға кешенді көзқарастың қажеттілігі көрсетілген. Мақалада сонымен қатар жерді пайдалану мен климаттың өзгеруін ескере отырып, бөгеттердің жобалық параметрлері мен сипаттамаларын жаңарту қажеттілігі көрсетілген. Самарқанд су қоймасының гидрожүйесі жаңа төгілудің ықтимал қауіптерін және техникалық жаңғырту қажеттілігін талқылау үшін мысал ретінде пайдаланылады. Мақалада іздестіру жұмыстарына, бөгеттерді орналастыруға және жобалауға ГАЖ негізінде кешенді тәсілді әзірлеу жобалау-іздестіру жұмыстарының сапасын арттырып, су қоймаларын жобалау мен пайдалануды жаңғыртуға әкелуі мүмкін деп болжанады. Зерттеу экологиялық және экономикалық мүдделерді ескере отырып, өзен ағынын икемді және қауіпсіз басқаруды қамтамасыз ету үшін заманауи зерттеу әдістерін, соның ішінде ғарыштық әдістерді пайдалануды ұсынады. Мақалада өзен ағынының сипаттамаларының ықтимал өзгерістерін және жерді пайдалану мен климаттық сценарийлердегі өзгерістердің әсерін ескере отырып, ГАЖ негізіндегі бөгеттерді орналастыру мен жобалаудың кешенді әдістемесі гидротехникалық инженерлердің тиімділігін арттырып, жұмысын оңтайландыруы мүмкін деген қорытындыға келді.
Түйін сөздер: бөгет, тоған, ГАЖ, СРМ, Landsat, жер жамылғысы.

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Пересмотр гидротехнических сооружений Казахстана: ГИС-подход к проектированию и расположению плотин с учетом сценариев изменения климата и землепользования

Аннотация. В данной статье рассматривается важность гидротехнических сооружений, в частности плотин, в экономике Казахстана в связи с нехваткой воды во многих регионах. В статье подчеркивается необходимость комплексного подхода к размещению и проектированию плотин с учетом изменения климата и сценариев землепользования. В статье также подчеркивается необходимость обновления проектных параметров и характеристик плотин с учетом изменений в землепользовании и климате. На примере гидроузла Самаркандского водохранилища рассматриваются потенциальные опасности нового водосброса и необходимость его технической модернизации. В статье высказывается предположение, что разработка комплексного подхода на основе ГИС к изыскательским работам, определению местоположения и проектированию плотин может повысить качество проектно-изыскательских работ и привести к модернизации проектирования и эксплуатации водохранилищ. В исследовании предлагается использовать современные методы исследования, в том числе космические, для обеспечения более гибкого и безопасного управления речным стоком с учетом экологических и экономических интересов. В статье делается вывод, что комплексная методология на основе ГИС для размещения и проектирования плотин, учитывающая потенциальные изменения характеристик речного стока и влияние изменений в землепользовании и климатических сценариях, может повысить эффективность и оптимизировать работу гидротехников.

Ключевые слова: плотины, дамбы, ГИС, ЦМР, Landsat, почвенный покров.

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