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## DEFINING THE BOUNDARIES AND AREA OF THE SAMARKAND RESERVOIR CATCHMENT BASED ON DIGITAL ELEVATION MODELS

In this study, the potential applicability of the Geographical Information System (GIS)-based approach in the catchment delineation and monitoring of hydraulic structures for a case of Samarkand reservoir in the Karaganda region of the Republic of Kazakhstan is presented. Different GIS tools were applied along with different datasets from different sources and resolutions to investigate their effects on catchment delineation and monitoring of hydraulic structures. The first step was to retrieve Digital Elevation Model (DEM) for the case study catchment. However, with the fact that the catchment is among the largest catchments in Central Asia, eight different pieces of DEMs had to be collected and then mosaiced to form one DEM for the entire catchment. Then the catchment was delineated to define its boundaries and stream networks using ArcHydro tools in ArcGIS software. To produce high-quality maps, the study tested DEMs from various open-source, commercial and open-source software. Based on the results of the study, the most suitable DEMs with a resolution of 10 m per pixel and covering the entire potential territory of the study catchment were downloaded from the OpenTopography website. DEM processing made it possible to obtain a fairly accurate outline of the catchment boundaries in vector format, as well as maps of surface runoff and elevations in raster format. The total area and length of the catchment boundaries were 228777 km<sup>2</sup> and 1118 km, respectively. As the study continues, the maps obtained will be used to develop a hydrological model and an improved approach to dam design and monitoring in river basins subjected to urbanization. The approach proposed in the study can be improved by using DEMs with a resolution below 10 m.

**Key words:** GIS, dam design, DEM, catchment delineation, surface runoff.

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### Жер бедерінің сандық үлгісі негізінде Самарқанд су қоймасының су жинау алабының шекарасы мен ауданын анықтау

Осы зерттеуде Қазақстан Республикасының Қарағанды облысындағы Самарқанд су қоймасы үлгісінде гидротехникалық құрылыстардың су жинау шекараларын айқындау және мониторингілеу үшін географиялық ақпараттық жүйесінде (ГАЗ) негізделген тәсілдің әлеуетті қолданылуы ұсынылған. ГАЗ-дің әртүрлі құралдары сан алуан көздерден алынған мәліметтер жиынтығымен бірге және олардың су жинау шекараларын анықтауға және гидротехникалық құрылыстарды бақылауға әсерін зерттеу үшін әртүрлі ажыратымдылығымен бірге қолданылды. Бірінші қадам жер бедерінің сандық үлгісін (ЖБСҮ) табу болып саналады. Алайда, бұл Орталық Азиядағы ең ірі су жинау қоймасы екені анық, сондықтан ЖБСҮ-нің сегіз әр түрлі бөлігін жинап, біріктіру қажет болды. Содан кейін су жинау қоймасы ArcGIS бағдарламалық жасақтамасында ArcHydro құралдарын қолдана отырып, оның шекаралары мен ағындар желісін анықтау үшін контуры айқындалды. Зерттеу барысында жоғары сапалы карталарды жасау үшін ЖБСҮ әртүрлі тегін көздерден, ашық бағдарламалардан және коммерциялық бағдарламалардан сыналды.

Зерттеу нәтижелері бойынша пиксельге 10 м ажыратымдылығы бар және зерттелетін су жинаудың барлық ықтимал аумағын қамтитын ең қолайлы ЖБСУ OpenTopography сайтынан жүктелді. ЖБСУ өңдеу векторлық форматта су жинау шекараларының жеткілікті дәл контурын, сондай-ақ растрлық форматта жер үсті ағындары мен биіктік карталарын алуға мүмкіндік берді. Су жинау шекараларының жалпы ауданы мен ұзындығы тиісінше 228777 км<sup>2</sup> және 1118 км құрады. Зерттеу жалғастырылған сайын алынған карталар гидрологиялық модельді әзірлеу және урбанизацияға ұшыраған өзен бассейндеріндегі бөгеттерді жобалау мен мониторингтеуді жетілдіру үшін пайдаланылатын болады. Зерттеуде ұсынылған тәсілді 10 м-ден аз ажыратымдылығы бар ЖБСУ пайдалану арқылы жақсартуға болады.

**Түйін сөздер:** ГАЗ, бөгеттерді жобалау, ЖБСУ, су жинау алаңын контурлау, жер үсті ағыны.

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### Определение границ и площади водосбора Самаркандского водохранилища на основе цифровых моделей рельефа

В данном исследовании представлена потенциальная применимость подхода, основанного на географической информационной системе (ГИС), для определения границ водосбора и мониторинга гидротехнических сооружений на примере Самаркандского водохранилища в Карагандинской области Республики Казахстан. Различные инструменты ГИС применялись вместе с наборами данных из разных источников и с разным разрешением, чтобы исследовать их влияние на определение границ водосбора и мониторинг гидротехнических сооружений. Первым шагом было получение цифровой модели рельефа (ЦМР) для исследуемого водосбора. Однако, учитывая тот факт, что водосбор является одним из крупнейших водосборов в Центральной Азии, необходимо было собрать восемь различных частей ЦМР и объединить их в единую для всего водосбора. Затем водосбор был оконтурен для определения его границ и сети ручьев с помощью инструментов ArcHydro в программном обеспечении ArcGIS. Для создания высококачественных карт в ходе исследования были протестированы ЦМР из различных бесплатных источников, коммерческих программ и программ с открытым исходным кодом. По результатам исследования, наиболее подходящие ЦМР с разрешением 10 м на пиксель и покрывающие всю потенциальную территорию исследуемого водосбора были загружены с сайта OpenTopography. Обработка ЦМР позволила получить достаточно точный контур границ водосбора в векторном формате, а также карты поверхностного стока и высот в растровом формате. Общая площадь и протяженность границ водосбора составили 228777 км<sup>2</sup> и 1118 км, соответственно. По мере продолжения исследования полученные карты будут использоваться для разработки гидрологической модели и усовершенствованного подхода к проектированию и мониторингу плотин в речных бассейнах, подверженных урбанизации. Предложенный в исследовании подход может быть улучшен путем использования ЦМР с разрешением менее 10 м.

**Ключевые слова:** ГИС, проектирование плотин, ЦМР, оконтуривание водосбора, поверхностный сток.

### Introduction

In general, hydraulic structures (HS) deal with different issues related to water. The infrastructures include dams, piping systems, pumping stations, gabion, irrigation schemes, as well as sewerage systems among many other aspects. Improving water management practices is among the roles of hydraulic structures, including quality of water, as well as environmental restoration and protection (Frenken, 2013).

The art of constructing HSs has been known since ancient times. The first historical references to

the construction of dams and reservoirs are found in the works of Herodotus. It is mentioned that the Persians built dams to divert water from their cities during the reign of Abbas I the Great. The stone dam near the city of Kashan was 36 m long, 16 m high, and 10 m thick, where a channel for passing water could be seen at the bottom. In ancient Egypt, reservoirs were located along the Nile River to develop new land. One of the oldest known dams was located 100 km from the city of Amman and dates back to 3000 BC. Stone was used in the construction of the dam, the wall was 4.5 m high and 1 m thick, and its length is unknown. Later, at a distance of

25 km from the city of Kair, a 102 m long dam was built. The feasibility of dam construction was largely determined by the Romans to build reservoirs for drought periods (Zhang, 2011).

According to the report of the International Commission on Large Dams, there were more than 45,000 large dams around the world at the end of the twentieth century. According to this report, more than half of them were built in developing countries. According to the technical characteristics, it is possible to distinguish the most famous modern dams. The highest artificial dam is the Jinping-1 hydro-

power plant on the Yalongjiang River in China, built of arch-concrete type and with a height of 305 m. One of the largest is a natural dam formed on Sarez Lake after the earthquake with a height of 567 m. In terms of nominal water volume, it is possible to distinguish the dam built in 1959 between Zambia and Zimbabwe on the Zambezi River. Its volume is 180.6 km<sup>3</sup>. As a rule, the reservoirs held back by HS are formed due to the accumulation of precipitation, underground or surface rivers flowing into it from the surrounding area, i.e., the catchment area (Fig. 1) (ANCOLD, 2012).

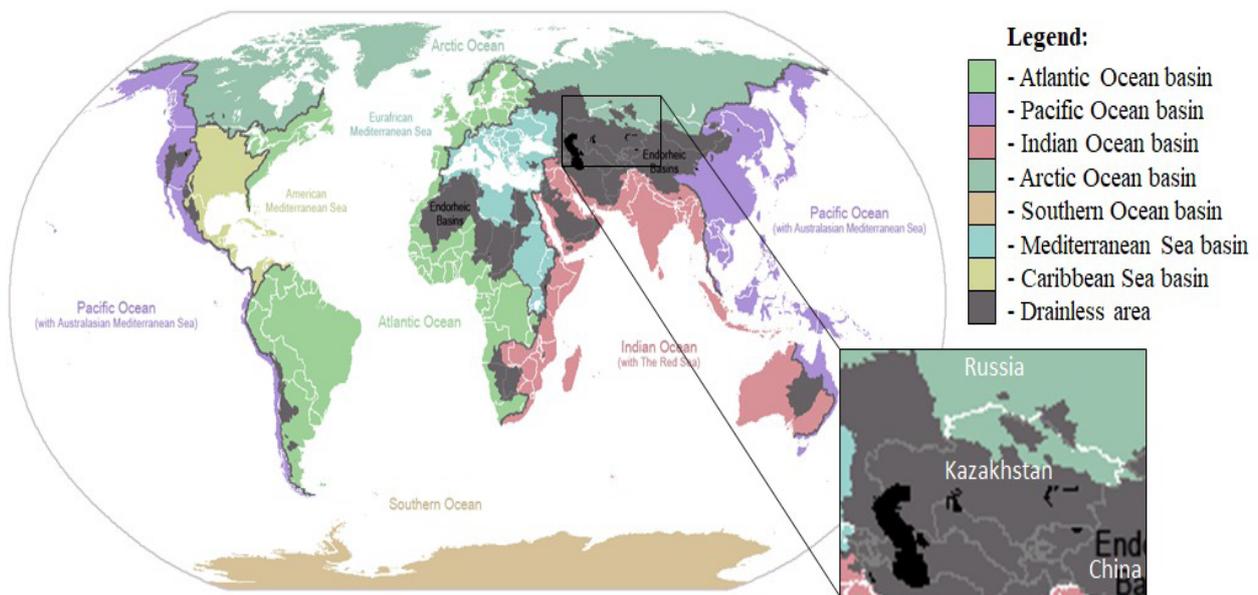


Figure 1 – Boundaries of the main catchments of the world and Kazakhstan

However, these structures need to be regularly monitored using efficient and cost-effective tools and approaches. Monitoring of the condition of hydraulic structures is carried out to ensure the management of the rational and safe maintenance of the structure. GIS-based approaches are among the most effective in the monitoring of hydraulic structures. GIS in civil engineering is widely used in transportation planning and management, and water resources planning and management, which mainly include watershed management (ANCOLD, 2012). Catchment delineation is among the important steps in watershed management that have a significant potential application in the monitoring of a hydraulic structure.

Catchment delineation helps to identify the surface water features within a catchment and understand the downstream impacts when planning and

implementing water quality and quantity-related protection and mitigation measures (Bowles et al., 2001).

In this study, a GIS-based approach is used for the catchment delineation as part of examining its potential for monitoring of hydraulic structures, for a case of Samarkand reservoir in the Karaganda region of the Republic of Kazakhstan. The catchment delineation process is achieved using ArcGIS software in conjunction with DEM.

## Materials and methods

### Case study description

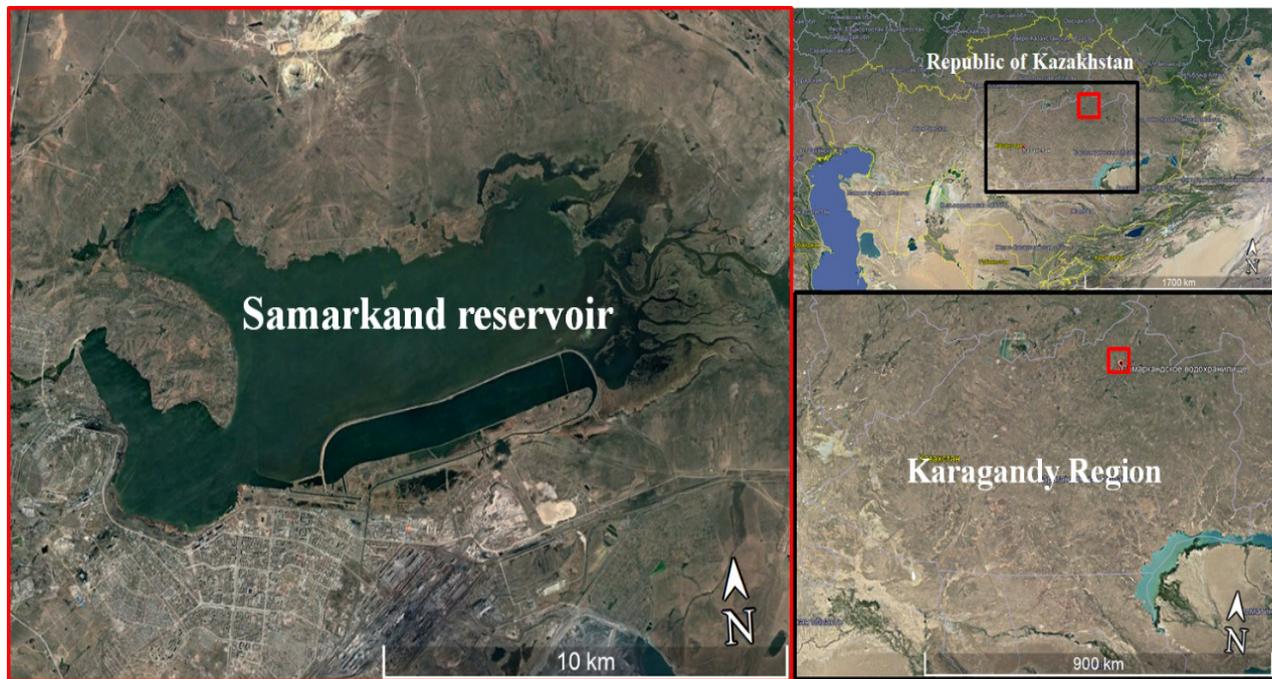
The selection of the case study is based on the fact that the catchment is one of the largest and old reservoirs of the Nura-Sarysu water basin, located on the Nura River in Temirtau City, Karaganda Region

of Kazakhstan (Fig. 2). The Samarkand reservoir is used by large enterprises such as Karmetkombinat, TEMK, power plants KarGRES-1, TETs-2, TETs-PVS, etc.

#### *Data collection*

In this study, DEM was the main input data and can be defined as a specialized database representing the relief of a surface between points that have known elevation. A rectangular DEM can also be created by interpolating known elevation data on the ground acquired from sources such as ground surveys and photogrammetric data capture. Their quality dictates the vertical and horizontal resolu-

tions. For defining catchment boundaries in GIS, the important thing is vertical resolution, that is, the difference of heights between modeled (or detected heights) and actual heights of the relief surface. Classically, a distinction is made between DEM resolutions of 10 m, 30 m, and 90 m, which are freely available. More accurate DEMs with a resolution of less than 1 m for research purposes can be obtained free of charge upon an official request from the authorized bodies if sufficient justification is provided, as their cost is quite high. DEMs can be in formats such as .tif, shp, etc. Several open access sources for retrieving DEMs were examined in this study (Table 1).



**Figure 2** – Location of the Samarkand Reservoir

**Table 1** – DEM data sources covered in this study

№	Name	Web site link
1	OpenTopography	<a href="https://portal.opentopography.org">https://portal.opentopography.org</a>
2	USGS	<a href="https://earthexplorer.usgs.gov">https://earthexplorer.usgs.gov</a>
3	ALOS	<a href="https://eorc.jaxa.jp">https://eorc.jaxa.jp</a>
4	Copernicus	<a href="https://scihub.copernicus.eu">https://scihub.copernicus.eu</a>
5	NASA	<a href="https://search.earthdata.nasa.gov">https://search.earthdata.nasa.gov</a>

Note that in the process of searching for DEM data, a number of difficulties were identified that can be encountered, for example:

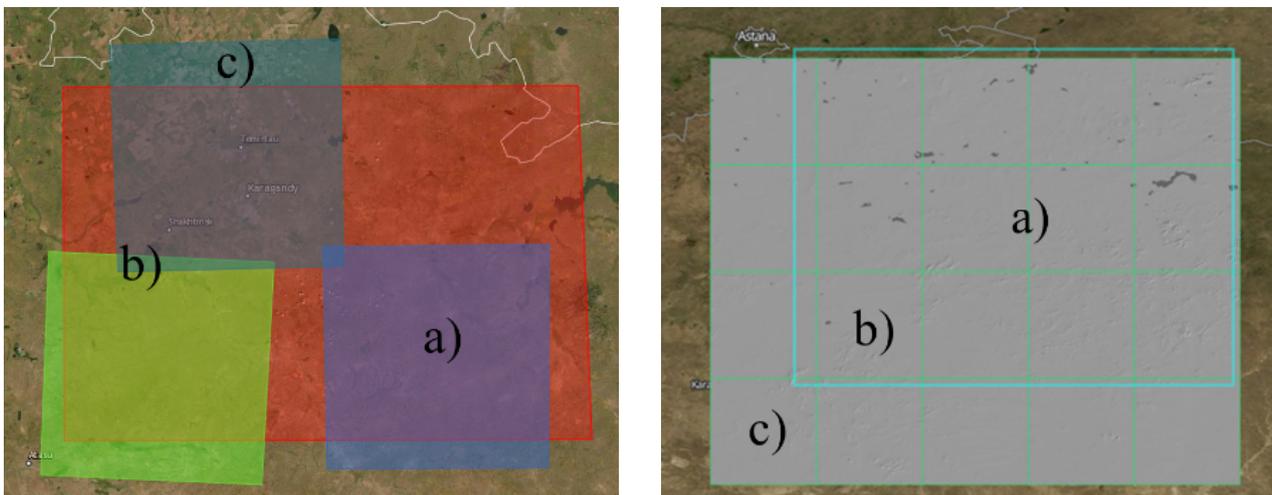
- (i) Searching for DEM with a resolution of 10 m and below;
- (ii) Absence of a single or a number of DEMs covering the entire study area (Fig. 3);
- (iii) Combining different DEMs with subsequent editing (Fig. 3).

*DEM preprocessing*

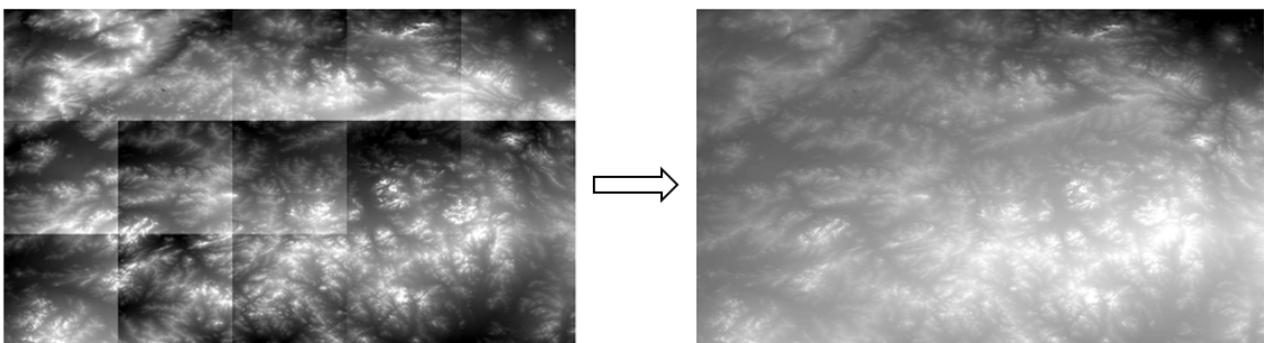
The catchment delineation process was carried out step by step with the help of the Spatial Analyst tools in ArcGIS software. Before filling sinks in the

DEM, the Mosaic To New Raster tool was used to combine multiple DEMs into one covering the entire case study. (Fig. 4).

At the next stage, the Fill Sinks tool was used. This stage of DEM processing made it possible to eliminate small defects on the surface of the raster, associated with the so-called “sinks”. The fill sinks tool in Spatial Analyst tools was used to fill sinks in the Digital Elevation Model. This was done to ensure that, if there are cells with higher elevation surrounding a cell with a lower elevation, hinders the water to flow and makes it trapped in the lower elevation cell, hence the water cannot flow out of the cell (Qin et al., 2017).



**Figure 3** – Examples of mismatches between the boundaries and sizes of the DEM and the study area:  
 a) study area; b) an intersection of the study area with the sub-area; c) area outside the study area



**Figure 4** – Combining DEM tiles into a single raster

The Flow Direction tool was used to determine sink flow directions. Flow direction tool was used to indicate the direction of the steepest descent to a neighbor cell and defined for each grid cell. Generally, this function computes the

flow direction for a given grid in which the values computed in the cells of the flow direction grid indicate the direction of the steepest descent from that cell (Fig. 5a). It is based on pixel depth in bits. In this case, ArcGIS automatically se-

lects one of three flow-directional determination algorithms:

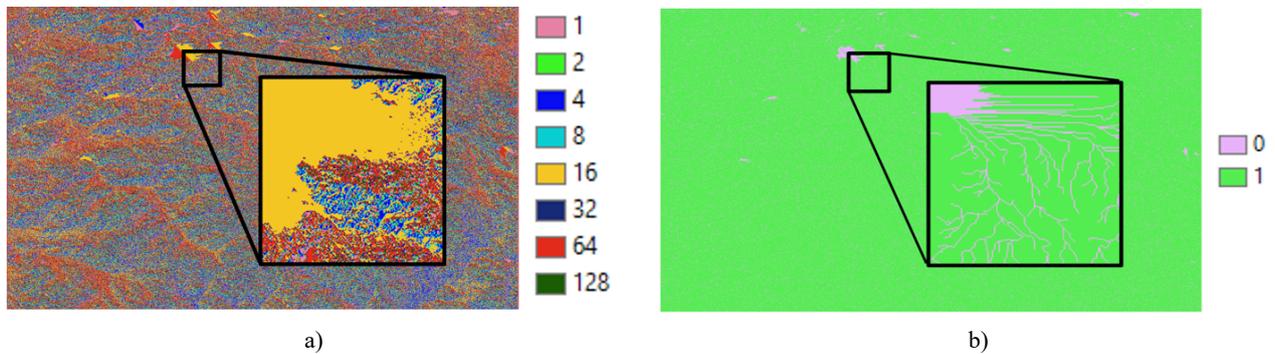
(i) D8 flow modeling algorithm, which constructs a flow direction from each pixel to its neighbor with the steepest slope neighbor.

(ii) Multiple Flow Direction (MFD) algorithm, which splits the flow from a cell to all downhill neighbors; here the flow splitting exponent is created using an adaptive approach based on local terrain conditions and is used to determine the fraction of flow that flows down to all downhill neighbors.

The D-Infinity flow algorithm (DINF), which defines the flow direction as the steepest downward slope. The flow direction is a floating-point raster represented as a single angle in degrees counter-clockwise from 0 to 360 (eastward only) (Tarboton, 2003).

To further simulate the flow of water volume along the slope (Fig. 5b), the Flow Accumulation tool was used, which applies an analogy to the same Flow Direction tool, but in this case, the pixel values are filled by identifying the flow volume and everything else, that is, the flow volume will have no pixel value (0), and the surrounding terrain takes a pixel value equal to 1.

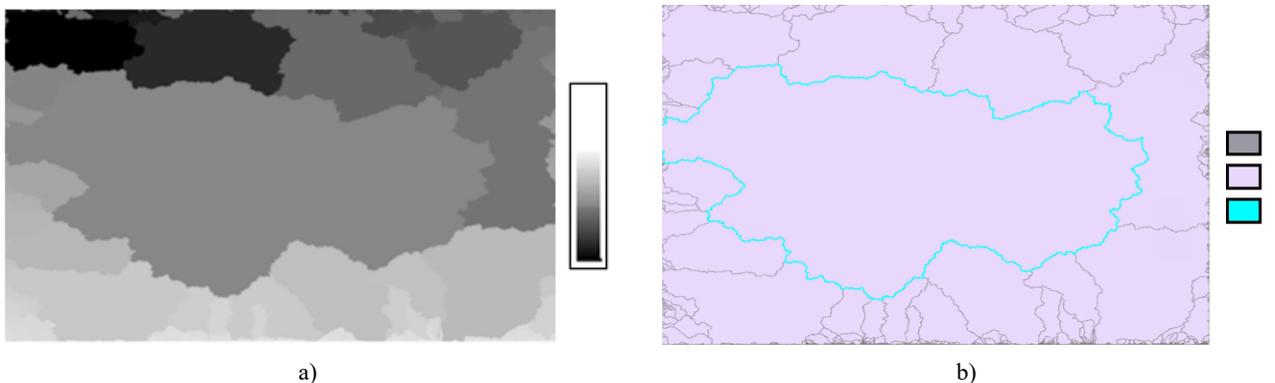
Flows over the entire drainage basin area are defined through the Basin tool. All drainage basins in the DEM are delineated by defining ridgelines between basins. The inlet flow direction raster is analyzed to find all sets of connected cells that belong to the same drainage basin. The creation of drainage basins begins with the identification of points of common outflow. The result is a grid of drainage basins in different shades of gray (Fig. 6a) (MaDGIC, 2014).



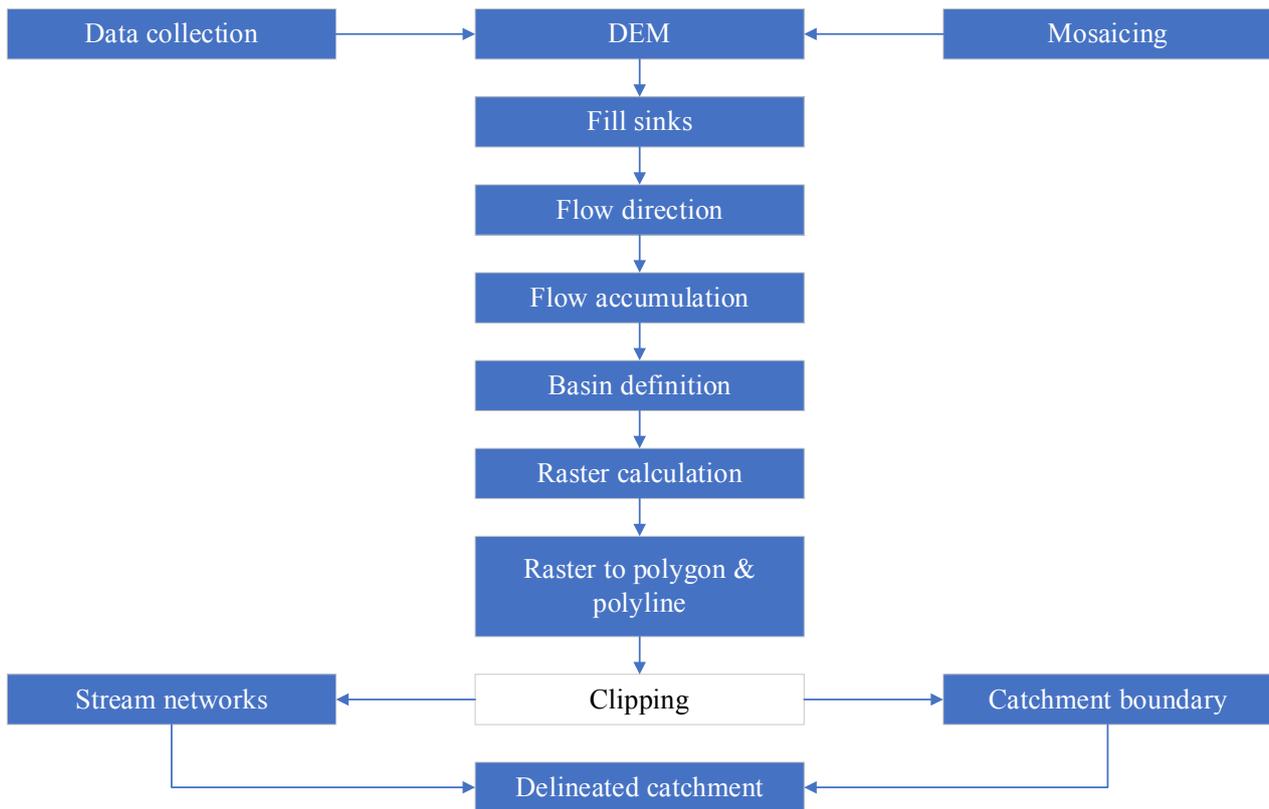
**Figure 5** – Flow direction maps: a) flow directions according to the pixel value; b) accumulation of pixels into one common stream

Drainage basins are formed, and then it is necessary to select the necessary contour is selected, which will be the boundaries of the study catchment for Samarkand Reservoir. For this purpose, the raster dataset is converted into polygons through the Raster to

Polygon tool. The logic of contour building is also based on the size of the same contained cell values, which form the drainage basin area and highlight it with a color different from other boundaries lying outside the investigated catchment area (Fig. 6b).



**Figure 6** – Drainage basin maps: a) raster format; b) vector format



**Figure 7** – Summary of the workflow

The final processing step is to cut out a fragment of one feature class using one or more objects of another class. In other words, the DEM was cut along the catchment boundary from the obtained polygon using the Clip tool.

Fig. 7 provides a summary of the main procedures during the catchment delineation process to the definition of stream networks and catchment boundary.

## Results and Discussion

The catchment was successfully delineated for different drainage threshold areas using gully grating points as outlets. In this study, it was observed that varied drainage threshold area parameters and resolutions of DEM play a significant role in determining catchment area and stream networks.

The selection of the threshold was observed to have a twofold impact on the watershed delineation process. The first issue is based on the speed of delineation. When a large threshold was selected, then a few initial subwatersheds were generated with a bit faster process and was efficient since the extracted grids were still large.

It was also observed that threshold selection plays an important role in the generation of adjoint catchments. When the threshold was more than 20,000, the delineation process produced empty adjoint catchments. Therefore, the threshold was reduced to 1000 the process was able to successfully generate the adjoint catchments. The threshold definition (stream definition) was performed after the flow direction and flow accumulation grids were determined.

The smaller threshold was observed to be resulting in a larger number of subwatersheds and stream networks. Moreover, the smaller threshold definition was observed to speed-up the delineation for a point (as the extracted flow direction grid is smaller) but increased the time to perform all the required preprocessing steps.

On the other hand, collecting suitable DEMs from open sources was observed to be a time-consuming process. Unfortunately, all organizations on the territory of the Republic of Kazakhstan provide these DEM images on a commercial basis, even taking into account the scientific goals pursued by students at universities. Probably this is a temporary trend since GIS development in Kazakhstan is rather new and not all regulations on data provision are still in place. So,

on the example of a large organization JSC NC “Kazakhstan Garysh Sapary”, we can conclude that research on “Optimization of the technical parameters and methodological approach to the use of remote sensing data by domestic satellites KazEOSat-1, 2” began only in 2018 (Бактыбеков, 2017; Duisenбай, 2018). Abroad, only high-precision images with a resolution of up to 10 meters are commercially available, while the rest is available to the public on a free-of-charge basis. They are stored on special servers of organizations studying space, which have their satellites or they supervise missions to collect data and send them to study the planet. Five large foreign servers with DEMs of different resolutions were reviewed. In one of them, in OpenTopography, DEMs with full coverage of the territory of Kazakhstan with a resolution of 10 m were found.

The selection of software for DEM processing is based on the high demand ranking, equal to 97% among the programs of this kind. ArcMap software allows to fully working with raster data and process DEMs. It should be noted that the second alternative

was to use second or third generation. The only distinguishing feature of which is considered is that the second version is free and open for private use and implementation of its tools.

The determination of the boundaries of the catchment boundaries consisted of several stages using different tools of the ArcMap software, with three basic algorithms of flow calculation techniques based on the data processed. As a result of the multistep processing of the DEM data, the boundary of the catchment (located in the Nura-Sarysu basin) was built, its area and boundary length were calculated, which were 22877 km<sup>2</sup> and 1118 km, respectively. This .shp file can be used to geographically overlay the contour on other types of spatial data, which allows highlighting or excluding information in or outside the catchment. The boundaries of the catchment were then validated using the Google Earth Pro engine, the results it was observed that the delineated catchment was sufficiently covering the study catchment from the .kml file generated using ArcGIS (Fig. 8).



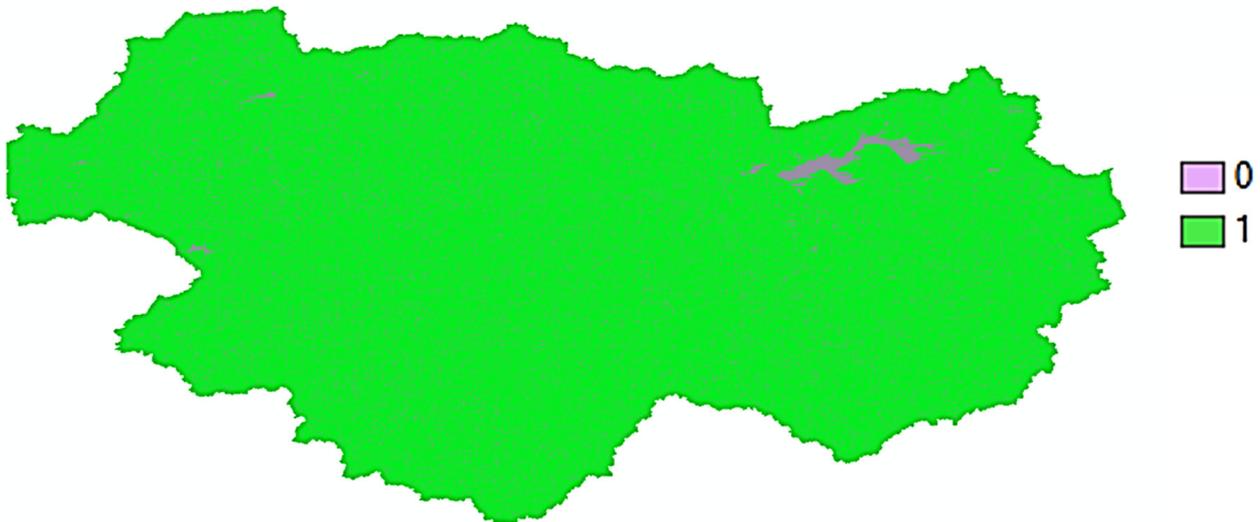
**Figure 8** – Catchment boundaries raptured on Google Earth (a) boundary only (b) boundary with fill (c) with nearby places

Thus, the results define the purpose and relevance of the study in connection with the increasing construction plans in Kazakhstan in the

next 10 years, as well as for the monitoring of existing hydrotechnical structures built more than 50 years ago.

Based on the catchment boundary obtained and the simulation using algorithms and pixel values, a simulation of water volume flows along the slopes was built (Fig. 9).

Further, a DEM of the catchment area with raster data was prepared, which can be used for a comprehensive study of the Nura-Sarysu water basin using other ArcGIS software tools.



**Figure 9** – Flow directions within the catchment area

The case study catchment delineation was accomplished, where the boundary of the entire catchment as well as its streams, were properly computed with a well-drained catchment with up to four stream orders. In general, the simulated fourth, third-order, and most of the second-order streams, matched perfectly with existing streams on the ground. However, most of the first-order streams could not be captured in the delineation, especially for the 30 m resolution DEM.

The approach investigated in this study is increasingly finding practical application in the modern principles of HS design. Domestic attempts to introduce GIS in the design and construction of HS were widely discussed at conferences, and a number of articles were devoted to this (Kabzhanova et al., 2020; Kabzhanova et al., 2019; Kabdulova et al., 2019). For example, the KazEOSat-1 first images of the Kazakhstan remote sensing satellite were used for flood forecasting in the Central Kazakhstan region. The object of the study was the problem of floods in the basin of the river Zhabai, which is a frequent phenomenon, and the obtained DEM in combination with data from the hydrometeorological service “Kazgidromet” allowed us to simulate and predict its frequency (Baktybekov, 2020). Another direction in the use of GIS is clearly shown in the example of the processing of forest resources of

the Republic of Kazakhstan. The model created by (Kabdulova et al., 2020) makes it possible to identify forest areas that have changed, in particular, due to logging and fires. In general, the use of GIS approaches can solve many global strategic tasks if there is the availability of high-resolution satellite images, as well as powerful technical equipment for fast data processing.

### Conclusion

The potential applicability of the GIS-based approach in the catchment delineation and monitoring of hydraulic structures for a case of Samarkand reservoir in the Karaganda region of the Republic of Kazakhstan was investigated. DEM was used as the main input data to the catchment delineation process in ArcGIS to demarcate the boundary of the catchment and define stream networks. From the delineation process, a well-drained catchment with up to four stream orders. In general, the simulated fourth, third-order, and most of the second-order streams, matched perfectly with existing streams on the ground. However, most of the first-order streams could not be captured in the delineation, especially for the 30m resolution DEM. Therefore, high-resolution DEMs are preferable for a more accurate definition of stream networks. The approach was

able to demarcate 228777 km<sup>2</sup> of the entire catchment area, which is equivalent to 1118 km of the perimeter. The results in this study revealed further that, using GIS-based tools for catchment delineation can be an effective approach for the monitoring process of HSs.

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