# Improvement of operational methods for the assessment of the water reservoir useful storage capacity using geoinformation systems. Case study of the Akdarya Reservoir, Samarqand Province, Uzbekistan.

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# THÈSE

PRÉSENTÉE A

## L'UNIVERSITÉ BORDEAUX 1

ÉCOLE DOCTORALE : Sciences et Environnements (ED 304)

Par Shavkat RAKHMATULLAEV

POUR OBTENIR LE GRADE DE

DOCTEUR
SPÉCIALITÉ : Géosciences, Hydrosciences

# IMPROVEMENT OF OPERATIONAL METHODS FOR THE ASSESSMENT OF THE WATER RESERVOIR USEFUL STORAGE CAPACITY USING GEOINFORMATION SYSTEMS

Case study of the Akdarya Reservoir, Samarqand Province, Uzbekistan

Directeurs de recherche : Philippe Le Coustumer & Masharif Bakiev
*Doctorat en cotutelle avec le « Tashkent Institute of Irrigation and Melioration »*

Soutenue à Tachkent le 10 décembre 2010.

Devant la commission d'examen formée de :

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*Université Bordeaux 1*
*Les Sciences et les Technologies au service de l'Homme et de l'environnement*

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# Abstract

Sedimentation processes in man-made water reservoirs reduce their main asset: the volume storage capacity. This raises engineering, environmental and economic issues for the communities around the world and in particular for the areas affected by strong water deficit. Because of Uzbekistan's arid climatic conditions and uneven spatial and temporal water resources distribution, responsive and innovative water availability assessment surveys of all major water reservoirs are required.

Bathymetric survey is a traditional method that is carried out for the estimation of reservoir volumes and surface areas for the corresponding reservoir stages in order to assess the water availability. Volume and surface area differences derived from multiple surveys of a reservoir provide storage loss estimates over time due to sedimentation. However, two main factors such as intensive field data measurement and post data-processing often limit the frequency of these surveys. Alternatively, innovative depth measurement technologies coupled with contouring and surface mapping programs provide automated reservoir volume and surface area calculations. This significantly reduces time, work load and financial burdens for reservoir sedimentation projects.

This study deals with the use of a geostatistical approach to assess the reservoir sedimentation in the Akdarya reservoir in Uzbekistan. Geostatistical approach includes (semi-) variogram analysis and interpolation (kriging and simulations (turning bands)) techniques predicting values at unsampled locations for generating digital bathymetric surface models of reservoir bottom conditions in order to calculate volume and surface area at given water elevation. Simulation enables to have range of reservoir volumes and surface areas with the same probability in comparison to the kriging and traditional methods. This gives a real estimation of the water resource availability for operators and managers to sustainably manage natural resources and hydraulic infrastructure.

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# I – ENGLISH EXTENDED ABSTRACT

The number of figures and tables refers to the Russian version with bilingual subtitles.

# *INTRODUCTION*

## Rationale, thesis structure and framework

### *Rationale*

Water reservoirs play an important role in areas with limited and erratic precipitation where water is stored and re-distributed later for different purposes. Irrigation is primarily a major water consumer in arid countries of Central Asia (namely Kyrgyzstan, Tajikistan, Kazakhstan, Uzbekistan and Turkmenistan) for the economic development, employment and food security of the region. The major rivers of Central Asia (*e.g.* Amu Darya, Syr Darya, and Zerafshan) are highly turbid watercourses.

Sedimentation reduces the main reservoir asset *i.e.* its volume capacity. In addition, vast territories of the region's countries have been transformed for agriculture to grow water intensive crops such as cotton, rice and wheat during the Soviet Union that dramatically accelerated soil erosion by water and wind. Thus many man-made water reservoirs are affected by high sedimentation rates.

Under the market-oriented conditions, financial constrains have resulted in the decrease of government assisted rehabilitation and maintenance works of hydraulic infrastructures programs by several folds despite any water reservoirs have been constructed more than 20-25 years ago and need substantial rehabilitation. For instance the majority of reservoirs have been silted by sediments. Recent drought years urged authorities to re-estimate the water availability in reservoirs of Uzbekistan for the sustainable use of the natural resources and hydraulic infrastructure.

Thus there is urgency to adopt an innovative approach in bathymetric surveys for the estimation of the reservoir volume loss of capacities due to sedimentation. New technologies such as GPS (Global Positioning System), acoustic depth measurement systems and contour mapping software have been proved to increase geo-referenced data, improve the accuracy of data and most importantly to substantially decrease the expenses of the bathymetric studies. In fact, since 2001 new geoinformation technologies have been used in bathymetric surveys in Uzbekistan. Last but not least there is limited information on water reservoirs in the Central Asian region in the international scientific literature.

### *Structure of the thesis*

The thesis consists of six chapters and introduction. The **introduction** part discusses the rationale of the study, research goal and objectives, innovations and the thesis structural organization framework. The **chapter 1** describes the sedimentation process in man-made reservoirs in Central Asia and particularly in Uzbekistan. Sedimentation in reservoirs has various technical, operational, environmental and economic impacts. The existing mitigation and prevention strategies against sedimentation are discussed.

The **chapter 2** outlines the results of the assessment on new technologies and current sedimentation calculation methods used for bathymetric surveying; in particular depth measurements procedures, geostatistical approach, variogram modeling and Kriging gridding techniques.

The **chapter 3** describes the study area and site characteristics. The **chapter 4** presents the materials and methods used in data collection, calculations and modeling. The **chapter 5** discusses the main results on historical data, variogram analysis, Kriging calculations and simulation results. In addition, economic efficiency results are discussed too. **Chapter 6** covers the discussion part of the study which is limitations of traditional depth measurement instrumentations and methods, possible error sources for Geostatistical technique. The perspectives and concrete recommendations for the implementation of Geostatistical method and other new geoinformation technologies are suggested for quick and accurate water resources availability assessments programs in Central Asia and in Uzbekistan.

*Thesis framework*

**The Purpose of the study** is the improvement of operational methods for the depth measurement, the application of Geostatistical analysis and the automated reservoir useful volume capacities evaluation using modern geoinformation systems.

**Research objectives**:

1. Analyze and review of modern technologies and methods used for carrying out bathymetric surveys of reservoirs,
2. Improve depth measurement technique with GPS (Global Positioning System) technology and Google Earth Internet system,
3. Recommend application of correction parameters for depth measurement developed by the International Hydrographic Organization in order to improve the actual depth measurement records,
4. Develop a Geostatistical method for the estimation of the reservoir useful volume capacities using SURFER software through variogram analysis and gridding bottom conditions as scientific based approach,
5. Create a bathymetric model on reservoir bottom conditions (Akdarya reservoir),
6. Forecast the losses of reservoir volumes based on historical records.

**Research object and subject**:

The research object is the run-of-the-river Akdarya reservoir that is located in the Samarkand province of Uzbekistan. The research subject is sedimentation in reservoir and bathymetric surveying using geoinformation systems in order to calculate the useful reservoir volume capacities.

**Research hypothesis**:

The developed recommendations will improve the quality of data, the automated calculations of reservoir volume capacities and thus will decrease the financial burdens for bathymetric surveys and operationally estimate the water availability of reservoirs for a sustainable management of natural resources and engineering infrastructures in Uzbekistan.

**Defendable positions**:

The main positions within the thesis are as following:

1. Developed and approbated Geostatistical method widely used in geodesy and earth sciences is used for hydrotechnical construction for calculation of reservoir useful volume capacities,
2. Systematic approach in the application of the geoinformation systems (GPS, CEEDUCER, SURFER, Google Earth) in Uzbekistan,
3. The creation of a local datum system for the Akdarya reservoir using GPS system in bathymetric surveying,
4. Formulae for the estimation of the error range for depth measurements according to the standards of IHO and development of several volume curves,
5. Results of variogram analysis and Kriging for the selection of science based parameters on grid size,
6. Developed 2-D bathymetric model of the Akdarya reservoir bottom conditions,
7. Forecasted results of dead and useful reservoir volume capacities and dynamics of the volume curve changes per elevations.

**Innovativeness**:

1. For Uzbekistan and hydraulic construction disciple the Geostatistical approach was elaborated and tested,
2. The systematic approach was shown to use modern geoinformation technologies (GPS, CEEDUCER, SURFER and Google Earth) in Uzbekistan,
3. For first time the depth accuracy coefficients have been used for the calculation of depth measurements in Uzbekistan and the construction of range of volume curves against single in previous methods,
4. Experimentally through variogram analysis the grid size was determined for the bathymetric model of the Akdarya reservoir,
5. The 2-D digital bathymetric model of Akdarya bottom conditions was developed,
6. The simple forecast method was developed for studying reservoir useful volume capacities.

**Scientific and practical significance**:

The main significance of the research results is the decrease of financial burdens for bathymetric surveys and the improvement in the calculations of reservoir sedimentation. The automated reservoir volume calculations will enable to operationally estimate the water resources availability and thus to sustainably manage scarce water resources and hydraulic infrastructures.

In addition the developed Geostatistical approach can be used for the calculation of sedimentation of lakes, irrigation canals and sediment detention ponds. The practical aspects are a substantial reduction of costs by 50 % for field measurements and – 80% for office calculations. The simple prediction method enables to visually show the volume curves and make decisions to increase the elevations of water intake structures.

**Material outcomes**:

The most significant outcome of the research is the publication of a methodological handbook on Geostatistical approach in calculation of useful reservoir volumes which is approved by the Ministry of Agriculture and Water Resources of the Republic of Uzbekistan and widely used by the Bathometric Center.

The economic efficiency of automated reservoir volume calculations is related to the reduction of financial costs by 180 US $ per $km^2$.

**Research approbation**:

The research results were presented at several national, regional and international conferences; one regional workshop conducted by the United Nations Economic Commission for Europe in partnership with the Uzbekistan water management organization; in frameworks of two fellowships 1) European Unions INTAS fellowship program for young scientists from former soviet union No.04-83-3665 (2005-2007) and 2) French Government Fellowship for outstanding PhD students Eiffel program No. 530909C (2007-2008). The scientific seminars at University of Bordeaux1, Center for Geosciences Development and Application (2007), at Tashkent Institute of Irrigation and Melioration, Department of Hydraulic Structures (2009), at specialized scientific seminar under the Permanent PhD Committee (2010).

**Publications**:

The total number of publications is 13 including 7 as conference contributions, one handbook, 3 journal articles in referenced journals by Supreme Attestation Committee of the Republic of Uzbekistan and 5 articles in international journals.

# *CHAPTER 1: STATE-OF-THE-ART ON SEDIMENTATION*

## 1.1 Sedimentation in water reservoirs

Water reservoirs created by dam construction on rivers have played an important role for societies around the globe throughout their history by regulating floods, generating hydropower, and re-distributing the river flow for irrigation.

Dams on rivers induce both river flow and sediment flux fragmentation which causes accelerated accumulation of sediments (Morris and Fan, 1998; Palmieri et al., 2001; Syvitski, 2003; Sternberg, 2006; Walling, 2006). Sedimentation is a natural geomorphologic process but human interference increases its rates. Sedimentation reduces the main reservoir asset *i.e.* its volume capacity over time due to the feeding rivers.

Hence, the utility of a reservoir diminishes as its volume capacity is reduced (Karaushev, 1977; Skrylnikov et al., 1987; Mahmood, 1987; Annandale, 1998; World Commission on Dams (WCD), 2000; International Commission on Large Dams (ICOLD), 2008; World Association for Sedimentation and Erosion Research (WASER), 2008). The Figure 1.1 depicts the general stages sedimentation process in man-made reservoir.

It is reported that an annual average 0.5-1% loss of volume capacities of small and large reservoirs is observed due to sedimentation in the world. It is estimated that such losses of storage capacities per year are worth billion US$ and if such a scenario continues, about 25% of the world reservoir total volume capacity will be vanished over the next 25-50 years (Mahmood, 1987; WCD, 2000).

Palmieri et al. (2003) reports that the loss in volume capacity requires an annual replacement cost of 13 billion US$. Recent estimates are even more dramatic. For instance Yang (2003) reports that the overall annual loss rate of reservoir volume capacity due to sedimentation is estimated to be 1 to 2 % of the total volume capacity. Moreover, Naisen and Lingyan (1998) reports that the average annual loss in volume capacity reaches 2.3 % in China, being the highest in the world.

Globally, more than 50% of the basin-scale sediment fluxes in regulated basins are potentially trapped in artificial impoundments, with a discharge-weighted sediment trapping of about 30% due to large reservoirs and an additional contribution of about 23% from small reservoirs (Vörösmarty et al., 2003).

## 1.2. Irrigation and water reservoirs in Central Asia

Due to their climatic characteristics, economic development strategies and geopolitical situation, Central Asian (CA) countries have been experiencing an everlasting competition over water resources. Mostly arid, these agrarian countries pursue their own development and integration into the global community through expanding irrigated lands, growing cash crops such as rice and wheat for meeting their domestic food security but also to export a large part of some productions such as cotton (Rakhmatullaev et al., 2009).

Irrigated agriculture is the dominant sector of the economy in the Central Asian (CA) countries, employing about 45% of the total population (World Bank, 2003; ICWC, 2004; IAMO, 2008; Abdullaev et al., 2009). This sector contributes to the region countries Gross Domestic Product (GDP) from 16 up to 30% with an average of 24% for the whole region (FAO, 2007). As a whole, 26% of the cultivated areas are irrigated, from 10% in Kazakhstan to over 99% in Turkmenistan.

Thus 91% of the total water withdrawal is used for agricultural purposes in the region (Ximing et al., 2003; UNEP, 2005; Weinthal, 2006). Over a period of 90 years (1913-2003) the areas under irrigation have increased by 3 times on average (Sattarov et al., 2006). This increase was due to the gigantic Soviet hydraulic program through construction of dams, irrigation canals, pumping stations and various hydraulic facilities.

Irrigation in CA region relies on a system of pumps and canals which is among the most complex in the world (O'Hara, 2000; Weinthal, 2006; UNDP, 2007). Cotton and wheat are the major crops followed by maize, vegetables and fruits. In Uzbekistan, which accounts for over half of the irrigated land in the CA region, it is estimated that about 70% of water is lost between the river and the crop, and poor drainage further exacerbates water management (World Bank, 2005).

Uneven spatial and temporal water resources and a Soviet inherited unified hydraulic infrastructure have raised transboundary reservoir management issues over water resources allocation among the countries in the region such as Kyrgyzstan, Tajikistan, Kazakhstan, Uzbekistan and Turkmenistan. The rivers such as Syr Darya and Amu Darya are already regulated by more than 78% and 94% respectively and attempts for new reservoir projects upstream raises increased concerns of the downstream countries (*e.g.* the Rogun hydropower station in Tajikistan and the Toktogul reservoir in Kyrgyzstan). For instance the uncoordinated use of reservoirs has caused the Arnasai lake problem in Uzbekistan with environmental, material damage and social unrest.

With an annual rainfall of 100–300 mm and a mean evaporation of 1600-2200 mm, Uzbekistan has a continental climate of the dry mid-latitude desert, characterized by hot summers and cold winters (Shultz, 1949; UNEP, 2005; FAO, 2007). Its climate is largely arid and its water resources are unevenly distributed both in space and time. There is a strong dependency on winter and spring rains and snowmelt from the Tien Shen and Pamir mountains. In fact these mountains are major contributors to the watersheds of CA countries (World Bank, 2005).

Thus the agricultural production of the region is predominantly based on irrigation, which makes irrigation water supply and management the major factors limiting crop yields in the region (Ibragimov et al., 2007). The complexity of water resource relations in this region is related to the soviet inheritance of interconnected hydraulic infrastructure and to the transboundary origin of water resources.

The Interstate Commission on Water Coordination (2004) reports that in Central Asia, for the period of 1960-1990, the total annual water intake was about 60.6 $km^3$ in 1960 and 116.2$km^3$ in 1990. Thus there was about a two fold increase in 30 years. In contrast the population of the region has increased by 2.7 folds and the area under irrigation increased by 1.7 fold.

The first water reservoirs of the Central Asian region have been constructed as early as in the X-XI centuries (Avakyan et al., 1987; Nikitin, 1991). The era of massive water reservoir construction begun in the late 1900s. For example, the Gindikush (Turkmenistan) reservoir was built in the Basin of the Murgab River in 1896 with a total volume capacity of 13 $Mm^3$ and 65 $Mm^3$ for the Sultanbent reservoirs in 1909-1910 (Irrigation of Uzbekistan, 1975; Skrylnikov et al., 1987). In 1940s several reservoirs have been constructed such as the Urtatokai reservoir in the Kassansai River Basin in Ferghana region and the Kattakurgan reservoir in the Zerafshan River Basin. For the last 30 years (from 1950 to 1980) more than 60 reservoirs have been constructed in the region.

There are more than 290 water reservoirs in the Central Asia with a total volume capacity over 163 $km^3$ that regulate more than 50% of the monthly regions river flow and the area occupied by reservoirs constitutes roughly 6% of the CA countries irrigated areas (Avakyan et al., 1987; Skrylnikov et al., 1987; Nikitin, 1991; FAO, 2007). The primary source for irrigation in the region is the surface flow from rivers and man-made reservoirs. For example, an average of about 30% of irrigation water is delivered from reservoirs, ranging as high as 54% in Turkmenistan and as low as 13% in Kyrgyzstan (UNEP, 2005; FAO, 2007).

## 1.3. Water reservoirs in Uzbekistan

Agriculture is a very important sector of the economy for employment, foreign cash revenues and food security in Uzbekistan. Climatic conditions and insufficient internal water resources have put pressure for water reservoirs. Uzbekistan is largely an arid region, where evaporation exceeds rainfall and annual precipitation is below 200mm (UNDP 2007). The streamflow is characterized by extreme intra-annual variability and also unevenly spatially distributed (Kazbekov et al. 2007).

Two main river basins are found in Uzbekistan – Amu Darya and Syr Darya. The transboundary rivers Amu Darya and Syr Darya satisfy 82% of the total water demand, whereas only 18% of the same demand is satisfied by internal Kashka Darya, Zarafshan and Surkhan Darya rivers in Uzbekistan (UNDP 2007). At present approximately 84% of water resources in Uzbekistan are used for irrigated agriculture (UNDP 2007).

The peak of dam construction is dated to the soviet period when its policy was aiming at expanding irrigated lands for the mass production of cotton. These impressive actions have resulted in a great increase in irrigated lands from 2.57 million ha in 1960 to 4.22 million ha by the late 1980's (UNDP, 2007). The dam construction is graphically illustrated in Figure 1.2. About 75% of dams were constructed in the 30-years period from 1961 to 1990 with 93% of a total reservoir capacity known as the "soviet period" (Rakhmatullaev and Le Coustumer, 2006; Rakhmatullaev et al., 2008b).

After the 1990's just a few dams have been constructed mainly to finish the already initiated projects. At present time two dams are being constructed in Uzbekistan for securing the water availability for the vegetation period. For example, for the mitigation of drought in the 2000-2001 years, the government of Uzbekistan in the Namangan province initiated the construction of the Rezaksai reservoir with a total capacity of 0.2 $km^3$ in the perspective of increasing the water availability up to 0.66 $km^3$.

About 24% of irrigation water comes from water reservoirs (Figure 1.3) (FAO 2007). The total number of man-made water reservoirs in Uzbekistan is 55 with the total gross volume capacity of about 19$km^3$, and useful volume capacity – 14.5$km^3$ (Table 1.1) (UNDP 2007 ; Rakhmatullaev 2006). The total surface area of reservoirs is estimated about 1450 $km^2$. The average dam height is about 39 m with a maximum of 168 m (Tupalang reservoir) and a minimum of 11.5 m (Uchkyzyl reservoir).

About 57% of all reservoirs have a volume capacity about 1 to 50 $Mm^3$ but only five have a volume capacity of more than 1 $km^3$. Moreover for the surface area, only eight reservoirs have a surface area greater than 50 $km^2$. Nine major reservoirs constitute about 86% (16.8 $km^3$) of the total reservoir volume capacity and about 94% (1362 $km^2$) of the total surface area in Uzbekistan.

There are almost no sites for construction of new reservoirs. Thus it is of strategic importance to rationally estimate the available water resources in existing reservoirs for assuring a guaranteed water supply to the different water users.

According to the Uzbekistan Ministry of Agriculture and Water Resources (UzMAWR), out of the 27 inspected reservoirs, 11 are almost completely silted up, and at 5 other reservoirs the silt has almost reached the level of the outlet structures (Table 1.2) (UNDP 2007).

Almost 90% of all dams are used for irrigation purposes and only two for hydropower (Andijan and Charvak). The Amu Darya river is regulated by 78% whereas only by 94% for the Syr Darya river (UNEP, 2005; Rakhmatullaev et al., 2008a; UNDP, 2007). For example, all main run-on-the-river reservoirs for the regulation of the Amu Darya and Syr Darya river flows are located beyond the boundaries of Uzbekistan, with the exception of the Andijan, Tuyamuin, and Janubiy Surkhan reservoirs.

Therefore Uzbekistan is vulnerable in terms of transboundary reservoir management for a sustainable water allocation. There are almost no sites left for the construction of new reservoirs. Thus it is a strategic importance to rationally calculate the available water resources in the existing reservoirs for assuring a guaranteed water supply for the agriculture, industry and municipalities.

## 1.4. Impacts coming from reservoir sedimentation

A reduced reservoir volume capacity diminishes the flow regulation for an assured water supply for irrigation, industrial activities and municipalities downstream. Sedimentation triggers operation and maintenance issues coupled with economic feasibility of the project, environmental concerns and social aspects (Lapshenkov, 1959; Bruk, 1985; Evrard, 1985; Morris and Fan, 1998; McPherson and Harmon, 1998; United States Army Corps of Engineers (USACE), 2001; Vörösmarty et al., 2003; International Hydrographic Organization (IHO), 2005). Figure 1.4 depicts the notions of useful and dead reservoir volume capacities.

Moreover the deterioration of water quality in reservoirs can be a major issue with increasing levels of various contaminants from agriculture, industry, and natural sources whether organic (pesticides, PCBs, PAHs) or inorganic (heavy metals) (WCD, 2000; ICOLD, 2008; Gadalia et al., 2005, Gadalia and Motelica, 2008).

Downstream effects of sedimentation include channel narrowing, reduction in braiding and associated loss of ecosystem complexity, river bed erosion and a reduction in the overbank flooding that is critical to many riparian species (Brandt, 2000; Wohl and Rathburn, 2003; Syvitski, 2003; Sternberg, 2006; Walling, 2006). Dam cavitation and abrasion of conduits, valves, sluice gates and hydropower turbines dramatically impact the hydraulic facilities and structures (USACE, 2001; IHO, 2005). Moreover social aspects can also be the unattractiveness for tourism and the loss of recreation opportunities (WCD, 2000; Knoblauch, 2006).

## 1.5. Prevention and mitigation strategies against sedimentation

There are various sedimentation mitigation measures and we have grouped them into four main categories (Figure 1.5).

1. The first group is composed of measures that are targeted to decrease the sediment influx from watershed areas to the reservoir. These are erosion preventive measures that are implemented in watershed areas such as implementation of various sediment detention engineering ponds, vegetation strips, or tillage-zero agronomic measures for decreasing the susceptibility of soils for erosion;
2. The second category represents the use of river’s own hydraulic energy to flush the sediments from the reservoir. For example, maneuvering of gates for discharging sediment through outflows with river regime. The correct organization of outflow holes in dam and discharge of most turbid waters in peak flood period with combination of periodic flushing;
3. The third category represents route sediments, reduce reservoir trap efficiency using sediment routing techniques such as drawdown during sediment-carrying floods, sediment bypass around the storage pool through special engineering tunnel, venting of turbid density currents.
4. The fourth group is mechanical dredging of accumulated sediments by tractors and other special machinery.

The analysis of former research has shown that there are no single mitigation measures that can effectively combat with sedimentation. All of these abovementioned measures exist in practice but none of measures could effectively produce good results.

For example, in small hydraulic head barrages the hydraulic flushing is not efficient due to water availability and sometimes mechanical dredging is not effective too due to its costs and access to reservoirs in harsh environmental conditions.

# *CHAPTER 2: ASSESSMENT OF MODERN GEOINFORMATION TECHNOLOGIES IN SEDIMENTATION*

There are various methods and technologies for conducting bathymetric surveying in hydrographic research. For example, for the last two decades single acoustic beam echo-sounder coupled with GPS system, airborne LIDAR system, multibeam solar systems are being extensively used in bathymetric surveying. These technologies reduce the use of traditional geodesic instrumentation and land surveying expenses; as a result high digital geo-referenced data is acquired. These technologies and methods are used for field sample collections.

The important chain in research cycle is data management and treatment for excluding biases and potential errors in order to get more precise and accurate estimations. There are many software products for interpolation and construction of bathymetric digital surfaces that in turn improves estimation and prediction of sedimentation volumes and creates digital bathymetric maps for future research efforts.

This chapter deals with new methods for interpolation (Geostatistics and variogram analysis) and technologies (SURFER, GPS and CEEDUCER) for the estimation of the useful reservoir storage capacity due to sedimentation. In addition to, the standards of the International Hydrographic Organization are being discussed for conducting hydrographic surveys in particular the correction depth coefficient for error limitations in depth measurement.

## 2.1. Critical review of current estimation methods on sedimentation

In the area of fluvial morphology, erosion and sedimentation research, significant development was carried out in the Former Soviet Union (FSU) that greatly contributed to this domain of knowledge. It should be worth to discuss in brief the contributions of Russian speaking scholars in the domain of water reservoir sedimentation.

Sedimentation of engineering hydraulic structures, reservoirs, irrigation channels and their mitigation measures have been studied extensively by the Soviet and scientists of Uzbekistan.

The main reasons affecting the non use of the current methods for accurate estimation of sedimentation are as follows:

1. Complexity of calculations and extensive requirement information,
2. Significant differences between field measurements and numerical calculations on sedimentation amounts and their spatial distribution,
3. The existing calculation methods were developed for specific water elevation conditions at reservoir,
4. Only small sediment size fractions were considered for calculations without reservoir bank deformations.

## 2.2. Bathymetric surveying

### 2.2.1. Marine hydrographic depth measurement systems

Acoustic depth measurement systems measure the elapsed time that an acoustic pulse takes to travel from a generating transducer to the waterway bottom and back (Figure 2.1). The travel time of the acoustic pulse depends on the velocity of propagation (v) in the water column. If the velocity of sound propagation in the water column is known, along with the distance between the transducer and the reference water surface, the corrected depth (d) can be computed by the measured travel time of the pulse.

Determining the sound velocity, v, is perhaps the most critical factor in using acoustic depth sounders. The sound velocity varies with the density and elastic properties of the water. A transducer converts electronic energy to acoustical pulses and vice versa. The type of transducer used is a major determining factor in the adequacy of a depth measurement.

### 2.1.2. Airborne hydrographic depth measurement systems (LIDAR)

The Scanning Hydrographic Operational Airborne LIDAR Survey (SHOALS) system was developed by USACE and has demonstrated the ability to achieve orders of magnitude increase in survey speed while collecting densely spaced high resolution data. The term LIDAR stands for LIght Detection And Ranging. The US Army Corps of Engineers accepted the SHOALS system in March 1994 following field testing which indicated that the system met or exceeded all design specifications.

A SHOAL consists of an airborne data collection system and a ground-based data processing system. The system operates by emitting laser pulses 400 times per second while being scanned in a 180 deg arc pattern across the flight path of the airborne platform (Figure 2.2)., which can be a helicopter or fixed wing aircraft. Each laser pulse travels from the airborne transmitter to the water where some light energy is reflected and detected by onboard optical sensors. The remaining light passes through the water column, reflects from the sea bottom, and returns to the optical sensors. The time difference between the water-surface and sea-bottom returns indicates the water depth.

SHOALS produces high density measurements that can be used for creating three dimensional digital elevation models from which navigation and bathymetric surveying projects can be monitored and managed. Data acquired by SHOALS is being used to generate channel condition reports, beach profiles, cross sections, and contours, perform volumetric analysis, and create complete 3-D digital elevation models of areas.

This technology is capable of rapidly collecting dense survey data over large areas. However, the main constraint of any LIDAR bathometer is water clarity. In clear waters SHOALS is effective to about 60m depths.

## 2.3. Global Positioning System (GPS)

The initial purpose of Global Positioning System (GPS) was military use for defense of United States of America. GPS is used for transmission of navigational signals all over the world. GPS provides continuous (24 hours/day), real-time, 3-dimensional positioning, navigation and timing worldwide.

Basically, GPS consists of three main separate interrelated elements: land segment (land control stations), space segment (satellites) and users' segment (GPS receivers). All of these three segments is unified by transmission and receiving radio signals (Figure 2.3.).

A GPS receiver calculates its position by a technique called satellite ranging, which involves measuring the distance between the GPS receiver and the GPS satellites it is tracking. The position of each satellite is *known*, and the satellites transmit their positions as part of the "messages" they send via radio waves. The GPS receiver on the ground is the *unknown* point, and must compute its position based on the information it receives from the satellites (Table 2.1).

## 2.4. International Hydrographic Organization depth measurement standards

There are various error sources in data acquisition and measurement in hydrographic survey, thus the International Hydrographic Organization recently developed new standards for hydrographic survey.

An error is the difference between a measured value and the correct or true value and can be categorized as a blunder, systematic error or random error. Blunders are generally large errors caused by inattentiveness or lack of skill on the part of the observer. Systematic errors are those that follow some physical law or rule by which they can be predicted. Random errors are generally small errors resulting from the limitations of measuring devices and processes, are equally likely to be negative or positive, and are governed by the laws of probability.

Blunders must be eliminated by the establishment of adequate "checking" procedures and are assumed not to be present in quality hydrographic survey data sets. Systematic errors are measured or modeled using calibration techniques and must be removed from survey data prior to evaluating them against the IHO Standards. Random errors result from the inability to perfectly measure any quantity or to perfectly model any systematic error.

## 2.5. Geostatistics

Geostatistics whose fundamental basis was defined by Matheron (1963) involves the analysis and prediction of spatial or temporal phenomena. Geostatistics is just a name associated with a class of techniques used to analyze and predict values of a variable distributed in space or time (Clark 2001). With recent progresses in automatic calculations, the use of geostatistics for the spatial analysis of environmental data has become extremely common both on land and sea (Mear et al. 2006). Geostatistics include tools that establish surface maps of any interested variable from the analysis of the spatial structure of data (semivariogram) and to predict the value (interpolation) of these parameters at unsampled points (kriging or simulation) (Figure 2.4) (Goovaerts 1999).

## 2.6. SURFER program

The main purpose of the SURFER7 is analysis and visualization of 2-D and 3-D data, describing the function of type $z=f(x,y)$, and the logical operation of package can be represented in three main functional blocks :

a) contouring and surface mapping;

b) gridding methods and supplementary operation with generated surfaces;

c) surface visualization.

# *CHAPTER 3: STUDY AREA AND SITE CHARACTERISTICS*

## 3.1. General setting

The Akdarya reservoir was created by the construction of an earthen dam on the Akdarya River in 1982. This reservoir is used as a seasonal flood regulating structure for irrigation of some 5,500ha of new agricultural lands and improving the melioration conditions of more than 12,000ha of the irrigated lands in two districts of the Samarkand province of Uzbekistan. It is located 15km northwest from the Ishtihan city of Samarkand province in Uzbekistan (Figure 3.1).

## 3.2. Relief and geomorphology

The modern Akdarya River Valley in terms of geomorphology and lithology is composed of pro-alluvium depositions. The valley is layered by loess loams with 5-40m thickness and underlying a layer of pebble with a thickness of about 300m. The modern floodplain part of Akdarya River is composed of loams, stones and pebbles of alluvial origin. The thickness of stones varies from 0.5 to 5m (Rakhmatullaev, 2007). The river channel is well defined, composed of pebble-cobble deposits. The absolute elevation of the river varies from 680.0m to 400.0m.

The relief of the surrounding areas is presented from right bank side as hills with smooth peaks, smoothly changing into alluvial and pro-alluvial uplands and floodplain valleys on the left bank with floodplain and terrace valleys. The surface of the territory is presented by modern deposits of river channels and washing cones of debris of small streams (Uzdavsuvloixa, 2002).

## 3.3. Climate

The study area is located in subtropical latitudes and is characterized by a high solar radiation reaching annually 440 hours. The geographic location of the study area in the centre of the continent is characterized by the aridity of local climate and significant temperature fluctuations. The mountain systems of Nurata in north govern local climatic conditions: precipitation and wind regimes.

The annual long-term mean precipitation is about 282mm. More than 90% of annual precipitation is observed from November to May. Over the period of June-September, there is no precipitation observed. The mean perennial evaporation from the reservoir is about 1200mm inducing a deficit balance about 918mm annually (Rakhmatullaev and Le Coustumer 2006). The evaporation from water surface according to Kattakurgan reservoir is about 1200mm per year.

## 3.4. Hydrology

Akdarya River is a right tributary of the Zarafshan River. The Zarafshan River is divided into tributaries at Ak Karadarya Hydraulic Scheme, east to Samarkand city where Zarafshan is separated into two perennial tributaries northern (Akdarya) and southern (Karadarya). Two tributaries form an island with a total length of 100km and 15km in width under the name “Miankul”. The two tributaries again re-merge into one Zarafshan River in the Navoi province.

The Akdarya reservoir is located on the Akdarya River downstream 50km from Ak Karadarya Hydraulic Scheme. The total length of the Akdarya River is about 131km and flows over wide floodplain terraces with width of 0.2-0.6km, maximum widths – 1.5-2.0km. The river channel is moderately meandering and branching. River banks are instable and steep in some places. The Akdarya River flows through wide Zarafshan Valley, which is composed of loess deposits (Samarkandgiprovodhoz, 1976).

There are several sources of water resources feeding into the Akdarya reservoir (Table 3.1). The network of irrigation channels and collector-drainage discharge systems are source for water feeding into the Akdarya reservoir. The traditional engineering practices have evolved in such direction that only during highwater years, waters of Zarafshan River is released to the Akdarya River. The last significant release was observed in 1998. This release discharge is ca. 100m$^3$/sec.

At present, Akdarya tributary is used as emergency channel from catastrophic flooding events of Zarafshan River, whereas the main flow passes through Karadarya tributary. In addition, the springs and temporarily streams are the third major source of water feeding the Akdarya River and the reservoir. The temporary streams can be observed during heavy rainstorms coming from the springs. The effective watershed area of Akdarya reservoir is about 2020km$^2$ of which active flow forming area – 1500km$^2$ (Uzdavsuvloixa 2002). The Table 3.2 depicts sediment and water discharges of Akdarya reservoir.

## 3.5. Akdarya technical characteristics

Akdarya reservoir was constructed by step-by-step approach (Table 3.3). The surface area of the reservoir at Full Pool Elevation (FPE) is about 12.7 km$^2$, the total storage volume is 112.5 million m$^3$. The main Akdarya reservoir characteristics are presented in Table 3.4. In order to increase the irrigated lands, authorities have increased reservoir volume capacity from 34 to 112.5 million m$^3$ by increasing the elevation of the dam crest by 7m since 1982.

# CHAPTER 4: MATERIALS AND METHODS

## 4.1. Traditional bathymetric survey

Traditional methods of analysis have relied on the topographic mapping and range survey data to estimate sediment volumes for a reservoir. The site of a reservoir prior to the inundation, referred to the original conditions, is marked on the topographic map, and a planimeter is used to roll areas encompassed by individual contours. These areas are then used to estimate the incremental volumes for the reservoir below the pool elevations, yielding the original reservoir volume capacity. The rate and the distribution of sediment are then computed by comparing reservoir bottom profiles along a set of ranges established for a reservoir.

Typically, the sediment range network is established and marked with monuments prior to a dam construction. Pre-inundation profiles are surveyed and used to develop elevation-volume capacity relationship based on the profile widths at prescribed elevation intervals. By resurveying the reservoir bottom along the ranges and comparing the profile widths, sediment volume and distribution are determined from the elevation-volume capacity relationships.

The range survey/end area method has provided adequate results in the past sedimentation analysis. However, the ranges can be difficult to locate and survey as monuments are destroyed or worn away. This leads to the surveying the fewer ranges to characterize sedimentation. Two factors, such as labour intensive field data measurement (depth soundings) and post data-processing often limit the frequency with which surveys may be conducted (Furnans and Austin 2008).

With traditional methods of depth measurements and few sampled points large errors and uncertainties are observed that increases errors in computation of water availability in water reservoirs. The potential sources of error are human induced during the data measurement in operation of boat and readings of transducer (e.g. penetration of signal through the water column and poor acoustic reflection of signal back from true reservoir bottom surface).

## 4.2. Depth measurement by CEEDUCER and GPS

In 2001 the “Bathymetric” Centre was established under the umbrella of UzMAWR which is authorized for bathymetric survey using new bathymetric survey system (CEEDUCER®) developed by the Bruttour International Pty Ltd. The system is composed of incorporated GPS (Global Positioning System) antenna and digital depth measuring transducer (Figure 4.1).

The bathymetric survey of Akdarya reservoir was conducted in 2003 from a moving boat using electronic depth-sounding equipment (transducer) in conjunction with GPS antenna and an automatic data recorder CEEDUCER® and all data was transferred into the laptop computer (Figure 4.2) (Joseph et al., 1998; Oett et al., 2000; Soler-Lopez 2003, 2004). The CEEDUCER® system is a very small, single unit (integrated GPS receiver, electronics processor and data logger), versatile survey measuring instrument that provides: GPS position DGPS (differential GPS), survey accuracy digital echo sounder, and 7.2 hour full data logging (dual frequency echo sounding). The specification of the GPS receiver are: survey type 8 or 12 channel (true parallel channels) accuracy 2-3m (8 channel), <1m (12 channel) DGPS combined Marine Beacon / Integrated GPS antenna 1 second update (optional).

The GPS receivers monitor the horizontal position of the survey boat while the depth sounder measures water depths (Figure 4.3). The GPS units were first used and by default were automatically converted into WGS84 projection system in (World Geodetic System of 1984) the static mode to establish a benchmark overlooking the reservoir. Satellite data were recorded simultaneously at the known government topographic benchmark (referred to as "Akdarya dam") (latitude 27°45'N., longitude 44°33'W.) and at a site overlooking the reservoir. Once established, the "Akdarya dam" benchmark was established as the reference station.

One GPS unit was installed at the reference station; the other GPS unit was installed in the survey boat to be used as the mobile station. The GPS on board independently calculated a position every second while receiving a set of correction signals from the reference station, converting the system into a DGPS. This combination maintained the data position accuracy within two meters. The bathymetric survey software integrated MiniCee® was used to navigate and to collect data. The software integrates the depth and position data, storing the x, y, (geographic locations) and z (depths) coordinates in a portable personal computer.

GPS was used to determine the latitude and longitude for each depth measurement. Sounding equipment was used to measure depth from a transducer (probe), operating at a frequency of 200 kHz to the bed of the reservoir. Depths recorded by the sounder, which has a resolution of 0.02% accuracy of measured depth, were measured at a fixed distance below the water surface (Table 4.1) (Bathymetric Center 2003).

The recorded depths and the constant value of the depth ecosounder were subtracted from the watersurface elevations at the time of the survey (as recorded at the dam gauge) to determine reservoir bottom elevations. The depths were synchronized with the GPS data to determine the location of the probe as the boat traversed across the reservoir (IHO 2005; Furnans and Austin 2007). The schematic illustration of depth sounding survey and conditions in Akdarya reservoir for 2003 is depicted in the Figure 4.4. The calibration of the transducer was performed two times daily before and after the measurements.

The depth soundings were collected every 20m and the transects (cross-sections) were about 200m apart beginning at the dam and continuing upstream across 35 cross-sections in Akdarya reservoir in 2003. The transects were perpendicular to the shoreline of the reservoir.

For the shallow water areas where transducer could not be operated, at representative depth several measures have been manually collected with stadia rod on boat. However, sediment accumulation and vegetation growth in the upstream reservoir areas limited the data collection. The shoreline delineation was performed during the survey by GPS (rover) receiver connected to base one that was identified as benchmark as close to water surface mark along the banks.

Initial editing of the data was performed using the MiniCee® software. Positions were corrected to eliminate anomalies that occurred when the correction signal from the reference station was lost because of local topographic features or electromagnetic interference. Position errors were corrected by interpolating back to the mid-point between the correct antecedent and preceding position. The depth data were also corrected to eliminate incorrect depth readings. Incorrect depth readings can result from insufficient signal gain or because of floating debris or because fish interfered with the transducer face. The incorrect depth readings were also interpolated between the correct antecedent or precedent depth readings. Once corrected, the edited data were transferred into the SURFER® 7 database for further processing.

Up to now, the centre has performed bathymetric surveys in 16 reservoirs in Uzbekistan (Bathymetric Centre, 2003). The dead storage in a reservoir is determined as the storage volume between the stream bed and the lowest elevation from which water can be withdrawn by gravity (Mahmood 1987). As it can be seen, the total volume capacities of all reservoirs have been decreased by about 18% whereas the dead storage capacities decreased by 55% on the average respectively. For example, the dead storage capacities of 7 reservoirs were decreased by more than 75%. This is alarming signal that in a foreseen future the sedimentation can be a major operation and maintenance issue for these reservoirs.

## 4.3. Geostatistical analysis

The chapter discusses the results after the application of a new geostatistical approach for generating bathymetric surface models of reservoir bottom from point measurement and transforming into continuous contour surfaces in Uzbekistan. Geostatistical approach can be considered as very helpful, reliable and efficient tools to increase the number of point measurements at unsampled places.

Variogram analysis is used for examining the structural relationship of data for the anisotropy analysis of a physical process that can have changing characteristics in the direction and space over traditional methods for bathymetric surveys (Joseph et al., 1998; Ortt et al., 2000; Soler-Lopez 2003, 2004; Furnans and Austin 2008).

Digital contour surfaces of reservoir bathymetry is performed by two interpolation methods: kriging and simulation (turning bands) techniques. In a first approach kriging interpolation method is used to estimate the bathymetry. In a second time, because kriging provides a smooth result of the reality and has consequences for future computations (volume, area), the simulation method (turning bands) has been chosen. 100 simulations have been carried out in order to introduce natural variability in the reservoir bathymetry and to get statistical probability distribution of reservoir volumes and surface areas for different reservoir stages.

## 4.4. Variogram analysis

Variogram analysis was used to examine the spatio-temporal correlations of the data. Variogram analysis is a prerequisite for interpolation (kriging or simulation), or making predictions (Mear et al, 2006; Clark 2001). Variogram analysis consists of the experimental variogram calculated from the data and the theoretical model fitted to the data. The experimental semi-variogram is calculated by the following equation:

$$\hat{\gamma}(h) = \frac{1}{2N_h} \sum_{x_j - x_i \approx h} \left[ z(x_j) - z(x_i) \right]^2$$

where : *γ(h)* – experimental semi-variogram is two-dimensional graph or formula describing the expected difference in value between pairs of samples with a given relative orientation and distance apart (*h*) between two measured attributes; *h* – distance between two discrete points that are used for calculation of dispersion; *n* – number of pairs of samples (depth); *z* – interested value or attribute; *i* and *i-h* – index of respective values of two samples of the distance *h*, apart.

The experimental variogram measures the mean variability between two points *z* and *z*+h, as a function of their distance *h*. The experimental variogram was calculated for several lag distances and is plotted as a two-dimensional graph. It is then generally fitted with a theoretical model, such as a spherical or exponential model. These models provide information about the structure of the spatial variation as well as the input parameters for spatial prediction by Kriging (Figure 4.5) (Saby et al. 2006).

$$\gamma(h) = C\left(\frac{3h}{2a} - \frac{h^3}{2a^3}\right), h \leq a$$
$$\gamma(h) = C, h \geq a$$

In a first approach we chose to use kriging because it is the method minimizing the best interpolation errors and allows for calculation of variance associated with the interpolation. Kriging calculates a weighted moving average equation which estimates the value of a regionalized variable at site specific location by taking into account the variographical information.

The optimum grid size for constructing the bathymetric surfaces was determined based on examination of the sampling distribution for the three periods.

The kriging interpolation gives the averaged smoothed surface and thus underestimates the realistic reservoir volume and surface area estimations. Thus, for introduction of natural variability we used turning bands interpolation method for simulation. 100 simulation calculations were performed by ISATIS® program.

# *CHAPTER 5: RESULTS AND DISCUSSION*

## 5.1. Historical surveys

For the determination of the sedimentation rates three bathymetric surveys, the original (pre-impoundment) in 1982, 1996 and 2003 were assessed for examining the evolution of the reservoir capacity over time (Table 5.1-5.2-5.3). The 1982 and 1996 surveys were carried out by traditional methods such as range survey/end area method and traditional measuring instrumentation. The 2003 survey was carried out as previously described by CEDUCEER®. Table 5.4 depicts the volumes, water surface areas at the full and minimum pool elevations of the Akdarya reservoir for three historical surveys.

The analysis of the sedimentation dynamics was performed for two periods i)1982-1996 and ii)1996-2003. It is interesting to examine the changes in volume and water area at full and minimum pool elevations (FPE, MPE). For example, for the period 1982-1996, the total sedimentation was about 11.8 million $m^3$, thus the total reservoir volume decreased by 10.5%, the water area decreased by 8% and the dead storage decreased by about 0.3 million $m^3$ (12%) at FPE. However, these changes differ for the reservoir at MPE, for instance the water area decreased by 53% compared to the original.

For the period of 1996-2003, the total sedimentation was around 7.5 million $m^3$, the total reservoir volume decreased by 7.5% to the 1996 level. On the other hand, the water area increased by 2.3 $km^2$ (16.5 %) due to significant right bank collapses, in some places ranging 10-50m. For example, the dead storage decreased by 0.74 million $m^3$ (34%) at the FPE in Akdarya reservoir. At the MPE, the water area of reservoir decreased by 44% (refer to Figure 5.1).

The volume storage capacity loss rate is a key component for calculating the remaining life of a reservoir (Ortt et al., 2000). Using the volumes of the accumulated sediments and the age of the reservoirs, the annual storage capacity loss rates can be calculated. For example, for the 21 years of the reservoir operation, the total loss of reservoir volume capacity is estimated to be about 19.3 million $m^3$. The Akdarya reservoir has lost its storage capacity at a rate of 0.92 million $m^3$ per year. As a percentage of its original storage volume, the annual loss rate for Akdarya reservoir is 0.8% up to 2003.

The high rate of loss is explained by the significant right-bank erosion in some places ranging from 20-50m. The upstream of the reservoir is heavily occupied by the vegetation cover and in some places locals have created artificial rice paddy plots and the area under such plantations is increasing.

The maximum depth according to design calculations was 23.4m but the maximum depth observed during the last survey was recorded as 18.1m. During the field survey, the area of shallow water increased especially in the entrance part of the river.

## 5.2. Depth Measurement

The process of obtaining an accurate bathymetric survey is substantially more difficult than that associated with land-based surveying. There are various error sources in data acquisition and measurement in bathymetric survey. Therefore the method is subject to the usual errors e.g. GPS limited availability and the definition of the water-mud interface (IHO 1998, 2005; USACE 2001).

Byrnes et al. (2002) and Johnston (2003) fully discuss about the limitations of bathymetry measurements and their significance relative to inherent survey errors and measurement uncertainties associated with data density. It is out of the scope of the paper to discuss about errors and uncertainties in sampling campaign of bathymetric survey. The full accuracy standards and uncertainties in bathymetric survey can be found in the following manuals (IHO 1998, 2005; USACE 2001).

Furnans and Austin (2008) report that original reservoir volume estimates are limited by the accuracy of existing topographic maps and land surveys estimates of the current capacities for reservoirs not re-surveyed since their construction. The traditional methods of analysis rely on topographic mapping and range survey data to estimate the sediment volumes of a reservoir.

The range method is based upon interpolating the volumes from one range transect to another. The further apart the transects are, the more the interpolation is involved and the greater the possible error is. The total error in determining reservoir capacity volumes through the use of this method have been estimated to be between 10 and 30% as reported by Morris and Dunbar et al. (Ortt et al., 2000). Small errors in the storage capacity calculations translate into proportionately large errors in sediment volume accumulation.

It must be pointed out that our applied method of simulation and estimation of reservoir volume and surface area refers to the assessment of the total volume of trapped sediments in the reservoir. However, the spatial distribution of the deposited sediment volume has profound significations for the sedimentation countermeasure plan.

For example, as Mahmood (1987) proposed, the methods for the calculation of the reservoir sedimentation can be divided according to physical aspects such as the total volume of trapped sediment and the spatial distribution of the deposit volume (Mahmood 1987). The location of deposited sediments within the reservoir may be of equal or even greater importance to the reservoir operations as is the total volume deposited.

## 5.3. Kriging results

First, the experimental semivariogram is calculated from the experimental data from 2003. Then the theoretical model is fitted in order to examine the anisotropy. The spherical model is chosen because of the equal spacing and orientation of the transects along which depths were measured.

Figure 5.2 depicts the semivariogram of the reservoir bottom elevations for the Akdarya reservoir. Anisotropy is defined as the ratio between the largest and the smallest variance in the data that any attribute characteristics tend to change with direction. The anisotropy was studied by fitting the theoretical model to the experimental variograms graphically. In order to perform this task, the variogram (y-axis) was fixed and the theoretical model was plotted by taking a tolerance of lag direction of 10 degrees and a step amount of 10 degrees. The smallest variance is observed in the N20direction and the largest variance in the N110 direction.

The important variogram properties are the sill (C) that is the amount of variation in the process that is assumed to generate data and the range (A) that is the distance beyond which there is no correlation between data. The theoretical model with the same variogram properties (sill, range, anisotropy ratio and angle) should be found and fixed for both directions. Sill value is 12 and range is about 1600m with a lag distance of 200m. (refer to the Figure 5.2).

After the variogram analysis, the interpolation is carried out with a kriging gridding method. In gridding, the neighbourhood search is carried out with a search shape of ellipse with radius 1 and 2 designated with 1600m (maximum lag distance on the variogram) and with a number of sectors that is 4 with 6 maximum number of data used from each sector. The Figure 5.3 illustrates the bathymetry of the Akdarya reservoir by kriging interpolation method.

The Figure 5.4 depicts the reservoir volume and surface area by kriging and experimental data (2003). There is no significant difference between the elevation-reservoir volume and elevation-surface area curves from experimental direct measurements and modelled (kriging) ones.

Figure 5.5 depicts the reservoir volume at different water elevations in space of the Akdarya reservoir. Bathymetric map has helpful visualization effect for a reservoir operator who can easily see how much water is available at different water elevations and its distribution in space. This is particularly important for water intake structures that are installed in a reservoir for irrigation diversions or public water supply systems. Operators can take preventive measures for alleviating such scenarios.

## 5.4. Geostatistical works

The principal sources of error that are reflected in data are related to the density and spatial configuration of the sample points (Johnston 2003). The spatial configuration is critical in the kriging process and in all interpolation methods. The kriging weights and the variance estimates are dependent of the variogram and the spatial distribution of the points but not of the measured values. This is why equidistant spacing would be the best in bathymetric data collection. Spacing of data points was much greater between transects than between points on a given transect. Such a sampling approach introduces unnecessarily large variance between transects into the modelled bathymetric surface.

## 5.5. Simulation results

After the kriging interpolation, 100 simulations (turning bands) by interpolation method have been carried out for generating bathymetric surface models of reservoir bottom in order to calculate the reservoir volume and the surface areas. The results are given in Table 5.6 and Figure 5.6. As it can be seen the kriging and experimental calculations most of the time for the water elevations fall within the range of minimum and maximum values of simulation. In particular, the significant difference in the reservoir volume is observed at higher water elevations due to the shape of the Akdarya reservoir.

For example, at 494.5 m water elevation there is a difference of about 2% between the simulated maximum reservoir volume (94.47) and the experimental one (93.17) that translates in the absolute values as 1.3 million $m^3$ of water. At lower 477 m water elevation, the difference in the order of magnitude between simulated maximum and experimental ones for reservoir volume is observed (Table 5.6). It should be kept in mind that the Akdarya reservoir has a relatively small reservoir volume capacity. If one considers the larger reservoirs of Andijan and Charvak with an area of 1.9 and 2.0 $km^3$ respectively, the difference in volumes might be in one order of magnitude

## 5.6. Prediction of the Akdarya reservoir volume loss

The following equation is used for the prediction of the reservoir volume losses in the Akdarya reservoir.

$$R_{annual} = (V_i – V_f)/t$$

Where: $R_{annual}$ is the mean annual actual sedimentation volume ($Mm^3$/year); $V_i$ is the initial reservoir volume ($Mm^3$); $V_f$ is the final reservoir volume ($Mm^3$); t is the number of years (year).

For the estimation of the percentage of annual loss of the reservoir volume capacity the following equation is used:

$$R\% = (R_{annual}/V_i) \times 100$$

The results of prediction calculations are given in Table 5.7 and Figure 5.7. After the annual reservoir volume storage loss is known then we have taken a 10-year increment for prediction calculations. For example, there will be 85% loss of dead storage capacity in 2025, i.e., it means that almost designed volume for sedimentation is vanished. In 2047 almost 50% of the useful reservoir storage capacity will be lost, thus expensive dredging activities should be carried out for a proper use of this hydraulic infrastructure. The Table 5.8 depicts the forecasted volumes of the Akdarya reservoir for 2003-2053. Figure 5.8 depicts the sediment accumulation (m) as total and by forecasted years.

## 5.7. Economic efficiency results

New contour and mapping programs have introduced automated reservoir volume and surface calculation. This has significantly reduced the time, workload and financial burdens of such projects. This is real financial savings for the introduction of the geostatistical approach in reservoir sedimentation projects. For example, the economic efficiency for the calculation of 1$km^2$ of reservoir decreased from 800,000 UZ sums to 540,000 UZ Sums (US$ 1=1335 UZ Sums as of 07.10.2008) (Table 5.9).

The savings per $1km^2$ is about US$ 195 dollars. For example, the Akdarya Reservoir surface area constitutes about $12.7km^2$ and the overall savings can be about US$ 2,500. For example, the surface area of neighbouring Kattakurgan reservoir is about $84.5km^2$. There are some reservoirs with surface area greater than $150km^2$ in Uzbekistan.

## *CONCLUSION AND PERSPECTIVES*

Climatic conditions and limitation of water resources put pressure on the sustainable agricultural production in Uzbekistan. Thus, there is urgency for adaptation of innovative estimation methods and technologies for cost-effective and accurate water resources availability assessments in man-made reservoirs.

About one fifth of the irrigation water comes from man-made reservoirs in Uzbekistan. The reservoir sedimentation surveys were carried out with traditional range survey/end area method over the years. From 2003 reservoir sedimentation surveys are being conducted with new bathymetric system that has GPS and electronic transducer capabilities. However, manual data management persists in the practice that is tedious and costly with large human induced errors for calculation of reservoir volume.

Proposed geostatistical approach in estimation of reservoir sedimentation with variogram analysis, interpolation of points at unsampled locations and output continuous digital bathymetric map of the reservoir bottom provide automated estimation of reservoir volume and surface area loss due to sedimentation at the desired water elevation increments. The proposed geostatistical method has shown it's cost-effective in bathymetric survey in Uzbekistan.

The geostatistical approach has advantages over the traditional computation methods with a statistical analysis of data variance and fitting known mathematical model for interpolation. Kriging interpolation method is a good first approximation. Simulation (turning bands) interpolation introduces range of volumes and surface areas in contrast to traditional estimates. Range volume values are more realistic estimates and provide water managers and dam operators with information about the possible minimum and maximum estimates. In turn, it is believed that there would be possibilities to react appropriately in decision making process over sustainable utilization of water resources and hydraulic infrastructure.

The thesis argues that in all reservoir volume and surface area calculations, the range should be foreseen for reflecting the realistic situation of resource availability. Geostatistical approach reduces the workload for post-data processing and has shown its economic efficiency for reservoir sedimentation projects and improves digital database for a given reservoir and future computations of reservoir volume evolution.

New methods such as DTM (Digital Terrain Model) methods and application of GIS capabilities must be incorporated in reservoir sedimentation projects for studying not only the total volume of sedimentation but also the spatial distribution of the sediment accumulation in reservoirs. This DTM method has a strong visualization effect for reservoir operators to observe where the most sedimentation occurs and where specific location mitigation measures can be carried out on a timely and cost-effective manner.

With the application of GIS and computer surface mapping software technologies a new data management scheme at the national scale can be envisioned with the creation of digital maps of reservoirs for sustainable operation physical infrastructure and management of water resources for years to come.

# II – RUSSIAN VERSION

# ВВЕДЕНИЕ

**Актуальность работы.** Как отметил Президент Республики Узбекистан И.А Каримов в книге «Мировой финансово-экономический кризис, пути и меры по его преодолению в условиях Узбекистана» приоритетным направлением для социально-экономического развития страны в этих условиях является широкое применение эффективных методов управления производством и рациональное использование природных и инфраструктурных ресурсов, а также внедрение достижений современной науки с использованием высокоэффективных наукоемких технологий [1].

Водохранилищные гидроузлы относятся к числу наиболее распространенных сложных и ответственных с экономической, экологической и социальной точек зрения инженерных объектов. Во всем мире уделяется особое внимание обеспечению их исправной и безотказной работе [13].

В настоящее время, обеспечению надежности и безопасности водохранилищ в нашей стране закреплено: Законами Республики Узбекистан «О воде и водопользовании» от 6 мая 1993г., «О безопасности гидротехнических сооружений» от 20 августа 1999г., и Постановление Правительства Республики Узбекистан «О мерах повышения безопасности работы и надежности эксплуатации крупных и особо важных водохозяйственных объектов на период 1999-2005», и это является подтверждением актуальности проблемы [2, 3, 4].

На территории Республики Узбекистан эксплуатируется одна из сложнейших инженерно-ирригационных инфраструктур мира. Водные ресурсы водохранилищ являются стратегическими ресурсами для устойчивого развития Республики в период наблюдаемых маловодий и геополитической обстановкой в сфере трансграничного управления водными ресурсами в Среднеазиатском регионе [6, 7, 15, 20, 25, 30, 39, 41, 48, 98].

Интенсивное развитие сельского хозяйства и повышение потребности в орошении земель характерное для климата Средней Азии, в частности Узбекистана, привела к резкому изменению режима движения водного и твердого потока в руслах рек путем строительства водохранилищ [17, 42, 52, 61, 83, 89].

Реки Амударья, Сырдарья, Зарафшан несут большое количество взвешенных веществ, и водохранилища заиляются наносами. Это приводить к нежелательной потере емкостей. Степень ежегодной потери емкостей водохранилищ в Республике составляет 0,5-1,0% и мертвые объемы заилены на 50-60% [9, 48, 58].

Данные многолетнего опыта эксплуатации водохранилищ показывает, что через определенное время, часть их регулирующих емкостей заиляются наносными отложениями. Заиляя водохранилища, наносы уменьшают их полезный объем и тем самым снижают и сокращают срок службы работы водохранилищ.

Таким образом, в данное время чрезвычайно важно разработать и применить оперативные методы анализа в определении полезных емкостей водохранилищ т.к., от этого зависит сроки эксплуатации водохранилищных гидроузлов и гарантированное водоснабжение отраслей народного хозяйства.

Из всего многообразия преобразующей деятельности человека, как по своим масштабам, так и по значению в глобальных экологических системах планеты является преобразование речного звена гидросферы путем гидротехнического строительства, в частности водохранилищ [5, 19, 23, 42].

Водохранилища это природно-технические объекты, ставшие неотъемлемой чертой ландшафта стран и важными элементами национального богатства [5, 80, 87, 101].

Народнохозяйственное значение водохранилищ нельзя переоценить. С помощью водохранилищ началось гарантированное обеспечение орошения сельскохозяйственных земель, водоснабжение городов и промышленных предприятий, производство электроэнергии, борьба с наводнениями, развитие отраслей народного хозяйства: судоходство, рыболовство и индустрия туризма [19, 27, 37, 42, 46, 52, 54, 62, 75, 92, 97, 102].

По данным Международной комиссии по большим плотинам (International Commission on Large Dams) существуют более 45 000 крупных водохранилищ (высота плотины более 15 м или емкостью более 3 млн.м$^3$) в 140 странах мира. Половина из них была построена для ирригации, с помощью которых орошается более 20% от общей площади (270 млн.га) сельскохозяйственных земель, где производится 12-16% сельскохозяйственной мировой продукции, и производится около 20% гидроэлектроэнергии [80, 102].

По данным Всемирной комиссии по плотинам (World Commission on Dams) и Всемирной ассоциации по исследованию эрозии и заиления (World Association on Sedimentation and Erosion Research) более 50% наносного стока регулируемых речных бассейнов осаждаются в водохранилищах [63, 99, 100].

Расчеты показали, что ежегодные потери объемов малых и больших водохранилищ процессу заиления составляет в среднем 0,5-1%, а в Китае - 2,2% от полного объема и экономический ущерб оценивается в 6 млрд. долларов США (1987г.) [75, 87, 103].

В 2003 г., по данным Мирового Банка ежегодный экономический ущерб от потери емкостей водохранилищ оценивается в 13 млрд. долларов США и ежегодные потери емкостей в 1-2%, и это значит, что около 25% мирового полного объема будет потеряна в течение 25-50 лет [89]. Эта проблема актуальна во многих странах мира [22, 29, 53, 69, 86, 93, 95].

В Узбекистане создано 55 искусственных водохранилищ, с помощью которых подается 24% (от общего объема) орошаемой воды [46, 70]. Общий совокупный полный и полезный объемы водохранилищ составляет 19км$^3$ и 14,5км$^3$ соответственно.

По данным государственного унитарного предприятия «Botiometrik markaz» Республиканского объединения «Узводремэксплуатация» Министерства сельского и водного хозяйства Республики Узбекистан (далее Батиметрический центр), степень ежегодной потери емкостей водохранилищ процессу заиления составляет для: Кайракумского – 0,8%; Чимкурганского – 0,5%; Южносурханского – 1,0% и Пачкамаркаского – 0,75%. За 10 лет работы Тахиаташского гидроузла в верхнем бьефе отложилось 21,67 млн.м$^3$, объем составил 49% от полного объема руслового водохранилища [9, 58].

Фактическая интенсивность заиления водохранилищ во много раз превышает проектные расчеты. По результатам исследований, фактический объем отложений в водохранилищах Республики Узбекистан превышает проектный объемы в среднем 1,5-

2 раза и более, это свидетельствует о недостаточной надежности используемых при составлении проектов традиционных методов расчетов заиления [9].

Изучению вопроса заиления водохранилищ и методов расчета посвящены работы многих исследователей, в том числе разработки отечественных ученых Узбекистана, которые позволили понять физический процесс отложения наносов и разработать методы расчета для эффективного управления водохранилищами. Однако в этих методах приняты различные допущения, что обусловлено сложностью рассматриваемого явления, недостаточной достоверностью исходных данных и ограничением традиционных измерительных приборов прошлых лет [54].

Обзор существующих методов расчета выявило следующее:

1) Сложность расчета, требующих наличие большего объема исходной информации и громоздких дополнительных вычислений.
2) Большие отклонения результатов расчета от натурных данных по объему и месторасположению отложений наносов.
3) Имеющие методы расчета были разработаны для русловых водохранилищ, где предполагается уровень воды при нормальном подпертом уровне (НПУ).
4) Рассматривались мелкие фракции наносов и не учитывались переработка берегов и наносы, приносимые ветром, которые могут составить примерно от 3 до 6% годового объема наносов.
5) А самое главное, традиционные методы расчета не позволяют в оперативном ключе определить и прогнозировать состояния потер регулирующих емкостей водохранилищ.

В эпоху бурного развития информационных технологий, новые разработки и оперативные методы стали широко использоваться в батиметрических исследованиях, в частности, в определении объемов заиления водохранилищ [79]. Они позволяют в сжатые сроки проводить: полевые обследования, камеральную обработку данных и автоматизировать расчеты таблиц координат объемов и строить кривые объемов по сравнению с традиционными методами, что в свою очередь значительно уменьшает финансовые затраты и время для проведения исследований [10, 47, 65, 71, 77, 82, 91, 96]. Развитие информационных технологий, дало новые возможности для оперативного анализа определения объемов заиления водохранилищ.

Как показала многолетняя практика, одним из эффективных методов расчета объема заиления является повторные батиметрические съемки чаш эксплуатируемых водохранилищ, позволяющие получать конечные объемы заиления. Значить необходимо широкое применение этих разработок в батиметрических исследованиях для повышения надежности работы водохранилищ в целях сохранения и эффективного использования водных ресурсов в Республике Узбекистан [35, 47, 78].

Из обзора изучения проблемы заиления и методов расчета емкостей водохранилищ становится очевидным, что данная проблема является актуальной и методы расчета находится в незавершенной стадии решения, поэтому настоящая диссертационная работа посвящена к использованию геоинформационных систем для расчета объемов заиления эксплуатируемых водохранилищ.

**Связь диссертационной работы с тематическими планами НИР.** Тема диссертационной работы входит в рамки приоритетного направления развития науки «Совершенствование системы рационального использования и восполнения водно-земельных ресурсов…» определенной Комитетом по координации развития науки и технологий при Кабинете Министров Республики Узбекистан и тематические планы научно-исследовательских работ факультета «Строительство и эксплуатация ирригационных гидротехнических сооружений» Ташкентского института ирригации и мелиорации и утверждена на Ученом совете ТИИМ 24 марта 2006 года, протокол № 6.

**Цель исследования.** Целью данной работы является совершенствование оперативных методов замера глубин, камеральной обработки данных и метода определения полезной емкости водохранилищ с использованием геоинформационных систем.

**Задачи исследования.** Сформулированы следующие задачи исследований:

1. Провести анализ и обзор современных технологий и методов в батиметрической съемке чаш водохранилищ.
2. Совершенствовать метод замера глубин с использованием батографа CEEDUCER® с привязкой к глобальной системе позиционирования (GPS-система), и получения космической съемки объекта с помощью общедоступного приложения Google Earth® сети Интернет.
3. Рекомендовать внесение поправочных коэффициентов для значений глубин, разработанных Международной гидрографической организацией (МГО) с учетом наблюдаемых погрешностей в натурных измерениях.
4. Разработать метод геостатистического анализа для определения полезной емкости водохранилищ с помощью компьютерной программы SURFER® путем вариограммного моделирования для прогноза значений выборок глубин, на местах их отсутствия с помощью интерполятора Kriging в создании научно-обоснованной сетки батиметрической модели чаши из дискретных точек измерений.
5. Создать цифровую батиметрическую модель чаши водоема (на примере Акдарьинского водохранилища).
6. Провести прогноз потер емкостей водохранилища по данным многолетних фактических объемов Акдарьинского водохранилища.

**Объект и предмет исследования.** Объектом исследования являются водохранилища, отстойники, озера и ирригационные каналы. Предметом исследования является оценка и прогноз состояния потерь полезных емкостей эксплуатируемых водохранилищ с использованием геоинформационых систем.

**Методика исследований.** Для решения поставленных задач методика исследования разделена на полевые и численные. Полевые обследования проводились на основе методики использования батографа CEEDUCER для замера глубин и их координат месторасположения с увязкой к GPS-системе. Численные исследования проводились на основе общепринятых методов статистического анализа в частности вариограммного моделирования (структурного анализа), и использование интерполяционного метода kriging при создании сетки батиметрической модели чаши водоема для расчета объемов Акдарьинского водохранилище.

**Гипотеза исследований**. Предложенные и разработанные рекомендации по совершенствованию оперативных методов определения полезной емкости водохранилищ в Республике Узбекистан будут способствовать в сжатые сроки и с меньшими финансовыми затратами оперативно строить кривые объемов с использованием современных геоинформационных систем в надежной эксплуатации водохранилищ и рациональному использованию стратегических водных ресурсов водохранилищ для устойчивого развития народного хозяйства.

**Защищаемые положения.** Основные положения, выносимые на защиту:

1. Разработанный и апробированный метод геостатистического анализа в гидротехническом строительстве для оперативного определения полезных емкостей водохранилищ.
2. Системный подход использования геоинформационных систем (GPS-система, батограф CEEDUCER, программа SURFER и приложения Google Earth сети

Интернет) в Республике Узбекистан для оперативной оценки и прогнозу состояния полезных емкостей водохранилищ.
3. Обоснован процесс создания локальной высотно-плановой сети объекта и географических координат глубин в GPS-системе.
4. Результаты расчета кривых объемов Акдарьинского водохранилища с использованием поправочных коэффициентов МГО.
5. Результаты численных исследований прогноза значения выборок глубин водохранилищ на местах их отсутствия, путем вариограммного моделирования.
6. Созданная цифровая батиметрическая модель чаши водоема (на примере Акдарьинского водохранилища).
7. Прогнозные результаты изменения мертвого и полезного объемов Акдарьинского водохранилища и динамики изменения прогнозных кривых объемов.

**Новизна работы** заключается в следующем:
1. Впервые разработан и апробирован метод геостатистического анализа в гидротехническом строительстве для определения полезных объемов водохранилищ.
2. Показан системный подход использования геоинформационных систем (GPS-система, батограф CEEDUCER, программа SURFER и приложения Google Earth сети Интернет) в Республике Узбекистан для оперативной оценки и прогнозу состояния полезных емкостей водохранилищ.
3. Получены новые результаты расчета кривых объемов водохранилища с учётом поправочных коэффициентов для значений измеряемых глубин согласно стандартам МГО.
4. Экспериментально установлен научно-обоснованный размер ячейки сетки батиметрической модели чаши водохранилища с помощью вариограммного моделирования.
5. Создана цифровая батиметрическая модель чаши Акдарьинского водохранилища.
6. Разработан метод прогноза полезной емкости Акдарьинского водохранилища с учетом многолетних фактических объемов объекта.

**Научная и практическая значимость результатов исследований.** Основная научная и практическая значимость полученных результатов исследований состоит в системном применении геоинформационных технологий научно-исследовательскими и проектными институтами в водохозяйственном направлении для оперативного определения и прогноза состояния объемов озер, водохранилищ, отстойников и ирригационных каналов, а также исследований деформации русел рек.

Разработанный геостатистический метод позволяет автоматизировать вес цикл проведения батиметрических исследований, и в сжатые сроки определить таблицу координат объемов и площадей зеркала водохранилища, и построить прогнозные кривые объемов для диспетчерских служб водохранилищ.

Основным практическим применением будет уменьшение время камеральной обработки на 80% и полевых – на 50% за счет увеличения области охвата измеряемой поверхности. Разработанный метод прогноза полезной емкости при абсолютных отметках позволяет оперативно определить прогноз наращивания отметок водозаборных и водовыпускных сооружений для надежной эксплуатации водохранилищного гидроузла из-за потер регулирующих емкостей.

**Реализация результатов.** Разработанная методология «Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилища» утверждено Министерством сельского и водного хозяйства Республики Узбекистан и используется в работе Батиметрического центра. Также, получен акт внедрения результатов научных исследований в производство в Республиканском объединении

«Узводремэксплуатация». Создана цифровая батиметрическая модель чаши Акдарьинского водохранилища.

Ожидаемая экономическая эффективность метода расчета полезной емкости оценивается в 260 тыс. сум на 1км$^2$ исследуемого объекта. Создана цифровая батиметрическая модель чаши Акдарьинского водохранилища. Ожидаемая экономическая эффективность составляет около 3 млн.сумов для Акдарьинского водохранилища. Кроме того, методика использована для расчета полезной емкости Южносурханского водохранилища (см. приложения 1 и 2).

**Апробация работы.** Основные положения диссертационной работы были изложены на IV научно-практической конференции магистрантов «Современные проблемы водного и сельского хозяйства», ТИИМ (12-13 мая 2005 г.); Республиканской научно-практической конференции, посвященной 60-летию факультета Строительство и эксплуатация ирригационных гидротехнических сооружений «Проблемы надёжности и безопасности гидротехнических сооружений», ТИИМ (Ташкент, 22-23 ноября, 2006 г.); IV научно-практической конференции «Молодых специалистов, получивших образование за рубежом» фонда Президента Республики Узбекистан ИСТЕЪДОД (Ташкент, 24-25 ноября, 2006 г.); VI научно-практической конференции магистрантов и молодых ученых «Современные проблемы водного и сельского хозяйства», ТИИМ (Ташкент, 18-19 мая 2007 г.); Международной научно-практической конференции «Инновация-2007», ТашГТУ (Ташкент, 24-26 октября 2007 г.); Региональном учебном курсе «По обеспечению безопасности гидротехнических сооружений» организованный Государственной инспекцией «Госводхознадзор» при Кабинете Министров Республики Узбекистан совместно с Европейской Экономической Комиссией Организации Объединенных Наций (ЕЭК ООН) (Ташкент, 11-14 мая 2009 г.); и по линии международного научно-исследовательского гранта ИНТАС для молодых ученых «INTAS Young Scientist Fellowship 2004, Nr.04-83-3665» (2005-2008 гг.); а также на научных семинарах кафедры «Гидротехнические сооружения и инженерные конструкции» ТИИМ и научно-исследовательского центра «Развитие прикладных геонаук» Французского Университета Бордо-1.

**Опубликованность результатов.** Основные результаты и положения диссертационной работы опубликованы в 10 научных работах, из которых 3 рецензируемых научно-технических журналах и «Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ».

**Структура и объем диссертации.** Работа состоит из введения, четырех глав, заключения, списка использованной литературы и приложений. В приложениях представлены акт внедрения результатов научных исследований в производство и «Руководство по применению…». Диссертация изложена на 113 страницах компьютерного текста (шрифт Times New Roman №14), включает 28 рисунков, 17 таблиц и список использованной литературы из 103 наименований. Общий объем работы составляет 143 страниц. Приложения состоят из 30 страниц.

Работа выполнена совместно на кафедре «Гидротехнические сооружения и инженерные конструкции» ТИИМ под научным руководством проф., доктора технических наук М.Р. Бакиева и научным руководством, проф., доктора философии (PhD) Филиппа Ле Костюмера (Philippe Le Coustumer) Научно-исследовательского центра «Развитие прикладных геонаук» Французского университета Бордо-1, которым автор выражает глубокую признательность за ценные советы и научные консультации. Также автор выражает признательность доцентам университета Бордо-1 Фредерику Хюно (Frederic Huneau) и Антуану Марашу (Antoine Marache), также проф. Микаэлю Мотелика-Хэйно (Mikeal Heino-Motelica) из университета Орлеан (Франция) за их практические советы и рекомендации.

**Содержание работы**.

Во **введении** кратко обосновывается актуальность работы, сформулированы цель и задачи исследований. Показана научная новизна, практическая ценность и реализация результатов.

В **первой главе** рассматривается современное состояние изученности проблемы заиления водохранилищ, а также значимость для Республики Узбекистан. Приводится обзор мероприятий по борьбе с этим явлением, а также обсуждаются негативные последствия заиления водохранилищ.

Во **второй главе** приводится критический анализ существующих методов расчета заиления и дается обоснования в разработке геостатистического метода анализа. Также рассматриваются современные методы и технологии при замере глубин в батиметрических исследованиях. Впервые проводиться обзор базовых концепций системы глобального позиционирования (GPS) для определения координат месторасположения плавательного средства, с борта которого проводится замер глубин применительно батиметрических исследований.

Рассматриваются основы геостатистики, особенности программы SURFER и поправочные коэффициенты, рекомендованные стандартами МГО для улучшения точности значений глубин с учетом наблюдаемых погрешностей в натурных измерениях.

В **третьей главе** кратко описывается объект исследования, и приводятся рекомендации для совершенствования методики батиметрической съемки чаши и разработка геостатистического метода для оперативного расчета полезной емкости водохранилища с использованием геоинформационных систем (CEEDUCER и SURFER).

В **четвертой главе** представлены результаты натурных, экспериментальных и численных исследований по определению полезной емкости Акдарьинского водохранилища. Приводится прогноз потер объемов и дается экономическая обоснованность разработок в оперативном анализе объемов заиления водохранилища.

В **заключении** приводятся основные выводы по результатам проведенных исследований и рекомендации.

# ГЛАВА 1.
# ИЗУЧЕННОСТЬ ВОПРОСА ЗАИЛЕНИЯ ВОДОХРАНИЛИЩ

Заиление водохранилищ обусловлено осаждением в его чаше наносов, поступающих с водосбора вместе с жидким стоком рек и ручьев, питающих водохранилище, а также твердого материала, попадающего в водоем в результате переработки берегов или ветрового (эолового) переноса пыли с прилегающих территорий. Главным фактором заиления обычно считается сток наносов [5, 7, 8, 24, 31, 32, 37].

Твердые частицы – продукты эрозии водосборов и русел, абразии берегов водоемов, переносимые водотоками, а также течениями в озерах, морях и водохранилищах и формирующие ложе водоемов, называют *наносами* [5, 36].

Всю совокупность наносов делят на взвешенные и влекомые (донные). Взвешенные наносы транспортируются в толще потока вплоть до поверхностных его слоёв, так как высота подъёма частиц соизмерима с глубиной потока. Донные наносы перекатываются, волочатся или сальтируют по дну [24].

Такое деление наносов условно, так как при изменении гидравлических характеристик потока существует переход из одной формы движения наносов в другую. Помимо этого идёт обмен наносами между дном и толщей потока, регулируемый турбулентностью потока [8, 40].

Особый интерес в практическом отношении представляет осаждение наносов в подпертых бьефах реки – в водохранилищах, образуемых в результате постройки на реке плотин [55].

## 1.1. Общая характеристика заиления водохранилищ

Водохранилище – искусственный водоем, образовавшийся в результате строительства на реке водоподпорного гидротехнического сооружения (плотины), существенно поднявшего уровни воды и затопившего ей русло, пойму и надпойменные террасы [5].

Водохранилища осуществляют сезонное и многолетнее регулирование стока, имеют значительный размах колебаний уровней воды, приводящий к возникновению больших площадей переменного затопления к постоянному изменению контакта водоема с берегами [33, 72].

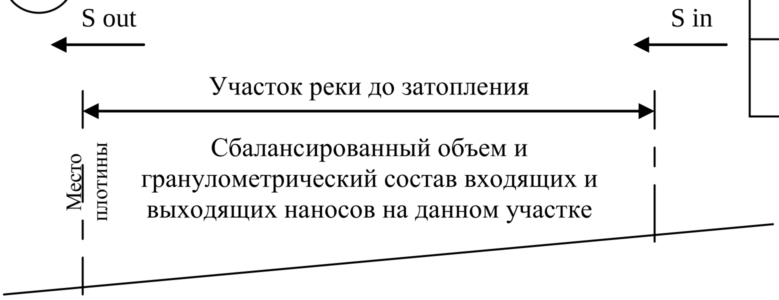
Водохранилища с мало изменяющимся уровнем осуществляют обычно суточное регулирование стока и являются небольшими по объему водоемами – подпертыми бьефами [41].

Наблюдения над существующими водохранилищами показывают, что через промежуток времени, зависящий от целого ряда гидрологических, гидротехнических, гидравлических, климатических и эксплуатационных условий происходит заиление водохранилища [54]. В результате полного заиления глубина во всем подпертом бьефе устанавливается приблизительно одна и та же и река, таким образом переходит к новому бытовому режиму [44, 65].

Процесс заиления водохранилищ, согласно многочисленным данным наблюдений и измерений может быть охарактеризован следующим образом (рис 1.1: По авт. Gregory L. Morris).

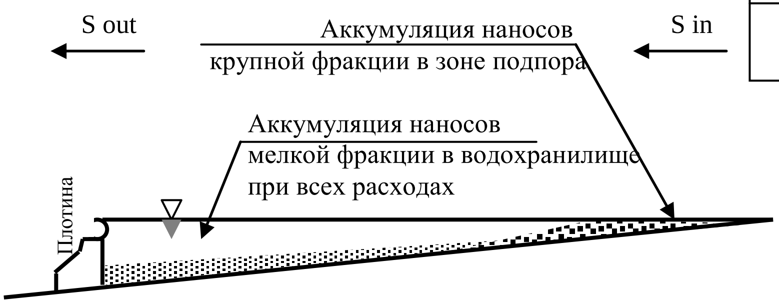
Систематическая аккумуляция наносов на участке водотока происходит, если количество наносов, поступающих через его верховой створ в потоке, больше транспортирующей способности последнего. Если нет внешних факторов, способствующих выносу наносов к устьевой области водотока, то идет их аккумуляция в водохранилищах [7, 18, 19].

1 **ДО ЗАТОПЛЕНИЯ**



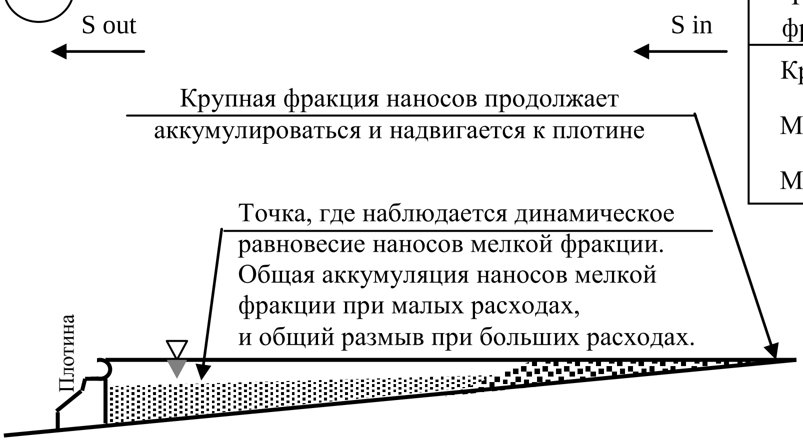

| Размер фракции | Расход | Баланс Наносов |
|---|---|---|
| Все | Все | $S_{out} \approx S$ |

2 **РЕЖИМ АККУМУЛЯЦИИ НАНОСОВ**



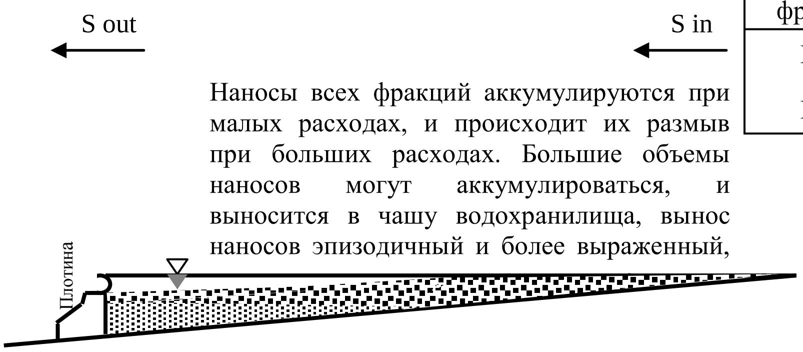

| Размер фракции | Расход | Баланс Наносов |
|---|---|---|
| Все | Все | $S_{out} < S_{in}$ |

3 **РЕЖИМ ЧАСТИЧНОГО БАЛАНСА НАНОСОВ**




| Размер фракции | Расход | Баланс Наносов |
|---|---|---|
| Крупная | Все | $S_{out} < S_{in}$ |
| Мелькая | Маленький | $S_{out} < S_{in}$ |
| Мелькая | | $S_{out} > S_{in}$ |

4 **РЕЖИМ БАЛАНСА НАНОСОВ**




| Размер фракции | Расход | Баланс Наносов |
|---|---|---|
| Все | Маленький | $S_{out} < S_{in}$ |
| Все | Большой | $S_{out} > S_{in}$ |

**Рис 1.1.** Схема заиления руслового водохранилища
**Figure 1.1.** Schematics of sedimentation stages of a reservoir

Осаждение наносов начинается с верховой части водохранилищ и продвигается постепенно вниз по течению. Режим наносов, поступающих из верхнего бьефа, в основном зависит от русловых процессов в подводящем русле реки, подпертого уровня воды перед плотиной, расхода воды реки и величины водозабора в каналы [37].

И.Ф. Карасев на основе системного подхода предложил деление всего периода заиления водохранилища на три стадии [42]:

1. Иррегулярный режим заиления, при котором все поступающие в водохранилище наносы аккумулируются им;
2. Регулярный режим заиления, характеризующийся наличием влияния тела заиления на транзит наносов;
3. Стадия заключительного режима, когда поступающие в водохранилище наносы проходят транзитом.

Переход от первой стадии ко второй, как показал ранее В.А. Скрыльников, осуществляется при снижении объема водохранилища $W_o$ до следующей величины:

$$W_o = 8.3 \times w_p \qquad (1.1)$$

где
$w_p$ - объем устойчивого русла в пределах от начального створа водохранилища до плотины, м$^3$ [27].

Первая стадия заиления может иметь место в тех водохранилищах, объемы которых удовлетворяют неравенству

$$W > 8.3 \times w_p \qquad (1.2)$$

Для второй стадии характерен экспоненциальный закон убывания во времени интенсивности заиления. Этот закон приблизительно описывается известными формулами В.Орта, Г.И. Шамова, В.С. Лапшенкова [9, 31, 34, 37].

Переход к третьей стадии четко выражается соответствием между поступлением наносов в водохранилище и их сбросом в нижний бьеф [27].

Сосредоточенная аккумуляция наносов обычно идет в зоне переменного подпора. Толщина этого слоя убывает в сторону плотины. Размыв, начинается непосредственно ниже плотины. Размыв постепенно распространяется все ниже по течению, естественно, в этом же направлении смещается и аккумулятивная зона [8, 9, 16, 17, 19, 63, 72, 99].

Особенно быстро за (несколько месяцев) уменьшается почти до нуля объемы небольших водохранилищ на горных реках, если заранее не предусмотрена периодическая промывка емкости этих водохранилищ. Равнинные водохранилища могут заилятся сотни и тысячи лет [24, 27, 33, 44].

## 1.2. Водохранилища Республики Узбекистан

С интенсивным развитием сельского хозяйства и повышением потребности в орошении земель началось строительство водохранилищ в начале 1940-х гг. в

Республике Узбекистан. Динамика строительства водохранилищ показана на (рис.1.2) [9, 27, 54].

Как видно из графика интенсивное строительство водохранилищ наблюдалось в период 1960 по 1990 гг. В этот период было построено более 80% всех водохранилищ и более 85% совокупного полного объема. Большинства водохранилищ эксплуатируются более 25-30 лет [48].

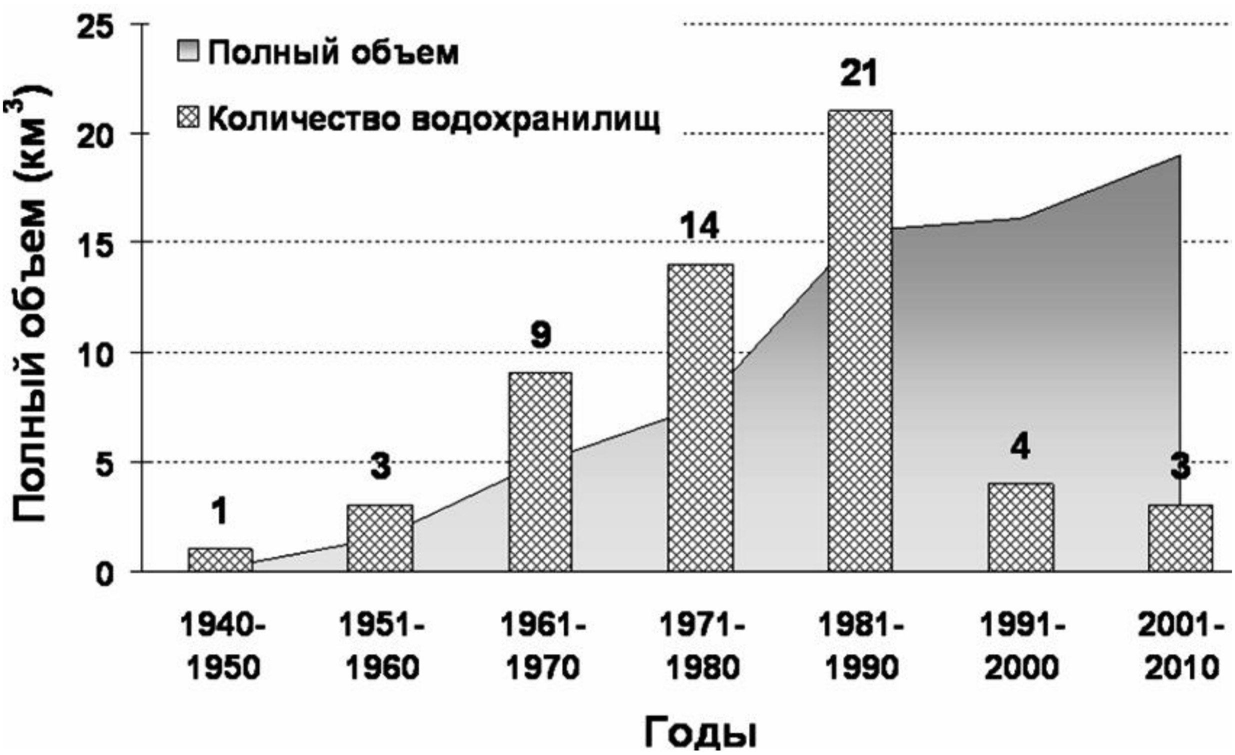



**Рис.1.2.** Строительство водохранилищ в Республике Узбекистан
**Figure 1.2.** Reservoir construction in Uzbekistan for the last century

Водохранилища Республики имеют очень высокую степень использования чаши, которая оценивается морфометрическим показателем, т.е., соотношением полезного объема на полный объем [54]. Эта величина составляет в основном 80 – 97% и этот показатель ниже 80% у Чарвакского - 78%, Южносурханского – 77%, Учкурганского – 40% и Руслового – 19%. Водохранилища с небольшим коэффициентом использования чаши, как правило, комплексного назначения и в большой степени используется в гидроэнергетике.

Использование речного стока водохранилищами характеризуется коэффициентом, т.е., соотношением объема, доставляемого потребителям за год к среднемноголетней годовой проточности в водохранилище. У большинства водохранилищ этот показатель больше 0,80, следовательно, степени использования водных ресурсов наших водохранилищ очень высок [54].

В настоящее время в Узбекистане создано 55 искусственных водохранилищ, из которых 30 расположены в бассейне р.Амударьи и 25 - в бассейне р.Сырдарьи с помощью которых подается 24% (от общего объема) орошаемой воды (рис.1.3.) [46, 70].


Источник: ФАО, Сельскохозяйственная и продовольственная организация ООН, 2007. http://www.fao.org

**Рис.1.3.** Источники орошаемой воды в Узбекистане
**Figure 1.3.** Sources of irrigation water in Uzbekistan

Общий совокупный проектный полный объем водохранилищ составляет 19км$^3$, - полезный 14,5км$^3$ (табл.1.1).

Таблица 1.1

Количество и полезный объем водохранилищ в Республике Узбекистан
**Table 1.1.** The number and total volumes of water reservoirs in Uzbekistan

| **Область** | **Кол-во** | **Полезный объем км$^3$** | **Область** | **Кол-во** | **Полезный объем км$^3$** |
|---|---|---|---|---|---|
| *Бассейн р.Амударья* | | | *Бассейн р.Сырдарья* | | |
| Хорезм | 1 | 4,5 | Андижан | 3 | 1,7 |
| Кашкадарья | 14 | 2,3 | Ташкент | 5 | 1,9 |
| Самарканд | 7 | 1,1 | Фергана | 4 | 0,25 |
| Сурхандарья | 4 | 0,9 | Наманган | 7 | 0,23 |
| Навои | 2 | 0,8 | Джизак | 4 | 0,18 |
| Бухара | 2 | 0,4 | Сырдарья | 2 | 0,01 |
| **Общий** | **30** | **10,1** | **Общий** | **25** | **4,45** |

Источник: Программа Развития ООН, 2007г.

По данным Минсельводхоза Республики Узбекистан из 27 обследованных водохранилищ практически полностью заилились 11, а на 5 – отложения наносов приблизились вплотную к водовыпускным сооружениям [46].

В табл. 1.2 приведены результаты обследований Батиметрического центра Минсельводхоза по 16 водохранилищам. В среднем, потеря полного объема водохранилища процессу заиления составляет 18% и мертвого – 55%, из них в 7 водохранилищах потеря мертвого объема составляет более 75%. Значительные потери мертвых объемов указывают на несоответствие проектных расчетов с наблюдаемым условиями. Причем, при проектировании мертвый объем рассчитывался как мероприятие по борьбе с заилением [9]. Потеря мертвых объемов наблюдается во всех водохранилищ в Республике и т.к., большинство наших водохранилищ уже эксплуатируются более 25-30лет.

Таблица 1.2

Полный и мертвый объемы водохранилищ

**Table 1.2.** The sedimentation in 16 reservoirs in Uzbekistan

| **Водохранилище** | **Проект объем, млн. м$^3$** | **Потеря объема %** | **Проект объем, млн. м$^3$** | **Потеря объема %** | **Введение в эксплуатацию Год** |
|---|---|---|---|---|---|
| | Полный объем | | Мертвый объем | | |
| Ташкентское | 250 | 16,9 | 26 | 76,3 | 1962 |
| Талимарджанское | 1525 | 3,9 | 125 | 2,23 | 1985 |
| Южносурханское | 800 | 37 | 100 | 78,7 | 1967 |
| Куймазарское | 310 | 11,2 | 47 | 6,7 | 1958 |
| Тудакульское | 1200 | 13,7 | 600 | 9,6 | 1983 |
| Ахангаранское | 198 | 4,8 | 13 | 27,7 | 1969 |
| Андижанское | 1900 | 13,4 | 150 | 39,2 | 1970 |
| Джизакское | 100 | 19,9 | 4 | 96,2 | 1966 |
| Каттакурганское | 900 | 22,5 | 24 | 87 | 1953 |
| Тупалангское | 100 | 16,6 | 8,79 | 88,4 | 1992 |
| Хиссаракское | 170 | 13,2 | 8,4 | 100 | 1985 |
| Чимкурганское | 500 | 22,7 | 50 | 31,8 | 1963 |
| Пачкамарское | 260 | 25,9 | 10 | 99,8 | 1967 |
| Акдарьинское | 112,5 | 17,2 | 2,5 | 41,6 | 1984 |
| Русловой | 2340 | 44,9 | 270 | 86,5 | 1980 |
| Капаракское | 960 | 1,9 | 410 | 1,65 | 1983 |
| **Средний** | | **17,8** | | **54,6** | |

Источник: Батиметрический центр, 2006г.

### 1.3. Последствия заиления водохранилищ

Регулирование речного стока посредством возведения плотины приводит к резкому изменению гидрологического и наносного режимов реки [5, 7, 72, 75]. Это проявляется в систематическом накоплении наносов выше сооружений и размыве берегов, дна, речных отложений в нижнем бьефе.

Аккумуляция наносов в подпертых бьефах – это реакция природы на вмешательство человека в её естественные процессы [44].

Согласно исследованиям Н.И. Алексеевского и Р.С. Чалова, природные условия водосборов не являются единственным фактором пространственно-временной изменчивости характеристик переноса и осаждения литогенного материала водными потоками [7].

Возрастающее влияние на них оказывает хозяйственная деятельность, одни виды которой вызывают увеличение, другие – уменьшение стока наносов. Тенденции антропогенных изменений могут быть местными или проявляться на больших по длине участках рек. Антропогенные факторы воздействующие на перемещение веществ водными потоками могут быть прямыми или косвенными: регулирование, изъятие и перераспределение стока воды в реках определяет направленность эрозионно-аккумулятивных процессов в их руслах и, таким образом, является фактором формирования речных наносов [7].

Вопрос о заилении водохранилищ имеет огромное практическое значение, М.А. Великанов утверждал, в особенности во всех тех случаях, где плотина строится с целью регулирования стока и где уменьшение объема водохранилища играет отрицательную роль при использовании реки [18].

Заиляя водохранилища, наносы уменьшают их полезный объем и тем самым снижают их полезное использование, а также сокращают срок работы водохранилищ (рис.1.4).

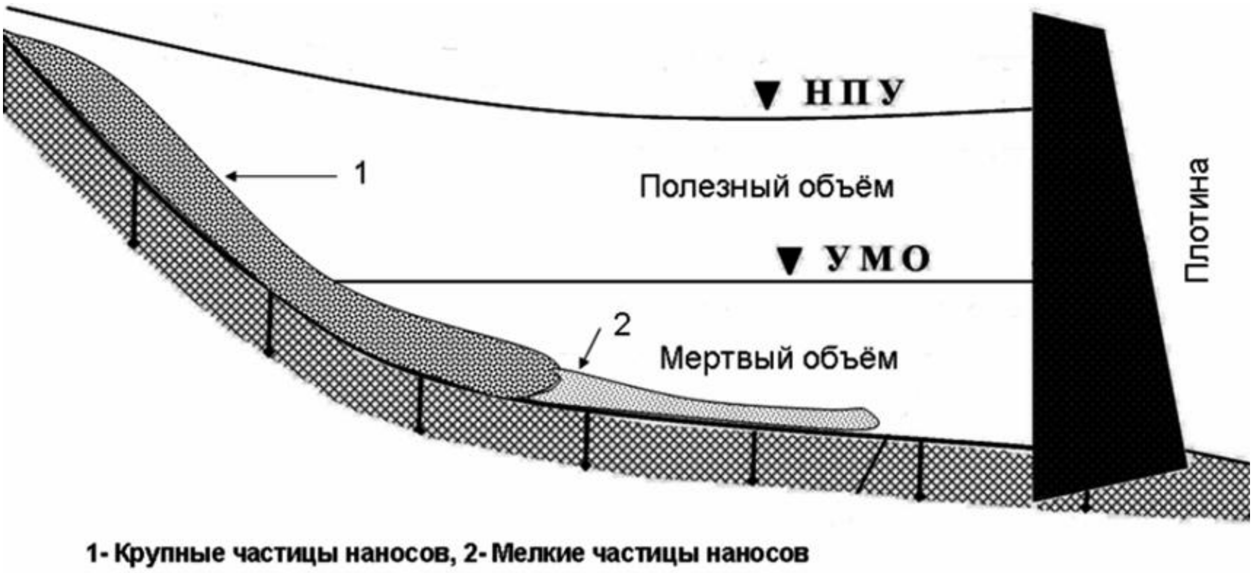



**Рис.1.4.** Полезный и мертвый объемы водохранилища и осаждение наносов
**Figure 1.4.** Useful and dead storage capacities in reservoir

Взвешенные наносы также негативно влияют на плотину, происходит абразия различных инженерных конструкций, входящих в состав водохранилища. Истирание и кавитация наносами лопаток турбин гидроэлектростанции (ГЭС) понижает их коэффициенты полезного действия и сокращает срок их службы [13, 17, 23].

Заиление уменьшает регулирующую роль водохранилища и тем самым уменьшает энергоотдачу гидроэлектростанции. В отношении судоходства заиление водохранилища также приводит к нежелательным последствиям, главным образом в хвостовой части подпорной кривой, нарастание дна в которой приводит к необходимости производить в реке усиленное землечерпание [5, 77].

В верхних бьефах наблюдается уменьшение уклонов, скоростей течения и транспортирующей способности потоков, что приводит к искусственному переводу транспортируемого материала в состав отложений. Сток наносов при этом значительно сокращается [38, 81].

Заиляя водохранилище, в корне меняется транспортирующая способность потока. В результате мутность его в нижнем бьефе уменьшается и происходит размывы ложа и берегов на огромных расстояниях вниз по течению [44].

Полное осаждение наносов было бы скорее вредно, чем полезно, так как часть мельчайших наносов, транспортируемых рекой  полезна как удобрение или как улучшающая почву добавка [53, 70].

Мутность потока в водохранилище увеличивается и влияет на биоценоз, т.е., проникновение солнечной радиации уменьшается по глубине и ограничивается деятельность хлорофилл. За счет этого наблюдается «озеленение» водоема и погибают различные биосистемы. В свою очередь, уменьшение биомассы негативно влияет на различные виды рыб [98].

В формировании химического состава воды предгорных водохранилищ превалирующую роль играют природные факторы, а равнинных – антропогенные, выражающиеся в сбросе в водохранилища высокоминерализированных коллекторно-дренажных вод и режиме регулирования стока [42, 52].

### 1.4. Мероприятия по борьбе с заилением

В специальной литературе, для борьбы с заилением имеются различные мероприятия, и мы сгруппировали на три основные категории (рис.1.5).


**Рис.1.5.** Методы борьбы с заилением водохранилищ
**Figure 1.5.** Sedimentation mitigation strategies

5. Первая группа состоит из методов, которые направлены на уменьшение стока поступающих наносов в водохранилище на площади водосбора реки и прилегающей территории [20, 56].
   - Эти противоэрозионные мероприятия, которые направлены на уменьшение твердого стока, путем обработки почвогрунтов водосбора агротехническими,

лесомелиоративными работами по укреплению берегов и уклонов склона, а также установкой наносоуловительных инженерных сооружений [54].

- Создание прудов (бассейнов) вверх по течению основного водохранилища и отстойники различного типов. Но это приведет к очень большим потерям воды на испарение [45].
- К инженерным сооружениям входят деривационные каналы, в основу которого заложена идея пропуска транзита наносов через часть зоны подпора и плотину гидроузла в период прохождения паводков, с последующим пропуском твердого стока после сработки водохранилища [78, 88]. Этот способ борьбы нецелесообразен при значительной длине обводного канала с большим поперечным сечением или наличием скальных трудноразрабатываемых пород [54].

6. Вторая категория представляет собой мероприятия организованные непосредственно в самом водохранилище [5, 54, 88, 99].
   - К ним относятся использования энергии самой реки, т.е. гидравлический промыв наносных отложений в водохранилище.
   - Механическая очистка наносных отложений землеснарядами и дноуглубительными мероприятиями.
   - При проектировании заложен мертвый объем водохранилища как первоначальное мероприятие по борьбе с заилением.
   - Скрыльников и др. (1987) описывает устройство для удаления наносов со дна водохранилища за счет статистического напора гидроузла [54]. При помощи лебедки на плавучей платформе, грунтозаборник опускается к поверхности дна в месте отложения наносов. Система труб заполняется водой. За счет использования суммарного напора притопленный с помощью понтонов грунтозаборник разрабатывает отложения наносов. Всасывает их и транспортирует пульпу по трубопроводу в нижний бьеф плотины.
7. Третья категория представляет собой мероприятия, которые проводятся в плотине водохранилища. Например, маневрирование щитами сбросных и промывных отверстий в плотине с увязкой режима реки. Сброс мутного потока или плотностных течений через гидротехнические туннели для систематического промыва, а также подъем отметок водозаборных сооружений и увеличение высоты плотины [20, 23].

Анализ работ показывает, что достаточно эффективных мероприятий по борьбе с процессом заиления водохранилищ пока еще нет. Все вышеперечисленные мероприятия были использованы в практике, но не одно мероприятие в отдельности не решает проблему заиления достаточно эффективно [41].

**Выводы по первой главе**

1. Величина и продолжительность процесса заиления, а также характер распределения наносных отложений в водохранилищах в основном зависят от гидрологических, геоморфологических, гидротехнических, эксплуатационных, климатических и других факторов.
2. Отложение наносов есть природный процесс, т.е. взаимосвязь между руслом и потоком. Но усиление этого процесса приводить хозяйственная деятельность, т.к. неправильная эксплуатация сооружений водохранилищного гидроузла, развитие эрозионных процессов, вызываемых сельскохозяйственной деятельностью человека в зоне водосбора реки, зарастание мелководья чаш водной растительностью, трансформация гидравлических условий работы водохранилища.
3. Заиляя водохранилища, наносы уменьшают их полезный объем и тем самым снижают их полезное использование, сокращают срок работы водохранилища и лопасти агрегатных установок и затворов. Также, наносы играют важную роль в формировании химического состава воды в водохранилище.
4. Существующие методы борьбы с заилением показали только частичное решение данной проблемы.  Это связано из-за недостатка воды в реке для промыва и значительной стоимости работ по механизированной очистке.

# ГЛАВА2
# СОВРЕМЕННЫЕ МЕТОДЫ И ТЕХНОЛОГИИ РАСЧЕТА ЗАИЛЕНИЯ ВОДОХРАНИЛИЩ

## 2.1. Обзор различных методов расчета

Главными задачами расчета заиления являются [54]:

1. Оценка срока службы водохранилища как емкости, регулирующий сток;
2. Получение величины общего объема заиления и регулирующей емкости водохранилища через заданное число лет;
3. Получение распределения отложений по длине водохранилища или на отдельных его участках, в частности, в зоне выклинивания подпора;
4. Оценка трансформации кривой подпора.

А.М. Никитин выделяет три направления изучения заиления водохранилищ: первое – **повторные батиметрические съемки чаш** водохранилищ, позволяющие получить конечные результаты заиления; второе – анализ компонентов **седиментационного баланса** на участке водохранилища; третье – получение **пространственной характеристики изменения режима заиления** путем проведения съемок динамики мутности, скоростей течения, фракционного и гранулометрического состава и донных отложений по акватории водохранилищ [42].

Натурные исследования заиления водохранилищ ведутся с конца XIX – начало XX вв. Особое внимание этому вопросу стали уделять, начиная с 1920 – 1930гг [27]. Одной из первых обобщающих работ, указывающей определенные пути расчета заиления водохранилищ, явилась работа Ф.Орта. Следует упомянуть работу Д.Бренна, который построил на основании многочисленных натурных данных интересный обобщающий график связи наносодерживающей способности водоема и его относительной емкости [28, 63, 65].

В 1939г., Г.И. Шамов составил обобщающую монографию по проблеме заиления водохранилищ. Он предложил сравнительно простой приближенный метод расчета общего заиления водохранилища, позволяющий по данным о морфологии водоема и о стоке наносов получить хронологический ход заиления. В последующие годы ряд детальных методов расчета заиления водохранилищ был предложены М.А. Мостковым, К.Н. Россинским, И.А. Кузьминым, А.А. Караушевым и др. [31, 32].

Изучение русловых процессов в бьефах водохранилищ началось в Узбекистане в 1950-е годы в связи с широким развитием регулирования речного стока [27].

Под руководством В.В. Пославского, С.Т. Алтунина и Э.П. Пилосова были организованы полевые исследования в верхнем и нижнем бьефах Фархадской плотины, Г.А. Цоя – на Кайраккумском водохранилище. Следует отметить натурные исследования С.А. Джамалова по изучению заиления водохранилищ на горных реках, а также детальное исследование процессов заиления малых водохранилищ на равнинных реках, выполненные Г.В. Лопатиным и К.Н. Лисициной [27].

С.Т. Алтунин предложил схему заиления водохранилища разделяющую его на озерную (свободной от отложений) и русловую (сосредоточены наносные отложений) части. В процессе заиления, русловая часть надвигается на озерную и одновременно распространяясь вверх по течению реки и создавая дополнительный так называемый динамический объем водохранилища [9, 54].

Наиболее обоснованную и подтверждаемую натурным данным методику расчета заиления водохранилищ предложил В.С. Лапшенков. В основу он положил формулу

(2.1) предложенную Г.И. Шамовым на основе эмпирической обработки отечественных и зарубежных водохранилищ. Зависимость выражает изменение объема подпорного бьефа по времени:

$$V_t = V_o e^{\varepsilon t} \qquad (2.1)$$

где

$V_o$ – предельно заиляемый объем (объем бьефа минус объем русла, формирующегося к концу заиления), м$^3$

$\varepsilon$ - характеристика заиляемости, зависящая от годового стока наносов (предельно заиляемого объема и начальной степени заиления),

$t$ – период эксплуатации водохранилища, годы.

В.С. Лапшенков обосновал эту формулу (2.1), сначала исходя из линейной связи между расходом сбрасываемых наносов и объемов отложений, полученных по натурным данным для заносимых бьефов, а затем на основе теории квазиламинарного режима осаждения при заилении [54]. Он уточнил выражения для ее параметров, причем теория квазиламинарного режима осаждения дала несколько иное выражение для определения показателя заиляемости, учитывающее гидравлическую крупность осаждающих наносов.

Для расчета распределения наносных отложений по длине водохранилища В.С. Лапшенков предложил распространить формулу (2.1) на любой створ водохранилища (с изменением $V_o$ и $\varepsilon$) и определить площадь заиления как разницу объемов отложений для двух створов, взятых при 1м.

Метод В.С. Лапшенкова использован при прогнозных расчетах многих проектов водохранилищ на реках Средней Азии и включен в качестве обязательного метода в строительные нормы. Разработкой методов расчета заиления водохранилищ занимались также А.Н. Гостунский, В.А. Скрыльников и др. [9, 20].

В.А. Скрыльников, анализируя осветление воды в водохранилище в зависимости от отношения объема русла $W_p$ к объему водохранилища $V$ по натурным и лабораторным данным, предложил разделить процесс заиления на две стадии. В первой стадии происходит почти полное осаждение стока наносов в водохранилище, характеризуемое постоянной степенью осветления $\varepsilon$ =95-97%, вторая начинается, когда в результате заиления объем водохранилища уменьшается до значений $V<7.7\text{-}W_p$, и характеризуется быстрым понижением степени осветления. Формула (2.1), по В.А. Скрыльникову, соответствует второй стадии заиления [54].

Существующие методы расчета процесса заиления в основном разработаны для схематизированных условий, часто существенно отличающихся от конкретных условий водохранилища и глубоководной (озерной) части регулирующей призмы.

В.С. Лапшенков разделяет эти методы на следующие три группы [37]:

**Первая группа** – методы этой группы основаны на материалах очень большого числа натурных исследований, в результате которых получены различные эмпирические зависимости или графики, связывающие объем отлагающих наносов (часто в %) с полным объемом водохранилища. При этом учитывается коэффициент зарегулирования стока, площадь водосбора реки, средняя мутность водотока, категории наносов, поступающих в водохранилище, глубина водохранилища, отметка дна и другие факторы.

К числу методов этой группы можно отнести работы Т.И. Шамова, Г.В. Лопатина, Д.И. Дрозда, и М.Я. Прыткова. Из зарубежных исследователей можно назвать работы

Т. Тейлора, Ф. Орта, Ж. Стивана, М. Брунее и У. Кира [5, 6, 9, 20, 28, 29, 30, 50, 54, 55, 56, 65, 87].

**Вторая группа** – балансовые методы, основанные на интегрировании дифференциального уравнения баланса наносов и русловых деформаций, связывающего отложения наносов между створами за элемент времени $\Delta t$ с изменением транспортирующей способности потока в этих створах в момент времени $t$. Теоретической основой, которых является система следующих трех дифференциальных уравнений:

Уравнение движения

$$\frac{\partial Z\textit{в}}{\partial x} = \frac{V^2}{C^2 R} + \frac{V}{g} * \frac{\partial V}{\partial x} + \frac{1}{g} * \frac{\partial V}{\partial t} \qquad (2.2)$$

Уравнение неразрывности

$$\frac{\partial Q}{\partial x} = \frac{\partial \Omega}{\partial t} = 0 \qquad (2.3)$$

Уравнение деформации

$$\frac{\partial Qs}{\partial x} + (1+\delta)[B * \frac{\partial Z\partial}{\partial t} + H * \frac{\partial B}{\partial t} + \frac{\partial(\rho * \Omega)}{\partial t}] \qquad (2.4)$$

где

$Z_в$ и $Z_д$ - соответственно отметки водной поверхности и дна, м;

$R$ и $C$ - гидравлический радиус, м и коэффициент Шези, $м^{1/2}$/сек;

$V$ и $\Omega$ - средняя скорость течения, м/сек и площадь, $м^2$;

$Q$ и $Q_s$ - расходы воды, $м^3$/сек и наносов, кг/сек;

$B$ и $H$ - ширина и средняя глубина потока, м;

$\rho$ - мутность потока, кг/$м^3$;

$\delta$ - пористость отложений.

При практической реализации данной системы уравнений, для замыкания исследователями принимаются уравнение расходов наносов, мутность, гидравлическое сопротивление, связи между основными размерами русла и связи между вертикальными и боковыми деформациями.

К числу методов второй группы относятся работы М.А. Великанова, А.В. Караушева, В.В. Романовского, И.И. Леви, М.А. Мосткова, С.Т. Алтунина, И.А. Бузунова, Ф.Ш. Мухамеджанова, К.И. Байманова и др. [9, 20].

**Третья группа** – методы, основанные на закономерностях осаждения наносов, установленных теоретически или экспериментально.

К числу методов третьей группы в основном относятся методы В.С. Лапшенкова, В.А. Скрыльникова, Х.Ш. Шапиро, Н.К. Отверченко, В.Б. Акулова, Г.Т. Давронова, И.А. Ахмедходжаевой и др. [9, 18, 54, 63].

При обзоре и анализе существующих методов расчета заиления водохранилищ было выявлено следующие:

1. Сложность расчета, требующих наличие большего объема исходной информации и громоздких дополнительных вычислений.
2. Большие отклонения результатов расчета от натурных данных по объему и месторасположению отложений наносов.
3. Имеющие методы расчета были разработаны для русловых водохранилищ, где предполагается уровень воды при НПУ.
4. Рассматриваются только мелкие фракции наносов и не учитываются переработка берегов и наносы, приносимые ветром, которые могут составлять примерно от 3 до 6% годового объема наносов.

Из обзора изучения проблемы заиления и методов расчета емкостей водохранилищ становится очевидным, что данная проблема является актуальной и методика расчета находится в незавершенной стадии решения, поэтому настоящая диссертационная работа посвящена к использованию геоинформационных систем для расчета объемов заиления эксплуатируемых водохранилищ.

## 2.2. Батиметрическая съемка чаши водоема

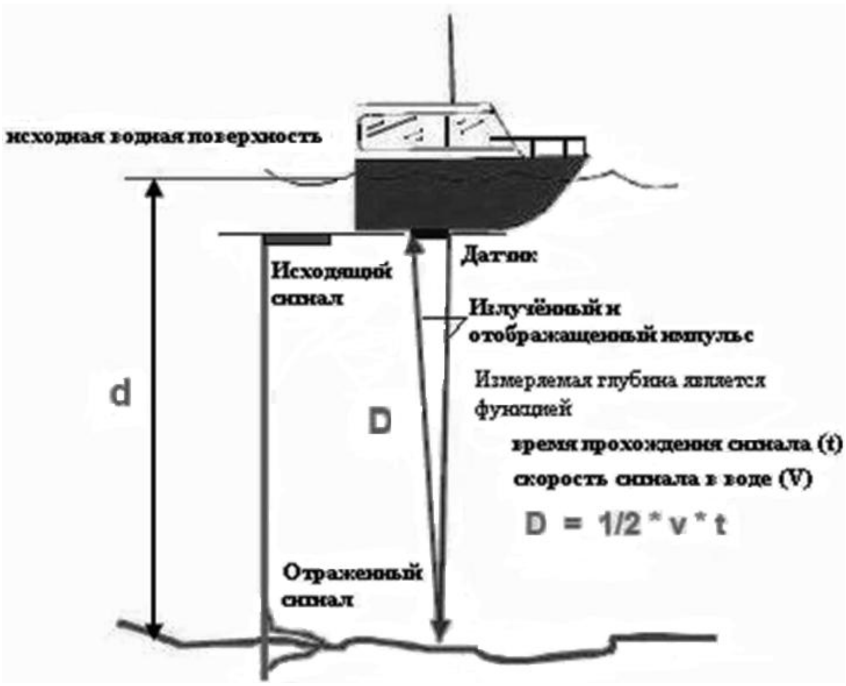
Одним из эффективных методов расчета объема заиления является повторные батиметрические съемки чаш эксплуатируемых водохранилищ, позволяющие получить конечные результаты заиления.

На сегодняшний день, существуют различные методы и технологии для проведения батиметрической съемки чаш водных объектов в гидрографических исследованиях. Например, широко используются акустическое эхолотирование с привязкой к GPS-системе, бортовая система эхолотирования LIDAR® и многопролетные гидролокаторы, которые позволяют исключить геодезические работы и в короткий срок провести эти изыскания с меньшими материальными затратами [47, 58, 64, 76, 77, 84, 85, 91, 96].

### 2.2.1. Гидроакустическая система замера глубин

Принципом работы этой системы является измерение затраченного времени звукового сигнала, излученным эхолот-датчиком (transducer) для прохождения толщи воды и отображения сигнала обратно от любой акустической отображающей поверхности к датчику (рис. 2.1) [77, 82].

На рис.2.1 $D$ – измеряемая глубина между отображающей поверхностью и эхолот-датчиком. Время прохождения сигнала зависит от скорости распространения сигнала ($v$) в толще воды. Если скорость распространения звукового сигнала в толще воды и расстояние между исходной водной поверхностью и эхолот-датчиком известна, то скорректированная глубина ($d$) может быть вычислена измеренным временем прохождения сигнала.




Источник: US Army Corps of Engineers. EM 1110-2-1003

**Рис. 2.1.** Система однопролетного гидроакустического метода для измерения глубины
**Figure 2.1.** Single beam acoustic depth measurement system

Скорректированная глубина к исходной водной поверхности вычисляется следующей формулой:

$$d = 1/2 \times (v \times t) + k + d_r \tag{2.5}$$

где
$d$ = скорректированная глубина от исходной водной поверхности (м),
$v$ = средняя скорость звукового сигнала в толще воды (м$^3$/сек),
$t$ = измеренное затраченное время сигнала от датчика до дна и обратно к датчику (сек),
$k$ = константа системы,
$d_r$ = расстояние от исходной водной поверхности к датчику (draft) (м).

Параметры $v$, $t$, $k$ и $d_r$ не определяются во время эхолотирования, а должны быть определены во время периодической тарировки измерительного оборудования. Истекшее время $t$, зависит от отражаемости поверхности и связанные методы обработки сигнала, использованные для распознания действительного отражения. Форма или резкость отображенного сигнала на рис.2.1 играет важную роль в точности определения глубины [77, 82].

Определение скорости звукового сигнала, $v$, является самым важным фактором в эхолотирование. Скорость звукового сигнала варьирует от плотности и других физико-химических свойств воды. Эти свойства воды зависит от температуры и содержания, взвешенных или растворённых веществ в воде, т.е. соленость. Значение температуры и солености воды резко варьирует от глубины и скорость звукового сигнала не будет постоянной на расстоянии от эхолот-датчика до дна, и отклонения могут быть очень значительными [82].

Например, если значение температуры изменить на один градус Цельсия то, произойдет изменение скорости звукового сигнала на 4,5 м/сек. На каждое изменение солености в 1 ‰, изменение скорости звукового сигнала выражается в 1,3 м/сек [77].

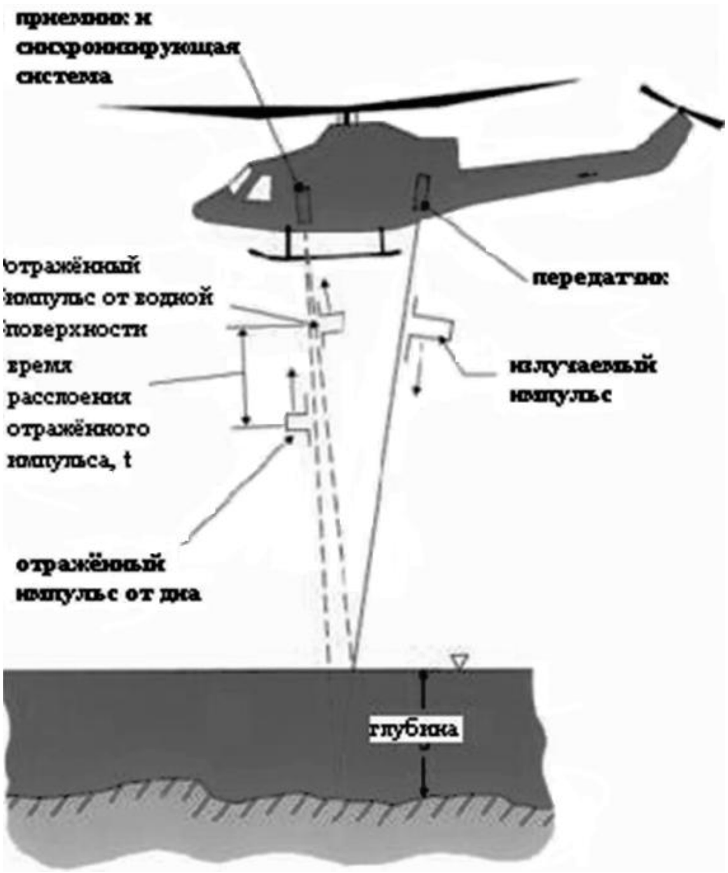
Частота акустического сигнала является параметром, которое определяет радиус действия и степень проникновения сигнала. Уменьшение амплитуды (затухание) звукового сигнала в воде пропорциональна частоте сигнала. Чем больше частота, тем и больше затухание звукового сигнала, и меньше радиус действия и проникновения к дну.

Типичные частоты, используемые в эхолотировании:

1. Глубины меньше 100 м, частоты больше 200 кГц;
2. Глубины меньше 1500 м, частоты от 50 до 200 кГц;
3. Глубины больше 1500 м, частоты от 12 до 50 кГц.

### 2.2.2. Бортовая гидрографическая система LIDAR

Эта бортовая гидрографическая система была разработана в США в 1990-х годах и предназначена для проведения батиметрической съемки водных объектов. Бортовой платформой может быть вертолет или маленький самолет. Эта система состоит их бортовой части, которая собирает данные и наземной, которая обрабатывает данные (рис.2.2) [76, 77].




Источник: US Army Corps of Engineers. EM 1110-2-1003.Глава 13.

**Рис. 2.2.** Бортовая система LIDAR

**Figure 2.2.** Airborne hydrographic system LIDAR

Принцип этой системы заключается в том что, она излучает лазерные импульсы частотой в 400 раз/сек и сканирует водную поверхность под углом 180 градусов. Лазерный импульс излучается от бортового датчика на водную поверхность, от которой отражается некоторая часть светового импульса и затем фиксируется бортовыми оптическими датчиками. Оставшийся световой импульс проходит через толщу воды, отражается от дна водоема и затем фиксируется бортовыми оптическими датчиками. Разница времени фиксации импульсов бортовыми оптическими датчиками отражения от водной поверхности и дна водоема и указывает на глубину.

Например, оперируя летательным аппаратом на высоте 300-500 м со скоростью до 70 м/сек позволяет проводить измерение глубины ячейки размером 4 м x 8 м и покрывает 35 км$^2$ в час. Плотность эхолотирования может быть изменена с помощью регулирования высоты полета летательного аппарата, скорости полета или выбором различной ширины сканирования.

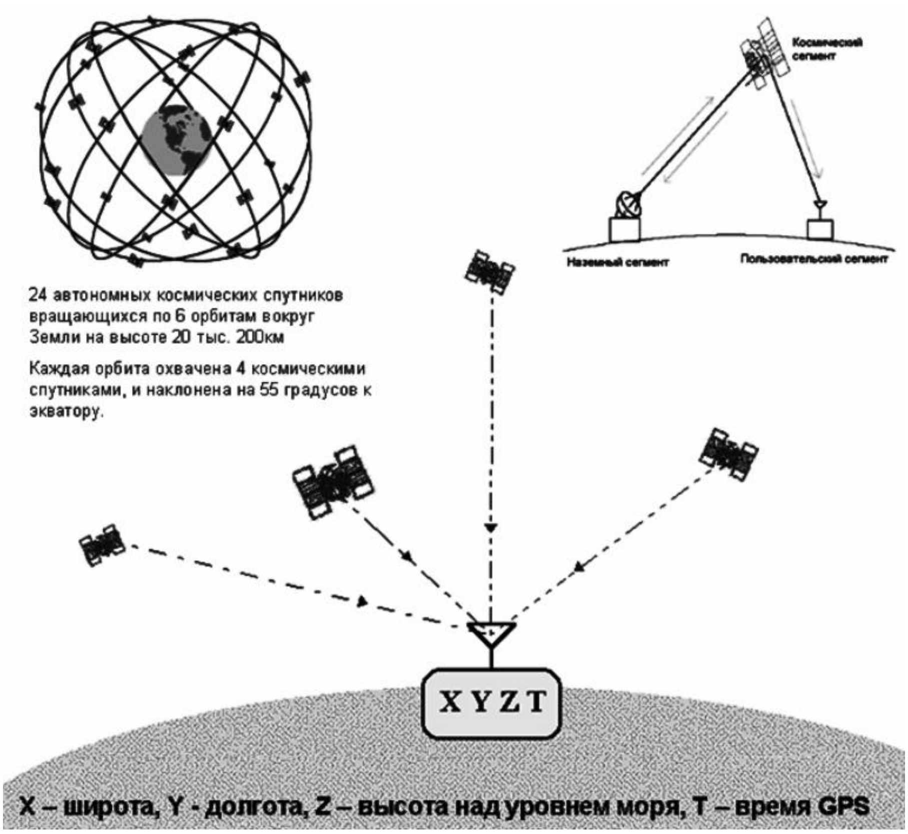
Эта система позволяет производит множество измерений для разработки пространственной цифровой модели местности для определения полезной емкости водохранилищ и определит объемы заиления.

Как и все системы, эта система также имеет ограничение и основным ограничивающим условием является прозрачность воды. В чистых водах, эта система функционирует на глубинах до 60 м, и не рекомендуется использовать эту систему в местах с высокой мутностью [77, 82].

## 2.3. Система глобального позиционирования (GPS)

Впервые, система глобального позиционирования – GPS (Global Positioning System) разрабатывалась для военных целей. Изначально, система GPS предназначалось для передачи навигационных сигналов, которые могут одновременно приниматься во всех регионах мира. Инициатором создания GPS-системы стало Министерство Обороны США в 1973 г. [76].

Глобальная система позиционирования (GPS) состоит из трех отдельных, связанных элементов: наземного сегмента (наземных станций слежения), космического сегмента (спутников) и пользовательского сегмента (персональных приемников GPS). Все три объединяются посредством передачи и приема радиосигналов рис. 2.3 [76].




Источник: Peter H.Dana. http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

**Рис. 2.3.** Состав системы GPS
**Figure 2.3.** Composition of GPS system

Системы GPS состоит из 24 автономных космических спутников вращающихся по 6 орбитам вокруг Земли на высоте 20 тыс. 200 км.

Каждая орбита охвачена 4 космическими спутниками, и наклонена на 55 градусов к экватору. Период обращения каждого автономного спутника по всей орбите составляет 12 часов. Орбиты расположены так, что в любой момент времени на линии прямой связи с любой точкой поверхности планеты находятся, по крайней мере, пять спутников, которые наклонены на 15 градусов к горизонтальной плоскости [76].

### 2.3.1. Принципы определения координат с помощью GPS системы

В основе определения координат GPS-приемника лежит вычисление расстояния от него до нескольких спутников, расположение которых считается известным (эти данные находятся в GPS-спутнике). В геодезии метод вычисления положения объекта по измерению его удаленности от точек с заданными координатами называется «трилатерацией» [43, 76].

Для определения трехмерных координат GPS-приемника используются как минимум, 4 спутника. Получив сигнал от 4 (или более) спутников, GPS-приемник ищет точку пересечения соответствующих сфер (рис. 2.3) [47].

Современные GPS-устройства обычно оснащены 6-8 приемниками, что позволяет отслеживать, практически, все навигационные спутники, находящиеся в зоне радиовидимости объекта. Если каналов меньше, чем «наблюдаемых» спутников, автоматически выбирается наиболее оптимальное сочетание спутников. Скорость обновления навигационных данных 1сек. Время обнаружения зависит от числа одновременно наблюдаемых спутников и режима определения местоположения.

Определение навигационных параметров может производиться в двух режимах - 2D (двумерном) и 3D (пространственном). В режиме 2D устанавливаются широта и долгота (высота считается известной). При этом достаточно присутствия в зоне радиовидимости 3 спутников. Время определения координат в режиме 2D обычно не превышает 2мин. Для определения пространственных координат абонента (режим 3D) требуется, чтобы в соответствующей зоне находились не менее 4 спутников. Гарантируются время обнаружения не более 3-4мин и погрешность вычисления координат — не более 100м [76].

Существует три основных принципа позиционирования: 1)абсолютное; 2)относительное; и 3)дифференциальное. В гидрографических исследованиях используется дифференциальное позиционирование. Три принципа позиционирования дают различные степени точности (см. таблицу 2.1) [76, 81].

Таблица 2.1

Степень точности позиционирования

**Table 2.1.** Positioning accuracies of location

| Принцип позиционирования | Точность |
|---|---|
| Абсолютный (стандартная система позиционирования) с измерением кода C/A на частоте L1 | 10-30 м |
| Абсолютный (точная система позиционирования) с измерением кода P (Y) на частоте L1/L2 | 5-15 м |
| Относительный с измерением статической фазы | 8-10 м или 6-10 м |
| Относительный с измерением фазы (RTK) | дециметр |
| Дифференциальный с измерением фазы кода (DGPS) | несколько метров |
| Дифференциальный с измерением несущей фазы (RTK DGPS) | несколько сантиметров |

Источник: US Army Corps of Engineers. EM 1110-2-1003.Глава 13.

## 2.4. Стандарты МГО в батиметрических обследованиях

При батиметрических обследованиях необходимо проводить два независимых измерения: X-Y (координаты месторасположения) и Z (глубину). В настоящее время для точного определения координат месторасположения эхолота-датчика на плавательном средстве широко используется система GPS. Для точного измерения величин глубин используют геостатистические методы анализа.

Необходимо кратко остановиться на обзоре погрешностей и ошибках в процессе измерения местоположения плавательного средства, на котором установлен GPS-датчик и эхолот для определения глубины. Под погрешностью или ошибкой понимается разница между измеренной величиной и фактической величиной измерения.

Существуют различные источники погрешности или ошибки в определении объема заиления в гидрографических изысканиях. Международная гидрографическая организация (МГО) (International Hydrographic Organization) разработала международный стандарт (S-44, 3-е издание, 1998) по гидрографическим исследованиям установив 95% интервал достоверности [81].

Необходимо вкратце рассказать о МГО. Это организация со штаб-квартирой в Монако была организована в 1920 году и её членами являются более 76 стран мира, такие как США, Канада, Германия, Англия, Франция, Россия, Китай, Австралия, Япония, Бразилия и др. Для полной информации посетите Интернет сайт организации по адресу http://www.iho.shom.fr [81].

Согласно международным стандартам по проведению гидрографических исследований разработанной МГО, погрешности или ошибки можно сгруппировать на следующие категории: 1) грубые; 2) систематические; 3) случайные [68, 74, 76, 81].

*Грубые погрешности (ошибки)* являются человеческим фактором, которые могут быть минимизированы в полевых измерениях или во время камеральной обработки данных. Грубые ошибки должны быть исключены различными проверочными процедурами и обучением специалистов.

*Систематические погрешности (ошибки)* могут быть смоделированы, и источником этой погрешности может быть неправильная калибровка оборудования или неправильное определение координат репера.

*Случайные погрешности* являются незначительными и возникают из-за ограничений измерительных приборов и процедур, а также являются положительными или отрицательными, и определяются статистическими законами вероятности. Случайные погрешности возникают вследствие неспособности точно измерить какую-либо величину или смоделировать систематическую погрешность.

В практике, согласно стандартам S-44 необходимо предположить, что случайные погрешности в гидрографических измерениях статистически нормально распределены (Гауссово распределение) [81].

Согласно статистике, 95% интервал достоверности означает на точность измеряемой величины или воспроизводство результатов измерений, т.е., 95 замеров глубин из 100 в гидрографическом обследовании воспроизводится с намеченной точностью.

Согласно международному стандарту S-44 все измерения глубины эхолотом должны быть выполнены относительно контрольной точке на берегу с 95% интервалом вероятности того, что фактическое местоположение должно находится в радиусе 1,5 мм от масштаба обследования. Например, для масштаба обследования в 1:10000, измерения глубины эхолотом должно быть определены в пределах 15 м относительно фактического местоположения с 95% интервалом достоверности [81].

Формула для определения пределов погрешностей в определении глубины:

$$\pm\sqrt{a^2 + (b * d)^2} \qquad (2.6)$$

где
$a$ = 1.0 м, $b$ = 0.023
$a$ – погрешность независимая от глубины, т.е., сумма всех постоянных погрешностей,
$b$ – фактор погрешности, которая зависит от глубины,
$d$ – глубина, м

(*b*d*) – погрешность, зависимая от глубины, т.е., сумма всех погрешностей, которые зависят от глубины.

## 2.5. Геостатистика

Геостатистика состоит из групп методик и методологий для проведения анализа и прогнозирования значений пространственно-временных величин для решения практических задач [73, 74, 84, 94, 95].

Целью геостатистического метода является прогноз значений величин на местах, где отсутствуют эти данные. При геостатистическом анализе должна существовать корреляция между пространственно-временными величинами и эти корреляции изучаются «структурным анализом» или «вариограммным моделированием». При этом анализе используются средневзвешенные значения величин, которые зависят от отдаленности соседних точек или пар точек значений друг от друга.

Геостатистический анализ проводится в следующей последовательности [35] (рис. 2.4).

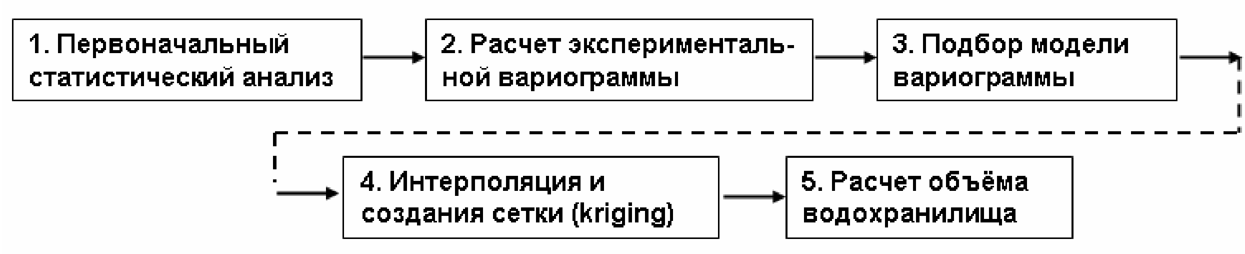



**Рис.2.4.** Метод геостатистического анализа
**Figure 2.4.** Schematics model of Geostatistical approach

1. Зондирующий статистический анализ проводится для первоначальной статистической обработки данных, для определения трендов и существование выбросов значений;
2. Вариограммное моделирование состоит из вычисления экспериментальной вариограммы и подбора математической функции к ней путем графического анализа. Также важным моментом исследований является изучение анизотропии (изменение физических характеристик среды в зависимости от направления их измерения). Анизотропия это соотношение между наибольшей и наименьшей дисперсии в данных интересующей величины;
3. Прогнозирование значений, где отсутствуют выборки этих величин с помощью интерполяционного метода –kriging и выбор оптимального размера ячейки сетки для построения батиметрической модели чаши водохранилища.

## 2.6. Программа SURFER

Основным назначением SURFER-7 является обработка и визуализация двумерных наборов данных, описываемых функцией типа $z=f(x,y)$, а логику работы с пакетом можно представить в виде трех основных функциональных блоков [35]:

а) Построение цифровой модели поверхности;
б) Вспомогательные операции с цифровыми моделями поверхности;

- Вычисление объема между двумя поверхностями;
- Переход от одной регулярной сетки к другой;
- Вычисление площади поверхности;

в) Визуализация поверхности.

Ключевой функцией SURFER является создание цифровой модели поверхности. Наиболее актуальная постановка данной задачи формулируется как переход от набора значений функции Z в произвольных (неупорядоченных) точках плоскости (N точек с координатами X,Y) к значениям этой функции в узлах некоторой регулярной сетки. В более общей постановке та же задача сводится к возможности вычисления значений функции в любой точке поверхности (а значит, и в узлах сетки) по исходному набору данных [49].

Пакет предоставляет пользователю довольно широкий набор математических методов интерполяции, которые позволяют выбрать наиболее оптимальную модель для решения конкретной прикладной задачи.

Но еще более важным достоинством SURFER является его возможность не только получить цифровую модель поверхности, но и провести оценку качества исходных данных и получаемых результатов. А это обеспечивает необходимые предпосылки для решения обратных задач, которые по большому счету и являются целью исследовательских работ [50, 51].

Основная особенность моделирования поверхности программой SURFER состоит в том, что территория разбивается на сетку с задаваемыми размерами сторон. Затем программа анализирует соответствие между заданных точек в горизонтальной плоскости и вершинами ячеек сетки модели [49].

Результатом этого анализа становятся значения глубин по оси Z для тех ячеек, в которых эти значения отсутствуют. Значение глубин рассчитываются по выбранному алгоритму на основе данных о соседних точках в зависимости от степени их влияния на точку расчета.

Цифровая модель поверхности традиционно представляется в виде значений в узлах прямоугольной регулярной сетки, дискретность которой определяется в зависимости от конкретной решаемой задачи [35, 49].

В принципе, возможно три варианта получения значений в узлах сетки; все они реализованы в пакете:

1. По исходным данным, заданным в произвольных точках области (в узлах нерегулярной сетки), с использованием алгоритмов интерполяции двухмерных функций;
2. Вычисление значений функции, заданной пользователем в явном виде; в состав пакета входит достаточно широкий набор функций — тригонометрических, Бесселя, экспоненциальных, статистических и некоторых других;
3. Переход от одной регулярной сетки к другой, например, при изменении дискретности сетки (здесь, как правило, используются достаточно простые алгоритмы интерполяции и сглаживания, так как считается, что переход выполняется от одной гладкой поверхности к другой).

Первый вариант получения сеточной модели чаше всего встречается в практических задачах, и именно алгоритмы интерполяции двухмерных функций при переходе от нерегулярной сетки к регулярной являются «козырем» пакета [49].

**Выводы по второй главе**

1. Обзор существующих методов расчета заиления показал недостатки, и сложность использования этих методов ввиду громоздких объемов исходной информации для расчетов. А также, значительные отклонения результатов натурных и расчетных исследований.
2. Геоинформационные технологии позволяют в сжатые сроки проводить сбор натурных данных и провести камеральную обработку данных с увязкой к GPS-системе. Это позволяет оперативно создавать в цифровом формате карты чаши объекта и проводить автоматизацию расчета объемов водохранилища.
3. С помощью GPS-системы можно быстро и эффективно в реальном времени определить точное месторасположение объектов в любое время года и дня, вне зависимости от метеоусловий. С известными координатами можно построить цифровую модель поверхности.
4. При различных условиях сбора натурных данных существуют различные факторы и источники погрешности в процессе сбора и использования техники и технологий, и поэтому очень важно учесть эти погрешности в расчетах с помощью интерполяционных моделей, в частности геостатистика.
5. Геостатистический метод позволяет проводить интерполяцию и прогноз значений из дискретных данных и с помощью вариограммного моделирования установить научно обоснованную ячейку сетки для батиметрической модели чаши водохранилища.
6. С помощью программы SURFER можно создать цифровую батиметрическую модель чаши объекта и рассчитать объемы и провести статистическую обработку данных в сжатые сроки и увеличить качество работ.

## ГЛАВА 3.
## ОБЪЕКТ ИССЛЕДОВАНИЯ И ТЕХНИКО-КЛИМАТИЧЕСКИЕ УСЛОВИЯ РАЙОНА

### 3.1. Акдарьинское водохранилище

Акдарьинское водохранилище руслового типа, сезонного регулирования, образовано строительством плотины в наиболее узком месте поймы р.Акдарья (рис. 3.1). Это водохранилище расположено в 15 км к северо-западу от г.Иштихан на границе Иштиханского и Каттакурганского туманов Самаркандской области Республики Узбекистан [26, 57, 60].

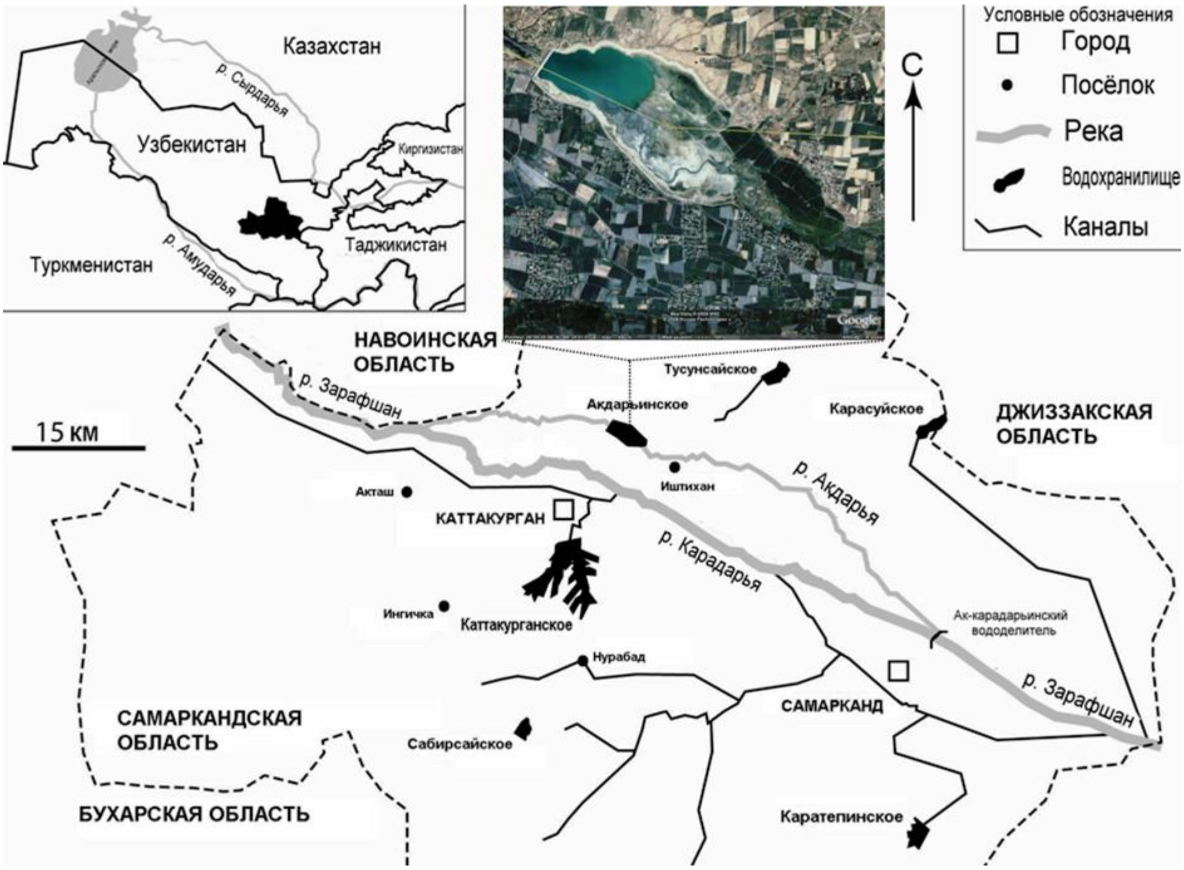



**Рис. 3.1.** Месторасположение Акдарьинского водохранилища
**Figure 3.1.** Location of Akdarya reservoir and study site

Основное предназначение водохранилища является орошение 5,5 тыс. га новых земель и повышения водообеспеченности 12 тыс. га староорошаемых земель Иштиханского и Каттакурганского туманов Самаркандской области [60].

### 3.2. Рельеф и геоморфология

Современная долина р.Акдарьи, как геоморфологически, так и литологически вложена в отложения пролювиальной долины. Последняя сложена лессовидными суглинками мощностью от 5 до 40 м, подстилает их мощная толща галечников около

300 м. Центральная часть плотины располагается в пойменной части р.Акдарья. Современная пойма реки сложена суглинками, мелкоземами и галечниками аллювиального генезиса. Мощность мелкоземов варьирует от 0,5 до 5 м [58, 60].

Русло реки хорошо выражено, сложено гравелисто-галечниковыми отложениями. Изменение высотных отметок на протяжении всего протока р.Акдарьи колеблется от 680,0 до 400,0 м абс.

Рельеф прилегающей местности представлен с правого берега низкогорьем с выровненными вершинами, постепенно переходящими в аллювиально и пролювиально предгорные равнины и пойменные равнины, по левому берегу с пойменными и террасовыми равнинами. Поверхность территории представлена современными отложениями русел рек и конусов выноса мелких водотоков [60].

### 3.3. Гидрологическая характеристика

Река Акдарья является правым рукавом реки Зарафшан, у Ак-карадарьинского вододелителя, расположенного восточнее г.Самарканда, р.Зарафшан разделяется на два постоянных рукава: северный (Акдарья) и южный (Карадарья). Рукава образуют остров длиной 100 км и 15 км шириной, под названием Мианкуль. Рукава вновь соединяются в одно русло западнее г.Хатырчи [60].

Акдарьинское водохранилище расположено на протоке Акдарья на 50 км ниже Ак-карадарьинского вододелителя. Река Акдарья имеет длину 131 км и протекает по широкой пойме состоящей из поймы и пойменной террасы, преобладающая ширина пойменной террасы 0,2-0,6 км при максимальных значениях на отдельных участках до 1,5-2,0 км. Русло умеренно извилистое и разветвленное. Берега неустойчивые и местами обрывистые или крутые. Река протекает по широкой Зарафшанской долине сложенной преимущественно лёссовыми отложениями [26].

В настоящее время Акдарья может быть служить только сбросными катастрофическим трактом р.Зарафшан, в то время как основной поток реки идет по её левому протоку Карадарья. Кроме того, Акдарья является приемником сбросных и выклинивающихся вод на всем протяжении и собирает доходящие до нее селевые паводки с правобережных притоков, имеющие место при выпадении обильных осадков (табл. 3.1) [60]. В Акдарьинское водохранилище попадать сток с площади 2020 км$^2$: из них активное стокоформирование - 1500 км$^2$ [59].

Таблица 3.1

Водные ресурсы в створе Акдарьинского водохранилища

**Table 3.1.** Water resources feeding Akdarya reservoir

| **Характеристика (млн. м$^3$)** | **Средний год** | **Маловодный год** |
|---|---|---|
| Сбросы из р. Зарафшан | 250 | 200 |
| Выклинивающиеся воды | 160 | 100 |
| Сбросные воды | 180 | 130 |
| ИТОГО | 590 | 430 |
| Водозабор | 230 | 210 |
| Сток в створе плотины | 360 | 220 |
| м$^3$/с | 11,4 | 7 |

Источник: Уздавсувлойиха, 2002г.

### 3.4. Климат

Рассматриваемая территория расположено в субтропических широтах и положение района в глубине континента обуславливает засушливость климата и значительные амплитуды колебания температур. Горные системы, ограничивающие, территорию с севера обуславливают местные особенности климата, и в частности режим осадков и ветра.

При анализе метеорологических элементов, определяющих основные черты климата, использованы данные наблюдений по метеостанциям г.Каттакурган и Каттакурганского водохранилища [26, 60].

Годовая норма осадков за многолетний период составляет 282 мм. Более 90% годовой нормы осадков выпадает в период ноябрь-май. В период июнь-сентябрь осадков практически не бывает. Суточный максимум 1% обеспеченности составляет 88 мм. Испарение с водной поверхности по данным наблюдений по Каттакурганскому водохранилищу составляет 1200 мм/год.

### 3.5. Твердый сток

В данном разделе рассматривается общий режим твердого стока реки в естественных условиях. Общая характеристика твердого стока рассматривается по данным наблюдений по створу Дупули (табл.3.2) [60].

Основной сток взвешенных наносов проходит в период апрель-сентябрь (до 95% от годового) среднегодовой сток взвешенных наносов составляет 4.4 млн.т., при колебаниях в зависимости от водности года 1,0 до 8.2 млн.т., наибольший суточный сток наносов достигает до 5100 кг/сек. Среднегодовая мутность составляет 0,87 кг/м$^3$ при амплитуде колебаний от 0,86 до 1,6 кг/м$^3$. Наблюденная максимальная мутность составляет 12 кг/м$^3$ [60].

Таблица 3.2

Характеристики твердого стока (взвешенные наносы) р. Зарафшан гидропост Дупули (среднемноголетние данные)

**Table 3.2.** Sediment and water discharge of Akdarya reservoir area

| **Характеристика** | **Январь** | **Февраль** | **Март** | **Апрель** | **Май** | **Июнь** | **Июль** | **Август** | **Сентябрь** | **Октябрь** | **Ноябрь** | **Декабрь** | **Год** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Расходы, $м^3$/сек | 38,3 | 35,1 | 34,8 | 50,1 | 141 | 335 | 464 | 375 | 193 | 85,7 | 56,3 | 44,4 | 154 |
| Расход взвешенных наносов, кг/сек | 2,51 | 2,38 | 4,02 | 15,3 | 105 | 288 | 673 | 476 | 97 | 8,4 | 3,4 | 2,7 | 138,6 |
| Мутность, кг/$м^3$ | 0,07 | 0,07 | 0,117 | 0,289 | 0,532 | 0,842 | 1,43 | 1,30 | 0,497 | 0,096 | 0,058 | 0,10 | 0,10 |
| Сток воды, млн.$м^3$ | 102 | 83,7 | 91,7 | 137 | 407 | 871 | 1240 | 972 | 498 | 233 | 150 | 121 | 4925 |
| Сток взвешенных наносов, тыс.т. | 6,72 | 5,78 | 10,8 | 39,7 | 281,2 | 746,5 | 1803 | 1275 | 251,4 | 22,5 | 8,81 | 7,23 | 4371 |

Источник: Уздавсувлойиха, 2002г.

### 3.6. Технические характеристики водохранилища

Технический проект строительства Акдарьинского водохранилища был выполнен институтом «Самаркандгипроводхоз» в 1980 г. и утвержден министром МС и ВХ УзССР (протокол №132 от 3 марта 1980 г.).

Было решено строить водохранилище поэтапно табл.3.3 [57].

Таблица 3.3

Этапы строительства Акдарьинского водохранилища

**Table 3.3.** Construction phases of Akdarya reservoir

| | Год | Полный объем водохранилища при НПУ (млн. $м^3$) | Отметка НПУ (м) |
|---|---|---|---|
| Строительство | | | |
| I-очередь | 1982 | 34 | 487,8 |
| II-очередь | | | |
| 1-комплекс | 1985 | 50 | 489,0 |
| 2-комплекс | 1987 | 70 | 491,5 |
| 3-комплекс | 1989 | 90 | 493,55 |
| Реконструкция | | | |
| | 2000 | 112,5 | 494,5 |

Источник: Уздавсувлойиха, 2002г.

**Состав и характеристика сооружений**

Земляная плотина. Плотина выполнена из галечникового грунта с наклонным ядром из суглинка. Высота плотины 20 м. Напор 16,5 м. Длина по гребню составляет 930 м. Абсолютная отметка гребня 498.00 м.

Левобережная дамба. Для увеличения емкости водохранилища вдоль низменного левого борта водохранилища построена дамба из суглинка с креплением откосов галечником и железобетонной облицовкой на верховом откосе. Высота дамбы 7м. Длина по гребню составляет 6400м. Абсолютная отметка гребня 498.00м.

Правобережная дамба. Правобережная дамба из суглинка с креплением откосов галечником и железобетонной облицовкой на верховом откосе. Высота дамбы 2 м. Длина по гребню составляет 530 м. Абсолютная отметка гребня 498.00 м. В табл. 3.4 приведены проектные данные Акдарьинского водохранилища.

Таблица 3.4

Проектные параметры Акдарьинского водохранилища

**Table 3.4.** Design characteristics of Akdarya reservoir

| Наименование | Показатель | Наименование | Показатель |
|---|---|---|---|
| Полный объем | 112,5 млн.$м^3$ | Отметка ФПУ | 496,7 м |
| Полезный объем | 110,0 млн.$м^3$ | Отметка НПУ | 494,5 м |
| Мертвый объем | 2,5 млн.$м^3$ | Отметка УМО | 480,85 м |
| Средняя глубина | 13,7 м | Площадь зеркала при НПУ | 12,7 $км^2$ |
| Площадь зеркала при УМО | 3,5 $км^2$ | Максимальная длина при НПУ | 8,5 км |
| Максимальная ширина НПУ | 2,4 км | Максимальная глубина при НПУ | 23,4 м |

Источник: Уздавсувлойиха, 2002г.

# ГЛАВА 4.
# МЕТОДИКА И ОБОРУДОВАНИЕ

## 4.1. Батиметрической съемки чаши водохранилища батографом CEEDUCER и GPS-системы

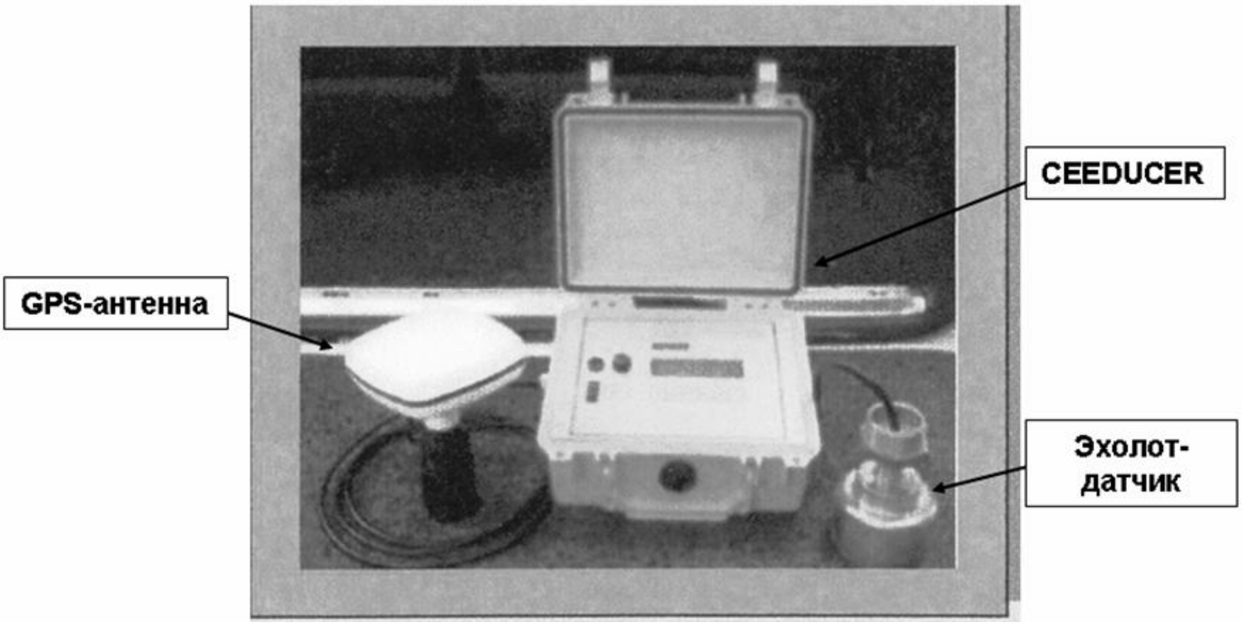
С 2001г. Батиметрический центр Минсельводхоза Республики Узбекистан начал использовать новую технику и оборудование CEEDUCER® австралийской компании Bruttour International Ltd для расчета объемов водохранилищ. Как показал опыт, эта технология показала хорошие результаты [58].

На CEEDUCER можно исключить некоторые виды геодезических работ и инструменты, составляющих традиционную методику.

Преимущества новой технологии:

- Исключение некоторых видов геодезических работ и инструментов;
- Для создания планово-высотного обоснования можно исключить применение теодолита и дальнометра;
- При создании локальной сети без ориентирования километровой сетки к государственной сетке достаточно одного геодезического пункта, имеющего координаты и отметку. При помощи базовой станции в позиции «HERE» можно получить координаты в системе WGS-84 (World Geodetic System, 1984г.) и развить локальную сеть для объекта в целом;
- Уменьшение периода обследовательских работ и уменьшение затрат.

CEEDUCER является компактным переносным устройством, которое состоит из следующих частей (рис.4.1) [66, 67]:




Источник: Руководство по применению батографа «CEEDUCER». http://www.bruttour.com.au

**Рис.4.1.** Оборудование «CEEDUCER»
**Figure 4.1.** Composition of CEEDUCER device

1. Датчика GPS 8- или 12-канальный, точность 2-3м (8-канальный) или <1м (12-канальный);
2. Цифровой эхолот-датчик (transducer)

- Частота акустического сигнала 200кГц
- Радиус действия измерения глубины от 30см до 99,99м
- Точность 0,02% от измеряемой глубины и разрешающая способность 1-см

3. Записывающее устройство CEEDUCER с микропроцессором, с помощью которого настраивают и сохраняют: координаты проекции в системе WGS-84, скорость звукового сигнала автоматически или ручная настройка, а также величину «draft», т.е, расстояние между эхолот-датчиком и водной поверхностью. Записывающее устройство работает 7,2 часа.

Система координат проекции WGS-84 (datum) - датумы лежат в основе процедуры преобразования координатных систем и картографических проекций, геометрические связи которых определены через измерение или вычисление. Одна из компонент определения системы координат - эллипсоид, используемый для аппроксимации формы Земли [66, 67].

На рис.4.2 показана компоновка оборудования, которая используется для проведения батиметрической съемки чаши водоема с батографом CEEDUCER [58, 66, 67].

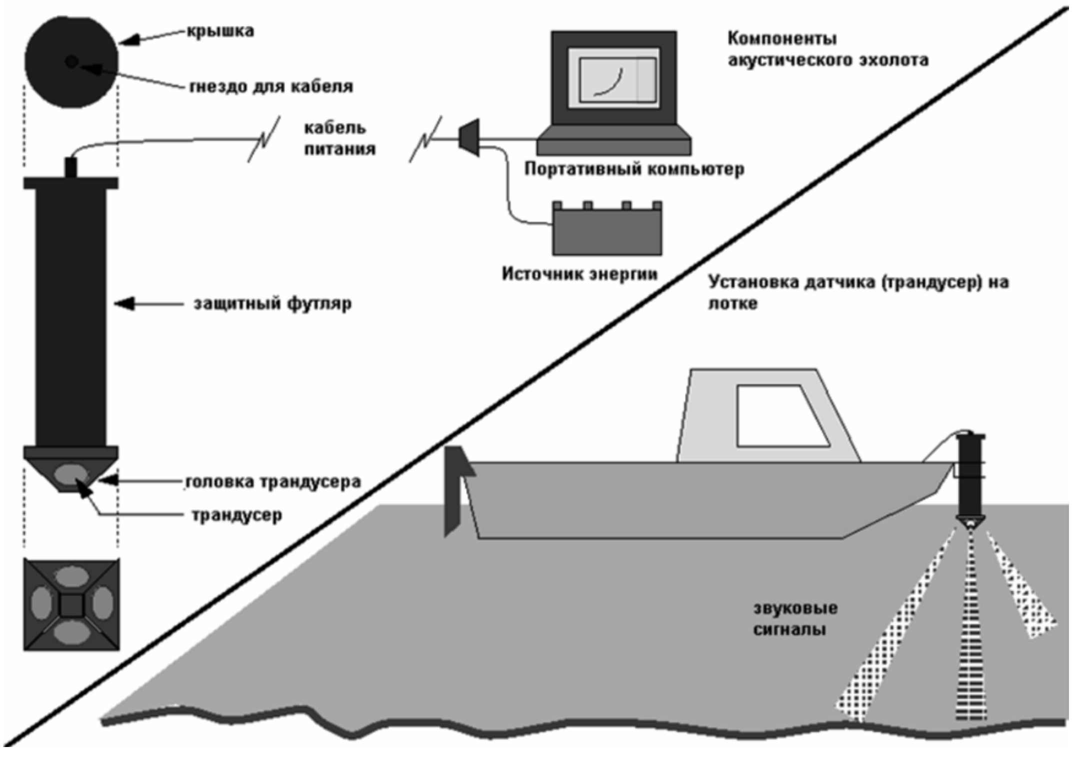



**Рис.4.2.** Схема компоновки оборудования для батиметрической съемки
**Figure 4.2.** Mounting of GPS+CEEDUCER on floating boat

Необходимо закрепить датчик-эхолот на плавательное средство таким образом, чтобы производить замер глубин и расположить антенну GPS вблизи и над датчиком-эхолотом (рис.4.3). Расположение датчика-эхолота является важной составной частью гидрографического обследования и рекомендуется расположить его по середине плавательного средства для наименьшего воздействия мотора и турбулентности воды.

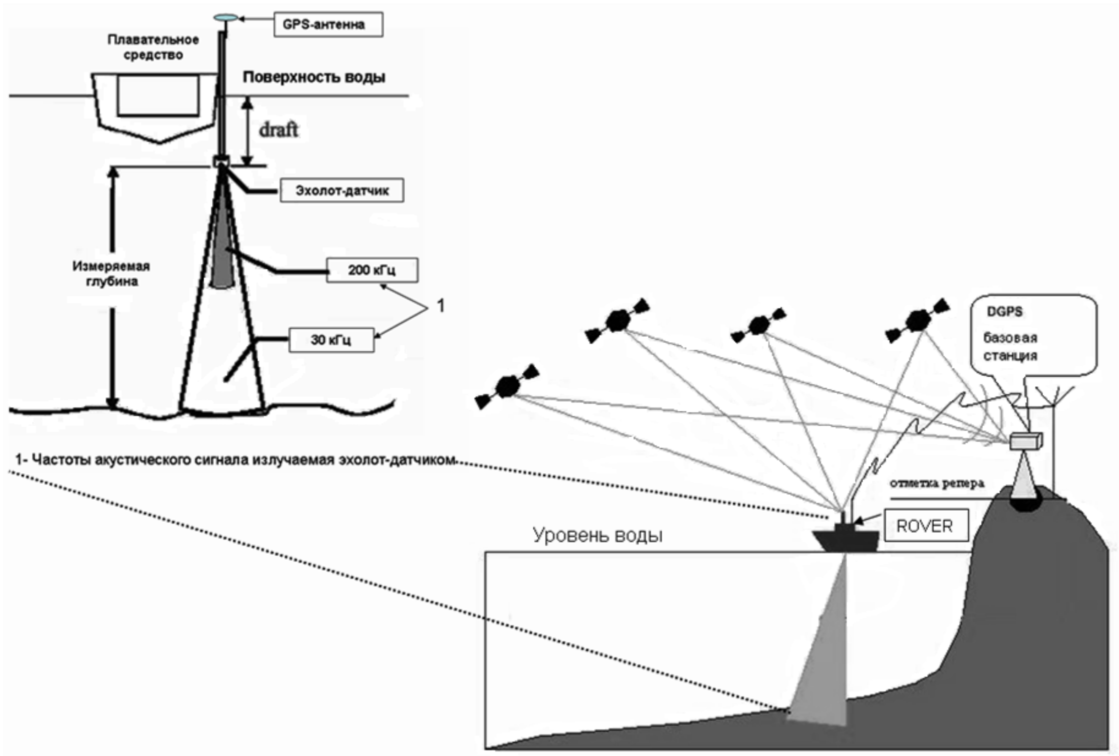



**Рис.4.3.** Расположение датчика-эхолота и антенны GPS
**Figure 4.3.** Depth measurements by GPS and CEEDUCER

При создании локальной высотно-плановой сети объекта только достаточно одного геодезического пункта, имеющего координаты и отметку. На этом пункте устанавливаем с помощью контрольного GPS-приемника базовую станцию [12, 14, 58].

Установив базовую станцию «BASE RTK» на геодезическом пункте «Остров», ввели отметку этого пункта в позиции «HERE» и при помощи «RTK ROVER» определили координаты других базовых точек, которые были выбраны при рекогносцировке, в Акдарьинском водохранилище были определены 3 базовых точек. Радиус действия телеметрической антенны 7 км [58].

Сравнивая известные координаты (базовой станции) с измеренными координатами, контрольный GPS-приемник вырабатывает поправки, которые передаются мобильному передатчику «ROVER» по радиоканалу.

Поправки, принятые от базовой станции, автоматически вносятся в мобильный передатчик на плавательном средстве, где производятся замеры глубин, т.е., получаем значения (X, Y) координат.

Тарировка датчика-эхолота проводилась два раза, до проведения батиметрической съемки и после каждого дня изыскательных работ (табл.4.1).

Таблица 4.1

Результаты тарировки датчика-эхолота
**Table 4.1.** Calibration of eco sounder in Akdarya reservoir

| Показание по рулетке (м) | Показание эхолота (м) | | | Среднее значение (м) |
|---|---|---|---|---|
| | 1 | 2 | 3 | |
| 3 | 2,99 | 3,01 | 3,02 | 3,01 |
| 4 | 4,01 | 4,02 | 4,02 | 4,02 |

| | | | | |
|---|---|---|---|---|
| 6 | 5,98 | 6,01 | 5,99 | 5,99 |
| 8 | 7,99 | 8,02 | 8,00 | 8,01 |
| 10 | 9,98 | 9,99 | 10,00 | 9,98 |
| 12 | 11,98 | 12,02 | 12,01 | 12,00 |
| 14 | 13,99 | 14,01 | 14,02 | 14,01 |
| 17 | 16,98 | 17,02 | 16,97 | 16,98 |
| 18 | 17,97 | 17,96 | 17,99 | 17,97 |
| 20 | 19,99 | 20,03 | 20,02 | 20,02 |

Источник: Батиметрический центр, 2006г

Фактическая измеряемая глубина плюс значение draft вычитаются от уровней водной поверхности и определяем глубину.

На местах мелководий, где невозможно работа CEEDUCER измерения глубины воды проводились в ручную, т.е., метровым шестом. Важным моментом является получение репрезентативных точек измерений в пределах воды. В начальных створах Акдарьинского водохранилища наблюдается зарастание растительностью и размывы правого берега, где местами образовались крупных оврагов от 10 до 50 м [58].

После замеров глубин, были проведены измерения координат с помощью GPS-антенны по периметру водохранилища на берегу, максимально приближено в водной линии для замыкания объекта для расчета объема и площадей водоема с помощью компьютерной программы SURFER.

Первоначальная обработка данных производиться пакетом программного обеспечения MiniCee®. Значения координат позиционирования были исправлены в силу наблюдаемых аномалий, которые вызваны потерей сигнала излучаемой базовой станцией GPS к мобильному устройству GPS, расположенной на плавательном средстве вызванной топографическими условиями местности. Значения координат настраивались путем интерполяции назад к средней точке измерения, которая расположена между двумя соседними точками. Значения глубин также исправлялись путем интерполяции назад к средней точке, расположенная между двумя соседними точками, где наблюдались аномалии [58].

На рис.4.4 показано состояние Акдарьинского водохранилища и траектория замера глубин с помощью батографа CEEDUCER в 2003г.

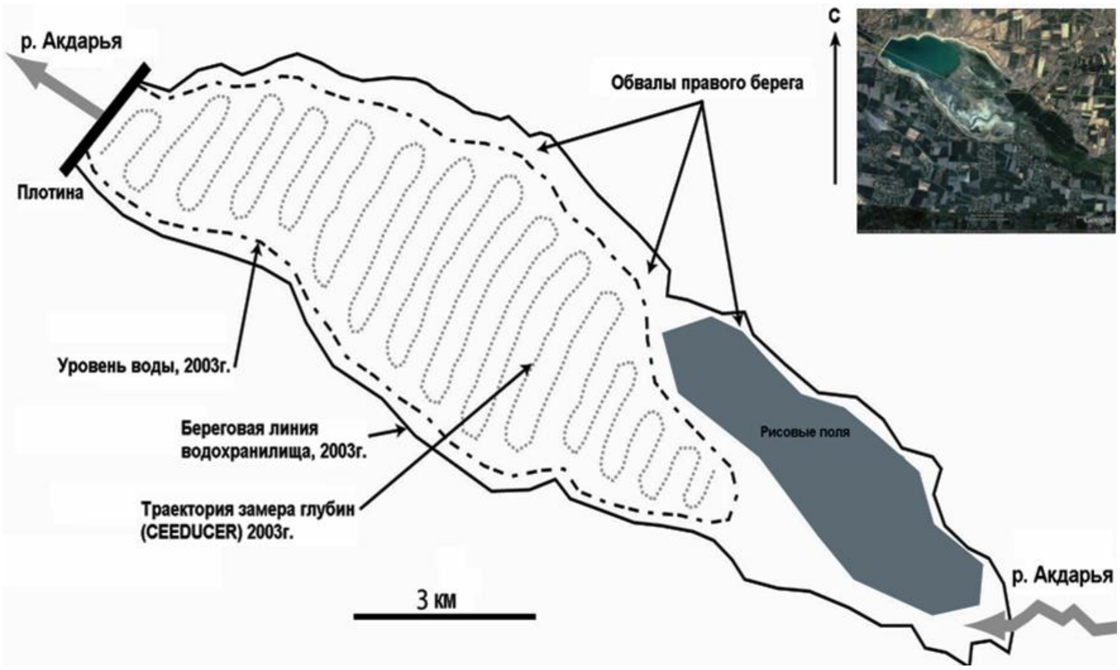



**Рис.4.4.** Состояние Акдарьинского водохранилища и замер глубин
**Figure 4.4.** Data measurements with bathymetric system CEEDUCER and current conditions of Akdarya reservoir in 2003

## 4.2. Геостатистический метод расчета объема водохранилища программой SURFER

### Вариограммное моделирование

Вариограммное моделирование представляет собой расчет экспериментальной вариограммы из данных и подбора модели вариограммы к этим данным. Вариограмма характеризует пространственную непрерывность или шероховатость (шум) в данных [73, 84].

Экспериментальную вариограмму рассчитываем по следующей формулой:

$$\hat{\gamma}(h) = \frac{1}{2N_h} \sum_{x_j - x_i \approx h} \left[ z(x_j) - z(x_i) \right]^2 \qquad (4.1)$$

где

*γ(h)* – двухмерный график и/или формула описывающей ожидаемые средние разности значений между парами выборок при определенном пространственном расположении и на расстоянии *(h)*, (м$^2$)

*h* – расстояние между двумя дискретными точками измерения, которые используются для вычисления дисперсии (м),

N – количество пар измерений величин ,

*z* – интересующая величина или атрибут данных,

*i* и *i-h* – индекс соответствующих величин двух измерений на расстоянии *h*.

Модель вариограммы выбираем из общеизвестных математических функций (линейная, логарифмическая, показательная, квадратичная и др.), которые описывают пространственные взаимосвязи. Соответствующая модель вариограммы подбирается путем графического анализа к форме кривой экспериментальной вариограммы и изучаем анизотропия в различных направлениях (рис.4.5) [64].

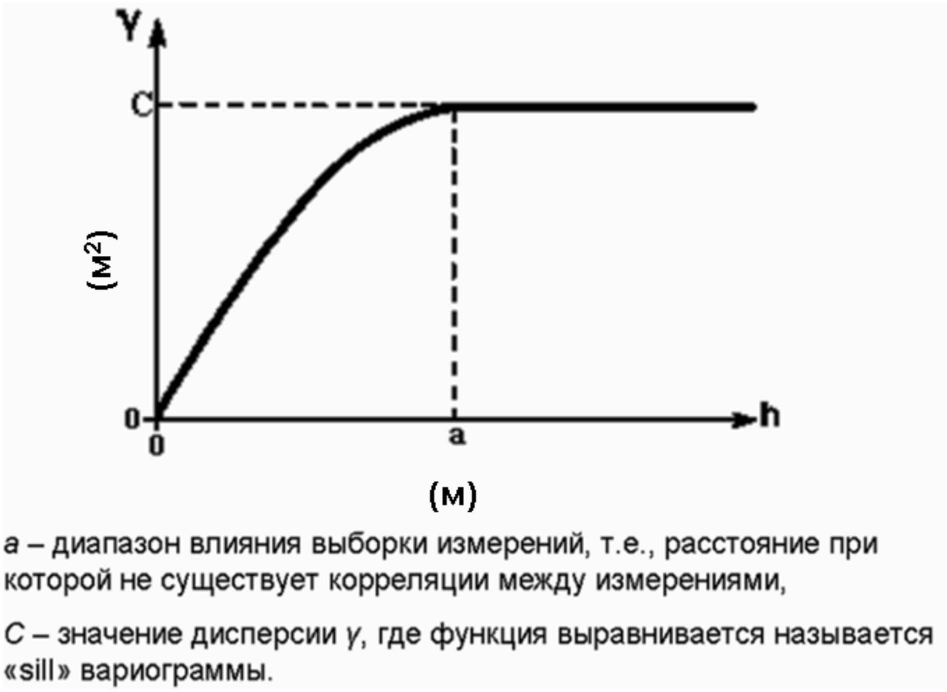



**Рис.4.5.** Сферическая модель вариограммы
**Figure 4.5.** Spherical variogram model

Сферическую модель вариограммы рассчитываем формулой

$$\gamma(h) = C(\frac{3h}{2a} - \frac{h^3}{2a^3}), h \le a$$
$$\gamma(h) = C, h \ge a \qquad (4.2)$$

где

$\gamma(h)$ –дисперсию ожидаемых разностей значений между парами выборок глубин на расстоянии $h$ (м$^2$);

$h$ – расстояние между двумя дискретными точками измерения (м);

$a$ – диапазон влияния выборки (м);

$C$ – значение дисперсии $\gamma$, где функция выравнивается (м$^2$).

Существенным фактором при построении сетки данных является степень точности отражения исходных данных в рассчитанной сетке. По этому признаку все интерполяторы подразделяются на *сглаживающие* и *точные*.

*Сглаживающие* интерполяторы равномерно распределяют факторы веса между точками и, соответственно, производят более ровные поверхности. Сглаживающие интерполяторы обычно применяются в тех случаях, когда в исходных данных предполагаются ошибки или же данные распределены неравномерно.

*Точные* интерполяторы присваивают вес 1.0 только тем исходным точкам, которые попадают точно в ячейку сетки. Уменьшение размера ячейки в рассчитываемой сетке обеспечивает большую вероятность совпадения горизонтальных координат исходного значения и ячейки, что гарантирует максимальную точность отражения исходных данных [81].

Нами была разработана руководство по применению программы SURFER-7, где подробно описана последовательность работы с программой для расчета объема водохранилища (см. приложение 3) [12, 14]. В этом разделе остановимся на основных этапах, и обсуждаются важные аспекты расчета (рис.4.6).


**Рис.4.6.** Этапы расчета объемов в программе SURFER
**Figure 4.6.** Steps for calculation of reservoir volumes by SURFER

**1. Создание файла данных X-Y-Z.** Файл данных X-Y-Z должен содержать минимум три столбца со значениями координат (*X, Y*) и глубины (*Z*). Рекомендуется вносить значения данных по следующей последовательности, *X*-значения, *Y*-значения и *Z*-значения. Программа SURFER принимает эту последовательность по умолчанию при расчетах. При сохранении Файла Данных необходимо выбрать Golden Software Data (*.dat) из списка возможных типов файлов.

**2. Вариограммное моделирование.** Одной из самых важных частей геостатистического анализа является расчет экспериментальной вариограммы и изучение анизотропии. Поэтому, этот аспект требует особенного внимания. Для создания экспериментальной вариограммы (Variogram) необходимо выбрать ранее созданный файл данных X-Y-Z. Затем настраиваем параметры variogram, т.е., шаг направления «lag direction», оценочную функцию «estimator type», максимальный шаг расстояния «max lag distance», количество шагов «number of lags», ширину шага «lag width», и вертикальную шкалу «vertical scale».

С помощью опции «Lag Direction» рассматриваем вариограмму в различных направлениях. Единицы измерения направления: 0° в направлении положительной X-оси, и 90° в направлении положительной Y-оси.

При создании модели вариограммы, необходимо рассмотреть экспериментальную вариограмму и математическую функцию во многих направлениях. Программа

SURFER 7 позволяет исследовать вариограмму во многих направлениях шагом направления в анимированном виде. Так как, программа SURFER 7 использует метод вариограммной сетки, которая может вычислять и мгновенно вычерчивать диаграмму. С помощью опции «Step Amount» уточняем инкремент шага направления в «lag Direction» каждый раз, когда нажимаем на кнопки «Step CW» или «Step CCW».

С помощью опции «Max Lag Distance» определяем длину шага расстояния на X-оси. Значение в опции «Max Lag Distance» уже определено при создании сетки вариограммы (New Variogram) для ограничения максимальной длины разделения при исследованиях.

С помощью опции «Number of Lags» определяем количество использованных (вычисленных и нанесенных на диаграмму) точек для построения экспериментальной вариограммы. Количество точек составляет 25 по умолчанию.

Необходимо выключить отметку «Auto», значение в опции «Lag Width», которая автоматически приравнивает числовое значение в опции «Max Lag Distance» деленное на число «Number of Lags». Например, если ввести числовое значение 100 в опцию «Max Lag Distance» и числовое значение 5 в опции «Number of Lags», тогда автоматически числовое значение в опции «Lag Width» будет 100/5=20. В этом случае первая точка диаграммы будет включать все пары точек с шагом расстояния от 0 до 20 м. Вторая точка диаграммы будет включать все пары точек с шагом расстояния от 20 до 40 м. Интервалы расстояний от 0 до 20,  от 20 до 40, ..., от 80 до 100; при этом не происходит перекрытие. С помощью опции «Lag Width» используем для сглаживания вариограммы.

С помощью опции «Vertical Scale» определяем размер (длину) Y-оси вариограммы. При выполнении шагового расчета с использованием кнопок «Step CCW» или «Step CW» вертикальная шкала изменяется при каждом шаге. При отключении отметки «Auto», вертикальная шкала остается постоянной, т. е., числовое значение не изменятся.

С помощью табулятора «MODEL» в диалоговом окне **Variogram Properties** устанавливаем модель вариограммы и её параметры. Расчет экспериментальной вариограммы из генеральной совокупности данных, является бесспорным путем для определения вариограммной модели.

В программе SURFER существует 10 общих математических функций: Nugget Effect (Эффект Самородка), Spherical (Сферическая), Exponential (Показательная), Linear (Линейная), Gaussian (Гауссово), Wave (Hole-Effect) (Волновая), Quadratic (Квадратичная), Rational Quadratic (Рационально квадратичная), Logarithmic (Логарифмическая), и Power (Степенная).

За исключением вариограммных моделей Linear, Logarithmic, and Power (у которых нет «sill»), параметры шкалы «Scale parameters» (обозначаются буквой «C» в уравнениях вариограммы) определяют «sill» для выбранных компонентов вариограммы. Таким образом, «sill» вариограммы состоит из эффекта самородка (Nugget Effect) и плюс сумма параметров шкалы «C». Во многих случаях, «sill» вариограммой модели равна дисперсии наблюдаемых данных.

С помощью параметра «Length (A)» определяем, как быстро убывает или возрастает компоненты вариограммы с возрастанием шага расстояния. Для математических функций Spherical и Quadratic, параметр «Length (A)» известен как диапазон вариограммы.

Конечным результатом вариограммного моделирования является экспериментальная вариограмма и математическая функция на одной диаграмме.

**3. Создания файла сетки.** После вариограммного моделирования необходимо рассчитать сетку для построения батиметрической модели чаши водохранилища с помощью интерполятора kriging. Файл сетки имеет расширение [.GRD].

**4. Создание контурной батиметрической карты.** Контурную карту создаем при помощи файла сетки Akdaryadata.grd (рис.4.7). Файл сохранен с расширением [.SRF].

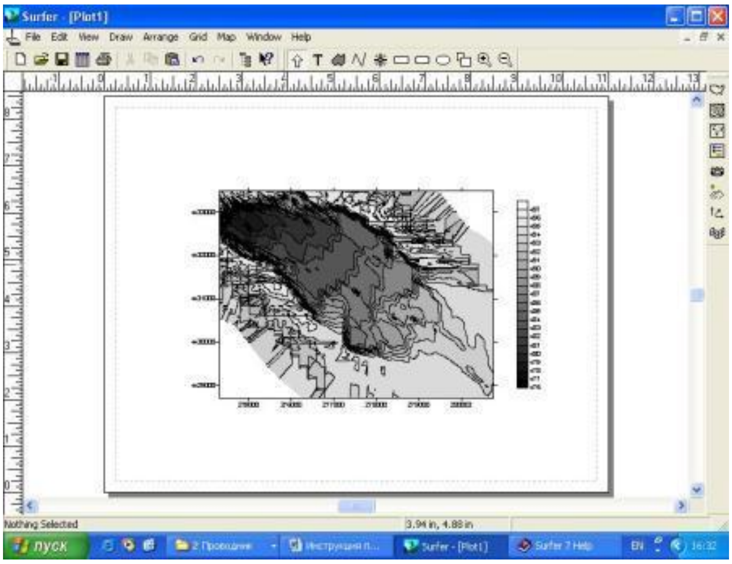



**Рис.4.7.** Контурная карта Акдарьинского водохранилища
**Figure 4.7.** Contour map of Akdarya reservoir bottom conditions

**5. Бланкирование (blank).** С помощью опции **Blank** удаляем ненужные узлы сетки в местах за пределами акватории водохранилища путем создания кода бланка для определенных групп в бланке файла сетки. Бланкированные сетки содержат узлы сетки по периметру водохранилища и те же максимальные и минимальные координаты, что и в оригинале файла сетки контурной карты. Бланкирование отмечает зоны сетки или карты с «отсутствием данных». В бланкированных зонах сетки: а) Контурные линии отсутствуют, б) Объемы и площади зеркала воды не рассчитываются.

Границы бланкирования определяют границу периметра водохранилища (рис.4.8). Бланкирование может быть установлено как внутри так и снаружи границы бланкирования.

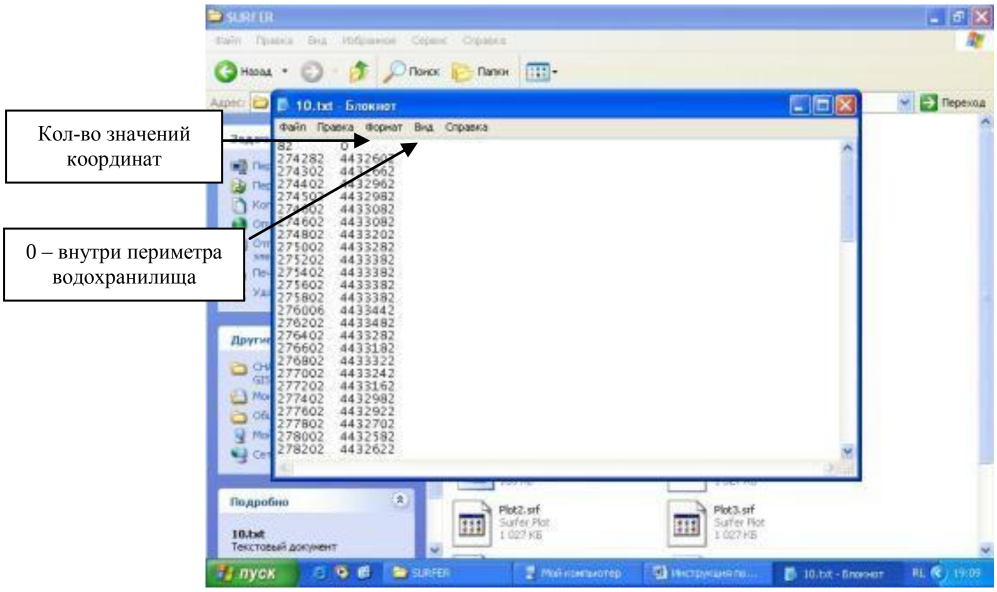



**Рис.4.8.** Файл бланкирования определяющих границу периметра водохранилища
**Figure 4.8.** Screenshot of blanking for boundary conditions

Файл бланка имеют расширение [.BLN] и единицы измерения числовых значений XY- координат являются одними и теми же, что и в файле сетки. Законченный вид батиметрической карты водохранилища с размещением поперечников показан на (рис.4.9).

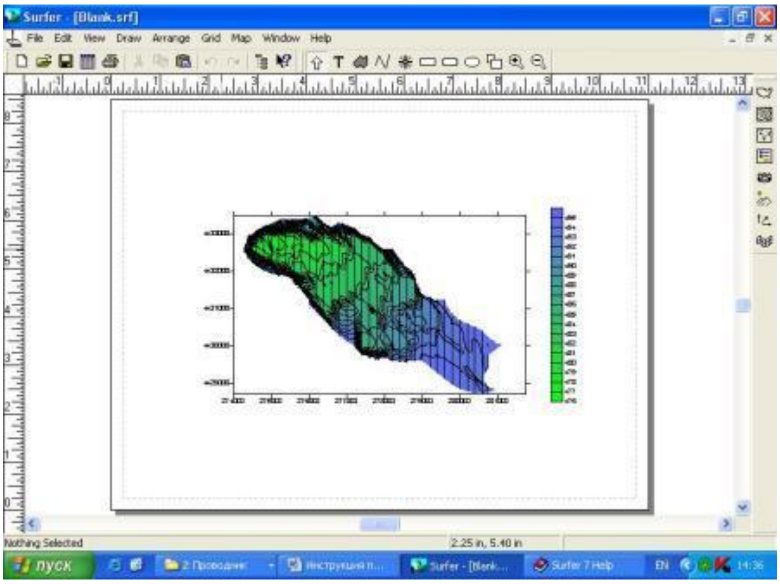



**Рис.4.9.** Батиметрическая карта Акдарьинского водохранилища
**Figure 4.9.** Bathymetric map of Akdarya reservoir bottom conditions

**6. Расчет объема и площади водохранилища.** С помощью команды **Grid|Volume** проводим расчет объема и площади водохранилища при различных абсолютных отметках, и строим кривые объемов и площадей.

Для расчета объема и площади, обозначаем абсолютную отметку в ячейке опции «Constant» для параметра верхней поверхности «Upper Surface» и указываем на файл сетки в ячейке опции «Grid File» для нижней поверхности «Lower Surface». Результаты в опции CUT & FILL VOLUMES-> Positive Volume [Cut] указывают объемы водохранилища. Для определения площади водной поверхности используем результаты в опции AREAS -> Positive Surface Area [Upper above Lower] (рис.4.10).

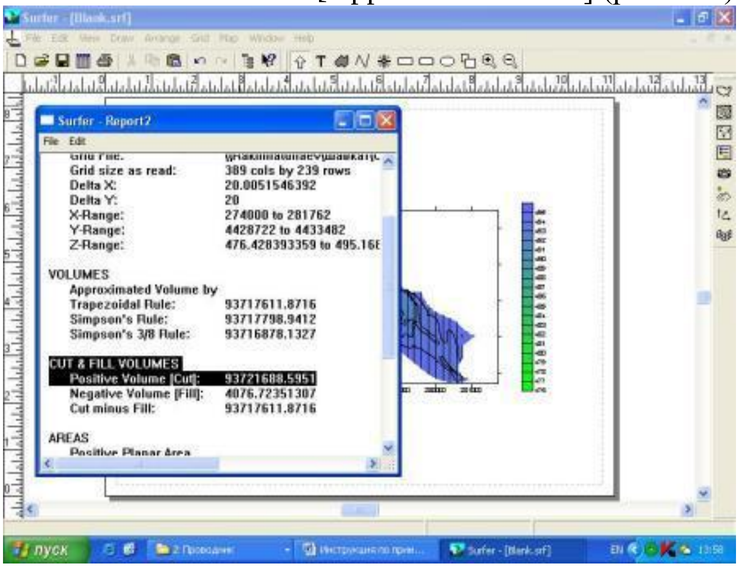



**Рис.4.10.** Объемы и площади Акдарьинского водохранилища

**Figure 4.10.** Akdarya reservoir volume and surface area

**Выводы по четвертой главе**

1. Строительство водохранилищ началось в 1940 гг. в Республике и большинства их них уже эксплуатируются более 25-30 лет. Наблюдается потеря емкостей водохранилищ процессу заиления и в ближайшее будущее будут потеряны мертвые объемы.
2. Использование новой технологии CEEDUCER позволяет исключить некоторые виды геодезические работы при создании планово-высотного обоснования для объекта и уменьшить период и затраты на батиметрическое обследование.
3. Геостатистический метод позволяет автоматизировать камеральную обработку данных при создании непрерывной батиметрической модели чаши водохранилища и провести расчет объема водохранилища.

# ГЛАВА 5.
# РЕЗУЛЬТАТЫ НАТУРНЫХ И ЧИСЛЕННЫХ ИССЛЕДОВАНИЙ

## 5.1. Результаты натурных исследований

Акдарьинское водохранилище была ведена в эксплуатацию в 1983 году. В табл.5.1 представлены координаты объемов Акдарьинского водохранилища (проектные). В 1996г., институтом «Самаркандгипроводхоз» были выполнены работы по определению заиления Акдарьинского водохранилища после 14 лет эксплуатации [50] (табл.5.2).

В 2003г., повторная батиметрическая съемка водохранилища была выполнена «Батиметрическим центром» с использованием современной технологии [58] (табл.5.3).

Таблица 5.1

Таблица координат объемов Акдарьинского водохранилища
(Проектная) 1982г.

**Table 5.1.** Volumes of Akdarya reservoir in 1982 (design stage)

| **Абс. отметка (м)** | **Объем (млн.м$^3$)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** |
| **477** | | | | | | | 0 | 0,05 | 0,1 | 0,15 |
| **478** | 0,20 | 0,25 | 0,30 | 0,35 | 0,40 | 0,50 | 0,55 | 0,60 | 0,65 | 0,70 |
| **479** | 0,75 | 0,80 | 0,85 | 0,90 | 0,95 | 0,98 | 1,0 | 1,15 | 1,25 | 1,35 |
| **480** | 1,45 | 1,60 | 1,70 | 1,85 | 2,0 | 2,15 | 2,30 | 2,40 | 2,50 | 2,65 |
| **481** | 2,80 | 2,95 | 3,0 | 3,50 | 3,75 | 4,0 | 4,25 | 4,50 | 4,75 | 5,0 |
| **482** | 5,25 | 5,50 | 5,75 | 6,0 | 6,50 | 6,75 | 7,0 | 7,50 | 7,75 | 8,0 |
| **483** | 8,50 | 8,75 | 9,0 | 9,50 | 9,75 | 10,0 | 10,50 | 11,0 | 11,50 | 11,75 |
| **484** | 12,0 | 12,50 | 13,0 | 13,50 | 14,0 | 14,50 | 15,0 | 15,50 | 16,0 | 16,50 |
| **485** | 17,0 | 17,50 | 18,0 | 18,50 | 19,0 | 19,50 | 20,0 | 20,50 | 21,0 | 21,50 |
| **486** | 22,0 | 23,,0 | 23,50 | 24,0 | 25,0 | 26,0 | 27,0 | 27,50 | 28,0 | 29,0 |
| **487** | 29,50 | 30,0 | 31,0 | 31,50 | 32,0 | 33,0 | 33,50 | 34,0 | 35,0 | 36,0 |
| **488** | 37,0 | 37,50 | 38,0 | 39,0 | 40,0 | 41,0 | 42,0 | 43,0 | 43,50 | 44,0 |
| **489** | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 |
| **490** | 55 | 55,5 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |
| **491** | 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 |
| **492** | 74 | 75 | 76 | 77 | 78 | 79 | 80 | 81 | 82 | 83 |
| **493** | 84 | 85 | 86 | 88 | 89 | 90 | | | | |
| **494** | | | | | | | | | | |

Источник: Самаркандгипроводхоз, 1976г.

Таблица 5.2

Таблица координат объемов Акдарьинского водохранилища
Принятая после 14 лет эксплуатации с 1.05.1997

**Table 5.2.** Volume of Akdarya reservoir in 1997

| **Абсолютная отметка (м)** | **Объем (млн.м$^3$)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** |
| **477** | | | 0 | 0,001 | 0,002 | 0,003 | 0,008 | 0,013 | 0,018 | 0,023 |
| **478** | 0,028 | 0,033 | 0,038 | 0,042 | 0,047 | 0,052 | 0,068 | 0,085 | 0,101 | 0,118 |
| **479** | 0,134 | 0,162 | 0,19 | 0,218 | 0,246 | 0,274 | 0,318 | 0,362 | 0,405 | 0,449 |
| **480** | 0,493 | 0,59 | 0,688 | 0,785 | 0,883 | 0,981 | 1,078 | 1,176 | 1,273 | 1,371 |
| **481** | 1,469 | 1,648 | 1,828 | 2,007 | 2,187 | 2,367 | 2,546 | 2,726 | 2,905 | 3,085 |
| **482** | 3,265 | 3,535 | 3,805 | 4,075 | 4,345 | 4,615 | 4,855 | 5,155 | 5,425 | 5,695 |
| **483** | 5,965 | 6,32 | 6,674 | 7,028 | 7,383 | 7,737 | 8,092 | 8,446 | 8,8 | 9,155 |
| **484** | 9,509 | 9,947 | 10,386 | 10,829 | 11,262 | 11,7 | 12,139 | 12,577 | 13,015 | 13,453 |
| **485** | 13,892 | 14,435 | 14,979 | 15,523 | 16,066 | 16,61 | 17,154 | 17,697 | 18,241 | 18,785 |
| **486** | 19,328 | 19,979 | 20,629 | 21,279 | 21,93 | 22,58 | 23,23 | 23,881 | 24,531 | 25,181 |
| **487** | 25,832 | 26,581 | 27,331 | 28,081 | 28,831 | 29,581 | 30,331 | 31,08 | 31,83 | 32,58 |
| **488** | 33,33 | 34,168 | 35,007 | 35,846 | 36,684 | 37,522 | 38,361 | 39,2 | 40,038 | 40,876 |
| **489** | 41,715 | 42,611 | 43,507 | 44,403 | 45,299 | 46,195 | 47,091 | 47,987 | 48,883 | 49,779 |
| **490** | 50,675 | 51,571 | 52,467 | 53,363 | 54,259 | 55,155 | 56,051 | 56,947 | 57,843 | 58,739 |
| **491** | 69,635 | 60,531 | 61,427 | 62,323 | 63,219 | 64,115 | 65,011 | 65,907 | 66,803 | 67,699 |
| **492** | 68,595 | 69,491 | 70,387 | 71,283 | 72,179 | 73,075 | 73,971 | 74,867 | 75,763 | 76,659 |
| **493** | 77,555 | 78,452 | 79,349 | 80,246 | 81,143 | 82,032 | 83,997 | 83,834 | 84,731 | 85,628 |
| **494** | **86,585** | | | | | | | | | |

Источник: Самаркандгипроводхоз, 1996г.

Таблица 5.3

Таблица координат объемов Акдарьинского водохранилища

Принятая после 24 лет эксплуатации с 10.03.2003

**Table 5.3.** Volumes of Akdarya reservoir in 2003

| **Абсолютная отметка (м)** | **Объем (млн.м$^3$)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** |
| **477** | 0,003 | 0,004 | 0,006 | 0,007 | 0,008 | 0,010 | 0,011 | 0,012 | 0,013 | 0,015 |
| **478** | 0,016 | 0,031 | 0,046 | 0,061 | 0,076 | 0,091 | 0,106 | 0,121 | 0,136 | 0,151 |
| **479** | 0,166 | 0,212 | 0,258 | 0,305 | 0,351 | 0,397 | 0,443 | 0,489 | 0,535 | 0,582 |
| **480** | 0,628 | 0,726 | 0,824 | 0,921 | 1,019 | 1,117 | 1,214 | 1,313 | 1,410 | 1,508 |
| **481** | 1,606 | 1,771 | 1,935 | 2,100 | 2,265 | 2,429 | 2,594 | 2,759 | 2,924 | 3,088 |
| **482** | 3,253 | 3,471 | 3,689 | 3,907 | 4,125 | 4,343 | 4,560 | 4,778 | 4,996 | 5,214 |
| **483** | 5,432 | 5,751 | 6,071 | 6,391 | 6,711 | 7,031 | 7,350 | 7,670 | 7,989 | 8,309 |
| **484** | 8,629 | 9,042 | 9,455 | 9,868 | 10,281 | 10,694 | 11,107 | 11,521 | 11,934 | 12,347 |
| **485** | 12,760 | 13,240 | 13,720 | 14,200 | 14,680 | 15,160 | 15,640 | 16,120 | 16,600 | 17,080 |
| **486** | 17,560 | 18,130 | 18,711 | 19,286 | 19,862 | 20,438 | 21,014 | 21,589 | 22,165 | 22,740 |
| **487** | 23,310 | 24,006 | 24,696 | 25,386 | 26,076 | 26,766 | 27,456 | 28,150 | 28,836 | 29,526 |
| **488** | 30,210 | 30,978 | 31,739 | 32,501 | 33,262 | 34,023 | 34,785 | 35,546 | 36,307 | 37,069 |
| **489** | 37,830 | 38,651 | 39,471 | 40,292 | 41,110 | 41,934 | 42,755 | 43,575 | 44,396 | 45,217 |
| **490** | 46,038 | 46,928 | 47,818 | 48,708 | 49,598 | 50,488 | 51,378 | 52,268 | 53,158 | 54,048 |
| **491** | 54,938 | 55,919 | 56,901 | 57,882 | 58,864 | 59,845 | 60,826 | 61,808 | 62,789 | 63,770 |
| **492** | 64,752 | 65,794 | 66,836 | 67,877 | 68,919 | 69,961 | 71,003 | 72,045 | 73,086 | 74,128 |
| **493** | 75,170 | 76,309 | 77,448 | 78,587 | 79,726 | 80,865 | 82,004 | 83,143 | 84,282 | 85,421 |
| **494** | 86,560 | 87,883 | 89,205 | 90,528 | 91,850 | **93,173** | | | | |

Источник: Батиметрический центр, 2003г.

В табл.5.4 приведены результаты обследований на различные периоды эксплуатации водохранилища.

Таблица 5.4

Объем и площадь зеркала воды Акдарьинского водохранилища

**Table 5.4.** Volume and surface area of Akdaya reservoir – historical datasets

| | **При НПУ** | | | | **При УМО** |
|---|---|---|---|---|---|
| | Полный объем, млн. $м^3$ | Площадь зеркала, $км^2$ | Полезный объем, $млн.м^3$ | Мертвый объем, $млн.м^3$ | Площадь зеркала, $км^2$ |
| Проектный (1982г.) | 112,5 | 12,7 | 110 | 2,5 | 3,5 |
| 1996г. | 100,7 | 11,67 | 98,5 | 2,2 | 1,64 |
| 2003г. | 93,17 | 13,97 | 91,71 | 1,46 | 0,92 |

Анализ динамики заиления Акдарьинского водохранилища был разделен на два периода. 1) Период с 1982 по 1996гг., 2) Период с 1997 по 2003гг.

Период 1982-1996гг. (15 лет).

Как видно из табл. 5.4, полный объем заиления составил 11,8 млн. $м^3$, т.е., объем сократился на 10,5%; площадь зеркала водохранилища уменьшилась на 1,03 $км^2$, т.е., на 8%; полезный объем сократился на 11,5 $млн.м^3$, т.е., 10,5%; а мертвый объем сократился на 0,3 $млн.^3$ (12%) при НПУ. При УМО площадь зеркала водохранилища сократилась на 1,86 $км^2$ (53%).

Период 1997-2003гг. (7 лет).

Как видно из табл. 5.4, полный объем заиления составил 7,5 млн. $м^3$, т.е., объем сократился на 7,5%; площадь зеркала водохранилища увеличилась на 2,3 $км^2$, т.е., площадь увеличилась на 16,5% за счет размыва правого берега, где местами размыв составил 10-50м с образованием крупных оврагов; полезный объем сократился на 6,79 $млн.м^3$, т.е., 6,9%; а мертвый объем сократился на 0,74 $млн.^3$ (33,6%) при НПУ. При УМО площадь зеркала водохранилища сократилась на 0,72 $км^2$ (43,9%).

Максимальная глубина при НПУ по проектным данным была 23,4 м, но в 2003г., эта величина составила всего лишь 18,11 м. Можно предположить нарастание дна на более 5 м, что свидетельствует об аккумуляции наносов в водохранилище.

Значительно увеличилась площадь мелководий до 2,0 м. особенно в начальной части водохранилища, например в 2003г., эта площадь была равна 1,5 $км^2$. Значения глубин мелководий варьировала от 0,2-0,5 м. В начальной части водохранилища было зафиксировано рисовые поля, ближе к правому берегу.

Рис.5.1 показывает результат обследований, где ясно видно увеличение объема заиления для различных периодов эксплуатации.

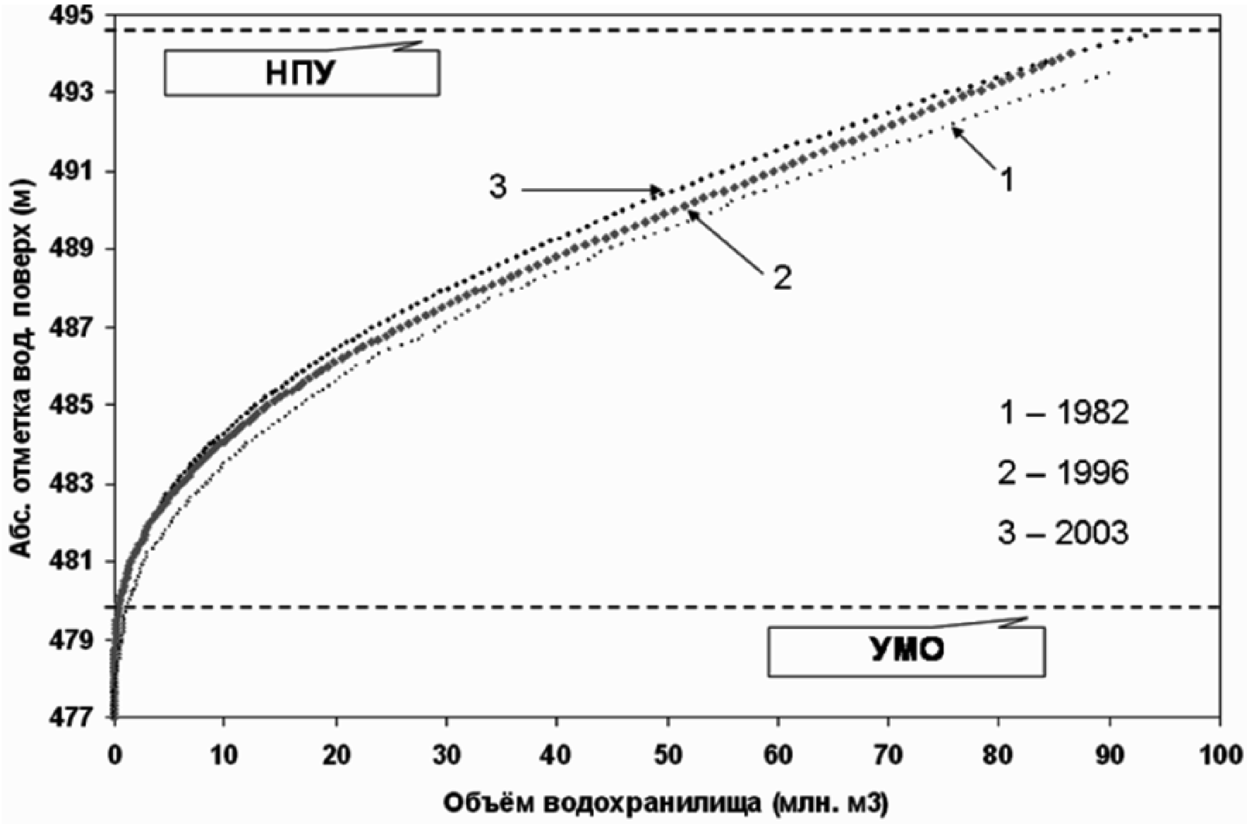



**Рис.5.1.** Кривые зависимости объема Акдарьинского водохранилища
**Figure 5.1.** Historical volume curves of Akdarya reservoir

За период эксплуатации (1983-2003 гг.) полный объем Акдарьинского водохранилища сократился на 19,3 млн.м$^3$ или ежегодная потеря емкости составляет 0,8%; полезный объем сократился на 18,3 млн.м$^3$ или ежегодная потеря емкости – 0,79%; мертвый объем сократился на 1,04 млн.м$^3$ или ежегодная потеря – 1,98% [10].

## 5.2. Результаты численных расчетов

В главе 4, нами описана последовательность методики геостатистического анализа для прогноза значений величин, на местах где эти данные отсутствуют с помощью программы SURFER и вариограммное моделирование.

Выбор сферической модели объясняется траекторий замера глубин по поперечникам, которые расположены перпендикулярно к берегам и равноудалены друг от друга в батиметрических обследованиях. В батиметрической съемке, расстояние между точками измерений глубин двух соседних поперечников больше, чем между двумя соседними точками измерений вдоль каждого поперечника. Поэтому, пространственное расположение точек выборок измерений является критическим в процессе интерполяции и создания сетки.

На рис.5.2 приведены результаты экспериментальных исследований вариограммного моделирования в двух направлениях $20^0$ и $110^0$ (т.е., дирекционные углы в геодезии). Дирекционными углами измеряют по ходу часовой стрелки от положительного направления оси абсцисс до ориентируемой линии и могут иметь значения от 0 до $360^0$ [21]. Наибольшая и наименьшая дисперсия в данных наблюдается в $110^0$ и $20^0$ дирекционных углах для Акдарьинского водохранилища, т.е., изучили анизотропию по поперечному и продольному профилям [51, 59].

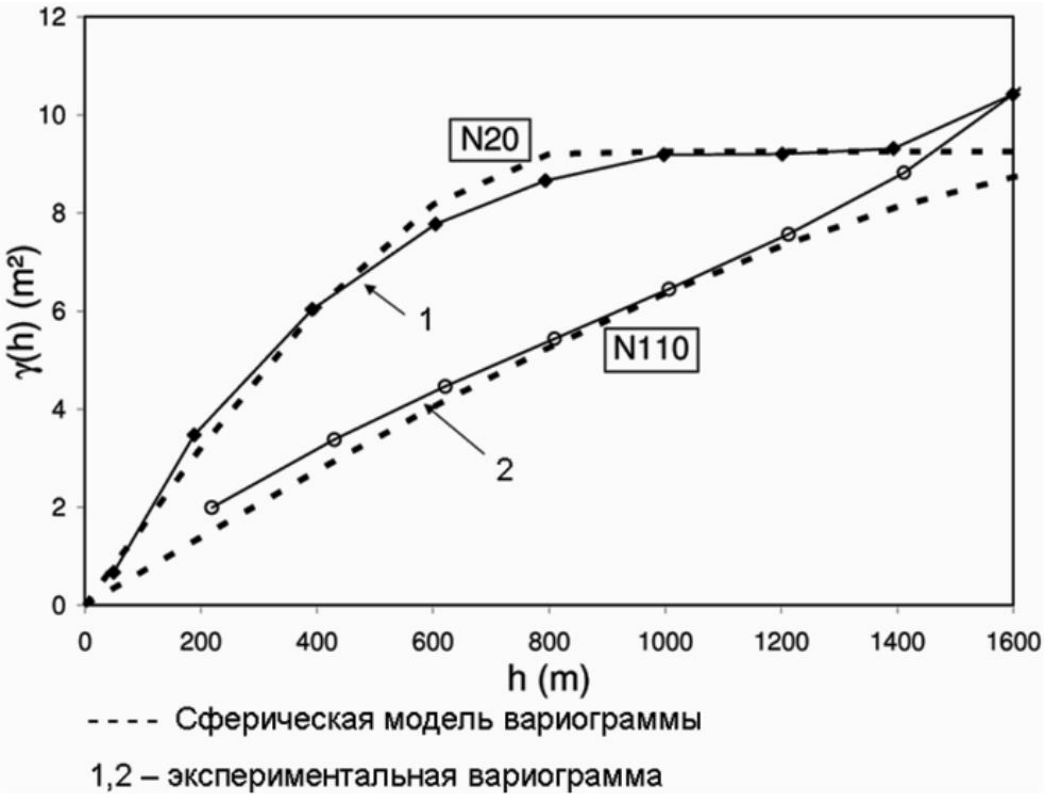



**Рис.5.2.** Сферическая модель и экспериментальные вариограммы
**Figure 5.2.** Experimental semivariogram of reservoir bottom elevations direction N20 (smallest variance) and N110 (largest variance) of Akdarya reservoir

Величины дирекционных углов зависят от характерного типа водохранилища по конфигурации. В специальной литературе существуют множество предложений по типизации морфолого-морфометрического строения водохранилищ. Форма водохранилищ разнообразна и варьирует от узких вытянутых водоемов до расширенных по форме неправильных эллипсов. Параметры (*C, A,* коэффициент анизотропии и дирекционный угол) должны быть определены и фиксированы одинаковыми значениями как для экспериментальной и модели вариограммы, в процессе графического анализа, когда подбирается модель вариограммы к экспериментальной.

Важными параметрами вариограммы является «sill» (*C*) – это численное значение ожидаемой разности (дисперсии) между парами выборок на расстоянии *h*, которое используется для интерполяции данных, где они отсутствуют. Следующим параметром является (*A*) – это расстояние, при котором не существует корреляции между значениями измерений [35, 64, 84].

В нашем случае, численное значение $C$=9 $м^2$ и $A$=1000 м с шагом расстояния в 200 м (см. рис.5.2). 1000 м – это максимальное значение длины расстояния в $110^0$ и 500 м в $20^0$ где существуют корреляция данных, которые используются для прогноза и интерполяции при создания сетки батиметрической модели чаши Акдарьинского водохранилища.

После вариограммного моделирования проводим интерполяцию для создания сетки с помощью метода kriging. При создании модели чаши, разбиваем территорию на сетку с задаваемыми размерами сторон в 500 и 1000 м. Форма сетки эллипсоидная, с 4 секторами. В каждой сетке выбираем 10 выборок точек для интерполяции. Затем анализируем соответствие между измеренными точками выборок глубины в горизонтальной плоскости и вершинами ячеек сетки модели.

На рис.5.3 приведена батиметрическая модель чаши Акдарьинского водохранилища при различных абсолютных отметках.

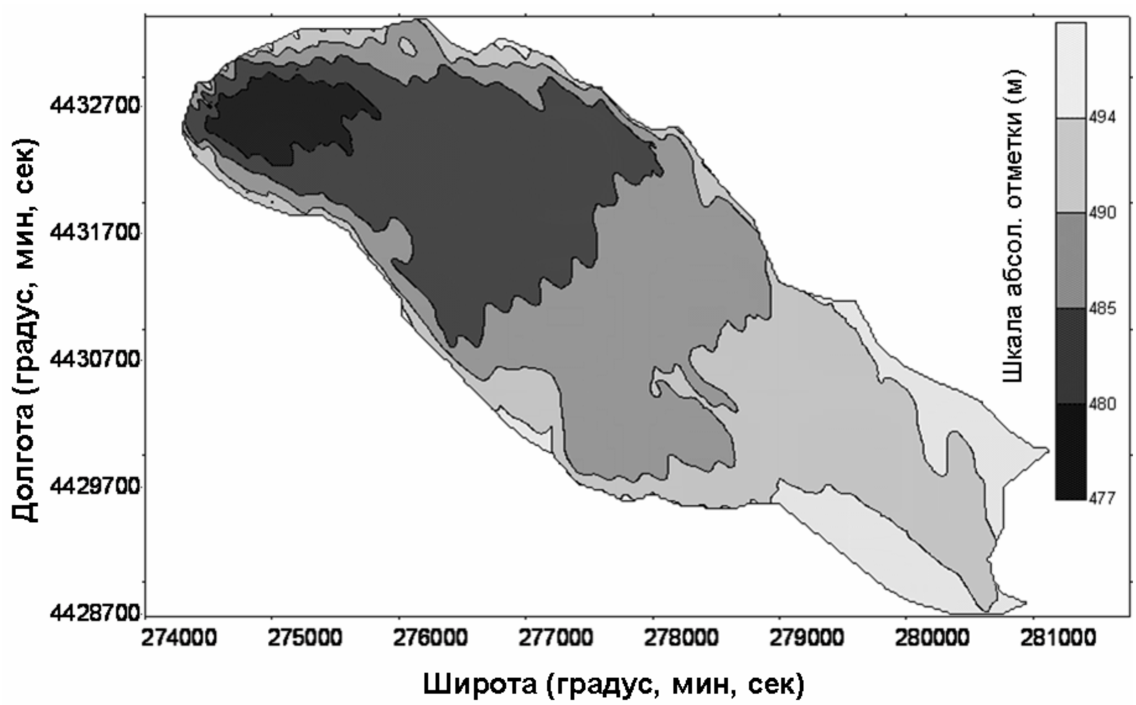



**Рис.5.3.** Батиметрическая модель чаши Акдарьинского водохранилища
**Figure 5.3.** Bathymetric map of Akdarya reservoir by kriging method

Предлагаемая методика геостатистического анализа имеет преимущество над традиционными тем, что при расчете объемов водохранилища можно получить не только численные значения, но и цифровую модель чаши. Это модель является эффективным визуальным инструментом для служб эксплуатации, которые могут наглядно видеть в двухмерном режиме распределение глубин водохранилища при различных отметках, и тем самым оперативно принимать решения о мероприятиях.

Для построения модели чаши Акдарьинского водохранилища были использованы данные 35 поперечников. Мы сократили в 2 раза количество поперечников и при помощи геостатистического метода рассчитали кривую объема. На рис.5.4 и 5.5 приведены результаты сопоставления фактической и расчетной кривых объемов и площади водной поверхности Акдарьинского водохранилища [48].

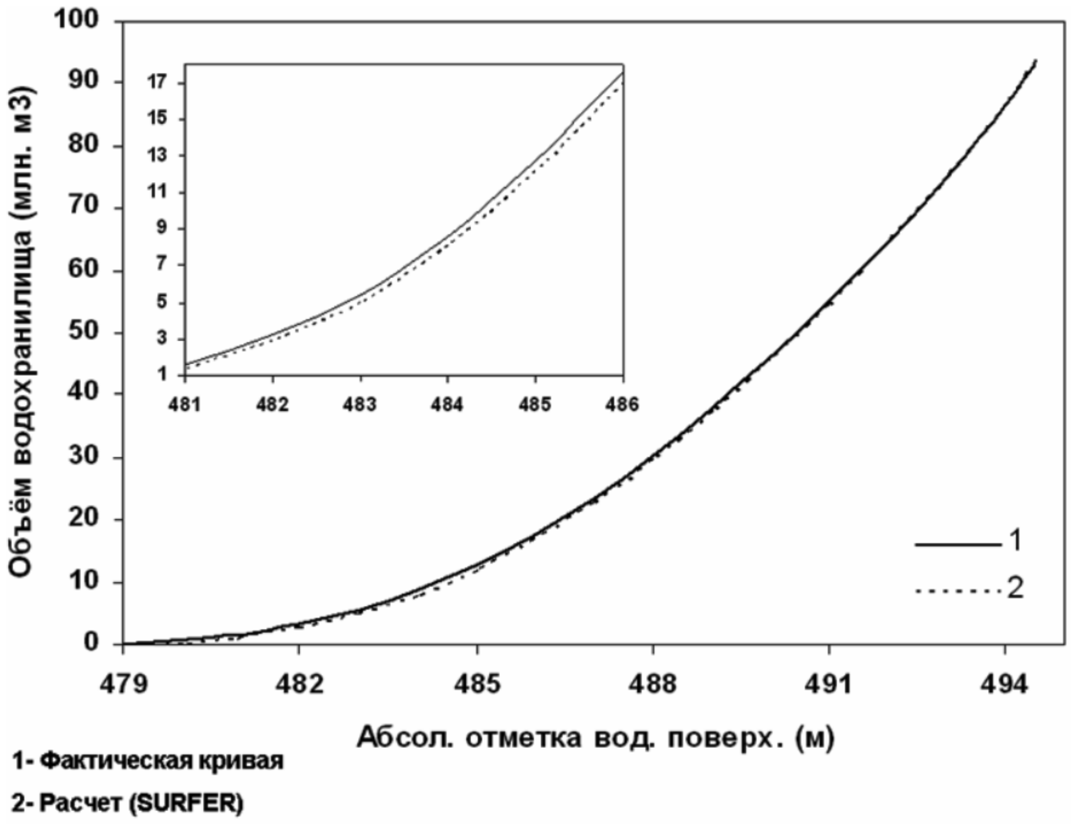



**Рис.5.4.** Кривые объемов Акдарьинского водохранилища
**Figure 5.4.** Akdarya reservoir volume by kriging and measurements (2003)

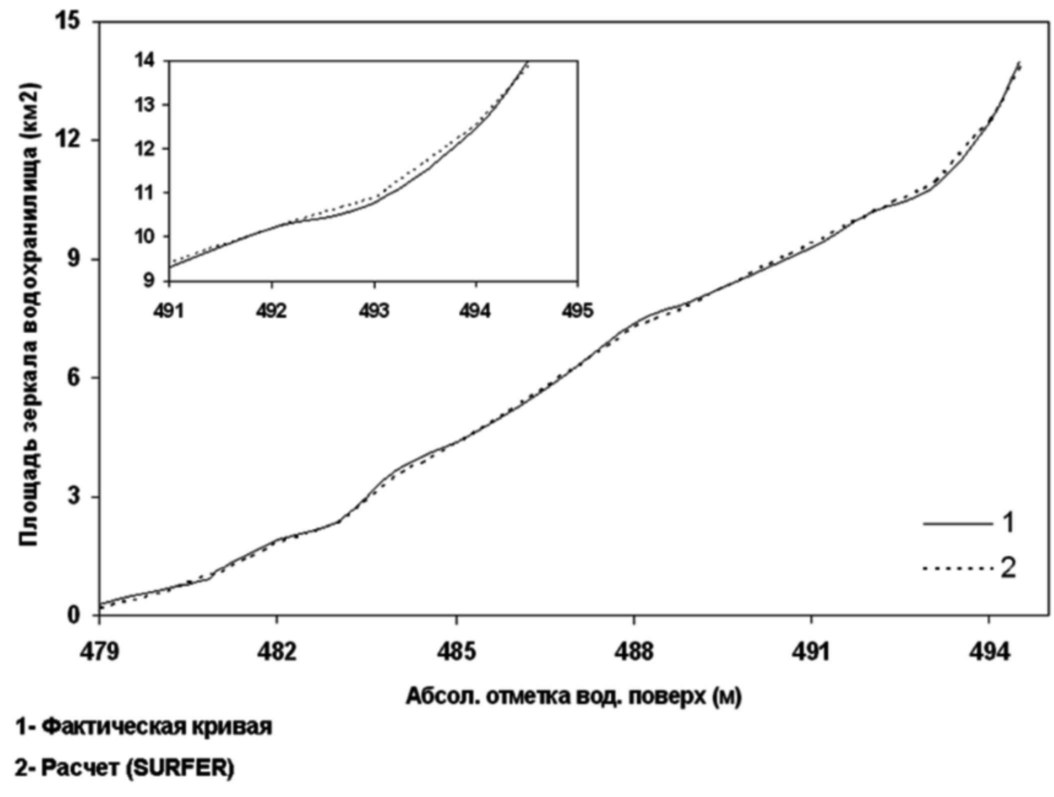



**Рис.5.5.** Кривые площади водной поверхности Акдарьинского водохранилища
**Figure 5.5.** Akdarya reservoir surface area by kriging and measurements (2003)

В табл. 5.5 приведены численные значения результатов натурных измерений и численных расчетов объемов и площадей водной поверхности Акдарьинского водохранилища.

Таблица 5.5

Объем и водная поверхность водохранилища при различных отметках водной поверхности

**Table 5.5.** Akdarya reservoir volume and water surface area at different water elevations

| **Абс. отметка (м)** | **Объем (млн.м$^3$)** | | **Площадь водной поверх. (км$^2$)** | |
|---|---|---|---|---|
| | **2003г.** | **Расчет** | **2003г.** | **Расчет** |
| **477** | 0,003 | 0,00074 | 0,0083 | 0,0036 |
| **480.5** | 1,12 | 1,05 | 0,95 | 0,97 |
| **485** | 12,76 | 12,634 | 4,39 | 4,42 |
| **490** | 46,04 | 46,27 | 8,62 | 8,66 |
| **494.5** | 93,17 | 93,83 | 13,98 | 13,97 |

Результаты исследований показывают сопоставимость расчетов, и авторы рекомендуют данную методику создания батиметрической модели чаши водохранилища при расчетах объемов водохранилища [47, 48, 49, 50, 51]. Это позволяет автоматизировать процесс в создании таблицы ординат кривой объема водохранилища для определения емкости. Автоматизация процесса значительно уменьшает затраты и улучшает качество работ.

На рис.5.6 и табл.5.6 приведены результаты расчетом с учетом поправочных коэффициентов МГО. В эпоху современных информационных технологий необходимо использовать эти ресурсы для дополнительных вычислений, которые позволяют поднят на качественно новый уровень определения объемов водохранилищ и рассчитать заиления.

Нами рекомендуется использовать поправочные коэффициенты, разработанные МГО для значений глубин с целью уменьшения погрешностей, которые наблюдаются в процессе замера глубин в полевых условиях. Это позволяет получать диапазон значений объема и площади водной поверхности водохранилища при построении кривых.

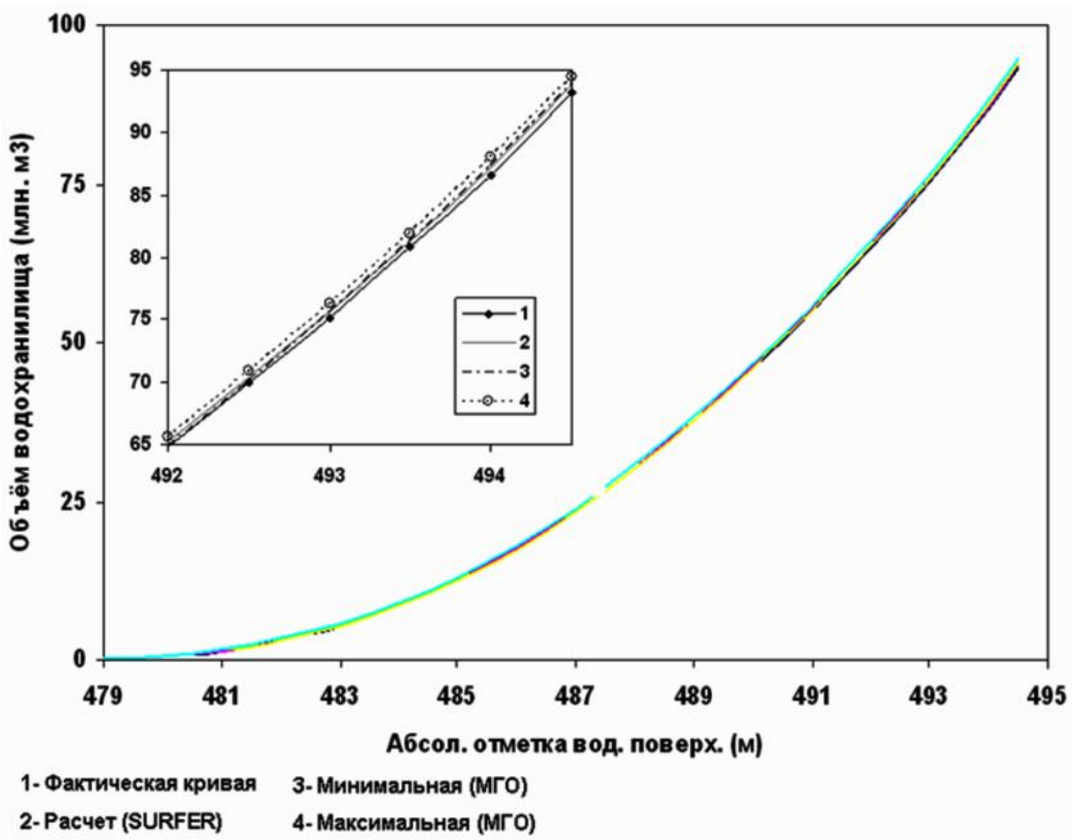



**Рис.5.6.** Кривая объема Акдарьинского водохранилища
**Figure 5.6.** Akdarya reservoir volumes vs water elevations for direct measurement, kriging and simulation

При НПУ (494,5 м) разница между натурными измерениями (93,17 млн.м$^3$) и расчетными по МГО (94,48 млн.м$^3$) составляет более 1,31 млн.м$^3$ и это объясняется тем, что при уменьшении количества поперечников в 2 раза и увеличением плотности данных результаты сопоставима и неувязка составляет около 2%. Значит нами разработанная методика расчета верна.

Теперь рассмотрим результаты по площадям зеркала воды в Акдарьинском водохранилище. При НПУ разница значений площадей составляет 0,52 км$^2$ и неувязка равна порядка 4% и это объясняется тем, что компьютерная программа SURFER вычисляет площадь объекта по нашим вводным данным, а использованные данные Батиметрического центра имели незамкнутый участок периметра.

Таблица 5.6

Объем и площадь водной поверхности при абсолютных отметках

**Table 5.6.** Comparison of reservoir volume and surface areas from direct measurements, kriging and simulation (minimum, mean, median, maximum) of Akdarya reservoir

| **Объем (млн. м$^3$)** | | | | |
|---|---|---|---|---|
| **Абс. отметка (м)** | **2003г.** | **Расчет** | **Поправочные коэффициенты (МГО, 1998г.)** | |
| | | | **Минимум** | **Максимум** |
| **477** | 0,003 | 0,00074 | 0,0012 | 0,011 |
| **480.5** | 1,12 | 1,05 | 1,07 | 1,24 |

| | | | | |
|---|---|---|---|---|
| **485** | 12,76 | 12,64 | 12,53 | 12,98 |
| **490** | 46,04 | 46,27 | 46,11 | 46,77 |
| **494.5** | 93,17 | 93,83 | 93,81 | 94,48 |
| **Площадь водной поверхности (км$^2$)** | | | | |
| **Абс. отметка (м)** | **2003г.** | **Расчет** | **Поправочные коэффициенты (МГО, 1998г.)** | |
| | | | **Минимум** | **Максимум** |
| **477** | 0,0084 | 0,0036 | 0,0044 | 0,024 |
| **480.5** | 0,95 | 0,98 | 0,94 | 1,04 |
| **485** | 4,39 | 4,43 | 4,42 | 4,54 |
| **490** | 8,63 | 8,65 | 8,62 | 8,73 |
| **494.5** | 13,98 | 13,97 | 13,25 | 13,46 |

### 5.3. Прогноз потер полезных емкостей

Ниже приводим расчет среднегодового фактического показателя объема заиления для Акдарьинского водохранилища.

$$R_г = (V_н - V_к)/t \tag{5.1}$$

где

$R_г$ - среднегодовой фактический объем заиления (млн.м$^3$/год);
$V_н$ – начальный объем водохранилища (млн.м$^3$);
$V_к$ – конечный объем водохранилища (млн.м$^3$);
$t$ – количество лет (год).

Для определения процентного показателя ежегодной потери ($R_{\%}$) емкости находим из следующего отношения

$$R_{\%} = (R_г/V_н) \times 100 \tag{5.2}$$

Зная показатель ежегодной потери объема, можно провести прогноз на ближайшее будущее. Шаг прогноза составляет каждые 10 лет (см. табл.5.7). По нашим прогнозам уже к 2025 году будет потеряно более 85% мертвого объема и это значит, что регулирующая емкость водохранилища будет неуправляемой, а ближе к 2047 году, т.е., через 25 лет будет потеряно 50% полного объема (рис.5.7).

Исходя, из этих соображений необходимо провести громоздкие землечерпательные работы, которые будут очень дорогостоящим мероприятием. Как видно из рис.5.7 происходить трансформация кривой. Это мы объясняем в силу прохождения наносов транзитом в нижний бьеф и потерей полезной емкости Акдарьинского водохранилища.

Таблица 5.7

Прогноз потер объемов Акдарьинского водохранилища

**Table 5.7.** Prediction of useful volume losses of Akdarya reservoir

| **При НПУ** |
|---|

| | Полный объем (%) | Полезный объем (%) | Мертвый объем (%) |
|---|---|---|---|
| Показатель ежегодной потери емкости | 0,8 | 0,8 | 1,9 |
| Фактическое | | | |
| 1982-2003 | 18 | 17 | 46 |
| Прогноз | | | |
| 2004-2014 | 26 | 25 | 65 |
| 2015-2025 | 34 | 33 | 84 |
| 2026-2036 | 42 | 41 | |
| 2037-2047 | 50 | 49 | |

Зная начальные и конечные объемы водохранилища можно прогнозировать потери емкостей для каждой отметки водной поверхности и построить кривую объемов (рис.5.7) и (табл.5.8). Что позволяет оперативно определить прогноз наращивания отметок водовыпускных сооружений для надежной эксплуатации водохранилищного гидроузла из-за заиления.

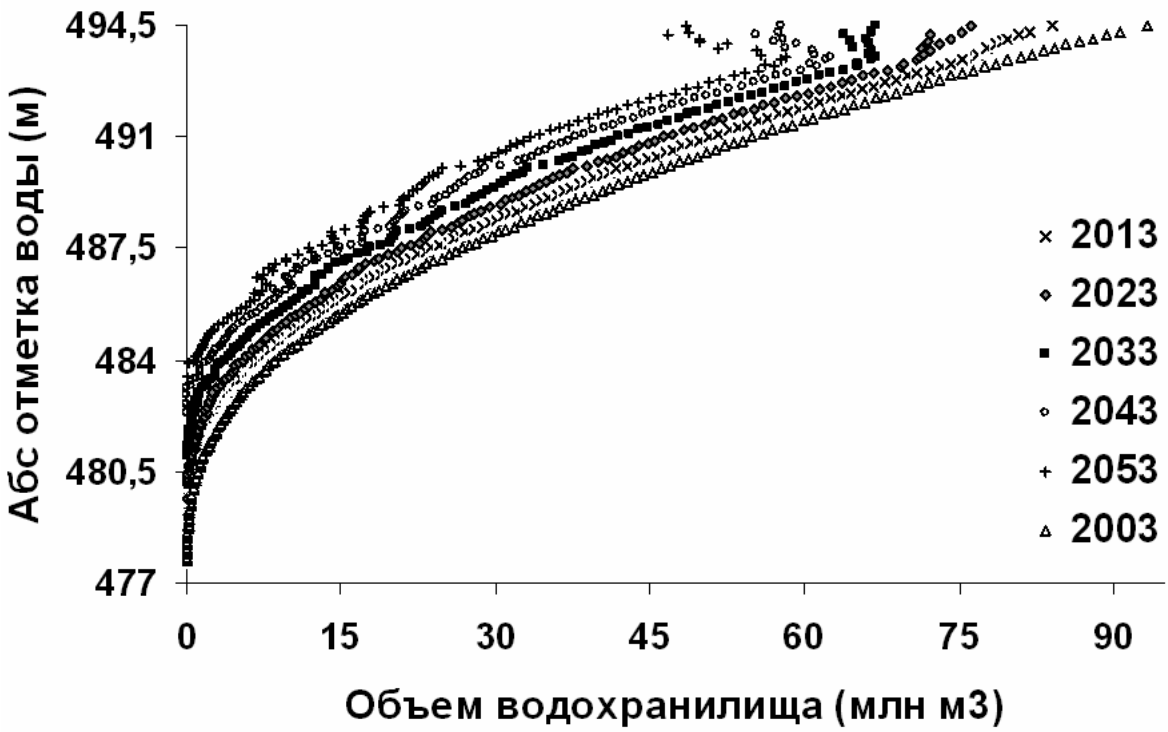



**Рис.5.7.** Прогнозные кривые объемов Акдарьинского водохранилища
**Figure 5.7.** Forecasted useful volume curves of Akdarya reservoir

Таблица 5.8

Прогнозные объемы Акдарьинского водохранилища (2003-2053гг.)

**Table 5.8.** Forecasted volumes of Akdarya reservoir (2003-2053)

| Абсолютная отметка (м) | Объемы (млн.$м^3$) | | Среднегодовой фактический объем заиления (млн.$м^3$/год) | Среднегодовая потеря емкости (%) | Прогнозные объемы водохранилища (млн.$м^3$) Шаг интервала 10 лет (2003-2053гг.) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1982 | 2003 | | | 2013 | 2023 | 2033 | 2043 | 2053 |
| 477,7 | 0,05 | 0,012 | 0,002 | 3,62 | -0,006 | | | | |
| 477,8 | 0,1 | 0,013 | 0,004 | 4,14 | -0,028 | | | | |
| 477,9 | 0,15 | 0,015 | 0,006 | 4,29 | -0,049 | | | | |
| 478 | 0,2 | 0,016 | 0,009 | 4,38 | -0,072 | | | | |
| 478,1 | 0,25 | 0,031 | 0,010 | 4,17 | -0,073 | | | | |
| 478,2 | 0,3 | 0,046 | 0,012 | 4,03 | -0,075 | | | | |
| 478,3 | 0,35 | 0,061 | 0,014 | 3,93 | -0,077 | | | | |
| 478,4 | 0,4 | 0,076 | 0,015 | 3,86 | -0,078 | | | | |
| 478,5 | 0,5 | 0,091 | 0,019 | 3,90 | -0,104 | | | | |
| 478,6 | 0,55 | 0,106 | 0,021 | 3,84 | -0,105 | | | | |
| 478,7 | 0,6 | 0,121 | 0,023 | 3,80 | -0,107 | | | | |
| 478,8 | 0,65 | 0,136 | 0,024 | 3,77 | -0,109 | | | | |
| 478,9 | 0,7 | 0,151 | 0,026 | 3,73 | -0,110 | | | | |
| 479 | 0,75 | 0,166 | 0,028 | 3,71 | -0,112 | | | | |
| 479,1 | 0,8 | 0,212 | 0,028 | 3,5 | -0,068 | | | | |
| 479,2 | 0,85 | 0,258 | 0,028 | 3,32 | -0,024 | | | | |
| 479,3 | 0,9 | 0,305 | 0,028 | 3,15 | 0,022 | -0,262 | | | |
| 479,4 | 0,95 | 0,351 | 0,029 | 3,00 | 0,066 | -0,219 | | | |
| 479,5 | 0,98 | 0,397 | 0,028 | 2,83 | 0,119 | -0,158 | | | |
| 479,6 | 1 | 0,443 | 0,027 | 2,65 | 0,178 | -0,087 | | | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 479,7 | 1,15 | 0,489 | 0,031 | 2,74 | 0,174 | -0,141 | | | |
| 479,8 | 1,25 | 0,535 | 0,034 | 2,72 | 0,195 | -0,146 | | | |
| 479,9 | 1,35 | 0,582 | 0,037 | 2,71 | 0,216 | -0,149 | | | |
| 480 | 1,45 | 0,628 | 0,039 | 2,70 | 0,237 | -0,155 | | | |
| 480,1 | 1,6 | 0,726 | 0,042 | 2,60 | 0,310 | -0,106 | | | |
| 480,2 | 1,7 | 0,824 | 0,042 | 2,45 | 0,407 | -0,010 | | | |
| 480,3 | 1,85 | 0,921 | 0,044 | 2,39 | 0,479 | 0,036 | -0,406 | | |
| 480,4 | 2 | 1,019 | 0,047 | 2,34 | 0,552 | 0,085 | -0,382 | | |
| 480,5 | 2,15 | 1,117 | 0,049 | 2,29 | 0,625 | 0,133 | -0,359 | | |
| 480,6 | 2,3 | 1,214 | 0,052 | 2,25 | 0,697 | 0,180 | -0,337 | | |
| 480,7 | 2,4 | 1,313 | 0,052 | 2,16 | 0,795 | 0,278 | -0,240 | | |
| 480,8 | 2,5 | 1,41 | 0,052 | 2,08 | 0,891 | 0,372 | -0,147 | | |
| 480,9 | 2,65 | 1,508 | 0,054 | 2,05 | 0,964 | 0,420 | -0,123 | | |
| 481 | 2,8 | 1,606 | 0,057 | 2,03 | 1,037 | 0,469 | -0,100 | | |
| 481,1 | 2,95 | 1,771 | 0,056 | 1,90 | 1,210 | 0,648 | 0,087 | -0,475 | |
| 481,2 | 3 | 1,935 | 0,051 | 1,69 | 1,428 | 0,921 | 0,414 | -0,094 | |
| 481,3 | 3,5 | 2,1 | 0,067 | 1,90 | 1,433 | 0,767 | 0,100 | -0,567 | |
| 481,4 | 3,75 | 2,265 | 0,071 | 1,89 | 1,558 | 0,851 | 0,144 | -0,564 | |
| 481,5 | 4 | 2,429 | 0,075 | 1,87 | 1,681 | 0,933 | 0,185 | -0,563 | |
| 481,6 | 4,25 | 2,594 | 0,079 | 1,86 | 1,805 | 1,017 | 0,228 | -0,560 | |
| 481,7 | 4,5 | 2,759 | 0,083 | 1,84 | 1,930 | 1,101 | 0,272 | -0,557 | |
| 481,8 | 4,75 | 2,924 | 0,087 | 1,83 | 2,054 | 1,185 | 0,315 | -0,554 | |
| 481,9 | 5 | 3,088 | 0,091 | 1,82 | 2,178 | 1,267 | 0,357 | -0,554 | |
| 482 | 5,25 | 3,253 | 0,095 | 1,81 | 2,302 | 1,351 | 0,400 | -0,551 | |
| 482,1 | 5,5 | 3,471 | 0,097 | 1,76 | 2,505 | 1,539 | 0,572 | -0,394 | |
| 482,2 | 5,75 | 3,689 | 0,098 | 1,71 | 2,708 | 1,726 | 0,745 | -0,237 | |
| 482,3 | 6 | 3,907 | 0,100 | 1,66 | 2,910 | 1,914 | 0,917 | -0,080 | |
| 482,4 | 6,5 | 4,125 | 0,113 | 1,74 | 2,994 | 1,863 | 0,732 | -0,399 | |
| 482,5 | 6,75 | 4,343 | 0,115 | 1,70 | 3,197 | 2,051 | 0,904 | -0,242 | |
| 482,6 | 7 | 4,56 | 0,116 | 1,66 | 3,398 | 2,236 | 1,074 | -0,088 | |
| 482,7 | 7,5 | 4,778 | 0,130 | 1,73 | 3,482 | 2,186 | 0,889 | -0,407 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 482,8 | 7,75 | 4,996 | 0,131 | 1,69 | 3,685 | 2,373 | 1,062 | -0,250 | |
| 482,9 | 8 | 5,214 | 0,133 | 1,66 | 3,887 | 2,561 | 1,234 | -0,093 | |
| 483 | 8,5 | 5,432 | 0,146 | 1,72 | 3,971 | 2,510 | 1,049 | -0,412 | |
| 483,1 | 8,75 | 5,751 | 0,143 | 1,63 | 4,323 | 2,895 | 1,467 | 0,039 | -1,389 |
| 483,2 | 9 | 6,071 | 0,139 | 1,55 | 4,676 | 3,281 | 1,887 | 0,492 | -0,903 |
| 483,3 | 9,5 | 6,391 | 0,148 | 1,56 | 4,911 | 3,430 | 1,950 | 0,469 | -1,011 |
| 483,4 | 9,75 | 6,711 | 0,145 | 1,48 | 5,264 | 3,817 | 2,370 | 0,922 | -0,525 |
| 483,5 | 10 | 7,031 | 0,141 | 1,41 | 5,617 | 4,203 | 2,790 | 1,376 | -0,038 |
| 483,6 | 10,5 | 7,35 | 0,150 | 1,43 | 5,850 | 4,350 | 2,850 | 1,350 | -0,150 |
| 483,7 | 11 | 7,67 | 0,159 | 1,44 | 6,084 | 4,499 | 2,913 | 1,327 | -0,259 |
| 483,8 | 11,5 | 7,989 | 0,167 | 1,45 | 6,317 | 4,645 | 2,973 | 1,301 | -0,371 |
| 483,9 | 11,75 | 8,309 | 0,164 | 1,39 | 6,670 | 5,032 | 3,393 | 1,755 | 0,116 |
| 484 | 12 | 8,629 | 0,161 | 1,34 | 7,024 | 5,419 | 3,813 | 2,208 | 0,603 |
| 484,1 | 12,5 | 9,042 | 0,165 | 1,32 | 7,395 | 5,749 | 4,102 | 2,455 | 0,809 |
| 484,2 | 13 | 9,455 | 0,169 | 1,30 | 7,767 | 6,079 | 4,391 | 2,703 | 1,015 |
| 484,3 | 13,5 | 9,868 | 0,173 | 1,28 | 8,138 | 6,409 | 4,679 | 2,950 | 1,220 |
| 484,4 | 14 | 10,281 | 0,177 | 1,26 | 8,510 | 6,739 | 4,968 | 3,197 | 1,426 |
| 484,5 | 14,5 | 10,694 | 0,181 | 1,25 | 8,882 | 7,069 | 5,257 | 3,444 | 1,632 |
| 484,6 | 15 | 11,107 | 0,185 | 1,24 | 9,253 | 7,399 | 5,546 | 3,692 | 1,838 |
| 484,7 | 15,5 | 11,521 | 0,189 | 1,22 | 9,626 | 7,731 | 5,837 | 3,942 | 2,047 |
| 484,8 | 16 | 11,934 | 0,194 | 1,21 | 9,998 | 8,062 | 6,125 | 4,189 | 2,253 |
| 484,9 | 16,5 | 12,347 | 0,198 | 1,20 | 10,369 | 8,392 | 6,414 | 4,437 | 2,459 |
| 485 | 17 | 12,76 | 0,202 | 1,19 | 10,741 | 8,722 | 6,703 | 4,684 | 2,665 |
| 485,1 | 17,5 | 13,24 | 0,203 | 1,16 | 11,211 | 9,183 | 7,154 | 5,126 | 3,097 |
| 485,2 | 18 | 13,72 | 0,204 | 1,13 | 11,682 | 9,644 | 7,606 | 5,568 | 3,530 |
| 485,3 | 18,5 | 14,2 | 0,205 | 1,11 | 12,152 | 10,105 | 8,057 | 6,010 | 3,962 |
| 485,4 | 19 | 14,68 | 0,206 | 1,08 | 12,623 | 10,566 | 8,509 | 6,451 | 4,394 |
| 485,5 | 19,5 | 15,16 | 0,207 | 1,06 | 13,093 | 11,027 | 8,960 | 6,893 | 4,827 |
| 485,6 | 20 | 15,64 | 0,208 | 1,04 | 13,564 | 11,488 | 9,411 | 7,335 | 5,259 |
| 485,7 | 20,5 | 16,12 | 0,209 | 1,02 | 14,034 | 11,949 | 9,863 | 7,777 | 5,691 |
| 485,8 | 21 | 16,6 | 0,210 | 1,00 | 14,505 | 12,410 | 10,314 | 8,219 | 6,124 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 485,9 | 21,5 | 17,08 | 0,210 | 0,98 | 14,975 | 12,870 | 10,766 | 8,661 | 6,556 |
| 486 | 22 | 17,56 | 0,211 | 0,96 | 15,446 | 13,331 | 11,217 | 9,103 | 6,989 |
| 486,1 | 23 | 18,13 | 0,232 | 1,01 | 15,811 | 13,492 | 11,173 | 8,854 | 6,535 |
| 486,2 | 23,5 | 18,711 | 0,228 | 0,97 | 16,431 | 14,150 | 11,870 | 9,589 | 7,309 |
| 486,3 | 24 | 19,286 | 0,224 | 0,94 | 17,041 | 14,796 | 12,552 | 10,307 | 8,062 |
| 486,4 | 25 | 19,862 | 0,245 | 0,98 | 17,415 | 14,969 | 12,522 | 10,075 | 7,629 |
| 486,5 | 26 | 20,438 | 0,265 | 1,02 | 17,789 | 15,141 | 12,492 | 9,844 | 7,195 |
| 486,6 | 27 | 21,014 | 0,285 | 1,06 | 18,164 | 15,313 | 12,463 | 9,612 | 6,762 |
| 486,7 | 27,5 | 21,589 | 0,281 | 1,02 | 18,774 | 15,959 | 13,145 | 10,330 | 7,515 |
| 486,8 | 28 | 22,165 | 0,278 | 0,99 | 19,386 | 16,608 | 13,829 | 11,051 | 8,272 |
| 486,9 | 29 | 22,74 | 0,298 | 1,03 | 19,759 | 16,778 | 13,797 | 10,816 | 7,835 |
| 487 | 29,5 | 23,31 | 0,295 | 1,00 | 20,362 | 17,415 | 14,467 | 11,520 | 8,572 |
| 487,1 | 30 | 24,006 | 0,285 | 0,95 | 21,152 | 18,297 | 15,443 | 12,589 | 9,735 |
| 487,2 | 31 | 24,696 | 0,300 | 0,97 | 21,694 | 18,692 | 15,690 | 12,688 | 9,686 |
| 487,3 | 31,5 | 25,386 | 0,291 | 0,92 | 22,475 | 19,563 | 16,652 | 13,740 | 10,829 |
| 487,4 | 32 | 26,076 | 0,282 | 0,88 | 23,255 | 20,434 | 17,613 | 14,792 | 11,971 |
| 487,5 | 33 | 26,766 | 0,297 | 0,90 | 23,797 | 20,829 | 17,860 | 14,892 | 11,923 |
| 487,6 | 33,5 | 27,456 | 0,288 | 0,86 | 24,578 | 21,700 | 18,822 | 15,944 | 13,066 |
| 487,7 | 34 | 28,15 | 0,279 | 0,82 | 25,364 | 22,579 | 19,793 | 17,007 | 14,221 |
| 487,8 | 35 | 28,836 | 0,294 | 0,84 | 25,901 | 22,966 | 20,030 | 17,095 | 14,160 |
| 487,9 | 36 | 29,526 | 0,308 | 0,86 | 26,443 | 23,360 | 20,277 | 17,195 | 14,112 |
| 488 | 37 | 30,21 | 0,323 | 0,87 | 26,977 | 23,743 | 20,510 | 17,277 | 14,043 |
| 488,1 | 37,5 | 30,978 | 0,311 | 0,83 | 27,872 | 24,767 | 21,661 | 18,555 | 15,449 |
| 488,2 | 38 | 31,739 | 0,298 | 0,78 | 28,758 | 25,776 | 22,795 | 19,813 | 16,832 |
| 488,3 | 39 | 32,501 | 0,309 | 0,79 | 29,406 | 26,311 | 23,217 | 20,122 | 17,027 |
| 488,4 | 40 | 33,262 | 0,321 | 0,80 | 30,053 | 26,845 | 23,636 | 20,428 | 17,219 |
| 488,5 | 41 | 34,023 | 0,332 | 0,81 | 30,701 | 27,378 | 24,056 | 20,733 | 17,411 |
| 488,6 | 42 | 34,785 | 0,344 | 0,82 | 31,349 | 27,914 | 24,478 | 21,042 | 17,606 |
| 488,7 | 43 | 35,546 | 0,355 | 0,83 | 31,996 | 28,447 | 24,897 | 21,348 | 17,798 |
| 488,8 | 43,5 | 36,307 | 0,343 | 0,79 | 32,882 | 29,457 | 26,031 | 22,606 | 19,181 |
| 488,9 | 44 | 37,069 | 0,330 | 0,75 | 33,769 | 30,468 | 27,168 | 23,867 | 20,567 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 489 | 45 | 37,83 | 0,341 | 0,76 | 34,416 | 31,001 | 27,587 | 24,173 | 20,759 |
| 489,1 | 46 | 38,651 | 0,350 | 0,76 | 35,151 | 31,652 | 28,152 | 24,653 | 21,153 |
| 489,2 | 47 | 39,471 | 0,359 | 0,76 | 35,886 | 32,301 | 28,715 | 25,130 | 21,545 |
| 489,3 | 48 | 40,292 | 0,367 | 0,76 | 36,622 | 32,951 | 29,281 | 25,610 | 21,940 |
| 489,4 | 49 | 41,11 | 0,376 | 0,77 | 37,353 | 33,596 | 29,839 | 26,081 | 22,324 |
| 489,5 | 50 | 41,934 | 0,384 | 0,77 | 38,093 | 34,252 | 30,411 | 26,570 | 22,729 |
| 489,6 | 51 | 42,755 | 0,393 | 0,77 | 38,829 | 34,903 | 30,976 | 27,050 | 23,124 |
| 489,7 | 52 | 43,575 | 0,401 | 0,77 | 39,563 | 35,551 | 31,539 | 27,527 | 23,515 |
| 489,8 | 53 | 44,396 | 0,410 | 0,77 | 40,299 | 36,202 | 32,105 | 28,007 | 23,910 |
| 489,9 | 54 | 45,217 | 0,418 | 0,77 | 41,035 | 36,852 | 32,670 | 28,487 | 24,305 |
| 490 | 55 | 46,038 | 0,427 | 0,78 | 41,770 | 37,503 | 33,235 | 28,968 | 24,700 |
| 490,1 | 55,5 | 46,928 | 0,408 | 0,74 | 42,846 | 38,764 | 34,682 | 30,600 | 26,518 |
| 490,2 | 56 | 47,818 | 0,390 | 0,70 | 43,922 | 40,026 | 36,129 | 32,233 | 28,337 |
| 490,3 | 57 | 48,708 | 0,395 | 0,69 | 44,759 | 40,811 | 36,862 | 32,914 | 28,965 |
| 490,4 | 58 | 49,598 | 0,400 | 0,69 | 45,597 | 41,596 | 37,595 | 33,594 | 29,593 |
| 490,5 | 59 | 50,488 | 0,405 | 0,69 | 46,435 | 42,381 | 38,328 | 34,275 | 30,221 |
| 490,6 | 60 | 51,378 | 0,411 | 0,68 | 47,272 | 43,167 | 39,061 | 34,955 | 30,849 |
| 490,7 | 61 | 52,268 | 0,416 | 0,68 | 48,110 | 43,952 | 39,794 | 35,636 | 31,478 |
| 490,8 | 62 | 53,158 | 0,421 | 0,68 | 48,948 | 44,737 | 40,527 | 36,316 | 32,106 |
| 490,9 | 63 | 54,048 | 0,426 | 0,68 | 49,785 | 45,522 | 41,259 | 36,997 | 32,734 |
| 491 | 64 | 54,938 | 0,432 | 0,67 | 50,623 | 46,308 | 41,992 | 37,677 | 33,362 |
| 491,1 | 65 | 55,919 | 0,432 | 0,67 | 51,595 | 47,270 | 42,946 | 38,622 | 34,298 |
| 491,2 | 66 | 56,901 | 0,433 | 0,66 | 52,568 | 48,235 | 43,902 | 39,570 | 35,237 |
| 491,3 | 67 | 57,882 | 0,434 | 0,65 | 53,540 | 49,198 | 44,856 | 40,514 | 36,172 |
| 491,4 | 68 | 58,864 | 0,435 | 0,64 | 54,514 | 50,163 | 45,813 | 41,462 | 37,112 |
| 491,5 | 69 | 59,845 | 0,436 | 0,63 | 55,485 | 51,126 | 46,766 | 42,407 | 38,047 |
| 491,6 | 70 | 60,826 | 0,437 | 0,62 | 56,457 | 52,089 | 47,720 | 43,352 | 38,983 |
| 491,7 | 71 | 61,808 | 0,438 | 0,62 | 57,431 | 53,054 | 48,677 | 44,299 | 39,922 |
| 491,8 | 72 | 62,789 | 0,439 | 0,61 | 58,403 | 54,017 | 49,630 | 45,244 | 40,858 |
| 491,9 | 73 | 63,77 | 0,440 | 0,60 | 59,375 | 54,980 | 50,584 | 46,189 | 41,794 |
| 492 | 74 | 64,752 | 0,440 | 0,60 | 60,348 | 55,944 | 51,541 | 47,137 | 42,733 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 492,1 | 75 | 65,794 | 0,438 | 0,58 | 61,410 | 57,026 | 52,643 | 48,259 | 43,875 |
| 492,2 | 76 | 66,836 | 0,436 | 0,57 | 62,472 | 58,108 | 53,745 | 49,381 | 45,017 |
| 492,3 | 77 | 67,877 | 0,434 | 0,56 | 63,533 | 59,188 | 54,844 | 50,500 | 46,156 |
| 492,4 | 78 | 68,919 | 0,432 | 0,55 | 64,595 | 60,270 | 55,946 | 51,622 | 47,298 |
| 492,5 | 79 | 69,961 | 0,430 | 0,54 | 65,657 | 61,352 | 57,048 | 52,744 | 48,440 |
| 492,6 | 80 | 71,003 | 0,428 | 0,54 | 66,719 | 62,434 | 58,150 | 53,866 | 49,582 |
| 492,7 | 81 | 72,045 | 0,426 | 0,53 | 67,781 | 63,516 | 59,252 | 54,988 | 50,724 |
| 492,8 | 82 | 73,086 | 0,424 | 0,52 | 68,841 | 64,596 | 60,352 | 56,107 | 51,862 |
| 492,9 | 83 | 74,128 | 0,422 | 0,51 | 69,903 | 65,678 | 61,454 | 57,229 | 53,004 |
| 493 | 84 | 75,17 | 0,420 | 0,50 | 70,965 | 66,760 | 62,556 | 58,351 | 54,146 |
| 493,1 | 85 | 76,309 | 0,414 | 0,49 | 72,170 | 68,032 | 63,893 | 59,755 | 55,616 |
| 493,2 | 86 | 77,448 | 0,407 | 0,47 | 73,376 | 69,303 | 65,231 | 61,158 | 57,086 |
| 493,3 | 88 | 78,587 | 0,448 | 0,51 | 74,105 | 69,622 | 65,140 | 60,657 | 56,175 |
| 493,4 | 89 | 79,726 | 0,442 | 0,50 | 75,310 | 70,894 | 66,477 | 62,061 | 57,645 |
| 493,5 | 90 | 80,865 | 0,435 | 0,48 | 76,515 | 71,165 | 66,815 | 62,465 | 58,115 |
| 493,6 | 93 | 82,004 | 0,524 | 0,56 | 76,768 | 71,532 | 66,295 | 61,059 | 55,823 |
| 493,7 | 95 | 83,143 | 0,565 | 0,59 | 77,497 | 72,165 | 66,519 | 60,873 | 55,226 |
| 493,8 | 98 | 84,282 | 0,653 | 0,67 | 77,750 | 71,217 | 64,685 | 58,152 | 51,620 |
| 493,9 | 100 | 85,421 | 0,694 | 0,69 | 78,479 | 73,165 | 66,223 | 59,280 | 52,338 |
| 494 | 102 | 86,56 | 0,735 | 0,72 | 79,208 | 71,855 | 64,503 | 57,150 | 49,798 |
| 494,1 | 105 | 87,883 | 0,815 | 0,78 | 79,732 | 74,165 | 66,014 | 57,863 | 49,712 |
| 494,2 | 107 | 89,205 | 0,847 | 0,79 | 80,731 | 72,257 | 63,784 | 55,310 | 46,836 |
| 494,3 | 109 | 90,528 | 0,880 | 0,81 | 81,732 | 75,165 | 66,369 | 57,573 | 48,776 |
| 495,4 | 111 | 91,85 | 0,912 | 0,82 | 82,731 | 73,612 | 64,493 | 55,374 | 46,255 |
| 494,5 | 112,5 | 93,173 | 0,920 | 0,82 | 83,970 | 76,165 | 66,962 | 57,758 | 48,555 |

На рис.5.8 приведены результаты прогноза аккумуляции наносов и через 50 лет, т.е., к 2053 году 6,4 м будут потеряны заилению в Акдарьинском водохранилище. По нашим расчетам при УМО 480,5 м абс будет полностью заилена в 2023 году.

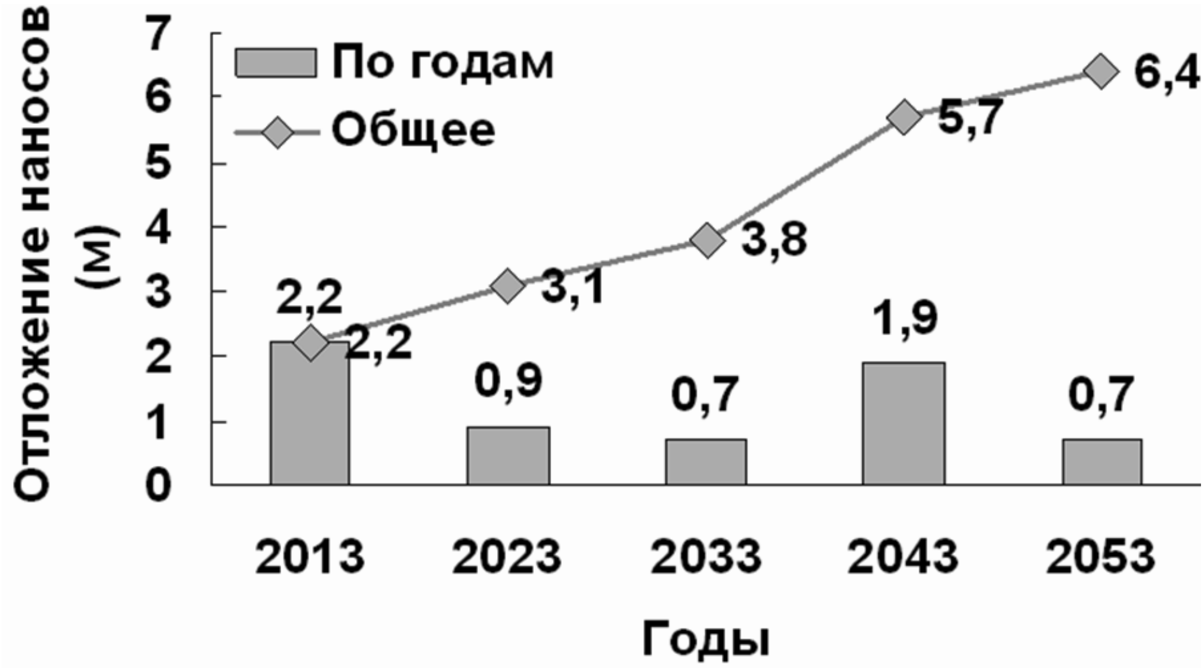



**Рис.5.8.** Отложение наносов в Акдарьинском водохранилище
**Figure 5.8.** Forecasted annual and total sediment accumulation in Akdarya reservoir

### 5.4. Расчет экономической эффективности

В этом разделе подробно рассмотрим экономическую эффективность от внедрения результатов исследований в производство.

Основным практическим применением разработанной методики геостатистического анализа будет автоматизация всего цикла расчета объемов водохранилища и определения объемов заиления, начиная от полевых работ, т.е., замера глубин с меньшим количеством поперечников, что в свою очередь уменьшает время и финансовые затраты на 50%. Второе кардинально уменьшить время камеральной обработки на 80% и сократить общие расходы батиметрических обследований (см. приложение 4) и табл. 5.9 [12, 14].

Таблица 5.9

Калькуляция по определению объемов для Акдарьинского водохранилища
**Table 5.9.** Calculation of economic efficiency of geostatistical approach vs traditional

| № | Вид работ | Норма чел/ час | Занят. Спец. Кол-во | Всего чел/ час | Стоимость (ГКС за 2005г.) 1 чел/час=1274,63 сум | Экон. эффект |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| **Полевые работы** | | | | | | |
| 9 | Замер глубин | 5 | 2 | 10 | 12746,3 | 6373,15 |
| **Камеральная обработка** | | | | | | |
| 16 | Построение поперечных профилей в «Excel» | 8 | 3 | 24 | 30591,12 | 15295,56 |
| 17 | Ввод данных в программу «AutoCAD» | 45 | 3 | 135 | 172075,05 | 172075,05 |
| 18 | Черчение карты объекта на миллиметровку | 12 | 2 | 24 | 30591,12 | 30591,12 |
| 19 | Обобщение | 3,1 | 3 | 9,3 | 11854,059 | 5927,03 |
| | Итого | | | | | 230,026 |
| | Прочие затраты подрядчика | 29,32% | | | 123986,13 | 30000 |
| | **Всего** | | | | | **260000** |

Ожидаемая экономическая эффективность для определения полезного объема 1 км$^2$ водохранилища снизится с нынешних 546 на 286 тыс.сум. Ожидаемая экономическая эффективность составляет около 3 млн.сумов для Акдарьинского водохранилища. Кроме того, методика использована для расчета полезной емкости Южносурханского водохранилища.

В наших расчетах мы рассмотрели только те пункты, которые имеют наибольшие показатели экономической эффективности. Необходимо отметить, что не только количественно, но и улучшается качество расчетов, т.к., уменьшаются потенциальные источники погрешностей с предыдущими методами расчета.

**Выводы по пятой главе**

1. За период эксплуатации (1983-2003гг.) Акдарьинского водохранилища было выявлено следующее: ежегодная потеря полного объема составляет 0,8%; полезного – 0,79%; и мертвого – 1,98%. Исходя из этого, мы произвели приближенный прогноз потери трех объемов. Например, и к 2035 году мертвый объем будет потерян полностью, а полный и полезный объемы сократятся на 50%.
2. Величины дирекционных углов зависят от характерного типа водохранилища по конфигурации, т.е., от формы водохранилища при изучении анизотропии.
3. Результаты исследований показывают сопоставимость расчетов между геостатистическим методом и натурными данными. Это позволяет автоматизировать процесс расчета объемов водохранилища, что позволяет значительно уменьшить затраты и поднят на новый качественный уровень проведения батиметрических исследований.
4. Основным практическим применением будет автоматизация расчета объемов водохранилища, что позволить уменьшить время камеральной обработки на 80% и полевых – на 50%.
5. Ожидаемая экономическая эффективность уменьшения затрат для определения полезного объема 1 $км^2$ площади водохранилища снизится с нынешних 546 на 286 тыс.сум.
6. Рекомендуется вносить поправочные коэффициенты, разработанных МГО для значений глубин, тем самым, решая вопросы количественного и качественного характера в замере глубин.

## ЗАКЛЮЧЕНИЕ

Создана научно- технологические основы определения полезной емкости эксплуатируемых водохранилищ с использованием геоинформационных систем:

1. Впервые разработан и апробирован метод геостатистического анализа в гидротехническом строительстве для оперативного определения и прогноза состояния потер регулирующих емкостей водохранилищ. Что позволяет автоматизировать расчет объемов водохранилища, за счет увеличения области охвата измеряемой поверхности, которая уменьшает время камеральной обработки на 80% и полевых – на 50%.
2. Показан системный подход использования геоинформационных систем (GPS-система, батограф CEEDUCER, программа SURFER и приложения Google Earth сети Интернет) в Республике Узбекистан для для оперативной оценки и прогнозу состояния полезных емкостей водохранилищ.
3. Получены новые результаты расчета кривых объемов водохранилища с учётом поправочных коэффициентов для значений измеряемых глубин согласно стандартам МГО в Республике Узбекистан.
4. Экспериментально установлен научно-обоснованный размер ячейки сетки батиметрической модели чаши водохранилища с помощью вариограммного моделирования.
5. Впервые создана цифровая батиметрическая модель чаши Акдарьинского водохранилища.
6. Показана необходимость приближенного метод прогноза полезной емкости Акдарьинского водохранилища с учетом многолетних фактических объемов объекта. Что позволяет оперативно определить прогноз наращивания отметок водозаборных и водовыпускных сооружений для надежной эксплуатации водохранилищного гидроузла с учетом уменьшения регулирующих емкостей.
7. Основные результаты работы легли в основу «Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ» утвержденной Министерством сельского и водного хозяйства Республики Узбекистан и используется Батиметрическим центром.
8. Результаты исследований внедрены в производство. Получен акт внедрения в производство от Республиканского объединения «Узводремэксплуатация». При этом ожидаемая экономическая эффективность уменьшения затрат для определения полезного объема на 1 км$^2$ площади водохранилища может снизится с 546 до 286 тыс.сум и составит 260 тыс. сум в батиметрических обследованиях. Ожидаемая экономическая эффективность составляет около 3 млн.сумов для Акдарьинского водохранилища. Кроме того, методика использована для определения полезной емкости Южносурханского водохранилища.
9. Результаты исследований дает возможности широкого применения геоинформационных технологий научно-исследовательскими и проектными институтами в водохозяйственном направлении для оперативного определения и прогноза состояния потер объемов водохранилищ, озер, отстойников и ирригационных каналов, а также исследований деформации русел рек.

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# APPENDICES

**ПРИЛОЖЕНИЯ**

Приложение 1

Акт внедрение в производство (Акдарьинское водохранилище)

Appendix 1. Protocol of application in industry for Akdarya reservoir

**«УТВЕРЖДАЮ»**
**Проректор ТИИМ по научным исследованиям**
**А.Т.Салохиддинов**
“13” январь 2009 г.

**«УТВЕРЖДАЮ»**
**Начальник Республиканского объединения «Узводремэксплуатация»**
**А.Б.Файзиев**
“30” январь 2009 г.

**АКТ ВНЕДРЕНИЯ**

результатов научно-исследовательских, опытно-конструкторских и технологических работ в производство

Заказчик **Республиканское объединение «Узводремэксплуатация»**
(наименование организации)

**Файзиев Аскар Бурневич**
(Ф.И.О. руководителя организации)

Настоящим актом подтверждается, что результаты работы: **Совершенствование оперативных методов определения полезной емкости водохранилищ с использованием геоинформационных систем (на примере Акдарьинского водохранилища)**
(наименование темы, № Гос. регистрации)

выполненной **Ташкентский институт ирригации и мелиорации, кафедрой «Гидротехнические сооружения и инженерные конструкции»**
(наименование ВУЗа, НИИ, КБ)

стоимость ----- тыс.сум
(цифрами и прописью)

выполняемой с «1» **марта** 2007г. по «30» **ноябрь** 2008г.
(сроки выполнения)

внедрены **для государственного унитарного предприятия «Батиметрический центр»**
(наименование предприятия, где осуществлялось внедрение)

1. Вид внедренных результатов **методика геостатистического анализа для научно-обоснованного выбора ячейки сетки в интерполяции значений величин, на местах, где эти данные отсутствуют при построении цифровой батиметрической модели чаши Акдарьинского водохранилища и руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ**
(эксплуатация изделий, работы, технологии)

2. Характеристика масштаба внедрения: **массовое, для всех водохранилищных гидроузлов, ирригационных каналов и отстойников при определении объемов заиления**
(уникальное, единичное, партия, массовое, серийное)

3. Форма внедрения: **методика геостатистического анализа, в частности вариограммное моделирование при интерполяции значений глубин, на местах, где эти данные отсутствуют и использование метода kriging для интерполяции и выбора ячейки сетки в построении цифровой батиметрической карты модели чаши Акдарьинского водохранилища и использование компьютерной программы SURFER-7 для автоматизации расчета объемов водохранилища и определения таблицы координат объемов и построения кривой объемов и площадей**
Методика, способ (метод)

4. Новизна результатов научно-исследовательских работ **заключается в модернизации и усовершенствовании оперативных методов замера глубин с привязкой GPS-системы**

**батографа CEEDUCER, интерполяции данных с помощью геостатистического метода и создания цифровой карты чаши водохранилища с программой SURFER-7, что позволяет автоматизировать методику расчета объемов водохранилища в сжатие сроки и уменьшение полевых обследований на 50% и камеральной обработки на 80% и использование приложения Google Earth сети Интернет для получения космической съемки объекта**

(пионерное, принципиально новые, качественно новые, модификация, модернизация старых разработок)

5. Опытно-производственная проверка **на Акдарьинском водохранилище**

(указать номер и дату актов испытаний, наименование предприятия, период)

6. Внедрены:

-в промышленное производство -------

(участок, цех (цеха), процесс)

-в проектные работы **Батиметрический центр**

(указать, объект, предприятие)

7. Годовой экономический эффект;

ожидаемый **на 1км$^2$ 260** тыс.сум.

(от внедрения в проект)

фактический **на 1км$^2$ 260** тыс.сум.

(от внедрения в производство)

в том числе долевое участие ------- тыс.сум.

8. Удельная экономическая эффективность внедренных результатов **1км$^2$ 260** тыс.сум.

9. Объём внедрения **одно водохранилище**, что составляет **100%** от общего объёма внедрения.

10. Социальный и научно-технический эффект **Совершенствуется методика проведения батиметрических исследований на качественно новом уровне с использованием новейших геоинформационных технологий, которые позволяют службам эксплуатации водохранилищ визуально изучить существующее состояние объекта в двухмерном изображении и оперативно разработать мероприятия для эффективной эксплуатации водохранилищного гидроузла**

(охрана окружающей среды, недр; улучшение и оздоровление условий труда, совершенствование структуры управления, научно-технических направлений, специальные назначения и т.д.)

Приложение: Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ.

**«СОГЛАСОВАНО»**
**от ТИИМ**

Директор ЦНПИ ТИИМ
**А.Г. Шеров**
Руководитель НИР
**М.Р. Бакиев**
Исполнитель
**Ш.А.Рахматуллаев**

**«СОГЛАСОВАНО»**
**от ПРЕДПРИЯТИЯ**

Директор государственного унитарного предприятия «Батиметрический центр»
**И.Н. Шарипов**
Ведущий специалист ГУП «Батиметрический центр»
**С.Б. Хамраев**

Приложение 2

Акт внедрения в производство (Далолатнома)

Appendix 2. Protocol of use of developed geostatistical approach by Botiometrik Markaz

**ЎЗБЕКИСТОН РЕСПУБЛИКАСИ**
**ҚИШЛОҚ ВА СУВ ХЎЖАЛИГИ ВАЗИРЛИГИ**

**ТОШКЕНТ ИРРИГАЦИЯ ВА МЕЛИОРАЦИЯ ИНСТИТУТИ**

**«ТАСДИҚЛАЙМАН»**
ТИМИ илмий тадқиқотлар
бўйича проректор
__________ А.Т. Салохиддинов
«11» 07 2009 й.

**«ТАСДИҚЛАЙМАН»**
«Botiometrik markaz» давлат
унитар корхона бошлиғи
__________ И.Н. Шарипов
«13» 07 2009 й.

**Илмий тадқиқот натижаларини ишлаб чиқаришга тадбиқ этиш тўғрисида**

## ДАЛОЛАТНОМА

**Тошкент ш.** **«10» 07 2009 й.**

Ушбу далолатнома имзо чекувчилар томонидан қуйидагилар ҳақида тузилди.

«Ирригация гидротехника иншоотларини қуриш ва улардан фойдаланиш» факультети «Гидротехника иншоотлари ва муҳандислик конструкциялар» кафедраси томонидан олиб борилаётган (илмий тадқиқот) «Совершенствование оперативных методов определения полезной емкости водохранилищ с использованием геоинформационных систем» мавзусидаги номзодлик диссертацияси бўйича олинган илмий тадқиқот ишларининг натижалари бўйича Оқдарё ва Жанубий Сурхон сув омборлари фойдали хажмларини аниқлаш Ўзбекистон Республикаси Қишлоқ ва сув хўжалиги вазирлиги «Botiometrik markaz» давлат унитар корхонаси томонидан ишлаб чиқаришга қўйидаги тартибда жорий қилинди:

| № | Муаллифлар | Бажарилган ишлар | Жорий этилган жойи |
|---|---|---|---|
| 1 | М.Р. Бакиев<br>Ш.А. Рахматуллаев | «Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ» қўлланма | ДУК «Botiometrik markaz» |

Ушбу далолатномани тасдиқлаймиз:

ИАТМ директори
__________ **А.Г. Шеров**

Патентшунос
__________ **С. Саидходжаев**

Мавзу раҳбари
__________ **М.Р. Бакиев**

Тадқиқотчи
__________ **Ш.А. Рахматуллаев**

«Botiometrik markaz» ДУК
бошлиғи ўринбосари
__________ **Р.Х. Расулов**

«Botiometrik markaz» ДУК
бош мутахассиси
__________ **С.Б. Хамраев**

Приложение 3

Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ

Appendix 3. Methodological manual on use of geostatistical approach and SURFER-7 for estimation of useful reservoir storage capacities approved by the Ministry of Agriculture and Water Resources of the Republic of Uzbekistan

**МИНИСТЕРСТВО СЕЛЬСКОГО И ВОДНОГО ХОЗЯЙСТВА РЕСПУБЛИКИ УЗБЕКИСТАН**

ТАШКЕНТСКИЙ ИНСТИТУТ ИРРИГАЦИИ И МЕЛИОРАЦИИ

**«Утверждаю»**
**Заместитель министра**
**сельского и водного хозяйства**
**_______ Ш.Р. Хамраев**
**«29» декабря 2008г.**

# РУКОВОДСТВО

## ПО ПРИМЕНЕНИЮ ПРОГРАММЫ SURFER-7 ДЛЯ РАСЧЕТА ПОЛЕЗНОЙ ЕМКОСТИ ВОДОХРАНИЛИЩ

**Ташкент 2008**

«Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ» разработано заведующим кафедрой «Гидротехнические сооружения и инженерные конструкции» Ташкентского института ирригации и мелиорации (ТИИМ), д.т.н., **проф. М.Р. Бакиевым** и директором Информационно-аналитической службы «Водные ресурсы» ТИИМ, **Ш.А. Рахматуллаевым**.

В работе приведена последовательность и методология создания цифровой батиметрической модели чаши водохранилища с использованием компьютерной программы SURFER-7 для расчета полезной емкости водохранилища (на примере Акдарьинского водохранилища).
Новизна работы заключается в следующем:

1. Уменьшается количество поперечников замера глубин на - 50%;
2. Уменьшается время для камеральной обработки на - 80%;
3. Происходит автоматизация расчета таблицы координат объемов водохранилища;
4. Экономическая эффективность метода оценивается в 260 тыс. сумов на 1км$^2$ исследуемого объекта в батиметрических обследованиях;
5. Получаем цифровую батиметрическую модель чаши водохранилища в двухмерном изображении.

Эти новшества позволяют поднят на качественно новый уровень проведения натурных батиметрических исследований.

(Рекомендовано к изданию ученым советом факультета строительства и эксплуатации ирригационных гидротехнических сооружений ТИИМ протоколом №_**4**_от«_**9**_»_**апреля**_ 2007г.)

Рецензенты:

И. Шарипов, - директор государственного унитарного предприятия «Батиометрический центр» Республиканского объединения «Узводремэксплуатация» Министерства сельского и водного хозяйства Республики Узбекистан

Ф. Гаппаров, к.т.н., заведующий отдела водохранилищ и каналов Среднеазиатского научно-исследовательского института ирригации им. В.Д. Журина (САНИИРИ)

©Ташкентский институт ирригации и мелиорации, Ташкент, 2008г.

## ВВЕДЕНИЕ

С помощью водохранилищ началось гарантированное орошение сельскохозяйственных земель, водоснабжение городов и промышленных предприятий, производство электроэнергии, борьба с наводнениями, судоходство, а также индустрия туризма [1].

Данные многолетнего опыта эксплуатации водохранилищ показывает, что часть их регулирующих емкостей занята интенсивно увеличивающимися объемами наносных отложений. Чрезвычайно важно дать точный прогноз заиления водохранилищ, так как от этого зависят сроки эксплуатации гидротехнических сооружений.

По данным «Батиметрического центра» Минсельводхоза РУз объем заиления общего объема Акдарьинского водохранилища составляет 17%, мертвого – 60%. За период эксплуатации водохранилища (1983-2004гг.) общий объем заиления составил 19,33 млн.$м^3$ или среднее заиление 0,9 млн.$м^3$ в год.

За 34 лет (1963-1997гг.) эксплуатации Туябугузского водохранилища объем заиления составил 59,81 млн.$м^3$. За 10 лет работы Тахиаташского гидроузла в верхнем бьефе отложилось 21,67 млн.$м^3$, объем составил 49% от полного объема руслового водохранилища [2].

Фактическая интенсивность заиления водохранилищ во много раз превышает расчетную. Это свидетельствует о недостаточной надежности используемых при составлении проектов традиционных методов расчетов заиления, разработанных для условий эксплуатации водохранилищ.

Бурное развитие информационных технологий позволили широко использовать новые разработки в гидрографических исследованиях, в частности в определении объемов заиления. Новые технологии увеличили плотность геоданных, улучшили точность измерений и автоматизировали процесс создания таблицы координат объемов водохранилища, что значительно уменьшили затраты для проведения батиметрических исследований.

Эти кардинальные изменения диктуют разработать новую методологию расчета объема заиления с использованием геоинформационных систем.

Основным назначением SURFER-7 является обработка и визуализация двумерных наборов данных, описываемых функцией типа $z=f(x,y)$, а логику работы с пакетом можно представить в виде трех основных функциональных блоков [3,4,5]:

а) построение цифровой модели поверхности;

б) расчет объема и водной площади водного объекта;

в) визуализация поверхности.

Ключевой функцией SURFER является создание цифровой модели поверхности. Наиболее актуальная постановка данной задачи формулируется как переход от набора значений функции $Z$ в произвольных (неупорядоченных) точках плоскости (N точек с координатами $X,Y$) к значениям этой функции в узлах некоторой регулярной сетки. В более общей постановке та же задача сводится к возможности вычисления значений функции в любой точке поверхности (а значит и в узлах сетки) по исходному набору данных [6,7,8].

## 1. ЭХОЛОТИРОВАНИЕ ЧАШИ ВОДОХРАНИЛИЩА С ПОМОЩЬЮ БАТОГРАФА CEEDUCER

Одним из эффективных методов расчета объема заиления является повторные батиметрические съемки чаш водохранилищ, позволяющие получить конечные результаты заиления. Новейшие технологии уже используются в нашей республике и целесообразно оптимизировать использование этих ресурсов в батиметрических исследованиях для повышения надежности работы сооружений водохранилищ в целях сохранения и эффективного использования водных ресурсов. Исходя, из этих соображений необходимо разработать новую методику и усовершенствовать расчет объема заиления с использованием геоинформационных систем.

С 2001г. Государственным унитарным предприятием «Батиометрический центр» Минсельводхоза Республики Узбекистан началось использование новой техники и оборудования «CEEDUCER» австралийской компании Bruttour International Ltd для расчета объема воды в водохранилище. Как показал опыт, эта технология показала хорошие результаты [2].

На «CEEDUCER» можно исключить некоторые виды геодезических работ и инструменты, составляющих традиционную методику.

Преимущества новой технологии:

- Исключение некоторых видов геодезических работ и инструментов;
- Для создания планово-высотного обоснования можно исключить применение теодолита и светодальнометра;
- При создании локальной сети без ориентирования километровой сетки к государственной сетке достаточно одного геодезического пункта, имеющего координаты и отметку. При помощи базовой станции в позиции «**HERE**» можно получить координаты в системе WGS-84 и развить локальную сеть для объекта в целом;
- Уменьшение периода обследовательских работ и уменьшение затрат.

«CEEDUCER» является компактным переносным устройством, которое состоит из следующих частей см. рис.1:

Датчика GPS 8- или 12-канальный, точность 2-3м (8-канальный) или <1м (12-канальный);

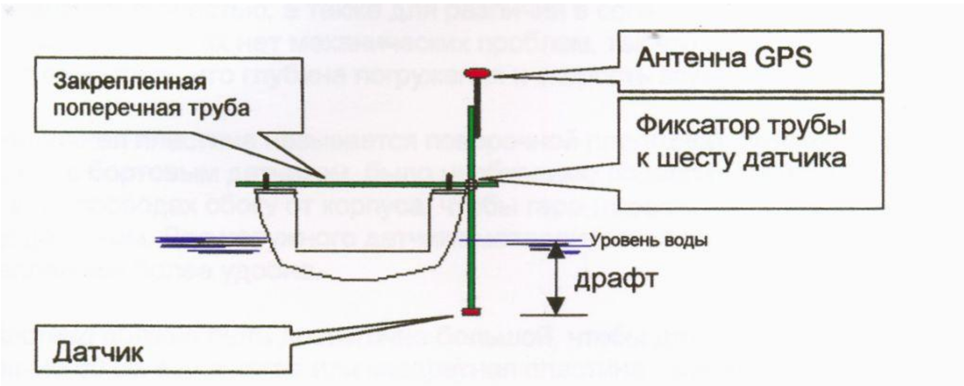
Цифровой датчик-эхолот (transducer)

- радиус действия измерения глубины от 30см до 99,99м
- скорость звукового сигнала настраивается автоматически или ручная настройка
- ручная настройка величины draft
- Точность 0,02% от измеряемой глубины и разрешающая способность 1-см


Источник: Руководство по применению батографа «CEEDUCER». http://www.bruttour.com.au

**Рис.1.** Оборудование «CEEDUCER»

Необходимо закрепить датчик-эхолот на плавательное средство таким образом, чтобы производить замер глубин и расположить антенну GPS вблизи и над датчиком-эхолотом рис.2. Расположение датчика-эхолота является важной составной частью гидрографического обследования и рекомендуется расположить его по середине плавательного средства для наименьшего воздействия мотора и турбулентности воды.




Источник: Руководство по применению батографа «CEEDUCER». http://www.bruttour.com.au

**Рис.2.** Расположение датчика-эхолота и антенны GPS

Установив базовую станцию «**BASE RTK**» на геодезическом пункте «Остров», ввели отметку этого пункта в позиции «**HERE**» и при помощи «**RTK ROVER**» определили координаты других базовых точек, которые были выбраны при рекогносцировке, в Акдарьинском водохранилище были определены 3 базовых точек. Радиус действия телеметрической антенны 7км.

Тарировка эхолота

Тарировка датчика-эхолота проводилась два раза, до проведения батиметрической съемки и после каждого дня изыскательных работ (табл.).

Таблица

Результаты тарировки датчика-эхолота

| **Показание** | **Показание эхолота (м)** | **Среднее** |
|---|---|---|

| по рулетке (м) | 1 | 2 | 3 | значение (м) |
|---|---|---|---|---|
| 3 | 2,99 | 3,01 | 3,02 | 3,01 |
| 4 | 4,01 | 4,02 | 4,02 | 4,02 |
| 6 | 5,98 | 6,01 | 5,99 | 5,99 |
| 8 | 7,99 | 8,02 | 8,00 | 8,01 |
| 10 | 9,98 | 9,99 | 10,00 | 9,98 |
| 12 | 11,98 | 12,02 | 12,01 | 12,00 |
| 14 | 13,99 | 14,01 | 14,02 | 14,01 |
| 17 | 16,98 | 17,02 | 16,97 | 16,98 |
| 18 | 17,97 | 17,96 | 17,99 | 17,97 |
| 20 | 19,99 | 20,03 | 20,02 | 20,02 |

Источник: «Батиметрический центр» Минсельводхоз Республики Узбекистан.

Целью геостатистического метода является прогноз значений величин на местах, где отсутствуют эти данные. Геостатистика состоит из групп методик и методологий для проведения анализа и прогнозирования значений «интересующих» пространственно-временных величин для решения практических задач. Рассмотрим методологию геостатистического анализа (рис.3).

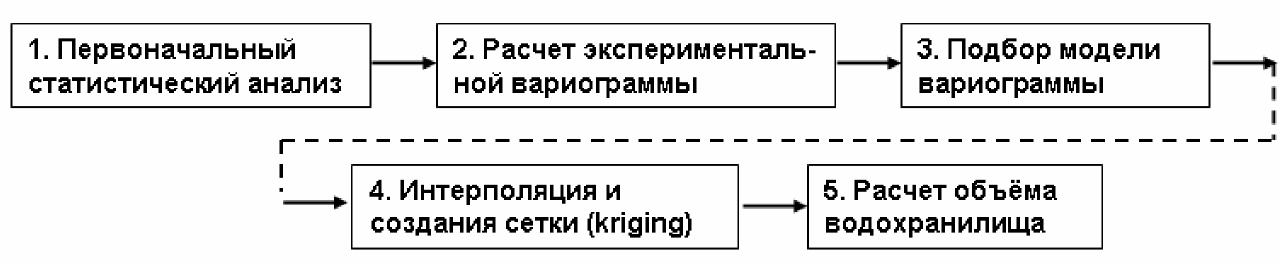
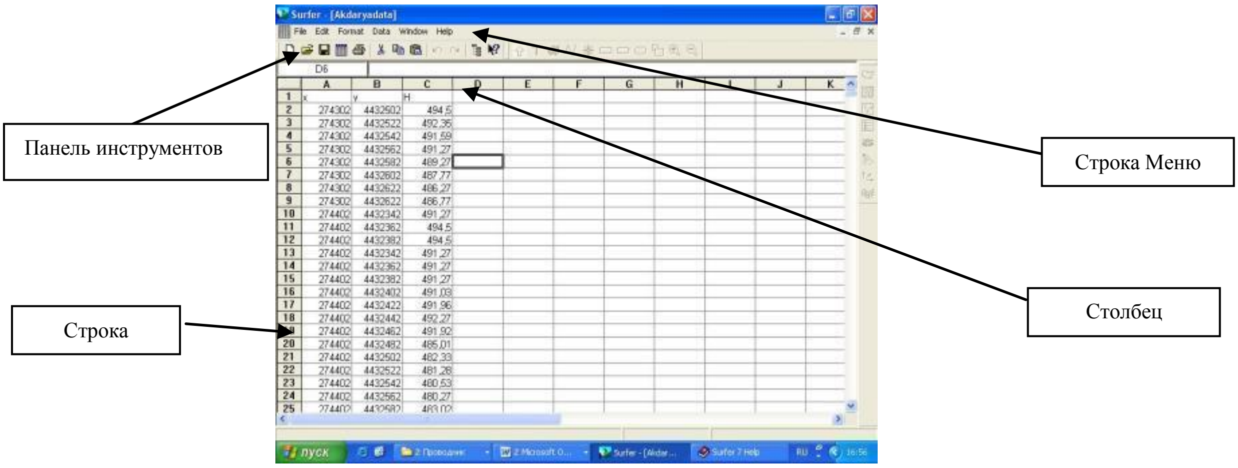



Рис.3. Этапы геостатистического метода в расчете объема водохранилища

## 2. СОЗДАНИЕ ФАЙЛА ДАННЫХ X-Y-Z

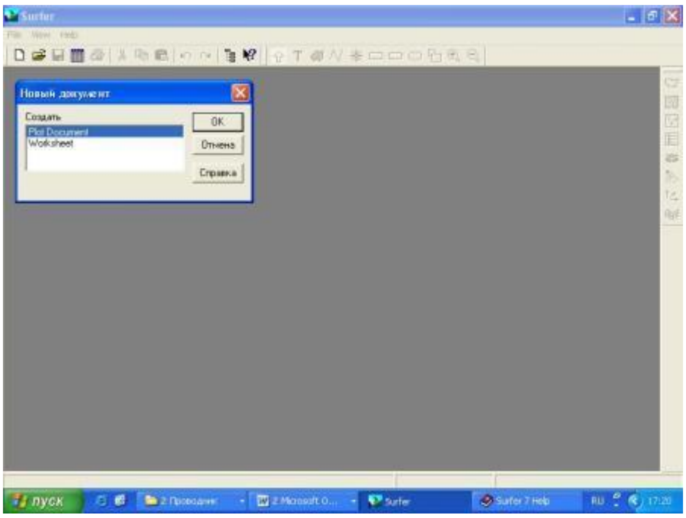
Файл данных X-Y-Z должен содержать минимум три столбца со значениями координат (*X*, *Y*) и глубины (*Z*). Рекомендуется вносить значения данных по следующей последовательности, *X*-значения в столбец A, *Y*-значения в столбец B, и *Z*-значения в столбец C. Программа SURFER принимает эту последовательность по умолчанию при расчетах.




**Создание Нового Файла Данных**
Для создания в SURFER листа с данными используется «worksheet».

Для открытия окна «worksheet» и ввода числовых значений данных:

1.Выбор команды **File | New** из панели Меню или нажмите на команду **New** из панели инструментов. Затем, нажмите на опцию **Worksheet** в диалоговом окне **Новый документ**. Нажмите на ОК.




2.Для активизации ячейки необходимо нажать на ячейку курсором или использовать клавиши стрелок вверх, вниз, вперед или назад.

3.Когда ячейка активизирована, нужно вводить числовые значения или текст.

4.Клавиши BACKSPACE и DELETE могут быть использованы для редактирования.

5.Нажмите на ENTER для ввода данных в ячейку.

**Сохранить Файл Данных**

После ввода всех данных:

1.Выбор команды **File | Save** из панели Меню или нажмите на команду **Save** из панели инструментов.

2. При сохранении Файла Данных в диалоговом окне **Save As**, необходимо выбрать Golden Software Data (*.dat) из списка возможных типов файлов.

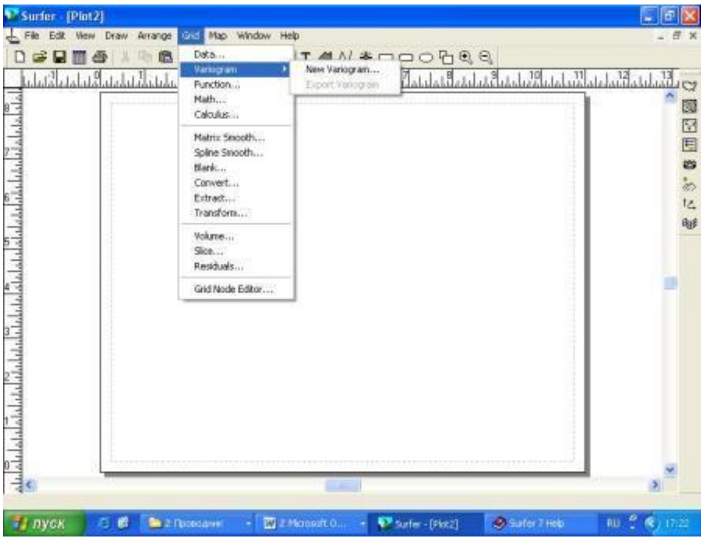
3. Введите имя файла в ячейку Имя Файла. Нажмите OK и файл будет сохранен в формате Golden Software Data [.dat]. Имя файла появится на верхней строке окна «worksheet».

## 3. ВАРИОГРАММНОЕ МОДЕЛИРОВАНИЕ

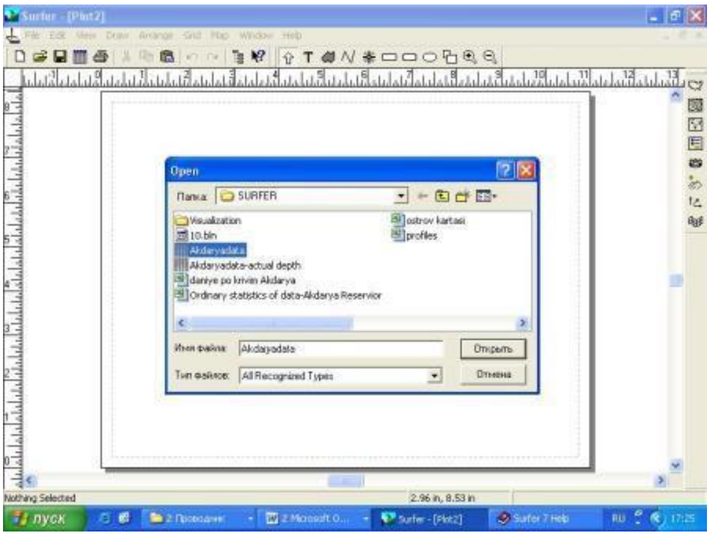
Одной из самых важных частей геостатистического анализа является расчет экспериментальной вариограммы и изучение анизотропии. Поэтому, этот аспект требует особенного внимания.

### Создание Вариограммы (Variogram)

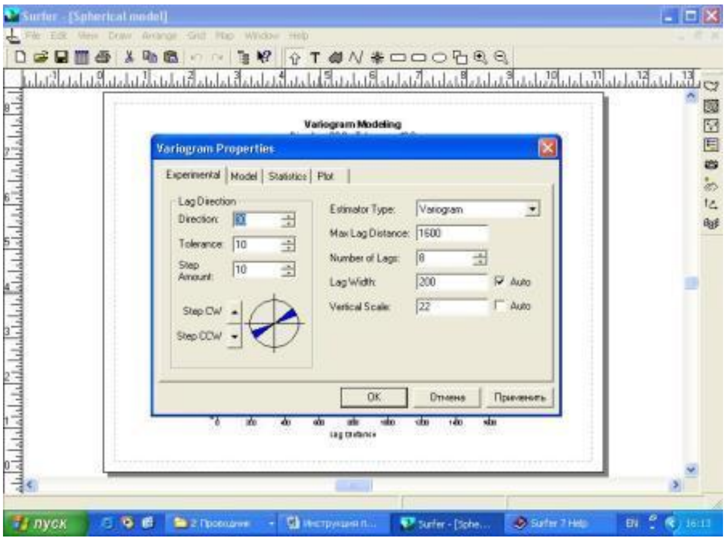
1.Выберите опцию **Grid | Variogram | New Variogram**.




2.Выберите файл данных Akdaryadata.dat в диалоговом окне Open.




3.Настройте данные с помощью опции «Data Columns» в табуляторе «DATA» диалогового окна **New Variogram**, и выберите настройки сетки variogram в табуляторе «OPTIONS».
4.После создания variogram, дважды нажмите на variogram для открытия диалогового окна **Variogram Properties**. Диалоговое окно **Variogram Properties** позволяет выбрать модель variogram (математическую функцию) в нашем случае, сферическая модель (линейная модель по умолчанию).




Диалоговое окно **Variogram Properties**

Табулятор «EXPERIMENTAL»
Табулятор «Experimental» в диалоговом окне **Variogram Properties** содержит параметры экспериментальной вариограммы: шаг направления «lag direction», оценочная функция «estimator type», максимальный шаг расстояния «max lag distance», количество шагов «number of lags», ширина шага «lag width», и вертикальная шкала «vertical scale».

Опция «Direction»

Опция «Lag Direction» позволяет рассматривать вариограмму в различных направлениях. Опция «Direction» определяет фокальное направление при расчете экспериментальной вариограммы. Единицы измерения направления: 0° в направлении положительной X-оси, и 90° в направлении положительной Y-оси.

Опция «Tolerance»

Эта опция определяет размер углового окна для построения экспериментальной вариограммы. Размер углового окна:

Направление + Допустимое отклонение < Угол < Направление + Допустимое отклонение

Ширина полного углового окна в два раза больше размера допустимого отклонения. Например, Допустимое отклонение по умолчанию 90° захватывает все направления. Диаграммное изображение текущего углового окна появляется в диалоговом окне.

Опции «Step Amount» и «Step Direction»

При создании модели вариограммы, необходимо просматривать экспериментальную вариограмму и математическую функцию во многих направлениях. Программа SURFER 7 позволяет пользователю исследовать вариограмму во многих направлениях шагом направления в анимированном виде. Так как, программа SURFER 7 использует метод вариограммной сетки, которая может вычислять и мгновенно вычерчивать диаграмму. Опция «Step Amount» уточняет инкремент шага направления в «lag Direction» каждый раз, когда нажимаются кнопки «Step CW» или «Step CCW». При нажатии кнопки «Step CW» шаг направления «lag Direction» уменьшается на величину (градус) указанную в «Step Amount» и автоматически диаграмма вариограммы обновляется, т. е, направление по часовой стрелке. При нажатии кнопки «Step CCW» шаг направления «lag Direction» увеличивается на величину (градус) указанную в «Step Amount» и автоматически диаграмма вариограммы обновляется, т. е, направление против часовой стрелки. Перетащите диалоговое окно **Variogram Properties** от графика вариограммы для просмотра изменений в диаграмме при каждом нажатии кнопок «Step CW» или «Step CCW».

Опция «Estimator Type»

Программа SURFER содержит четыре оценочных функций: variogram, standardized variogram, autocovariance, и autocorrelation. Оценочная функция Variogram используется по умолчанию.

Опция «Max Lag Distance»

Опция «Max Lag Distance» определяет длину шага расстояния на X-оси. Это значение не должно превышать значение в опции «Max Lag Distance» в диалоговом окне **New Variogram**. Значение в опции «Max Lag Distance» уже определено при создании сетки вариограммы (New Variogram) для ограничения максимальной длины разделения при исследованиях. Значение в опции «Max Lag Distance» определенное в этом диалоговом окне ограничивает максимальное значение длины расстояния, которое будет рассматриваться для создания сетки. Обычно значение в опции «Max Lag Distance» определенное в табуляторе «Experimental» диалогового окна **Variogram Properties** меньше чем значение в опции «Max Lag Distance» определенное при создании сетки вариограммы.

Опция «Number of Lags»

Опция «Number of Lags» определяет количество использованных (вычисленных и нанесенных на диаграмму) точек (шагов) для построения экспериментальной вариограммы. Количество точек (шагов) составляет 25 по умолчанию.

Опция «Lag Width»

При включении отметки «Auto», значение в опции «Lag Width» будет автоматически приравнена числовому значению в опции «Max Lag Distance» деленное на число «Number of Lags». Например, если ввести числовое значение 100 в опции «Max Lag Distance» и числовое значение 5 в опции «Number of Lags», тогда автоматически числовое значение в опции «Lag Width» будет 100 / 5 = 20. В этом случае, первая точка диаграммы будет включать все пары точек с шагом расстояния от 0 до 20м. Вторая точка диаграммы будет включать все пары точек с шагом расстояния от 20 до 40м. Интервалы расстояний от 0 до 20, от 20 до 40, ..., от 80 до 100; при этом не происходит перекрытие. Опция «Lag Width» используется для сглаживания вариограммы.

Опция «Vertical Scale»

Опция «Vertical Scale» определяет размер (длину) Y-оси вариограммы. Если включена отметка «Auto» то тогда, вертикальная шкала автоматически определятся для вариограммы. При включении отметки «Auto» вертикальная шкала вычисляется при каждом расчете вариограммы. При выполнении шагового расчета с использованием кнопок «Step CCW» или «Step CW» вертикальная шкала изменяется при каждом шаге.

При отключении отметки «Auto», вертикальная шкала остается постоянной, т. е., числовое значение не изменятся. При работе с кнопками «Step CCW» и «Step CW» для поворачивания шага расстояния следует выключить отметку «Auto» для избегания изменений вертикальной шкалы, это позволяет визуальному сравнению диаграмм.
Табулятор «MODEL»

Табулятор «MODEL» в диалоговом окне **Variogram Properties** позволяет пользователю установить определенную вариограммную модель и её параметры. Расчет экспериментальной вариограммы из генеральной совокупности данных, является бесспорным путем для определения вариограммной модели.

Программа SURFER позволяет разработать комбинированную вариограммную модель. Программа SURFER позволяет неограниченное комбинирование нескольких моделей (математических функций) и поэтому существует большое количество возможных комбинаций вариограммных моделей. Нажмите на кнопки «Add» и «Remove» для изменения параметров вариограммы. Существует 10 общих математических функций: Nugget Effect (Эффект Самородка), Spherical (Сферическая), Exponential (Показательная), Linear (Линейная), Gaussian (Гауссово), Wave (Hole-Effect) (Волновая), Quadratic (Квадратичная), Rational Quadratic (Рационально квадратичная), Logarithmic (Логарифмическая), и Power (Степенная).

За исключением вариограммных моделей Linear, Logarithmic, and Power (у которых нет «sill»), параметры шкалы «Scale parameters» (обозначаются буквой «C» в уравнениях вариограммы) определяют «sill» для выбранных компонентов вариограммы. Таким образом, «sill» вариограммы состоит из эффекта самородка (Nugget Effect) и плюс сумма параметров шкалы «C». Во многих случаях, «sill» вариограммой модели равна дисперсии наблюдаемых данных (Barnes, 1991).

Параметры «Length (A)» определяют, как быстро убывает или возрастает компоненты вариограммы с возрастанием шага расстояния. Параметр «Length (A)» для вариограммного компонента используется для градации шага расстояния. Для математических функций Spherical и Quadratic, параметр «Length (A)» известен как диапазон вариограммы.

Табулятор «STATISTICS»

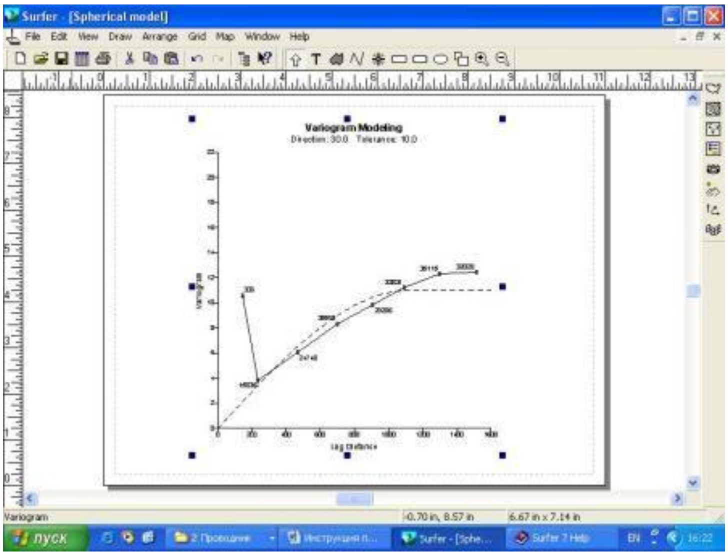
Табулятор «STATISTICS» в диалоговом окне **Variogram Properties** показывает гистограммы и  диаграммы разброса данных и элементарные статистические расчета данных.

Опции «X, Y, Z Histogram» показывают распределение X, Y, и Z данных соответственно.  Гистограмма появляется справа к этим опциям. Опция «XY Scatter» показывает распределение данных в формате диаграммы разброса.
Линейка прокрутки справа опции «statistics» показывает статистику данных. Нажмите на кнопку «Report» чтобы открыть статистические данные генеральной совокупности данных и информацию о вариограмме в отдельном окне «report».

Табулятор «PLOT»

Многие визуальные свойства диаграммы вариограммы изменяются этим табулятором. Можно изменять название диаграмма, шрифт заголовка в опции «Title». Для создания нескольких заголовок нажмите CTRL+ENTER для переноса на следующую сроку. Для дисплея символов «Symbols», линии диаграммы «plot Line», линии вариограммной модели «Model line», линии дисперсии «Variance line», подзаголовка «direction/tolerance Subtitle», или количество пар точек «number of Pairs», включите отметки соответствующих ячеек опций. Для изменения свойств функции нажмите на соответствующие кнопки и введите изменения в диалоговых окнах.

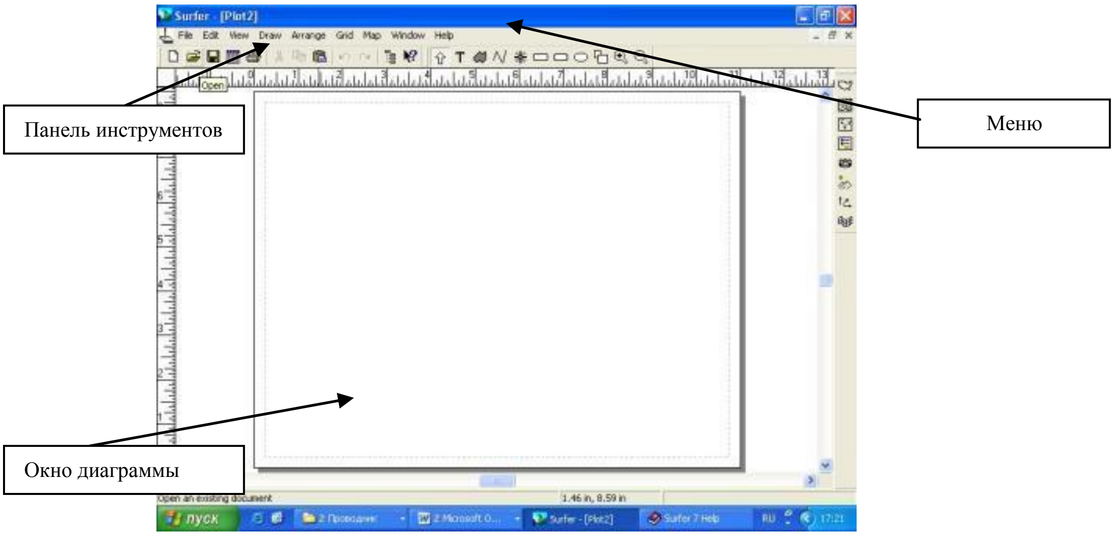
Конечным результатом является экспериментальная вариограмма и математическая функция на одной диаграмме.



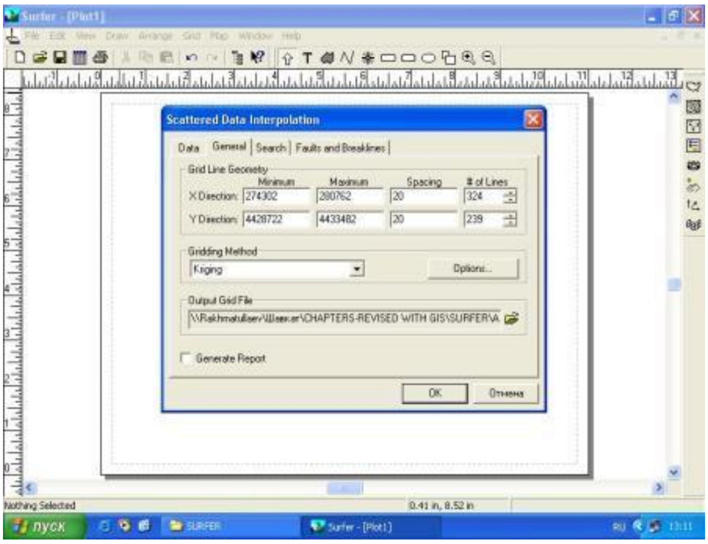

## 4. СОЗДАНИЯ ФАЙЛА СЕТКИ

1. Если окно «worksheet» открыта, нажмите на команду **Window** из панели Меню и выберите опцию **Plot1**. Или, для открытия нового окна Plot с помощью команды **File | New (Plot Document).**

2. Выберите команду **Grid | Data**. Появится окно **Open**. Это позволит выбрать файл данных X-Y-Z для создания файла сетки.




3.Выберите файл Akdaryadata.data. Нажмите на Open и появится диалоговое окно **Scattered Data Interpolation**. Или дважды нажмите на имя файла и появится тоже самое диалоговое окно.




4.Диалоговое окно **Scattered Data Interpolation** позволяет контролировать параметры создания сетки чащи водохранилища. Необходимо, рассмотреть различные опции каждой табуляции этого диалогового окна.

Табулятор «DATA» показывает Столбцы с координатами *X* и *Y*, и числовые значения *Z*-данных в файле данных X-Y-Z.

Табулятор «GENERAL» показывает опцию «Grid Line Geometry», которое указывает на максимальные и минимальные значения сетки координат *X*-*Y*, интервал сетки (размер) «spacing», количество линий сетки (количество строк и столбцов) «# of Lines» для использования разбивки сетки в файле сетки.

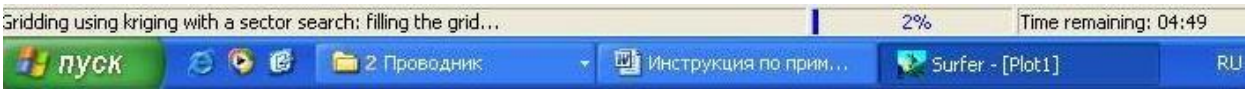
Опция «Gridding Method» в табуляторе «GENERAL» показывает интерполяционный метод, который будет использован и её параметры для создания сетки.
Опция «Output Grid File» в табуляторе «GENERAL» показывает место сохранения файл сетки на компьютере.

Опция «Generate Report» в табуляторе «GENERAL» генерирует статистический отчет о данных.

Табулятор «SEARCH» показывает радиус поиска для каждого узла сетки.

Табулятор «FAULTS AND BREAKLINES» показывает имя файла, которое содержит информацию о геологических разломах и сдвигах в исследуемой территории при создании сетки.

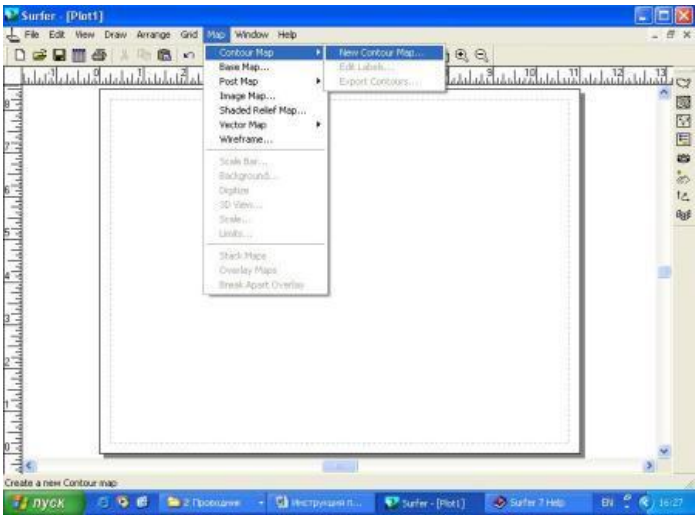
5. Нажмите OK.  Строка текущего состояния внизу окна показывает прогресс процедуры создания сетки. Когда процесс создания сетки завершен, файл сетки Akdaryadata.grd, SURFER производить звуковой сигнал о завершении создания файла сетки.  Файл сетки имеет расширение [.GRD]. Если включена опция «Generate Report», то появляется новое окно отчета «Data Filter Report».



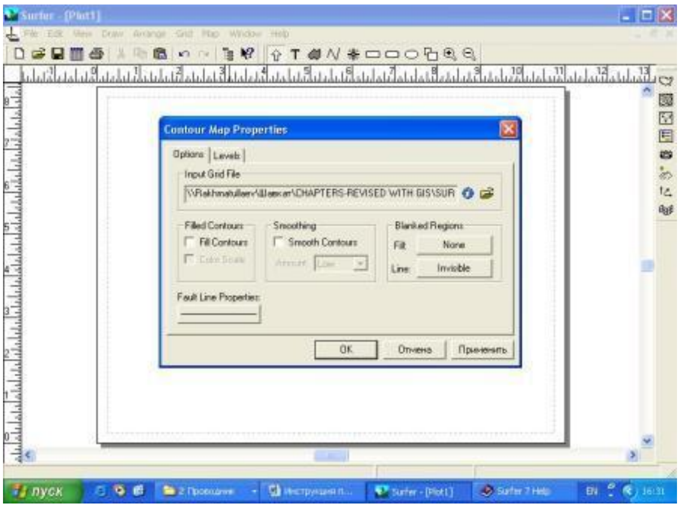
## 5. СОЗДАНИЕ КОНТУРНОЙ БАТИМЕТРИЧЕСКОЙ КАРТЫ

Команда **Map | Contour Map** создает контурную карту основанную на файл сетки:

1. Выберите команду **Map | Contour Map | New Contour Map**, или нажмите на инструмент **Contour**. Появляется диалоговое окно **Open Grid**. Созданный файл сетки Akdaryadata.grd автоматически вносится в ячейку Имя Файла. Нажмите на кнопку Open, и появится диалоговое окно **Contour Map Properties**.

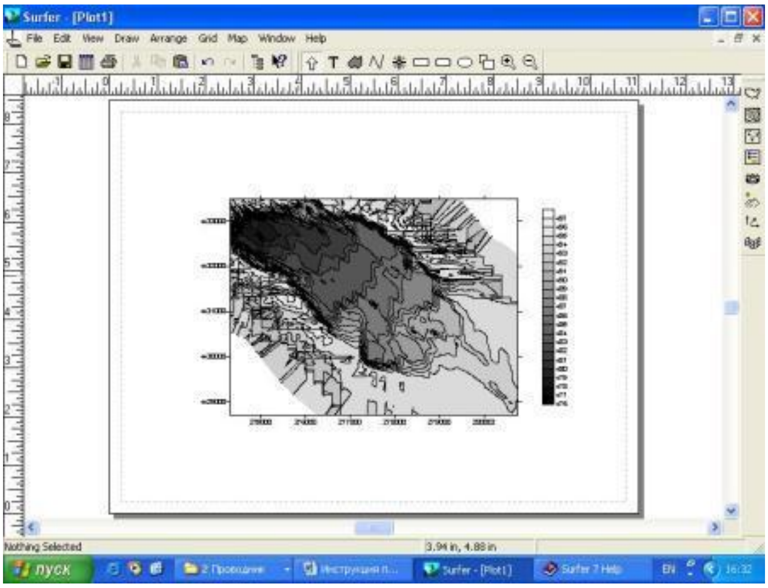



2. Параметры по умолчанию в диалоговом окне **Contour Map Properties** дают приемлемую контурную карту. Контурная карта создается при помощи файла сетки Akdaryadata.grd.




4.Можно изменить любые параметры и нажать на OK для дисплея карты на экран.

5.Для изменения любых параметров карты можно дважды нажав на карту, и появится диалоговое окно **Contour Map Properties**. Или же, нажмите на правую кнопку мышки, и появится диалоговое окно нажмите на **Properties** и появится диалоговое окно **Contour Map Properties**.



**Сохранить карту**:

1.Выберите команду **File | Save** или нажмите на инструмент **Save**. Появится диалоговое окно **Save As** потому что карта сохранятся впервые**.**

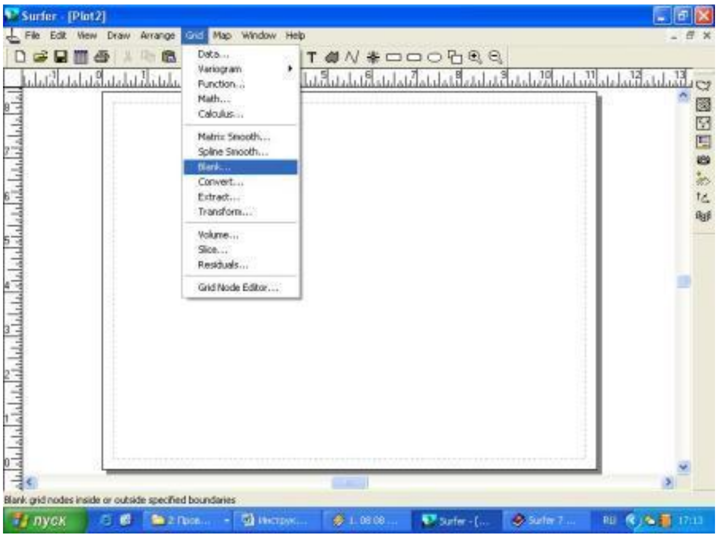
2.Введите имя файла в ячейку Имя Файла.

3.Нажмите на Save и файл сохранен с расширением [.SRF]. Сохраненная карта остается на дисплее окна.

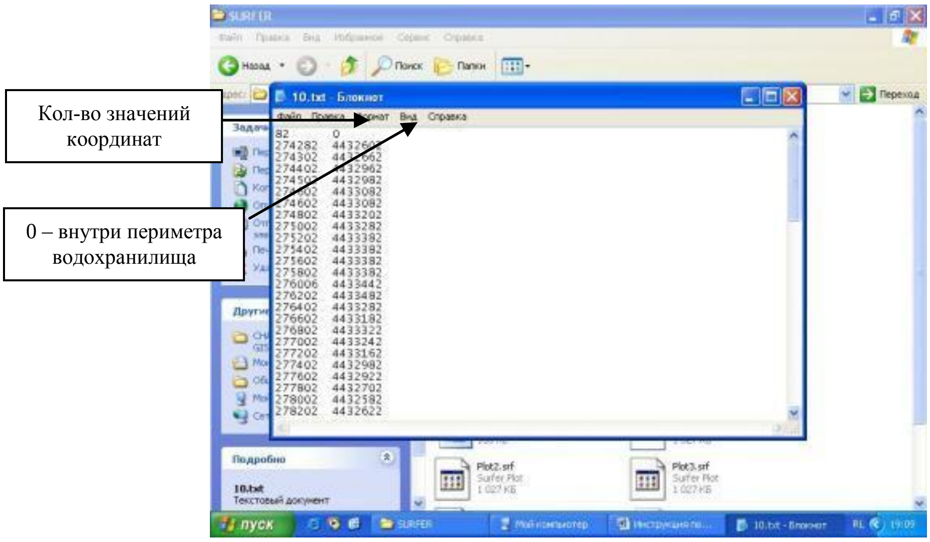
## 6. БЛАНКИРОВАНИЕ (BLANK)

Создание бланка файла сетки

Команда **Grid | Blank** используется для удаления ненужных узлов сетки в местах за пределами акватории водохранилища. Опция бланкирование устанавливает код бланка для определенных групп в бланке файла сетки. Бланкированные сетки содержат узлы сетки по периметру водохранилища и те же максимальные и минимальные координаты, что и в оригинале файла сетки контурной карты.




Границы бланкирования определяются как файл бланкирования в файле формата ASCII, которое содержит значения XY- координат определяющих границу периметра водохранилища. Файл бланкирования может быть создан в файле «worksheet» программы SURFER. Бланкирование может быть установлено как внутри так и снаружи границы бланкирования.



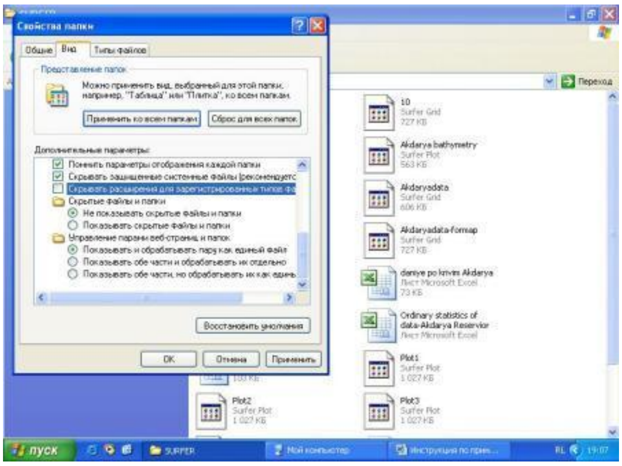

Бланкирование отмечает зоны сетки или карты с «отсутствием данных». В бланкированных зонах сетки:

- Контурные линии отсутствуют.
- Объемы и площади зеркала воды не рассчитываются.

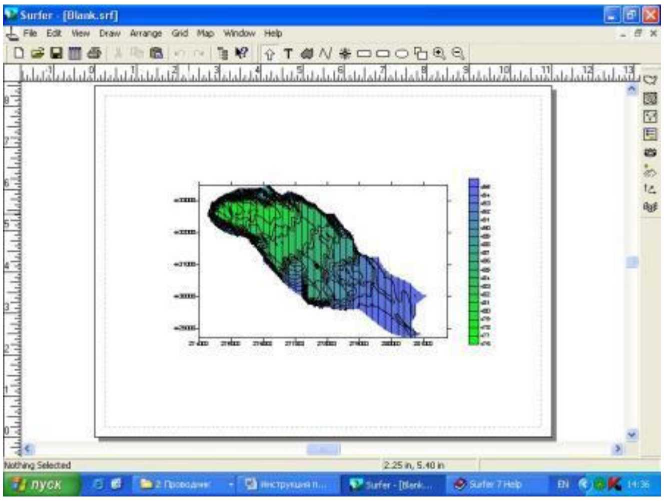
**Формат Файл Бланка**

Файл бланка имеют расширение [.BLN] и используются для предоставления информации о границе зоны бланкирования в файле сетки. Файл бланка являются файл формата ASCII с разделяющими запятыми, содержащий серии координат (XY-координат) периметра водохранилища. Единицы измерения числовых значений XY-координат являются одними и теми же, что и в файле сетки.

Необходимо, переименовать расширение текстового файла TXT на BLN для создания файла бланка.



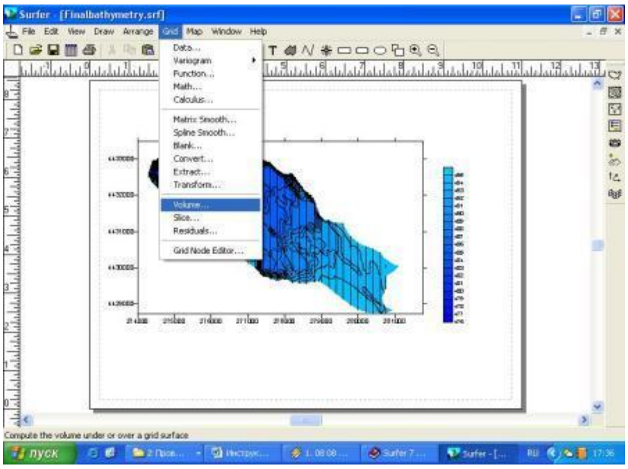

Законченный вид батиметрической карты водохранилища с размещением поперечников.




## 7. РАСЧЕТ ОБЪЕМА И ПЛОЩАДИ ВОДОХРАНИЛИЩА

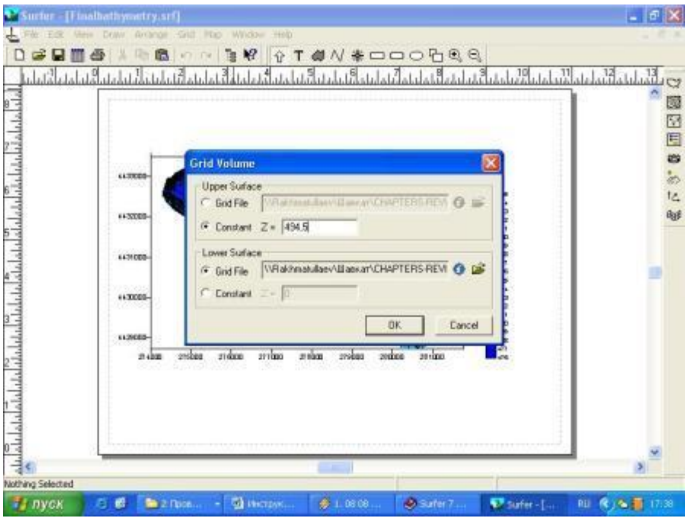
Выберите команду **Grid | Volume** для расчета объема водохранилища и площади водной поверхности.

1.Выберите команду **Grid | Volume** для дисплея диалогового окна **Open Grid**.



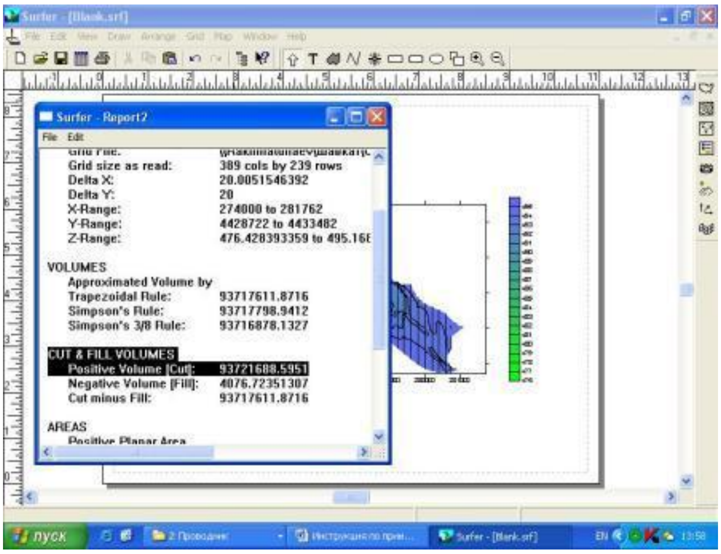

2. Определите имя файла сетки для расчета объема и площади водной поверхности водохранилища.

3.Нажмите на OK и появится диалоговое окно **Grid Volume**. Уточненный файл сетки можно обозначить как для верхней и нижней поверхности.




4. Для расчета объема и площади, необходимо указать абсолютную отметку в ячейке опции «Constant» для параметра верхней поверхности «Upper Surface» и указать на файл сетки в ячейке опции «Grid File» для нижней поверхности «Lower Surface» и нажать на OK.

5. Появится диалоговое окно **Grid Volume Report,** где необходимо использовать результаты в опции CUT & FILL VOLUMES -> Positive Volume [Cut] для определения объема водохранилища. Для определения площади водной поверхности необходимо использовать результаты в опции AREAS -> Positive Surface Area [Upper above Lower].




6. Выберите команду **File | Save As** для сохранения отчета в виде текстового файла или можно скопировать информацию в программу MS Excel для построения кривых объемов и площадей.

7. Для каждой абсолютной отметки высчитываем объем и площадь водной поверхности водохранилища и строим кривые объема и площади (рис.4).

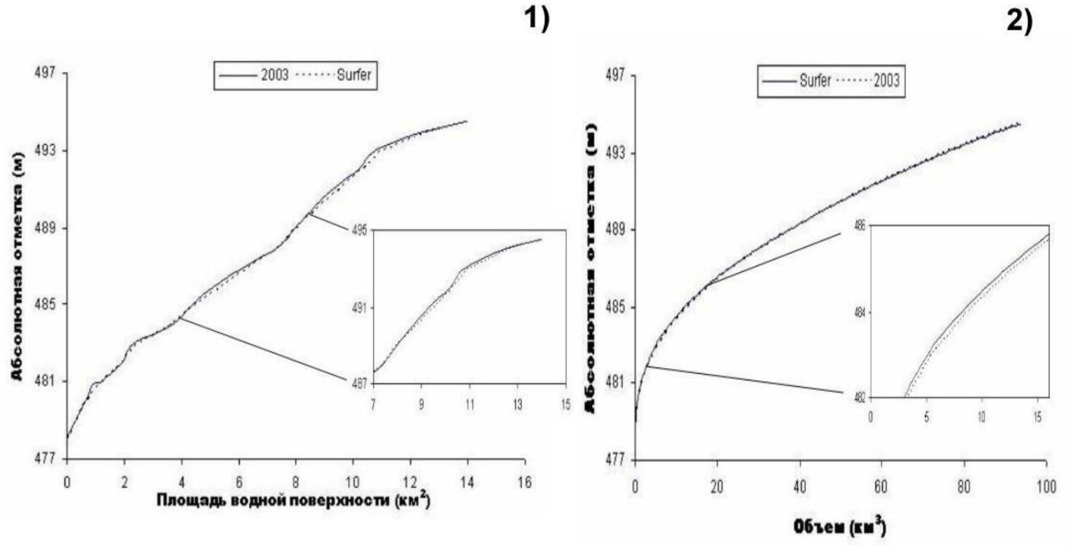



Рис.4. Кривые объема и площадь зеркала водохранилища

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**ОГЛАВЛЕНИЕ**

М.Р. Бакиев, Ш.А. Рахматуллаев. Руководство по применению программы SURFER-7 для расчета полезной емкости водохранилищ. Ташкентский институт ирригации и мелиорации, Ташкент, 2008г., 24с.

**Аннотация**:
В памятке приведена последовательность и методология создания цифровой батиметрической модели чащи водохранилища с использованием компьютерной программы SURFER-7 для расчета полезной емкости водохранилища (на примере Акдарьинского водохранилища). Основной задачей использования программы SURFER-7 является прогноз и интерполяция значений величин на местах, где отсутствуют эти данные и обработка и визуализация двухмерных наборов данных, что позволяет а) построение цифровой модели чаши водохранилища; б) определение объемов и площади водной поверхности водохранилища, а также в) двух- и трех-мерное визуализация поверхности водного объекта.
Новизна заключается в расчете объема водохранилища с уменьшением количества поперечников, что позволяет уменьшить время и затраты на проведение батиметрических обследований.

**Аннотация**
Эслатмада Оқдарёсув омбори мисолида сув обморининг фойдали ҳажми узгаришиларини аниқлаш мақсадида SURFER-7 компьютер дастурини қўллаш бўйича услубий кўрсатмалар ёритилган. SURFER-7 дастури қўлланилишининг асосий вазифаси маълумотлар (сув омбори чуқурлиги) етарли бўлмаган ҳолатда чўқиндилар ҳаммини интерполяция ва башорат қилиш.
Ушбу дастур куйидаги максадларда ишлатилади:
А) сув омборининг косаси рақамли моделини тузиш;
Б) сув омборининг сув ҳажми ва юзасини куринишини аниқлаш;
В) сув сатхининг икки ва уч-улчамли куринишини аниқлаш.
Ушбу дастурнинг илмий янгилиги шундай иборатки – сув омбори ҳажмининг улчашда кундаланг кесимларнинг сони камайаяди ва бу уз навбатида батиометрик изланишларнинг олиб борилишида вақт ва кам ҳаражатларга эришилишига олиб келади.

**Summary**
The instruction discusses procedures and methodology for generating digital bed surface of reservoir with help of SURFER-7 software in order to estimate useful storage capacity of Akdarya reservoir. The ma in objective of SURFER-7 is prediction and interpolation of geo-data in places where with no data available and treatment and visualization of data for a) construction of digital bed surface model of reservoir; b) estimation of useful storage reservoir capacity and area; c) 2-D and 3-D visualization of generated bed surface of reservoir. The innovativeness of the approach is estimation of reservoir useful storage capacity with decrease in number of cross-sections which in turn decreases time and expenses for conducting bathymetric research studies.

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Корректор Т.Болтаев
Компьютерная верстка И. Авазов

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Приложение 4

Калькуляция стоимости определения объемов водохранилищ Батиметрическим Центром

Appendix 4. Cost calculation of reservoir volume estimation by Botiometrik Markaz

**К А Л Ь К У Л Я Ц И Я**

**стоимости на проведение исследования по определению полезного объёма 1км2 водохранилища батографическим оборудованием CEEDUCER**

| Наименование операций | Площадь исследуемого объекта, км2 | № | Краткое содержание основных видов работ и удельный вес каждой операции (в процентах от общего объема работ) | Норма времени чел/час | Занят. спец. | Всего чел/час | Стоимость (согласно данным ГКС за 2005 г. 1 чел/час = 1274,63 сум. |
|---|---|---|---|---|---|---|---|
| I | II | III | IV | V | VI | VII | VIII |
| Измерение полезного объема водохранилища | 1 | | **Полевые работы** | | | | |
| | | 1 | Подготовка рабочего оборудования к измерению (Зарядка внешней и внутренней батареи) | 6 | 3 | 18 | 22943,34 |
| | | 2 | Сверка показателей характеристик объекта во время измерения | 0,5 | 3 | 1,5 | 1911,945 |
| | | 3 | Подготовка моторной лодки для полевых работ | 0,5 | 3 | 1,5 | 1911,945 |
| | | 4 | Установка рабочего оборудования на моторную лодку | 0,5 | 3 | 1,5 | 1911,945 |
| | | 5 | Определение значения драфта (расстояние между поверхностью воды и эхолота) | 0,35 | 2 | 0,7 | 892,241 |
| | | 6 | Установление связи со спутниковыми станциями оборудования "CEEDUCER" с помощью антенны GPS | 0,25 | 2 | 0,5 | 637,315 |
| | | 7 | Настройка рабочей программы "CEEDUCER" и внесение поправок | 0,2 | 2 | 0,4 | 509,852 |
| | | 8 | Проведение тарировки эхолота перед измерением | 0,5 | 2 | 1 | 1274,63 |
| | | 9 | Измерение объекта (1 км.2 поверхности когда расстояние между створами 20 м.) | 5 | 2 | 10 | 12746,3 |
| | | 10 | Определение координат объекта по контуру водохранилища по 1-ой точке на каждом 5-ом метре прохождения, для черчения карты по координатной сетке в (x,y), (800 точек на 1 км2) | 20 | 1 | 20 | 25492,6 |
| | | 11 | Проведение тарировки эхолота после измерения | 0,5 | 2 | 1 | 1274,63 |
| | | 12 | Перекачать данные с памяти "CEEDUCER" на память компьютера | 1 | 3 | 3 | 3823,89 |
| | | 13 | Первичный просмотр данных в программе "CEEDUC2" | 1 | 3 | 3 | 3823,89 |
| | | | **Камеральная обработка** | | | | |
| | | 14 | Полная обработка данных с помощью программы "CEEDUC2" и установление оптимального расстояния между точками в створе | 2 | 3 | 6 | 7647,78 |
| | | 15 | Перекачка обработанных данных в программу "Excel" | 1,5 | 3 | 4,5 | 5735,835 |
| | | 16 | Построение профилей створов в программе "Excel" | 8 | 3 | 24 | 30591,12 |
| | | 17 | Ввод в программу AutoCAD данных по контуру объекта и данных профилей створов | 45 | 3 | 135 | 172075,05 |
| | | 18 | Черчение карты объекта в нужном масштабе (на мил-лиметровку) | 12 | 2 | 24 | 30591,12 |
| | | 19 | Обобщение всех полученных данных и оформление технического отчета | 3,1 | 3 | 9,3 | 11854,059 |

| | | | |
|---|---|---|---|
| | | **Итого:** | 337 649,09 |
| Отчисление на социальное страхование | 24% | | 81 035,88 |
| | | **Итого:** | 418 685,26 |
| Материальные затраты (без учета командировочных расходов) | 0,1% | | 4 186,85 |
| | | **Итого:** | 422 872,22 |
| Прочие затраты подрядчика | 29,32% | | 123 986,13 |
| | | **ВСЕГО:** | 546 858,35 |

**Калькуляцию составил** И.Н.Шарипов

**Хронометраж провели :**

**Зам начальник** Х.А.Шомайрамов

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**Главный специалисты** С.Б.Хамраев

Ш.Ю.Мукумов

Согласовано:

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ORIGINAL ARTICLE

# Groundwater resources use and management in the Amu Darya River Basin (Central Asia)

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**Abstract** This paper analyses groundwater resources use and management in the socio-economic context of the Amu Darya River Basin which covers a part of the following landlocked Central Asian countries: Afghanistan, Tajikistan, Turkmenistan and Uzbekistan. These agrarian nations for sustaining their vital agricultural productions started to use groundwater during the recent drought years (1998–2001) because of its relatively good quality and quantity and as an alternative to highly mineralized surface waters. Present extent of groundwater resources use is discussed with consideration to their reserves, quality, and institutional management and transboundary aspects within the basin. After the collapse of the centralized water resources management system and infrastructure of the former Soviet Union, new underdeveloped systems are being practiced over the whole Amu Darya River Basin. The critical situation of groundwater management in Afghanistan is also discussed. This work attempts to document the management and use of groundwater in the Amu Darya Basin and present time management realities, with fragmented and weak national and regional regulation on groundwater. Special attention is given to groundwater resources in irrigated agriculture, which increased use in all countries of the basin is due to quick access to underground resources and relatively good quality and quantity.

**Keywords** Groundwater · Aquifer · Water management · Amu Darya · Central Asia

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## Introduction

In Central Asia, the Amu Darya River Basin (ADRB) which namely covers part of Afghanistan and the former soviet republics of Tajikistan, Uzbekistan, and Turkmenistan, groundwater resources are becoming an alternative source of supply for irrigated agriculture and livestock ranching especially in the events of recent droughts and in the context of highly contaminated surface waters due to high levels of salts and pesticides coming from irrigated lands. Due to their climatic characteristics, economic development strategies and geopolitical situation, ADRB countries have been experiencing everlasting competition over water resources. Mostly arid, these agrarian countries pursue their own development and integration into the global community through expanding irrigated lands, growing cash crops such as rice and wheat for meeting their domestic food security but also to export a large part of some productions like cotton.

Groundwater resources were not widely used for irrigated agriculture in Central Asian Republics (CAR) during the soviet period due to sufficient amount of surface water, reliable water supply, and irrigation infrastructure delivered to the farmers. Thus, the groundwater resources were used primarily for livestock sector and very site-specific purposes for example drinking water supply in both urban and rural areas. During the pre-independence period, water allocation and irrigation system infrastructures were well maintained and operated with massive funding coming from the central government.

Since the independence of the CAR, the situation has changed dramatically in terms of institutional, political, and technical systems. Political transition from planned economy to market has introduced "new" concepts like land tenure, water rights, and different kinds of ownership. The institutional changes are described as transition from former state collective farms *kholkhoz* and *sovkhoz* into smaller forms of present private farms. But many farmers were not in the capacity to pump and irrigate lands on an individual basis.

In a very different situation, Afghanistan has traditionally relied on surface water and groundwater springs and karezes in irrigated agriculture. According to the estimates of International Water Management Institute (IWMI), the share of groundwater irrigation of the cultivated area is 11.5% of the total in Afghanistan (Shah 2007). During the recent drought years (1998–2001), the use of deeper groundwater, abstracted via pumped dug wells and boreholes has increased rapidly. Private farmers have drilled many of these new wells and boreholes, and in some areas, groundwater abstraction rates are already exceeding, or will soon exceed, sustainable groundwater resources (Banks and Soldal 2002; Uhl 2003; Masood and Mahwash 2004).

Groundwater overdraw is not everywhere the case in ADRB but the water drought experienced in 1998–2001 has encouraged people to consider groundwater as an alternative to the declining surface water resources. Then many farmers, who could afford, started to exploit groundwater for the irrigation purposes and mainly to sustain the production during low flow periods and maintain the salinity of irrigation water compatible with agriculture. In addition, it should be stated that from the quantitative point of view shallow groundwater is a reliable source of water and people who are distant from source of surface water can obtain it easily for the watering of their fields.

The main goal of this paper is to document and analyze the new realities of the groundwater use both quantitatively and qualitatively in the basin in current settings and to overview main issues and perspectives for sustainable interstate use of groundwater resources as a strategic potential in reducing the poverty in ADRB countries.

## Amu Darya River Basin characteristics

### Physiography

The Endoreic Basin of Amu Darya River is located in the inner part of the Eurasian Continent (Fig. 1). The catchment area comprises 534,739 km$^2$ (Water Resources of USSR 1971). 61% of the catchment area lies on the territory of the former Soviet Union and flows through the territories of the new independent states of Tajikistan, Uzbekistan, and Turkmenistan and 39% on the territory of Afghanistan (Water Resources of USSR 1971; Uhl 2003).

The Amu Darya River is formed by the confluence of the Pyanj and Vash Rivers in the Pamir Mountains and

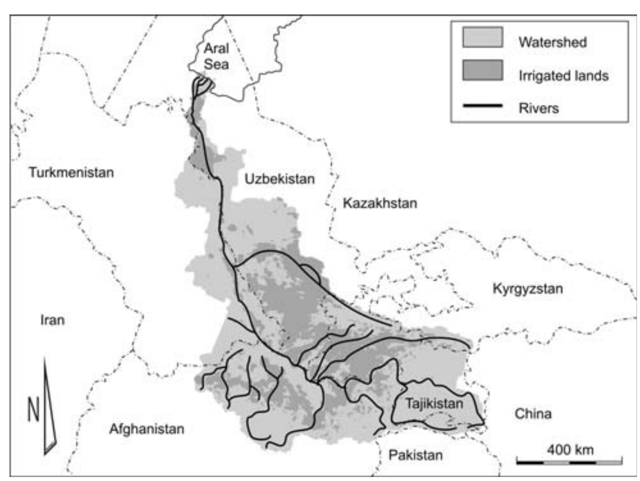


**Fig. 1** Map of the Amu Darya River Basin and location of main irrigation areas

discharges into the Aral Sea after a run of 2,550 km. Two Rivers, Zaravshan and Kashkadarya, are related to Amu Darya in term of water catchment characteristics but do not discharge into the Amu Darya River (Mirzaev 1974; Masood and Mahwash 2004). The Amu Darya watershed is divided into two unequal parts, a large north-western part where plains are dominant and elevations not greater than 200 m and a smaller south-eastern part characterized by high mountain ranges of 5,000-6,000 m of Central Pamir and Tian Shan. The presence of these high mountain ranges facilitates the formation of great water courses despite the very arid conditions of the region since it can accumulate atmospheric moisture, and behave as a huge feeding reservoir. The major part of the territory of the ADRB is composed of desert–steppe areas. The juxtaposition of mountains and deserts exerts a great influence upon the hydrogeological conditions, thus favoring the formation of considerable groundwater resources in a number of arid regions. The proximity of mountains and deserts in Central Asia determines the existence of two subtypes of groundwater formation in arid conditions: autochthonous and allochthonous (Ostrovsky 2007). The autochthonous subtype is developed in regions not influenced by mountainous systems and is characterized by groundwater formation from in situ water resources, and mainly from precipitation. The allochthonous subtype is typical of deserts where groundwater is formed under the influence of mountainous systems. It is commonly held that arid zones are characterized by the presence of basins that have no runoff to the ocean and where all precipitation is used up through evapotranspiration. However, if arid zones are considered within their climatic boundaries, then the balance of precipitation and evaporation cannot be equilibrated, as the total amount of evaporation also includes evaporation of both surface runoff and groundwater discharge from mountainous humid regions (Ostrovsky 2007).

## Hydroclimatology

The north-western plain of Central Asia is characterized by very hot summer (mean July temperature about 25.5°C) and cold winters (mean January temperature about 2.4°C). The ADRB is open to the dry air masses formed in Arctic and Siberia coming from the North. As they are blown towards western and southern parts of the basin these cold air masses are heated and then can encounter tropical air masses coming from the south. Unstable winters over the region are resulting from this mixing front between dry cold air masses and tropical warm air masses (Aizen et al. 2001).

The basin is characterized by uneven distribution and quantity of precipitation. The average mean annual precipitation over the basin is about 170 mm (Shultz 1949), with great contrast between north-western steppes (100 mm/year) and mountainous areas of the south-eastern (1000 mm/year). The important role of mountains and glaciers should be pointed out as these areas can store precipitation as snow and ice and deliver it through summer melting to rivers and associated alluvial aquifers during dry season (July and August). On an average 96% of the basin area receives approximately less than 300 mm/year (Shultz 1949) and most of the rainfall occurs in winter and spring from December to April.

The dominant process in this very arid region is evapotranspiration which can potentially amount to 1,500–2,000 mm/year (Létolle and Mainguet 1993; Nezlin et al. 2004) and is responsible for the loss of great volumes of water.

## Hydrogeology

The region is characterized by very complicated hydrogeological conditions. At first, the complex geological history of the Pamir and Tian Shan Mountainous area is responsible for a huge diversity in term of aquifer and water bearing sediments. These regions are composed of Palaeozoic, Mesozoic, and Cenozoic formations and significant shallow groundwater resources are located in valleys, where 10–100 m thickness deposit of semi-consolidated coarse to medium Quaternary sediments have accumulated. In the piedmont area fresh confined groundwater can be found in the peripheral parts of Quaternary debris cones. Deeper aquifers in carbonate rocks (depths from 700 to 800 m up to 1,000–1,200 m) contain thermal water, widely used in Tajikistan and Uzbekistan for medicinal purposes and bottled as table mineral water (Shultz 1949).

Plains region of the ADRB are covered by alluvial sand, loam, and clay dating from the Quaternary and Pliocene and that can be interstratified, giving birth in some places to confined or semi-confined aquifers. Groundwater in these surface formations are strongly hydraulically connected to Amu Darya River and mainly recharged by losses of rivers (allochthonous river runoff), irrigation canals, and irrigated fields. A lot of shallow aquifers are salinized (1–10 g/l) or involved into salinization processes. Salinization results from agricultural practises but is also related to the sodic nature of soil like solonetz and solontchaks. It must be noted that groundwater mineralization tends to decrease with depth (Ostrovsky 2007) and that mineralization processes are strongly correlated to groundwater level rise caused by irrigation.

Confined aquifers can be found in the deep Cretaceous sandstone formations of the Aral Sea area and provide artesian waters. In some parts these deep groundwater can show high mineralization which prevent them from any use. Mineralization can even reach values around 25–50 g/l at depth close to the Aral Sea region (Water Resources of USSR 1971).

In the Soviet times, groundwater resources were explored for the purpose of irrigation. Although they proved to be abundant, the primary focus was placed on the use of surface water. In Central Asia, groundwater constitutes a resource of fresh water that is comparable or exceeds surface waters in terms of volume. In many places this renewable resource can be effectively utilized with simple wells, which may, particularly, work as artesian wells in the lower parts of mountain slopes and mountain valleys.

## Groundwater reserves and extraction

### Groundwater reserves and use

Groundwater resources can be classified according to their recharge processes, two main classes can be distinguished: (1) groundwater formed under natural conditions in the mountain zone and catchment areas by infiltration of rainfall (autochthonous groundwater) (2) groundwater formed from the infiltration losses from irrigated areas in the rest of the ADRB (allochthonous groundwater). The total regional groundwater reserves are estimated to be 25 km$^3$/year (Mirzaev 1974) which represents about 58% of the Aral Sea Basin reserves (Table 1).

Groundwater's and surface waters are strongly hydraulically connected one to another, and according to an established system in the ADRB groundwater availability is characterized by the so called "natural recharge capacity" which can be considered as the regional operational reserve (Water resources of USSR 1971). This is a potential yield of each aquifer, which under the pressure of anthropogenic factors can be reasonably tapped in order to satisfy the needs. This is based on both the existing installed pump capacity and the level of knowledge of the aquifer recharge characteristics. "Approved capacities" confer the right to design and construct new withdrawal points (Table 1).

Aquifers in Uzbekistan and Tajikistan are relatively the most intensively exploited. About 99% of approved groundwater reserves are used in Uzbekistan, whereas in Tajikistan and Turkmenistan only about 30–40% are used for various purposes (Table 1). This can be explained by both intensive groundwater abstraction infrastructure in Uzbekistan with funding from the central government in irrigated areas and by uncontrolled water extraction by local farmers and the population in more isolated areas which tend to tap the aquifers to the maximum of their possibilities.

In Turkmenistan, about 134 large groundwater bodies can be identified and used for various needs (Khatamov 2002; Orlovsky and Orlovsky 2002). The total intake of groundwater resources varies from 4.7 to 6.7 km$^3$/year out of which 45% is used for drinking supply, 30% for irrigation and rest for livestock ranching. Groundwater from the first water-bearing horizon serves as a major water source in the desert areas. In 1994, according to different sources, there were from 5,695 to 6,138 water wells and up to 619 boreholes, which supplied water to about 68% of pastures (Babaev and Kolodin 1995; Babaev and Kolodin 1997). In the recent years, a number of new water wells were built, but at the same time the old ones were destroyed. So the exact number of functioning wells and boreholes is now unknown.

In Tajikistan, many groundwater bodies can be identified in the very complex structural framework of the country but all limited in term of extension. According to the National Hydrometeorological Agency, the total amount withdrawn annually is about 2.372 km$^3$ in 2004 (Table 2) without negative impact since the approved reserved are about 6.972 km$^3$ (Salimov 2001). About 40% of groundwater is used for irrigation and about 49% for domestic drinking supply. In 1994, the total numbers of wells was 4,795 and out of which 511 are wellspring and 4,358 are operational wells (Orlovsky and Orlovsky 2002).

In Uzbekistan, around 94 major aquifers can be identified with a total groundwater volume of about 18.9 km$^3$, this includes 7.6 km$^3$ with mineralization of up to 1 g/l and 7.9 km$^3$ with mineralization from 1 to 3 g/l. 85% of the

**Table 1** Groundwater reserves and their use by states in ADRB in km$^3$/year (UNDP 2007)

| Country | Estimated regional reserve | Approved reserves for use | Factual withdrawal in 1999 | Use category | | |
|---|---|---|---|---|---|---|
| | | | | Drinking water supply | Industry | Irrigation |
| Tajikistan | 18.7 | 6.02 | 2.29 | 0.485 | 0.200 | 0.428 |
| Turkmenistan | 3.36 | 1.22 | 0.457 | 0.210 | 0.036 | 0.15 |
| Uzbekistan | 18.45 | 7.79 | 7.74 | 3.36 | 0.715 | 2.15 |
| Total, Aral Sea Basin | 43.48 | 16.93 | 11.037 | 4.30 | 1.08 | 4.04 |

**Table 2** Groundwater recharge and withdrawals in the ADRB (UNDP 2007)

| Country | Average annual groundwater recharge | | Annual groundwater withdrawals | | | |
|---|---|---|---|---|---|---|
| | Total ($km^3$) years vary | Per capita ($m^3$) year 2000 | Year | Total ($km^3$) | Percentage of annual recharge | Per capita ($m^3$) |
| Afghanistan | 29.0 | 127 | – | – | – | – |
| Tajikistan | 6.0 | 970 | 1994 | 2.3 | 37.7 | 398.7 |
| Turkmenistan | 3.4 | 753 | 1994 | 0.4 | 11.9 | 100.3 |
| Uzbekistan | 19.7 | 809 | 1994 | 7.4 | 37.6 | 334.3 |

groundwater resource is recharged from surface water and only 1/3 is formed on the territory of neighboring countries and which could be called as "transboundary" groundwater resources (Mirzaev 1974; Borisov 1990). The percentage of groundwater used in irrigation amounted to 6.4% of the total irrigated land in Uzbekistan. Limits to groundwater abstraction for each aquifer in Uzbekistan have been established in order to avoid significant consequences to surface flow reduction. This quantity is estimated at 6.8 $km^3$/year for Uzbekistan. However, the actual groundwater abstraction is slightly superior (estimated at 7.5 $km^3$/year) and thus tends to lead to a surface flow reduction (Kazbekov et al. 2007).

The great aquifers or regional operational reserves of Uzbekistan have been primarily identified according to drinking water standards. For example, for the 1965–1995 period the fresh drinking groundwater resources in Uzbekistan have decreased from 471 to 294 $m^3$/sec and comprise only 34% of total groundwater resources compared to the 56% of total groundwater resources it represented in the past (Borisov et al. 2002). In 2001, total extraction of groundwater decreased by 4.9% and irrigation by 10.4% in the Uzbek part of the ADRB in comparison to 1995. The observed decrease in extraction is due to the reduction of operation hours of wells, worn out of pumping systems and bad condition of wells. In comparison with 1995 the total withdrawal decreased by 38.7% (Borisov et al. 2002).

On the other hand, groundwater reserves increased from 844 to 853 $m^3$/s in Uzbekistan from 1995 to 2001 (Borisov et al. 2002). The increase is explained by the development of irrigated lands. As a result of infiltration of water losses, the level of groundwater of unconfined aquifers began to rise also entailing the dissolution of salts contained in the upper part of soil profiles (Kitamura et al. 2006; Northey et al. 2006). This is particularly true in the lower reaches of Amu Darya River where the groundwater resources were at 15–20 m depth in 1980s and started to rise 1–1.5 m depth in early 2000 (Borisov et al. 2002).

The surface of irrigated areas with high groundwater table level has increased by 21% in ADRB (Table 3) that is to say from 1.29 million ha in 1990 to 1.56 million ha in 1999 in CAR (UNDP 2007).

**Table 3** Irrigated lands with high groundwater table level in ADRB, evolution from 1990 to 1999 (FAO 2007)

| Country | Areas with a water table <2 m ($10^3$ ha) | | Increase (%) (1990–1999) |
|---|---|---|---|
| | 1990 | 1999 | |
| Tajikistan | 92 | 111 | 21 |
| Uzbekistan | 670 | 801 | 20 |
| Turkmenistan | 528 | 654 | 24 |
| Total | 1,290 | 1,566 | 21 |

After the drought of 1998–2001 groundwater use has increased in lower reaches of ADRB. For instance, the Government of Uzbekistan has issued special decrees to overcome the consequences of the drought. The main purposes of the decrees were to drill 2,600 shallow wells in rural districts for population needs. The second purpose of these measures was to repair old wells that were used for both agriculture and drinking water supply (Kuchuhidze et al. 2003).

## Groundwater extraction methods

Groundwater extraction methods in Central Asia are much contrasted and can go from the traditional karezes systems in Afghanistan to modern pumping plants in Uzbekistan.

Karezes are human-made underground channels common in Afghanistan. They are often very old, having been constructed several hundred years ago. They are typically located in the foothills of mountain areas, but can be constructed anywhere where the water table is relatively shallow and where there is a consistent slope of the terrain. Karezes essentially skim water off the top of the water table. This means that, in effect, it is practically impossible to overexploit an aquifer using karezes (Fuchinoue et al. 2002). On the negative side, they are extremely vulnerable to even relatively small drops in the water table caused by climatic factors or pumping of nearby wells. Karezes may be used for irrigation and drinking water. Due to decline in water table related to the current drought in Afghanistan, flows available for irrigation from karezes have become inadequate in many areas and farming viability is suffering. Thus, dug wells and boreholes are typically drilled at shallow depth (up to 20 m) in Neogene and Quaternary sediments (Banks and Soldal 2002). They may be used for drinking water or for irrigation purposes and most of the time fitted with hand pump. In some areas, artesian aquifer may exist at depth. In this case, pumps are not required in boreholes; they simply overflow under their own pressure. In the Mazrah area of Guzara District (Herat), private irrigation boreholes drilled to 60–65 m deep encounter artesian resources of fresh groundwater. Typical yields of about 5 l/s flow uncontrolled for 24 h/day from these boreholes. Such uncontrolled overflow is extremely undesirable from a water resource point of view (Banks and Soldal 2002). For irrigation, most of the lands were irrigated either by surface water or by groundwater from karezes or natural springs. This situation is rapidly changing. Lift irrigation is new technology and, although in overall terms it still accounts for a relatively modest share of total irrigated land, its use is growing explosively.

For the CAR the major share of groundwater extraction is coming from borehole and dug wells thanks to heavy equipments developed during the soviet period and still operating in many places. According to Uzbekistan Research Institute on Hydrogeology and Engineering Geology (HYDROENGEO) and Ministry of Agriculture and Water Resources of Uzbekistan, the extraction of groundwater is made mainly from borehole but at very different depth and with many kinds of design, mainly inherited from Russian technologies. Extraction of shallow groundwater up to 6.0 m is operated manually, deeper unconfined aquifer (30–150 m) from Quaternary are exploited with electrical submersible pumps of varying capacity of 10–70 l/s (Borisov 1990).

### Cost of groundwater extraction

According to the HYDROENGEO Institute, the use of groundwater is not economically profitable for irrigation due to its high extraction costs and economic inefficiency in Uzbekistan (Mirzaev 1974; Borisov 1990). The global production cost per 1 $m^3$ of groundwater is about 0.5–1.0 US$ (UNDP 2007). Cost per 1 $m^3$ of surface gravity irrigation for a farmer is estimated to be 0.13–0.15 US$, and in the areas of pumped irrigation is about 0.3 US$ (UNDP 2007). Thus, production cost in the case of groundwater exploitation is clearly higher than that of surface water exploitation.

However, the use of groundwater resources for irrigation purposes is justified in water scarce conditions and in special places of the territory of Central Asia. For instance in the ADRB by 2003 approximately 27,000 boreholes were drilled to counterpoise the pernicious effects of the drought, with depth varying between 50 and 500 m with a cost of drilling for one borehole ranging within 500–2,000 US$.

Decentralized water supply of rural population, especially downstream the Amu Darya River, is provided by unconfined groundwater resources coming from shallow wells of 15–20 m. Extraction of groundwater is manually operated with hand pumps which cost's about 100 US$ each. The drilling and equipment of the tube with steel pipes can reach about 100–150 US$ in unconsolidated sediments like sands (UNDP 2007).

In Afghanistan, according to Banks and Soldal (2002), dug wells are typically 3–4 times cheaper than boreholes. Typical drilling prices in Afghanistan are 5–6 US$/m in soft strata, 12 US$/m in hard strata. In some parts of Afghanistan, where the demand is high, prices can reach 18–20 US$/m (Banks and Soldal 2002) and are thus dedicated to a very limited number of people who can afford such prices.

## Groundwater and agriculture

### Massive irrigation

Irrigation in Central Asia and particularly in Uzbekistan relies on a system of pumps and canals which is among the most complex in the world. Cotton and wheat are the major crops in the ADRB followed by maize, vegetables, and fruits. As previously said with annual rainfall of 100–300 mm, the CAR's climate is that of the dry mid-latitude desert, with a continental climate that is characterized by hot summers and cold winters. Thus, agricultural production in Central Asia is predominantly based on irrigation, which makes irrigation water supply and management the major factors limiting crop yields in the region (Ibragimov et al. 2007).

Agriculture is the dominant sector of the economy in the ADRB countries, employing from 44 up to 80% of the workforce (Table 4). This sector contributes to the basin countries Gross Domestic Product (GDP) from 16 up to 36% with an average of 26% over the basin. All of the ADRB countries are landlocked with arid climatic conditions and agricultural lands are heavily dependent on irrigation to insure acceptable production. Almost all of the agricultural lands are irrigated in Turkmenistan, while the average is around 75% in the other basin counties. Climatic conditions and recent droughts coupled with increased deteriorating quality of surface water prone water users to use more groundwater resources. The Table 4 summarizes

Table 4 Main characteristics of agricultural sector of the ADRB countries (FAO 2007)

| Country | Share of employment in agriculture (%) | Share of agriculture contribution to GDP (%) | Irrigated land (million ha) Amu Darya Basin | Share of irrigated to the total cultivated land (%) |
|---|---|---|---|---|
| Afghanistan | 80 | 36.1 | 1.16 | 50 |
| Tajikistan | 67.2 | 23.6 | 0.43 | 17 |
| Uzbekistan | 44 | 27.3 | 2.48 | 80 |
| Turkmenistan | 48.2 | 16.7 | 1.74 | 96 |

the main characteristics of agriculture and irrigation in the ADRB countries.

In Afghanistan, the estimated annual groundwater volume used for irrigation is minimal (1 $km^3$/year) in comparison with the groundwater recharge estimate (2.97 $km^3$/year) indicating a significant surplus of groundwater reserves in this part of the ADRB and the real potential for future development of groundwater resources for irrigation (Uhl 2003). The total withdrawal of groundwater in Uzbekistan for 2003 is about 2 $km^3$/year and it is used at 40% for irrigation purposes (Kazbekov et al. 2007). In Turkmenistan, agriculture is almost impossible without irrigation as shown in Table 4 and as a consequence this country is mostly impacted by pernicious effects of lift irrigation. From 1986 to 1998 strong rise in the water table was recorded with an increase from 7 to 41% in the surface of farming land with groundwater level less than 2 m.

In Tajikistan, the structure of agriculture is still heavily centralized and big collective farms are operating complex wells and irrigation systems. In 2000 there were roughly 1,000 operational boreholes and numerous wells that totaled 0.428 $km^3$/year discharge mainly used for irrigation purpose. According to Salimov (2001) about 30,000 ha of lands were irrigated with groundwater resources.

### Livestock rearing

In the Uzbek desert and mountain zones of the ADRB, numerous small settlements can be found. These territories are part of pasturelands. The mountain pasturelands have available groundwater resources but in most cases these are in poor conditions from pollution and contamination point of view. The livestock rearing under the desert conditions is off course limited by the water supply availability even if in general, water supply of pasturelands requires very little quantity of water (from 10 to 25 $m^3$/day) for cattle watering ponds (Babu and Toshmatov 2000).

In Tajikistan, water supply of pasturelands for livestock ranching is supplied by both surface and groundwater resources. The vast areas of the foothills of the Central Tajikistan, plains of Pamir, and South-Tajik depression are rich winter pasturelands, the groundwater reserves can here supply millions of animals (Babu and Toshmatov 2000). At present time, just a limited part of available pasturelands is used for ranching alongside of streams and large springs.

In Turkmenistan about 5,200 wells, 50 boreholes, and 330 springs are used to water the cattle. We must also point out the use in this country of more than 600 *takyrs* as collectors of atmospheric precipitation (Orlovsky and Orlovsky 2002).

## Groundwater quality

The two major land quality problems in the ADRB are the interrelated issues of salinity and waterlogging caused by high groundwater levels, only 50% of the irrigated land is classed as nonsaline (Banks and Soldal 2002). In the upper reaches of the ADRB, less than 10% of the land is saline or highly saline, while downstream (especially in Karakalpakstan) about 95% of the land is saline, highly saline or very highly saline. Salinity is closely related to drainage conditions. Moreover, a reduction in the quantity of water allocated to each farm, lower water quality, and the decay of companies responsible for maintaining the drainage network have resulted in increased salinization. Though loss of crop production due to soil salinization is important but salinized lands are generally still cultivated since no alternatives are available at present time (Heaven et al. 2002).

Less than 10% of the CAR's groundwater volume has a salinity level less than 1 g/l, equivalent to the highest quality irrigation water (FAO 2007). Overall, most groundwater has salinity levels between 1 and 3 g/l with approximately 15% showing values between 3 and 5 g/l and nearly 27% having salinities >5 g/l (Chembarisov and Bakhritdinov 1989; O'Hara 1997; Gadalia et al. 2005).

In Uzbekistan, the regional operational groundwater reserves in 2003 comprised 9.17 $km^3$/year out of which groundwater with mineralization lower than 1 g/l constitutes only around 30% and the rest of groundwater of 1–5 g/l.

Shallow groundwater sources have become increasingly salinized in the lower Amu Darya River in 2001. Several bore and open wells that were used as potable water supply sources have been recently abandoned because of increased salinity, thus preventing from any drinking use. Many wells were also recharging much more slowly than in the recent past and providing lower yields. As a consequence, queues at wells were increasing and the amount of water available for daily withdrawal was decreasing at many sites (Medecins Sans Frontieres 2001).

The dramatic change in the quality of groundwater resources observed in some places of the basin is linked to irrigation and melioration of lands; and reallocation and extraction of river flow (especially since 1965). Discharge of collector-drainage water into the river systems, its re-use and chemization of agriculture has led to regional pollution of unconfined groundwater resources by salts, nitrates, and pesticides (Papa et al. 2004). Such water consumption patterns are well reflected in temporal changes in groundwater depth and salinity, which both showed a rapid increase in the late 1990s. The overall spatial distribution of groundwater salinity shows also strong spatial association with the type of aquifer rock and with the distance from the river along the main irrigation canals (Ibragimov et al. 2007). Coarser sediments showed higher groundwater salinity than finer sediments. Groundwater pollution occurs progressively from upstream to downstream along the river stream. The mineralization of shallow groundwater in upstream of Amu Darya River is about 1–3 g/l and in midstream and downstream it can increase up to 5–20 g/l (Crosa et al. 2006a, b). This increase is the direct expression of the intense development of irrigation and drainage systems for the last 40 years and the consecutive mobilization of large amounts of salts already present in soils or added via agricultural practises.

In the whole ADRB man-caused influence have lead to pollution and to the decrease of groundwater resources and operational reserves of fresh groundwater resources on an average, for the last 30 years, by 0.17 $km^3$/year or in total by 5.1 $km^3$ in Uzbekistan (Borisov 1990). Contamination levels registered in both surface and groundwater are so high that it is not possible to count on any natural purification process from percolation and infiltration of groundwater through the soil (UNDP 2007). Despite this fact, farmers are forced to continue to use groundwater for agriculture, domestic, livestock, and drinking purposes since no other water resources can be exploited.

In the lower Amu Darya (part of Uzbekistan and Turkmenistan), the groundwater quality is also deteriorated in rural areas due to very poor sewage systems. Traditionally, all rural households have their toilets in close vicinity (10–30 m away) from their houses and as a consequence shallow groundwater is very often contaminated by sewage.

Due to this reduction of high-quality water resources by 30–40% compared to 1965–1970, the government of Uzbekistan undertakes extreme measures involving the creation of highly protected territories of groundwater resources with the aim of improvement of groundwater quality. With limited use of manure and pesticides and respectful development of local industry, these measures will tend to regulate and to reduce the water use in the national economy. These measures also include the renovation of the available wells which are often in very bad condition, the construction of new wells and the installation of new efficient pumps and efficient conveyance systems.

## Transboundary groundwater issues

### Problems coming from groundwater sharing

Groundwater regimes and quality are determined both by natural factors and by the level of abstraction; it doesn't depend on administrative boundaries (UNESCO 2001). As such, the management of internationally shared groundwater is of special importance in the ADRB (Struckmeier et al. 2006). Transboundary groundwater is assumed to include: aquifers which are located in two or more countries; and aquifers which are used in combination with surface water, and for which changes in extracted volumes may lead to changes in surface water quantity and use.

The combined use of both groundwater and surface water can be beneficial where long term sustainable groundwater extractions (not exceeding the natural recharge) replace scarce surface water resources (Zaisheng et al. 2008). However, if aquifers are not properly managed, many negative effects may occur: rise of groundwater levels and deterioration of soil conditions; local draw-down of groundwater levels around extraction points thus reducing surface water availability; pollution of aquifers because of human activities such as mining, treatment of industrial waste water, cattle-breeding; and overexploitation and long term damage to the groundwater potential.

These effects have local impacts, which may extend to the territories of neighboring states. Often, measures which provide positive effects on the territory of one country like irrigation of new areas, canal construction, and public water supply development, lead to negative effects in adjacent countries and preventive measures in the affected states may be expensive and may take several decades to become effective, essentially due to political reasons.

About 30% of the 338 aquifers of the ADRB area are international, but they represent the majority of the extracted groundwater. The main international aquifers areas include the area around the Tuyamuyn reservoir and its supply canals between Turkmenistan and Uzbekistan; the piedmont zone in the Hungry Steppe with shared aquifers between Tajikistan and Uzbekistan; and aquifers on the border between the Kashkadarya oblast of Uzbekistan and the Lebab velayat of Turkmenistan. Obviously, conflicts may arise for many reasons in these regions. The main ones are the lack of proper groundwater accounting and registration of installed pumps and the lack of proper

**Table 5** The different groundwater management organizations in ADRB

| Country | Surface water | Groundwater | Other relevant agency |
|---|---|---|---|
| Afghanistan | Ministry of Water and Power | Ministry of Mines and Industry | |
| Tajikistan | Ministry of Melioration and Water Resources | State Hydrologeological Service | Ministry of Environmental Protection, Tajikistan Public Water Supply Service |
| Uzbekistan | Ministry of Agriculture and Water Resources | State Committee on Geology and Mineral Resources | State Committee on Safety in Industry and Mining for Thermal and Mineral Waters |
| Turkmenistan | Ministry of Land Reclamation and Water Resources | Ministry of Geology | Ministry of Environmental Protection |

groundwater assessments, both in the design studies and in practical operations.

Groundwater response times generally include a delay of 1–2 years, and for some areas even of 3, 5, or 10 years or even sometimes centuries or millennia for confined resources (Huneau et al. 2001; Kazbekov et al. 2007). It is then difficult to establish the direct influence of groundwater exploitation development projects without good quality pre-implementation observations. In the absence of proper management measures, special research is then needed to evaluate the consequences; it is usually carried out by the damaged party when the negative effects are already clearly showing. In the ADRB, most of the problems are arising from the absence of proper regulations (limits) of groundwater withdrawal, in particular during dry years and in situations where over-extraction affects aquifers in neighboring states or has an impact on transboundary rivers. A key problem is the lack of legal documents and international agreements to:

1. determine responsibilities when problems arise;
2. establish the rights of reimbursement of the damaged party;
3. require negative effects to be reversed;
4. require inspection of pumping installations.

## Lack of institutional management of groundwater

It should be stressed out that, withdrawal and discharge of international groundwater and drainage water, which are the main source of potential conflicts, require cooperative regulation and management within the whole Aral Sea basin. The development of a set of management measures should thus be considered, to reduce the negative influence of multiple uses of groundwater and drainage water, to be submitted to the Interstate Commission for Water Coordination (ICWC) for analysis and further preparation for decision making on the evaluation of the areas and size of shared aquifers and drainage water catchments; transboundary problems should be specified and proposals prepared to share the management of international groundwater.

Apart from the ICWC, whose role is to organise international water management within the watersheds of Amu Darya and Syr Darya Rivers, almost no structure is dedicated to groundwater. Table 5 summarizes the main structures in charge of groundwater management in the different countries of the ADRB. As previously said, the extreme fragmentation and dilution of responsibilities shown in Table 5 is in clear disfavor with a proper and concerted groundwater management. The situation in Afghanistan is particularly critical since there is no regulatory framework for controlling and managing groundwater resources. In the literature, it is documented that the Ministry of Mines and Industry is the state responsible authority. But in practice, however, the ministries lack the resources and technical expertise to adequately manage the resources for which they have responsibility. There also appears to be no effective system of permits or licensing for drilling and for water abstraction in this country. In this regulatory vacuum, the United Nations and some nongovernmental organisations have accepted some responsibility for water resources.

In the CAR, there are established frameworks for both surface and groundwater resources management. However, it must be pointed out that no special regulation on groundwater has been proposed. Another major problem is the overlapping of the responsibility between different state authorities within a same country (Table 5).

Despite the various views and opinions of the parties involved, cooperation in transboundary water resource management in the ADRB has made significant steps forward over the last 10 years (UNDP 2007). A certain consensus on the principle of reasonable and equitable sharing of water in accordance with the adopted regional agreements has already been achieved. However, there is still a lack of coordination and inconsistency in water use priority that leads to losses of the limited water resource, aggravation of tension and threat of conflict (Wegerich 2007). In order to fully cooperate, the countries involved must have confidence in each other and be prepared to compromise both in the area of their own interest and in the interest of the social and environmental needs of the region.

## Conclusion

Although water supply was formerly centrally organised, since independence in 1991 the CAR and Afghanistan have continued their dispute on meeting their individual and increasing water demands. Since then, the lack of water has gradually devastated the irrigation-dependent cotton, winter wheat and other major crop production. In addition, the lack of water has engendered the ecological catastrophe of the Aral Sea Basin, at the tail end of both Amu Darya and Syr Darya.

Groundwater can be a strategic resource for these landlocked countries not only for drinking but also for agricultural production and environmental issues as demonstrated by Jarsjo and Destouni (2004). The lessons learned from the 1998 to 2001 droughts have proved the feasibility of groundwater developments in lower reaches of Amu Darya and elsewhere in the basin. And even if poor situation of the Amu Darya River has been observed both in quality and quantity in recent years, groundwater can still be reasonably exploited in many places were water salinity remains acceptable.

There is a tendency for substantial unregulated groundwater withdrawal in the basin by farmers and populations for various purposes as an alternative source of water for irrigation. Historically, the agriculture sector has a very heavy weight on the basin country economies in terms of employment, financial revenues and food security. Thus, for many good reasons the development of groundwater use is inevitable and better management strategies and cooperation between the different partners involved is necessary. Unfortunately, the intricate management system of groundwater in the basin countries in terms of engineering infrastructure and institutional coordination is inadequate and, as a result, States are financially totally unable to overcome and to prevent the physical deterioration of hydraulic structures and to maintain an efficient water supply on large scale. In addition, transboundary agreements on joint utilization of groundwater resources are weak and fragmented in terms of regulation and institution levels.

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ORIGINAL ARTICLE

# Geostatistical approach for the assessment of the water reservoir capacity in arid regions: a case study of the Akdarya reservoir, Uzbekistan

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**Abstract** The paper presents the results of a new geostatistical approach to generate bathymetric surface models from point measurement converted into continuous contour surfaces of reservoir bottoms in Uzbekistan. Sedimentation of reservoirs raises engineering, environmental and economical issues for the communities around the world in areas affected by a strong water deficit. Because of Uzbekistan's arid climatic conditions, and uneven spatial and temporal water resources distribution, responsive and innovative water availability assessment surveys of all major water reservoirs are required. Bathymetric surveying is a traditional method that is carried out for the estimation of reservoir volumes and surface areas of the corresponding reservoir stages in order to assess the water availability. Volume and surface area differences derived from multiple surveys of a reservoir provide storage loss estimates over time due to sedimentation. However, two main factors, such as intensive field data measurement and post data-processing, often limit the frequency of these surveys. Alternatively, innovative depth measurement technologies coupled with contouring and surface mapping programs provide automated reservoir volume and surface area calculations. This significantly reduces time, workload and financial burdens for reservoir sedimentation projects. This research proposes the use of geostatistical approach to assess the reservoir sedimentation in the Akdarya reservoir of Uzbekistan. The geostatistical approach includes (semi-) variogram analysis and interpolation (kriging and simulations—turning bands) techniques predicting values at un-sampled locations for generating digital bathymetric surface models of reservoir bottom conditions in order to calculate the volume and surface area at a given water elevation. The simulation enables to have range of reservoir volumes and surface areas with the same probability, in comparison to the kriging and traditional methods. This gives a real estimation of the resource availability for water operators to manage natural resources and hydraulic infrastructure in a sustainable manner.

**Keywords** Water reservoir · Sedimentation · Bathymetric survey · Geostatistics · Volume estimation · Central Asia

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## Introduction

### Sedimentation in water reservoirs

Dam on a watercourse induces river fragmentation in both fluid and sediment fluxes. Though sedimentation is a natural geomorphologic process, human inference by dam construction accelerates the filling up of the reservoir capacity over time (Mahmood 1987; Matty et al. 1987; WCD 2000; ICOLD 2005; Viseras et al. 2009). The sedimentation causes reduction of the reservoir storage capacity and diminishes the flow regulation affecting the water supply of different water users. The utility of a

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reservoir diminishes as its storage capacity is reduced (Bruk 1985; WCD 2000; IHP 2002; Rakhmatullaev et al. 2010; Ahmed and Sanchez 2010; Liu et al. 2010). As the stream flows, its sediment carrying capacity is diminished due to the decrease in flow velocity and increase in the cross-sectional area resulting in the sediments starting to deposit (McManus 1985; Mahmood 1987; Haan et al. 1994). The downstream movement of a stream's sediment load is then interrupted by reservoirs (Vörösmarty et al. 2003). Sedimentation triggers several important issues, such as operation and maintenance of engineering facilities, economical feasibility of the project, environmental problems with social aspects upstream and downstream (Evrard 1985; Brandt 2000; Vörösmarty et al. 2003; Davis and Koop 2006; Graf 2006; Sternberg 2006). It is reported that annually in the world an average 0.5–1% of the volume capacities of small and large reservoirs is lost because of sedimentation (Mahmood 1987). Palmieri et al. (2001) report that the loss in volume capacity requires an annual replacement cost of US$13 billion dollars. The reservoir sedimentation is a practical issue in many parts of the world with different climatic conditions and levels of engineering sophistication (Naisen and Lingyan 1998; Krasa et al. 2005; Radoane and Radoane 2005; Renwick et al. 2005).

## Reservoirs in Uzbekistan

Agriculture is a very important sector for the Uzbek economy. It provides employment, foreign cash revenue and food security (O'Hara 2000; Sokolov 2006; Abdullaev et al. 2009). Climatic conditions and insufficient internal water resources have put pressure on water reservoirs. Uzbekistan is, in fact, largely an arid country where evaporation (1200–1600 mm) exceeds rainfall and annual precipitation is below 200 mm (Shultz 1949; Irrigation of Uzbekistan 1981; UNDP 2007). Regional streamflow is characterized by an extreme intra-annual variability and is also unevenly spatially distributed (World Bank 2003; Kazbekov et al. 2007). The two main transboundary rivers of Uzbekistan, the Amu Darya and Syr Darya, satisfy 82% of the total water demand of Uzbekistan, whereas only 18% of the demand is satisfied by the internal Kashka Darya, Zarafshan and Surkhan Darya rivers (Shultz 1949; Heaven et al. 2002; Dukhovny 2003; Micklin 2004). At present, approximately 90% of water resources in Uzbekistan are used for irrigated agriculture (UNDP 2007; Rakhmatullaev et al. 2009) and about 24% of irrigation water comes from water reservoirs, the remainder is pumped from rivers and aquifers (FAO 2007). There are 55 manmade water reservoirs in Uzbekistan with a total volume capacity of about 19 $km^3$ and a useful volume capacity of 14.5 $km^3$ (Rakhmatullaev 2006; UNDP 2007). There are almost no remaining attractive sites for the construction of new reservoirs in Uzbekistan; as 78% of the flow of the Amu Darya is regulated and 94% of the Syr Darya (Fig. 1) (UNDP 2007). Thus, it is of strategic importance to rationally estimate the available water resources in existing reservoirs to ensure a guaranteed water supply to the different water users. In fact, according to the Uzbekistan

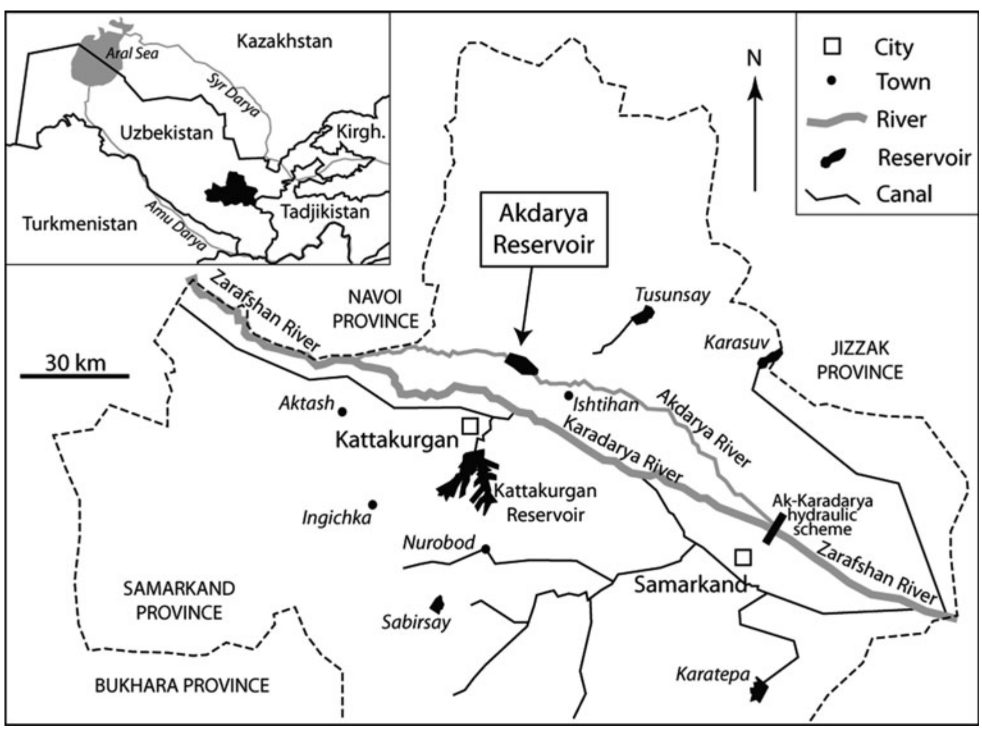



**Fig. 1** Location of Akdarya reservoir in Samarkand province of Uzbekistan

Ministry of Agriculture and Water Resources (UzMAWR), out of the 27 inspected reservoirs, 11 are almost completely silted up, and, at 5 other reservoirs, the silt has almost reached the level of the outlet structures (UNDP 2007).

### Objectives

The primary concern of this paper is a bathymetric survey of the Akdarya reservoir which was carried out to estimate the reservoir volume and surface area for corresponding reservoir stages (water elevations) in order to quantify the water availability (Ortt et al. 2000; USACE 2001; IHO 2005). Volume and surface area differences derived from multiple surveys of individual reservoirs then provide estimates of the capacity loss over time due to sedimentation. In Uzbekistan, bathymetric surveys were carried out with traditional methods, such as range survey/end area method, to calculate the reservoir's volume and surface area for different reservoir stages. Traditional methods of analysis have relied on the topographic mapping and range survey data to estimate sediment volumes for a given reservoir.

The range survey/end area method has provided adequate results for past sedimentation analysis (USACE 2001; IHO 2005). However, the ranges can be difficult to locate and surveys as monuments can be destroyed or worn away. This leads to the surveying of fewer ranges to characterize sedimentation. Two factors such as intensive field data measurement (depth soundings) and post data-processing often limit the frequency with which surveys may be conducted (Furnans and Austin 2008).

There are many commercial computer contouring and surface mapping programs, which quickly and easily transform random surveying data into continuous curved face contours using interpolation. These computer technologies create digital surfaces that represent relatively accurate reservoir bottom conditions and support automated reservoir volumes and surface areas calculations. Automated reservoir volume calculation allows to quickly developing volume-elevation and surface-elevation curves for the estimation of sediment rates (Furnans and Austin 2008). This in turn significantly reduces time, workload and financial burdens for sedimentation survey projects.

Geostatistical approaches can provide more helpful, reliable and efficient tools to increase the number of measurement points at unsampled locations, and variogram analyses for examining structural relationship of data. Variogram analysis provide information for anisotropy analysis of a physical process that can have changed characteristics in the direction and space over traditional methods for bathymetric or topographic surveys (Joseph et al. 1998; Ortt et al. 2000; Marache et al. 2002; Soler-Lopez 2003, 2004; Furnans and Austin 2008).

Digital contour surfaces of reservoir bathymetry are performed by two interpolation methods, the kriging and simulation (turning bands) techniques. In a first approach, the kriging interpolation method is used to estimate the bathymetry. In a second part, because kriging provides a smooth result of the reality and has consequences for future computations (volume, area), the simulation method (turning bands) was chosen. One hundred simulations were carried out in order to introduce natural variability in the reservoir bathymetry and to get a statistical probability distribution of reservoir volumes and surface areas for different reservoir stages.

The final objective of the paper is a discussion of technical approaches for the application of Geographic Information System (GIS), Google Earth® and Digital Terrain Model (DTM) methods for reservoir sedimentation studies that supplements existing tools to predict the life span of the reservoir due to sedimentation. In addition, the choice of the methodology for all future bathymetric surveys in Uzbekistan will be discussed.

## Study area and site characteristics

### General setting

The Akdarya reservoir was created by the construction of an earthen dam on the Akdarya River in 1982. This reservoir is used as a seasonal flood regulating structure, for the irrigation of some 5,500 ha of new agricultural lands and to improve the conditions of more than 12,000 ha of irrigated lands in two districts of the Samarkand province of Uzbekistan (Fig. 1). It is located 15 km northwest of the Ishtihan town. The surface area of the reservoir at full pool elevation (FPE) is about 12.7 $km^2$, the total storage volume is 112.5 $Mm^3$. In order to increase the irrigated lands, authorities have increased the reservoir volume capacity from 34 to 112.5 $Mm^3$ by raising the dam crest by 7 m since 1982 (Samarkandgiprovodxoz 1976).

### Relief and geomorphology

The modern Akdarya River valley is in-filled with pro-alluvium deposits. The valley is layered by 5–40 m of loess and loams, underlying a 300-m thick layer of gravel. The modern floodplain part of the Akdarya River is composed of loams, stones and pebbles of alluvial origin. The thickness of modern deposits varies from 0.5 to 5 m (Rakhmatullaev 2007). The river channel is well defined, composed of pebble–cobble deposits. The absolute elevation of the river varies from 680 to 400 m above the sea level. On the right bank, the relief of surrounding areas is presented by the hills with smooth peaks changing into

**Table 1** Main meteorological characteristics of Akdarya river basin (Uzdavsuvloiha 2002)

| Characteristics | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air temperature (°C) | −1.9 | 1.8 | 7.2 | 13.9 | 20.0 | 24.9 | 27.2 | 25.1 | 19.1 | 11.0 | 5.9 | 1.4 | 13.0 |
| Precipitation (mm) | 42 | 42 | 56 | 48 | 22 | 4 | 0 | 0 | 1 | 11 | 23 | 33 | 282 |
| Daily max. precipitation (mm) | 30 | 38 | 43 | 62 | 88 | 18 | 1 | 7 | 3 | 23 | 25 | 26 | 88 |
| Humidity (%) | 80 | 77 | 76 | 67 | 54 | 38 | 34 | 36 | 39 | 52 | 66 | 80 | 58 |
| Evaporation (mm) | 30 | 20 | 16 | 33 | 110 | 200 | 254 | 223 | 142 | 75 | 54 | 43 | 1200 |
| Mean monthly wind speed (m/sec) | 2.1 | 2.7 | 2.8 | 2.8 | 2.6 | 2.4 | 2.5 | 2.1 | 2.0 | 1.8 | 2.0 | 1.9 | 2.3 |

alluvial and pro-alluvial uplands. The left bank is composed of floodplains and terrace valleys deposits (Uzdavsuvloiha 2002).

## Climate

The study area is located in the subtropical latitudes of the centre of the Asiatic continent and it is characterized by aridity and significant temperature fluctuations. The mountain system of Nurata in the north governs local climatic conditions, such as precipitation and wind regimes. The main meteorological characteristics are presented in Table 1. The annual long-term mean precipitation is about 282 mm. More than 90% of annual precipitation is observed from November to May. Over the period of June–September, there is no precipitation observed. The mean evaporation from the reservoir is about 1200 mm inducing a deficit balance about 918 mm annually (Uzdavsuvloiha 2002; Rakhmatullaev and Le Coustumer 2006).

## Hydrological characteristics

The Akdarya River is a tributary of the Zarafshan River (Fig. 1). The Zarafshan River is divided into tributaries at the Ak Karadarya Hydraulic Scheme. East of the Samarkand city, the Zarafshan is separated into two perennial tributaries, a northern one (Akdarya) and a southern one (Karadarya). These two tributaries form an island with a total length of about 100 km and about 15 km wide under the name "Miankul". The two tributaries again merge into one Zarafshan River in Navoi province. The Akdarya reservoir is located on the Akdarya River 50 km downstream from Ak Karadarya Hydraulic Scheme (Fig. 1). The total length of the Akdarya River is about 131 km and it flows over wide floodplain terraces. The river width is about 0.2–0.6 km, with a maximum width of about 1.5–2.0 km. The river channel is moderately meandering and branching. Riverbanks are unstable and steep in some places. The Akdarya River flows through the Zarafshan Valley, which is composed of loess deposits (Samarkandgiprovodxoz 1976).

There are several kinds of water resources feeding the Akdarya reservoir (Table 2), including the network of regional irrigation channels and drainage-collector discharge systems, which directly feeds the reservoir. Traditional engineering practices have evolved in such direction that only during high-water years waters of Zarafshan River are released to the Akdarya River. The last significant discharge was observed in 1998 (Uzdavsuvloiha 2002). This release discharge was about 100 $m^3/s$. At present time, the Akdarya tributary is used as an emergency channel from catastrophic flooding events of the Zarafshan River, whereas the main flow passes through the Karadarya tributary. The springs and temporary streams are the third major source of water feeding the Akdarya River and its reservoir. The temporary streams can be observed during heavy rainstorms during the spring season. The effective watershed area of the Akdarya reservoir is about 2020 $km^2$ (Uzdavsuvloiha 2002). Figure 2 depicts the water and suspended sediment discharge in a year. The peak of sediment discharge is observed during the flood of the Akdarya River. As the Akdarya River is used as an artificial channel for conveying excess water of the Zarafshan River, the streamflow entrains the most of available sediment and discharges downstream. The dry climatic and geomorphological conditions contribute to rising limb of sediment discharge curve, i.e. most available

**Table 2** Water resources balance feeding Akdarya reservoir (Uzdavsuvloiha 2002)

| | Mean water year ($Mm^3$) | Drought year ($Mm^3$) |
|---|---|---|
| Source of discharge | | |
| 1. Discharge from Zarafshan river | 250 | 200 |
| 2. Springs | 160 | 100 |
| 3. Irrigation and collector-drainage canals | 180 | 130 |
| Total | 590 | 430 |
| Water intake | 230 | 210 |
| Discharge in the reservoir | 360 | 220 |

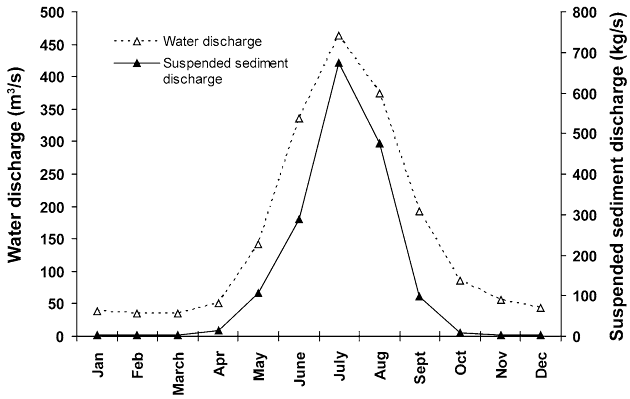



**Fig. 2** Diagram of water discharge versus sediment discharge of Akdarya River (Uzdavsuvloiha 2002)

sediment loads can be carried out by the Akdarya River in the event of high floods.

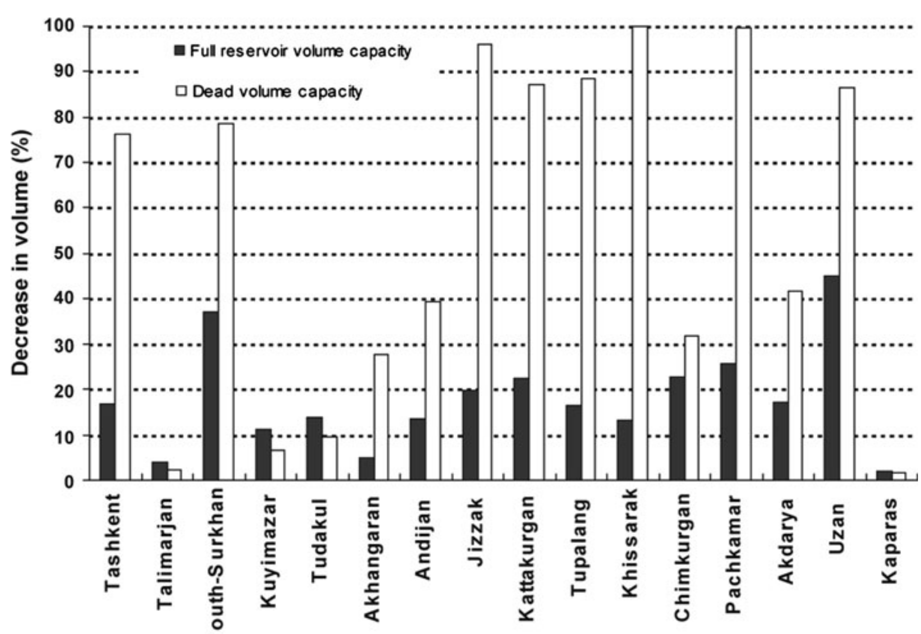
## Materials and methods

In 2001, the "Uzbek Bathymetric Centre" was established under the umbrella of UzMAWR and was authorized to survey the reservoirs using the bathymetric investigation system (CEEDUCER®) developed by Bruttour International Pty Ltd (Bruttour International Pty. Ltd 2003). This system is composed of an incorporated Global Positioning System (GPS) antenna and a digital depth measuring transducer. Up to now, the centre has performed bathymetric surveys of 16 reservoirs in Uzbekistan (Bathymetric Center 2003). Figure 3 illustrates the loss of the total and dead reservoir volume capacities in 16 reservoirs in Uzbekistan due to sedimentation. The dead volume storage in a reservoir is determined as the storage volume between the streambed and the lowest elevation from which water can be withdrawn by gravity (Mahmood 1987). As it can be seen, the total volume capacities of all reservoirs have decreased by about 18%, whereas the dead storage capacities decreased by 55% on the average. In comparison, the dead storage capacities of 7 Uzbek reservoirs were decreased by more than 75%. This is an alarming signal that in a foreseen future, the sedimentation can be a major operation and maintenance issue for these reservoirs and threatens the guaranteed water supply to water users.

### Bathymetric survey

The bathymetric survey of Akdarya reservoir was conducted in 2003 from a moving boat using electronic depth-sounding equipment (transducer) in conjunction with a GPS antenna and an automatic data recorder CEEDUCER®. All data recorded were transferred into a laptop computer (Joseph et al. 1998; Ortt et al. 2000; Soler-Lopez 2003, 2004). The system CEEDUCER® is a very small, single unit (integrated GPS receiver, electronics processor and data logger), versatile survey-measuring instrument that provides GPS position, DGPS (differential GPS), digital echo sounder and 7.2 h full data logging (dual frequency echo sounding). The specifications of the GPS receiver are as follows: survey type 8 or 12 channels (true parallel) with an accuracy of 2–3 m (8 channels) and lower than 1 m (12 channels). DGPS combined Marine Beacon/Integrated GPS antenna with 1 s update.

**Fig. 3** Decrease in total and dead volume capacities due to sedimentation in 16 reservoirs in Uzbekistan



The GPS receivers monitor the horizontal position of the survey boat while the depth sounder measures the water depth. The GPS units were first used and by default were automatically converted into a World Geodetic System of 1984 (WGS84) projection system in the static mode to establish a benchmark overlooking the reservoir. Satellite data were recorded simultaneously at the known government geodesic benchmark (referred to as “the Akdarya dam”) (latitude 27°45′N., longitude 44°33′W.) and at a site overlooking the reservoir. Once established, the “Akdarya dam” benchmark was programmed as the reference station.

One GPS unit was installed at the reference station; the other GPS unit was installed in the survey boat to be used as a mobile station. The GPS on board independently calculated a position every second, while receiving a set of correction signals from the reference station, converting the system into a DGPS. This combination maintained the data horizontal position accuracy within a tolerance of 2 m. The bathymetric survey integrated software MiniCee® and was used to navigate and to collect data. The software integrates the depth and position data, storing the *x*, *y* (geographic locations) and *z* (depths) coordinates in a portable computer.

GPS was used to determine the latitude and longitude for each depth measurement. Sounding equipment was used to measure depth from a transducer (probe), operating at a frequency of 200 kHz to the bed of the reservoir. Depths recorded by the sounder, which has a resolution of 0.02%, were measured at a fixed distance below the water surface (Bathymetric Center 2003). The recorded depths and the constant value of the depth ecosounder were subtracted from the water surface elevations at the time of the survey (as recorded at the dam gauge) to determine reservoir bottom elevations. The depths were synchronized with the GPS data to determine the location of the probe as the boat traversed across the reservoir (IHO 2005; Furnans and Austin 2008). The schematic illustration of the depth sounding survey and conditions in the Akdarya reservoir for 2003 is depicted in Fig. 4. The calibration of the transducer was performed twice daily, before and after the measurements collection.

For the shallow water areas where the transducer could not be operated, representative depth measures were manually collected with a stadia rod from the boat. However, sediment accumulation and vegetation growth in the upstream reservoir areas limited the data collection. The shoreline delineation was performed during the survey by GPS receiver as close as possible to water surface marks along the reservoir shoreline.

Initial editing of the data was performed using the MiniCee® software. Positions were corrected to eliminate anomalies that occurred when the correction signal from the reference station was lost because of local topographic features or electromagnetic interference. Position errors were corrected by interpolating back to the mid-point between the correct antecedent and preceding position. The depth data were also corrected to eliminate incorrect depth readings. Incorrect depth readings can result from an insufficient signal gain or because floating debris or fish interfered with the transducer face. The incorrect depth readings were also interpolated between the correct antecedent and precedent depth readings. Once corrected, the edited data were transferred into the Golden Software’s SURFER® 7 database for further processing.

## Geostatistical analysis, variogram analysis

With recent progresses in automatic calculations, the use of geostatistics for the spatial analysis of environmental data has become extremely common on both land and sea (Mear et al. 2006). Geostatistics include tools that establish surface maps of any interested variable from the analysis of the spatial structure of data (semivariogram) and to predict

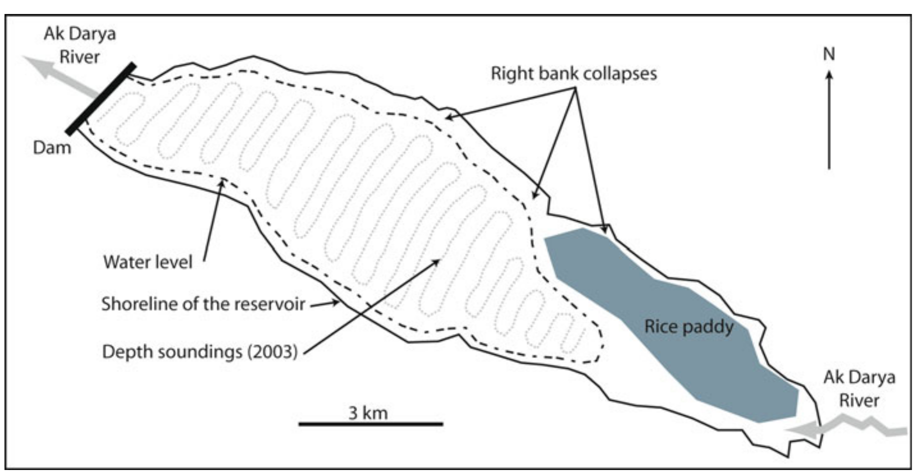



**Fig. 4** Data measurements with bathymetric system CEEDUCER and current conditions of Akdarya reservoir in 2003

the value (interpolation) of these parameters at unsampled points (kriging or simulation) (Chilès and Delfiner 1999; Goovaerts 1999).

Variogram analysis was used to examine the spatial or temporal correlations of the data. Variogram analysis is a prerequisite for interpolation (kriging or simulation) or making predictions (Clark 2001; Mear et al. 2006). Variogram analysis consists of the experimental variogram calculated from the data and the theoretical model fitted to the data. The experimental variogram measures the mean variability between two points $z$ and $z + \text{h}$, as a function of their distance $h$.

The experimental semi-variogram is calculated by the following equation:

$$\hat{\gamma}(h) = \frac{1}{2\,N_h} \sum_{x_j - x_i \approx h} \left[z(x_j) - z(x_i)\right]^2$$

where $\gamma(h)$ is the experimental semi-variogram taking into account the difference in value between pairs of samples with a given relative orientation and distance apart ($h$) between two measured attributes, $h$ is the distance between two discrete points that are used for variogram calculation, $n$ is the number of pairs of samples for a given $h$, $z$ is the investigating attribute, $i$ and $j$ are the indexes of respective values of two samples apart of the distance $h$.

The experimental variogram is calculated for several lag distances and is plotted as a two-dimensional graph $\gamma(h) = f(h)$. It is then fitted with a theoretical model which provides information about the structure of the spatial variation, as well as the input parameters for spatial prediction by kriging (Saby et al. 2006).

In a first approach, we chose to use kriging, because it is the estimation method minimizing the best interpolation errors and allowing the calculation of variance associated with the interpolation. Kriging calculates a weighted moving average equation, which estimates the value of a regionalized variable at site-specific location by taking into account the variographical information. The optimum grid size for the construction of the bathymetric surfaces was determined based on examination of the sampling distribution for the three periods. The kriging interpolation gives the averaged smoothed surface and thus will underestimate the realistic reservoir volume and surface area calculation. Therefore, for the introduction of natural variability we used as a second approach turning bands interpolation method for simulation. One hundred simulations calculations were performed using the ISATIS® program (Geovariances 2009). Post-processing of simulations allows obtaining a statistical distribution of reservoir volume and surface area.

## Results and discussion

### Historical surveys

For the determination of sedimentation rates, three bathymetric surveys, the original (pre-impoundment) in 1982, and the 1996 and 2003 ones were used to examine the evolution of the reservoir capacity over time. The 1982 and 1996 surveys were carried out by traditional methods, such as range survey/end area method and traditional measuring instrumentation. The 2003 survey was carried out as previously described by CEDUCEER®. Table 3 depicts the volumes, water surface areas at full and minimum pool elevations of the Akdarya reservoir for three historical surveys. The analysis of sedimentation dynamics was performed for two periods: 1982–1996 and 1996–2003. The changes in volume and water area at full (FPE) and minimum pool elevation (MPE) were examined.

For the 1982–1996 period, the total sedimentation volume was 11.8 $Mm^3$ which can be interpreted as the total reservoir volume decreased by 10.5%. The water area decreased by 8% and the dead storage decreased by 12% at FPE. However, these changes differ for the reservoir at MPE, for instance, the water area decreased by 53% to the original. This decrease is caused by the reservoir's morphological shape and its location in lowlands (plains).

For the period of 1996–2003, the total sedimentation was 7.5 $Mm^3$ and the total reservoir volume decreased by 7.5% compared to the 1996 level. In addition, the water area increased by 2.3 $km^2$ (16.5%) due to significant right

**Table 3** Volumes and water surface areas of Akdarya reservoir at full and minimum pool elevations from the creation of the reservoir (1982), for 1996 and 2003

| Year | Full pool elevation | | | | Minimum pool elevation |
|---|---|---|---|---|---|
| | Full volume capacity ($Mm^3$) | Water surface area ($km^2$) | Useful volume capacity ($Mm^3$) | Dead volume capacity ($Mm^3$) | Water surface area ($km^2$) |
| 1982 | 112.5 | 12.7 | 110 | 2.5 | 3.5 |
| 1996 | 100.7 | 11.67 | 98.5 | 2.2 | 1.64 |
| 2003 | 93.17 | 13.97 | 91.71 | 1.46 | 0.92 |

bank collapses, in some places reaching 10–50 m in width (Fig. 4). The dead storage decreased by 0.74 $Mm^3$ (34%) at the FPE in Akdarya reservoir. At the MPE, the water area of reservoir decreased by 44%.

The volume storage capacity loss rate is a key component for calculating the remaining life of a reservoir (Ortt et al. 2000). Using the volumes of accumulated sediment and the age of the reservoirs, the annual storage capacity loss rates can be calculated. During the 21 years of reservoir operation, the total loss of reservoir capacity due to sediments is estimated to be about 19.3 $Mm^3$. The Akdarya reservoir has lost its storage capacity at a rate of 0.92 $Mm^3$ per year. As a percentage of its original storage volume, the annual loss rate for Akdarya reservoir is 0.8% up to 2003. The high rate of loss is explained by the significant right-bank erosion processes in some places reaching 20–50 m collapses and local geomorphological conditions with high sediment amounts coming from surrounding agricultural lands.

The maximum depth according to the design calculations was 23.4 m, but the deepest depth observed during the last survey was recorded at 18.1 m. During the field survey, the area of shallow water increased, especially in the entrance part of the river where nowadays the upstream of the reservoir is also heavily occupied by the vegetation cover and in some places locals have created artificial rice paddy plots, the area with such plantations is always increasing (Figs. 1, 4).

## Data measurement

The depth soundings were collected every 20 m. The transects (cross-sections) were about 200 m apart beginning at the dam and continuing upstream. Figure 5 illustrates the 2003 depth sounding measurements across 35 sections in Akdarya reservoir. The transects were perpendicular to the shoreline of the reservoir. The process of obtaining an accurate bathymetric survey is substantially more difficult than that associated with land-based surveying. There are various error sources in data acquisition and measurement in bathymetric survey, such as GPS limited availability, the definition of the water–mud interface and human errors in measurements (IHO 1998, 2005; USACE 2001).

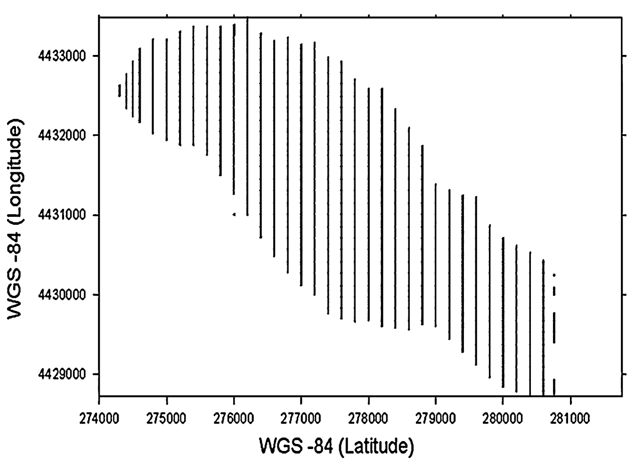



**Fig. 5** Actual depth measurement points in Akdarya reservoir in 2003 (Bathymetric Center 2003)

Furnans and Austin (2008) report that original reservoir volume estimates are limited by the accuracy of existing topographic maps and land surveys estimates of the current capacities for reservoirs not re-surveyed since their construction. The range method is based upon interpolating the volumes from one range transect to another. The farther apart the transects, the more interpolation is involved and intuitively more errors can be observed (Byrnes et al. 2002; Johnston 2003). For example, there can be local topographic or other peculiarities, such as water intake structures or significant dredge works in area between transects. The complication can be of natural river inflow areas. The total error in determining reservoir capacity volumes with this method have been estimated to be between 10 and 30% (Ortt et al. 2000).

With traditional methods of depth measurements and few sampled points, large errors and uncertainties are observed that increases errors in the computation of water availability in the reservoirs. The potential sources of error are (1) human induced during data measurement in the boat operation, and (2) readings of the transducer (e.g. penetration of sonar signal through the water column and poor acoustic reflection of signal back from true reservoir bottom surface) (IHO 1998).

## Geostatistical work

### *Variographical analysis*

First, the experimental semivariogram was calculated and constructed from the direct field measurements. In order to look for possible directions of anisotropy (difference in spatial structuration of the variable as a function of the studied direction), directional variograms were computed every 10° and with a 200 m lag. In this study, the directional variograms showed an anisotropy whose principal directions were N20 and N110. Figure 6 depicts the semivariogram of reservoir bottom elevations for the Akdarya reservoir. For a given lag, the smallest variogram values were observed in the N110 direction and the largest values in the N20 direction. Furthermore, a stationary variogram was exhibited at N20 (with a sill equal to 9 $m^2$ for a range of 800 m, distance beyond which there is no correlation between data) and a non-stationary behaviour

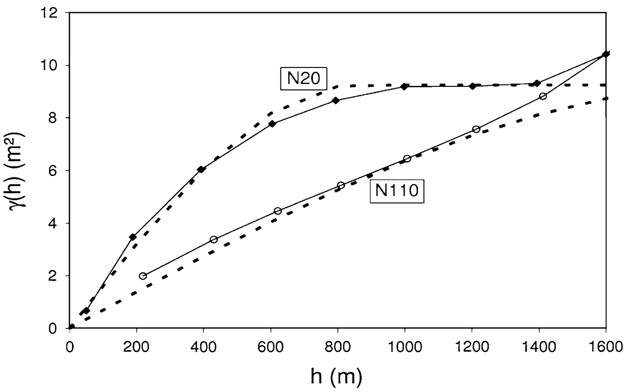



**Fig. 6** Experimental semivariogram of reservoir bottom elevations direction N20 (smallest variance) and N110 (largest variance) of Akdarya reservoir

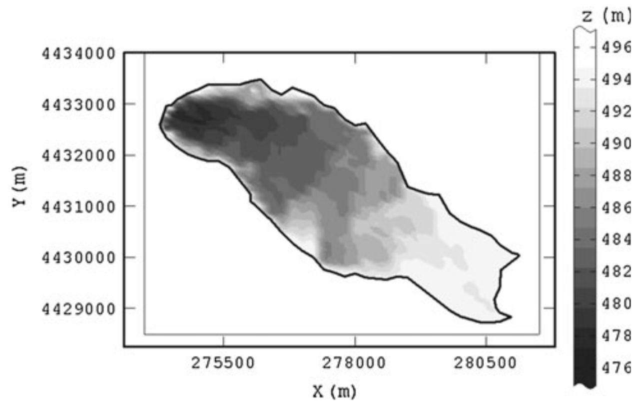



**Fig. 7** Bathymetric map of Akdarya reservoir by kriging interpolation method

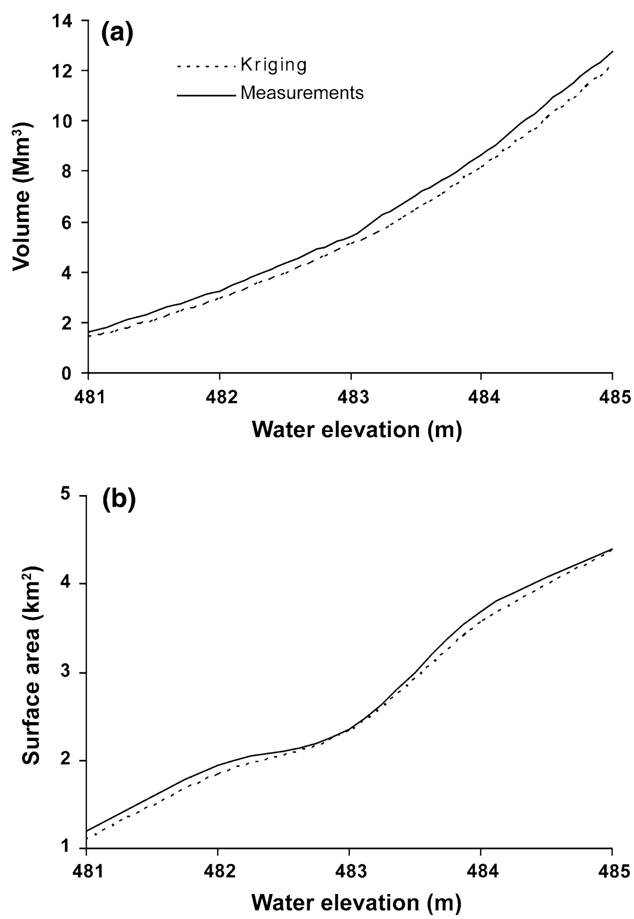



**Fig. 8** Akdarya reservoir volume (**a**) and surface area (**b**) by kriging and experimental data (2003)

for N110. A variable is stationary if its statistical distribution is invariant by translation in space (and its moments too). On a variogram, we can check that a variable is stationary (at least a second order stationnarity) if we can observe a sill, as in the N20 direction. For a non-stationary behaviour (as in the N110 direction), the variogram does not reach a sill, indicating a global drift in data (for example a constant increase of values in this direction). Second, the theoretical model was fitted with a spherical model and the anisotropy was defined as the ratio between the largest and the smallest variance (Fig. 6, dotted charts). The fitting was the best for $h$ less than 1000 m, because of neighbourhood problems, which is addressed by the kriging.

*Kriging results*

After the variogram analysis, the interpolation was carried out using a kriging gridding method. In order to estimate a value at a non-sampled point, we considered measured points in a given neighbourhood. The chosen neighbourhood was an ellipse with axes equal to 1000 m and 500 m in N110 and N20 directions, respectively. The ellipse was then decomposed in 4 sectors and we chose to have an optimum number of data equal to 10 in each sector. The Figure 7 illustrates the bathymetry of Akdarya reservoir by kriging interpolation method.

There is no significant difference between the elevation-reservoir volume and the elevation-surface area curves from direct measurements and modelled (kriging). The Figure 8 depicts the reservoir volume and the surface area by kriging and the direct measurements data (2003) for selected water elevations, where the significant differences were observed. The computation of the reservoir volume and surface area by kriging was performed by reducing the number of actual cross-sections from 35 to 17. In particular, we reduced the cross-sections in the middle parts of reservoir due to smooth uniform bed conditions observed from field measurements. This shows that fewer depth soundings, but representative points can be measured regardless of using any surface contouring packages used. Figure 9 depicts the reservoir volume of Akdarya at different water elevations. The 2D bathymetric map has

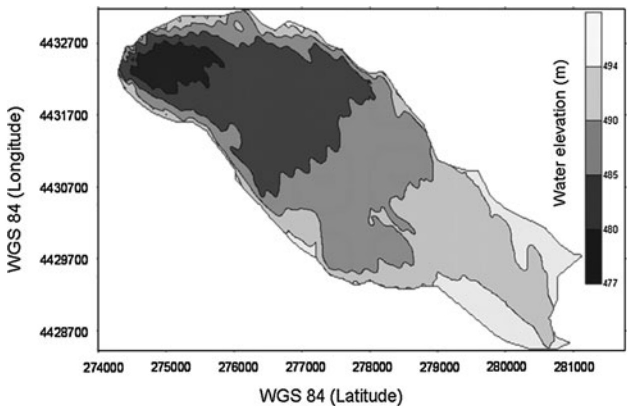



**Fig. 9** Reservoir volume of Akdarya at different water elevations

visualization effect for a reservoir operator who can use this information in decision making over operation and maintenance works. This is particularly important for the water intake structures that are installed in a reservoir for irrigation diversions or public water supply systems. Operators could take site specific preventive measures to alleviate for such scenarios.

The principal source of error that is reflected within the dataset is related to the density and the spatial configuration of the sample points (Johnston 2003). The spatial configuration is critical in the kriging process and in all interpolation methods. The kriging weights and the variance of estimation are dependent of the variogram, and the spatial distribution of the points but not of the measured values. This is why equidistant spacing would be the best in bathymetric data collection. Spacing of data points was much greater between transects than between points on a given transect. Such a sampling approach introduces necessarily larger variances (so error) between transects into the modelled bathymetric surface. Because kriging minimizes the variance of estimation (it gives a smooth image of the reality and only an estimation of volume and area) turning bands simulation methods have been carried out.

*Simulation results*

After the kriging interpolation, 100 turning bands simulations were carried out to compile bathymetric surface models of reservoir bottom, in order to calculate reservoir volume and surface areas. Simulations allow to introduce variability and to obtain a statistical distribution of reservoir volume and area for any water level. The results are given in Table 4 and Fig. 10. Generally, for water elevations, the kriging and direct measurement calculations fall within the range of minimum and maximum values of simulation. In particular, the significant difference in reservoir volume is observed at higher water elevations due to the morphological shape of the Akdarya reservoir. At a 494.5-m water elevation, there is a difference of about 2% between the simulated maximum reservoir volume (94.47 $Mm^3$) and the measured one (93.17 $Mm^3$), that corresponds to 1.3 $Mm^3$ of water. Figure 11 shows the cumulative distributions of the reservoir volume and area for a water elevation equal to 494.5 m.

Economical efficiency results

New contour and mapping programs have introduced automated reservoir volume and surface calculations. This has significantly reduced the time, workload and financial burdens of such projects. This is real financial savings for the introduction of geostatistical approach in reservoir sedimentation projects in the conditions of Uzbekistan. For

**Table 4** Comparison of reservoir volume and surface areas from experimental, kriging, and simulation (minimum, mean, median, maximum) of Akdarya reservoir

| Water elevation (m) | Measured | Kriging | Simulation | | | |
|---|---|---|---|---|---|---|
| | | | Minimum | Mean | Median | Maximum |
| Volume ($Mm^3$) | | | | | | |
| 477 | 0.003 | 0.00074 | 0.0012 | 0.0044 | 0.0041 | 0.011 |
| 480.5 | 1.12 | 1.05 | 1.07 | 1.16 | 1.16 | 1.24 |
| 485 | 12.76 | 12.64 | 12.53 | 12.79 | 12.78 | 12.97 |
| 490 | 46.04 | 46.27 | 46.11 | 46.41 | 46.41 | 46.77 |
| 494.5 | 93.17 | 93.83 | 93.81 | 94.15 | 94.15 | 94.48 |
| Surface ($km^2$) | | | | | | |
| 477 | 0.0084 | 0.0036 | 0.0044 | 0.012 | 0.011 | 0.024 |
| 480.5 | 0.95 | 0.98 | 0.94 | 0.98 | 0.98 | 1.04 |
| 485 | 4.39 | 4.43 | 4.42 | 4.48 | 4.48 | 4.54 |
| 490 | 8.63 | 8.66 | 8.62 | 8.68 | 8.68 | 8.73 |
| 494.5 | 13.98 | 13.97 | 13.25 | 13.36 | 13.35 | 13.46 |

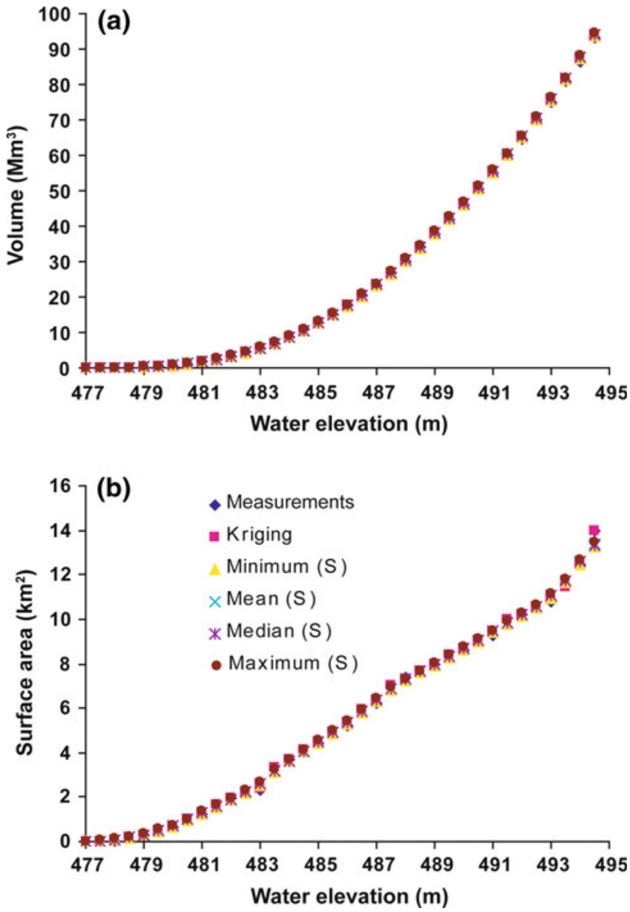



**Fig. 10** Akdarya Reservoir volume (**a**) and surface area (**b**) versus water elevation for experimental, kriging and simulation

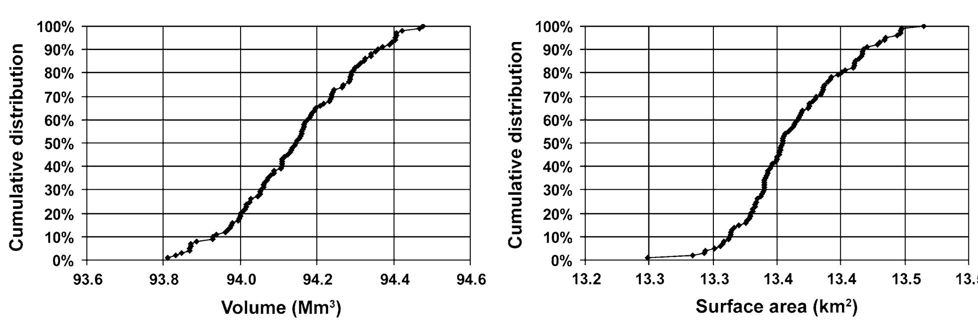
example, the economic efficiency for calculation of 1 km$^2$ of reservoir decreases from 570 (conventional method) to 385 $US (geostatistical method). The largest savings is obtained from the reduction of the field work and post-data analysis by 50%. The most important aspect in the geostatistical approach is the increase of the calculated area of the bathymetry with a decreased number of transects. It must be pointed out that this method of simulation and estimation of reservoir volume and surface area refers to the assessment of the total volume of trapped sediments in the reservoir. However, the spatial distribution of the deposited sediment volume has profound significations for the sedimentation countermeasure plan. The location of the deposited sediment within the reservoir may be of equal or even greater importance to the reservoir operations, as is the total volume deposited (Mahmood 1987).

## Perspectives in Uzbekistan

The USACE has started to apply a new DTM method for the sedimentation analysis and the calculation of reservoir volumes and surface areas in 2000 (Smith 2000). The DTM method relies on the digital conversion of historical topographic mapping and the collection of the recent sounding survey data for the creation of digital surface models of reservoir bottoms. The DTM method calculates sediment volumes over the entire reservoir area by comparing historical topography and recent sounding data digital surfaces. Topographic mapping of the site prior to the inundation represents the original reservoir bottom conditions. These topographic maps are digitized and geo-referenced to produce the contour coverage. Contour data are processed in a GIS software package. GIS has being used for the reservoir sedimentation in recent surveys elsewhere (Sawunyama et al. 2006). The final calculations for the sediment volumes are determined by subtracting the original reservoir capacity from the recent resurveyed capacity. Water and sediment depth models are created as a result. The water depths are calculated by subtracting the resurveyed DTM from the seasonal pool elevation, sediment depths are calculated by subtracting the original surface from the resurveyed one. The sediment depth grid provides a tool for the visualization of the spatial sediment distribution over the reservoir. This greatly enhances the illustration of the sediment accumulation for the operators and the water managers, and enables them to locate intensive sediment accumulation areas. Consequently, it will be a real asset for mitigation measures to be undertaken.

In addition, the Google Earth® program can be incorporated into the reservoir sedimentation studies as a supplemental analysis instrument for various periods of re-

**Fig. 11** Cumulative distribution of reservoir volume and area for a water elevation equal to 494.5 m (simulations outputs)



surveying, which will enable both researchers and dam operators to see the changes in the concerned area.

Recent research indicates that sediment yield from watersheds should be incorporated into the reservoir sedimentation studies. The new paradigm for such initiatives can be the Integrated Sediment Management programs that are advocated around the world (SedNet 2004). The integrated reservoir sedimentation studies would improve decision-making process for choosing the appropriate preventive measures, such as hydraulic flushing, sluicing, and hydraulic or mechanical dry dredging operations. This in turn can decrease the overall financial expenses for mitigation actions. For example, according to UzMAWR the rivers of Uzbekistan Amu Darya, Syr Darya and Zarafshan transport about 80–85% of the total annual sediment yield during the peak flows. Thus, on time operational modes of reservoirs maintenance can substantially reduce sediment accumulation in the reservoirs by hydraulic flushing and manoeuvring sluice gates.

## Conclusion

The reservoir sedimentation surveys were carried out with traditional range survey/end area method over the years. Since 2003, reservoir sedimentation surveys have been conducted with new bathymetric system that incorporates GPS and electronic transducer capabilities. However, manual data management persists in the practice, which is tedious and costly with large human induced errors for calculation of reservoir volume.

Geostatistical approach has many advantages compared to the traditional computation methods with statistical analysis of data variance and known fitting mathematical model for interpolation. Kriging interpolation method is a good first approximation. Simulation (turning bands) interpolation introduces range of volumes and surface areas in contrast to traditional estimates. Range volume values are more realistic estimates and provide water managers and dam operators with information about possible minimum and maximum estimates. In turn, it is believed that there would be possibilities to react appropriately in the decision making process. Presently, only single volume curves are used for the assessment of reservoir sedimentation in Uzbekistan. Geostatistical approach reduces the workload for post-data processing and has shown its economic efficiency for reservoir sedimentation projects and improves digital database for a given reservoir and future computations of reservoir volume evolution.

New methods, such as DTM methods and application of GIS capabilities must be incorporated in reservoir sedimentation projects for studying not only the total volume of sedimentation, but the spatial distribution of sediment accumulation in the reservoir. This DTM method provides reservoir operators with a better visualization of sedimentation processes and thus enables them to launch mitigation measures on a timely manner.

With the application of GIS and computer surface mapping software technologies, the new data management schemes at the national scale can be envisioned with the creation of digital maps of reservoirs for sustainable operation of Uzbekistan environment and physical infrastructure for the coming years.

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# WATER RESERVOIRS, IRRIGATION AND SEDIMENTATION IN CENTRAL ASIA: A FIRST-CUT ASSESSMENT FOR UZBEKISTAN

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**Abstract**

Water reservoirs play an important role in areas with limited and erratic precipitation where water is stored and re-distributed later for different purposes. Irrigation is primarily a major water consumer in arid countries of Central Asia for the economic development, employment and food security of the region. The major rivers of Central Asia (*e.g.* Amu Darya, Syr Darya, and Zerafshan) are turbid watercourses. Sedimentation reduces the main reservoir asset *i.e.* its volume capacity. In addition, vast territories of the region's countries have been transformed for agriculture to grow water intensive crops such as cotton, rice and wheat during the Soviet Union that dramatically accelerated soil erosion by water and wind. Thus many man-made water reservoirs are affected by high sedimentation rates. Moreover, uneven spatial and temporal water resources and a Soviet inherited unified hydraulic infrastructure have raised transboundary reservoir management issues over water resources allocation among the countries in the region such as Kyrgyzstan, Tajikistan, Kazakhstan, Uzbekistan and Turkmenistan. The rivers such as Syr Darya and Amu Darya are already regulated by more than 78% and 94% respectively and attempts for new reservoir projects upstream raises increased concerns of the downstream countries (*e.g.* the Rogun hydropower station in Tajikistan and the Toktogul reservoir in Kyrgyzstan). For instance the uncoordinated use of reservoirs has caused the Arnasai lake problem in Uzbekistan with environmental, material damage and social unrest.

The aim of this paper is first to review the present conditions and the role of man-made water reservoirs for irrigation in Central Asia with special focus on Uzbekistan, second to document past and current reservoir sedimentation conditions in Uzbekistan and third to discuss research carried out by Soviet and present time local research community in the domain of erosion and sedimentation in the region.

**Keywords**: water management, erosion, sedimentation rate, water reservoirs, Central Asia

## 1 Introduction

Due to their climatic characteristics, economic development strategies and geopolitical situation, Central Asian (CA) countries have been experiencing an everlasting competition over water resources. Mostly arid, these agrarian countries pursue their own development and integration into the global community through expanding irrigated lands, growing cash crops such as rice and wheat for meeting their domestic food security but also to export a large part of some productions such as cotton (Rakhmatullaev et al., 2009).

Water reservoirs created by dam construction on rivers have played an important role for societies around the globe throughout their history by regulating floods, generating hydropower, and re-distributing the river flow for irrigation. Dams on rivers induce both river flow and sediment flux fragmentation which causes accelerated accumulation of sediments (Morris and Fan, 1998; Palmieri et al., 2001; Syvitski, 2003; Sternberg, 2006; Walling, 2006). Sedimentation is a natural geomorphologic process but human interference increases its rates. Sedimentation reduces the main reservoir asset *i.e.* its volume capacity over time due to the feeding rivers. Hence, the utility of a reservoir diminishes as its volume capacity is reduced (Karaushev, 1977; Skrylnikov et al., 1987; Mahmood, 1987; Annandale, 1998; World Commission on Dams (WCD), 2000; International Commission on Large Dams (ICOLD), 2008; World Association for Sedimentation and Erosion Research (WASER), 2008).

It is reported that an annual average 0.5-1% loss of volume capacities of small and large reservoirs is observed due to sedimentation in the world. It is estimated that such losses of storage capacities per year are worth billion US$ and if such a scenario continues, about 25% of the world reservoir total volume capacity will be vanished over the next 25-50 years (Mahmood, 1987; WCD, 2000). Palmieri et al. (2003) reports that the loss in volume capacity requires an annual replacement cost of 13 billion US$. Recent estimates are even more dramatic. For instance Yang (2003) reports that the overall annual loss rate of reservoir volume capacity due to sedimentation is estimated to be 1 to 2 % of the total volume capacity. Moreover, Naisen and Lingyan (1998) reports that the average annual loss in volume capacity reaches 2.3 % in China, being the highest in the world.

Globally, more than 50% of the basin-scale sediment fluxes in regulated basins are potentially trapped in artificial impoundments, with a discharge-weighted sediment trapping of about 30% due to large reservoirs and an additional contribution of about 23% from small reservoirs (Vörösmarty et al., 2003).

A reduced reservoir volume capacity diminishes the flow regulation for an assured water supply for irrigation, industrial activities and municipalities downstream. Sedimentation triggers operation and maintenance issues coupled with economic feasibility of the project, environmental concerns and social aspects (Lapshenkov, 1959; Bruk, 1985; Evrard, 1985; Morris and Fan, 1998; McPherson and Harmon, 1998; United States Army Corps of Engineers (USACE), 2001; Vörösmarty et al., 2003; International Hydrographic Organization (IHO), 2005). Moreover the deterioration of water quality in reservoirs can be a major issue with increasing levels of various contaminants from agriculture, industry, and natural sources whether organic (pesticides, PCBs, PAHs) or inorganic (heavy metals) (WCD, 2000; ICOLD, 2008; Gadalia et al., 2005, Gadalia and Motelica, 2008).

Downstream effects of sedimentation include channel narrowing, reduction in braiding and associated loss of ecosystem complexity, river bed erosion and a reduction in the overbank flooding that is critical to many riparian species (Brandt, 2000; Wohl and Rathburn, 2003; Syvitski, 2003; Sternberg, 2006; Walling, 2006). Dam cavitation and abrasion of conduits, valves, sluice gates and hydropower turbines dramatically impact the hydraulic facilities and structures (USACE, 2001; IHO, 2005). Moreover social aspects can also be the unattractiveness for tourism and the loss of recreation opportunities (WCD, 2000; Knoblauch, 2006).

After the fundamental and extremely fast political transformation of the whole region (collapse of the Former Soviet Union (FSU) and emergence of National States), the unified physical hydraulic infrastructure and its management have been fragmented. For instance, each year the CA countries negotiate the water allocation from transboundary reservoirs such as the Toktogul reservoir in Kyrgyzstan, which has an explicit impact on the management of the entire Syr Darya River system. This large reservoir works in both irrigation-energy regimes but downstream States favoring the irrigation operation mode over energy production. New water reservoirs are being planed upstream for the regulation of the river flow and to increase the hydropower generation opportunities in Tajikistan and Afghanistan on the Amu Darya River system and in Kyrgyzstan on the Syr Darya River system respectively.

Under the market-oriented conditions, financial constrains have resulted in the decrease of government assisted rehabilitation and maintenance works of hydraulic infrastructures programs by several folds despite any water reservoirs have been constructed more than 20-25 years ago and need substantial rehabilitation. For instance the majority of reservoirs have been silted by sediments. Recent drought years urged authorities to re-estimate the water availability in reservoirs of Uzbekistan for the sustainable use of the natural resources and hydraulic infrastructure.

Thus there is urgency to adopt an innovative approach in bathymetric surveys for estimation of reservoir volume capacities due to sedimentation. New technologies such as GPS (Global Positioning System), acoustic depth measurement systems and contour mapping software have proved to increase geo-referenced data, improve the accuracy of data and most importantly substantially decrease the expenses of the bathymetric studies. In fact, since 2001 new geoinformation technologies have been used in bathymetric surveys in Uzbekistan. Last but not least there is limited information on water reservoirs in CA region in the international scientific literature.

Thus the first objective of this paper is to present the first-cut assessment on water reservoirs, their role for irrigated agriculture and the transboundary aspects of water reservoir management in CA region. The second objective is to discuss the current reservoir sedimentation conditions, extent and characteristics of man-made reservoirs in Uzbekistan.The third objective is to briefly overview some research on sedimentation and erosion carried out in the region by Soviet and local research communities.

## 2 Irrigation and water reservoirs in Central Asia

With an annual rainfall of 100–300 mm and a mean evaporation of 1600-2200 mm, Uzbekistan has a continental climate of the dry mid-latitude desert, characterized by hot summers and cold winters (Shultz, 1949; UNEP, 2005; FAO, 2007). Its climate is largely arid and its water resources are unevenly distributed both in space and time. There is a strong dependency on winter and spring rains and snowmelt from the Tien Shen and Pamir mountains.. In fact these mountains are major contributors to the watersheds of CA countries (World Bank, 2005).

Thus the agricultural production of the region is predominantly based on irrigation, which makes irrigation water supply and management the major factors limiting crop yields in the region (Ibragimov et al., 2007). The complexity of water resource relations in this region is related to the soviet inheritance of interconnected hydraulic infrastructure and to the transboundary origin of water resources.

Interstate Commission on Water Coordination (2004) reports that in Central Asia, for the period of 1960-1990, the total annual water intake was about 60.6 $km^3$ in 1960 and 116.2$km^3$ in 1990. Thus there was about a two fold increase in 30 years. In contrast the population of the region has increased by 2.7 folds and the area under irrigation increased by 1.7 fold.

Man-made reservoirs play a particularly important role where natural precipitation is erratic or seasonal because they store water during wet periods to make it available during dry periods. The role of water reservoirs has become very important in periods of water scarcity which are being documented in the region. World Bank (2005) reports that in drought year of

2000-2001 river flows dropped to between 35% and 40% below average levels. For example, the irrigation water scarcity became progressively worse particularly in downstream areas in the north of Uzbekistan. Economic damage was in order of hundreds of millions of US dollars with implication to population livelihoods and environmental issues. As recent research shows, a decreasing trend is evident in the Amu Darya discharge; in fact the discharge of Syr Darya did not decrease since 1985 (Nezlin et al., 2004).

The first water reservoirs of the Central Asian region have been constructed as early as in the X-XI centuries (Avakyan et al., 1987; Nikitin, 1991). The era of massive water reservoir construction begun in the late 1900s. For example, the Gindikush (Turkmenistan) reservoir was built in the Basin of the Murgab River in 1896 with a total volume capacity of 13 $Mm^3$ and 65 $Mm^3$ for the Sultanbent reservoirs in 1909-1910 (Irrigation of Uzbekistan, 1975; Skrylnikov et al., 1987). In 1940s several reservoirs have been constructed such as the Urtatokai reservoir in the Kassansai River Basin in Ferghana region and the Kattakurgan reservoir in the Zerafshan River Basin. For the last 30 years (from 1950 to 1980) more than 60 reservoirs have been constructed in the region (Table 1). Figure 1 depicts the schematic distribution of the main water reservoirs and their volume capacities in the CA region excluding reservoirs in central and northern region of Kazakhstan.

*2.1. Threats to water resources*

There are more than 290 water reservoirs in the Central Asia with a total volume capacity over 163 $km^3$ that regulate more than 50% of the monthly regions river flow and the area occupied by reservoirs constitutes roughly 6% of the CA countries irrigated areas (Table 2) (Avakyan et al., 1987; Skrylnikov et al., 1987; Nikitin, 1991; FAO, 2007). The primary source for irrigation in the region is the surface flow from rivers and man-made reservoirs. For example, an average of about 30% of irrigation water is delivered from reservoirs, ranging as high as 54% in Turkmenistan and as low as 13% in Kyrgyzstan (UNEP, 2005; FAO, 2007).

After the dissolution of FSU, the land-locked arid countries of CA region have directed their natural resources utilization towards economic development from previous planned to a market-oriented economy. Irrigated agriculture is the dominant sector of the economy in the CA countries, employing about 45% of the total population (World Bank, 2003; ICWC, 2004; IAMO, 2008; Abdullaev et al., 2009). This sector contributes to the region countries Gross Domestic Product (GDP) from 16 up to 30% with an average of 24% for the whole region (FAO, 2007). As a whole, 26% of the cultivated areas are irrigated, from 10% in Kazakhstan to over 99% in Turkmenistan. Thus 91% of the total water withdrawal is used for agricultural purposes in the region (Ximing et al., 2003; UNEP, 2005; Weinthal, 2006). Figure 2 shows the historical increase of irrigated lands in CA region for the last century. Over a period of 90 years (1913-2003) the areas under irrigation have increased by 3 times on average (Sattarov et al., 2006). This increase was due to a gigantic Soviet hydraulic program through construction of dams, irrigation canals, pumping stations and various hydraulic facilities.

Irrigation in CA region relies on a system of pumps and canals which is among the most complex in the world (O'Hara, 2000; Weinthal, 2006; UNDP, 2007). Cotton and wheat are the major crops followed by maize, vegetables and fruits. In Uzbekistan, which accounts for over half of the irrigated land in the CA region, it is estimated that about 70% of water is lost between the river and the crop, and poor drainage further exacerbates water management (World Bank, 2005).

Additionally there has been a general warming up in the CA countries on the order of 1–2 $^0$C since the beginning of the 20th century that might have a strong potential impact on the regional temperatures and precipitation regime but also on natural ecosystems and agricultural crops (Lioubimtseva et al., 2005). With drought and climate change in the region, water resources will be more stringent and transboundary management of hydraulic structures has to be developed in harmonic cooperation to meet current concerns for satisfying all involved parties.

Khorst (2001) reports that according to the estimations made by the Uzbek Hydro-Meteorological Committee, the pessimistic scenarios of water resources transformations due to global warming and reduction of ice and snow accumulations in CA region would be the reduction of discharge by 15-20% and 20-30% for the Syr Darya River and the Amu Darya River respectively. The following case study illustrates the consequences of inappropriate management of transboundary reservoirs known as the “Arnasai Lake” problem.

*2.2. Case of the Arnasai Lake - Transboundary reservoir management*

For the regulation of the CAR rivers, hundreds of man-made water reservoirs were constructed to mitigate natural shortage of water resources (Figure 1). Competition for water resources is prioritized by the downstream countries (Uzbekistan, Turkmenistan and Kazakhstan) for irrigation whereas upstream countries (Tajikistan and Kyrgyzstan) use them mainly for hydropower generation (O’Hara, 2000; ICG, 2002; UNEP, 2005). There has been a serious conflict related to the water resource management of some hydraulic infrastructures like the Toktogul reservoir located in Kyrgyzstan in the recent post-soviet period (Figure 3) (ICG, 2002; Weinthal, 2006). This water storage infrastructure serves for the needs of the entire Syr Darya River basin. Its main purpose is to regulate and secure the Syr Darya River flow during the vegetation period (April-October). It was designed to release 8.5 $km^3$ of water during the vegetation season and in order to restore the storage only 2.8 $km^3$ during the non-vegetation season. However the situation has significantly changed due to the end of the FSU. At present, new independent states can hardly negotiate on proper water allocation quotas for irrigated agriculture in summer for downstream countries and electricity generation in winter for upstream countries (O’Hara, 2000; ICG, 2002; UNEP, 2005; Weinthal, 2006).

The following example vividly shows that catastrophic environmental, economic and social issues can be caused by an inappropriate use of transboundary water reservoir. This is the so called “Arnasai Lakes” problem (UNDP 2007). The Syr Darya river flow is regulated within a volume of about 34 $km^3$ by the cascade reservoir of the Naryin-Syrdarya system. This system is arranged according to the following scheme (Figure 3), the Toktogul reservoir upstream (Kyrgyzstan) with a total volume capacity of more than 19.5 $km^3$ is operated in an irrigation-energy production regime (UNDP, 2007). The two reservoirs of Charvak and Andijan (Uzbekistan) with a total volume capacities of 2.0 $km^3$ and 1.9 $km^3$ respectively are located downstream and the Kairakkum reservoir in Tajikistan, middle reach of the river with a total volume capacity of 4.2 $km^3$ together with the Chardara reservoir in Kazakhstan with a total volume capacity of 5.7 $km^3$ which closes the system and operates in irrigation mode for water users downstream.

In 1969 a catastrophic flood forced to discharge about 2.7 $km^3$ from the Chardara reservoir to the Arnasai topographic depression creating here a huge new permanent lake. Until 1993 the Arnasai system, with a total area of 2,000 $km^2$, was stabilized, but from 1993, further releases from the Chardara reservoir caused a rise in the water level of 8.7 m. By the summer of 2003, the total area of this lake system reached 3,491 $km^2$ and today Arnasai is the largest system of lakes in Uzbekistan comprising the Aidarkul, Tuzkan, and Upper Arnasai lakes (UNDP, 2007).

Some experts argue that the creation of this lake system is favorable to the surrounding ecosystems and micro climate but it should be mentioned that as a result of the continuous water discharges in winter for hydropower generation, about 180,000 ha of land were flooded in the Jizzak and Navoi provinces of Uzbekistan. In addition, flooding has an impact on the local infrastructures resulting in the loss of tens of kilometers of roads, electric power lines, gas pipelines and other facilities. In addition, about 2,500 inhabitants of two settlements are at risk to lose their livelihoods because of flooding. The total damage is estimated to about 700 million US$ (UNDP, 2007).

Recently, in 2008, Kazakhstan started to construct the Koksarai reservoir downstream of the Chardara reservoir as a countermeasure for flooding of its agricultural and settlement areas with a design capacity of about 3 $km^3$ and a total dam length of more than 44.7 km, cost is estimated about 100 million US$. But is should be pointed out that the decision to construct this hydraulic structure is only on the initiative of Kazakhstan without consensus with Uzbekistan.

## 3 Water resources, reservoirs and sedimentation in Uzbekistan

### *3.1. Water resources*

Uzbekistan is largely an arid region, where evaporation exceeds rainfall and annual precipitation is below 200 mm (UNDP, 2007). This means that agricultural production is impossible without irrigation. The streamflow is characterized by an extreme intra-annual variability and is also unevenly spatially distributed (Kazbekov et al., 2007; Rakhmatullaev et al., 2009). Two main river basins are found in Uzbekistan, the Amu Darya and the Syr Darya (Schlüter et al., 2005). The transboundary rivers Amu Darya and Syr Darya satisfy 82% of the total water demand for irrigation, whereas only 18% of the same demand is satisfied by the internal rivers Kashka Darya, Zerafshan and Surkhan Darya in Uzbekistan (Figure 3) (UNEP, 2005; UNDP, 2007; Rakhmatullaev et al., 2008a).

According to experts, the total amount of flow produced in the Amu Darya basin is estimated at 78.46 $km^3$/year and about 6% of the average total surface water resources of the Amu Darya river basin are generated within Uzbekistan (Crosa et al., 2006; UNEP, 2005; FAO, 2007). The Amu Darya River stretches from its source the Pyandj River to the Aral Sea over 2540 km, including about 1000 km within the territory of Uzbekistan. The total amount of flow produced in the Syr Darya basin is estimated at 37.14 $km^3$/year and about 13% of the average surface water resources of the Syr Darya River basin, are generated within Uzbekistan (Nezlin et al., 2004; FAO, 2007; Rakhmatullaev et al., 2009). The total length of the Syr Darya River is 2800 km, of which 2000 km flows through the territory of Uzbekistan. The long-term average runoff of the Zerafshan River is estimated to be 5.91 $km^3$ and only 0.76 $km^3$ of runoff is formed in Uzbekistan. The Zerafshan River starts in Tajikistan and the third largest river basin in Uzbekistan. Thus, the total water deficit in Uzbekistan is estimated to 2.5 $km^3$/year in the Syr Darya river basin and between 1.5 to 3.0 $km^3$ in the Amu Darya river basin depending on water availability in a particular year (O'Hara, 2000, Weinthal, 2006; UNDP, 2007; FAO, 2007).

The total cultivated land in Uzbekistan is estimated to be about 5.2 million ha, of which 4.2 million ha are irrigated (FAO, 2007). Figure 4 shows the evolution of the irrigated land area and of the specific water intake for irrigation during the last century. It illustrates the trends in the increase of the irrigated land and in specific water intake. As it can be seen the area of irrigated land will certainly increase in the future and the specific water intake will peak at 13,000 $m^3$/ha even in a foreseeable future (UNDP, 2007).

### *3.2. Reservoirs*

At present time, approximately 90% of the water resources in Uzbekistan are used for irrigated agriculture. In fact water is withdrawn from the surface runoff by a system of 1130 pumping stations that irrigate over 50% of the total irrigated land, via a 22,300 km long network of inter-farm and main canals, and 42 water intake structures (with a capacity of 10-300 $m^3$/sec) (UNDP, 2007). In fact about 24% of irrigation water in Uzbekistan comes from water reservoirs (Figure 5).

This complex hydraulic infrastructure is financed and maintained by the government. However, with the transition period of Uzbekistan from a centralised to a market-oriented economy, financial flows have been reduced. For example, over a 10 years span (1991-2001) the government investment portfolio assigned for rehabilitation activities has decreased from 27% to 8%, the capital investment to the water sector being reduced by 5 times (UNDP, 2007). This reduction in investment portfolio has further worsened the operation and maintenance of existing infrastructure and this particularly concerns water reservoirs.

The total number of man-made water reservoirs in Uzbekistan is 55 (Table 2) (UNDP, 2007; Rakhmatullaev et al., 2008b). The total gross volume capacity of all reservoirs is about 19 km$^3$ and the useful volume capacity is about 14.5 km$^3$ whereas the total surface area of reservoirs is estimated about 1450 km$^2$. The average dam height is about 39 m with a maximum of 168 m (Tupalang reservoir) and a minimum of 11.5 m (Uchkyzyl reservoir). About 57% of all reservoirs have a volume capacity about 1 to 50 Mm$^3$ but only five have a volume capacity of more than 1 km$^3$. Moreover for the surface area, only eight reservoirs have a surface area greater than 50 km$^2$. Table 3 gives the main characteristics of large water reservoirs in Uzbekistan. These nine major reservoirs constitute about 86% (16.8 km$^3$) of the total reservoir volume capacity and about 94% (1362 km$^2$) of the total surface area in Uzbekistan.

Almost 90% of all dams are used for irrigation purposes and only two for hydropower (Andijan and Charvak). The Amu Darya river is regulated by 78% whereas only by 94% for the Syr Darya river (UNEP, 2005; Rakhmatullaev et al., 2008a; UNDP, 2007). For example, all main run-on-the-river reservoirs for the regulation of the Amu Darya and Syr Darya river flows are located beyond the boundaries of Uzbekistan, with the exception of the Andijan, Tuyamuin, and Janubiy Surkhan reservoirs (Figure 3). Therefore Uzbekistan is vulnerable in terms of transboundary reservoir management for a sustainable water allocation. There are almost no sites left for the construction of new reservoirs. Thus it is a strategic importance to rationally calculate the available water resources in the existing reservoirs for assuring a guaranteed water supply for the agriculture, industry and municipalities.

The peak of dam construction is dated to the soviet period when its policy was aiming at expanding irrigated lands for the mass production of cotton. These impressive actions have resulted in a great increase in irrigated lands from 2.57 million ha in 1960 to 4.22 million ha by the late 1980's (UNDP, 2007). The dam construction is graphically illustrated in Figure 6. About 75% of dams were constructed in the 30-years period from 1961 to 1990 with 93% of a total reservoir capacity known as the "soviet period" (Rakhmatullaev and Le Coustumer, 2006; Rakhmatullaev et al., 2008b). After the 1990's just a few dams have been constructed mainly to finish the already initiated projects. At present time two dams are being constructed in Uzbekistan for securing water availability for the vegetation period. For example, for the mitigation of drought in the 2000-2001 years, the government of Uzbekistan in the Namangan province initiated the construction of the Rezaksai reservoir with a total capacity of 0.2 km$^3$ in the perspective of increasing the water availability up to 0.66 km$^3$.

### *3.3. Sedimentation and erosion*

The environmental concerns related to land degradation are desertification, loss of biodiversity, land salinization and overgrazing of lands that can generate high rates of erosion and sedimentation (Tookey 2007; UNEP 2005; UNDP 2007).

The World Bank (2005) reports that the loss of vegetative cover on rain-fed and pasture lands in Uzbekistan has contributed to the severity of runoff, floods, landslides and drought when adverse weather events did occur. In Uzbekistan, the common forms of erosion are mainly wind and irrigation. In particular, wind erosion is dominant in desert regions of Khorezm, Bukhara and Karakalpakstan. According to Talipov (1992) the wind erosion is observed above a wind velocity of 15 m/s. Figure 7 depicts the percent of affected lands to different types of erosion in Uzbekistan. The erosion by water and irrigation has increased due to the improper irrigation methods and to the increase of irrigated areas on steep slopes. In addition, the main contributing factors are deforestation and overgrazing (UNESCO, 2000). Nowadays, wind erosion has dramatically decreased by 50% against 1980s due to preventive action plans by vegetation strips around irrigated areas but the specific losses of humus layer over a season due to erosion can still reach 80 t/ha (UNDP, 2007). According to a recent study by the UNDP, around 0.8 million ha of land is subject to water erosion and more than 2.3 million ha suffered from wind erosion in Uzbekistan.

UNEP (2005) reports that about 75% of the total number of mudflows in the CA region has occurred in Uzbekistan. According to the World Resource Institute, the percentage of watershed basin affected by water-related erosion is about 5% for the CA region and for

Uzbekistan (Revenga et al., 1998). Talopiv (1992) reports that the mean annual soil erosion by water is estimated to be between 100-150 tons/ha whereas its value varies from 25 to 50 tons/ha for gentle slopes to 500 tons/ha for steep slopes. To combat the erosion various mitigation measures have been used in Uzbekistan such as the implementation of vegetation strips, terracing on steep slopes, implementation of engineering erosion preventive structures and the application of conservation tillage techniques (Rakhmatullaev and Le Coustumer 2006; Rakhmatullaev et al. 2008b).

Smalley et al (2006) discusses the loess formation processes in eastern part of Uzbekistan near the capital of Tashkent. According to their arguments the hydrocollapse and water erosion are closely related and are controlled by the complex nature of the loess ground. Dust clouds in eastern Uzbekistan are largely loess related, but in the west dust material is raised from the drying Aral Sea bed; this is mainly composed of clay minerals agglomerated material and can carry on dangerous pollutants.

### *3.4. Silting up of reservoirs*

According to the Uzbekistan Ministry of Agriculture and Water Resources (UzMAWR), 11 out of the 27 inspected reservoirs are almost completely silted up and at 5 other reservoirs the silt has almost reached the level of the outlet structures (UNDP, 2007).

In 2001 the Uzbek Bathymetric Center was established under the umbrella of UzMAWR, which is authorized for bathymetric surveys using new technology including GPS (Global Positioning System), depth measuring transducer CEEDUCER® of Bruttour International PTY Ltd. Bathymetric survey are then carried out from a moving boat using electronic depth-sounding equipment in conjunction with GPS and an automatic data recorder CEEDUCER® with its base station located on the shoreline according to standards (McPherson and Harmon, 1998; USACE, 2001; IHO, 2005). GPS was used to determine the latitude and longitude for each depth measurement. Sounding equipment was used to measure depth from a transducer probe, operating at the frequency of 200 kHz to the bed of the reservoir. Depths recorded by the sounder were measured at a fixed distance below the water surface (Bathymetric Center, 2003). The recorded depths and the constant value of the depth sounder were subtracted from the water surface elevation to obtain elevations of the reservoir bed. The depths were synchronized with the GPS data to determine the location of the probe as the boat traversed across the reservoir.

The center has performed bathymetric surveys in 16 reservoirs in Uzbekistan (Table 5) (Bathymetric Center, 2003). As it can be seen the total volume capacities and the dead storage capacities of all reservoirs have decreased by about 18% and 55% respectively on the average. For example, the dead volume capacities of 7 reservoirs decreased by more than 75%. This is an alarming signal that in new future the sedimentation rates can be unprecedented with operation and maintenance issues.

## 4 Research on reservoir sedimentation in the former Soviet Union

In the area of fluvial morphology, erosion and sedimentation research, significant development was carried out in the FSU that greatly contributed to this domain of knowledge. It should be worth to discuss in brief the contributions of Russian speaking scholars in the domain of water reservoir sedimentation.

Sedimentation of engineering hydraulic structures, reservoirs, irrigation channels and their mitigation measures have been studied extensively by the Soviet and scientists of Uzbekistan. We have to mention the fundamental research works of the following authors: Altunin (1962), Avakyan (1987), Velikanov (1954), Vuglinskiy (1991), Ibad-Zade (1989), Karaushev (1969 and 1977), Popov (1977), Shamov (1939), Lapshenkov (1959); Uzbekistan scholars: Muhamedov (1976), Nikitin (1991), Skrylnikov (1987), Ismagilov (1997), Bakiev and others (Karaushev, 1977; Irrigation of Uzbekistan, 1975, Rakhmatullaev et al., 2008b).

Shvartsman (1994) reviews the common reservoir sedimentation computation methods based on the mean long-term annual sediment inflow of the river to the total reservoir volume used in FSU. It is known that the major contributing source of the reservoir sedimentation is suspended and bedload sediments carried out by streamflow and to less extent the bank erosion and eolian sediments carried out by wind from surrounding areas in the vicinity of the reservoir. According to the research of Skrylnikov (1987) this can contribute to about 3-6% of the total sediment load.

The two main characteristics such as water exchange duration ($T_c$) and sedimentation rate ($t_c$) are first preliminary indexes used for reservoir sedimentation in the FSU.
The value of $T_c$ is expressed in years and determined from the following equation:

$$T_c = W / V_{in} \quad (1)$$

where: $W$ is the reservoir volume at full pool elevation ($m^3$) and $V_{in}$ is the mean annual long-term river inflow to the reservoir ($m^3$/year).
The value of $t_c$ is estimated from the following expression

$$t_c = W / V_s \quad (2)$$

where: $W$ is the reservoir volume at full pool elevation ($m^3$) and $V_s$ is the mean annual long-term sediment inflow flux to the reservoir ($m^3$/year).

Indeed the actual reservoir sedimentation always exceeds the value of estimated $t_c$ because of the part of sediments load discharged downstream. The abovementioned methods give only preliminary generalized assessment of reservoir sedimentation. Under the conditions of $T_c > 0.02$ then the total reservoir sedimentation is estimated. For example, the first step is computation of $t_c$ value and if this value exceeds 200 years then this ought to be the potential reservoir operation period. In this case, the sediment accumulation volume in a specified number of years is calculated as a product of a mean annual sediment inflow load by the number of years. On the other hand, if the value of $t_c$ is less than 200 years then the reservoir sedimentation should be estimated taking into account the sediment discharged downstream. The following data should be available for use of abovementioned methods such as mean long-term water discharge, total sediment discharge of streamflow to the reservoir, morphological shapes of the streamflow and reservoir.

Bobravitskaya (2002) reviews the erosion and sediment yield models used in the FSU and outlines the major retrospective development in the domain of soil erosion studies, soil classification system, global and regional soil maps in the FSU and major soil erosion factors and processes with integration of various qualitative and quantitative assessment methods and models in particular.

Bobravitskaya and Zubkova (1997) comprehensively reviewed the estimation methods for determining annual suspended sediment yield in rivers that has been developed and still used in the countries of the FSU. There are about 24 major factors of anthropogenic origin that impact the sediment yield such as construction of hydraulic structures on riverine systems, land use on slopes, deforestation, irrigated agriculture, mining, fires and others. It is out of scope of the paper and for detailed discussion of methods used and developments in this area one should consult the abovementioned authors.

Ismagilov (1997) has first reviewed fluvial sediment transport estimation methods that are available from the international scientific community for the arid CAR. One can cite the first review papers by Golosov et al (2008) and Alekseevskiy et al (2008) for fluvial geomorphology sciences development in the FSU with principles and different methods used in this domain of research. The paper briefly overviews the major developments in erosion and sedimentation studies carried out in the CAR which have been transformed significantly due to the massive water resource development in the era of Soviet legacy. The early studies for examining channel deformations in reservoir basins in Uzbekistan have been documented in the 1950’s with massive development of irrigation steppes and regulation of flow regimes in Uzbekistan (Irrigation of Uzbekistan, 1975).

In 1939 Shamov wrote a generalized monograph on reservoir sedimentation (Karaushev, 1969). He suggested a relatively simple approximate sedimentation calculation method that looks at the morphological characteristics of water body and sediment yield for examining the chronology of the reservoir sedimentation. In later periods, more detailed reservoir sedimentation calculation methods have been developed by various authors (Irrigation of Uzbekistan, 1975, Rakhmatullaev and Le Coustumer, 2006).

Skrylnikov et al. (1987) reports that Altunin (1962) has suggested that the reservoir sedimentation process can be subdivided into lake (free from sediments) and channel (concentrated with sediments) parts. In the process of sedimentation, the channel part advances onto the lake part and at the same time advances upstream, thus constructing supplemental dynamic reservoir storage (Irrigation of Uzbekistan, 1975).

Lapshenkov (1959) has proposed a more elaborated sedimentation estimation method that has proved to be correlated by field observations (Skrylnikov et al., 1987). Lapshenkov (1959) has also proposed an equation describing a linear relationship between the released sediment discharge and the volume of sediment accumulation for low head barrages based on quasi-laminar theory of sediment settling in sedimentation process.

The equation expresses the volume change in the reservoir over time:

$$V_t = V_o x e^{\varepsilon t} \quad (3)$$

Where:

$V_o$ - is the maximum (upper limit) of sedimented volume (reservoir volume minus river channel volume at the end of the sedimentation period), $m^3$

$\varepsilon$ -the sedimentation characteristics depending on annual sediment yield (maximum volume that will be silted and initial level of sedimentation), $m^3$

*t* the period of reservoir operation in years.

For the calculations of the sediment distribution along the length of the reservoir Lapshenkov (1959) has suggested to use the above mentioned equation for any cross-section of a reservoir (changing $V_o$ and $\varepsilon$) and determine the sedimentation area as the difference in accumulation deposited in two adjusted cross-sections apart of 1 m between them. The Lapshenkov method was extensively used for the prediction and calculation of sedimentation rates in the design of many reservoirs in Central Asia and is considered as a standard.

The rate of reservoir sedimentation is characterized by $\varepsilon$ (clarification coefficient, i.e., the fraction of sediments that is retained in reservoir) which depends on the volume of the reservoirs, water discharge, sediment size distribution and turbidity. It is known that prior to the impoundment, the sediment carrying capacity of river is not altered and can therefore transport all sizes of sediments. The initial headwater volume capacity of reservoir $W_i$ includes the volume capacity of the river channel ($W_r$) that transports all sediment fractions. $W_r$ is calculated by multiplying the cross-sectional area of the river channel by the length of the reach where hydraulic head is observed in headwater part of the reservoir. Prior to the impoundment there is no hydraulic head in headwater part of the reservoir thus $W_i$ equals to $W_r$ and the coefficient of clarification is zero. Therefore, under the conditions $W_i/W_r$ =1, then $\varepsilon$ =0, and when $W_i/W_r$ <1, then $\varepsilon$ >0. Skrylnikov et al. (1987) while analyzing the coefficient of water clarification has suggested to divide the sedimentation process into two phases: in the first phase full accumulation of sediments in reservoir occurs, characterized by a constant level of clarification $\varepsilon$ =95 to 97%, the second phase is observed when the reservoir storage decreases to the level of $W_i < 7.7\text{-}W_r$ ,because of sedimentation processes, and is characterized by a rapid reduction of the clarification level (Skrylnikov et al., 1987; Rakhmatullaev et al., 2008b).

**5 Conclusion and Perspectives**

Uzbekistan which is located downstream of the two main rivers of Central Asia (Amu Darya and Syr Darya) experiences a water deficit allocation both in time and space for irrigation due to climatic conditions and the human induced water reservoir system. Agriculture based on irrigation is a dominant sector for employment, state foreign revenues and livelihood in Uzbekistan. Thus it is of paramount importance to accurately estimate the available water resources in reservoirs for an assured water allocation and sustainable management of the existing physical hydrological infrastructure. In fact almost the majority of reservoirs has lost their dead storage capacities due to sedimentation and in the next 20-30 years reservoirs will loss their functionality if mitigation measures are not undertaken.

The transboundary nature of the hydraulic engineering infrastructure systems of Uzbekistan gives a geopolitical dimension to the management and use of water reservoirs. The uneven distribution of water resources and the heritage of soviet regulating infrastructure of the Naryn-Syrdarya reservoir system have a profound impact on the environment and the competition for irrigation or energy sectors in the CA. For example, the Charvak reservoir was filled with water only by 50% in 2008. This will put extra pressure on the water reservoirs that already accounts for 24% of irrigation water in Uzbekistan.

With the reduction of government financial investment portfolio in the rehabilitation and maintenance of hydraulic structures, it is urgent to adopt an innovative approach for reservoir sedimentation survey projects with the use of geoinformation technologies. We would like to propose the following recommendations to be used for the estimation of the sedimentation impacts on reservoirs.

1. New technologies and methods for the prediction of the water availability and loss of reservoir volume to sedimentation have proved to be cost-effective in reducing the number of personnel and time for such surveys by several folds based on the use of contour and mapping programs with interpolation techniques
2. Research must be carried out on the estimation of erosion and sedimentation yields on the watershed across Uzbekistan to develop a comprehensive database on the magnitude of erosion and sedimentation rates. Introduction of an Integrated Sediment Management Concept must be incorporated into the decision making processes in the early stages of the planning of the construction of new reservoirs, and active involvement of the research community into the decision making procedure will benefit to the sustainable use and management of both physical hydraulic infrastructure and consequently to the optimal use of the scarce water resources of Uzbekistan.

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* Data for Kazakhstan from FAO, 2007

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Table 1. Construction of water reservoirs in the Central Asian region (Skrylnikov et al., 1987)

| **Parameter** | **Prior 1918** | **1919-1940** | **1941-1950** | **1951-1960** | **1961-1970** | **1971-1980** | **1981-1985** |
|---|---|---|---|---|---|---|---|
| No. of reservoirs | 5 | 2 | 4 | 17 | 21 | 19 | 7 |
| Volume capacity ($km^3$) | 0.172 | 0.167 | 1.25 | 7.23 | 4.68 | 35.0 | 0.89 |
| Cumulative Volume capacity ($km^3$) | 0.17 | 0.34 | 1.59 | 8.82 | 13.45 | 48.45 | 49.34 |

Table 2. Distribution of reservoirs in Central Asia by country and their share to irrigation (Food and Agriculture Organization of United Nations)

| **Country** | **Total reservoir volume capacity ($km^3$)[a]** | **Number of reservoirs** | **Irrigation water from reservoirs (%)[b]** |
|---|---|---|---|
| Kazakhstan | 88.8 | 180 | 32 |
| Kyrgyzstan | 23.5 | 18 | 13 |
| Tajikistan | 29 | 19 | 28 |
| Turkmenistan | 2.89 | 18 | 54 |
| Uzbekistan | 19 | 55 | 24 |
| **Total in CA** | **163.19** | **290** | |

[a] FAO, 2007; [b] FAO, 1994.

Table 3. Distribution of water reservoirs in Uzbekistan by administrative boundaries (United Nations Development Program, 2007)

| **Province** | **Number** | **Useful Volume Capacity ($km^3$)** | **Province** | **Number** | **Useful Volume Capacity ($km^3$)** |
|---|---|---|---|---|---|
| *Amu Darya River Basin* | | | *Syr Darya River Basin* | | |
| Khorezm | 1 | 4.5 | Andijan | 3 | 1.7 |
| Kashkadarya | 14 | 2.3 | Tashkent | 5 | 1.9 |
| Samarkand | 7 | 1.1 | Fergana | 4 | 0.25 |
| Surkhandarya | 4 | 0.9 | Namangan | 7 | 0.23 |
| Navoi | 2 | 0.8 | Jizzak | 4 | 0.18 |
| Bukhara | 2 | 0.4 | Syrdarya | 2 | 0.01 |
| **Total** | **30** | **10.1** | | **25** | **4.45** |

Table 4. Characteristics of the large water reservoirs in Uzbekistan (Bathymetric Center of the Ministry of Agriculture and Water Resources of the Republic of Uzbekistan, 2003)

| **Reservoir** | **River Basin** | **Started to operate (Year)** | **Dam height (m)** | **Total volume capacity ($km^3$)** | **Surface area ($km^2$)** |
|---|---|---|---|---|---|
| Tuyamuin[a] | Amu Darya | 1980 | 34 | 7.80 | 650 |
| Charvak | Chirchiq | 1977 | 168 | 2.0 | 40.3 |
| Andijan | Kora Darya | 1970 | 121 | 1.90 | 55.5 |
| Tallimarjan | Amu Darya | 1985 | 36 | 1.52 | 77.3 |
| Tudakul | Amu Darya | 1983 | 12 | 1.20 | 162 |
| Kattakurgan | Zerafshan | 1953 | 31.2 | 0.82 | 84.5 |
| Janubiy Surhan | Surkhan Darya | 1967 | 30 | 0.80 | 65 |
| Chimkurgan | Kashka Darya | 1963 | 33 | 0.50 | 49.2 |
| Kuyimazar | Amu Darya | 1958 | 23.5 | 0.32 | 178.5 |

[a] Tuyamuin is composed of four reservoirs: 1) Ruslovoy with volume capacity (2.34$km^3$); 2) Sultansanjar with volume capacity (2.69$km^3$); 3) Kaparas with volume capacity (0.96$km^3$); 4) Koshbulak with volume capacity (1.81$km^3$).

Table 5. 16 Reservoirs in Uzbekistan where sedimentation estimation was carried out by new technologies (Bathymetric Center of the Ministry of Agriculture and Water Resources of the Republic of Uzbekistan, 2003)

| **Reservoir** | **Initial Volume ($Mm^3$)** | **Silted volume (%)** | **Initial Volume ($Mm^3$)** | **Silted Volume (%)** | **Started to operate (Year)** |
|---|---|---|---|---|---|
| | Total Volume Capacity | | Dead Volume Capacity | | |
| Tashkent | 250 | 16.9 | 26 | 76.3 | 1962 |
| Talimarjan | 1525 | 3.9 | 125 | 2.23 | 1985 |
| Janubiy Surkhandarya | 800 | 37 | 100 | 78.7 | 1967 |
| Kuyimazar | 310 | 11.2 | 47 | 6.7 | 1958 |
| Tudakul | 1200 | 13.7 | 600 | 9.6 | 1983 |
| Akhangaran | 198 | 4.8 | 13 | 27.7 | 1969 |
| Andijan | 1900 | 13.4 | 150 | 39.2 | 1970 |
| Jizzak | 100 | 19.9 | 4 | 96.2 | 1966 |
| Kattakurgan | 900 | 22.5 | 24 | 87 | 1953 |
| Tupalang | 100 | 16.6 | 8.79 | 88.4 | 1992 |
| Khissarak | 170 | 13.2 | 8.4 | 100 | 1985 |
| Chimkurgan | 500 | 22.7 | 50 | 31.8 | 1963 |
| Pachkamar | 260 | 25.9 | 10 | 99.8 | 1967 |
| Akdarya | 112.5 | 17.2 | 2.5 | 41.6 | 1984 |
| Ruslovoy | 2340 | 44.9 | 270 | 86.5 | 1980 |
| Kaparas | 960 | 1.9 | 410 | 1.65 | 1983 |
| **Average** | | **17.8** | | **54.6** | |

Fig. 1.

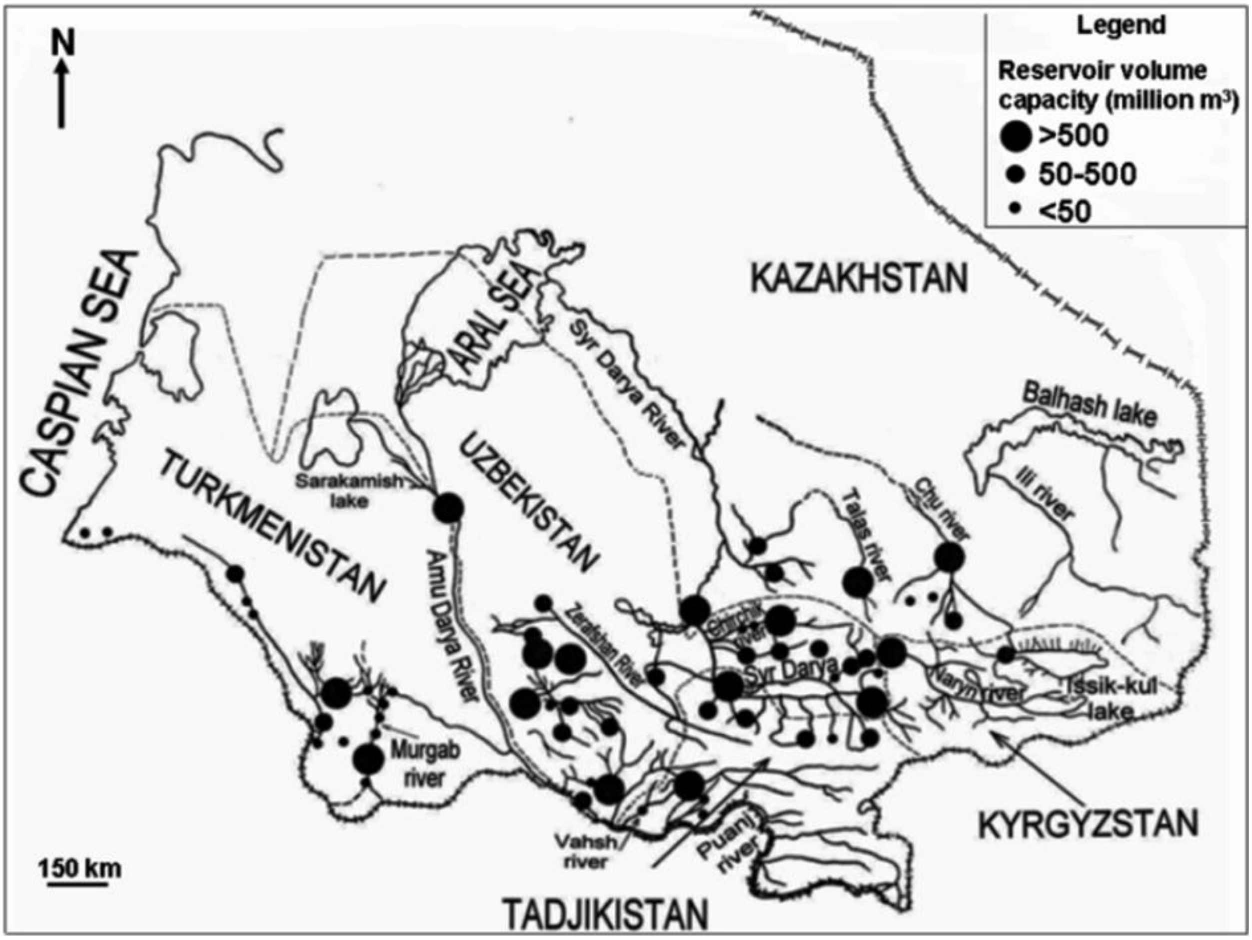

Legend
Reservoir volume capacity (million m³)
>500
50-500
<50
N
CASPIAN SEA
KAZAKHSTAN
ARAL SEA
Syr Darya River
TURKMENISTAN
UZBEKISTAN
Sarakamish lake
Amu Darya River
Balhash lake
Ili river
Talas river
Chu river
Zerafshan River
Syr Darya
Naryn river
Issik-kul lake
Murgab river
Vahsh river
Puanj river
KYRGYZSTAN
150 km
TADJIKISTAN

Fig. 2.

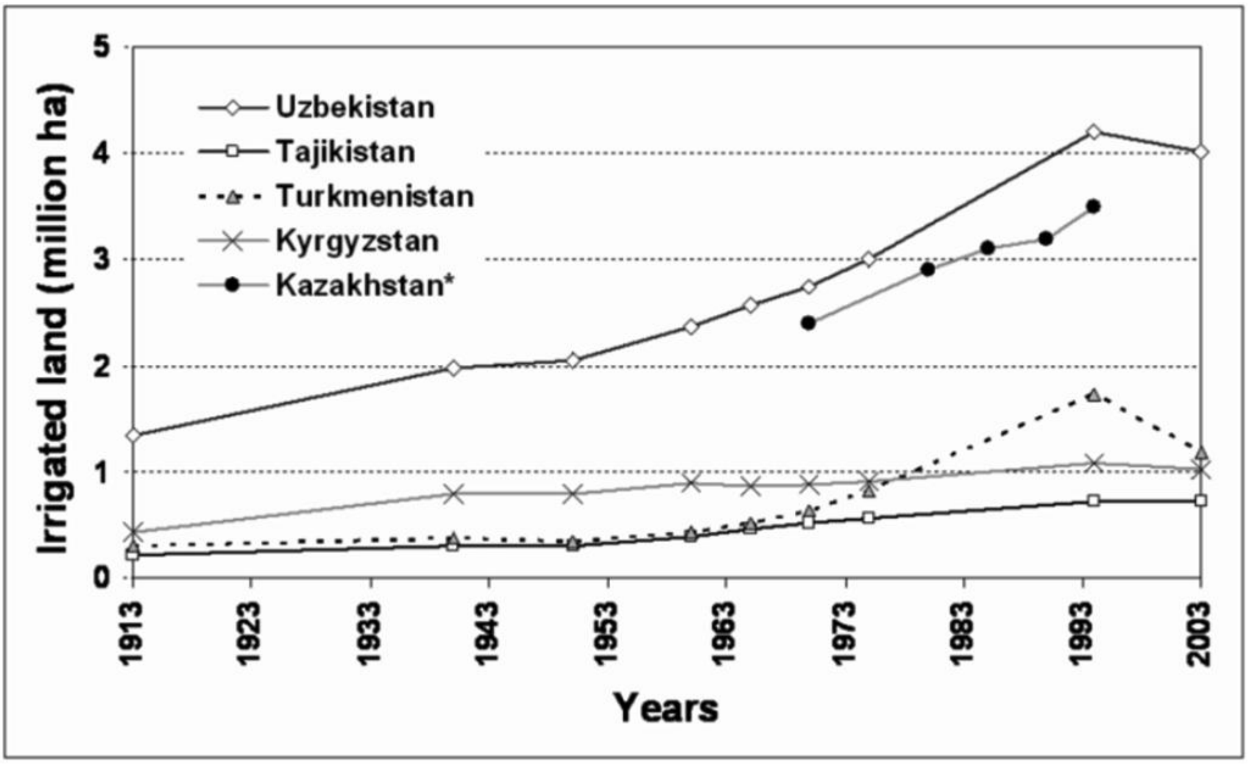

Irrigated land (million ha)
0
1
2
3
4
5
Uzbekistan
Tajikistan
Turkmenistan
Kyrgyzstan
Kazakhstan*
1913
1923
1933
1943
1953
1963
1973
1983
1993
2003
Years

Fig. 3.

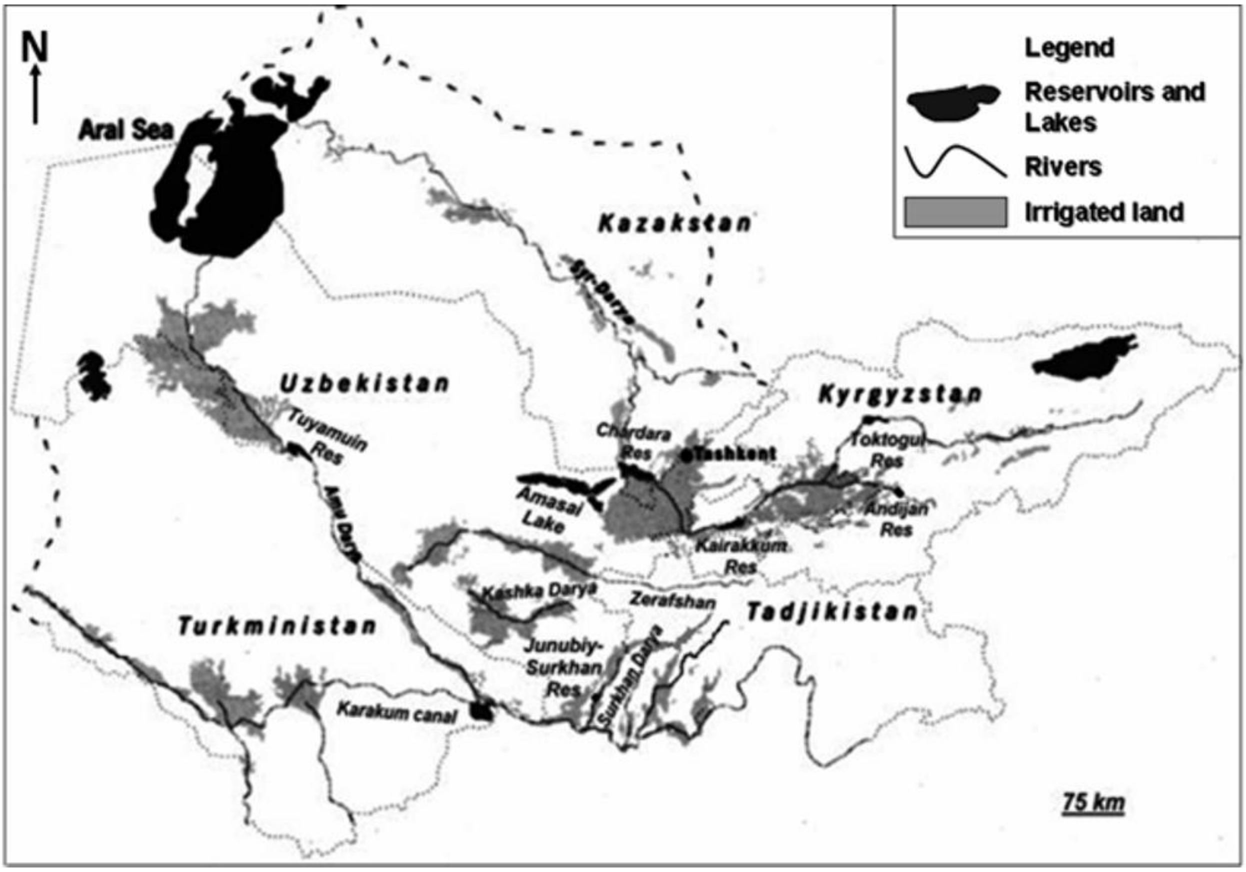

N
Legend
Reservoirs and Lakes
Rivers
Irrigated land
Aral Sea
Kazakstan
Syr-Darya
Uzbekistan
Kyrgyzstan
Tuyamuin Res
Amu Darya
Chardara Res
Tashkent
Toktogul Res
Amasai Lake
Andijan Res
Kairakkum Res
Kashka Darya
Zerafshan
Tadjikistan
Turkministan
Junubiy-Surkhan Res
Surkhan Darya
Karakum canal
75 km

Fig. 4.

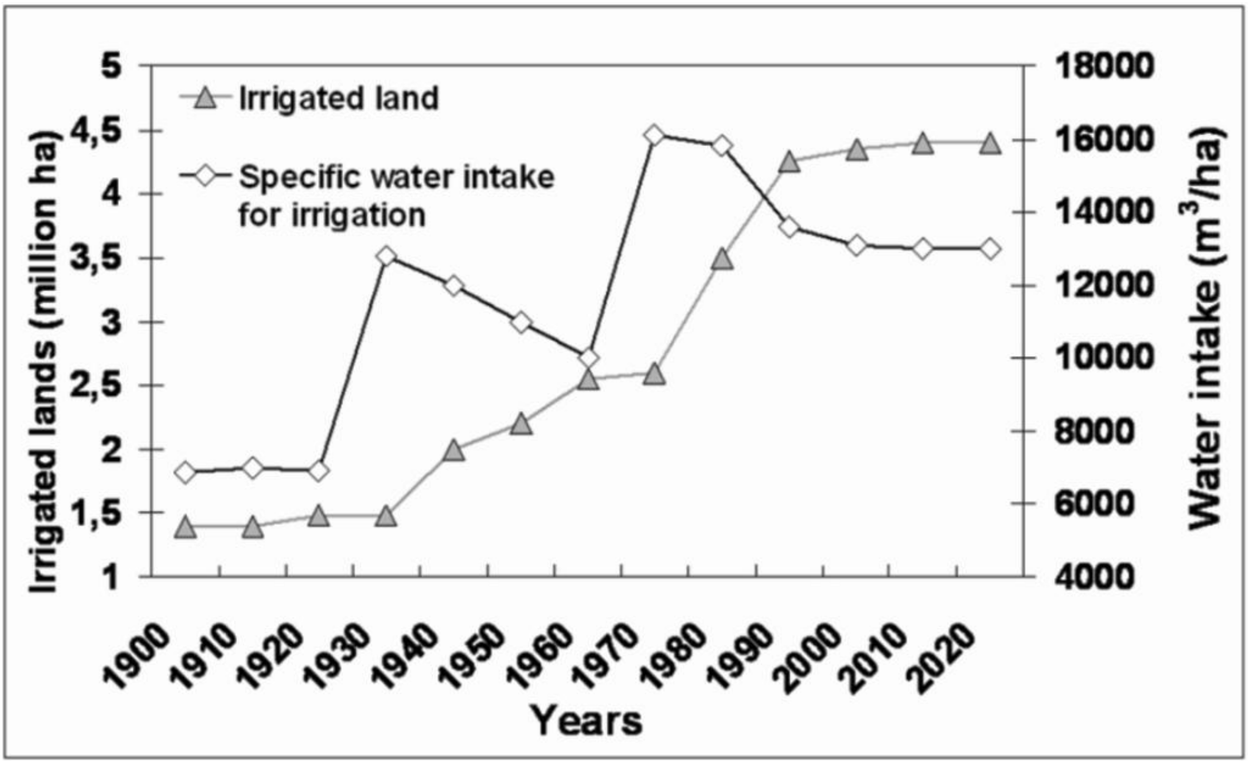

Irrigated land
Specific water intake
for irrigation
Irrigated lands (million ha)
Water intake (m3/ha)
5
4,5
4
3,5
3
2,5
2
1,5
1
18000
16000
14000
12000
10000
8000
6000
4000
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Years

Fig. 5.

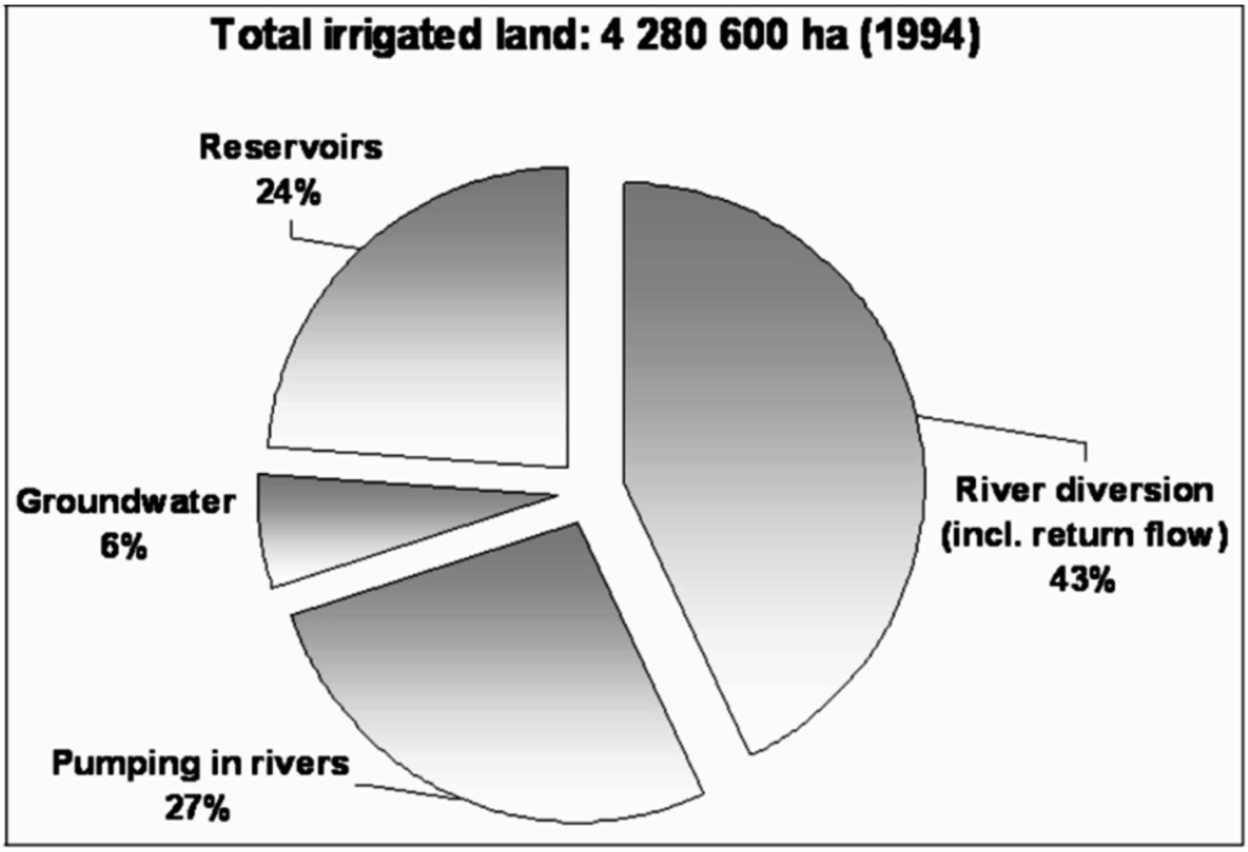

Total irrigated land: 4 280 600 ha (1994)
Reservoirs
24%
Groundwater
6%
River diversion
(incl. return flow)
43%
Pumping in rivers
27%

Fig. 6.

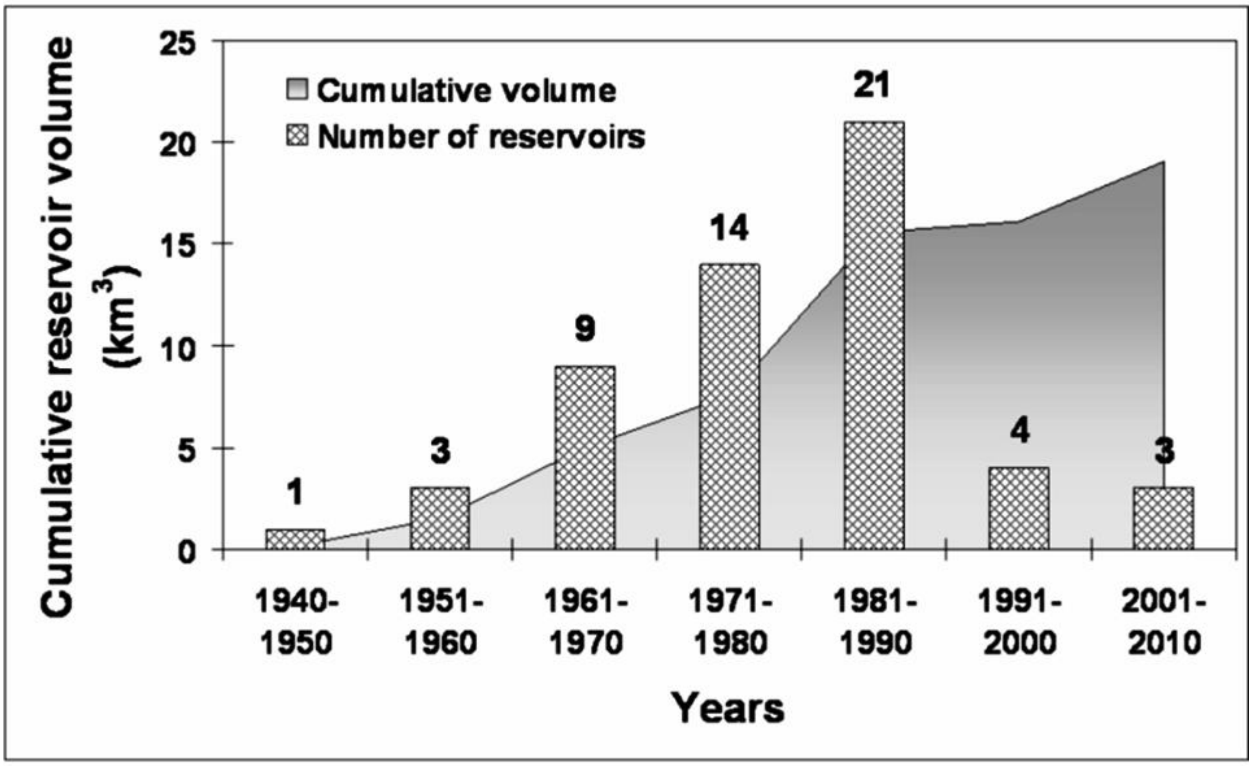
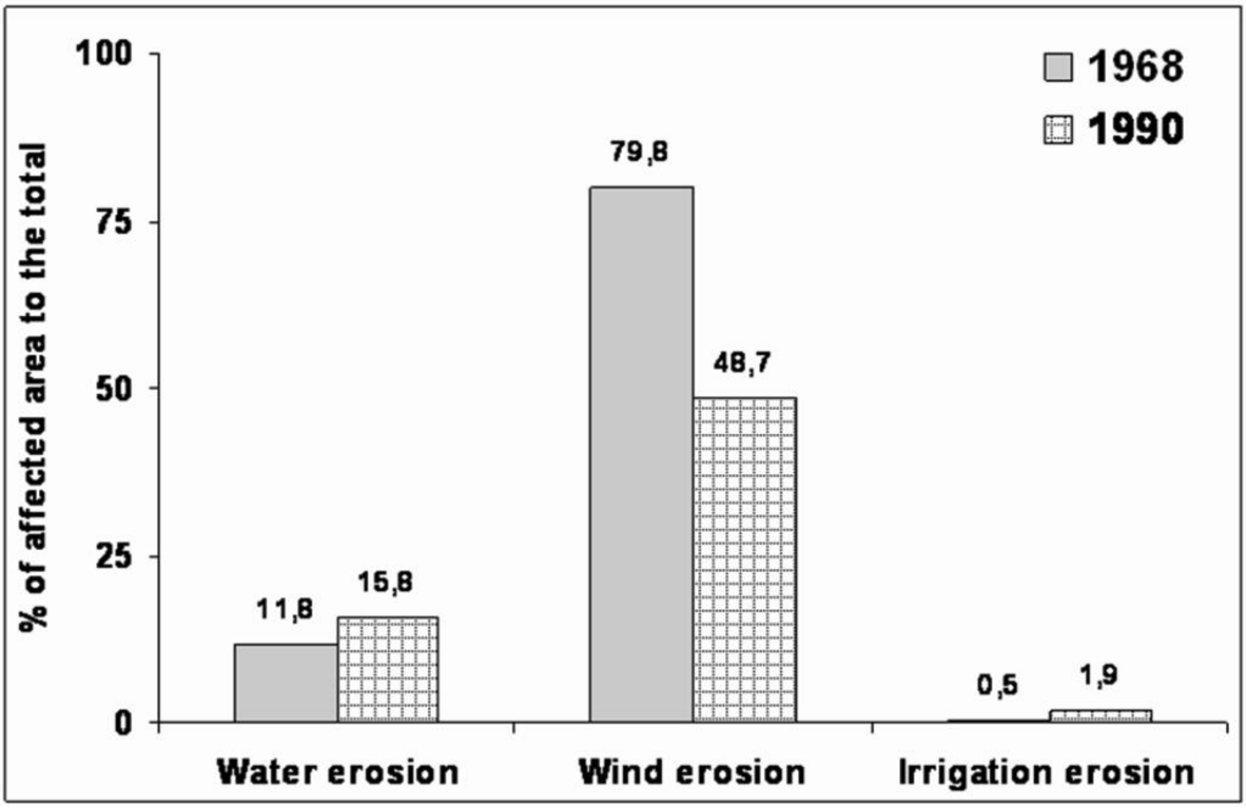

Cumulative volume
Number of reservoirs
Cumulative reservoir volume (km$^3$)
25
20
15
10
5
0
1
3
9
14
21
4
3
1940-1950
1951-1960
1961-1970
1971-1980
1981-1990
1991-2000
2001-2010
Years

Fig. 7.


1968
1990
% of affected area to the total
100
75
50
25
0
11,8
15,8
79,8
48,7
0,5
1,9
Water erosion
Wind erosion
Irrigation erosion

*Book chapter for NOVA Science Publishers*

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*Chapter 4*

# SUSTAINABLE IRRIGATED AGRICULTURAL PRODUCTION OF COUNTRIES IN ECONOMIC TRANSITION: CHALLENGES AND OPPORTUNITIES (A CASE STUDY OF UZBEKISTAN, CENTRAL ASIA)

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## ABSTRACT

For the fulfillment of the thirsty ambition of self-sufficiency of the Soviets for cotton production, the arid Central Asian region, particularly, Uzbekistan has been extensively exploited. In fact, vast tracts of deserts have been converted into irrigated agricultural lands without proper consideration of the environment and technical standards. As a result, trends in natural resource degradation (soil salinity, desertification, water quality) as well as declining crop yields have dramatically increased.

The agricultural sector is the backbone for employment, food security and export revenues of the Central Asian countries. Since the independence of the Central Asian countries (after the breakup of the former Soviet Union), the situation has changed dramatically in terms of institutional, political and technical systems. Political transition, which is defined as a shift from a once planned centralized economy to a market-driven one, has introduced 'new' concepts like land tenure, water rights and different kinds of ownership. All such transformations have impacted the agricultural production in Central Asia.

The institutional change can be described as decentralization of the farming systems, i.e. transition from the former state collective farms into the smaller forms of private farms. The institutional interventions are aimed to increase agricultural production through improving water management. It is arguable that private production systems are the most effective business-driven forces but the situation is quite different in Central Asia due to the irrigated agriculture.

The biggest challenge for a sustainable irrigated agricultural production lies in the recent reforms of the water management sector in Central Asia and Uzbekistan. Water users' associations have been established to replace the former collective farming systems for irrigation water distribution and maintenance of irrigation infrastructures at the on-farm level. The intention of the national government was to shift the operation, maintenance and management of irrigation infrastructures to non governmental institutions (decentralization). However, these institutions have not fulfilled their promising tasks because of i) a rapid increase in the number of private farms along canals; ii) the cropping structure which is a mosaic with different crop water requirements compared to the former monoculture; iii) poor financial, training and technical capacities of the newly established institutions; iv) a state-ordered agricultural production quota system (for cotton and wheat).

This paper analyzes the historical aspects of the transformation in the farming production institutions in Central Asia with a special focus on Uzbekistan and comprehensively overviews the main current challenges facing the farming system and potential opportunities for reversing the situation.

**Keywords**: irrigated agriculture; water users' associations; agricultural water management; soil and water pollution; cotton production; Central Asia

# 1. INTRODUCTION

After the fundamental and extremely fast political transformation of the Central Asian (CA) region (collapse of the Former Soviet Union and emergence of National States), the land-locked arid countries of Central Asia (Kazakhstan, Tajikistan, Kyrgyzstan, Uzbekistan and Turkmenistan) have directed their natural resources utilization for the economic development from a previously central-planned economic system to a market-oriented one. The once interconnected branches of economies in Central Asia have become fragmented and collapsed (UNEP, 2005). Many thousands of jobs have been destroyed. Business and industry sectors with rich oil and gas reserves have shown their flexibility under a new transformation process but the most impacted was agriculture.

In this hard period, agriculture has played a vital role for absorbing employment of rural populations. Kandiyoti (1999) describes the agricultural sector as being a “shock absorber” for the surplus of rural labor. In fact, in the CA region, agriculture employs about 45% of the total population and its share in GDP (Gross National Product) is 24% on average (FAO, 2009). Some 22 million people depend directly or indirectly on irrigated agriculture in these countries (World Bank, 2003). Besides, the export of cotton contributes to significant foreign cash revenues for Tajikistan, Turkmenistan and Uzbekistan. Sustainability of irrigated agriculture is one of the main platforms for food security, employment, livelihoods and environmental protection.

With the independence of the CA countries, the situation has changed dramatically in terms of institutional, political and technical systems (IAMO, 2008). Political transition from a once planned centralized economy to a market-driven one has introduced ‘new’ concepts like land tenure, water rights and different kinds of ownership. Institutional reforms have been implemented for arrangements of previously state-owned collective farms into a new private form of farming system. Ideally the de-centralization of farming systems should have created new opportunities for rural people. Indeed the fast privatization of agricultural lands has created thousands of workplaces with the complete privatization of agricultural parcels in Kyrgyzstan and long-term leases in the rest of the Central Asian states (Sehring, 2008).

The reform of agriculture was inevitable in the process of political and economic transformation. The private form of farming system would be better and contribute to agricultural production and, as a result, to tax returns for governments. The climatic conditions and limited water resources of the region impose the practice of irrigated agriculture only, which makes irrigation water supply and management the major factors limiting crop yields in the region (Ibragimov et al., 2007).

About 7.9 million ha of the total irrigated lands in Central Asia, of which about half (4.2 million ha) is irrigated, is in Uzbekistan (World Bank, 2005). Over a period of 90 years (1913–2003) the areas under irrigation have increased by 3 times on average in the CA region, e.g., from 4.51 million ha in 1960 to 6.92 million ha in 1980 and to 7.85 million ha in 2000 (UNEP, 2005; Sattarov et al., 2006). This increase was due to a gigantic Soviet hydraulic program through the construction of dams, irrigation canals, pumping stations and various hydraulic facilities. This hydraulic infrastructure is considered as one of the most complex in the world (O'Hara, 2000; Ximing et al., 2000; UNDP, 2007).

Additionally there has been a general warming up in the CA countries on the order of 1–2$^{0}$C since the beginning of the 20th century that might have a strong impact on the regional temperatures and precipitation regime but also on natural ecosystems and agricultural crops (Lioubimtseva et al., 2005).

From a technical point of view the major bulk of hydraulic infrastructure (irrigation and drainage) are in poor conditions and government financial programs for the maintenance have been substantially reduced (UNESCO, 2000; Sokolov, 2006; UNDP, 2007).

The aim of this paper is to comprehensively review the two sets of problems that most impact the sustainability of irrigated agricultural production systems in Central Asia with special focus on Uzbekistan. The first set of problems is reforms in agricultural production systems (de-collectivization), i.e. transformation of a former collective farming into current private farming systems. The second set of problems is the on-farm irrigation water distribution and infrastructure management by recently created local institutions such as the Water Users Associations (WUA).

Along with de-centralization in agriculture, water management system was also transformed in Uzbekistan at two levels (Abdullaev et al., 2008). In this paper we will deal with only irrigation water management at the on-farm level. The irrigation water management was transformed from once a territorial-based management to a hydrographic principle at the basin level. The second level is the creation of WUA at the on-farm level. A WUA is a self-managing group of farmers working together to operate and maintain their irrigation and drainage network (only inter-farm or on-farm level) to ensure a fair and equitable water distribution and increase crop yields (Abdullaev et al., 2009; Kazbekov et al., 2009).

At the watershed level main the irrigation water distribution management and hydraulic infrastructure were left for the government for operation and maintenance. At the on-farm level (secondary and tertiary) irrigation canals were shifted to WUAs. However, these institutions have not fulfilled their promising tasks because of i) a rapid increase of the number of private farms instead of a few former collective ones along a single irrigation canal; ii) along a irrigation canal the cropping structure is a mosaic with different crop water requirements, irrigation regimes in comparison to the former monocultural cropping structure; iii) a poor financial, capacity building and technical capabilities of the new established institutions; iv) a state ordered agricultural production quota system (for cotton and wheat).

Last but not least there are environmental concerns such as land degradation (elevated land salinity and waterlogging) of irrigated lands. Poor incentives of farmers to preserve the irrigation water, physical deterioration of the irrigation and drainage networks exacerbate the sustainability of irrigated agriculture. As a result the crop yields have declined by 50 percent (UNESCO, 2000). The continued soil degradation would jeopardize the sustainability of irrigated agriculture and impact the livelihoods of million people.

## 2. UZBEKISTAN

Uzbekistan is located in the heart of Central Asia with a population over 27 million and borders with Kazakhstan in the north, Kyrgyzstan in the north-east, Tajikistan in the east, Afghanistan in the south and Turkmenistan in the south west (Figure1). Administratively, Uzbekistan is divided into 12 provinces (viloyat) and one autonomous Republic of Karakalpakstan. The deserts (Kara Kum and Kyzyl Kum) and plains (Turan and Ustyurt) stretch from south-east to north-west and constitute roughly 80% of the landscape, the mountain systems of western Tian Shan and Pamir Alay occupying the rest of its territory (Shultz, 1949; Irrigation of Uzbekistan, 1979).

The average monthly air temperature for January ranges from $+3^0$C in the south (Termez) to $-8^0$C in the north (Usyurt plateau) and in the summer temperatures can reach $45\text{-}49^0$C. The average annual precipitation in the desert zone is less than 200 mm while in the piedmont and highland zones it can be of 400-800 mm with a maximum of 2000 mm in the mountain areas (Goskompriroda of Uzbekistan, 2005; UNDP, 2007). The annual average evaporation is about 1600-2200 mm. Thus agricultural production is impossible without irrigation.

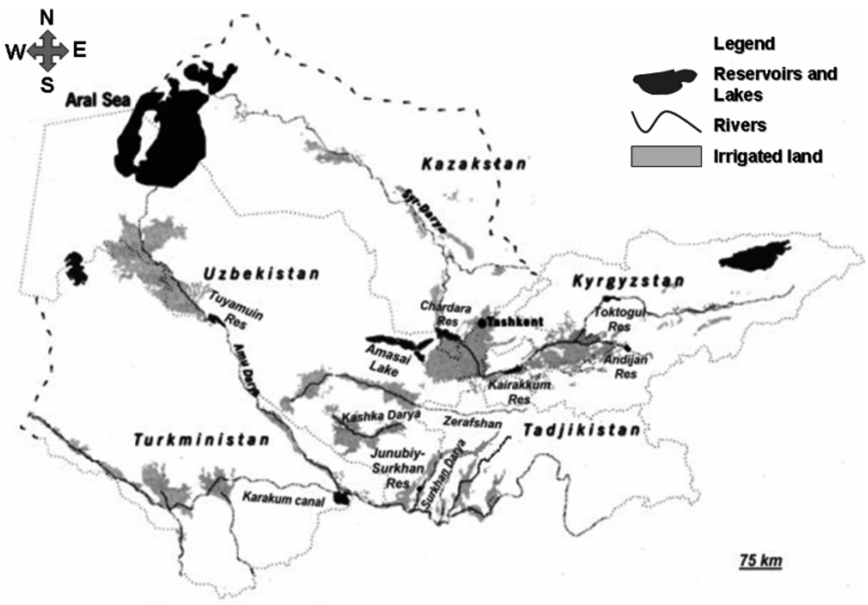


Figure 1. Location of Uzbekistan and Central Asia

## 2.1. Water Resources

With an annual rainfall of 100–300 mm and a mean evaporation of 1600-2200 mm, Uzbekistan has a continental climate of a dry mid-latitude desert, characterized by hot summers and cold winters (Shultz, 1949; FAO, 2009). Its climate is largely arid and its water resources are unevenly distributed both in space and time. There is a strong dependency on winter and spring rains and snowmelt from the Tian Shan and Pamir mountains. In fact these mountains are major contributors to the watersheds of the CA countries (World Bank, 2005; Hagg et al., 2007).

The streamflow is characterized by an extreme intra-annual variability and also unevenly spatially distributed (Rakhmatullaev et al., 2009). Two main river basins are found in Uzbekistan, the Amu Darya and the Syr Darya (Dukhovny, 2007). These transboundary rivers satisfy 82% of the total water demand for irrigation, whereas only 18% of the same demand is satisfied by the internal Kashka Darya, Zerafshan and Surkhan Darya rivers in Uzbekistan (Figure 1) (Shultz, 1949; Nezlin et al., 2004). Uzbekistan heavily depends on transboundary sources of water and on average only 9.52km$^3$ of water resources are generated within the country whereas 94.8km$^3$ comes from outside (Statistics Committee of Uzbekistan, 2006; Rakhmatullaev et al., 2009).

## 2.2. Soils

The soils of Uzbekistan vary according to the latitude and altitude zones which in turn are associated with particular climatic conditions and vegetation cover (Figure2 and Table1). Due to climatic conditions and aridity about 14.6 million ha (32% of all soil types) are represented by desert type of soils (grey-brownish desert, sandy and takyr with their subtypes). These soils cannot be used for irrigation because of their inherited characteristics, available water resources for irrigation, salinization and harsh relief; they are instead mainly used for cattle breeding of camels and sheep (Talipov, 1992).

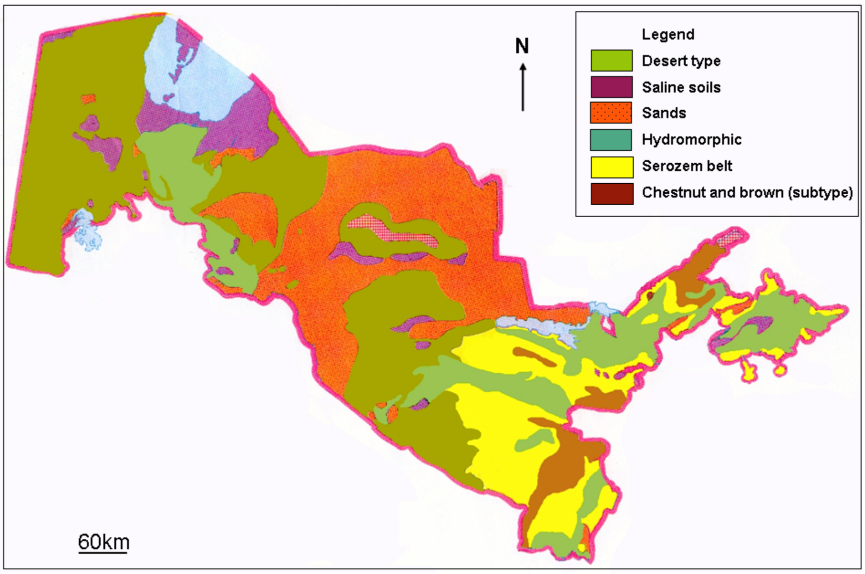


Figure 2. Soil map of Uzbekistan

Saline soils (solonchak and their subtypes) are distributed in Karakalpakstan and near the Aral Sea area and occupy about 1.3 million of ha (3%) and prevail in the local depressions located in lowland plains, lake basins and between mountains (UNDP, 2007). With appropriate irrigation and drainage systems, they can be used for agriculture. Sands cover more than 12 million of ha (about 28% of the total surface) in Uzbekistan and are unsuitable for agriculture. About a total 63% of soils (out of total of 44.89 million of ha) in Uzbekistan cannot be used for irrigation due to their inherited soil characteristics, available irrigation and drainage facilities.

**Table 1. Soil type distribution in Uzbekistan (Talipov, 1992)**

| Soil type | Area Million ha | % of area occupied to the total | Altitude (above sea level) m |
|---|---|---|---|
| | Plain zone | | |
| Grey-brown desert | 11.5 | 25 | 150-250 |
| Sandy | 1.37 | 3 | 120-150 |
| Takyr | 1.78 | 4 | 120-180 |
| Meadow-takyr | 0.47 | 1 | 120-150 |
| Meadow and wetland-meadow | 1.85 | 4 | 80-100 |
| Solonchak | 1.27 | 3 | 80-100 |
| Sands | 12.1 | 28 | 120-150 |
| | Piedmont and mountain zone | | |
| Light serozem | 2.59 | 6 | 250-500 |
| Typical zerozem | 3.05 | 7 | 500-700 |
| Dark serozem | 1.06 | 2 | 750-1200 |
| Brown and brownish middle-altitude | 1.66 | 4 | 1200-2800 |
| Light brownish high-altitude | 0.54 | 1 | 2800-3500 |
| Meadow-serozem | 0.78 | 2 | 250-500 |
| Meadow and wetland-meadow | 0.75 | 2 | 250-500 |
| Rock | 3.0 | 6 | - |
| Water surface | 1.12 | 2 | - |
| Total | 44.89 | 100 | |

The hydromorphic soils (meadow, meadow-takyr and their subtypes) are distributed over 3.8 million ha (9% of the total surface) in all regions of Uzbekistan but can be found particularly in the middle and lower river reaches of Amu Darya, Syr Darya, Zerafshan, Kashka Darya, Surkhan Darya, and in the Aral Sea wetlands. These soils have a high humus content of 2.5-10% with high absorption capacity and used widely for rice cultivation (Goskompriroda of Uzbekistan, 2005).

The soils of the serozem belt (light, typical and dark) are distributed over 6.7 million ha (15%) on the lower margin of the piedmont plains with an altitude of 200 to 700-900 m above sea level. These soil types have a high humus content (2-4%) and are less subject to salinization and can be used for rain-fed and irrigated agriculture. With the application of agronomic measures (e.g. fertilizers and conservation tillage) these soils can be used more productively for agriculture (Statistics Committee of Uzbekistan, 2006).

About 2% of the land surface in Uzbekistan is occupied with water bodies (reservoirs, lakes, rivers) and 6% by rocks. About 5% of the land (2.2 million ha) are represented by chestnut, brown and light brown soil types in mountains in altitude from 1200 to 1600 m above the sea level and subjected to erosion. The main usages of these soils are plantation of trees and pastures (UNEP, 2005).

## 2.3. Irrigated Agriculture and Cotton Production

The total cultivated land in Uzbekistan is estimated to be 5.2 million of ha, of which 4.2 million ha are irrigated (UNESCO, 2000). Figure3 depicts the evolution of the irrigated lands in Uzbekistan for the last century. The irrigated lands almost increased by 3 fold over the last century: about 1.3 million ha in 1900, 2.6 million ha in 1950 and 4.2 million in 2000 (UNEP, 2005). However, Uzbekistan has witnessed a population boom; in fact there was an increase of 4 fold of the total population i.e. from 6.5 million in 1940 to over 26 million in 2007. As a result, the irrigated lands per capita reduced from 0.41 ha/person in 1940 to only 0.16 ha/person in 2008 (UNDP, 2009) (Table2).

Figure 3. Evolution of irrigated lands in Uzbekistan for the last century

**Table 2. Population and per capita irrigated lands transformation in Uzbekistan for the last century (Talipov, 1992; UNDP, 2009)**

| Year | Total Population (‘000 persons) | Per capita irrigated land (ha/person) |
|---|---|---|
| 1940 | 6551 | 0.41 |
| 1960 | 8722 | 0.30 |
| 1970 | 11799 | 0.22 |
| 1980 | 16158 | 0.20 |
| 1990 | 19906 | 0.19 |
| 2000 | 24487 | 0.17 |
| 2007 | 26663 | 0.16 |

This expansion is supported by the complex irrigation hydraulic infrastructure consisting of more than 14,000 different scale pumping stations, over 28,300 km of inter-farm ditches and main irrigation canals and more than 137,000 km of on-farm irrigation ditches, 42 water diversion structures (with a capacity of 10-300 $m^3$/sec), 55 water reservoirs and about 30,000 km of drainage systems (Royal Haskoning, 2001) (Table3).

**Table 3. Irrigation network of Uzbekistan (Royal Haskoning, 2001; UNDP, 2007)**

| Hydraulic structures | Location in the system | Unit |
|---|---|---|
| Irrigation canal | Main | 7923 km |
| | Inter-farm | 20 437 km |
| | On-farm (include) | 137 385 km |
| | Concrete lined | 12 103 km |
| | Chute | 21 668 km |
| | Conduit | 3308 km |
| Pumping station | Inter-farm | 1466 pieces |
| | On-farm | 12 780 pieces |
| Drainage system | Inter-farm | 29 939 km |
| | On-farm (include) | |
| | Open | 106 321 km |
| | Closed | 30 242 km |
| | Vertical drainage wells | 4309 pieces |
| Irrigation well | | 5022 pieces |
| Water reservoir | | 55 pieces |
| Water intake | | 42 pieces |

In order to increase the area under agricultural production, large scale hydraulic projects were started in soviet Uzbekistan. For example, in 1939 during 17 days, an irrigation canal named Lyagan with a total length of 32 km was manually dug with the daily participation of more than 13 000 – 14 000 persons (Talipov, 1992). The Big Ferghana irrigation canal which stretches over 270 km was dug in less than 45 days with the assistance of 160 000 persons (Rakhmatullaev et al., 2003).

In later periods, there have been gigantic projects to construct irrigation canals, water reservoirs, pumping stations and other hydraulic structures with a strong support from Moscow by enormous financial and technical resources. However, environmental concerns were ignored by the centralized Moscow administration and today several known ecological catastrophes such as the Aral Sea catastrophe are witnessed. The detailed discussion on the historical evolution of irrigation in Central Asia can be found in O'Hara (2000).

Talipov (1992) reports that the Soviet Union imported about 80% of its cotton products in 1920s and in order to be self-sufficient for its textile industry by internal cotton production, the Central Asian region was used as a cotton producing platform. The area sown under the cotton increased by 7.5 fold from 1924 to 1990. Figure4 depicts the evolution of area sown under cotton and its yield in Uzbekistan for the last century. For example, in 1913 the area sown under cotton constituted roughly 35% (out of total sown area) whereas at the end of 1990, it accounted to more than 56%. The area under cereals was reduced from 48% (out of total sown area) in 1913 to only 13% in 1990.

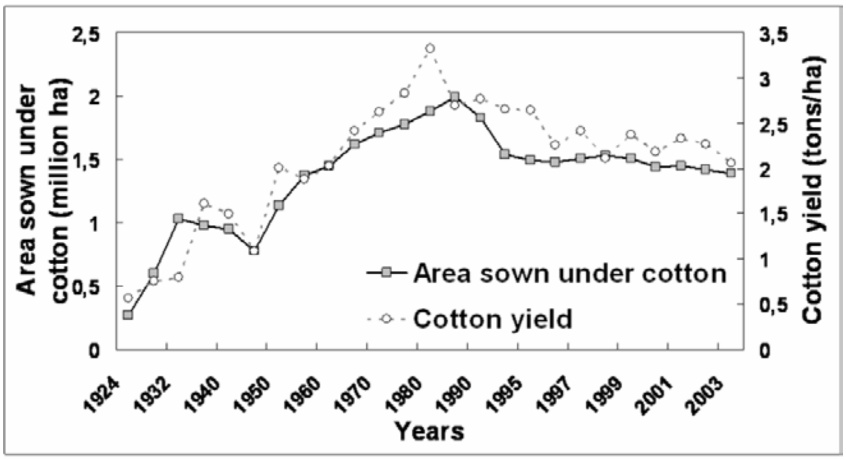

Figure 4. Area sown under cotton and its yield for the last century in Uzbekistan

The operation and maintenance of this complex hydraulic infrastructure was supported by the central Soviet administration. After the breakup of the Soviet Union, the financial flows have ceased substantially for rehabilitation works. For example, over a 10-year span (1991-2001) the government investment portfolio for irrigation infrastructure rehabilitation has decreased from 27% to 8% and the capital investment for construction to the water sector was reduced by 5 times (UNDP, 2007).

This reduction in the investment portfolio has further worsened the operation and maintenance of the existing infrastructure and everlasting increase of electricity prices. The increase for electricity costs have ramifications for the sustainability of irrigation infrastructure because as early mentioned about half of total irrigated lands (2.2 million ha) in Uzbekistan are operated via various lift and diversion facilities. Indeed about 80% of the total Ministry of Agriculture and Water Resources of the Republic of Uzbekistan budget is devoted to electricity costs for the operation of lift infrastructure.

## 2.4. Irrigated Land Quality Classification System

An irrigated land quality classification system in Uzbekistan is termed as *bonitet*.[1] Bonitet Score reflects the soils potential productivity (i.e. yield potential of cotton) based on inherent fertility and quality (Noble et al., 2005). It is expressed as a score on the scale of 1 to 100 (Table4). Assessment of irrigated land quality is conducted over every 10 year span in Uzbekistan.

**Table 4. Land quality classification in Uzbekistan**

| Classes | Description | Bonitet Score |
|---|---|---|
| 10 | Best | 91-100 |
| 9 | Best | 81-90 |
| 8 | Good | 71-80 |
| 7 | Good | 61-70 |
| 6 | Average | 51-60 |
| 5 | Average | 41-50 |
| 4 | Below average | 31-40 |
| 3 | Below average | 21-30 |
| 2 | Bad | 11-20 |
| 1 | Bad | 0-10 |

[1] Bonitet is used by Government officials to classify land into classes based on their potential productivity and quality to set annual production targets for a farm.

This assessment system is based on the relationship between indicators and characteristics of soils such as the humus content, soil texture, salinity level and erosivity with its productivity. The generalized characteristics of the irrigated land quality is quantified by a relative quantity values-bonitet score (Talipov, 1992; Shadibaev, 2009). The bonitet score is conducted relatively to a cotton yield of the best soil quality in Uzbekistan, (e.g. cotton yield of 0.04 tons per 1 bonitet score and wheat yield of 0.06 tons per 1 bonitet score). Thus, the classes 1-4 are lands that need amelioration and remedial actions for improving the soils.

The recent official average value of the bonitet score for Uzbekistan is estimated to be 55. However the actual value is estimated to be 52-53. Figure5 depicts the evolution of the bonitet score for Uzbekistan. The bonitet score decreased from 60 in the 1970s to 52 in 2000s. As the principle of bonitet classification system was designed to estimate the cotton yield from the field plot. The bonitet score is still used a major indicator for potential crop yields of an agricultural land plot and thus lands with higher bonitet score are more attractive for farmers.

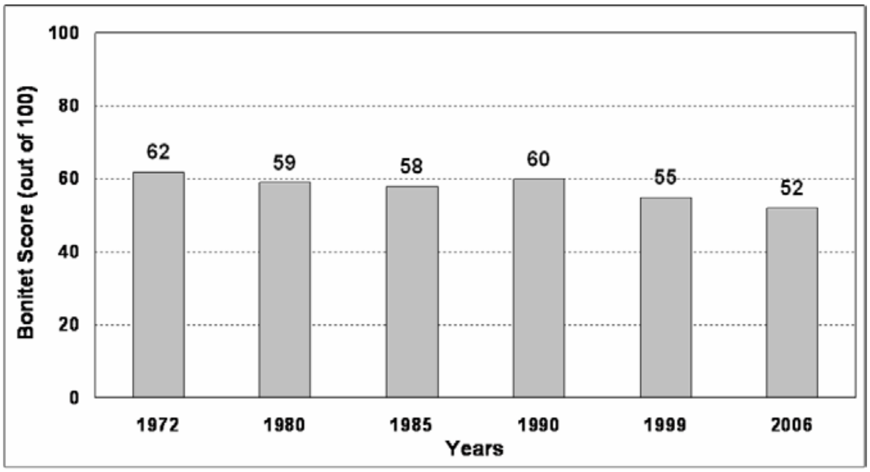


Figure 5. Institutional water management hierarchy in Uzbekistan

## 3. Environmental Threats

According to UNESCO (2000) the average percent of irrigated land affected by salinization in Central Asian region is about 23% with a range of in the low 6% in Kyrgyzstan and in the high 50% in Uzbekistan. In addition, the groundwater table has increased and the area of irrigated land with high groundwater levels (less than 2 meters below the surface) exceeds 30% of the total irrigated land in the region (Toderich et al., 2008).

Sustainability of irrigated agriculture in Uzbekistan is threatened by the salinization of land and water resources (Tookey, 2007). The land and water quality degradation is observed as a result of the excess water withdrawal over the actual crop requirements that impact the crop yields, decreased aggregate national income and affect the livelihoods of population (Murray-Rust et al., 2003).

These problems are the result of seepage from unlined canals, inadequate provision of surface and subsurface drainage and poor water management. Approximately, half of the irrigated area falls under different types of salt-affected soils and average yield of cotton losses may be as high as 50 percent. The annual economic losses due to land salinity and its abandonment are estimated to be more than US$43 million in Uzbekistan (World Bank, 2003; UNDP, 2007). Though the loss of crop production due to soil salinization is important, salinized land is generally still cultivated since no alternatives are available at the present time.

## 4. Institutional Management

There have been various main transformations in agricultural production system through primitive nomadic agricultural practices to the sophisticated and heavy mechanized agricultural production in the Central Asia region. Table5 depicts the major transformation phases in agricultural farming systems in Uzbekistan for the last century.

**Table 5. Typology of farming systems in Uzbekistan**

| Period | Type of farming system | Ownership | Command area (ha) |
|---|---|---|---|
| Prior 1900’s | Nomadic | Private | various |
| 1920-1940 | Kolkhoz | State cooperative farm | 10 000-20 000 |
| 1940-1980 | Sovkhoz | State farm | Up to 100 000 |
| 1990-2006 | Shirkat | Semi-Cooperative farm | 1500 - 2000 |
| 2005-present | Fermer | Private farm | 20 |

| | | | |
|---|---|---|---|
| 2000-present | Dekhkan | Individual farm | 1 |

## 4.1. Ancient Period

The earliest material evidence of irrigated agriculture is dated to the sixth millennium BC, in the simplest form of liman (flood-land) farming (Mukhamedjanov, 1978). The evidence also demonstrates a shift from simple use of water resources to increased regulation of seasonal river flows though melioration of individual plots, diverting surplus water and cleaning silt from riverbeds. This allowed increasing the area under irrigation.

In the latter part of the VII century when the region came under Arab control, extensive and sophisticated irrigation networks were constructed which could deliver water for many kilometres from its source to the irrigated lands (Irrigation of Uzbekistan, 1979; Mukhamedjanov, 1978; O'Hara, 2000; Rakhmatullaev et al., 2003). In this period, the world famous remnants of civilization such as Samarkand, Bukhara, Khiva, and Kokand (Uzbekistan), Merv (Turkmenistan) have emerged.

There were three *khanates* (kingdoms) – Kokand, Khiva and Bukhara from the XIII to late the XIX centuries in the territory of modern Uzbekistan. The Figure6 depicts the hierarchy over water management in ancient times in Uzbekistan.

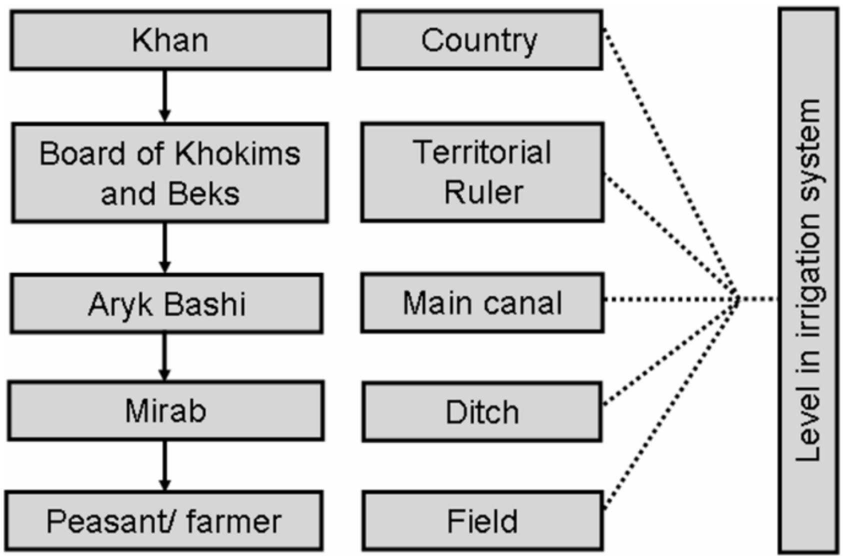

Figure 6. Hashar working for the cleaning of an irrigation canal in ancient Khorezm (Irrigation of Uzbekistan, 1979)

The *khan* (king) was in the head of the water delivery hierarchy. Each of them had a board of *khokim* and *bek*, local rulers who were appointed by the khan. Each administrative territory was managed by a khokim or bek. Each khokim or bek had appointed *aryk bashi* on the main irrigation canal. The aryk bashi is a person who reported on the water level in main irrigation canal and decided what water intake gates to be opened or closed (Mukhamedjanov, 1978; O'Hara, 2000). On the level of irrigation ditches, a *mirab* was responsible for water allocation and operation of irrigation ditches. The mirab was elected by local people in general and local farmers from respected persons within the community for water allocation and distribution. The *dekhkans,* peasant farmers, were the end users of the irrigation water (Rakhmatullaev et al., 2003).

The land belonged to the khan and the dekhkans had a long term rent for their plots. The size of the land rented to dekhkans depended on the family size. The tax or rent payment was in the form of raw materials, mainly quarter part of the grain harvest. The average assessment fee was 1/10 of the harvest and it usually went to the mirab. However, the payment was never a consistent percentage of the crop, as the farmer paid depending on how satisfied he was with the job that the mirab was doing (Irrigation of Uzbekistan, 1979; O'Hara, 2000). Then the mirab estimated the needed amount of water and paid for the water to the arik bashi. Therefore, the mirabs and dekhkans had no interest in taking any extra amount water that exceeded their needs (Muhamedjanov, 1978).

The dekhkans were free to move to other kingdoms. Therefore, more dekhkans in the kingdom was in the direct interest of each khan. In VI and VII centuries, the region experienced the economical growth in the routine of the Great Silk Road. The taxation system was organized in a very smart way, i.e., one-fourth of the harvest was taxed whatever the dekhkans grow (Rakhmatullaev et al., 2003). This system was successful because the dekhkans decided what to grow. Usually the agricultural production was market driven. Alternatively, whatever agricultural goods were expensive and needed in the local markets (bazaar), the favor was given to those crops in a given year. Therefore, the state's policy was dependent on market concepts.

For the maintenance and rehabilitation works of the existing irrigation canals and construction of new hydraulic infrastructure the *hashar* was practiced in the region (Figure 7). Hashar is the action that pulls community to accomplish maintenance, rehabilitation and construction works on a voluntary basis in Uzbekistan. This form of actions still widely practiced in Uzbekistan. The hashar accomplished two things. First, it acts as a mobilization mechanism for labour input and material resources within community. Second it was a mean of maintenance of the infrastructures (O'Hara, 2000; Rakhmatullaev et al., 2003).

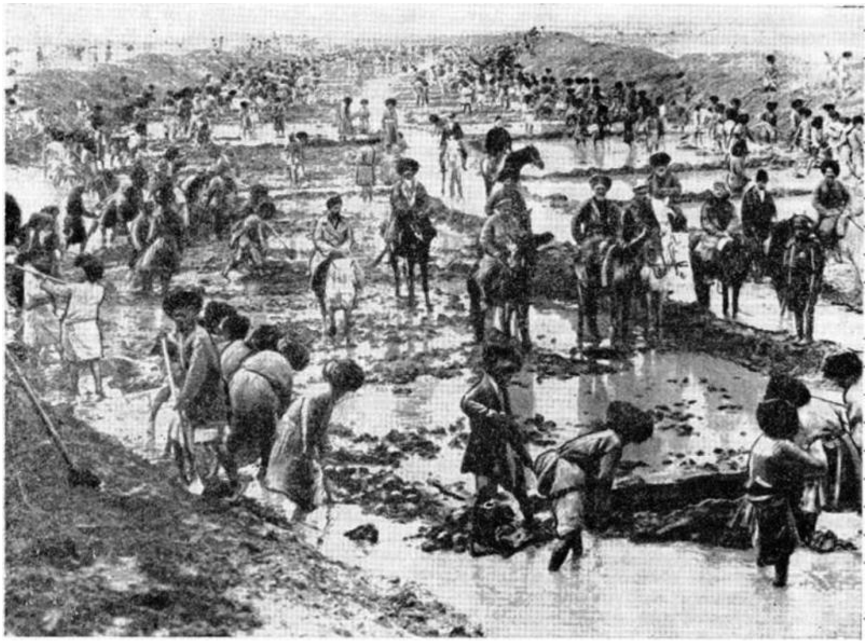

Figure 7. Hashar work for cleaning irrigation canal in ancient Khorezm (Irrigation of Uzbekistan, 1979).

For example, for the construction or rehabilitation of irrigation canals, mirabs or aryk bashi called for hashar works. Each village had to mobilize their labor force for hashar. Villages at the upstream of the irrigation canal who would expect to receive more and cleaner water were expected to contribute more in terms of time and resources. Hashar was obligatory to all water users to take part in this annual maintenance works. Individuals who refused to participate were fined or denied access to water. Thus, "hashar was a system that linked benefits to duty" (O'Hara, 2000).

Prior to be part of the former Soviet Union, Uzbekistan came under Tsarist control after the invasion of Russia. With the new administration, irrigation reforms were attempted to be introduced. However, these reforms failed because of many appointed irrigation officials were unaccustomed to the traditional methods of management and the authorities declared that irrigation would be run “by custom” (Thurman, 1999).

## 4.2. Soviet Period

There have been two main types of farming systems in the former Soviet Union *kholkhoz* [2] (cooperative farm) and *sovkhoz* (state farm). The principal difference between these two forms of ownership was that a sovkhoz was a state enterprise whose workers were employed at fixed wages. By contrast, a kolkhoz paid its workers from its own annual earnings (Yalchin and Mollinga, 2007). According to Talipov (1992) by 1940 the collectivization of the former private farms (around 800,000 farms) into collective farming systems (kolkhoz) was accomplished through the establishment of 7629 kolkhoz. However, by the end 1990’s the proportion of sovkhoz has been increased due to the fact that sovkhoz was considered as a more socialist production entity in contrast to the cooperative ownership of kolkhoz. As a result, by the end of 1990’s only 9.5% and 63% of the total agricultural lands were managed by kolkhoz and sovkhoz respectively.

The kolkhoz type was mainly specialized in the production of cotton, fruits and vegetables, tobacco and other (lemon and fishery). On the other hand, the sovkhoz was specialized in the production of husbandry, poultry, vineyards, rice, wheat, cotton and others. In 1991, the total number of kolkhoz was 941 with a total irrigated area of 1.5 million ha whereas the total number of sovkhoz was 1017 with a total irrigated area of 2.1 million ha (Talipov, 1992).

In order to increase the agricultural production, the soviets implemented various progressive measures such as mechanization, agronomic practices, development of irrigation infrastructure. As all kolkhoz and sovkhoz were specialized in the production of certain agricultural product, a central management body compromising with trained irrigation engineers,

2 Kolkhoz (Russian). A large collective farm comprises several agricultural experts and farm laborers responsible for agricultural production and delivery targeted outputs for cotton and wheat to the government. A typical area under management of kolkhoz ranges in size from 10,000 to 20,000 ha (Noble et al., 2005).

agronomists, veterinarians and other professionals was put into place. Irrigation water distribution was carried out by professionals and much of subsidies were granted for collective farms. However, the processing and manufacture aspects of agricultural produce were neglected in favor of inter-republic trade in the soviet times (Yalchin and Mollinga, 2007).

### 4.3. Post-Independence Period

Since the independence of Uzbekistan the situation has changed dramatically in terms of institutional, political and technical systems (Veldwisch, 2007). Political transition from a planned economy to market has introduced "new" concepts like land tenure, water rights and different kinds of ownership (Morgounov and Zuidema, 2001; Yakubov and Ul Hassan, 2007).

In 1990, the former collective farms were transformed to collective family farming units called *shirkat*. The shirkat is a collective farm which pays a fixed monthly salary and supplementary dividends from its annual profits for its workers (Yalchin and Mollinga, 2007). The organizational management of the shirkat was similar to the former kolkhoz system with significant difference in contract arrangements for crop production. The shirkat has a single management unit comprising of a head, professionals (engineer, agronomist, accountant and etc). The shirkat contracts several brigades (working units) for agricultural production on annual basis for meeting state quota for cotton and wheat yields. In addition, every year the workers would sign a contract with the shirkat management for leasing a plot with his/her state quota for cotton and wheat.

As the shirkat farming system has shown its inefficiency, private farm system (*fermer* and *dekhkan*) has been advocated. The main difference between the two types of farming systems is that fermer farms have contract with the central government to meet the targeted cotton and wheat production whereas dekhkan farms do not have such contracts for meeting the targeted cotton and wheat crop production and only produce for meeting their own needs. This is true for only cotton and wheat productions (Yakubov and Mathrithilake, 2009).

*Fermer* is a private farm, successor of kolkhoz and responsible for the targeted production of cotton and wheat to the government. The fermer can lease the plot in size ranging from a minimum of 10 ha to several hundred ha, with an average size of approximately 20 ha (as of 2000). These fermer farms have flexibility in the hiring of labor and access to other subsidized inputs from government (such as fertilizers, lease of machinery and access to bank credits). According to the Ministry of Agriculture and Water Resources of the Republic of Uzbekistan (2009) as of 2009 there are about 220,000 fermer farms in Uzbekistan.

*Dekhkan* farmers have an average plot size of 0.12 ha and do not have the right to hire workers: only family members can work on the plots, which are given to the dekhkan farmers on a lifelong lease and can be passed on as inheritance to their children. There are more than 3.5 million dekhkans in Uzbekistan (UNDP, 2007). Those who are not employed by the new farms (fermer) are officially classified as dekhkan farmers, and work on the small plots allocated to them in the process of land distribution.

All agricultural land is still technically owned by the state and is not tradable or transferable. Leases of private farms (fermer and dekhkan) are in principle valid for a minimum of 10 and a maximum of 50 years. Fermer farms have often been subject to arbitrary decisions on the part of local authorities. For example, their land plots can be taken away and reallocated if they do not comply with local authorities' decisions about its use or have shown poor performance over targeted production of cotton and wheat.

The further reforms have been initiated in agricultural production system such as enlargement of fermer farm units in 2008 in Uzbekistan (MAWR of Uzbekistan, 2009). The main objective of recent reforms is to consolidate smaller poor performing fermer farms into efficient large fermer farms. Before this reform there were about 220 000 fermer farms in Uzbekistan with an average agricultural land of 27 ha per fermer farm whereas after the consolidation process the average size of fermer farm becomes 57 ha totaling of 104 000 fermer farms (MAWR Uzbekistan, 2009).

## 5. Current Challenges and Perspectives

The major current challenge facing irrigated agriculture in Central Asia and specifically in Uzbekistan is weak water management institutions, i.e., water users associations at the on-farm level. It is known that water management is a political process and important part of overall development policy of a given country (Abdullaev et al., 2009). Many international donor assistance programs have been launched and implemented for institutional interventions in water management in the region. However, interrelated aspects such as financial, technical and governance issues have been bottlenecked for proper progress of such interventions. Prior to discussion of

WUA challenges first the farmers current challenges will be discussed in regard to irrigated agriculture.

## 5.1. Challenges for Farmers

***Land Tenure***

As previously stated the agricultural lands are not privatized and technically owned by government in Uzbekistan. The farmers are interested in investing their resources for the amelioration of lands and improving the irrigation infrastructures in order to increase the agricultural production and their incomes. However, there is no guarantee that their lands can not be taken out and re-allocated to different farmers on arbitrary decisions of the local authorities. As a result, farmers fear to lose their invested capitals. In Uzbekistan, under the following conditions the farmer land can be taken away and re-allocated: 1) not meeting the targeted cotton and wheat state quota; 2) bankruptcy of farmers; 3) non transparent administrative procedures.

In addition, the farmers fear to invest their own financial resources because the re-allocation can only be carried out by state authorities and farmers cannot sell their land leases to other farmers in order to partially compensate already invested funds. In contracts between the state and farmers there is no clear identification of mutual rights for co-financing of irrigation infrastructures rehabilitation works. In addition, there are no incentives (reduction of state quota for cotton and wheat, tax returns) for farmers in cases of investing resources for rehabilitation of irrigation infrastructures.

***Cropping Structure***

The state quota for cotton and wheat is based on the bonitet scoring system in Uzbekistan as previously discussed. The main bottlenecked aspect is that the bonitet score was carried out in late 2000s and is now outdated. Most probably the current scores are higher because in most instances the ameliorative soil conditions have deteriorated to date and farmers cannot meet their targeted state quota which in turn is putting them into the high risk of losing their lands. For example, in a given land plot, previously prescribed bonitet score is used for the estimation of cotton and wheat yields. Local authorities are reluctant to the reduction of area sown under cotton and wheat, although farmer can meet the targeted yield on a smaller area with new fertilizer application or other innovative techniques. The local authorities fear that the decrease of cotton and wheat sown areas can be viewed from higher management hierarchy as non compliance to the common rules. In fact, there is a perception that by reducing the overall area prescribed for sowing cotton and wheat would result a lower crop harvest.

***Consulting/Extension Service***

After the fundamental transformation processes in Uzbekistan, the farmers are left without strong extension/consulting services either private or quasi-governmental. Many farmers are willing to pay for consultancies on new irrigation methods and technologies, cost-effective amelioration techniques, water conservation, legal aspects and marketing. However, there is no legislation for government or private extension and consultancies services in Uzbekistan. Thus the farmers are striving to overcome their current problems with old fashioned common known irrigation and agronomic techniques.

## 5.2. Challenges for Water Users Associations

A WUA is a self-managing group of farmers working together to operate and maintain their irrigation and drainage network (only inter-farm or on-farm level) to ensure fair and equitable water distribution and increase crop yields (Kazbekov et al., 2009). The WUA was established to replace the shirkat for on-farm irrigation infrastructure (canal and small water diversion facilities with gates) operation, maintenance and water distribution. According to the official statistics the total number of WUA is 1711 in Uzbekistan (MAWR of Uzbekistan, 2009). WUAs already serve around 3.6 million ha of land and 111,000 km of irrigation canals in Uzbekistan.

Most of these WUAs were established in the 2003–2006 period and now play an important role in the allocation and distribution of irrigation water, the collection of irrigation service fees and the maintenance of the irrigation infrastructure (Abdullaev et al., 2008). However due to the poor technical and financial capacities of farmer members of these institutions (WUA) and WUA itself is very limited institution for proper operation and maintenance of irrigation infrastructures.

***Territorial vs. Hydrographic***

The current WUA is established on the former kolkhoz territory, i.e., most of the WUA are organized on administrative territorial principle not the hydrographic. A farmer signs an annual contract for the irrigation water delivery with WUA in form of its annual membership fee. The geographic location of farmer's field parcel can force him/her to sign several contracts with different WUAs either because of administrative boundaries or several irrigation canals pass through that farmer's land plot. There are also positive aspects of such geographic location such as a guaranteed water supply but overall the farmer overpays his dues in comparison with the rest within the concerned area. The most complication arises for farmers located at the tail-end of the irrigation system, especially in dry years.

***Financial Incapacity***

Thus the WUA barely can support its limited personnel with monthly salaries from collecting membership fees from individual farmers. In addition, the most professional and trained specialists once worked at collective farms have left for other areas of employment such as business and trade. The current WUA does not have in terms of quantity and quality experts for consulting local farmers on irrigation regimes, cropping structure, appropriate water and agronomic practices and business planning.

WUA's budgetary resources are based on the individual farmers' membership fees. At the moment, each farmer signs an annual contract on irrigation water delivery with the WUA. However, the farmers cannot pay on a timely manner their respective membership fees to WUA because many of them can receive their earned money for cotton and wheat (state quota ordered crops) only from the previous harvest year. The state quota system on cotton and wheat has been designed in such a way that farmers on its obligation for meeting targeted harvest should produce and sell at government fixed prices. On the other hand, the government subsidizes the inputs (fertilizers, water) for farmers. The farmers can use the rest of low-cost fertilizers for producing other cash crops, fodder for husbandry practice and partially compensate their income earnings. The state quota system is put under critics by many scholars and experts for being an inefficient system for agricultural production.

Under Uzbekistan present conditions, the main detrimental factor of this system is not the monetary value of the purchased price of cotton and wheat by government but rather the complicated control of fiscal and financial system, i.e. substantial delays of getting money from banks. In addition, the farmers cannot use their earned funds for barter arrangements.

***Increase Number of Farmers***

With the de-collectivization of former soviet collective farms and the emergence of new private forms of farming systems there has been a rapid increase of the number of farms specialized in different cropping structures along a single irrigation canal. Thus each cropping system requires different irrigation application regimes. Many farmers favor to use only simple flooding irrigation methods instead of costly drip irrigation and other alternatives. Thus, WUA can hardly cope with the large number of farmers.

***Technical Aspects***

The most difficult aspect is the technical deterioration of existing irrigation infrastructures and improper allocation of funds for operation and maintenance works. There are widely non-existing or heavily deteriorated water measuring structures in place and thus it is extremely inconvenient for monitoring the right amounts of water. In fact, only nominal water measuring mechanisms are widely carried out for payments option of irrigation delivery service fees.

## 5.3. Perspectives

***Farmers***

The most practical and viable recommendations for individual farmers should be the regulation of legal arrangements defining the concrete and transparent mechanisms for the re-allocation procedure of land tenure rights from local government authorities. The most important is that the farmer should have a right to sell his/her land lease for another potential farmer in order to compensate his/her invested assets. Then farmers would be on the safe side and motivated to invest their own technical and financial resources for amelioration of lands and for rehabilitation and maintenance of irrigation infrastructures.

The second paramount aspect is the concrete definition of responsibilities and rights of farmers and government for the amelioration of lands and rehabilitation of irrigation infrastructures in land lease contracts signed between the farmer and the government. In most cases, there is no clear definition of such rights or whole responsibility shifted to farmers. As a result, farmers are at high legal risks under court rulings. The clear and concrete definition of such responsibilities and rights would stimulate farmers to improve the amelioration conditions of their lands and actively participate with technical and material contributions for rehabilitation of irrigation infrastructures.

The third aspect is the incentive mechanisms for farmers’ contributions in such activities. For example, the decrease of state quota for cotton and wheat either in quantity or options for farmers to sow the two crops on less parcels while meeting the state quota.

The fourth aspect is that the current bonitet scores should be carried out for all lands and updated accordingly by the responsible government authorities. In addition, each farmer can hire licensed private consulting company for independent bonitet scoring. There is a dilemma as the bonitet score can only be carried out by specialized state organization, thus such licensing should be shifted to private sector and necessary amendments into the regulations should be envisaged. Proper and updated bonitet score would be beneficial both for farmers and government in order to meet state quota on cotton and wheat.

The fifth aspect is provision of farmers with a more flexible system for cultivating different cash crop varieties on their plots. If the government would allow the decreasing of the size of lands sown under cotton and wheat while meeting the state quotas, the remaining lands could be used effectively for cultivation of cash crops. As a result, the income generation would be promising and farmers could contribute for amelioration works and rehabilitation of irrigation infrastructures. There was a promising sign from the government of Uzbekistan in 2008, who has issued the degree that the total size of area sown under cotton should be reduced by 75 000 ha and these lands can be used for cultivation of different crops (Shadibaev, 2009).

***Water Users Associations***

The first aspect is the development of mechanisms for financial sustainability of WUA. The only source of income for WUA is the annual membership fees from its farmer members. Instead for diversifying the income sources in kind contributions should be introduced as in Kyrgyzstan and Tajikistan (Sehring, 2009). In kinds contributions can be either natural produce or manpower for cleaning irrigation infrastructures. For example, the farmer who installs on his/her own expense the water measuring device can have some privileges, i.e. first irrigation water delivery.

The next aspect is consultancy/extension service for farmers. As Muhamedjanov et al (2008) proposes that consultancy/extension services should be established under the umbrella of the of Basin Irrigation Systems Authority (BISA) which were established for replacing previous provincial water management organizations in Uzbekistan. The main disadvantage of such consultancy/extension service is emergence of another inefficient and bureaucratic machine. Instead the consultancy/extension should be in solely form of private companies at the WUA level. The reasons are that WUA is directly working with individual farmers and such private companies with WUA partnership will have substantial impacts as cost-effectiveness and targeted consultancy service provision. Another important aspect as early mentioned is that there is no legal framework for such consultancies. For extension service the prominent academic universities and research institutions with WUA and private consultancy companies can have synergetic partnerships for training and know-how technology transfer.

## CONCLUSION

The Central Asian countries have faced new challenges for practicing a sustainable irrigated agriculture, particularly in terms of institutional challenges. The physical deterioration of irrigation and drainage infrastructures is a technical issue that would impose constraints on agricultural production, environmental concerns and, as a result, on the livelihoods of many millions of farmers. In fact poor conditions of irrigation infrastructures impact the efficient irrigation water distribution at various levels of the irrigation conveyance system. Global climate change and the transboundary nature of water resources would be major supplemental aspects for the sustainability of irrigated agriculture production in Central Asia.

The national and international donor programs would play a pivotal role for reversing the current situation if the intervention measures would be targeted to institutional changes such as land tenure, water rights, and incentives for rehabilitation of irrigation and drainage networks.

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*Article*

# Facts and Perspectives of Water Reservoirs in Central Asia: A Special Focus on Uzbekistan

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**Abstract:** The political transformation of the Central Asian region has induced the implosion of the interconnected physical hydraulic infrastructure and its institutional management system. Land-locked Central Asian countries, with their climatic conditions and transboundary water resources, have been striving to meet their food security, to increase agricultural production, to sustain energy sectors, and to protect the environment. The existing water reservoirs are strategic infrastructures for irrigation and hydropower generation. Upstream countries (Tajikistan and Kyrgyzstan) favor the reservoirs' operation for energy supply, while downstream countries (Uzbekistan, Turkmenistan and Kazakhstan) push for irrigation use. This paper provides an overview of the current challenges and perspectives (technical, institutional, and legal regulations) and presents recommendations for the sustainable management of man-made water reservoirs in Uzbekistan.

**Keywords:** transboundary waters; dam management; water reservoirs; irrigation; hydropower; sedimentation; water policy

## 1. Introduction

After the disintegration of the former Soviet Union, transboundary water management and governance have become a hot topic in Central Asia over the last two decades [1-3]. In fact, the United Nations Development Program (UNDP) [4] report that the Central Asian region loses $1.7 billion per year, *i.e.*, three percent of the region's GDP (Gross Domestic Product), from the poor water management that lowers the agricultural yields. Moreover, some 22 million people depend, directly or indirectly, on irrigated agriculture in these countries [5]. The sustainability of irrigated agriculture is one of the main platforms for food security, employment, livelihoods, and environmental protection in Central Asia.

The Central Asia countries (Tajikistan, Kyrgyzstan, Kazakhstan, Turkmenistan, and Uzbekistan) have inherited an interconnected and sophisticated hydraulic infrastructure system from the Soviet era. As described by Libert *et al.* [6] and Rakhmatullaev *et al.* [7], from an engineering perspective, the hydraulic mission of the Soviet administration was set up to be based upon the construction of large dams and water reservoirs in the mountainous areas of upstream countries (Tajikistan and Kyrgyzstan). This was due to the areas' attractiveness of natural conditions and higher water accumulation per unit area in comparison to the conditions of the plains (lowland) within the downstream countries (Uzbekistan, Kazakhstan, and Turkmenistan). On the other hand, the lowlands were suitable for practicing irrigated agriculture and for growing water intensive agricultural crops (cotton, rice, and wheat).

The recent pivotal area of discussions is hydropower *versus* irrigation for the operation of reservoirs and dams in Central Asia, e.g., the Toktogul reservoir in Kyrgyzstan (Syr Darya River Basin) and the construction of the Rogun hydropower station in Tajikistan (Amu Darya River Basin).

In fact, in the region, various paramount technical, operational, and biophysical aspects that are not transboundary issues impact the sustainable operation and management of dams and their associated water reservoirs. Examples of these aspects include sedimentation, improper operation, overuse of hydraulic infrastructures against designed operational regimes, and the lack of national legal and institutional frameworks for dam safety. Moreover, there is no warning system for alerting downstream countries in the event of technical accidents or natural disasters. These acute issues have to be seriously addressed at the national and regional levels.

Some experts argue that within the region, global warming will have a severe impact on the formation of water resources in the mountain systems of the Tian Shan and Pamir-Alay because of the decrease in ice cover [8]. In fact, these mountain systems are major contributors to the watersheds of the region. Research reports that since the beginning of the 20th century, a general warming trend in Central Asia, on the order of 1–2 °C, has been observed, which might have a potential impact on the regional temperature, evaporation, and precipitation regimes [9]. According to the estimates made by the Uzbekistan Hydro Meteorological Committee, the pessimistic scenarios of water resource transformations describe a reduction of the river discharges by 15–20% and 20–30% for the Syr Darya River and the Amu Darya River, respectively [10]. Water resources will be more stringent, and transboundary management of these hydraulic infrastructures has to be conducted in harmonious cooperation to meet the current concerns of all involved parties.

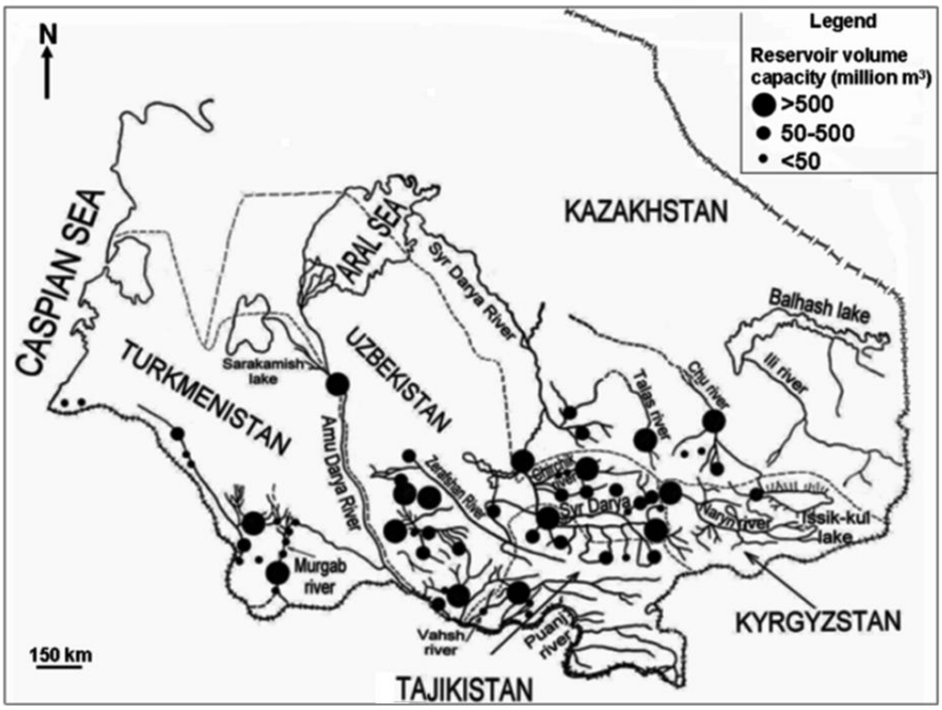
The World Commission on Dams (WCD) [11] outlines that large hydraulic infrastructures, such as dams and their associated water reservoirs, have played an important role in the regional development of many parts of the world. In the Central Asian region, where natural precipitation is erratic or seasonal, with uneven spatial and temporal water resource distribution, and arid climatic conditions, man-made water reservoirs play a particularly paramount role [12]. In fact, reservoirs store water during wet periods to make it available during dry periods, and in so doing, regulate floods, generate hydropower, and enable irrigation [13]. Thus, it is important to discuss the technical, management aspects of dams and the dams' associated water reservoirs.

The primary objective of this paper is to review the situation on dams and water reservoirs in terms of the technical, legal, and institutional aspects of the new geopolitical realities within the region. Special attention will be paid to the Uzbekistan experience and on improving the country's large hydraulic infrastructure safety framework. Perspectives and recommendations are given for improving hydraulic infrastructure operation and management in Uzbekistan, and for examining, on a Central Asian level, the regional dialogue for cooperation.

## 2. Water Reservoirs in Central Asia

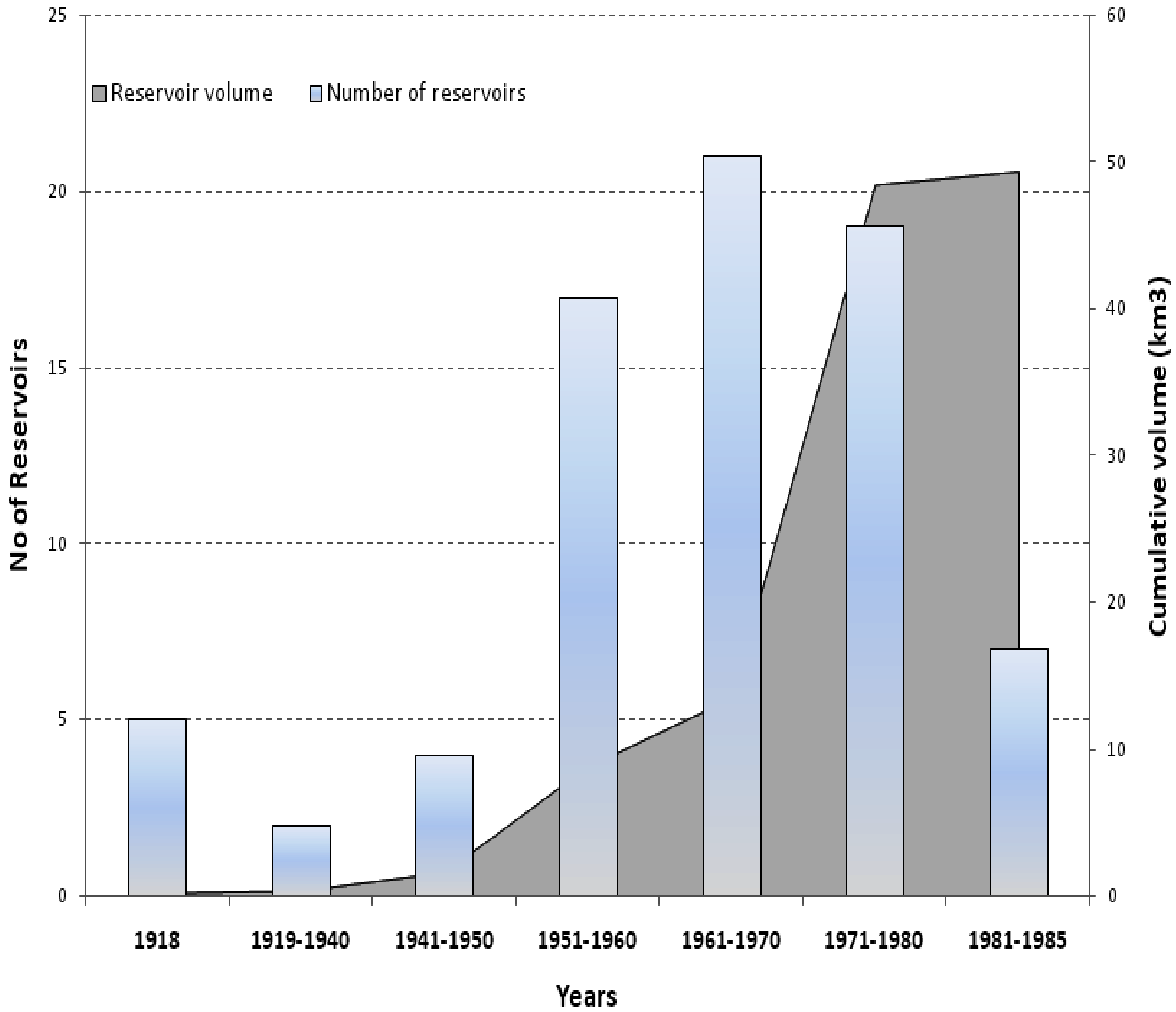
In the Central Asian region, the first water reservoirs were constructed as early as the tenth through 11th centuries [14,15]. For the regulation of the region's rivers, hundreds of man-made water reservoirs were constructed to mitigate the natural shortage of water resources. Additionally, these reservoirs generated hydropower, irrigation, and water supplies for municipalities and industry, and provided water for recreational purposes (Figure 1).

**Figure 1.** Schematic location of the main water reservoirs and their volume capacities in Central Asia (excluding reservoirs in the central and northern region of Kazakhstan), adopted and modified from [15].



The era of massive water reservoir construction was documented in the late 1900s. From 1950 to 1980, more than 60 large reservoirs were constructed in the region (Figure 2). The gross reservoir volume has increased by 50-fold, from 0.17 to 49.3 km$^3$, as a part of the unprecedented increase of water storage capacities around the globe. Most of the dams and water reservoirs in the region have been constructed for irrigation purposes, with a few for hydropower generation. As a result, over a period of 90 years (1913–2003), the areas under irrigation have increased three-fold in Central Asia, e.g., from 4.51 million ha in 1960 to 6.92 million ha in 1980, and to 7.85 million ha in 2000 [16,17]. The peak of dam construction is dated to the Soviet period, when the USSR's policy was aimed at expanding irrigated lands for the mass production of cotton [18].

**Figure 2.** The number of reservoirs constructed and the cumulative volume capacity in Central Asia during the last century [18].




At the moment, there are more than 290 water reservoirs in Central Asia, with a total volume capacity of over 163 km$^3$. They regulate more than 50% of the monthly regional river flow, and the area occupied by the reservoirs constitutes roughly 6% of the irrigated areas of Central Asian countries (Table 1) [19]. For example, on average, about 30% of irrigation water is delivered from reservoirs in the region. The percentages range up to 54% in Turkmenistan and down to as low as 13% in Kyrgyzstan.

**Table 1.** Distribution of water reservoirs by total volume and numbers in Central Asian countries. CA = Central Asia.

| **Country** | **Total reservoir volume capacity (km$^3$)** | **Number of reservoirs** | **Irrigation water from reservoirs (%)** |
|---|---|---|---|
| Kazakhstan * | 88.8 | 180 * | 32 |
| Kyrgyzstan | 23.5 | 18 | 13 |
| Tajikistan | 29 | 19 | 28 |
| Turkmenistan | 2.89 | 18 | 54 |
| Uzbekistan | 19 | 55 | 24 |
| Total in CA | 163.19 | 290 | Average 30 |

* The number of reservoirs represents the whole of Kazakhstan.

There are 45 large-scale hydropower stations, with a gross capacity of 36.7 GWh/year, on large water reservoirs in the Central Asian region [20]. However, only 11% of the hydropower is generated in Uzbekistan, whereas more than 90% is produced in Tajikistan [21]. Kyrgyzstan and Tajikistan have about 78% of the total hydropower potential of the region, but utilize only 10% of that potential.

*Reservoirs in Uzbekistan*

The total number of man-made water reservoirs in Uzbekistan is 55 (Table 2) [22].

**Table 2.** Distribution of water reservoirs in Uzbekistan by administrative boundaries.

| **Province** | **Number** | **Useful Volume Capacity (km$^3$)** | **Province** | **Number** | **Useful Volume Capacity (km$^3$)** |
|---|---|---|---|---|---|
| *Amu Darya River Basin* | | | *Syr Darya River Basin* | | |
| Khorezm | 1 | 4.5 | Andijan | 3 | 1.7 |
| Kashkadarya | 14 | 2.3 | Tashkent | 5 | 1.9 |
| Samarkand | 7 | 1.1 | Fergana | 4 | 0.25 |
| Surkhandarya | 4 | 0.9 | Namangan | 7 | 0.23 |
| Navoi | 2 | 0.8 | Jizzak | 4 | 0.18 |
| Bukhara | 2 | 0.4 | Syrdarya | 2 | 0.01 |
| Total | 30 | 10.1 | | 25 | 4.45 |

In Uzbekistan, the total gross volume capacity of all reservoirs is about 19 km$^3$, and the useful volume capacity is about 14.5 km$^3$, whereas the total surface area of reservoirs is estimated at *ca.*, 1,450 km$^2$. The total reservoir volume capacity is defined as the maximum amount of water stored, whereas the useful volume capacity is the actual available water storage. The arithmetical difference between the two values is defined as the dead storage of a reservoir. In other words, the dead volume storage in a reservoir is determined as the storage volume between the stream bed and the lowest elevation from which water can be withdrawn by gravity [23]. The difference observed between the total capacity and the useful capacity is an indicator of the efficiency of dam and water management.

The 4.5 $km^3$ difference represents a loss of 26% that is due to topographic peculiarities, *i.e.*, most of the water reservoirs are constructed in the lowlands of Uzbekistan.

Nine major reservoirs constitute about 86% (16.8 $km^3$) of the total reservoir volume capacity, and about 94% (1362 $km^2$) of the total surface area (Table 3) [24]. Almost 90% of all dams are used for irrigation purposes, whereas two are used for hydropower (Andijan and Charvak). About 75% of dams were constructed in the 30-year period from 1961 to 1990, with 93% of the total reservoir capacity coming from a time known as the "Soviet Period". At the moment, three water reservoirs, for increasing the water storage capacities, are being constructed in the Namangan, Jizzak, and Samarkand provinces of Uzbekistan.

All dams and their associated water reservoirs are aging, and numerous biophysical, technical, and management issues need to be addressed in order to attain a sustainable management of water resources and hydraulic infrastructures. For hydraulic structures which have a transboundary importance, these issues should be addressed, in particular, at the national level.

## 3. Threats to Water Reservoirs in Uzbekistan

Almost all the hydraulic infrastructures in Uzbekistan, but particularly dams and their associated water reservoirs, are aging (constructed during the 1930–1940 period) [25]. Thus, there is some urgency to perform operations that would improve the safety of such structures in order to avoid devastating emergency situations in the event of technical operational failures or natural phenomena, such as earthquakes. For example, the civil engineering of the dams, in terms of life cycle and survey, and also water practices and legal aspects, are linked to the management of the dams and resources, at different steps and scales. This management is a key point of discussion at the national level, and is very often problematic at an international one (*i.e.*, case of the transboundary rivers).

### *3.1. Reservoir Sedimentation*

A reduced reservoir volume capacity, due to sedimentation, triggers operational and maintenance issues. These issues are exacerbated by uncertainty over the economic feasibility of corrective measures and by environmental and social concerns [26]. Sedimentation is a natural geomorphologic process, but human interference increases its rates. Sedimentation reduces the main reservoir asset, *i.e.*, its volume capacity, over time because of the feeding rivers. It is reported that globally, sedimentation has been observed to cause an annual average of 0.5–1% loss with respect to the volume capacities of small and large reservoirs [11,23]. Palmieri *et al.* [27] reports that the loss in volume capacity requires an annual replacement cost of 13 billion US dollars.

The most recent reports indicate that the average annual reservoir volume loss is estimated at 0.5% in Uzbekistan (Table 3) [24]. The total volume capacities of major reservoirs have decreased by about 20% and the nation's dams' dead storage capacities have decreased by 55%. For example, the dead volume capacities of seven reservoirs decreased by more than 75%. This is an alarming signal that in the future, the sedimentation rates can be unprecedented, with several operational and maintenance problems.

Due to the naturally high turbidity of the watercourses, reservoir sedimentation is an acute issue in Central Asia. In fact, most of the reservoirs have been silted to a great extent. Sedimentation impacts the guaranteed water supply for the different water users (irrigation, industry, and hydropower) at the national and regional levels.

For example, the direct loss of reservoir volume capacity leads to lower hydropower production capacity available for sale, less irrigated land for food production, and a reduced flood routing capacity. Moreover, the deterioration of water quality in reservoirs can be a major issue, with increasing levels of various contaminants from agriculture, industry, and natural sources, whether organic (pesticides, PCBs, PAHs) or inorganic (trace metals) [12,26]. Dam cavitation and abrasion of conduits, valves, sluice gates, and hydropower turbines dramatically impact hydraulic facilities and structures. Moreover, social aspects can result. For example, the region may be rendered less attractive for tourism, and recreational opportunities can be lost.

**Table 3.** Loss of reservoir volume (total and dead) of selected major reservoirs in Uzbekistan.

| Reservoir | River Basin | Total Volume ($Mm^3$) | Silted volume (%) | Started to operate (Year) |
|---|---|---|---|---|
| Talimarjan | Amu Darya | 1,525 | 3.9 | 1985 |
| Janubiy Surkhan | Surkhan Darya | 800 | 37 | 1967 |
| Kuyimazar | Amu Darya | 310 | 11.2 | 1958 |
| Tudakul | Amu Darya | 1,200 | 13.7 | 1983 |
| Andijan | Kara Darya | 1,900 | 13.4 | 1970 |
| Kattakurgan | Zerafshan | 900 | 22.5 | 1953 |
| Chimkurgan | Kashka Darya | 500 | 22.7 | 1963 |
| Ruslovoy * | Amu Darya | 2,340 | 44.9 | 1980 |
| Kaparas * | Amu Darya | 960 | 1.9 | 1983 |
| Average | | | 19 | |

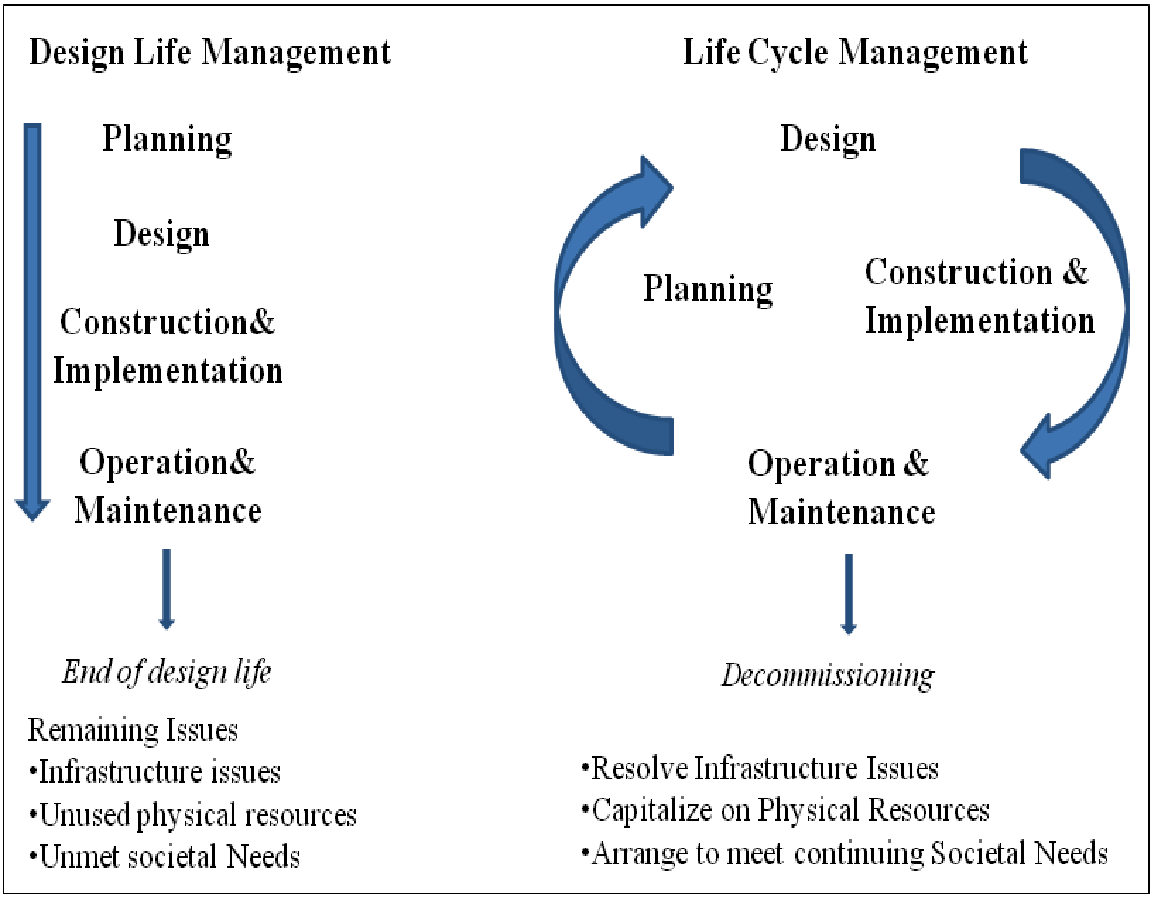
* Tuyamuin is composed of four reservoirs: (1) Ruslovoy—2.34 $km^3$; (2) Sultansanjar—2.69 $km^3$; (3) Kaparas—0.96 $km^3$; (4) Koshbulak—1.81 $km^3$.

Common engineering practice advocates for a "design for life" approach for dam and reservoir conception. The design for life approach assumes a finite project life, which means that future generations should bear all occurring costs and profits [11,23,26].

Palmieri *et al.* [27] proposed a new "life cycle management" approach for the sustainable management and use of hydraulic infrastructures (Figure 3). The ultimate goal of this approach is sustainable use, where the major functions of the dam are preserved, through good management and maintenance. It means that these hydraulic infrastructures should be considered as economic assets and that through proper mitigation measures, there should be long-term benefits generated for the local populations.

The design life approach follows a linear time-line and assumes that the project will have served its purpose at the end of its design life. In contrast, the concept of life cycle management encourages a cyclic time-line and sustainable use. The main element in this approach is decommissioning. In the design life approach, the financial costs for decommissioning are not foreseen, whereas in the life cycle management, such costs are taken into consideration through a retirement fund, *i.e.*, contributions from benefits and other sources.

**Figure 3.** The main elements of the "design life" *versus* "life cycle" management approaches (modified from [27]).




### *3.2. Water Reservoirs Operation Guidelines*

It is known that all large scale hydraulic infrastructures, in particular dams and water reservoirs, are designed and constructed according to a design operation regime, which safeguards the durability of the operations. However, the real situation is quite different in Uzbekistan. The weighted decision for the operation of water reservoirs lies in the hand of local government authorities (hokimiyats, *i.e.*, governors), who are responsible for the agricultural production of cotton and wheat [28]. The water management organizations are left with only a technical assistance role for water supply matters. In most cases, the design operation regime is violated. These violations create severe circumstances for the hydraulic infrastructures. Infrastructure fatigue puts additional pressure for the proper management of scare water resources.

### *3.3. Institutional and Legal Frameworks of Water Reservoirs*

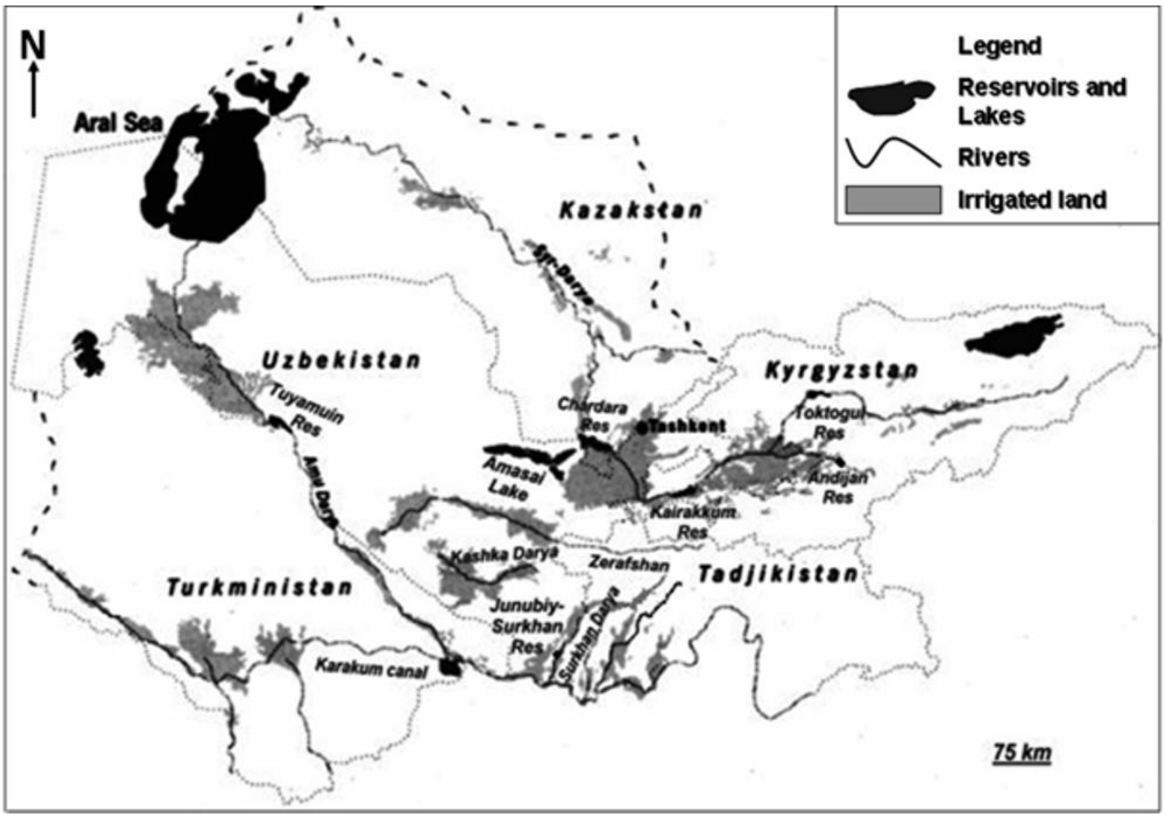
The hydraulic infrastructures, in particular dams and their associated water reservoirs, are managed, rehabilitated, and operated by the Ministry of Agriculture and Water Resources of Uzbekistan [29]. The hydropower plants are managed and operated by the State Joint Stock Company, UzbekEnergo. For example, about 11.5% of the power generation is produced through 29 hydropower plants and two large dams (Charvak and Andijan). There is an overlap of responsibilities of these two state agencies on the management of dams and their associated water reservoirs.

In Uzbekistan, a national law for the safety of hydraulic structures was adopted in 1999. Gosvodkhoznadzor, under the Cabinet of Ministries of the Republic of Uzbekistan, is a state inspection agency that controls and monitors the technical conditions and safety operations of large-scale hydraulic infrastructures [30]. There are almost 273 large hydraulic infrastructures (55 water reservoirs, 35 pumping stations, 29 hydropower plants, 60 irrigation main canals, 64 water-intake schemes, 24 main collectors, and 7 riverbank protection structures). Gosvodkhoznadzor inspects the safety of large hydraulic infrastructures and sanctions the Ministry of Agriculture and Water Resources of Uzbekistan for proper actions and mitigation measures. Unfortunately, in most cases, the recommendations of Gosvodkhoznadzor are only conceived of as suggestions by the Ministry.

## 4. Transboundary Issues of Water Reservoirs for Uzbekistan

Uneven spatial and temporal water resources, and a Soviet inherited unified hydraulic infrastructure, have raised transboundary reservoir management issues over water resource allocation among the countries of the region (*i.e.*, Kyrgyzstan, Tajikistan, Kazakhstan, Uzbekistan and Turkmenistan). The rivers, such as Syr Darya and Amu Darya, are already regulated by more than 78% and 94% respectively, and attempts for new reservoir projects upstream raise increased concerns for the downstream countries (e.g., the Rogun hydropower station in Tajikistan and the Toktogul reservoir in Kyrgyzstan) (Figure 4).

**Figure 4.** The major transboundary rivers in Central Asia, modified from [10].



Competition for water resources is prioritized by the downstream countries (Uzbekistan, Turkmenistan, and Kazakhstan) for irrigation, whereas upstream countries (Tajikistan and Kyrgyzstan) use them mainly for hydropower generation [5,14]. There has been a serious conflict related to the water resource management of some hydraulic infrastructures, like the Toktogul reservoir located in Kyrgyzstan in the recent post-Soviet period.

This water storage infrastructure serves the needs of the entire Syr Darya River basin. Its main purpose is to regulate and secure the Syr Darya River flow during the growing season (April–September) for irrigation. It was designed to release 8.5 $km^3$ of water during the growing season and about 2.8 $km^3$ during the non-growing season (October–March).

The Toktogul dam's surplus hydropower generation in the summer is transmitted into the former Central Asian Power System Grid for use by the downstream countries of Kazakhstan and Uzbekistan. For compensation, Kazakhstan supplied fossil fuels, and Uzbekistan provided electricity, to Kyrgyzstan for electricity needs in winter months.

However, the situation has significantly changed due to the end of the former Soviet Union. During 1990 to 2000, summer releases declined to 45% and winter releases increased to 55% of the annual discharges [25].

## 5. Regional Institutional and Legal Frameworks

One important bottleneck, for the sustainable and cooperative management and operation of dams and their associated water reservoirs, lies in the absence of national legal frameworks and appropriate institutions in all the Central Asian countries, except Uzbekistan [9]. After the dissolution of the former Soviet Union, large hydraulic infrastructures have been left without proper attention from the Central Asian countries. For example, in Kazakhstan, hydropower plants are managed by semi-private entities, whereas reservoirs are still operated by the government water management authorities. Therefore, there is always a dispute for the coordinated operation and maintenance of hydropower plant and dam.

International assistance programs have tried to support regional dialogue on the cooperative use and operation of transboundary hydraulic infrastructures, but little success was achieved, due to the cost-sharing of operation and the maintenance price of such transboundary structures. UNECE (United Nations Economic Commission for Europe) is actively participating in the development of a regional agreement on cooperation on dam safety, and in particular, in the information exchange and notification of other countries (in case of accidents with dams) [8].

## 6. Perspectives and Recommendations

The following key perspectives and recommendations are discussed for the sustainable management of the water reservoirs and dams in the region and Uzbekistan.

### *6.1. Mini Hydropower Schemes*

In the light of hot negotiations among and between riparian states over the water-energy nexus, small hydropower schemes should be advocated in all Central Asian countries as compromises.

The small hydropower schemes are attractive in terms of financial, technical, management, and environmental feasibility aspects. These mini hydropower schemes would not significantly alter, for different water uses upstream and downstream, the hydrological regimes of the main transboundary watercourses. Furthermore these schemes are financially attractive for the international donor communities, and are less environmentally impact-oriented for upstream and downstream riparian ecosystems. Almost all the attractive potential sites for large dam and water reservoirs are used in the region. Another argument for the small hydropower schemes is the issue of seismological conditions at upstream sites. In the event of tectonics, the small hydropower schemes have less devastating effects for local communities, ecosystems, and for states (in terms of financial burdens).

### *6.2. Institutional and Legal Framework*

For a regional cooperation on dams and water reservoirs management in Central Asia, the authors recommend the creation of a regional chapter of the International Commission on Large Dams (ICOLD), which can play a role as a neutral key regional institution on dam safety issues. Under the umbrella of the Central Asia ICOLD, national working groups can cooperate and discuss various topicalities regarding the development of mutually beneficial procedures, regulation norms, and standards on the monitoring of hydro infrastructure safety. The mandates of such an organization could be the harmonization of the cooperation of Central Asian states on dam safety, monitoring procedures, information exchange, and the development of a comprehensive database. This can be a first step to the creation of a regional platform for the discussion of current issues on planning, design, operation, maintenance, and management of large hydraulic structures.

In order to synchronize cooperation on the management of dams and their associated water reservoirs, each country should develop its own laws on safety of hydraulic infrastructures. Only Uzbekistan has adopted such a law in 1999. Only after each country has its own law can a regional legal framework be developed through consultations.

### *6.3. Mitigation Measures*

For a regional cooperation on dams and water reservoirs safety, proper technical and management activities should take place at the national level in order to sustainably operate and manage these sophisticated infrastructures. It is time to review and assess the present technical conditions of all large infrastructures for each country.

The best practices (mitigation measures) can then be shared and duplicated among other regional countries. For example, in Uzbekistan, a new GIS (Geographic Information System), in combination with depth measurement systems, are being used for the operative estimation of reservoir sedimentation volumes [17].

As the infrastructure fatigue will be reached in this century, appropriate planning programs should be designed and implemented, such as a retirement fund for dam and water reservoirs [31]. The retirement fund is intended to accumulate annual contributions made during the life of the dam to pay for any actions required at its retirement, for example, a change of purpose (e.g., recreation, farming, environment creation) from its present irrigation or hydropower generation, and in extreme cases, the partial or complete removal of the dam. However, the partial or full decommissioning of dams would not be economically feasible in the region, due to the high financial costs, and the lack of existence of real local expertise. A practical approach that can still be attractive to local authorities is to change the dam's or reservoir's purpose.

## 7. Conclusions

Large hydraulic infrastructures have played an important role for the Central Asian region's development and have brought many benefits, regionally and nationally, through irrigation, hydropower generation, and water supply for industry and recreation. However, these hydraulic structures are facing numerous problematic issues, such as infrastructure fatigue, biophysical issues, and problems with operation and maintenance on national levels, due to the decrease of substantial financial assistance programs.

As the infrastructure fatigue is unavoidable, the new life cycle management approach should be recommended to all national authorities for the sustainable operation of such engineering infrastructures and for the use of scare water resources.

With new geopolitical realms in the region after the collapse of the former Soviet Union and the emergence of new independent states, regional and transboundary issues have arisen for the cooperative management of water resources and the cost sharing of operation and maintenance. In the domain of large hydraulic infrastructure safety issues, transparent legal and institutional frameworks should be developed and adopted, reflecting a transnational good spirit of cooperation.

A regional platform should be developed, such as a branch of the ICOLD, which will serve as a professional union for the harmonized management and the joint operation of dams and water reservoirs on transboundary watercourses.

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