

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 unsampled 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

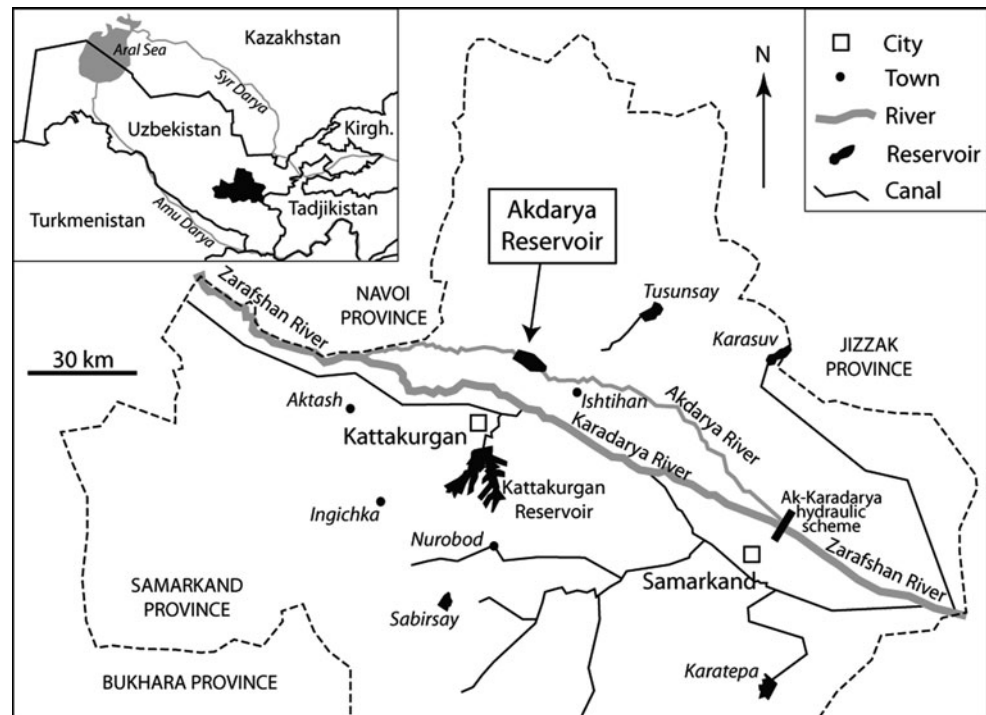
reservoir diminishes as its storage capacity is reduced (Bruk 1985; WCD 2000; IHP 2002; Rakhmatullaev et al. 2010; Ahmed and Sanchez 2010; Liu et al. 2010). As the stream flows, its sediment carrying capacity is diminished due to the decrease in flow velocity and increase in the cross-sectional area 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 km³ and a useful volume capacity of 14.5 km³ (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 km², the total storage volume is 112.5 Mm³. In order to increase the irrigated lands, authorities have increased the reservoir volume capacity from 34 to 112.5 Mm³ by raising the dam crest by 7 m since 1982 (Samarkandgiprovodhoz 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 (Samarkandgiprovodhoz 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 m³/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 km² (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

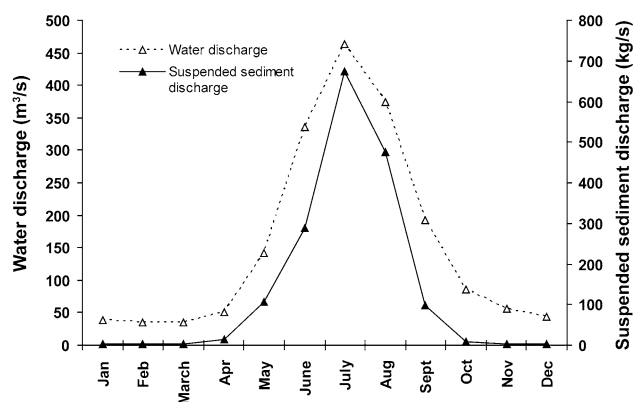


Fig. 2 Diagram of water discharge versus sediment discharge of Akdarya River (Uzdavsubloha 2002)

sediment loads can be carried out by the Akdarya River in the event of high floods.

Materials and methods

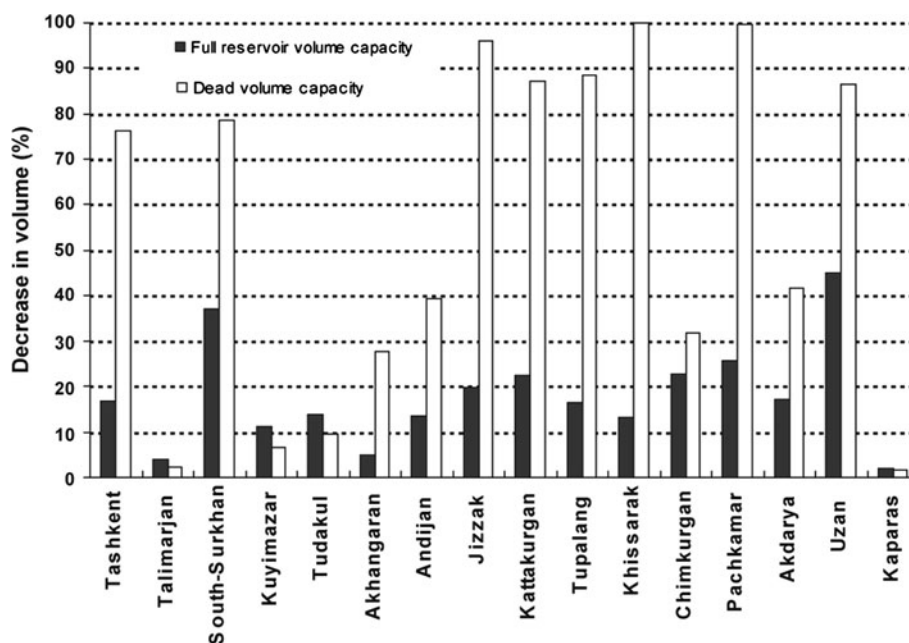
In 2001, the “Uzbek Bathymetric Centre” was established under the umbrella of UzMAWR and was authorized to survey the reservoirs using the bathymetric investigation system (CEEDUCER[®]) developed by Bruttour International Pty Ltd (Bruttour International Pty. Ltd 2003). This system is composed of an incorporated 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.

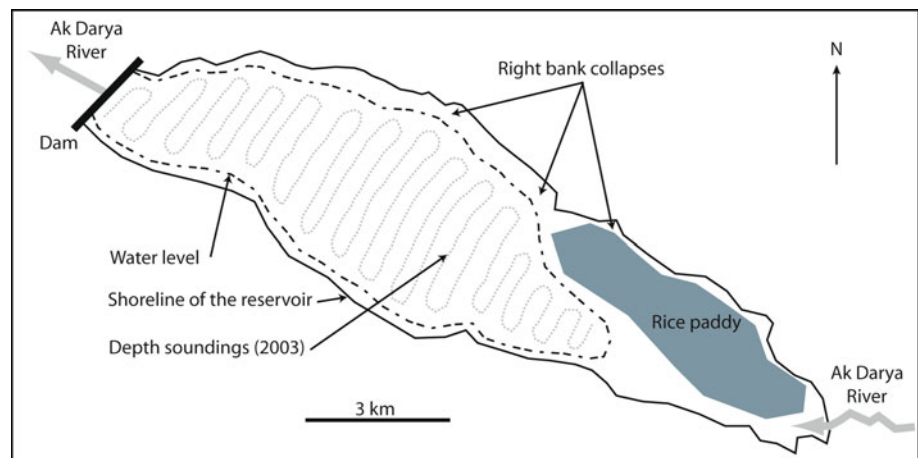
For the shallow water areas where the transducer could not be operated, representative depth measures were manually collected with a stadia rod from the boat. However, sediment accumulation and vegetation growth in the upstream reservoir areas limited the data collection. The shoreline delineation was 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 $z + h$, as a function of their distance h .

The experimental semi-variogram is calculated by the following equation:

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

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 (Geostatistics 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 Mm³ 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 Mm³ and the total reservoir volume decreased by 7.5% compared to the 1996 level. In addition, the water area increased by 2.3 km² (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

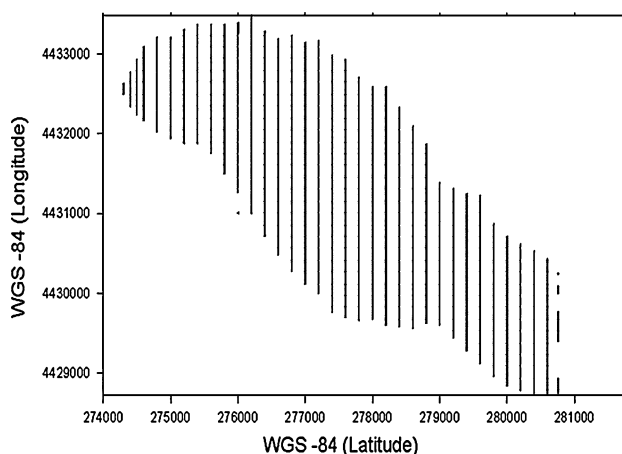


Fig. 5 Actual depth measurement points in Akdarya reservoir in 2003 (Bathymetric Center 2003)

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).

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

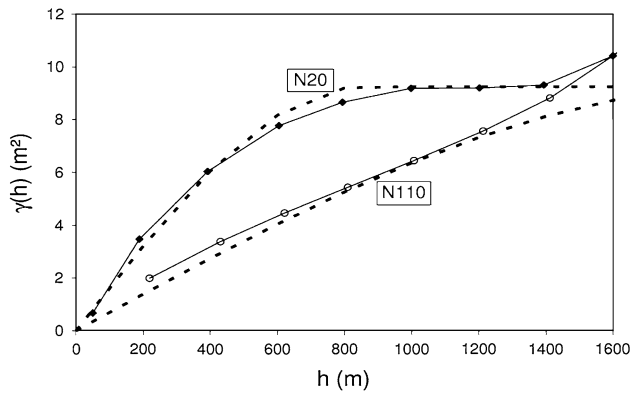


Fig. 6 Experimental semivariogram of reservoir bottom elevations direction N20 (smallest variance) and N110 (largest variance) of Akdarya reservoir

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

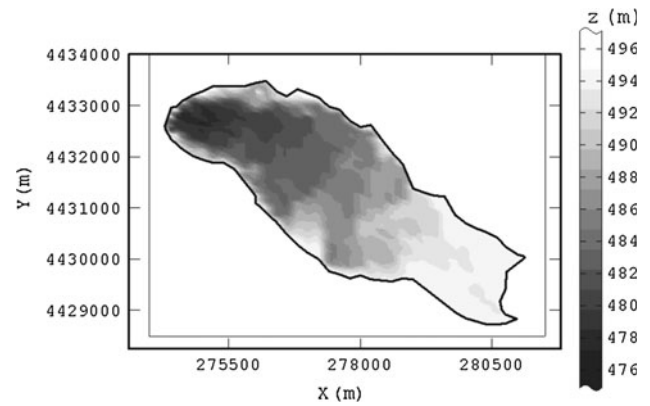


Fig. 7 Bathymetric map of Akdarya reservoir by kriging interpolation method

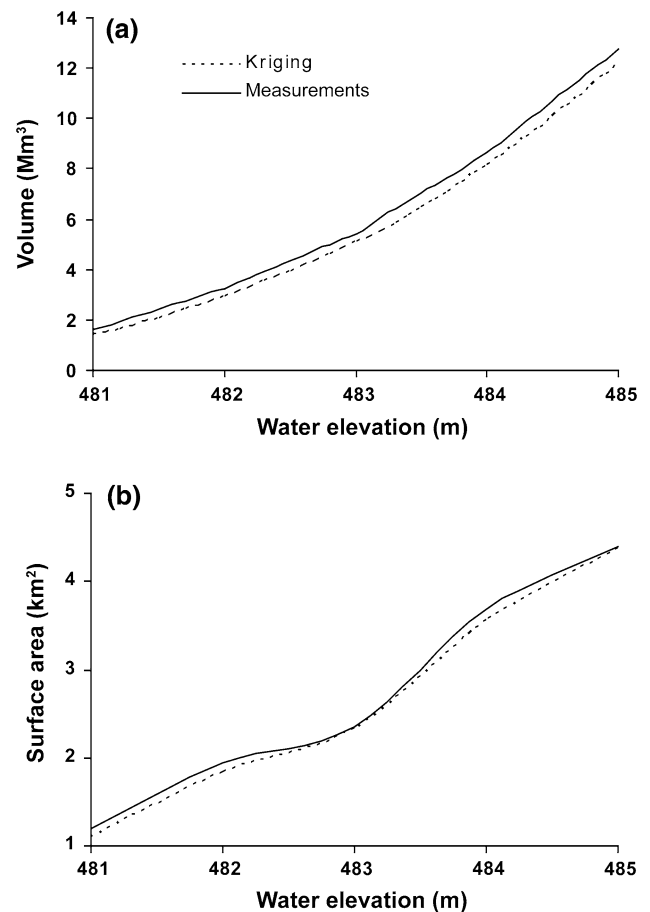


Fig. 8 Akdarya reservoir volume (a) and surface area (b) by kriging and experimental data (2003)

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

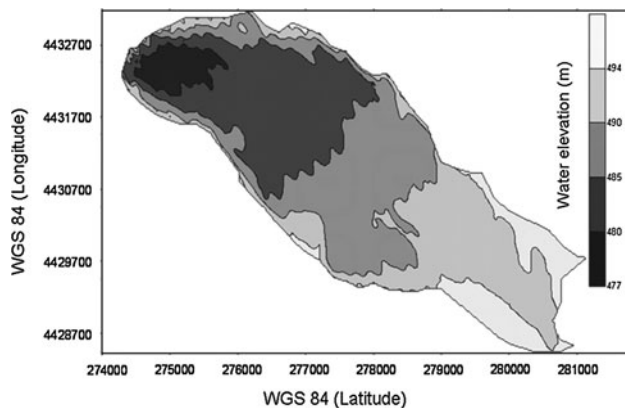


Fig. 9 Reservoir volume of Akdarya at different water elevations

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 Mm³) and the measured one (93.17 Mm³), that corresponds to 1.3 Mm³ 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

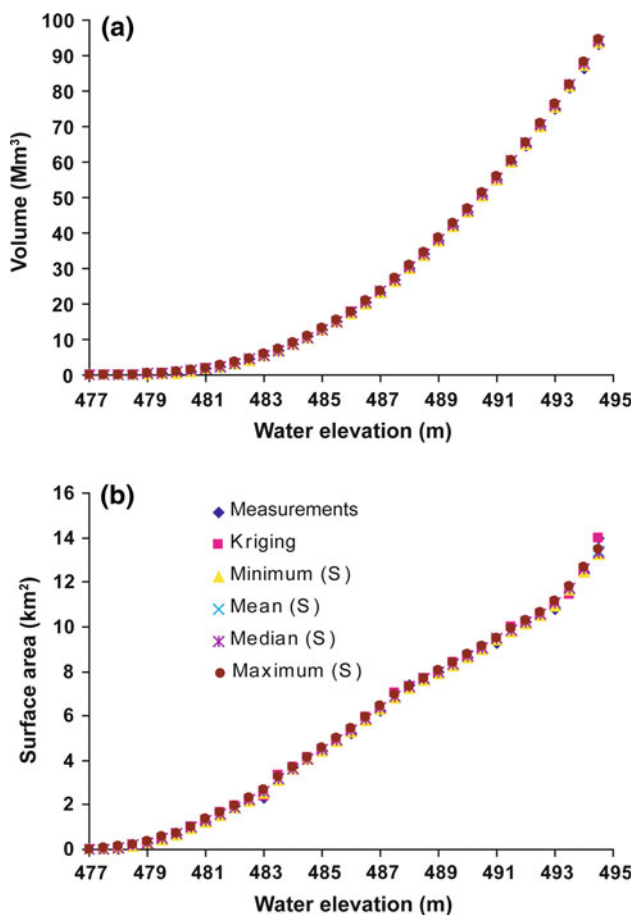


Fig. 10 Akdarya Reservoir volume (a) and surface area (b) versus water elevation for experimental, kriging and simulation

example, the economic efficiency for calculation of 1 km² 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

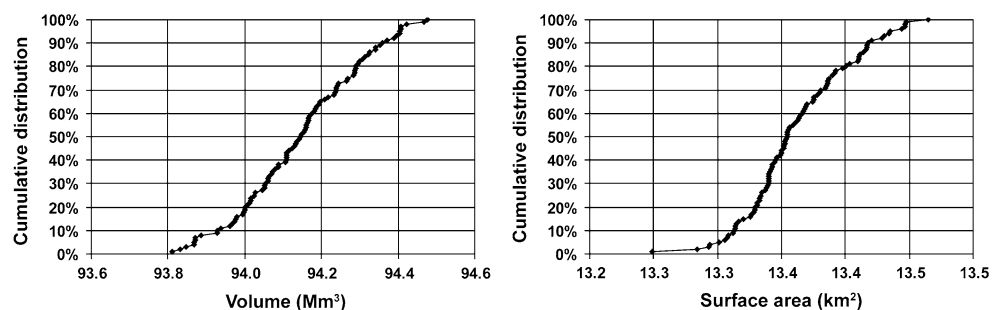
the reservoir. However, the spatial distribution of the deposited sediment volume has profound significations for the sedimentation countermeasure plan. The location of the deposited sediment within the reservoir may be of equal or even greater importance to the reservoir operations, as is the total 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 been 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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