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Assessment of Spatial Sediment Distribution and Deposition in Reservoirs: Case study of Cubuk I & II, Turkey

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Abstract:The amount of sediment deposition in a reservoir is controlled by the type of sediment deposited (suspended or bed load), the detention storage time, the shape of the reservoir, and operational practices. Determination of sediment distribution and deposition in reservoirs are significant issue for dam designers estimating probable lifespan of a reservoir. Sediment accumulation is the most significant problem in the region, such as, Cubuk I was no longer used after 70 years of its operation due to sediment deposition. In this study, Remote Sensing (RS) and Geographic Information System (GIS) software were used to assess sedimentation through time in the Cubuk I and Cubuk II reservoirs via Bathymetric maps. Results indicate that a significant amount of siltation occurred between 1978 and 1983: Cubuk I reservoir accumulated 3 m of sediment within 6 years and Cubuk II accumulated about 10 m. Therefore, efficient siltation management practices should be performed to control sediment accumulation in these human made structures.

Keywords -*Bathymetry, Sediment Deposition, Reservoir Management, Storage Capacity*

I. Introduction

Reservoirs around the world have been filled with sediment at a rate of approximately 1% per year (WCD, 2000). This means that in 50 years most of the world's reservoirs will lose half of the current storage. Without appropriate precautions, sediment accumulation in reservoirs will cause environmental and economic consequences, especially in semiarid regions where reservoirs were mostly built for irrigation and water supply, as well as generating electricity or flood control. The capacity loss of reservoirs in arid regions is as high as 6000 – 8000 m^3/km^2/year (White, 2000). However, illustrating sediment distribution and deposition in a reservoir is a complex phenomenon because of numerous controlling variables affecting sediment load in small retention reservoirs and their translocation under various hydraulic conditions.

Sediment transport and deposition in a reservoir depend on reservoir geometry, flood frequency, river regime, sediment consolidation, management practices, and land-use changes over time (Borland and Miller, 1960). Previous studies have mostly focused on sediment deposited in larger reservoirs. The two most common empirical methods are the Area – Increment Method (AIM) (Cristofano, 1953) and the Empirical Area – Reduction Method (EARM) of Borland and Miller (1958), which was developed on the basis of siltation process of dead storage from 30 reservoirs. With respect to the scarce studies of sediment deposition in a small reservoir, Dendy (1982) represents the method of spatial bottom sediment distribution in reservoirs of storage capacity from 20,000 m^3 to 1.7 million m^3. Michalec et al. (2008) elaborated Dendy's method for smaller reservoirs at Zeslawice on the River Dlubnia. They found that over 58% of sediment accumulates in the reservoir delta.

Geographic Information System (Evans et al., 2002) and remote sensing satellite images (Solomonson, 1973; Holeyer, 1978; Khoram, 1981) can be useful tools in modeling bathymetry and the spatial distribution of sediment accumulation in a reservoir. Smith et al. (1980) also tried to determine reservoir siltation in the world's largest human made reservoir, behind the Aswan Dam, by using infrared areal images. Their results indicate that siltation during peak flow was largely confined to the deltas of main streams entering the reservoirs. The area of extensive siltation and the amount of sediment accumulation were determined by bathymetric surveys. The main aim of this study was to propose a methodology to assess the effects of reservoir sedimentation by comparing the bathymetric surveys of 1978 and 1983 and determining the spatial and temporal distribution of sediments within the Cubuk I and Cubuk II reservoirs.

II. Site Characteristics

Cubuk Creek is 70 km long and is the main study site of this research. The Cubuk joins the Ankara River that runs through the town of Cubuk. Cubuk Creek (Figure 1) illustrate the general characteristics of flashy streams in which stream flow rises sharply after rainfall and then falls more gradually. Discharge varies seasonally, with higher flow in the winter and spring and lower flows during summer and early fall. The streams have deposited alluvial materials (gravel, sand, clay, and silt) to a depth of 25-30 m and a width of 1-1.5 km along the channels, thus many sandpits have been operated within the streams.

Cubuk I, a concrete gravity dam, is located 12 km north of the center of Ankara city, on Cubuk Creek. Cubuk Creek, with a total length of 70 km, originates from the southern side of the Aydos Mountains at an elevation of 2044 m, and has two moderately large (approximately 1 km² (Cubuk I); 1.2 km² (Cubuk II)) reservoirs. Cubuk I was the first reservoir built in the Republic of Turkey. The construction of Cubuk I began in 1930 and was completed in 1936 with no power unit. Because of a huge amount of siltation, the reservoir has been recently used only for recreational purposes. The initial capacity of the reservoir is smaller than the annual discharge of the watershed: capacity loss is approximately 50% (Yilmaz, 2003). Clay and silt dominate reservoir sediments (Kilic, 1986). Cubuk II Reservoir was built in 1963 on Cubuk Creek 54 km north of Ankara. After construction of Cubuk II between 1964 and 1983, sediment yield in the basin was 350 ton/year/km² (Kilic, 1986). Recently, Cubuk II Reservoir has been used for recreational and water supply. Andesite, basalt, and volcanic agglomerate are abundant in the region (Table 1).

Table 1: Some characteristics of Cubuk I and Cubuk reservoirs in Central Turkey

Charactersitics	**Cubuk I Reservoir**	**Cubuk II Reservoir**
Geographic Coordinates	40.004763, 32.933904	40.305479, 33.016605
Drainage Area	910 km²	190 km²
Mean Annual Precipitation	418 mm	448 mm
Elevation	890 m	1005 m
Basin Slope	0.013 %	0.006 %
Relief Ratio	0.0033	0.0296
Geology	Triassic aged volcanic / metamorphic rocks	Triassic aged volcanic rocks
Land Cover	Cultivated lands	Grasslands

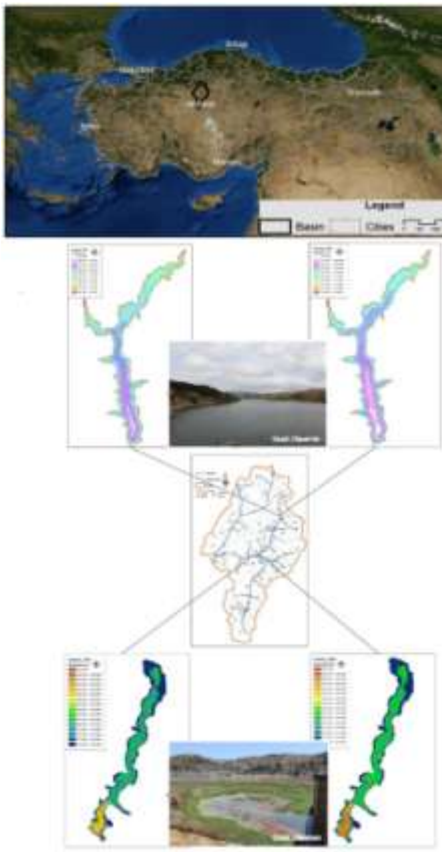

Figure 1: Digitized bathymetric maps for Cubuk I and Cubuk II Reservoirs (1978-1983)

III. Materials and Methods

Spatial distribution of sediment within the Cubuk I and Cubuk II reservoirs in the Central Anatolia Peninsula was investigated using bathymetric survey data as well as areal images. Sediment accumulation in the reservoirs was analyzed by comparing 1978 bathymetric survey data versus 1983 bathymetric surveys from Cubuk I and Cubuk II reservoirs (1/5000 scale). While a previous hard copy of bathymetry was available from State Hydraulic Works (DSI), a more detailed and recent digital bathymetry dataset is necessary for reservoir sedimentation practices. In fact, more getting more useful and accurate results requires longer time periods of data with higher resolution.

First, hard copy bathymetric maps obtained from DSI were digitized using ArcGIS 10.2 software. However, in the bathymetry of Cubuk I and Cubuk II reservoirs, some contours do not exist after a certain distance, which not only decreases the accuracy of the dataset, but also made the digitizing process more difficult. Second, the contours with elevation and their symbols were integrated into the software and stored in projected UTM coordinates, Zone 36N, using WGS-84 datum. Afterward, changes in the water surface area of the mean depth and changes in the shoreline of the reservoirs between 1978 and 1983 were observed by plotting cross section lines of “X and Y”. Comparison of these two digitized bathymetric maps allowed visualization of reservoir bottom topography.

1.1. Interpretation of the Bathymetric Surveys (1978-1983) from Cubuk I

The total surface area of the reservoir is 1.20 km² at normal water level. The water surface area of the reservoir increased slightly between 1978 and 1983 (Figure 2). The graph shows the changes in the water surface area versus water depth. Fluctuation at depths of 10 m, 11 m, and 15 m may be caused by sediment accumulation and mobility in the reservoir. Water depths of 26 m, 27 m, and 28 m did not exist in the bathymetric data of 1983, which possibly reflects sediment deposition in the deepest portion of the reservoir. Due to the low resolution of bathymetric data, the results in this section have some potential errors.

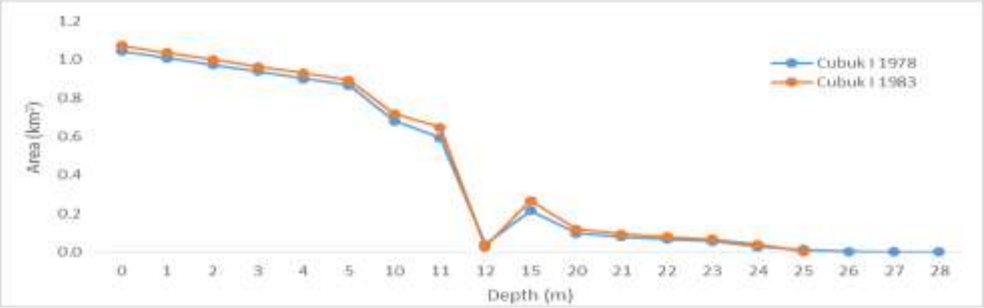

Figure 2: Changes in water surface area of the Cubuk I Reservoir

The bathymetric surveys of Cubuk I Reservoir (1978 – 1983) indicate a variation of the lowest elevation value. The earlier version of the data had the polygon of 892 m as a polygon with the lowest elevation. The latest version of the bathymetry shows 895 m as the lowest polygon, which means a 3 m loss of reservoir capacity at the deepest portion of the reservoir. During this time period, the contours of elevation 905 m (in the bathymetric map of 1978) increased 1 meter, and some of them disappeared in the middle section of the reservoir. Moreover, some contours’ geometry, especially at the downstream end of the reservoir, appeared to differ over 6 years. The northeast portion of the polygon (905 m) appears to be a fork in the earlier map, but not in the next version (Figure 3 and Figure 4).

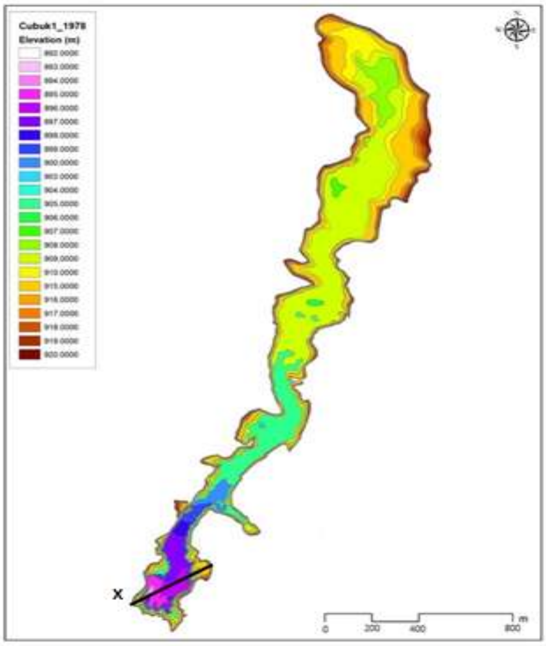

Figure 3: Map of Cubuk I Reservoir bathymetry in 1978 shows cross section line of X

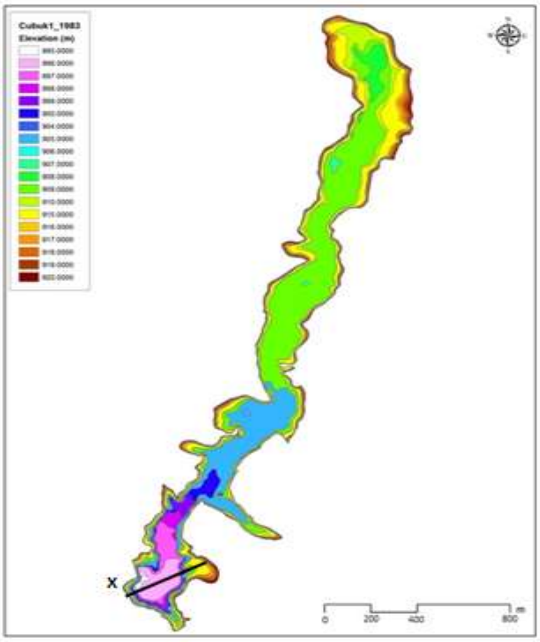

Figure 4: Map of Cubuk I Reservoir bathymetry in 1983 shows cross section line of X

1.2. Interpretation of the 1978 and 1983 Bathymetric Surveys from Cubuk II

The total surface area of the Cubuk II Reservoir is also 1.20 km² at normal water level. Between 1978 and 1983, the water surface area of the reservoir differs slightly (Figure 5). Changes in the water surface area versus water depth at 30 m and 50 m can be related to sediment deposition and sediment mobility in the reservoir. Similarly, the depth value of 60 m did not exist in 1983 due to sediment deposition in the deepest portion of the reservoir. The mean depth of the reservoir differs between Cubuk I (~ 25 m), Cubuk II (~ 60m).

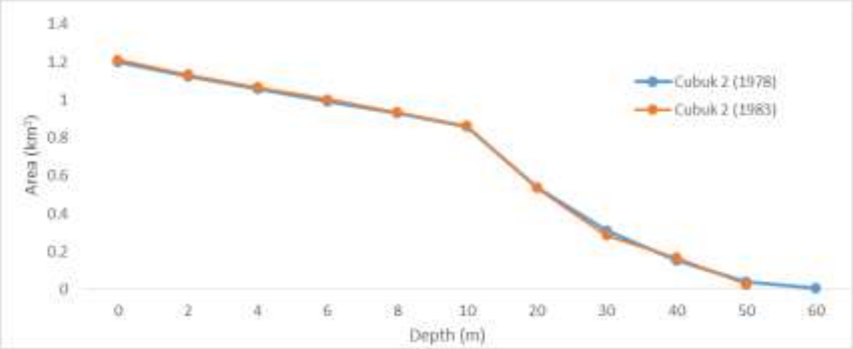

Figure 5: Changes in water surface area of Cubuk II Reservoir

Comparison of bathymetric maps for 1978 and 1983 for Cubuk II reservoir shows a change in the lowest elevation value. The bathymetry map of 1978 had the elevation of 1060 m as the lowest altitude, but the 1983 map had 1070 m as the lowest elevation. The 1070 m contours of 1978 also disappear at the lower portion of the reservoir. Also, some of the polygons' geometry (e.g., 1080 m and 1090 m polygons) varied during the seven years (Figure 6, Figure 7).

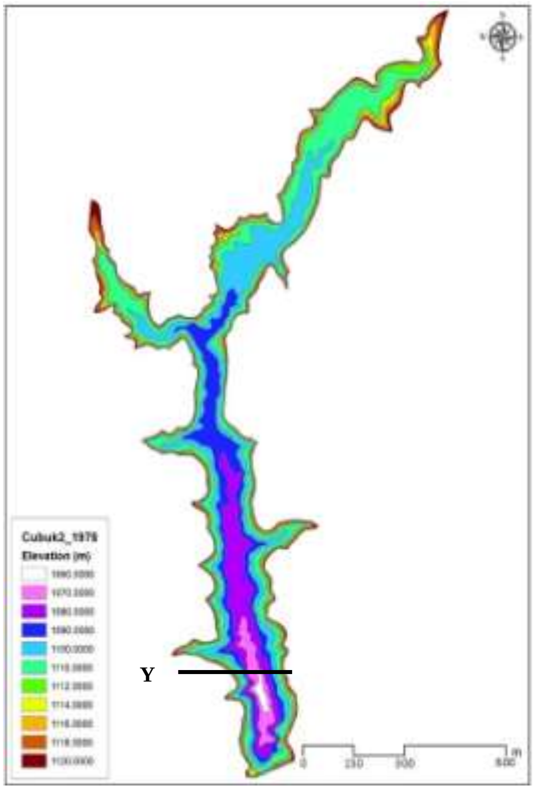

Figure 6: Map of Cubuk II bathymetric in 1978

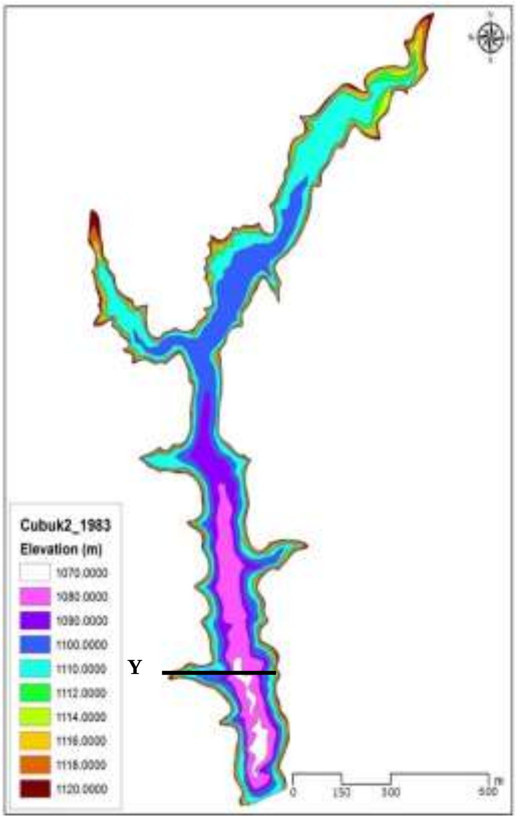

Figure 7: Map of Cubuk II bathymetric in 1983

Cross-section profiles were utilized to understand geomorphic and sedimentary units by using digitized bathymetric maps (Figure 8). The cross section profile of X at the western portion of the reservoir shows a steeper side slope with a general semi-circular bottom. The eastern portion of the bottom topography indicates more variation in elevation. In general, the X profile indicates the bottom geometry of the reservoir becoming higher and narrower, the top width of the reservoir remaining almost uniform, and the depth of the reservoir decreasing about 3 meters between 1978 and 1983.

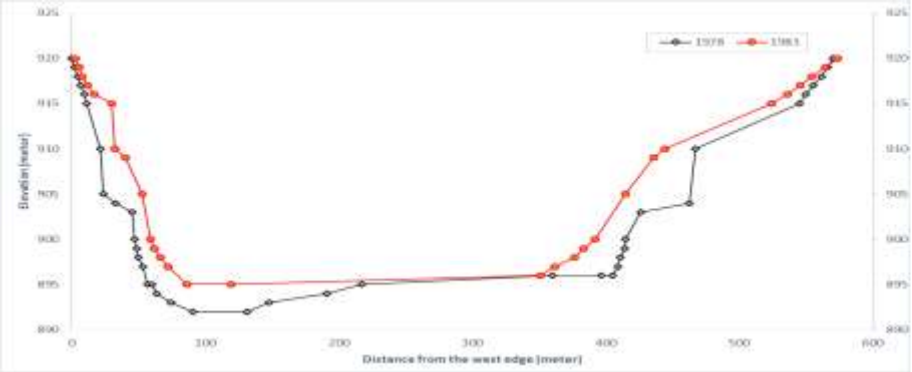

Figure 8: A cross section of X profile from the Cubuk I Reservoir in 1978 and 1983

A diagrammatic cross-section of Y profile from Cubuk II has an asymmetrical valley cross-section profile. The eastern side of the profile shows a steeper slope compared to the western portion of the reservoir. The elevation at the western portion of the reservoir has been raised. In contrast, the eastern section of the bottom topography shows incision, especially beyond 400 m from the western edge of the reservoir. In terms of the variation in the deepest polygon in the lake, profile Y does not show any variation because the elevation of 1060 m had been narrowed within 7 years and the profile line does not cross the polygon of 1060 m in 1983 (Figure 9). This change was probably due to a higher quantity of sediment deposition which masked the valley bottom topography in the lower portion of the reservoir.

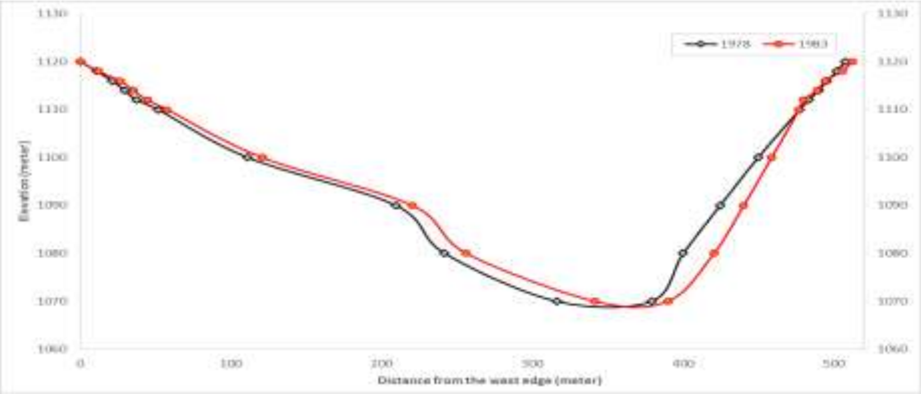

Figure 9: A cross section of Y profile from the Cubuk II Reservoir in 1978 and 1983

IV. Results

Sediment transported by stream flow may vary based on the quality and quantity of water entering a reservoir. Besides other variables, a larger amount of stream water caries coarser sediment and a greater quantity of bed load as well as suspended and dissolved load. Based on long term annual stream flow data (Figure 10) obtained from DSI, Cubuk II Reservoir has more variations than Cubuk I Reservoir because Cubuk II is likely to be more affected by natural events due to being located upstream. On the other hand, the potential water supply for the City of Cubuk and for other purposes such as irrigation decreases inflow to the Cubuk I Reservoir.

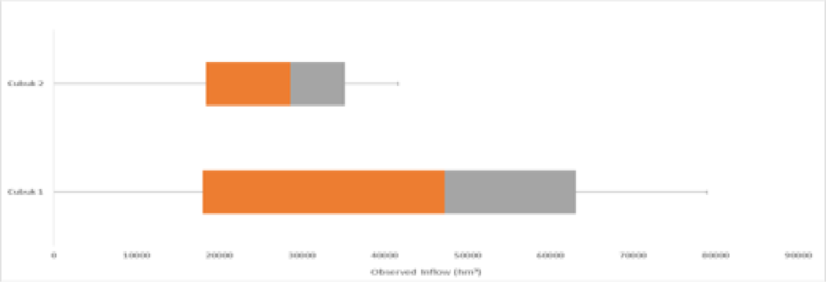

Figure 10: Annual observed discharge into the Cubuk I and Cubuk II Reservoirs (1977-2008)

The amount of sediment deposition in a reservoir also varies based upon the texture and size of sediment in the river system, the shape of the reservoir, detention storage time, and the manner of reservoir operation. In many cases, sediment settles out of the turbidity current and is deposited along the length of the reservoir as a thin layer across the bottom of a reservoir. The turbidity current may be supercritical (Frd> 1) or subcritical (Frd> 1) depending on the slope. Although the sediment particles in a turbidity flow are often cohesive, subcritical flow in a gradual slope is capable of carrying large amounts of finer suspended or dissolved materials into the deeper sections of the reservoir.

4.1. Historical Changes in the Storage Capacity

The storage capacity of Cubuk I and Cubuk II Reservoirs decreased between 1936 and 1983 (Figure 11 & 12), (Table 2). However, there was a slight increase in the storage capacity in 1967 and the storage capacity of Cubuk II Reservoir was increased in 1978. After 1944, the municipality of Cubuk's waste water went into the Cubuk I Reservoir and the reservoir lost its water source functionality within 50 years because of both sedimentation and waste water input caused by population growth.

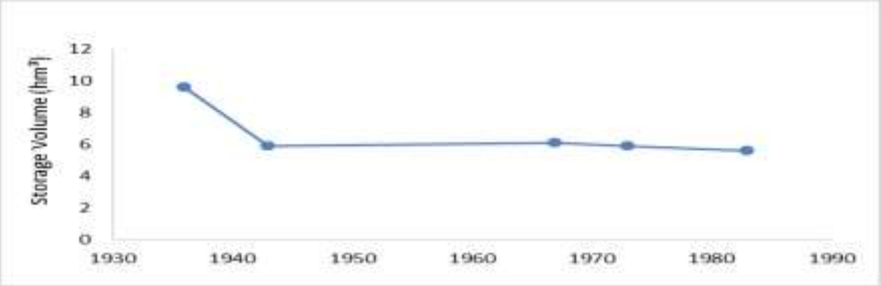

Figure 11: Historical changes of storage capacity in the Cubuk I Reservoir

The main reason for water storage losses of the reservoirs is siltation in the reservoir pool. Suspended sediment particles are deposited all over the reservoir as larger amount of sediment load than coarse sediments, which are usually accumulated in the upper reach of the reservoir as a delta. On the other hand, some coarser and finer materials may be deposited in natural and artificial barriers in the channels and their floodplains based on the amount and distribution of precipitation, steepness and slope of the surface area, soil texture, land cover, and land use (Yilmaz, 2003).

		1936	1943	1967	1973	1983
Cubuk I	MAX	9.6	5.9	6.1	5.9	5.6
hm^3	MIN	0.4	0	0.1	0	0

		1964	1973	1978	1983
Cubuk II	MAX	25	22.7	23.8	22.4
hm^3	MIN	1.9	0.6	0.6	0.3

Table 2: The historical changes of storage capacity in the Cubuk I and Cubuk II

The capacity of Cubuk I Reservoir was 12.5 hm^3 at normal water level. The bathymetric data indicate a reduction in volume of ~ 42 %, and the capacity of the reservoir decreased by an average of 5.25 hm^3 between 1936 and 1983. In other words, Cubuk I Reservoir has lost 1 % of its capacity every year, as noted in earlier studies (WCD, 2000).

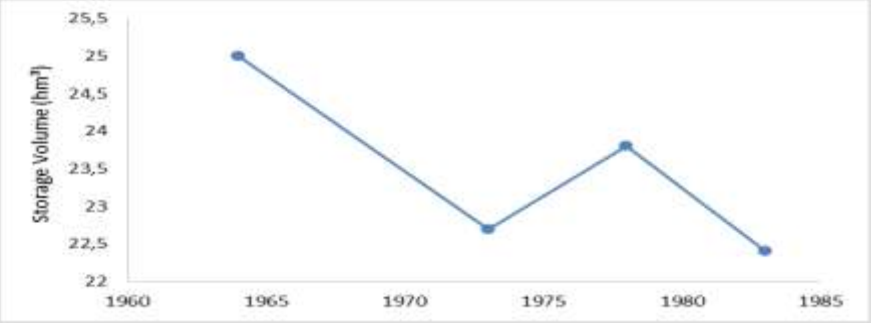

Figure 12: The historical changes of storage capacity in the Cubuk II Reservoir

4.2. Sediment Deposition in the Cubuk I Reservoir

The behavior of the Cubuk I Reservoir respecting sedimentation was expressed by plotting the change in the reservoir capacity between 1936 and 1983 based on the data obtained from DSI. The total sediment yield rate to Cubuk I Reservoir during 1935 – 1964 was computed as 303 m^3 / y/ km^2 (DSI).

The change in the reservoir bottom topography may be occurring at the downstream end due to the finer grain size materials that came from the tributaries. The reservoir was no longer used after 70 years because it filled with sediments. Dominant particle types are silt, clay and sand size materials in the basin (Kilic, 1984). These finer particles are likely transported to the deeper sections of the reservoir and deposited temporarily. An image taken in 2014 when the reservoir is drained shows deposition along the reservoir bed.

Figure 13 illustrates that water and sediment fluxes increased between 1989 and 1996. In April 1992, there was a big rain storm, but the 1996 flood did not generate a large sediment load to the reservoir because sediment transport depends upon numerous other factors.

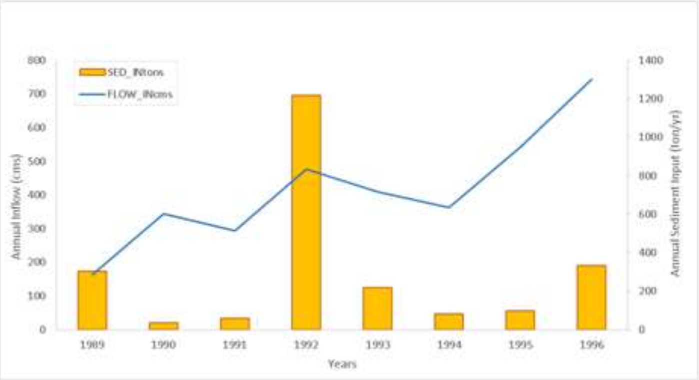

Figure 13: Annual sediment flux to Cubuk I Reservoir (simulated)

4.3. Sediment Deposition in the Cubuk II Reservoir

The drainage area of the Cubuk I Reservoir was reduced after the operation of Cubuk II Reservoir (in 1964) because Cubuk II is located upstream of Cubuk I. Cubuk II Reservoir collects most of the sediment coming from upstream, especially during a peak flow. Similarly, the capacity of Cubuk II Reservoir was reduced between 1964 and 1983. The only year of rising storage capacity was 1978. The graph showing changes in water surface area indicates that there was about 10 m lost from deposition in the deepest section of the reservoir. From the areal images, I identified a delta at the entrance of the main tributary. Delta formation and deposition along the length of the reservoir seem to occur.

The variation in cross sections of the reservoir headwater area indicates that the location of the delta does not influence the channel width at the main stream entrance into the reservoir. However, the river generates a meandering channel in the alluvial deposits (Figure 62). On the other hand, annual water and sediment inflow to the Cubuk II Reservoir was increased between 1989 – 1996. Especially during peak flow periods such as in 1992 and in 1996, a huge amount of sediment was brought to the reservoir by peak flow. The chart showing annual sediment and water inflow to Cubuk II Reservoir seems more consistent than the other chart for Cubuk I as higher stream flow generates more sediment flux (Figure 14).

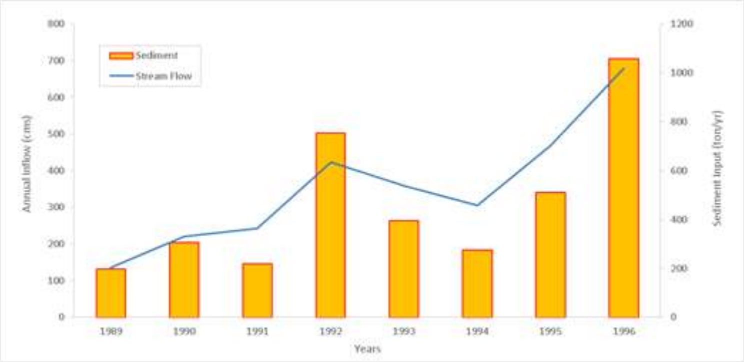

Figure 14: Annual sediment flux to Cubuk II Reservoir (simulated)

V. Conclusion

The storage capacity of the Cubuk I and Cubuk II Reservoirs decreased between 1936 and 1983 because of siltation. A significant amount of siltation occurred between the year of 1978 and 1983: Cubuk I reservoir accumulated 3 m of sediment within 6 years and Cubuk II accumulated about 10 m. In general, stream flow carries substantial sediment after a big storm such as the one in April 1992. Delta formation is clearly observed at the headwater area of Cubuk II Reservoir and other ephemeral tributaries also contribute lower amounts of suspended sediments, especially during spring. Besides reservoir shoreline management practices along the steeper slopes, debris dams (upstream check points) could be used along the main tributaries that bring large amount of sediment into reservoirs. Reservoir sediment management practices should be also performed for each upstream debris dam in order to extend the life of these human made structures. Collection of more accurate spatially and temporally distributed data on bathymetry can help to reduce model uncertainty, so future studies in the catchment should focus on improving the database by obtaining more recent higher resolution bathymetric maps.

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