Sediment yield estimation of a hydrological basin using measurements of reservoir deposits: A case study for the Kremasta reservoir, Western Greece.

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Abstract: Sediment discharge measurements in streams are quite rare even in technologically advanced countries, whilst comprehensive physically based models are generally unable to reliably estimate sediment yield of large-scale hydrological basins. A more realistic and reliable alternative method for sediment yield estimation, suitable for watersheds with a dam at the outlet, is the hydrographic surveying of the reservoir’s invert and comparison with the one prior to the dam construction resulting to the computation of sediment deposits’ volume and mass. This method has been applied to the Acheloos River basin with the hydrographic surveying of Kremasta, a large reservoir with net storage capacity exceeding 3 cubic kilometers. The sediment yield has been estimated not only for the total watershed but also for each of the three tributaries (Acheloos R., Agrafiotis R. and Megdobas R.). Besides, the soil erosion of the watershed has been estimated using an implementation of the Universal Soil Loss Equation on a geographical information system. The sediment delivery ratios have been finally computed combining the sediment yield and soil erosion estimates.

Key words: delivery ratio, sediment yield, hydrographic survey, Digital Elevation Models, source erosion, Kremasta reservoir, Greece

1. INTRODUCTION

The deposition of sediment in reservoirs can variously impact their performance through storage capacity losses, damage to valves and conduits, reduced flood attenuation and changes in water quality. Though generally
not recognised as a widespread water resource problem in Greece, growing
evidence points to areas with locally severe sediment discharge problems,
particularly in the upland areas of western Greece (Zarris et al., 2001). The
production, transportation and deposition of sediment are extremely variable
both in space and time. There is variation within and between catchments,
such that Campbell (1992) reported that 70% of the sediment load for a river
in Alberta, Canada was contributed by only 2% of its area. He suggested that
drainage basins are “fuzzy systems”, with internal basins constantly
changing and this may cause major difficulties in estimates of catchment
sediment yields. Additionally, simple statistical models (such as the
sediment rating curves) and advanced physically-based models fail to
produce an accurate estimation of sediment yields in large scale water
systems. The difficulties of recording such variations have led researchers
such as Heinmann (1984), Duck and McManus (1994), Rowan et al. (1995)
to prefer the use of reservoir studies for establishing catchment sediment
yields. Foster and Walling (1994) have suggested that, given the absence of
long-term fluvial sediment monitoring programmes in global terms, the
sediment records stored in lakes and reservoirs offer very considerable
potential for reconstructing the history of sediment mobilisation and
transport over the past 100 years.

2. RESEARCH APPROACH

2.1 Description of the Kremasta reservoir

The Kremasta reservoir was constructed in 1964 and is located in North-
Western Greece. The reservoir area at the spillway crest is 80.6 km² and the
total storage volume is 4495 hm³. The reservoir watershed has an area of
3292 km², elevation ranging from +284 m to +2433 m and the mean annual
inflow to the reservoir equals 117.1 m³/s. This inflow is largely provided by
Acheloos River and to a lesser extent by Agrafiotis River and Megdovas
River (see Figure 1). Mean annual areal precipitation equals 1433 mm. The
geology of the catchment is largely dominated by limestone and flysch.
2.2 Description of research method

A key element of the proposed method is to construct the Digital Elevation Models (DEM) for two periods of interest, one prior to the dam construction (1964) and the other during the hydrographic survey (1998-99). The hydrographic survey has been carried out using a differential Global Positioning System (GPS) technique and a typical fathometer operating at the frequency of 130 kHz for depth determination. Therefore the method is subject to the usual errors e.g. GPS limited availability and the definition of the water-mud interface. The DEM at the time prior to the dam completion was constructed from digitising the original survey maps (scale 1:5000). The corresponding DEM from the hydrographic survey resulted from an irregular network of points in three dimensions (position and elevation). The associated grids were interpolated from triangulation with linear interpolation procedures available in the SURFER mapping package. The difference in elevation results in the volume of deposited sediments.

The spatial distribution of accumulated sediment in the reservoir shows profoundly that the total incoming sediment remains in the reservoir and particularly at the uppermost parts (deltaic deposits) (see Figure 2).
The total sediment deposits volume was calculated equal to 66.6 hm$^3$. To convert volumetric changes to sediment yield in mass units the material properties of the deposited sediment were also investigated by collecting two core samples from the reservoir invert using appropriate instrumentation (i.e. LONGYEAR 36 hydraulic corer). Direct measurement of deposits density was not possible mainly because it was impossible to collect undisturbed samples. However, density was estimated from the proportion of sand, silt and clay in the samples using the Lane and Koelzer (1943) formula. The total sediment mass accumulated in the reservoir for the whole period of dam operation was estimated at 112.5 Mt. Therefore the mean annual sediment yield is estimated equal to 1005 t/km$^2$ and the corresponding mean annual sediment discharge equal to 106.4 kg/s. The final results in terms of accumulated volume, accumulated mass, mean annual sediment yield and discharge for the whole catchment as well as the three tributary sub basins are shown in Table 1.

Agrafiotis River basin, which is the smallest one, contributes the most considerable sediment load per unit catchment area. The corresponding value is one of the highest mean annual sediment yield found in international
Sediment yield estimation using reservoir deposits

literature and is a result of rainfall intensity, geology, morphology and the small extent of its area.

Table 1: Characteristic variables for the each sub-catchment.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Basin Area (km²)</th>
<th>Accumulated volume (hm³)</th>
<th>Accumulated mass (Mt)</th>
<th>Mean annual sediment yield (t/km²)</th>
<th>Mean annual sediment discharge (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acheloos R.</td>
<td>1733</td>
<td>41.3</td>
<td>69.8</td>
<td>1184.6</td>
<td>66.0</td>
</tr>
<tr>
<td>Agrafiotis R.</td>
<td>320</td>
<td>13.1</td>
<td>22.1</td>
<td>2034.8</td>
<td>20.9</td>
</tr>
<tr>
<td>Megdovas R.</td>
<td>1239</td>
<td>12.2</td>
<td>20.6</td>
<td>489.4</td>
<td>19.5</td>
</tr>
<tr>
<td>Total</td>
<td>3292</td>
<td>66.6</td>
<td>112.5</td>
<td>1005.6</td>
<td>106.4</td>
</tr>
</tbody>
</table>

In contrast to sediment yield, mean annual sediment discharge is less significant due to the smaller extent of its watershed, but is still higher than the adjacent Megdovas River catchment.

2.3 Source erosion estimation

Source erosion may be computed using the well known Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978). The numerical values of the different factors of the equation have been computed after processing data collected in small catchments in the United States. This obviously suggests a weakness of the method in case of applying it elsewhere from the US with different climatic and topographic conditions. Additionally, USLE does not account for sediment transport in hillslopes and streams and does not perform well in large scale catchments. However, in terms of computing only the catchment soil erosion, USLE is a quite satisfactory preliminary approximation. The value of the rainfall erosivity factor $R$ is computed from the mean annual rainfall using the relation given by Schwertmann et al. (1990).

In the present study soil erosion was computed using a GIS implementation of the USLE. The graphical interface is called SEAGIS (after Soil Erosion Assessment using GIS) and was originally developed at the Danish Hydraulic Institute (DHI, 2000).

Mean annual erosion rates ($Y_e$) and sediment delivery ratios ($D$) (i.e. the ratio of sediment yield to source erosion) for each catchment are shown in Table 2. Delivery ratios follow the well-established trend of decreasing values with increasing catchment surface.
Table 2: Source erosion and delivery ratios.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Area (km²)</th>
<th>Mean annual source erosion (t/km²)</th>
<th>Delivery ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acheloos R.</td>
<td>1733</td>
<td>7077</td>
<td>0.17</td>
</tr>
<tr>
<td>Agrafiots R.</td>
<td>320</td>
<td>4847</td>
<td>0.42</td>
</tr>
<tr>
<td>Megdovas R.</td>
<td>1239</td>
<td>2251</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3292</strong></td>
<td><strong>5040</strong></td>
<td><strong>0.20</strong></td>
</tr>
</tbody>
</table>

3. DISCUSSION

The value of sediment volume for 50 years of the dam operation was determined in the original dam design study equal to 394 hm³ (ECI, 1974). This value is profoundly higher than the actual one resulted from the hydrographic survey. The reason of the over-dimension of the reservoir’s dead volume lies in the sediment discharge measurements taken at that time. A total of 29 suspended sediment measurements had been accomplished in two months time during a winter period and a sediment rating curve had been evaluated. Besides the purely statistical considerations related to serially correlated error terms (Weber et al., 1976, Lemke, 1991), it is obvious that the two month period is too short to lead to a reliable estimation of the interannual sediment yield.

Additionally, the spatial distribution of the sediment deposits in the reservoir illustrates that at least for large reservoirs, the concept of designing the dead volume near the dam (i.e., below a certain constant reservoir level) is under serious doubt. Specifically, for the reservoir under study, the deposits tend to occupy a significant (in absolute terms) part of the reservoir’s useful volume whilst the nominal dead volume is almost empty of sediments.

Sediment delivery ratios resulted from the above methodology shows a generally compatible behavior with existing data. For example, delivery ratios are in very close agreement with the relation given by Laurence (1996), who correlated data from various catchments of the world and concluded that delivery ratio \( D \) is expressed according to catchment area \( A \) (km²) with the power law \( D = A^{0.2} \). Renfro (1972) on the other side using different source of data concluded in the relationship \( \log D = 1.877 - 0.1419 \log(25.9A) \), where \( D \) is expressed as a percentage and \( A \) in km². The associated values are 0.2 and 0.15 respectively. However, mean annual sediment yield values are considerably higher than corresponding values given in the literature. For instance, Dendy and Bolton (1976) used data from the US which suggested that there is a statistically significant relationship between mean annual sediment yield (t/km²/y) and drainage area (km²).
expressed as $Y_i = 674A^{-0.2}$. In our case this leads to a seriously underestimated value of 133.4 t/km². Furthermore, Parker and Osterkamp (1995) compiled mean annual suspended sediment discharges from 24 gauged rivers in the US. Drainage areas ranged from $1.6 \times 10^3$ to $1.8 \times 10^6$ km². Mean annual suspended sediment yields ranged from less than 5 to over 1480 t/km². A possible explanation for the considerable higher sediment yields in Greece lies on the fact that morphological factors (e.g. tectonic activity) coupled with the dominant geological layers (e.g. flysch) act as additional forces to sediment availability within the catchment.

4. CONCLUSIONS

Measurements of sediment deposits in a reservoir are a quite satisfactory method for reconstructing sediment yield records of a drainage basin. In order for the method to be reliable the reservoir must be large enough so that its trap efficiency approaches unity. An apparent weakness of the method is that it gives only an interannual average of the sediment yield and not its temporal evolution. However, if frequent hydrographic surveying of the reservoir is permitted (e.g. every 5 years) then sediment yield can be computed in finer time scales. Alternatively, this method can be combined with hydrological models as well as sediment discharge measurements in upstream locations to reconstruct the temporal evolution of reservoir sedimentation.

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