Sediment yield estimation from a hydrographic survey: A case study for the Kremasta reservoir basin, Greece.

D. ZARRIS[1], E. LYKOUDI[2] AND D. KOUTSOYIANNIS[1]
(1) Department of Water Resources, Faculty of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 5, Zographou, Greece.
(2) Department of Geological Sciences, Faculty of Mining Engineering and Metallurgy, National Technical University of Athens, Heroon Polytechneiou 5, Zographou, Greece.

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 *Campell* (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 potentional 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 km^2 and the total storage volume is 4495 hm^3. The reservoir watershed has an area of 3292 km^2, elevation ranging from +284 m to +2433 m and the mean annual inflow to the reservoir equals 117.1 m^3/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.

Figure 1: Kremasta reservoir watershed.

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*).

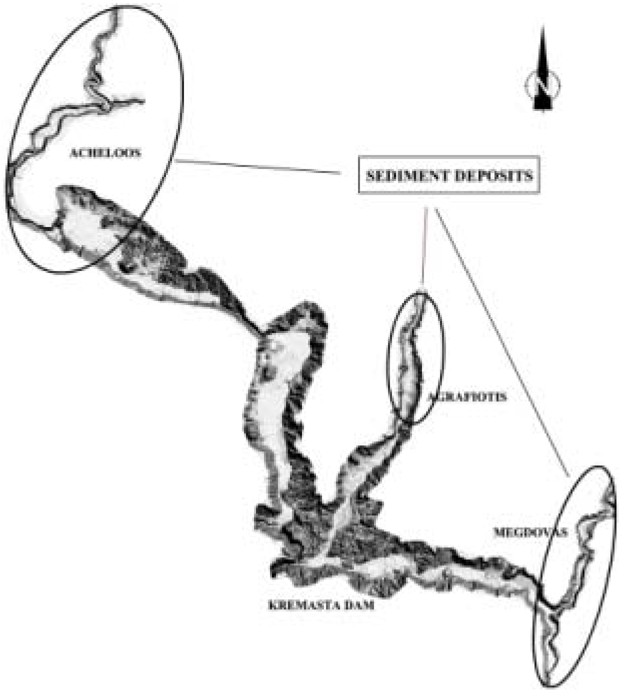

Figure 2: Spatial distribution of accumulated sediments in the Kremasta reservoir.

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

Table 1: Characteristic variables for each sub-catchment.

Basin	Area (km^2)	Accumulated volume (hm^3)	Accumulated mass (Mt)	Mean annual sediment yield (t/km^2)	Mean annual sediment discharge (kg/s)
Acheloos R.	1733	41.3	69.8	1184.6	66.0
Agrafiotis R.	320	13.1	22.1	2034.8	20.9
Megdovas R.	1239	12.2	20.6	489.4	19.5
Total	3292	66.6	112.5	1005.6	106.4

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.

Basin	Area (km^2)	Mean annual source erosion (t/km^2)	Delivery ratio
Acheloos R.	1733	7077	0.17
Agrafiotis R.	320	4847	0.42
Megdovas R.	1239	2251	0.22
Total	3292	5040	0.20

3. SEDIMENT DELIVERY PROCESSES

The value of sediment volume for 50 years of the dam operation was determined in the original dam design study equal to 394 hm^3 (*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 overyear 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 (km^2) 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 km^2. 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 ($t/km^2/y$) and drainage area (km^2) expressed as $Y_i = 674A^{-0.2}$. In our case this leads to a seriously underestimated value of 133.4 t/km^2. Furthermore, *Parker and Osterkamp* (1995) compiled mean annual suspended sediment discharges from 24 gauged rivers in the US. Drainage areas ranged from 1.6×10^3 to 1.8×10^6 km^2. Mean annual suspended sediment yields ranged from less than 5 to over 1480 t/km^2. 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. CONCLUSION AND DISCUSSION

The hydrographic survey of a reservoir is a quite satisfactory procedure for reconstructing sediment yield records of a drainage basin. An apparent weakness of the method is that it gives only an overyear 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.

Its strongest merit, however, remains the illustration of the spatial distribution of accumulated sediments within the reservoir. Dead storage remains almost free of deposited sediments whilst parts of the nominal useful storage are occupied from accumulated sediments. This obviously means that the total loss of stored water is significantly greater than it was originally assumed and it certainly becomes a waste of a valuable natural resource. In this specific case, the depositional pattern inside the reservoir reveals the apparent necessity of reconsidering the dead volume principle, in terms of a thorough investigation and modelling of sediment yield in the water resources management context.

AKNOWLEDGMENTS

This work is part of a research project funded from the General Secretariat of Research and Technology (GSRT) and the Public Power Corporation (PPC). The authors would like to thank D. Paradeisis, T. Zissopoulos and J. Kotsis for their valuable assistance during the hydrographic survey of the Kremasta reservoir and also N. Mamassis and A. Koukouvinos for their contributions in GIS issues. The assistance of the PPC supervisor of the project H. Makrygiorgos is very much appreciated. The authors are very much indebted in the Danish Hydraulic Institute (DHI) for offering the SEAGIS software for the source erosion analysis. Last but not least the authors would like to show their gratitude to the staff of the PPC responsible for the digitisation of the initial topographic maps.

REFERENCES

Campell, I.A.: 1992, Spatial and temporal variations in erosion and sediment yield. In: Erosion and sediment transport monitoring programmes in river basins, Proc. Intern. Symp., Oslo, 24-28 August, IAHS Publ. No. 210, pp 455-465.

Danish Hydraulic Institute: 1999, SEAGIS v. 1.0: Documentation and user's manual.
Dendy, F.E. and G.C. Bolton: 1976, Sediment yield-runoff drainage area relationships in the United States, J. Soil and Water Cons., 31, 264-266.
Duck, R.W. and J. McManus: 1994, A long term estimate of bedload and suspended sediment yield derived from reservoir deposits, Journal of Hydrology, 159, 365-373.
Engineering Consultants Inc.: 1974, Technical record of investigation, authorisation, design and construction of dam and power project, Kremasta project report Volume I, Colorado, USA.
Foster, I.D.L. and D.E. Walling: 1994, Using reservoir deposits to reconstruct changing sediment yields and sources in the catchment of Old Mill reservoir, South Devon, UK over the past 50 years, Hydrological Sciences, 39, 4, pp. 347-368.
Heineman, H.G.: 1984, Reservoir trap efficiency, In: Erosion and sediment yield: some methods of measurement and modelling, pp. 201-217, University Press, Cambridge.
Lane, E.W. and V.A. Koelzer: 1943, Density of sediments deposited in reservoirs, Rep. No. 9, St. Paul US Engrg., District Sub-Office Univ. of Iowa, USA.
Lemke, K.: 1991, Transfer function models of suspended sediment concentration, Water Resour. Res., 27 (3), 293-305.
Parker, R.S. and W.R. Osterkamp: 1995, Identifying trends in sediment discharge from alternations in upstream land use. Proceedings of a Boulder Symposium "Effects of scale in interpretation and management of sediment and water quality, IAHS Pub., No. 226, 207-213.
Renfro, G.W.: 1972, Use of erosion equations and sediment delivery ratios for predicting sediment yield, in "Sediment yield workshop: Present and prospective technology for predicting sediment yield and sources" Proceedings USDA Sedim. Labor., USA, pp. 33-45.
Rowan, J.S., P. Goodwill and M. Greco: 1995, Temporal variability in catchment sediment yield determined from repeated bathymetric surveys: Abbeystead Reservoir, UK, Phys. Chem. Earth, (20) 2, 199-206.
Schwertmann, U., W. Vogl and M. Kainz: 1990, Bodenerosion durch Wasser, Verlag Eugen Ulmer, Stuttgart.
Weber, J.E., M.M. Fogel and L. Duckstein: 1976, The use of multiple regression models in predicting sediment yields, Water Resources Bulletin, 12 (1), 1-18.
Wischmeier, W.H. and D.D. Smith: 1965, Predicting rainfall erosion losses from cropland east of the Rocky Mountains, Agric. Handbook 282, U.S. Gov. Print. Office, Washington, DC.
Wischmeier, W.H. and D.D. Smith: 1978, Predicting rainfall erosion losses; A guide to Conservation planning, Agriculture Handbook No. 537, USDA Sci. and Educ. Admin., Washington D.C.
Zarris, D., E. Lykoudi and D. Koutsoyiannis: 2001, Appraisal of river sediment deposits in reservoirs of hydropower dams, Research Project, Final Report, National Technical University of Athens, Greece (in Greek).