Sediment Budgets 2 (Proceedings of symposium S1 held during the Seventh IAHS Scientific Assembly at Foz do Iguaçu, Brazil, April 2005). IAHS Publ. 292, 2005.

Some experience on the prediction of suspended sediment concentrations and fluxes in Croatia

JOSIP PETRAS, NEVEN KUSPILIC & DUSKA KUNSTEK
Faculty of Civil Engineering, University of Zagreb, Kaciceva 26, 10000 Zagreb, Croatia
kuspa@grad.hr

Abstract Botonega Reservoir was constructed as a multi-purpose facility for flood control and for the storage of surface runoff for drinking water and irrigation. Because of the underlying flysch deposits and hilly terrain, soil erosion in the region is extensive. In order to assess the impact of erosion and sediment transport into the reservoir, soil erosion intensity, as well as sediment yields and transport, were estimated for the catchment. The initial evaluation was carried out according to Gavrilovic's parametric method, which is traditionally used in Croatia. During an 11-year period, hydrological surveys were conducted in the catchment. The calculated values generated using Gavrilovic's method are approximately 11 times higher than the measured quantities, and hence, appear unreliable. However, upon combining Gavrilovic's method with GIS technology, estimations of sediment production and transport for the 11-year measurement period only exceeded the measured values by 37%. This leads to the conclusion that Gavrilovic's method, when used in conjunction with GIS technology, can produce reasonably accurate estimations.
Key words catchment area; erosion processes; Gavrilovic's parametric method; GIS; suspended sediment

INTRODUCTION

Botonega Reservoir was constructed in the central part of Istria (Croatia) in 1987 as a multi-purpose facility for flood mitigation and for the storage of surface runoff for drinking water and irrigation (Elektroprojekt, 1971). The reservoir represents the major water source in the region, and economic development in Istria would be impossible without it. Because the reservoir catchment is quite hilly, as well as underlain by extensive flysch deposits, local soil erosion is intense.

During the reservoir design phase, estimates of the annual sediment yield, as well as annual siltation rates, were developed; these amounted to 300 m^3 km^2 $year^{-1}$, or 21 000 m^3 $year^{-1}$, respectively. Further, a total siltation rate of 2 100 000 m^3 was estimated for the proposed 100-year service life of the facility. These estimates were made in accordance with published standard procedures and were based on the physical characteristics of the catchment that were observed during field surveys (Elektroprojekt, 1971).

There are numerous published documents associated with estimating catchment sediment yields and for predicting reservoir siltation rates (UNEP/PAP/MAP/ RAC, 1997; USDA, 1997; Morris & Fan, 1998). However, in Croatia, the standard procedure for estimating catchment sediment yields and subsequent sediment transport, is based on the parametric method developed by Gavrilovic (1972). Unfortunately, application of the Gavrilovic method indicated that catchment sediment yields, and the subsequent reservoir siltation rates, would be markedly higher than estimated using the other procedures. If accurate, the life expectancy for the Botonega Reservoir would be about 33 years, a markedly shorter period than planned (~100 years). On the other hand, bathymetric surveys indicated that actual reservoir siltation rates were substantially lower than predicted by Gavrilovic's method. A discussion of the Gavrilovic method, as applied to the Botonega Reservoir, is presented.

THE BOTONEGA RESERVOIR CATCHMENT

The total estimated volume of the Botonega Reservoir is 19.7×10^6 m^3, of which some 2.2×10^6 m^3 were set aside for siltation losses (Elektroprojekt, 1971). The area of the reservoir catchment is 71.5 km^2; elevations range from 40 to 400 m a.s.l. (Elektroprojekt, 1971). Mean annual precipitation is 1130 mm, with maximum rainfall occurring in spring and autumn; daily precipitation maxima can exceed 100 mm (Elektroprojekt, 1971). Local relief is very indented and highly incised, and the catchment encompasses a dense network of high velocity streams. Hence, conditions in the catchment favour elevated levels of erosion and flooding. Thirteen different soil types have been identified in the catchment, many are erosion-prone (Elektroprojekt, 1971). Most of the catchment is underlain by Eocene flysch, consisting of alternating layers of marl and sandstone, conglomerate and limestone, which helps explain the sharp relief, shallow soils, and limited vegetative cover (Elektroprojekt, 1971). The marl-bearing layers of the flysch are particularly erosion-prone, whereas the sandstone and limestone layers are more resistant. Because flysch is compact, and tends to be relatively impermeable, geological weathering is very slow, and plant roots can not penetrate through the soil into the underling rock. These factors all contribute to the development of highly erodible soil layers.

GAVRILOVIC'S METHOD

Basically, the method focuses on evaluating the existing state of erosion in a catchment. Estimations of sediment yield are made according to the parametric formula:

$$W_y = T \cdot H_y \cdot \pi \cdot Z^{3/2} \quad (1)$$

with sediment transport into the reservoir calculated according to:

$$G_y = W_y \cdot R_u \quad (2)$$

where W_y is the specific annual erosion within the watershed (m^3 km^{-2} year^{-1}); T is the temperature coefficient of the area, $T = (0.1\ t_0 + 0.1\ )^{0.5}$, where t_0 is the average annual air temperature (°C); H_y is the average annual precipitation (mm); Z is an indicator (coefficient) of soil erosion; G_y is the specific annual sediment transport into the reservoir (m^3 km^{-2} year^{-1}); $\pi = 3.14$; and R_u is the coefficient of sediment transport ($R_u < 1$).

The reliability of this method primarily depends on the coefficients Z and R_u. The coefficient R_u is calculated according to:

$$R_u = (O \cdot D)^{0.5}/0.25(L + 10) \tag{3}$$

where O is the length of the border of the catchment area (km); and D is the mean difference in the elevation of the catchment (km), calculated according to the formula:

$$D = N_{sr} - N_u \tag{4}$$

where N_{sr} is the mean altitude of the catchment area up to the profile for which sediment transport is being calculated (a.m.s.l.); N_u is the height of the bottom of the watercourse bed at the profile for which sediment transport (income) is being calculated (a.m.s.l.); and L is the length of the catchment area along the channel of the main watercourse (km). The coefficient Z has to be calculated according to:

$$Z = Y \cdot X \cdot a(b + I_{sr}^{0.5}) \tag{5}$$

where Y is a coefficient (parameter) of soil resistance to erosion; X is a coefficient (parameter) of existing vegetative status; a, coefficient of the catchment-wide reclamation for the purposes of erosion reduction; b is a coefficient of visible and clearly dominant erosion processes; and I_{sr} is a parameter of topography (average slope gradient for the catchment area).

Gavrilovic (1972) provided recommendations for defining the various coefficients (Y, X, a, and b) in equation (5). He also created an analytical equation (6) for estimating the percentage that bed load transport represents out of total sediment transport (estimated by equation (2)) on the basis of field measurements and laboratory analyses of sediment samples:

$$BL = Z(Y_v - 1)/(\pi \cdot Y_s) \tag{6}$$

where BL is the percentage of bedload; Z is an erosion coefficient according to equattion (5); Y_v is the specific mass of bedload sediment (t m^{-3}); and Y_s is the specific mass of suspended sediment (t m^{-3}).

According to equation (6), bedload sediment can be estimated as:

$$G_d = c \cdot G_y \tag{7}$$

and, consequently, the suspended sediment is:

$$G_s = (1 - c) \cdot G_y \tag{8}$$

where G_y is the annual total sediment flux into the reservoir (m^3 km^{-2} year^{-1}) according to equation (2); G_d is the specific annual bedload sediment transported into the reservoir (m^3 km^{-2} year^{-1}); and G_s is the specific annual suspended sediment flux into reservoir (m^3 km^{-2} year^{-1}).

GIS TECHNOLOGY APPLIED TO THE PREDICTION OF SEDIMENT FLUXES

It would appear that a marriage between the physical principles of erosion, combined with current GIS software, could provide a means for accurately predicting total sediment transport. There are numerous parametric methods for estimating sediment yield and transport (UNEP/PAP/MAP/RAC, 1997; USDA, 1997, Morris & Fan, 1998). All tend to be based on supplying calibrated values that represent the four basic factors that control the rate of erosion: (a) climate (e.g. precipitation, temperature); (b) vegetation (e.g. type, density); (c) relief (e.g. differences in elevation; slope angle); and (d) soil properties (e.g. erodibility; porosity). In practice, calibrating parametric models for predicting erosion and sediment transport requires detailed preparation including map digitization, extended field sampling and subsequent laboratory analyses, and extensive data processing and model validation. The current availability of aerial and satellite remote sensing data, as well as digital and specialized (thematic) maps, should substantially simplify the process of estimating erosion and subsequent sediment transport (ESRI, 1995, 1996, 1997).

Through the use of GIS technology and software, it should be possible to identify the areas within a given catchment that have similar erosion potential. This would require the generation of a digital elevation model and the identification of areas having similar mean gradients, lengths, differences in elevation, etc. Essentially, the final product would be a multi-layered map identifying areas with equivalent erosion potential (CORINE, 1992). This idea devolves back to the procedures developed for erosion potential mapping within the 1997 UNEP/PAP Programme (United Nations Environment Programme/Priority Actions Programme) (UNEP/PAP/MAP/RAC, 1997). The appropriate GIS technology was developed by Husnjak (2000) and Holjevic (2002). By pre-defining those areas of equal erosion potential, the level of field work and subsequent laboratory analyses required to parameterize these discrete erodibility classes could be limited to a few selected sites within a single catchment.

PREDICTING SEDIMENT YIELDS AND TOTAL SEDIMENT TRANSPORT

An initial approximation of total sediment flux into Botonega Reservoir was made by applying Gavrilovic's method in the traditional way. The values employed for the requisite parameters were generated using Gavrilovic's recommendations, which attempt to approximate existing soil erosion processes and which employed 1:25 000 scale topographic maps of the catchment. Using this approach, sediment yield was estimated at 1100 m^3 km^2 $year^{-1}$, whereas total sediment flux was estimated at 79 000 m^3 $year^{-1}$. These estimates were some 3.7 times higher than those generated during the design phase of reservoir construction, and meant that the service life of the facility would be some 30 rather than 100 years. These calculations were made just after the reservoir opened, and unleashed a major effort to try and develop an appropriate management plan to substantially reduce the rate of erosion in the catchment. The resulting plan combined biological measures (e.g. increasing the vegetative cover to reduce erosion) with infrastructural changes (e.g. construction of sediment detention ponds).

In 1989, a soil detention barrier was built upstream, but relatively near the reservoir. The barrier was an earthen dam with a sediment capacity of 165 000 m^3. Relatively clear water flows out of the detention basin through a box-like concrete overflow (Holjevic, 2002). Bed load is totally retained, whereas suspended sediment is limited as a result of reduced water velocities. In 2000, 11 years after construction of the earthen dam, a bathymetric survey indicated that some 19 000 m^3 of sediment had been deposited in the detention basin (Holjevic, 2002). This result was compared to an estimate generated using Gavrilovic's method, applied in the traditional way, for the

25.5 km^2 subcatchment that represented the sediment source for the detention barrier. The estimate, generated by using equation (2) was 19 500 m^3 year^{-1}, some 11 times higher than the actual measurement. This led to the conclusion that Gavrilovic's method was unreliable. Unfortunately, the traditional application of the method is highly subjective, and dependent on the analyst's ability to adequately evaluate the requisite erosion parameters.

On the other hand, a good deal of the subjectivity associated with the traditional application of the method can be eliminated through the use of appropriate GIS

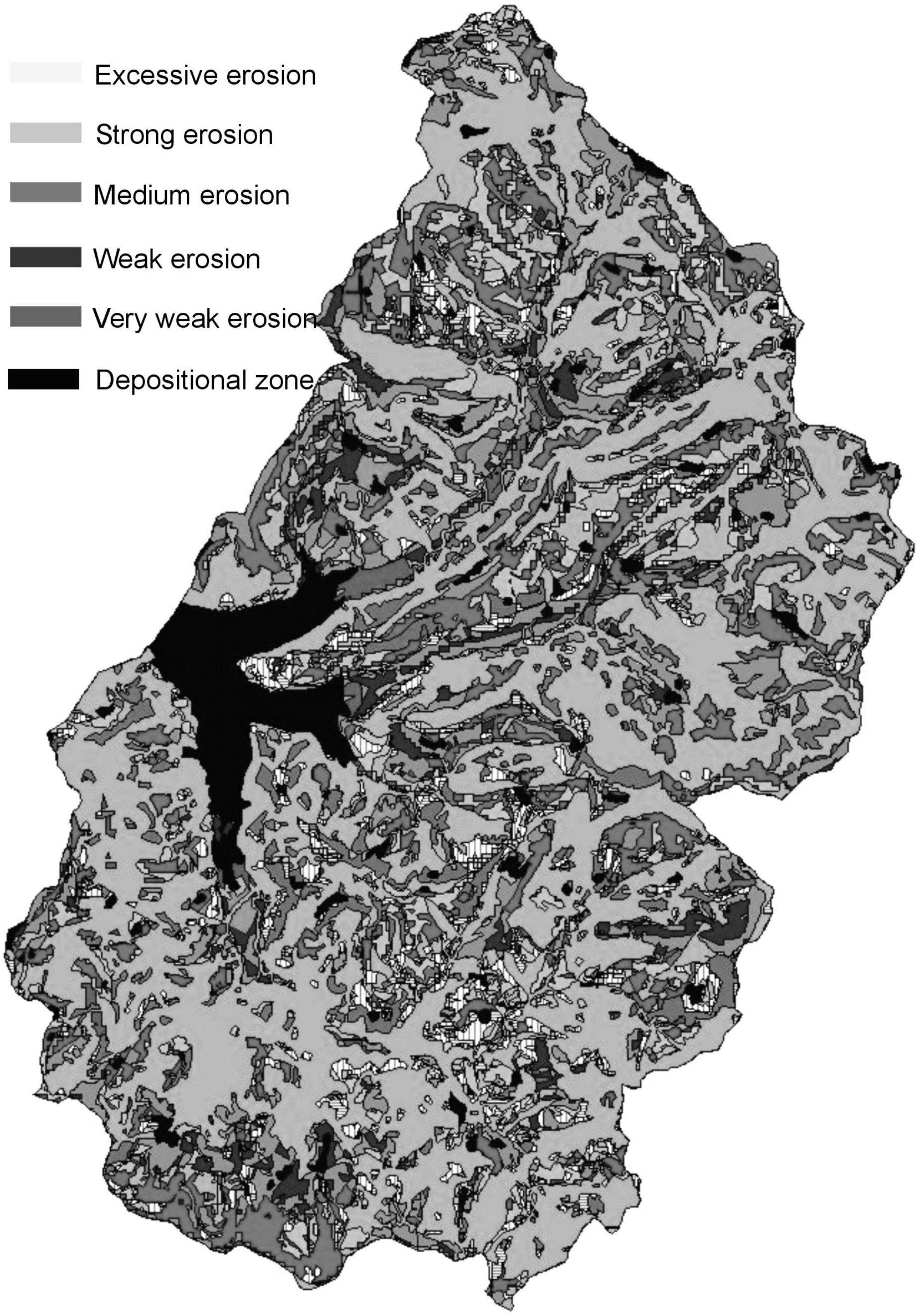

Fig. 1 Map of erosion intensity for the Botonega Dam watershed.

software. When Gavrilovic's method was applied in conjunction with parameters estimated using GIS software (Fig. 1), the new estimate amounted to 26 000 m^3 in 11 years; this is only 37% higher than the estimate obtained from the bathymetric survey. This revised estimate would indicate that Gavrilovic's method is capable of producing reasonably accurate estimates of sediment yield and transport, provided that it is used in conjunction with GIS software. It should be noted that part of the validation of the combined Gavrilovic/GIS technique required measurements of the suspended sediment inflow and outflow from the detention barrier. Unfortunately, this revealed that some 90% of the suspended sediment entering the detention barrier was not retained, and ultimately, wound up in the Botonega Reservoir. Hence, the effectiveness of the detention barrier is questionable.

CONCLUSIONS

The estimation of catchment-specific sediment yields and total sediment transport using Gavrilovic's method in the traditional way appears to be fairly inaccurate; possibly as a result of the subjective methods employed to estimate the requisite parameters. However, if subjective judgment is replaced with GIS-generated estimates of the same parameters, the method tends to produce more accurate results. Hence, the problems associated with Gavrilovic's method are not so much related to the underlying theory, but to the experience and insight of the analyst.

REFERENCES

Elektroprojekt (1971) *Akumulacija Botonega.* Main design documentation, Zagreb, Croatia.

Gavrilovic, S. (1972) *Inzenjering o bujicnim tokovima i eroziji*, Jurnal: *Izgradnja*, Beograd, ex Yugoslavija.

Morris, G. L. & Fan, J. (1998) *Reservoir Sedimentation Handbook*; *Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use.* MacGraw-Hill, New York, USA.

UNEP/PAP/MAP/RAC (1997) *Guidelines for Mapping and Measurement of Rainfall-Induced Erosion Processes in the Mediterranean Coastal Areas*, United Nations Environment Program/Priority Action Programme/Mediterranean Action Plan /Regional Activity Centre, Split, Croatia.

USDA (US Department of Agriculture) (1997) *Predicting Soil Erosion by Water*—A Guide to Conservation Planning with the Revised Universal Soil Loss Equation. Agriculture Handbook Number 703.

CORINE (Coordination of Information on the Environment) (1992) Soil erosion risk and important land resources in the southern regions of the European Community—an assessment to evaluate and map the distribution of land quality and soil erosion risk. *Commission of the European Communities Publication B-1049*.

ESRI (Environmental Systems Research Institute, Inc.) (1995) *Understanding GIS—The ARC/INFO Method*. Redlands, USA.

ESRI (Environmental Systems Research Institute, Inc.) (1996) *ArcView GIS—The Geographic Information System for Everyone*. Redlands, USA.

ESRI (Environmental Systems Research Institute, Inc.) (1997) *ArcView 3D Analyst—3D Surface Creation, Visualization and Analysis*. Redlands, USA.

Husnjak (2000) Procjena rizika erozije tla vodom metodom kartiranja u Hrvatskoj. PhD Thesis, Faculty of Agronomy University of Zagreb, Croatia.

Holjevic (2002) *Procjena erozije tla i pronosa nanosa primjenom GIS-tehnologije*. Master's Thesis, Faculty of Civil Engineering, University of Zagreb, Croatia.