Rain water harvesting and management of small reservoirs in arid and semiarid areas

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Modeling small dams′ siltation with MUSLE

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Abstract

Williams proposed in 1975 an equation derived from the Universal Soil Loss Equation (USLE) and adapted it to runoff models. This equation, called the Modified Universal Soil Loss Equation (MUSLE) requires flood parameters: peak of discharge, flow volume, and four parameters describing soil loss ability. These parameters are defined for standard runoff plots and may be extrapolated to small watersheds according to topography, soil, and land use and vegetation maps. Several methods are proposed in the literature to estimate these parameters with better or less precision. Using a water balance model, it is possible to estimate the instantaneous discharge entering into a reservoir and to obtain the flood parameters required by MUSLE. Other parameters necessary for using USLE are:

- K measures the resistance of the soil to erosion, it depends on the soil composition, percentage of organic matter, structure, permeability, and of different ratios: fine sand, loam, clay, and stones.
- LS comprehends land erodibility linked to relief, it depends of the length and the inclination of the slopes.
- C is defined as the ratio between the soil losses observed in two standard plots for the same soil, the first plot is cultivated, the second is bare; C varies between 0 and 1 during the year.
- P is a coefficient between 0 and 1 expressing erosion reduction to soil conservation practices.

In a first stage, these parameters were considered constant for the watershed and the MUSLE is computed by an optimization method. The total amount of soil losses during the floods are added and the result is compared to observed dam siltation. In a second stage, the parameters were estimated with fuzzy logic.

Introduction

Large reservoir sedimentation has been noticed in several places in the south and east Mediterranean countries. The top soils here consist of decomposed limestone, sandstone and marl that are eroded. Due to agricultural activities in unforested areas, high intensity rainfall causes soil erosion and consequently reservoir sedimentation. Globally, the dam volume lost is estimated as between 3 and 10% (Gazzalo et al., 1977). Less than ten years after their construction several dams, in the semiarid area, were filled with sediments up to the level of inlet so that it was impossible to use the outlet pipe. Some of these were filled with sediments up to the level of the spillway.

When the dykes have been filled with sediments, there exists no economical solution to recover the lost reservoir volume. Usually, new dykes will be built in the vicinity. An ancient Syrian dam, in Badia of Homs called the Bardeh dam that was built in the roman period was recently used in a rehabilitation experiment (Kara Damour and Miski, 1997). The reservoir volume as recovered by opening a hole of 1.6 m diameter in the dam wall and forming a sloping tunnel towards the filled reservoir. The water reaching the lake and leaving through the hole could dredge about 800 000 m^3 of sediments by the mid-sixties. The hole was then closed with concrete and the dam became ready to store water again. However, again it has been filled up with sediments up to the crest of the dyke.

When small reservoir constructions are initiated, empirical formulas are often used to estimate the amount of bed load and suspended load at dam site (Fournier's or Tixeront's formula in Chérif et al., 1995). In central Tunisia, in the semiarid dorsal region that extends from Cap Bon to the Algerian border, 30 artificial reservoirs were chosen to constitute a network of hydrological observations (Albergel and Rejeb, 1997). These lakes have highly diverse intake areas ranging from somewhat uninhabited semi-forests to areas that are devoted entirely to agriculture. Their watershed areas vary from a few hectares to several dozen square kilometers. They are also representative of the rainfall gradient of the semiarid region, which is 250 to 500 mm of rainfall annually. The data obtained in this network are used to calibrate models for simulation of sediment transport and dam siltation.

Williams (1977) proposed an equation derived from the Universal Soil Loss Equation (USLE) and adapted to runoff models. This equation, named the Modified Universal Soil Loss Equation (MUSLE) requires various flood parameters, e.g., peak discharge, flow volume, and four parameters describing soil loss ability. These parameters are based on standardized runoff plots and then extrapolated to small watersheds according to topography, soil, land use, and vegetation. Several methods are proposed in the literature to estimate these parameters with better or worse precision.

In this paper we try to calibrate MUSLE with the data observed in the 18 watersheds of the small reservoirs in the semiarid mountains of Tunisia. Peak discharge and flow volume were measured for each event (Albergel et al., 1998). An estimation of the total annual soil loss was obtained through bathymetry measurements taking into account the sediment transport evacuated by the spillway. The model is validated by a comparison between the calculated soil losses and the observed silting up of the lakes. A method to estimate the MUSLE parameters is shortly presented.

Annual soil loss estimation

The bathymetry of each reservoir was done at least once every hydrological year, and was compared with a detailed ground survey, making it possible to determine the reservoir's rate of silting, and to estimate depth-volume and depth-surface relationships.

The bathymetry of the reservoir was assessed with spot probing of the lake bottom following transverse lines held by a cable stretched between two shores of the reservoir. The end of each transverse line was adjusted to level and positioned on the lake's plane. Each estimated point (approximately 500 per reservoir) was defined by three Cartesian coordinates (horizontal position and depth). A geostatistical approach using kriging (Matheron, 1965) made it possible to establish the resevoir's depth-volume ratio. The volume of silt was determined from the difference in effective reservoir volume from one year to the next. The reservoir acts as a sediment trap, and when the sediment is not discharged, the sediment volume corresponds to total sediment transport of the watershed. The density of the sediment is measured for samples taken when the lake is empty.

In the case of discharge, the volumes discharged were assigned an average concentration of solid matter. This concentration was calculated for samples taken during the floods. Figure 1 shows the initial bathymetry of the reservoir Fidh Ali in central Tunisia, built in 1991. Figure 2 shows the results of the bathymetry for 1991, 1993,1996, and 1997.

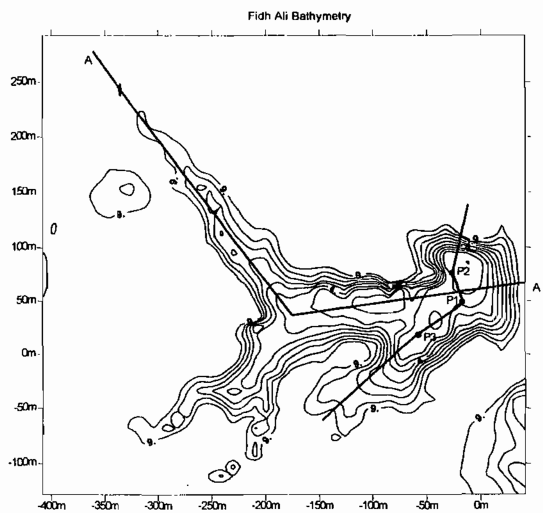

Figure 1. Bathymetry of Fidh Ali in 1991 (initial volume was 135 000 m^3).

The total erosion was measured for each observed watershed. In table 1, we give an example of data for five Hydromed pilot sites, El Gouazine, Fidh Ali, Es Senega, Kamech, and M'Richet El Anze.

Table 1. Siltation of reservoirs and watershed erosion of five areas in Tunisia.

Lake	Date of the dyke	Date of last bathymetry	Initial volume m^3	Silt volume m^3	Watershed erosion (t)
El Gouazine	1990	1998	237,000	16,000	20,600
Fidh Ali	1991	1998	135,000	46,000	55,200
Es Senega	1991	1998	80,400	12,100	17,200
Kamech	1993	1998	142,000	15,000	28,300
M'Richet	1991	1998	42,400	8,700	10,600

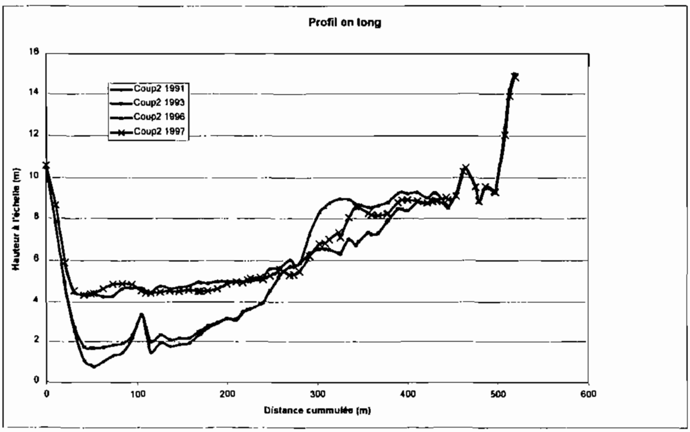

Figure 2. Time evolution of sediment build-up for Fidh Ali reservoir.

In Fig. 2 the dike crest height represents an y-axis value of 0. From 0 to 250 m we have a first type of sedimentation appearing in calm water and constituted by fine particles. More upslope, the lake bed presents holes and bumps, the flood deposits the sediments by waves. A deposit measured one year can be eroded next year, as the deposit measured at 300 m in 1996 was eroded in 1997.

Modified Universal Soil Loss Equation (MUSLE)

During a storm event causing a flood in a small watershed, the total amount of soil losses can be calculated by the Williams equation (Hadley, 1985):

$$A = \alpha \times (Q_{max} \times V_{flood})^{\beta} \times K \times (LS) \times C \times P \quad \text{(1) MUSLE}$$

where A = total amount of soil loss during the flood (t), Q_{max} = peak of discharge (m^3s^{-1}), V_{flood} = volume of the flood (m^3). The K is resistence of the soil to erosion, it depends on soil composition, percentage of organic matter, structure, permeability, and on different ratios of fine sand, loam, clay, and stones. The LS includes land erodibility linked to the relief, it depends on lengths and the inclination of the slopes. The C is defined as the ratio between observed soil losses in two standard plots for the same soil, where the first plot is cultivated and the second is bare; (C varies between 0 and 1 during the year). The P is a coefficient between 0 and 1 expressing erosion reduction due to soil conservation practices. The α and β are two constants. Williams (1977) found the values α=11.8 and β=0.56 in S.I. units.

Applying MUSLE to dam siltation

Statistical method

In a first stage, the product αxKxLSxCxP and β are considered constant and having the same value for one watershed. Values of these parameters are computed by an optimization method. The total amount of sediment transported by the flow considered as the total erosion is calculated using the following equation:

$$T = V_s \times d + \sum_i S_i \times C_i$$

where T = total amount of sediment transported between two bathymetric measurements (t), V_s = total measured volume of sediment (m^3), d = average density of the sediments, i = number of floods occurring between two measurements of bathymetry, S_i = volume of water discharged over the spillway during the flood i (m^3), C_i = the average concentration of solid matter measured in the samples during the flood i ($t\ m^{-3}$).

This total amount is compared with a total amount calculated with MUSLE as

$$T_c = \sum_i a(V_i Q_i)^{\beta}$$

The two first measurements of bathymetry are used to calibrate the model and to calculate α and β, the others are used for validation. Table 2 gives the values of the observed and calculated solid transport at Kamech reservoir.

Date	Observed transport (t)	Calculated transport (t)	
1991	0	0	Dyke building
01/10/94	1666	1666	Beginning of the observations
05/07/95	993	993	Calibration
31/07/96	8725	8014	Calibration
30/04/98	3468	3026	Validation

This model allows one to compute the solid transport for each flood since the beginning of the measurements. Figure 3 shows the sediment transport at the Kamech reservoir since the 1st October 1994. The solid transport is not a linear function of time. The hydrological year 1995-1996 caused about 60% of the sedimentation.

Analytic method

For dams where there are few or no bathymetry observations it may be useful to use the MUSLE by determining the coefficients K, LS, C, and P. In practical terms, these parameters are defined for standard erosion plots and very difficult to estimate for a field catchment.

In a recent study, the Modified Universal Soil Loss Equation (MUSLE) was successfully applied using the USLE parameters as fuzzy numbers in 18 Tunisian watersheds (Albergel et al., 1998). The validation of the model was done by a comparison between the calculated soil losses and the observed silting up of the lakes for which the sediments evacuated by the spillway were added.

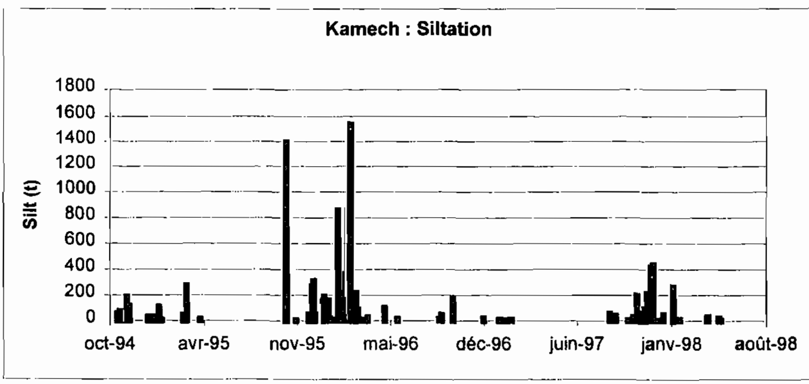

Figure 3. Sediment transport at Kamech reservoir.

Conclusion

Since 1994, measurements of sediment rates in 30 reservoirs have been executed. This kind of observations is very expensive and cumbersome. In order to simplify this procedure we need to find an easy methodology based on readily observed variables such as daily rainfall and characteristics of the watersheds. These experiments are believed to lead forward to such a methodology. Studies like this may also lead to the revealing of which areas siltation is the most serious and to indicators that may be used as early warning signs of siltation.

References

Albergel, J. and Rejeb, N., (1997) Les lacs collinaires en Tunisie : Enjeux, contraintes et perspectives. Cr. Acad. Agric. Fr., 1997, pp. 77-88. Séance du 19 Mars 1997. Note présentée par J. Albergel. Discussion pp. 101-104.

Albergel, J., Bargaoui, Z., Onibon, H., and Pepin, Y., (1998) Applying MUSLE with fuzzy parameters. Water. Resour. Res. (submitted).

Albergel, J., Nasri, S., and Boufaroua, M., (1998) Small dams water balance: experimental settlement, data processing and modeling. Lund Hydromed Workshop.

Cherif, Mizouri, M., Aouina, M.S., Khaldi, R., Laribi, M.M., (1985) Guide de conservation des eaux et du sol. DCES, FAO, *Projet PNUD/FAO TUN/86/020*; 273 p.

Gazzalo, T. and Bassi, G., (1969) Contribution à l'étude du degré d'érosion des sols constituants les bassins versants des cours d'eau italiens. Extraits de publications de l'Agence Italienne d'Hydraulique, n° 53.

Hadley, R.F, Lal R., Onstad, C.A., Waling, D.E., Yaïr, A., (1985) Recent developments in erosion and sediments yield studies. UNESCO, Paris, 172 p.

Kara Damour, S. and Miski, A. F., (1997) Small dams and hill reservoirs in Syria. ACSAD.

Karaouchov, A.V., (1977) Les débits solides, analyses et répartition géographiques. Hydrométeoidat, Leningrad, 238 p.

Matheron, G., (1965) Les variables régionalisées et leur estimation. Paris, Masson, 360 p.

Nouvelot, J.F., (1993) Guide des pratiques hydrologiques sur les petits bassins versants ruraux en Afrique tropicale et équatoriale. CIEH/ORSTOM/CEMAGREF/FAO . Montpellier. 500 p.

Williams, J.R., (1977) Sediment delevery ratios determined with sediment and runoff models. *AISH*, pub. no. 122.

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