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Lulseged Tamene Desta "Reservoir Siltation in Ethiopia: Causes, Source areas, and Management options", University of Bonn, Center for Development Research (ZEF), 2005

Problem statement

More than 85 % of the population of Ethiopia directly depends on agriculture, which is highly influenced by rainfall that is erratic and unpredictable. Shortage of rainfall and its variability have led to recurrent and substantial declines in agricultural production claiming thousands of human and livestock lives. The uncertain water supply also |,, restricts farmers' willingness to invest in yield-enhancing inputs causing further decline in productivity. Efforts to increase the coping capacity of people against shocks produced by rainfall variations and improving their food security, therefore, require provision of adequate water and its proper utilization.

Against this background, the government of Ethiopia launched an extensive surface water harvesting program with the objective of increasing self-sufficiency in food production using supplemental irrigation. To this effect, appropriate institutional arrangements were made and intensive construction of micro-dams started in 1995. In the Tigray region of northern Ethiopia alone, over 50 micro-dams have been built to date and substantial gains in food security, ground water replenishment and ecological stability were recorded. Studies show that farmers' income grew 4 -7 fold in some localities after the construction of micro-dams. However, these benefits were only of short duration because of a rapid loss in water storage capacity of the reservoirs due to siltation. The rapid siltation of reservoirs has socioeconomic implications not only because the food security improvement plan through supplemental irrigation can not be sustained but also because the money spent for the construction of micro-dams (ca. 200,000 Euros per dam) could have been used for other purposes. There is, therefore, an urgent need to assess the causes of the problem and suggest possible amelioration measures.

This study attempts an integrated investigation of the severity of siltation, the major determinant factors, main sediment source areas and possible interventions necessary to minimize rapid siltation. The study was conducted in the Tigray region of northern Ethiopia. Catchments of a size of 3-20 km^2 with different forms of erosion processes and a mosaic of heterogeneous environmental factors were studied.

Objectives

The four main objectives of the study were to 1) estimate the annual rate of reservoir siltation; 2) investigate the major factors that lead to siltation; 3) identify and flag hot-spot areas that contribute the most sediment; 4) analyze the sediment yield reduction potentials of different management options.

Methodological Approaches

Four principal methods were employed to achieve each of the four objectives.

1. Estimate the annual rate of sediment deposition

To prioritize catchments that require urgent management intervention, quantitative information on the rate of sediment deposition is necessary. Different approaches exist to estimate sediment deposition in reservoirs. Reservoir survey methods are considered to be more the reliable and representative techniques. Two methods were employed to estimate sediment deposition in eleven reservoirs: sediment-pit analysis and bathymetric survey. Pit-based surveys were conducted for reservoirs that were dry during the field work, and for the remaining bathymetric surveys were performed.

In the pit-based method, several pits were opened on the reservoir floor and the thickness of sediment was measured for each pit. Next, Thiessen polygon interpolation was used to estimate the "area of influence" of each pit. Then, the volume (m3) of sediment trapped in each polygon was calculated by multiplying sediment thickness (m) by the area of each polygon (m^2). The total volume of sediment trapped in each reservoir would be the sum of the sediment load of all polygons. In the bathymetric survey, the original reservoir capacity of each reservoir was compared with the current capacity. Current bathymetric maps and storage capacity of reservoirs were derived by measuring the depths from the water surface to the top of the sediment at more than 600 locations for each reservoir. The differences between original and current storage capacities of each reservoir gave the volume of sediment deposition (m^3).

The measured sediment volume (m^3) was converted to sediment mass (ton) using dry-bulk density. The weight of deposited sediment was also adjusted for reservoir trap efficiency. Finally, total annual sediment yield ($t\ yr^{-1}$) and area-specific sediment yield ($t\ ha^{-1}\ yr^{-1}$) of each reservoir was calculated.

2. Assess the determinant factors of reservoir siltation

In order to prescribe problem-oriented management interventions to tackle rapid siltation, knowledge of the factors determining upland erosion is necessary. Spatial variability in the environmental attributes of catchments (e.g., terrain, soils, surface cover, drainage network, rainfall) reflects the spatial variability in sediment yield. Integrated analysis of sediment yield in relation to corresponding environmental attributes of catchments could thus help identify the dominant factors governing soil loss variability and evaluate cause-effect relationships. In this study, quantitative data related to catchment environmental attributes were collected based on analysis of digital elevation models, satellite images, and field survey. Pearson's correlation, multiple regression and principal component analyses were then performed to assess the effect of catchment environmental attributes on sediment yield in the reservoirs.

3. Identify major sediment source areas

Reduction of reservoir siltation requires reduction of upland erosion through watershed management. Given the widely variable rates of soil loss from different landscape units, erosion control methods should focus on the units responsible for the delivery of most sediment. As a result, it is important to identify and flag landscape positions that experience high soil loss where site-specific management practices should be focused.

Soil erosion models represent an efficient means of investigating the physical processes governing erosion rates and identifying high erosion risk areas. Recent advances in the development of GIS allow incorporating heterogeneity in catchments and enable basin attributes controlling sediment movement to be considered in a spatially explicit manner. GIS-based spatially distributed models were applied in this study on four catchments, selected for their differences in terrain, land cover and management, intensity of gully erosion and the amount of sediment deposition in reservoirs.

4. Evaluate 'land-use planning'- based management options

Appropriate land use and management practices that maintain good ground cover are useful means to reduce sediment delivery. Experiences show that sediment yield can be reduced by enclosing upslope areas that are at high soil-loss risk to exclude farming and grazing. In line with this, different spatial scenarios were conducted to evaluate the sediment yield reduction potentials of alternative land use and conservation options. The Unite Stream Power-based Erosion/Deposition (USPED) model was used to simulate the effect of different land use/cover (LUC)-planning measures on annual sediment yield from catchments. The simulations mainly focused on reorganizing LUC-types based on predefined criteria such as gullies, slope, and intensity of erosion. For each scenario, LUC-types of the targeted landscapes were converted to enclosures, areas protected from human and livestock intervention to regenerate, and the resulting sediment yield calculated. The scenarios were run for two catchments that experienced high rates of sediment deposition.

Results and discussion

How severe is the reservoir siltation problem?

The reservoir survey data shows that area-specific sediment yield ranges from ca. 3 to 49 t ha^{-1} y^{-1} with a mean value of ca.19 t ha^{-1} y^{-1}. The average net soil loss rate observed in this study is above the 'tolerable' soil loss and the annual soil formation rates estimated for Ethiopia. The mean sediment yield of 19 t ha^{-1} y^{-1} is also higher than the mean global (15 t ha^{-1} y^{-1}) and African (91 ha^{-1} y^{-1}) sediment yield rates.

Based on our results, over half-of the reservoirs have lost more than 100 % of their dead storage capacity in less than 25 % of their expected service time. Most of the reservoirs will also be filled with sediments within less than 50 % of their projected service lives. This shows that the planned food security improvement scheme, for which the reservoirs were built, is under threat. Rapid failure of reservoirs also means a much lower internal rate of return and waste of money spent for the construction of the dams, which could have been invested for other purposes.

What are the determinant/actors of reservoir siltation?

Statistical analyses of the relationship between sediment yield into reservoirs and corresponding catchment attributes showed that height (altitude) difference, surface ruggedness (terrain irregularity), surface lithology, degree of gully-related erosion and surface cover played major roles in sediment yield variability of catchments. The height difference indicated significant positive correlation with sediment yield because with increasing altitude difference the runoff and potential energy available to detach and transport soil particles becomes higher. The surface ruggedness was also significantly correlated with net soil loss because removal of water and sediment from the channel and watershed surface increases with rapid variation in the slope of catchments.

The surface lithology revealed a high positive correlation with sediment yield; catchments mainly of credible shale and marl had a higher soil loss than others because such lithologic surfaces are more prone to soil detachment and transport. On the other hand, catchments mainly of less credible rocks such as sandstone and metavolcanics showed low soil loss partly because of their higher degree of consolidation.

The gullies showed high positive correlation with sediment deposition in reservoirs. This may be because gullies play double roles: both supply and transport of sediment. A dense network of gullies provides efficient catchment connectivity to deliver sediment to downslope positions. Gullies are also major sources of sediment in most of , the catchments due to bank collapse and through remobilization of sediment deposited in floodplains. Livestock disturbances of gully floors and banks as well as trampling of areas near reservoirs worsen the process of gully erosion in most of the study sites.

The primary correlation results highlighted that land use/cover (e.g., dense bush/shrub) was poorly correlated with sediment yield. This was unexpected because in theory, dense bush/shrub reduces soil loss as it absorbs some of the energy of running water. The reason could be due to the masking effect of other factors mainly because of high autocorrelation. When principal component analysis was applied to reduce the dimensionality of the data into a few uncorrelated components, the effect of surface cover on sediment yield became indeed evident as land use/cover types formed the second significant principal component.

Slope indicated poor correlation with sediment yield. This may be because of the masking effect by other factors. It was observed that steep slope areas are those with dense surface cover and resistant lithology, while gentle slope areas had generally poor surface cover and erodible lithology. In addition, most of the conservation efforts were concentrated on the remote steep' slopes positions. The influence of slope is, therefore, neutralized by the combined effects of natural and human factors. The relationship between sediment yield and slope improved when correlation was performed after excluding some catchments with the above combinations of attributes.

In general, the co-existence of pronounced terrain, erodible lithology, poor surface cover, and widespread gullies accelerated reservoir siltation. Consequently, these factors need to be considered when selecting runoff collection sites for dam construction. Catchments characterized by the aforementioned attributes also need a land management plan. Since erosion prone areas are found distributed across catchments, the question remains pinpointing landscape positions from where most of the sediment originates.

Where do most of the sediments come from?

The results of erosion models indicated that the landscape positions where erosion was above the tolerable limit were located on the upslopes with steepness generally greater than 15 degrees and around gullies. These areas in most cases are characterized by convex terrain with high flow rates, which can facilitate sediment delivery to downslope positions. However, widespread and collapsing gullies, which experience high soil loss, were located in the lower positions of catchments where the slopes are not very steep. Some of the upslope positions with steep slopes had less erodible cliffs with little soil material to be transported while the lower positions of catchments and piedmont sides were susceptible to rill/gully erosion as they were intensively cultivated and overgrazed.

Field data showed that the models generally correctly identified 'hot-spot' areas of erosion; thus enabled identifying the landscape positions that required prior conservation planning. The next issue is then which management practiced/conservation measures can effectively reduce siltation?

What management options could help reduce siltation?

The model scenario that considered conservation of gullies and their banks gave a sediment yield reduction of over 50 % compared to the status quo. This reduction could be accomplished with less than 5 % of the agricultural land as set-aside. When areas with slope of > 25 % were enclosed, a soil loss reduction of about 13 % could be achieved. By conserving gullies and enclosing areas with slope >25 %, the sediment yield reduction could improve to over 55 %. When areas experiencing soil loss of > 25 t ha^{-1} y^{-1} are enclosed, a sediment yield reduction of ca. 50 % could be achieved. Through integrated management of erosion-sensitive areas and conservation of gullies, the soil loss reduction could be ca. 65 %.

Most scenarios showed that a relatively large sacrifice in the proportion of cultivated land may be required (except for the case of gullies) to achieve a reasonable decrease in sediment yield. Given the current pressure on agricultural land, this might only be achieved when compensation payments are provided by the government to make the change economically feasible for farmers.

Conclusion

In Ethiopia, a combination of natural and human factors causes reservoir siltation. To make the food security plan through water harvesting successful, appropriate measures need to be taken. Applying the results of this study could help achieve this goal. The quantitative tracing of sediment offers insight in the severity of the problem and identifies the sites that require attention. The statistical analyses of the landscapes help in ranking the catchment attributes that cause siltation and need correction or protection. The modelling approach can identify the major sediment sources where intervention will need to be focused. Finally, the spatial simulations help assessing the efficiency and location of possible management measures. Finally, it would be particularly useful and economical to go through the integrated approached discussed so far prior to the construction of dams for water harvesting or energy generation.

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