IMPACTS OF LAND USE CHANGE ON THE SEDIMENTATION OF THE MANGLA RESERVOIR, PAKISTAN

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Land use changes alter soil erosion patterns, which in-turn change the sediment yield of a catchment. Experimental investigation and worldwide catchment studies revealed the sensitive relation between land use, erosion rate and relevant human activities[1]. Different land use types tend to reduce or increase the sediment inflow.

The problem might seem quite simple to analyse at a local scale; however, the sediment yield of a river basin is affected by other factors, such as surface run-off, temperature, slope stability, making the sedimentary processes more complicated to model and requiring basin scale approaches. The multipurpose Mangla Reservoir, in Pakistan, is losing its storage capacity at a yearly rate of about 0.5 % (1,970 million of m3 lost between 1967 and 2010, before up-raising the dam in 2011). The impacts of land use changes in the Mangla Dam basin were assessed, showing that the current trend will not be affected greatly if the land use remains unchanged from the present conditions. However, if large levels of deforestation occur in the future, the increase in the sedimentation rate would have a dramatic effect on the sustainability of the Mangla Reservoir.

Background

Pakistan is confronting a major issue of sedimentation, which is continuously reducing the useful storage space of reservoirs. The global storage capacity loss due to sedimentation is of 0.5 to 1% annually[2]. The sustainability of reservoirs, vital parts of the infrastructure developed to meet the country's needs for drinking water, agriculture and power generation, is under threat. Urgent measures are required for attaining sustainable use of reservoirs, thereby changing them from exhaustible into sustainable renewable resources[3,4].

The Mangla Dam, was constructed across the Jhelum River between 1961 and 1965 and was commissioned in 1967. Its primary purpose is irrigation, with secondary functions of hydropower production, fisheries and flood control. Its height at construction was 138.38 m, with a design gross storage of around 7,250 million of m^3 (Mm^3). In order to counteract the loss of storage due to sedimentation, the dam was raised up to around 147 m, which brought the gross storage to around 9,110 Mm^3 in 2011. The reservoir collects the water from the Jhelum River (Figure 1) and plays an important role in managing the water resources of Pakistan. Particularly, the reservoir supplies water, through a network of interlinked rivers and canals, to the eastern rivers (Ravi, Sutlej, and Bias rivers) which suffer from water scarcity.

Most of Mangla Reservoir's catchment is hilly, with steep slopes and relatively thin vegetation. This results in high sediment inputs into the reservoir, particularly during the rainy monsoon season from July to September. Periodic bathymetric surveys carried out by the Water and Power Development Authority (WAPDA) have shown that more than 20% of gross storage capacity of the reservoir was lost over the period of 1967 and 2010, which means that the gross storage capacity of the reservoir is declining at an average rate of about 0.5% per year. Evidence of this large sedimentation process is the formation of a delta on the left bank of the reservoir (Figures 2), gradually advancing toward the dam structures[5].

Statistics have indicated that there exists a deforestation trend in the basin of the Mangla Dam due to rapid population growth. Usually, inhabitants of the Himalayan region cover the majority of their energy needs from the forests. Fuelwood is identified as the most significant cause of deforestation in developing countries[6]. It accounts for more than 54% of global harvest per annum, and the Mangla Dam catchment is not an exception. Other significant reasons for deforestation include timber logging for shelter, livestock fodder, wood export, clearance for cultivation and urbanization[7]. In addition, agriculture is growing in the region. Poor practices increase the surface of loose soil which is more prone to erosion.

Herein this article presents an investigation to verify if both, deforestation and increased agricultural practices, are a major catchment-scale factors determining the sedimentation of the Mangla Reservoir. A modelling approach, supported by field observations and data, was developed at the basin scale. Several scenarios

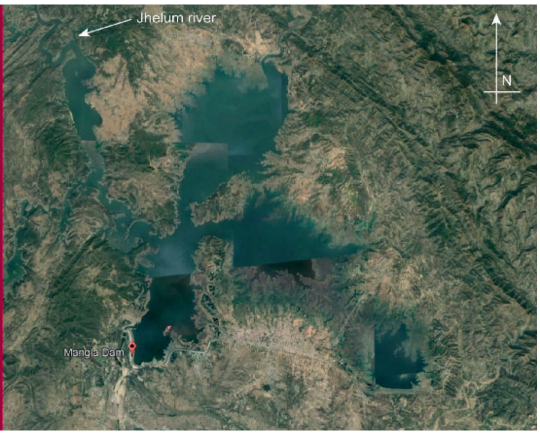

Figure 1. Mangla Reservoir with indication of the Jhelum river (source Google Earth)

Figure 2. Formation of a delta in the left side of Mangla Reservoir (source Google Earth)

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of land use development were tested comprising (a) the continuation of a similar situation in terms of land use as the present one (where business is the usual scenario), and (b) two different conditions of deforestation activity within the catchment defined by worst case scenarios.

Modelling approach

The Jhelum River is the major contributor of sediment arriving to Mangla Reservoir. The catchment corresponding to the Jhelum River is about 80% of the total Mangla Dam watershed. The total sediment yield of the upper Jhelum river was estimated and the impacts of possible future land use changes were evaluated using the Soil and Water Assessment Tool (SWAT)[8]. SWAT is a semi-distributed, physical based model which was mainly developed to evaluate land management impacts in complex river basins. The whole catchment is divided into small sub-catchments which are then reclassified in HRUs (Hydrologic Response Units) as the basic simulation units. An HRU is a homogeneous entity in terms of soil type, land cover and slope. The model then integrates the contributions at the sub-catchment level using a weighted-area average method. SWAT requires different catchment data at different spatial scales: catchment, sub-catchment and HRU. Climatic data are defined at the sub-catchment level and SWAT applies the same data to each HRU in that particular sub-catchment. Flow routing and snow melt data are provided at the global catchment level whereas land management and soil data are processed at the HRU level.

For modelling purposes, the catchment of the Mangla Dam was taken as the geographic unit for the aggregation of data, planning and computations. The existing trends in land use change were projected into the future to predict upcoming configurations. Possible future *worst-case scenarios* were formulated under two hypotheses that, in order to satisfy the food production needs of a growing population, 15% or 21% of the forested land will be converted into irrigated agriculture, respectively. SWAT simulated the hydrological processes in the watershed. The future land-use changes were incorporated into the model to predict the future variations in water and sediment balance in the Mangla Reservoir.

Data

Remote sensing and observed data were used for the modelling setup, calibration and validation. Remote sensing data included:

- Digital Elevation Model (DEM) of the catchment, extracted from Shuttle Radar Topography Mission (SRTM) with 90 m resolution (released by the U.S. Geological Survey in 2013).
- Soil Maps obtained from the Food and Agriculture Organization (FAO) classification project (400 x 400 m resolution).
- Land Use Land Cover (LULC) maps from USGS Global Land Cover Characterization (GLCC) database, which is a series of land cover dataset classifications primarily based on unsupervised classification of 1-km Advanced Very High Resolution Radiometer (AVHRR) 10-day Normalized Difference Vegetation Index (NDVI) composites.
- Meteorology data obtained from The National Centre for Environmental Prediction (NCEP) for Climate Forecast System Reanalysis (CFSR).

Observed data, used for model calibration and validation, included:

- Hydrological daily data from the Surface Water Hydrology Project (SWHP) conducted by WAPDA Pakistan. Observed data at the "Azad Pattan" gauging station, the last station upstream of the Mangla Reservoir, was used. The flow discharge of the Jhelum River at "Azad Pattan" station represents almost 80% of the discharge entering the Mangla Reservoir.
- Sedimentation data collected by WAPDA Pakistan. Unlike flow data, which was observed on daily basis, sediment data was observed fortnightly and when required/necessary. Observed sediment concentrations at the "Azad Pattan" gauging station could be obtained from WAPDA on different dates. Rating curves were then developed to compute the total sediment yield.

Model setup

The SWAT model setup involved the following steps:

- **Watershed delineation**: the whole catchment was delineated into 29 sub-catchments using a threshold area of 500 km^2. The process was accomplished through manual delineation which provided flexibility to edit closure locations and sub-catchment shape.
- **HRU analysis**: developed soil and land use maps were used as model data input along with slopes of the area. In order to develop utmost land use detail, the threshold value for land use was set to zero. However, 10% threshold value was assigned to slopes and soil classes. The overall catchment was subdivided into three slope classes according to FAO guidelines: undulating areas with 0 to 8% slopes; steep lands with 8% to 30% slopes; mountainous areas with slopes exceeding 30%. Following this procedure, a total number of 840 HRUs was generated.
- **Meteorological data**: SWAT performed simulations using different meteorological variables, such as solar radiation, wind speed, relative humidity, temperature and rainfall. For the purpose of this research, only temperature and precipitation data were available. Therefore, in the proceeding steps the Hargreaves method was used for estimating evapotranspiration.

Depending upon the data input, suitable methods for reproducing different processes were defined: the SCS curve number method for surface runoff simulation, the Hargreaves method for evapotranspiration, variable storage method for surface routing, and the simplified Bagnold's method for sediment routing.

The simulations were made for the period wherein observed data was available, *i.e.* from January 1st 1979 to December 31st 1995. The first two years (1979 to 1981) were regarded as a 'warmup period'. The simulations were made on a daily time step, as it was more appropriate for accurate sediment yield estimations, although the output is presented monthly for the sake of legibility.

This work is part of a more general thematic research held at the River Basin Development chair group of IHE Delft, which includes the three-years research program on Sustainable Hydropower and Multipurpose Storage to meet Water, Food, and Energy Development Goals: A Program for Collaborative Research and Innovation (S-MultiStor), https://www.un-ihe.org/projects/sustainable-hydropower-and-multipurpose-storage-meet-water-food-and-energy-sdgs.
The program is supported by the Programmatic Cooperation between the Directorate-General for International Cooperation (DGIS) of the Dutch Ministry of Foreign Affairs and IHE Delft in the period 2016 - 2020. This program investigates and demonstrates improved approaches to sustainable multipurpose storage, including sedimentary issues. S-MultiStor creates a common research and innovation platform, where researchers from IHE Delft and southern partner institutions engage with leading international initiatives in a structured program of collaboration. Activities are focused on Irrawaddy Basin (Myanmar), Zambezi Basin (Southern Africa) and Magdalena Basin (Colombia). Targeted development outcomes include improved catchment management for water, food and energy security that is socially and environmentally sustainable.

SWAT-CUP was used for sensitivity analysis, calibration and validation of the model. This is an independent software for automated calibration and uncertainty analysis. It includes five different algorithms for calibration. In this research the "Sequential Uncertainty Fitting, version 2 (SUFI–2)" algorithm was employed which uses the transposed modelling method for calibration. Uncertainty of input parameters was considered as uniformly distributed, whereas the uncertainty of output parameters was represented by the 95 PPU (95% prediction uncertainty) band. The method works under the hypothesis that with the increase in input uncertainty, output uncertainty also increases and *vice versa*. Briefly, the goal of calibration was to narrow down the uncertainty in output parameters to fall within the 95 PPU band. This objective was achieved by successive iterations, which resulted in sequential change in the weight of the 95 PPU band. Every iteration consisted of 500 simulations.

The hydrological component was calibrated by varying the parameters for soil and vegetation, such as the SCS Curve Number for moisture condition II, the soil evaporation compensation factor, the plant available water capacity, the surface runoff coefficient and the plant uptake compensation factor. The model calibration was assessed using a number of performance estimators (Percentage BIAS, coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE)). The choice of the best set of parameters was made according to the maximum NSE. Observed discharge data at the outlet, *i.e.* at "Azad Pattan" gauging station, was compared with the simulated discharges. Calibration was implemented for eight years (1981 to 1988) and a remaining period of seven years (1989 to 1995) was used for validation. Calibration and validation was accomplished on a mean monthly basis.

For the calibration of the sediment transport component, the parameters that have been used are the channel and basin erodibility factors. The calibration and validation procedure is the same as the one adopted for the hydrological component. However, the objective function selected for the optimization was the Percentage BIAS instead of NSE, because the limited number of observed data did not allow a full consideration of the temporal variations of sediment transport.

Main results and conclusions

The simulation period from 1981 to 1995 was considered as the *base case simulation*. The simulation was performed after model calibration for flow and sediment transport. Figure 4 shows the time evolution of the flow discharge and sediment transport rate. The future *business as usual* LULC scenarios were developed for the years 2035 (12.97% deforestation) and 2060 (18.84% deforestation) by projecting the current land use trend. The deforested areas were converted to other land use types, such as irrigated agriculture, built up areas, barren land, horticulture, plantation and exposed rock according to prevailing trends. In addition, two *worst case scenarios* were developed under the hypothesis that, in order to meet the food production needs of a growing population, 15% and 21% of the total catchment area would be fully converted to agricultural irrigated land. The future LULC scenarios were built and updated in SWAT. While updating the LULC scenarios in SWAT, all other inputs (weather and soil type) remained unchanged. The results of the simulations were compared on long term monthly, yearly and seasonal basis.

The comparison of sedimentation rates between the *base case scenario* and *business-as-usual scenario* shows that no significant change is to be expected. The current modest trend on the land use change does not have substantial effect on sedimentation in the Mangla Reservoir: an increase of 0.42% in sedimentation on a mean monthly basis by 2035, and an increase of 0.70% by 2060, are to be expected. However, in the *worst-case scenarios*, where a large scale deforestation is to occur, with a complete transformation of forest areas to cultivable ones, substantial increases in the sedimentation rate are expected: 1.3% for the scenario of 15% deforestation and 2.05% for the scenario of 21% deforestation by 2035 and 2060, respectively. Moreover, results show clearly that the conversion of forested areas into agricultural lands should be discouraged to attain sustainability of the Mangla Reservoir. Instead, to meet the ever-increasing needs of food, modern agricultural practices should be adopted in order to increase the productivity of present-day agricultural areas and/or to decrease the soil loss (*e.g.* through conservation tillage). ■

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Figure 3. Example of a sedimentation area in the Mangla Reservoir

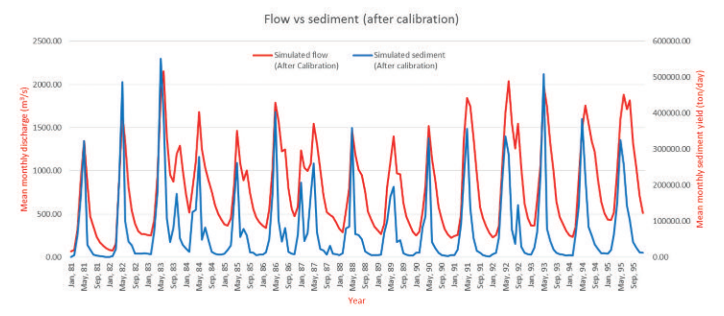

Figure 4. Simulation outputs for the base case scenario. Red: flow discharge, Blue: sediment transport rate.