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Modelling Runoff and Sedimentation Yield Using Soil and Water Assessment Tool for Wyra River Basin

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ABSTRACT

Sediment deposition is a natural process that occurs in all reservoirs, resulting in significant storage loss, which has an adverse effect on the economic development of the local area. It is necessary to take appropriate action to control the sedimentation and prevent loss of the storage capacity of the reservoir. In the present study, runoff and sediment data collected at the Konijerla hydrometric station of Wyra reservoir for the period of 1991 to 2019 are used. Data from 2011 to 2016 is used to calibrate and the data from 2017 to 2019 is used to validate the SWAT model. The Wyra watershed consists of 26 sub-basins and 47 HRUs (Hydrological Response Units). Out of these sub-basins, one of the sub-basins is contributing 18.8% of sedimentation. It was also observed that two other sub-basins, though less in area, generate high sediments. Seasonal sediment analysis showed that sedimentation increased by 12% in the month of August for wet years. Overall sedimentation increased in wet years by 10.60% and in dry years, it decreased by 18.78%. The SWAT model was satisfactory in the calibration and validation periods for various parameters used. Hence, this model can be used for sedimentation study, as well as a planning tool in the reservoir capacity management.

Keywords: reservoir; runoff; sedimentation; SWAT; watershed.

INTRODUCTION

Environmental degradation of land is a regular phenomenon occurring all around the world. The main cause of the degradation is deforestation, erosion of soil or rock mass due to wind or rain, change in land use, grazing of grass or bushes by livestock and siltation of rivers or river-beds by human habitat. These alter the hydrological cycle and limit the supply of water to various riparian uses. Proper utilisation of the water resources necessitates both spatial and temporal assessment and management of water resource quality and quantity (Garg and Jothiprakash 2008; Jain and Srinivasulu 2006; Jain and Kothyari 2000). A river is an open system with complex behaviour. The behaviour of this complex system depends on two effects. The water flow carries sediment, and the presence of sediment affects the physical and mechanical behaviour of the water flow. The river bed boundary restricts the water flow, and the water flow changes the shape of the river bed boundary through the erosion and deposition of sediment. Only by fully understanding the above two effects and their interconnections can reveal the internal mechanism and complex behaviour of the river system. Most of the silt carried in the river is the flushing material with fine particle size, and its content is mainly determined by the erosion of the surface soil of the watershed by the surface runoff, which depend on factors such as watershed slope, soil, vegetation, seasonal climate change, rainfall intensity, and human activities (Dawson and Wilby 2001; Beasley et al., 1980). When the sediment floats in the water, on the one hand, the gravity makes it settle continuously; on the other hand, the turbulence of the water flow continuously lifts a part of the sediment upward. The two must be in balance to maintain the suspension of the sediment (Agarwal et al., 2006; Krishna Rao et al., 2015; Jain 2001). But these two factors are disturbed due to human activities. River sediment is an important indicator that must be considered in the construction and operation of water conservancy projects. It is related to issues such as flood control, water storage, river bed erosion and sedimentation, and aquatic ecology (Kothyari et al., 2002; Lewis et al., 2013; Miao et al., 2011).

Sedimentation has a negative impact on the regional ecological environment, downstream water environment and water security. Comparing sedimentation discharge with river runoff is an important analysis in surface river process to quantify the land degradation and soil resource reduction along the river (Siyam et al., 2005; Tan et al., 2019). Assessing the changes and impacts of the sediment load of rivers in recent decades can provide a basis for the scientific management of water and soil resources and the ecological environment of the rivers. Studies have been carried out on many major rivers in the world by Verstraeten and Poesen (2000), who analysed the trend of sediment discharge of 145 major rivers in the world, and found that the sediment discharge of nearly half of the rivers had decreased significantly (47%), mainly due to the effect of loss in the reservoir storage capacity. Their study also revealed that only 5% rivers showed an increasing trend in sediment discharge.

In recent years, the sediment problems of major rivers, such as the Yellow River, Yangtze, Indus, Brahmaputra, Krishna, Ganga and Mekong have received continuous attention. There is a lack of observations of river sediment concentration, especially in the less developed countries (Arega and Dwarakish 2015; Giustolisi and Laucelli 2005;). Understanding the spatial and temporal distribution characteristics of the river sediment is important. Due to the lateral erosion of river channels, the expansion of gully banks is formed. The increasing water and soil erosion have caused the cultivated layer to become shallower, causing decrease in the fertility of the soil (Issa et al., 2015; Chitata et al., 2014). For the sustainable development of any region, studying the trend and driving mechanism of soil and water loss through the change of river sediment load are important (Van and Meixner 2006; Yang et al., 2008). Research on changes in river sediment load faces mainly data limitations. In most cases, only the observation of suspended sediment concentration was carried out for river sediment, with no measurement of transported sediment load (Jiang et al., 2015; Van Liew et al., 2005).

The present study is carried out on the Wyra river, a tributary of Munneru vagu, which is yet another tributary of Krishna River in the district of Khammam of Telangana state. To carry out research on the changes and impact of sediment load, the SWAT model was used along with the extent of river basin and land use information. This study has further compared the spatial characteristics of river sediment load and its changes and trends in recent decades (1991–2019). The main research objective of this paper is to construct a sediment transport model by using SWAT model with the available meteorological and physical data from the Wyra river basin. The study also attempts to evaluate the performance of the hydrological and sediment prediction model in relation to the available historical data of discharge and sedimentation at the Konijerla hydrometric station.

STUDY AREA

Wyra reservoir was chosen for the study, which is located on the Wyra river. Built in 1929, it supplies potable water as well as irrigation water to the existing ayacut (command area) of about 7463 acres under both the left and right flank canals. The reservoir has a catchment area of around 710 km^2, and due to the steep topography of the watershed, it is subjected to high intensity storms and carries large quantities of sediment. Figure 1 displays the location map of the Wyra reservoir.

SWAT MODELLING

The SWAT (Soil and Water Assessment Tool) is a long-period distributed watershed hydrological model, which can predict runoff and sediment yield in different areas of the watershed under different soil types and land use. It is usually used to assess the long-term impact of land management models on water flow, sedimentation and agricultural nutrients in complex watersheds. SWAT has gradually become an indispensable part of the water resources and environmental protection management and planning. This model, developed by the US Department of Agriculture, is suitable for the calculation of sedimentation on a larger watershed scale.

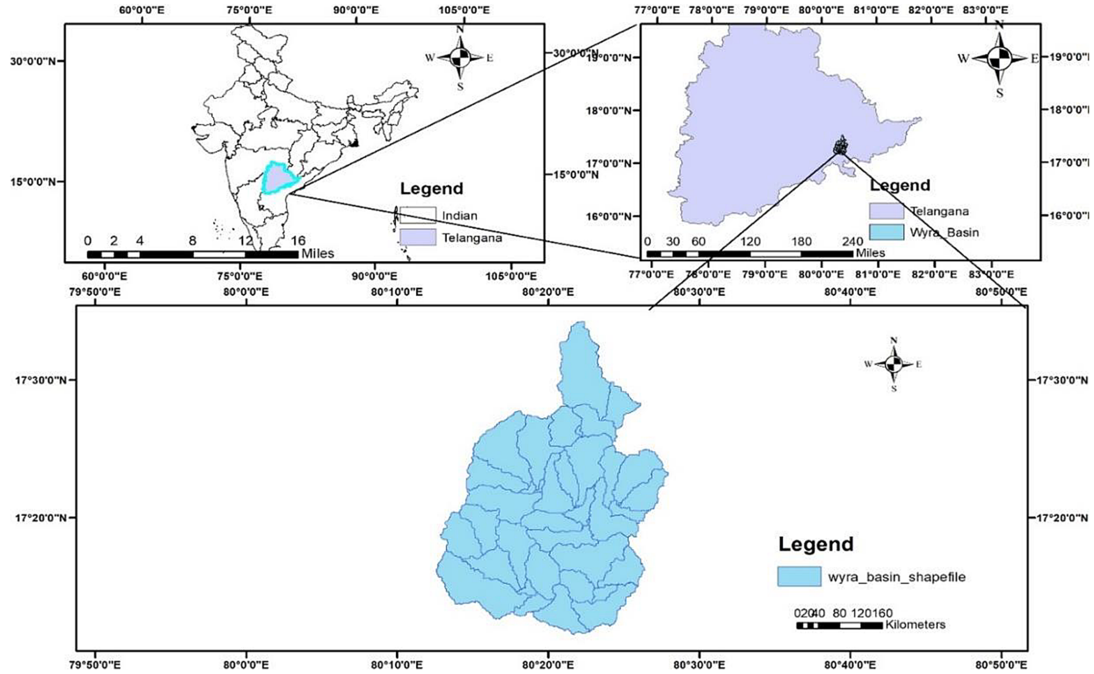

Figure 1. Location map of Wyra reservoir

SWAT mainly simulates and predicts runoff, water quality and sedimentation by using various meteorological data. The SWAT model for watershed simulation is not only suitable for areas with large terrain fluctuations such as mountains and hills but also for the river plain and lake water network areas. SWAT first divides the entire basin into several sub-basins and then into hydrological response units (HRUs), based on the topographic features of the basin like land use type, soil type and slope area threshold of the watershed and river network distribution. SWAT assumes that the land use type, soil type, and slope are constant during the simulation period, and hence the generated HRUs will not change the values of attributes due to different simulation years. On each individual HRU, SWAT uses a conceptual model to estimate rainfall, runoff, sediment, etc. After these calculations are completed, the channel flow routing is performed. Finally, the flow rate, sediment volume and pollution load of the outlet section are obtained. The hydrological process of the watershed simulation by the SWAT model can be divided into: (i) The land surface part, which controls the input of water, sand, nutrients, etc. in each sub-basin; and (ii) The water surface part, which determines the transport of water, sand and other substances from the river network to the outlet of the basin. SWAT uses the principle of water balance as given in Eq. 1.

$$St = S_o + \sum\nolimits^t_{i=1} (R_{day} - Q_{surf} - E_t - S_{seep} - Q_{gw})\ St = S_0 + \sum\nolimits^t_{i=1} (R_{day} - Q_{surf} - E_t - S_{seep} - Q_{gw}) \quad (1)$$

where: S_t – soil water content; S_0 – the previous soil moisture content; t – the time step of the model simulation; R_{day} – the first i-th day's precipitation; Q_{surf} – the surface runoff on the i-th day; E_t – the actual evaporation capacity; S_{seep} – the soil infiltration.

Soil types and land use maps

The world soil database was used for the study area. Reclassification and resampling were carried out according to the built-in soil types of SWAT to meet the accuracy requirements of the model. The soil database was established by using SWAT to calculate the parameters required for modelling. The land use and land cover data were downloaded from https://power.larc.nasa.gov/data-access-viewer/. Through remote sensing and visual interpretation, deferent land use types in the study area were identified. Finally, it was divided into 6 categories, and the reclassification results and spatial distribution are shown in Figure 2. According to the soil map, the catchment area is fully covered by the red soils. The major part of the watershed is covered by the cropland/grassland (43.6%) and irrigated cropland (23.65%). The remaining area is covered by the

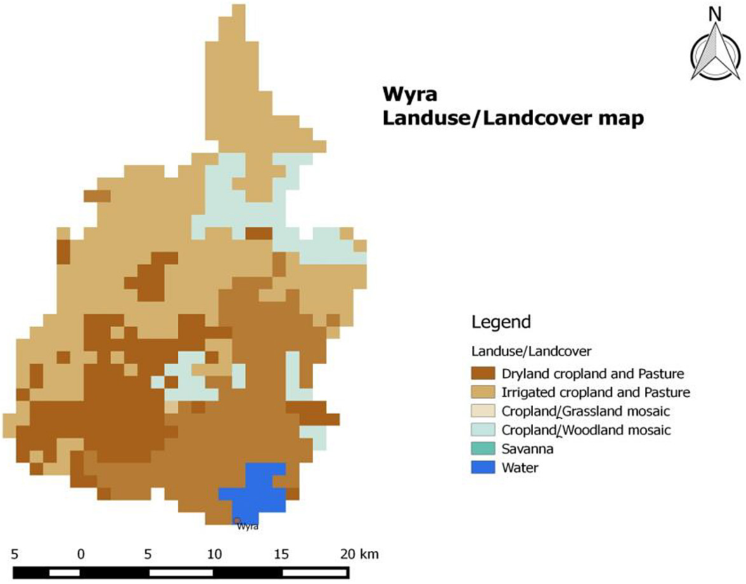

Figure 2. Soil type data in Wyra watershed

dryland cropland (19.17%), savanna (10.81%) and cropland/ woodland (0.15%) and water bodies cover the rest of the area.

Meteorological data

The meteorological data required for the SWAT model include daily average rainfall, maximum and minimum temperature, solar radiation, wind speed, and relative humidity. The string WGEN (weather generator) was used to add these data files in the form of tables to the SWAT reference database. The actual measured runoff and sedimentation used the monthly average data from 1991 to 2019 at the Konijerla hydrometric station at the outlet of the basin.

Division of sub-watersheds and hydrological response units

The study area watershed, covering 644 km^2, was divided into 26 sub-basins and 46 hydrological response units (HRUs), as shown in Figure 3. To create the HRUs, 10% for the land use, 10% for the soil and 10% for the slope were considered as threshold. The WGEN input file contains the statistical data needed to generate representative daily climatic data for the sub-basins.

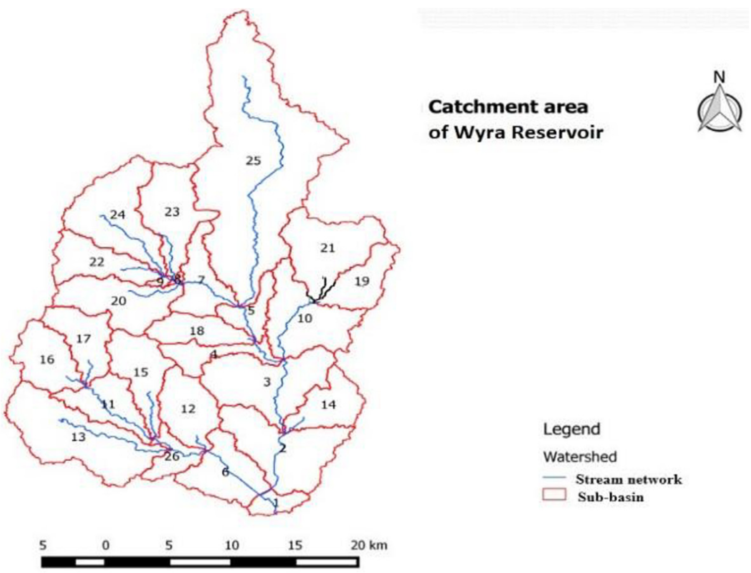

Figure 3. Sub-basins of Wyra watershed

Rainfall analysis

The rainfall distribution of Wyra watershed has been studied with 28 years (1991–2019) of precipitation data. It can be clearly seen from Figure 4, that the highest annual rainfall occurred in 2013 and the lowest was in 2011. From the literature, it is identified that in the wet years, sedimention is high when compared to the normal and dry rainfall years. For this study, dry and wet years are considered as follows:

- dry year – when the rainfall values are below the (average – standard deviation) line;
- wet years – when the rainfall values are above the (average + standard deviation) line;
- normal years – when the rainfall values are between (average+standard deviation) and (average – standard deviation) lines.

Through this analysis wet, dry and normal years are seperated and used to determine how the sedimention is taking place during wet, dry and normal years. In the rainfall analysis, both 'the average + standard devation line' and 'the average – standard devation line' were plotted. These values are considered based on spatial distribution of annual rainfall happenning in the watershed. The years 1994, 1995, 2005, 2006, 2008, 2010 and 2013 are cosidered as wet years and the years 1993, 1999, 2014 and 2015 are considered as dry years. The remaining years are considered as normal years. For the sesonal variation sediment analysis, only two wet seasons i.e., August & September and two dry seasons i.e., March & April are considered instead of calculating for all the seasonal months.

Model calibration and validation

Model parameter determination

Only the measured runoff data and sedimentation of Wyra reservoir from 1999 to 2019 were available. The monthly runoff data from Konijerla hydrometric station from 2009 to 2012 were used to calibrate the model and the monthly runoff data and sedimentation from 2013 to 2016 were used to validate the model. Table 1 shows the final parameter values after automatic and manual adjustments.

Model performance

The two criteria selected for model calibration are Nash–Sutcliffe coefficient (NSE) and Coefficient of Determination (R^2). These criteria are evaluated using the simulated and observed streamflow for selected gauging station.

Table 1. Most sensitive parameters with calibrated values

Sl. No.	Parameter name	Physical meaning	Range	Calibrated values
1	V_CN2	Initial SCS runoff curve number	-0.2 to 0.2	0.007
2	V_ALPHA_BF	α factor of base flow/day	0.0 to 1.0	0.313
3	R_SOL_AWC	Saturated water content of soil/(mm/mm)	-0.2 to 0.20	0.184
4	V_GWQMN	Depth threshold when regressive flow occurs in shallow water layer/mm	0 to 5000	677.38
5	V_ESCO	Soil evaporation compensation factor	0 to 1	0.1945
6	V_GW_DELAY	Groundwater delay time (days)	0 to 500	42.61

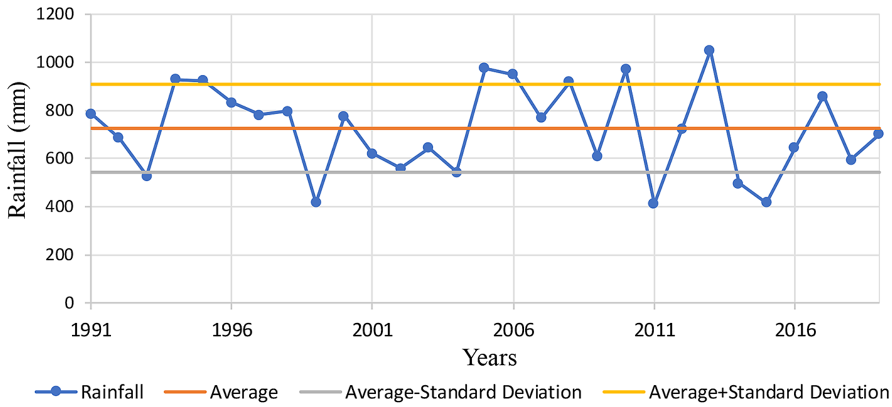

Figure 4. Average annual rainfall in the study area from 1991 to 2019

$$\text{NSE} = 1\text{-}\left[\frac{\sum_{i=1}^{n}(O_i - S_i)^\wedge 2}{\sum_{i}^{n}(O_i - O_{avg})^\wedge 2}\right] \quad (2)$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(O_i - O_{avg}) * (S_i - S_{avg})}{(\sum_{i=1}^{n}(O_i - O_{avg})^2 * \sum_{i=1}^{n}(S_i - S_{avg})^2)^\wedge 0.5}\right\}^2 \quad (3)$$

where: n – number of data; O_i – observed streamflow; O_{avg} – mean of observed streamflow, Si – simulated streamflow and S_{avg} – mean of simulated streamflow.

Simulation efficiency evaluation

Nash-Sutcliffe efficiency coefficient NSE and coefficient of determination R^2 are used to evaluate the applicability of the model. For the model to be considered satisfactory, generally the value of NSE should be greater than 0.50, and R^2 be greater than 0.60. For the calibration of the model, the average monthly flow data of the years between 2009 to 2012 were used, while for validation, the data for the years 2013 to 2016 were used. The evaluation indices of the monthly runoff simulation effect in the calibration period and validation period are shown in Table 2. The NSE values were 0.83 and 0.84 and that of R^2 were 0.78 and 0.77 for calibration and validation periods respectively.

Table 2. Evaluation indices of monthly runoff simulation (at Konijerla hydrometric station)

Simulation period	R^2	NSE
Calibration period (2009–2012)	0.84	0.83
Validated period (2013–2016)	0.77	0.78

Figure 5 and 6 compare the simulated and observed monthly river flow values as a consequence of the model simulation using the pre-calibrated model. Significant differences between the observed and simulated data may be noticed, during calibration and validation periods emphasising the necessity of model calibration for achieving good prediction accuracy.

Calibration and validation of the sediment transport model

The calibration of the SWAT model was performed using data for the period from 2009 to 2012. The value of Shields' parameter, grain size and soil factors were varied till a reasonable match was obtained between the simulated and observed sediment graphs. From daily simulation values, the monthly sum of sediment load is taken for calibration. The model performance measures during calibration are shown in the Table 3. These values indicate that the model performance is very satisfactory. The sediment load tends to underestimate

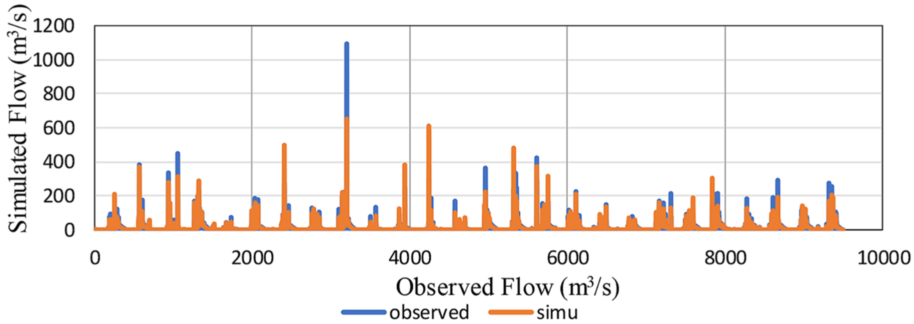

Figure 5. Observed flow and simulated flow during calibration period

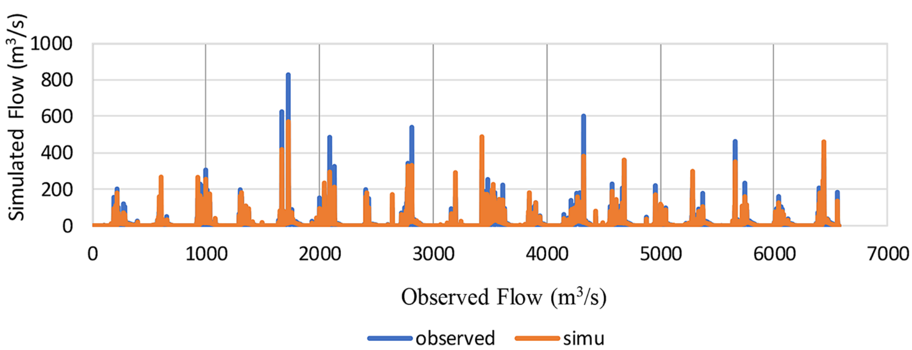

Figure 6. Correlation of observed flow and simulated flow during validation

Table 3. Performance measures of the model during calibration and validation

Performance measure	Calibration period	Validation period
NSE	0.73	0.51
R^2	0.86	0.80

during the calibration period. The simulated and observed sediment graphs are plotted in Figure 7.

The values of grain size, Shields' parameter and soil factor after calibration were 0.5 mm, 0.033 and 0.009 respectively. Data from the years 2013 to 2016 were utilised to validate the SWAT model. Same parameters are used for both calibration and validation. Table 3 displays the model's performance metrics during validation. These numbers show that the model's performance is very satisfactory. The validation period tends to overestimate the amount of sediment and the Figure 8 illustrates the simulated and observed sediment graphs.

RESULTS

Model calibration and validation are critical steps in the simulation process, as they are used to evaluate model prediction results. The surface runoff was calibrated by comparing the simulated and observed runoff. After obtaining acceptable runoff data, the same parameter values were used for both the sediment calibration and validation. The SWAT model is used in combination with a Geographic Information System in the current study. The module Arc SWAT allows interaction between the Open Source model and the GIS software. The ArcSWAT 2012 software interface is used for watershed hydrological modelling. The model divided the watershed into 26 sub-basins, which were then divided into 46 HRUs (hydrological response units). They are produced by combining climate data, plant cover, soil types, and slope.

Sediment yield in the basin

The divided sub-basins are used in the calculation of the sediment yield of the Wyra watershed. In addition, it is analysed for each of the 46 HRUs delimited within the basin by the SWAT model. The characteristics within each sub-basin are highly varied.

It can be seen that sub-basins 5, 12, 23, 9, 13, 3, 2 and 25 are having a high erosion which is in the range between 1914 to 373 tonnes, followed by sub-basins 10, 4, 22, 11, 6, 8, 17 and 7 are in intermediate level of erosion which is in the range

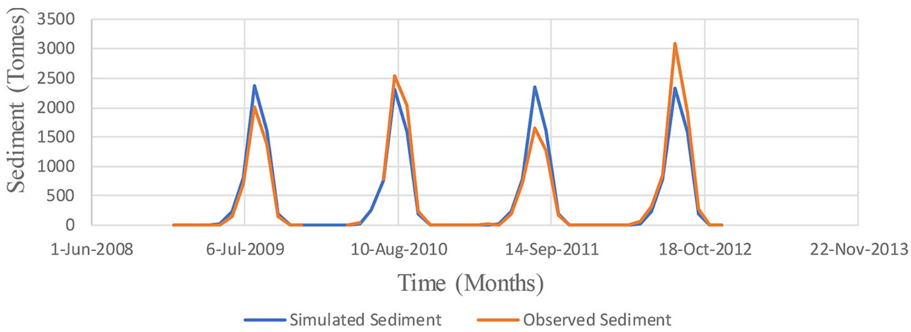

Figure 7. Computed sediment and observed sediment load during calibration

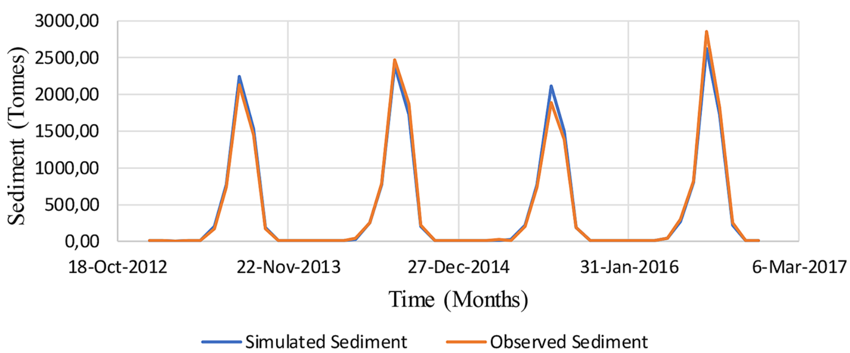

Figure 8. Computed sediment and observed sediment load during validation

between 372 to 263 tonnes. Remaining sub-basins show quite a little erosion which is in the range between 228 to 85 tonnes. Erosion rates by sub-basin can be seen in the Figure 6. However, these results are to be interpreted with caution. The values shown in figure are average, the same ones that are not uniform for the entire extension of each sub-basin. From the Figure 9 we can observe that sub-basin 5 was contributing highest percentage of sediment i.e., 18.88% and lowest sediment contribution was by from sub-basin 24 i.e., 1.05%. Out of 26 sub-basins below 2 tonnes producing sub-basins are seven, above 2 to 3 tonnes producing sub-basins are eight, above 3 to 4 tonnes and above 4 tonnes producing sub-basins are six each.

Sediment rate vs area of each sub-basin analysis

The entire area of each sub-basin does not produce the average sediment volume, there are areas where erosion is concentrated, due to the particular characteristics that can occur in each one. To look in greater detail, the erosion rate is analysed using the HRUs of the model. Details of comparing between area and sedimentation are shown in Figure 10. It can be seen that area wise, sub-basins 25 and 8 are having high and low erosion rates. But in terms of sediment yield sub-basins 5 and 1 are showing high and low values. It is observed that sub-basins 8 and 9 are having less area but the sediment yield is more. Interestingly, sub-basin 12 which is second largest having above 3.58 km^2 but in terms of sediment yield it is just 993 tonnes. Similar pattern follows for sub-basins 13, 3 and 2.

Seasonal sediment analysis

To understand seasonal wise distribution of sedimentation two wet months i.e., August and September and two dry months i.e., April and May are considered. For this analysis sub-basins 3, 4, 5, 8, 9, 12, 13 and 23 were only considered, because these basins are having the erosion area of 20% of the basin area (see Figure 9) but are contributing more than 57% of the sedimentation of the entire watershed area (see Figure 10). Seasonal sedimentation analysis is done differently for wet years, dry years and normal years as discussed in section 3.5. The analysis showed that wet years are contributing more sedimentation in flood years than that of normal and dry years. It shows that the wet years have

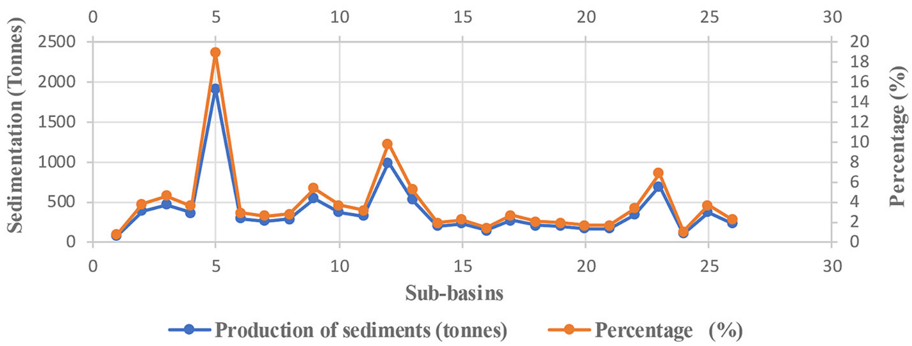

Figure 9. Sediment rate generated by each sub-basin

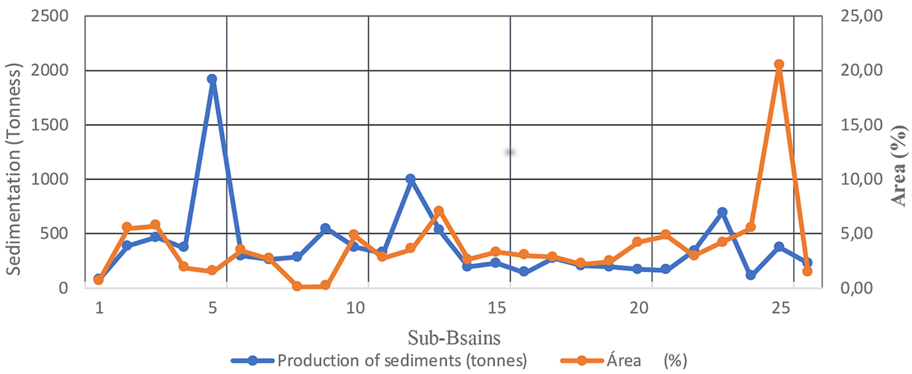

Figure 10. Sediment yield over time

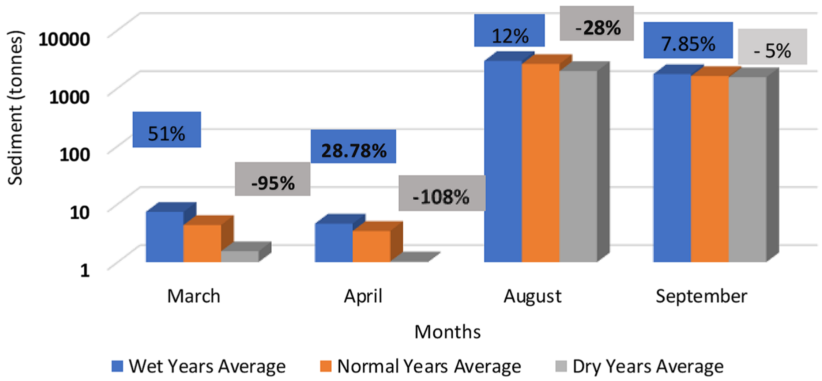

Figure 11. Average wet, dry and normal years sedimentation and percentage difference of wet and dry years with respect to normal years

higher sediment yields than that of normal and dry years. But in dry period also, some amount of sedimentation was occurring due to more deforestation. The average sedimentation yield for the three periods for the selected sub-basins and for the chosen months are shown in Figure 11, the sedimentation peaks are observed during the months of floods, while in the dry season the sediment yield is very close to 1 ton. The sedimentation difference between wet and dry years with respect to the normal years are shown in the Figure 11. It is observed that in the month of March, the wet years average sedimentation is increased by 51%, where as in dry season it is decreased by 95%. It is noticed that the highest sedimentation producing month i.e., August in wet years increased by 12% and decreased by 28% in dry years.

Soil analysis

When analysing the sediments produced by each sub-basin, it can be seen that the type of soil has an enormous influence. So, type of soils of Wyra watershed are downloaded from the NASA website https://power.larc.nasa.gov/data-access-viewer/. It is observed that sub-basins 5, 7, 13 and 17 have red clayey soils, which corresponds to the major sediments generated. However, it shows great resistance to rain erosion due to its unique characteristics and the continuity of the layers that make it up. The type of soil is red loamy, calcareous and red gravelly clayey. Sub-basins 3, 5, 6, 8, 9, 10 and part of 4 and 7 are formed by this type of soil. The erosive capacity of this type of red soil in particular is very high with medium intensity of rainfall. The concentration of erosion is greater especially on steep slopes. Particularly sub-basins 23, 5, 14, 18 and 20 are contributing a medium level of erosion with less intensity of rainfall. Where the slopes are moderate the erosive factor becomes most determining factor. The location of crops and higher quality grasslands, are in this sub-basin. In the higher altitude areas next to the flow of the water network, very good quality grasslands are located and this improves the impermeable nature of that soil.

CONCLUSIONS

In the study sediment transport modelling of the Wyra river using SWAT model was carried out. The SWAT model was calibrated for 4 years (2013–2016) and validated for 3 years (2017 to 2019). The set of 6 parameters were calibrated by automatic calibration in SWAT. The model showed good performance with NSE as 0.83 and 0.78 and R^2 as 0.84 and 0.77 during calibration and validation respectively in sedimentation analysis. It is identified that out of the 26 sub-basins, the sub-basins 5 and 8 are contributing nearly 18.88% of sedimentation. From seasonal sediment analysis, it is observed that in the month August, sediment erosion was increased by 12%. Overall sediment erosion in wet years increased by 10.59% and in dry years decreased by 18.78% respectively. This tells that sediment erosion is purely influenced by the climatic changes and the deforestation. Most of the soils observed in the study area are gravelly red clay soils. The SWAT model used in the study was found to give satisfactory results and thus can be used in similar catchments to determine the sedimentation graph in the river.

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