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Formulating a Soil Erosion Model & Accounting for its Effects on the Dam Capacity - Pavana Dam Catchment

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ABSTRACT:

Soil erosion and sedimentation by water involves the process of detachment, transportation and deposition of sediment by raindrop impact and flowing water. Soil erosion model is a set of empirical or realistic equations and logistics, to evaluate the quantity of soil erosion in a particular catchment area. Soil erosion results in accumulation of sediments in different parts of a reservoir, in different quantities. This results in reduction of the reservoir capacity and tampering of the water quality in the reservoir.

Research shows that prediction of sediment distribution in reservoirs is an important issue for dam designers to determine the reservoir active storage capacity, outlet sill level, dam stability, recreational features and backwater conditions. Hence the failure of these mentioned parameters is a victim of Soil Erosion. The significance of sedimentation is overlooked at this point of time, which if ignored incessantly, in future, might lead to excessive silting of reservoir.

This study is performed using Geographical Information System (GIS). In GIS, layers of the factors affecting soil erosion i.e. topography, rainfall, geology, vegetation etc; are plotted. Using this layered analysis, the quantity of soil erosion or silt will be calculated using the Standard Mathematical Empirical Equation RUSLE. ***(Revised Universal Soil Loss Equation)*** *.The above factors are* ***Weighted,*** *according to a survey conducted, as per the opinion of various experts from the related field. From these results, the amount of soil erosion for the next 3 years will be calculated. Also the silting effect of the catchment on the reservoir is estimated by the identifying Critical Source Area's. Physical Validation of the current monsoon is also to be studied, by testing 200 samples obtained from the* ***Parana dam catchment,*** *Pune, for* ***Total Solids*** *and* ***Turbidity,*** *to estimate approximately, the amount of silt entering into the reservoir, thus resulting in adverse effects on the reservoir.*

Keywords: Soil Erosion, Realistic Equations, GIS, Sedimentation, Reservoir capacity, Critical Source Areas, RUSLE, Layered Analysis, Weighted.

1. INTRODUCTION:

Erosion is a natural geological phenomenon resulting from the removal of soil particles by water or wind, transporting them elsewhere, while some human activities can significantly increase erosion rates. Erosion is triggered by a combination of factors such as steep slopes, climate (e.g.long dry periods followed by heavy rainfall), inappropriate land use, land cover patterns (e.g. Sparse vegetation) and ecological disasters (e.g. forest fires). Moreover, some intrinsic features of a soil can make it more prone to erosion (e.g. a thin layer of topsoil, silty texture or low organic matter content). Geology, topography, soil characteristics, vegetation, and climate interact in a complex manner to determine the types, intensities, and locations of runoff production and the associated soil erosion and transport of sediments. The locations and magnitude of active erosion and sediment transport will change in space and time depending on hydrologic conditions. Prediction of changes in runoff production, erosion, and sediment transport requires an accurate, explicit representation of the spatial and temporal variations in hydrologic processes, as well as the relationships between local site hydrology, topography, soils, vegetation, climate, and land use. The need for predictability under future conditions requires process representation within the models and incorporation of site- specific conditions for the estimation of model parameter values

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2. LITERATURE SURVEY:

2.1 Soil Erosion Model:

Different indicators of soil erosion have been identified and it is a common opinion that the area actually affected by erosion is in fact the best indicator for soil erosion. Equally interesting to the actual erosion rate is the risk of future erosion in a specific area. The area at risk can be estimated using an appropriate model of soil erosion. Effective modeling can provide information about current erosion, its trends and allow scenario analysis. The integration of existing soil erosion models, field data and data provided by remote sensing technologies, through the use of geographic information systems (GJS), appears to be an asset to further exploit.A large variety of models can be found in the literature that could be used in soil erosion risk assessment These models can be classified as follows:

1. Empirical and mechanistic models:
2. Static and dynamic models:
3. Deterministic and stochastic models:
4. Spatial dimensions in models:
5. Qualitative and quantitative models:
6. Long-term or event-based models (temporal scale).
7. Single point or spatially distributed models (spatial scale).

2.2 Universal Soil Loss Equation (USLE)

One of the most widely applied empirical models for assessing the sheet and rill erosion is the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith in 1978 (8). The USLE is an Empirical equation and is based on over twenty years of soil loss data collected from agricultural field plots. The USLE computes soil erosrbn as the product of six factors representing rainfall erosivity, soil erodibility, slope length, slope steepness, cover management practices, and support conservation practices (Renard et al. 1997).

USLE was developed mainly for soil erosion estimation in croplands or gently sloping topography. USLE estimates soil loss from a hill-slope caused by raindrop impact and overland flow (commonly termed "interrill" erosion), plus rill erosion. It does not estimate gully or stream-channel erosion. Although USLE has many shortcomings and limitations, it is widely used, especially at regional and national level, because of its relative simplicity and robustness (9) and because it represents a standardized approach.

$A = R \times K \times L\ S \times C * P$

where,

A = Estimated Average annual soil loss, R = Rain Erosivity Factor, K = Soil Erodibility Factor, L = Slope Length Factor, S = Slope Steepness Factor, C = Cover Management Factor, P = Support Practice factor

2.3 Field Application Of The Usle:

The USLE was originally developed for estimating soil erosion occurring on agricultural field plots. In any field plot, the process of soil erosion is difficult to observe on a regular basis because it occurs so slowly over time. The USLE estimates the longterm average annual soil loss of that field plot based on limited input. Another benefit was that mitigation actions could be considered and the USLE can be recalculated to forecast what the resulting soil loss would be.

2.4 Revised Universal Soil Loss Equation (RUSLE):

RUSLE is a computation method that may be used for site evaluation and planning purposes and also for assisting in the decision process of selecting erosion control measures. It provides an estimate of the severity of erosion and also numerical results that can validate the benefits of planned erosion control measures in the risky areas (11). Soil erosion is one of the major hazards threatening the productivity of farmland. The amount of sediment carried in the fluvial system is usually governed by the availability of the upstream supply of soil loss from watersheds rather than the transport capacity of rivers. Upland erosion pollutes surface water and often causes serious problems when deposition occurs _Frenette and Julien 1987_. This study selected a RUSLE model that involves GIS data. RUSLE was developed by Renard et al. _1991_ for watershed-scale applications, and much research has been performed using experimental data. The RUSLE model is shown below Renard et al. 1991_

A = R * K * L * S * C * P

3. Aim:

Formulating a Soil Erosion Model, to check the Contribution of Soil Erosion as one of the major parameter, influencing the Reduction in Dam Storage Capacity in India.

4. Methodology Adopted

For the following study, we have adopted the Pavana Dam Catchment as out Study Area, as it serves as the main reservoir for the satisfying the water demand in the whole of Pimpri Chinchwad Municipal Corporation. (PCMC)

4.1 GIS Modelling:

Geographical Information System (GIS), is a computer based program which gives an overview of the possible soil erosion. By using GIS we can identify Critical Source Areas, which are the exact locations where erosion occurs or is prone to occur. In GIS, we can combine remotely sensed data to formulate a single database to analyze various factors of soil erosion such as land cover, land use, slope specifications etc. By this we can overcome the drawbacks of using and analyzing the remotely sensed data individually, which also is a tedious and quite cumbersome job.

Using GIS, images of land cover, land use, terrestrial ecology, geology, topography etc. and also soil classification can be analyzed with different scales and spatial resolutions. We can also use GIS for analyzing the Water-Content in soil. As the proposed catchment consists mainly of expansive soils, the content of water which it holds increases, as the soil expands. As the soil expands it loses adhesion with its parent mass, resulting in erosion. There are vulnerable soil patches which can be identified and worked upon with corrective measures also the exact locations of such identical vulnerable soil patches can be . predicted and accounted for, thus avoiding excessive erosion.

Thus we can establish a system that will harness, co-ordinate, and enhance existing Earth Observation (EO) data and monitoring information from satellites and Earth-based sensors, in order to support decision making for the environment and security.

4.2 Mathematical Modelling:

Mathematical Modelling includes simulation of the data by which evaluation of results becomes easy and furthermore, prediction of the Critical Source Areas is possible. We can simulate the runoff and flood possibilities for the proposed catchment using hydrological data to identify specifically the type of erosion occurring such as gully erosion, rill erosion etc. As the runoff is more, it transfers more sediment mass with it, resulting in more erosion.

Current Rainfall data can be obtained and the amount of runoff and thus sedimentation can be calculated. Now, the further data can be simulated, predicting the runoff values and the quantity of sedimentation at various rainfall intensities. The natural variability of floods cannot be represented appropriately by single design floods. Different hydrological scenarios are needed for sustainable design of flood protection structures such as flood control reservoirs, polders etc.

When the soil remains dry, it absorbs some amount of water from the rainfall. There is no erosion at this point. But after the soil becomes completely saturated, it cannot hold more water and the excessive water starts eroding the soil causing runoff. There is an increase in the kinematic properties of water causing excessive erosion. This water carries with it, the eroded soil, and deposits the same into the reservoir thus resulting in excessive silting and reduction of the reservoir capacity. Hence the amount of water that will cause runoff or excessive floods can be simulated and accounted for its prevention. This is how we can use Mathematical Modelling to decrease the intensity and amount of soil erosion thus protecting the reservoir damage.

Physical Validation:

Physical Validation includes in-situ collection of water samples from different pre-decide,d locations and analyzing the amount of sediment the water samples carries with it. This can be done by collecting water samples in two seasons for better interpretation of results i.e. during monsoon and post-monsoon. At different locations, samples can be extracted and tested for the sediment intensity. This sediment intensity can be calculated using the standard tests of Turbidity and Total Solids. Turbidity will reveal the amount of suspended sediment that the sample contains and Total Solids will expose the amount of total solids in different forms.

Reversal of work:

After identifying the sediment load in water flow for particular runoff of particular area for particular intensity and duration of rainfall, we will have a correction factor for that area for GIS modelling. By using the concepts of weight, we can, similarly, find out the total erosion of the different critical source areas, thus resulting in more accurate data of soil erosion, sediment loads and possible sedimentations in different parts of river basins and reservoirs.

The amount of rainfall that causes erosion will be calculated first and the amount of sedimentation can be simulated. Inversely, by finding out the sedimentation in water, we can predict the soil erosion, the runoff and thus the intensity of rainfall in that particular area. If this proves to be appropriate, then a new database can be compiled and used for further safety measures to be adopted in favour of soil erosion.

Also Physical modelling will validate the results obtained from the above 2 phases i.e. GIS modelling and Mathematical modelling.

5 Case Studies:

5.1 SOIL EROSION MODELLING BY USING GIS AND REMOTE SENSING: GANOS MOUNTAIN, TURKEY.

Objective: Calculation of the size of amount of soil loss per hectare in **GANOS MOUNTAIN, Turkey,** using Remote Sensing and GIS.

Area of Study: Ganos Mountain, over Thrace Peninsula region, Turkey. (2^{nd} highest peak in that peninsula.)

Observations:

1.) The main causes of Soil Erosion observed were, cultivation without using particular control techniques, unplanned land use, uncontrolled urban development and deforestation.

2.) If vegetation of about 15% is present, the soil erosion and runoff is reduced by 75%.

Methodology:

1.) **Morgan method** was used rather than USLE as it has more powerful fundamentals than USLE and it is a more flexible method.

2.) Data for sloppiness, altitude of the study area, pH values, Surface textures, Stoniness, Drainage class of soil, soil depth, land use classes and crop texture was procured.

3.) **LANDSAT-5 TM** Remorely Sensed images from 1992 were obtained.

4.) Analysis was done using GIS softwares **-ILWISandERDAS.**

5.) **Digital Elevation Model (DEM)** was developed by spatial interpolation of digitized contour lines from 1:50000 scale, using transform algorithm and pixel correction was applied.

6.) Calculation was done by:

Water phase:

E = R(11.9 + 8.71oglO(I))

Q = Rexp(-Rc/Ro)

[R c = 1000 MS BD RD (E t / E o) 0.5

Ro = R/Rn]

Sediment phase:

F = K(Eexp(-0,0 5A))10-3(5)

G = CQ2(sinS)10-3

Operating functions:

E : Kinetic energy of rainfall (J /m 2)

Q : volume of overland flow (mm)

F : Rate of splash detachment (kg / m 2)

G : Transport capacity of overland flow (kg /m2)

Input Parameters:

MS : Soil moisture content at field capacity

BD : Bulk density of the top soil layer (g /cm3)

RD : Topsoil rooting depth (m)

E **t** / E **o** : Ratio of actual (E t) to potential (E o) evapotranspiration

R : Annual rainfall (mm)

Rn : Number of rain days in the year

I: Typical value for intensity of erosive rain (mm/h)

K : Soil detachability index (g / J)

S : Steepness of the ground slope expressed as the slope angle

A : Percentage rainfall contributing to permanent interception and stem flow

C : Crop cover management factor

W : Rate of increase in soil depth by weathering at the rock soil interface (mm / year)

V : Rate of increase of the topsoil rooting layer (mm / year).

7) Calculations Included - Kinetic Energy of Rainfall, overland flow and annual precipitation. Also the soil loss per hectare per pixel of mapping was calculated.

Results and Conclusion:

a) It was seen that soil erosion was high i.e. **10 ton per hectare.**

b) If slope was more than 16°, the value of erosion went upto **20 ton per hectare.**

c) Also in areas where proper land cover techniques were adopted and proper land use was seen, the erosion reduced by leaps and bounds thus reducing the excessive sedimentation.

5.2 Determining the Sediment Delivery Ratio Using the Sediment-Rating Curve and Geographic Information System-Embedded Soil Erosion Model on a Basin Scale:

Objective: This study includes a model based approach to calculate sediment delivery ratio - SDR and use of empirical models to calculate sediment yield.

Methodology:

There are a few methods used to calculate the amount of eroded soil, namely, sediment-rating curve method, measurement of sediment deposit, and other empirical methods. When a precipitation event occurs, the surface runoff is transported by a number of routes into local streams or the local watertable (Maidment 1993). The soil erosion is related to the water flow that eventually reaches the saturated overland flow, which is controlled by the abundance and type of vegetation and underlying soil. Therefore, only some of the eroded soil is routed to the basin outlet. The ratio between the basin sediment yield at the basin outlet and soil erosion over the basin is called the sediment delivery ratio (SDR). It is a dimensionless scalar and conventionally expressed as,

SDR =Y/E.

where *Y* = average sediment yield per unit area and E=average erosion over that same area (Walling 1983).

This study developed a triangle irregular network (TIN), using a 1:5,000-scale digital topographic map crafted by the National Geography Institute, Suwon, Korea.

Land cover plays a decisive role in causing soil erosion based on the intensity of rainfall. Therefore, it is crucial to secure an accurate land-cover map. RUSLE was developed by Renard et al. (1991) for watershed-scale applications, and much research has been performed using experimental data. The RUSLE model is shown below,

$A = R * K * L * S * C * P * 1$

where ,A=annual soil loss(ton/ha/yr);R = rainfall-runoff erosivity factor (107 J /ha mm/yr); K=soil credibility factor (ton/ha/R); L=slope length factor;S= Aslope steepness factor; C=cover management factor; and P= support practice factor

Conclusions of Case Study:

This study determines the SDR using the sediment-rating curve constructed on the basis of the measured sediment yield and simulated soil erosion based on a GIS-based empirical model. To consider the rainfall effect when simulating soil erosion, two cases of equations were compared, namely, rainfall amount and rainfall intensity. The *R2* between the simulated soil erosion and the measurement sediment yields with rainfall amount were 0.423 for Donghyang and 0.632 for Cheonchen; however, the values with rainfall intensity were 0.874 and 0.948, respectively.

The *R2* and *EI with* rainfall intensity for Donghwang_Cheoncheon_ were higher as 0.868 and 0.865 (0.889 and 0.878) in the validation process. This result implies that a simulation of soil erosion with rainfall intensity gives better performance.

The model-based approach for determining the SDR presented herein was calibrated using field measurements for the time period of 2002-2005 and validated for the time period of 2006-2008. The results generally show that the constructed sedimentrating curve and GIS-embedded soil erosion model could provide reasonable accuracy in determining the SDR for a basin scale in Korea. This finding is advantageous in that the approach presented herein is based on the measurement of SSC, which is relatively easily available, and a soil erosion model. The GIS embedded method in this study allows one to easily quantify the impact of a single factor on overall results, and the method is easily updated with an improved data set. The current research is somewhat limited, but this study has value, as it offers a viable foundation for future study.

Limitations:

- The accuracy of physical data, influencing physical validation.
- The data is used as per the original form that is procured, no corrections if present, is introduced.
- The paper includes consideration of expansive soils. No rocky mass or other form of soil is included.
- The parameters influencing soil erosion will be selected on the basis of data availability and resources present.

Conclusion:

1. The model can be used where the factors erosion are similar.
2. Variations observed in the data can be incorporated thus the model can be modified accordingly.
3. The critical source areas are identified which reveal the exact location of soil erosion. Hence knowing the exact location and form of erosion, measures of mitigating erosion can be adopted accordingly.
4. Using this model for areas having similar nature, values of either absent parameters or overall effect of existing parameters can be worked out.
5. The model is a combination f 3 individual system (Phases), hence the lacunas of single phase models are

eliminated (error reduction) and the advantage of individual methods are considered in a combined form.

6. In India, soil erosion and sedimentation is not given the required emphasis, this can be one of the first step to create a new database for reducing the soil erosion effect on the reservoir.

Future Scope:

1. Models for rocky areas or different type of soils can be established.
2. The corrections can be applied to the procured data and then can be analysed for better practicable results.
3. The sedimentation deposition parameter and its actual effect on the reservoir can be considered in future study.
4. More emphasis can be given for mitigating the soil erosion according to the depth of study and the effect of erosion.

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