Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes (Proceedings of a symposium held at Vienna, July 1998). IAHS Publ. no. 249, 1998.

Surface erosion, sediment transport, and reservoir sedimentation

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Abstract Systematic plans and policies are needed to reduce adverse impacts of sedimentation and prolong the useful life of reservoirs. The ability to estimate the rate of watershed surface erosion, sediment transport, scour and deposition in a river system, and sediment deposition and distribution in a reservoir is essential to the development of sound sediment management plans and policies. The empirical Universal Soil Loss Equation has been applied in the eastern United States for the estimation of soil loss from agriculture land. The general application of this equation to other conditions remains questionable. A process based model for estimating surface erosion is needed. Most computer models for the stimulation and prediction of sediment transport in rivers and reservoirs are one-dimensional. Although truly two- or three-dimensional models are available, they require extensive field data for calibration and may be difficult to apply. A semi-two-dimensional model for water and sediment routing is an effective tool to solve river engineering problems. This paper provides a brief description of a systematic and integrated approach based on well established sediment transport equations, minimum energy dissipation rate theory, and the Bureau of Reclamation's Generalized Stream Tube model for Alluvial River Simulation (GSTARS 2.0). Examples of computed results are used to illustrate the applicability of different components of this approach.

INTRODUCTION

As a result of runoff from rainfall or snowmelt, soil particles on the surface of a watershed can be eroded and transported through the processes of sheet, rill, and gully erosion. Once eroded, sediment particles are transported through a river system and are eventually deposited in a reservoir or at sea. With the exception of sediment transport in rivers, engineering practices for the determination of surface erosion are mainly empirical. Engineering techniques used for the determination of reservoir sedimentation processes rely mainly on field surveys. Field surveys can be used for the determination of what has happened but not for predictive purposes.

During the 1997 19th Congress of the International Commission on Large Dams (ICOLD), the Sedimentation Committee passed a resolution encouraging all member countries to (a) develop methods for the prediction of the rate of surface erosion based on rainfall and soil properties, and (b) develop computer models for the simulation and prediction of reservoir sedimentation processes. This paper provides a brief description of an ongoing study in compliance with the above two ICOLD resolutions. Preliminary results will be presented to demonstrate the feasibility of a systematic and rational approach for the determination of surface erosion rate and sediment transport in rivers. The possibility of developing a reservoir sedimentation management model is also addressed.

SURFACE EROSION

There are four methods which can be used for the estimation of the rate of surface erosion or the rate of sediment yield from a watershed. A brief description of each method is given in this section.

Universal Soil Loss Equation The empirical Universal Soil Loss Equation is:

$$A = R\,K\,L\,S\,C\,P \tag{1}$$

where
A = computed soil loss in tons acre^{-1} year^{-1},
R = rainfall factor,
K = soil-erodibility factor,
L = slope-length factor,
S = slope-steepness factor,
C = cropping-management factor,
P = erosion-control practice factor.
Equation (1) was proposed by Wischmeier & Smith (1962, 1965, 1978) based on statistical analyses of data from 47 locations in 24 states in the central and eastern United States. Because all the parameters in equation (1) were based on agriculture practices in humid areas in the United States, its application is limited to agricultural areas of the central and eastern United States. A detailed description of equation (1) and how to apply it was summarized by Yang (1996).

Sediment yield as a function of drainage area Empirical sediment yield equations can be developed strictly as a function of drainage area based on reservoir sediment survey data. For example, Strand (1975) developed the following empirical equation for Arizona, New Mexico, and California:

$$Q_s = 2.4\,A_d^{-0.229} \tag{2}$$

where
Q_s = sediment yield in acre-feet per square mile per year,
A_d = drainage area in square miles.
Strand & Pemberton (1982) developed a similar empirical equation for the semiarid climate of the southwestern United States:

$$Q_s = 1.84\,A_d^{-0.24} \tag{3}$$

Sediment yield as a function of nine drainage basin characteristics This method classifies sediment yield as a function of nine individual drainage basin characteristics. These nine factors are surface geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion. Their recommended values are shown in Table 1. This is a subjective procedure. Only experienced engineers with a thorough understanding of the drainage basin can

Table 1 List of drainage basin characteristics and possible range of numerical ratings (modified from Pacific Southwest Inter-Agency Committee, Water management Subcommittee, 1968).

Drainage basin characteristic	Sediment yield levels: High rating	Moderate rating	Low rating
Surface geology	10: marine shales and related mudstones and siltstones	5: rocks of medium hardness moderately weathered and fractured	0: massive hard formations
Soils	10: fine textured and easily dispersed or single grain silts and fine sands	5: medium textured, occasional rock fragments, or caliche crusted layers	0: frequent rock fragments, aggregated clays, or high organic content
Climate	10: frequent intense convective storms	5: infrequent convective storms, moderate intensity	0: humid climate with low intensity rainfall, arid climate with low intensity rainfall, or arid climate with rare convective storms
Runoff	10: high flows or volume per unit area	5: moderate flows or runoff volume per unit area	0: low flows or volume per unit area or rare runoff events
Topography	20: steep slopes (in excess of 30%), high relief, little or no flood plain development	10: moderate slopes (about 20%), moderate flood plain development	0: gentle slopes (less than 5%), extensive flood plain development
Ground cover	10: ground cover less than 20%, no rock or organic litter in surface soil	0: ground cover less than 40%, noticeable organic litter in surface soil	-10: area completely covered by vegetation, rock fragments, organic litter with little opportunity for rainfall to erode soil
Land use	10: more than 50% cultivated, sparse vegetation, and no rock in surface soil	0: less than 25% cultivated, less than 50% recently logged, less than 50% intensively grazed	-10: no cultivation, no recent logging, and only low intensity grazing, if any
Upland erosion	25: rill, gully, or landslide erosion over more than 50% of the area	10: rill, gully, or landslide erosion over about 25% of area	0: no apparent signs or erosion
Channel erosion	25: continuous or frequent bank erosion, or active headcuts and degradation in tributary channels	10: occasional channel erosion of bed or banks	0: wide shallow channels with mild gradients, channels in massive rock, large boulders, or dense vegetation or artificially protected channels

assign reasonable values to each of the basin characteristics for estimating an annual basin erosion rate. Table 2 can be used as a reference for assigning drainage basin sediment yield classification. Based on information in Tables 1 and 2, the estimated

Table 2 Drainage basin sediment yield classification (from Randle, 1996).

Drainage basin classification number	Total rating	Annual sediment yield (acre-ft mi^{-2})
1	>100	>3
2	75 to 100	1.0 to 3.0
3	50 to 75	0.5 to 1.0
4	25 to 50	0.2 to 0.5
5	0 to 25	<0.2

sediment yield rating and the 100-year sediment yields for three proposed reservoirs are shown in Tables 3 and 4, respectively.

Physically-based equation for surface and rill erosion Yang (1973) developed the following unit stream power equation for sand transport:

$$\begin{aligned}\log C_{ts} &= 5.435 - 0.286 \log \frac{\omega d}{\nu} - 0.457 \log \frac{U_*}{\omega} \\ &+ \left(1.799 - 0.409 \log \frac{\omega d}{\nu} - 0.314 \log \frac{U_*}{\omega}\right) \log \left(\frac{VS}{\omega} - \frac{V_{cr} S}{\omega}\right)\end{aligned} \tag{4}$$

where

C_{ts} = total sand concentration in ppm by weight,
ω = sediment fall velocity,
d = sediment particle diameter,
ν = kinematic viscosity,
U_* = shear velocity,
S = energy or water surface slope,
VS = unit stream power,
V_{cr} = average flow velocity at incipient motion.

The dimensionless critical average flow velocity in equation (4) can be expressed by:

$$\frac{V_{cr}}{\omega} = \frac{2.5}{\log(U_* d / \nu) - 0.06} + 0.66 \qquad \text{for } 1.2 < \frac{U_* d}{\nu} < 70 \tag{5}$$

$$\frac{V_{cr}}{\omega} = 2.05 \qquad \text{for } 70 \le \frac{U_* d}{\nu} \tag{6}$$

Table 3 Estimated numerical ratings for the proposed reservoir drainage basins (from Randle, 1996).

Drainage basin characteristics	Possible ratings	Estimated sediment yield rating:		Estimate description
Surface geology	0 to 10	5	Moderate	Varies from hard dense crystalline rocks to unconsolidated alluvium and wind-blown sand
Soils	0 to 10	0	Low	Surface material is sand, rock fragments, and bedrock outcrops
Climate	0 to 10	0	Low	Arid climate with rare convective storms
Runoff	0 to 10	0	Low	On average, only 2–2 storms per year that produce runoff
Topography	0 to 20	20	High	Desert foothill terrain that is steep to very steep and dissected Piedmont slopes
Ground cover	-10 to 10	10	High	Little vegetation except for sparsely spaced desert brush and grass
Land use	-10 to 10	-10	Low	There is no cultivation or grazing
Upland erosion	0 to 25	10	Moderate	Upland mountains and hills are composed of older, more consolidated rocks and are estimated to have moderate erosion rates
Channel erosion	0 to 25	25	High	Erosion on the dissected Piedmont slopes is the dominant process today and has been for the past several thousand years. Desert pavement is generally conspicuous
Total rating		60	Class 3	0.5 to 1.0 acre-ft per mi^2 per year

Table 4 100-year sediment yield estimates (from Randle, 1996).

Reservoir	Drainage name	Area (mi^2)	100-year sediment yield (acre-ft): @ 0.5 acre-ft mi^{-2} $year^{-1}$	@1.0 acre-ft mi^{-2} $year^{-1}$
All American Canal East	Unnamed Wash East	8.5	425	850
	Mission Wash	7.1	355	710
	Mission Wash East	2.2	110	220
	Total	17.8	900	2000
All American Canal West	Picacho Wash	43.7	2185	4370
	Unnamed Wash	30.2	1510	3020
	Picacho Wash East	2.0	100	200
	Total	75.9	4000	8000
Gila Gravity Main Canal	Canal drainage areas	9.7	485	970
	Reservoir drainage area	10.1	505	1010
	Total	19.8	1000	2000

Moore & Burch (1986) tested the applicability of equation (4) to the prediction of sheet and rill erosion rates. They found that the critical unit stream power required at incipient motion for sheet erosion is a constant:

$$V_{cr}S = 0.002 \text{ m s}^{-1} \qquad (7)$$

If equation (7) is used in conjunction with equation (4), sheet and rill erosion rates can be predicted. Comparisons between measured and predicted surface erosion rates based on Moore & Burch (1986) laboratory data are shown in Fig. 1. Figure 2 shows

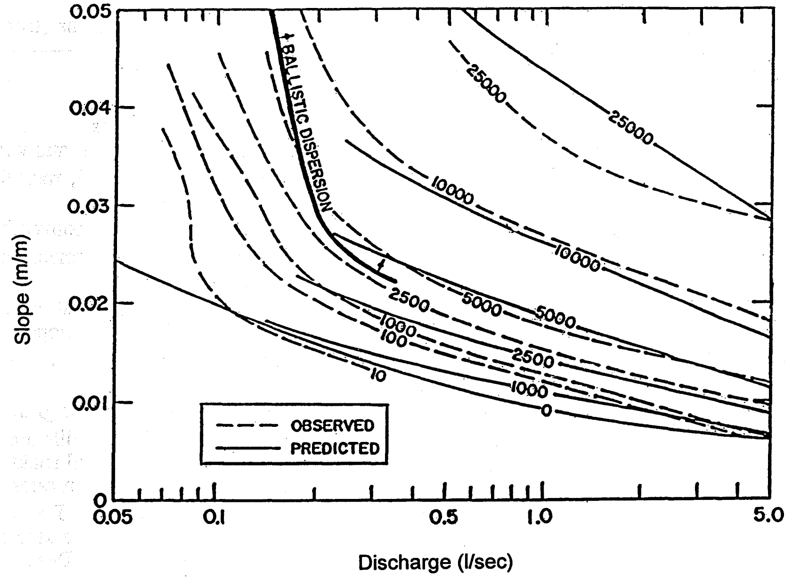

Fig. 1 Comparison between measured rill erosion rates and computed results based on the unit stream power formula (from Moore & Burch, 1986).

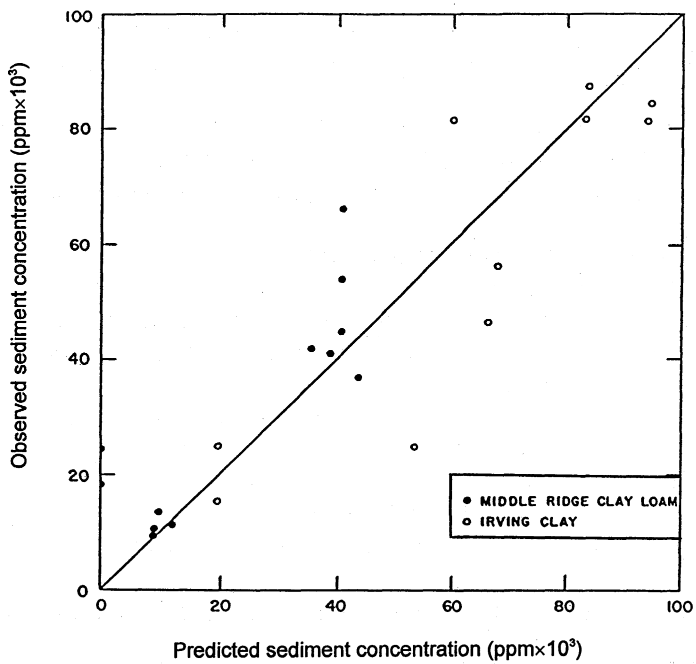

Fig. 2 Comparison between measured and computed clay transport rates based on the unit stream power formula (from Moore & Burch, 1986).

that equations (4) and (7) also can be used to predict sediment transport rates in the clay size range if the average median aggregate size for sediment is used.

The sheet flow velocity is difficult to measure. Moore & Burch (1986) expressed the unit stream power as a function of Manning's coefficient n, discharge Q, and width of flow B:

$$VS = (Q/B)^{0.4} S^{1.3}/n^{0.6} \tag{8}$$

and combined with equations (4) and (7) into the following form:

$$\log C_{ts} = 5.0105 + 1.363 \log[\{(Q/B)^{0.4} S^{1.3}/n^{0.6} - 0.002\}/\omega] \tag{9}$$

Yang (1996) provided step-by-step procedures and examples to demonstrate how to apply the unit stream power theory and minimum energy dissipation rate theory, or its simplified minimum unit stream power theory, to the estimation of surface and rill erosion rates. Randle (1996) applied these procedures to the estimation of sediment yield for the proposed All American Canal East Reservoir, All American Canal West Reservoir, and the Gila Gravity Main Canal Reservoir. Tables 5 and 6 summarize the estimated sediment volume, peak sediment concentration, and the total 100-year sediment yield volume for the Gila Gravity Main Canal Reservoir.

GSTARS 2.0 COMPUTER MODEL FOR ALLUVIAL RIVER SIMULATION

The Generalized Stream Tube model for Alluvial River Simulation (GSTARS) was first released by the US Bureau of Reclamation in 1986 (Molinas & Yang, 1986) for

CYBER mainframe computer application. A revised and enhanced model GSTARS version 2.0 (GSTARS 2.0) was released by Yang *et al.* (1998). GSTARS 2.0 has the following capabilities:

(a) The model can be used as a fixed-bed model to compute water surface profiles for subcritical, supercritical, or a combination of both flow conditions involving hydraulic jumps. These water surface profile computations include but are not limited to:
   - manmade channels with no sediment,
   - spillways and wasteways,
   - rivers and channels where bed elevation changes are negligible.

(b) The model can be used as a movable-bed model to route water and sediment through alluvial channels.

(c) The use of stream tubes allows the model to compute the variation of hydraulic and sediment conditions not only in the longitudinal but also in the lateral direction. The model becomes one-dimensional with the selection of a single stream tube. Selection of multiple stream tubes allows more detailed simulation of changes in cross-section geometries in the lateral and vertical directions.

Table 5 Estimated sediment yield and peak sediment concentration for the proposed Gila Gravity Main Canal Reservoir (from Randle, 1996).

Recurrence interval (years)	Peak discharge ($ft^3 s^{-1}$)	Sediment volume (acre-feet):					
		0.06 mm	0.1 mm	0.2 mm	0.5 mm	1 mm	2 mm
100	4461	192.19	58.20	12.94	2.70	1.05	0.53
50	3283	114.76	34.80	7.73	1.61	0.63	0.31
25	2307	62.72	19.02	4.22	0.88	0.34	0.17
10	1315	23.54	7.14	1.58	0.33	0.13	0.06
5	755	8.63	2.62	0.58	0.12	0.05	0.02
100-year volume			480.60	106.70	22.23	8.67	4.34
Average 100-year sediment yield (acre-feet mi^{-2})			47.58	10.56	2.20	0.86	0.43
Recurrence interval (years)	Peak discharge ($ft^3 s^{-1}$)	Peak sediment concentration (ppm):					
		0.06 mm	0.1 mm	0.2 mm	0.5 mm	1 mm	2 mm
100	4461	997 109	302.353	67 130	13 990	5 465	2724
50	3283	821 128	248 991	55 282	11 521	4 500	2243
25	2307	653 132	198 049	43 972	9 164	3 580	1784
10	1315	447 191	135 602	30 107	6 274	2 451	1222
5	755	300 328	91 069	20 220	4 214	1 646	820

Table 6 Estimated 100-year sediment volume for the proposed Gila Gravity Main Canal Reservoir (from Randle, 1996).

Drainage area	Total 100-year sediment volume (acre-feet):					
	0.06 mm	0.1 mm	0.2 mm	0.5 mm	1 mm	2 mm
Reservoir drainage area		481	107	22	9	4
Canal drainage area*		462	102	21	8	4
Total drainage area		943	209	43	17	8

*Computed by multiplying the average 100-year sediment yield per unit area (computed for the reservoir drainage area, see Table 4) by the canal drainage area of 9.7 miles^2.

(d) The armouring computations allow simulation of riverbed changes with coarse materials.

(e) The model can simulate channel widening and narrowing processes with the selection of the minimization procedure option based on the theory of minimum energy dissipation rate or its simplified theory of minimum total stream power.

(f) The channel side stability option allows simulation of channel geometry change based on the angle of repose of bank materials.

GSTARS 2.0 also provides the following 13 sediment transport functions for users to choose:

- Meyer-Peter and Müller's (1948) formula,
- Laursen's (1958) formula,
- Toffaleti's (1969) method,
- Engelund & Hansen's (1972) method,
- Ackers & White's (1973) and revised (1990) methods,
- Yang's (1973) sand and (1984) gravel transport formulae,
- Yang's (1979) sand and (1984) gravel transport formulae,
- Parker's (1990) method,
- Yang's (1996) modified formula,
- Krone's (1962) and Ariathurai & Krone's (1976) methods for silt and clay transport.

With proper selection of sediment transport function, GSTARS 2.0 can be applied to a wide range of sediment conditions with particle size ranging from clay, silt, sand, to gravel. GSTARS 2.0 also has the ability to consider the effects of wash load on sediment transport rate by using the modified unit stream power formula proposed by Yang *et al.* (1996).

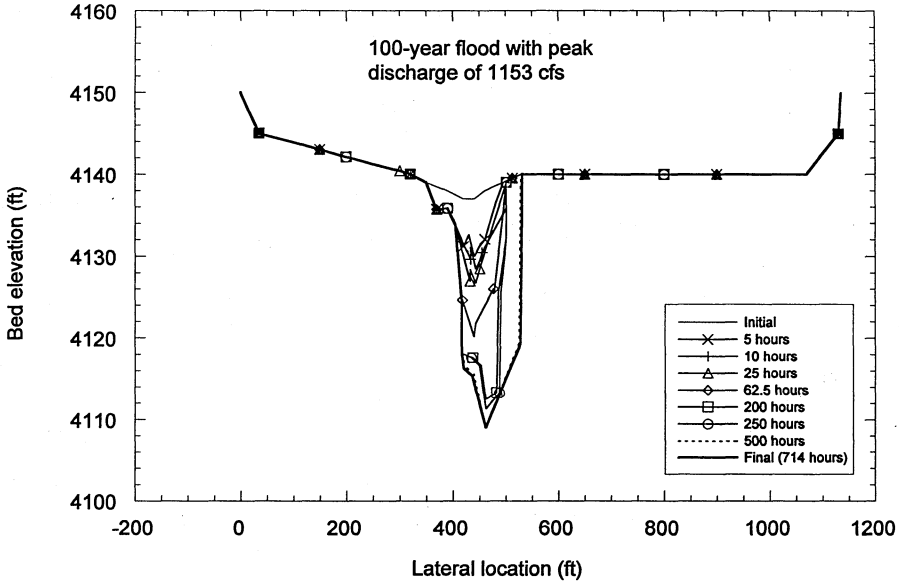

Fig. 3 Predicted channel development at the station 130 ft downstream of the Willow Creek Dam emergency spillway (from Yang *et al.*, 1998).

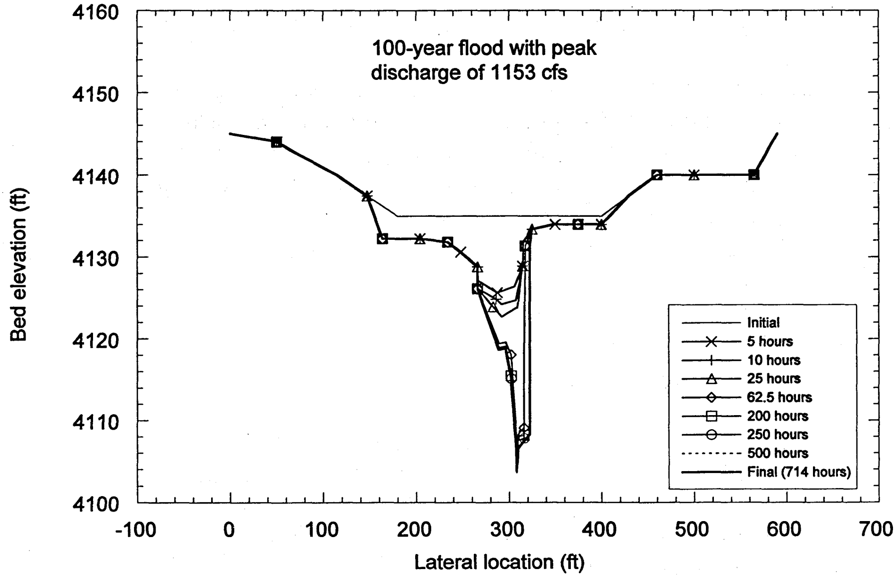

Fig. 4 Predicted channel development at the station 831 ft downstream of the Willow Creek Dam emergency spillway (from Yang *et al.*, 1998).

Figures 3 and 4 demonstrate GSTARS 2.0 capabilities in predicting the sediment transport and channel forming processes downstream from the Willow Creek emergency spillway. Yang's (1973) and (1979) formulae were used in the Willow Creek study. These figures show that both channel width and depth can change during the channel forming process.

GSTARS 2.0 can be applied to compute the longitudinal bed profile of a reservoir due to sedimentation. However, further developments and enhancements of GSTARS 2.0 are needed to incorporate reservoir operation criteria, sluicing, delta formation, etc., before the model can be used as an engineering and management tool for the simulation and prediction of the sedimentation processes in a reservoir.

SYSTEMATIC APPROACH TO STUDY SEDIMENT YIELD, TRANSPORT, AND RESERVOIR SEDIMENTATION PROCESSES

Yang (1996) stated that: "It is now possible to use the unit stream power theory to determine the total rate of sediment yield and transport from a watershed regardless of whether the sediment particles are transported by sheet, rill, or river flows. By doing so, the actual amount of sediment entering a reservoir can be determined using a consistent and rational method." GSTARS 2.0 can be used as a basis to develop a watershed and channel network model to determine the amount of sediment inflow to a river reach under various hydrological, hydraulic, geological and sediment conditions. GSTARS 2.0 can be further enhanced to become a reservoir sedimentation management tool to determine reservoir sediment distribution and appropriate operation rules to prolong the useful life of a reservoir.

SUMMARY

This paper provides a brief description of a systematic and rational approach to determine the rate of surface erosion, sediment transport in rivers, and the possibility of developing a reservoir sedimentation engineering and management computer model. This approach is based on the theory of unit stream power and the theory of minimum energy dissipation rate or its simplified versions of minimum stream power and minimum unit stream power. Examples of computed results demonstrate the applicabilities of various components of this approach. Further studies are needed to develop a well-integrated systematic computer model. This model should have the ability to simulate and predict sediment yield, sediment transport process in a river system, and sediment distribution in a reservoir, based on the hydrological, hydraulic, geological, and sedimentary characteristics of a river basin.

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