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MODELING OF SEDIMENT YIELD WITH FLOOD DISCHARGE FROM SURROUNDING CATCHMENTS INTO THE POWER PLANTS

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Abstract: The sediment mix water generated during rainy season from the surrounding has caused flooding in power plants due to which plants have to shut down for 2 to 3 months. In the present study, modelling of sediment yield with flood discharge from the surrounding catchments into the power plants is carried out. For this purpose, a semi-distributed model: Soil and Water Assessment Tool (SWAT) model was identified and a model was developed that simulate the production and transport of sediment load along with the discharge through the natural reach into the power plant. Then the model was calibrated and validated using semi-automated Sequential uncertainty fitting (SUFI2) calibration process built in SWAT calibration and uncertainty program (SWAT CUP) using the precipitation data from 2000 to 2006 and 2007 to 2014 respectively. Based on the validated parameters sediment flow was again calculated using SWAT. The performance of the model was evaluated using statistical and graphical methods to assess the capability of the model in simulating the runoff and sediment yield for the study area. It was found that simulated results have good agreement with the observed data. Further, safety measures like retaining wall, recharge ponds and soak pits were recommended. This study would provide useful information for constructing the proper structure to prevent the entry of sediment - flood water mixture into the power plants from the surrounding catchment.

KEY WORDS: sediment transport, SWAT, SWAT-CUP, SUFI2, power plants

1. INTRODUCTION

Energy refers to the most important issue in the world. In India, most of the electricity generated is from coal based thermal power plants i.e. 130221MW (growth of electricity sector in India, 2013). Electricity consumption in India is increasing at a very faster rate than compared with the overall energy supply. There are two biggest challenges in building new power plants is the i) appropriate site selection and its ii) construction for its long term efficiency. The plants site selection include many factors like topography of the plant site, power transmission network feasibility, types of landuse and soil present, water resources and population, etc. Among these factors elevation and slope plays an important role. Generally, there are two types of power plant, (a) Thermal power plant in which coal or gaseous fuel is used and (b) Hydro power plant in which high head of water is required. In both the cases, least RL (reduced level) is required for the plant i.e. the site of the power plant should be at minimum elevation. Due to minimum elevation, there is a possibility of flooding taking place in the plant premises during rainy season.

In Indian context, all the above measures have not been considered during construction of the power plant due to which plants area gets flooded by stormwater during rainy season. As a result, the plant is shut down for 3 to 4 months which causes huge economy losses. When the stormwater enters the plant area, it carries lots of sediment along with it. This sediment gets deposited and prevents the normal operation of the plant. Flushing of stormwater is easier but it becomes difficult to pump sediment mix water because sediment blocks the passage of flow.

In the present study, modeling of sediment yield with flood discharge from the surrounding catchments into the power plants is examined for the first time. For this purpose, a semi-distributed model: Soil and Water Assessment Tool (SWAT) model was developed that simulate the stormwater flow, production and transport of sediment load through the natural reach into the power plant. The area of the plant basin was divided into four sub-catchments based on threshold value using ArcSWAT interface model. The semi-automated Sequential Uncertainty Fitting (SUFI2) calibration process built in SWAT calibration and uncertainty program (SWAT CUP) were used to calibrate and validate the model parameters using the precipitation and sediment load data for the last 14 years. The performance of the model was evaluated using the statistical and graphical methods to assess the capability of the model in simulating the runoff and sediment yield for the study area. It was found that simulated results obtained was in good agreement with the observed data. Further, safety measures like retaining wall, recharge ponds, soak pits, and strengthening of existing walls and reconstruction of drainage system at critical locations was suggested to block the entry of sediment-water mixture into the power plant. This study would provide useful information for constructing the proper structure to prevent the entry of sediment - flood water mixture into the power plants from the surrounding areas.

2. STUDY AREA

Study area i.e. power plant area located 45 km away from Bhatinda town near Banawala village in Mansa District in the state of Punjab, India (Figure 1). The Plant is located at 29^0 53’ 47.25” N and 75^0 12’ 39.47” E, and 29^0 56’ 14.52” N and 75^0 15’ 8.53” E. Plant catchment area is a small catchment independent of nallahs. The area has been in Indo-Gangetic alluvial plain. Southern part of the area forms the flood plain of Ghaggar River and generally inundated in the flood season. The Ghaggar River, mainly rain-fed and carries base flow throughout the year in its upper reaches. It originated in Shiwaliks and enters into Mansa district from eastern side and flows in west-southern direction. The whole area has been found to be fairly even. The highest point of the area lies at 217.37m (MSL) and the lowest level at 204.577m (MSL). The slope of the land is from North-East to South-west.

Climate of the region has been found to be semi-arid & warm to hot. The temperature varies between 4.5^OC (minimum) in winter and 41.2^OC (Maximum) in summer. The average annual rainfall in the area is about 424 mm. The monsoon season starts from June and continues up to September accounting maximum rainfall of around 85 to 90% of rainfall. The winter season starts from December and continues up to February and the summer season starts from March to May. The area experiences low to medium humidity due to very high temperature. June found to be the hottest month and January to be the coldest.

In general, the study area found to be plain. During the rainy season, the power plant area gets flooded by the stormwater which is generated from the catchment. The Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) 30 m resolution Digital Elevation Model (DEM) used for the plant study.

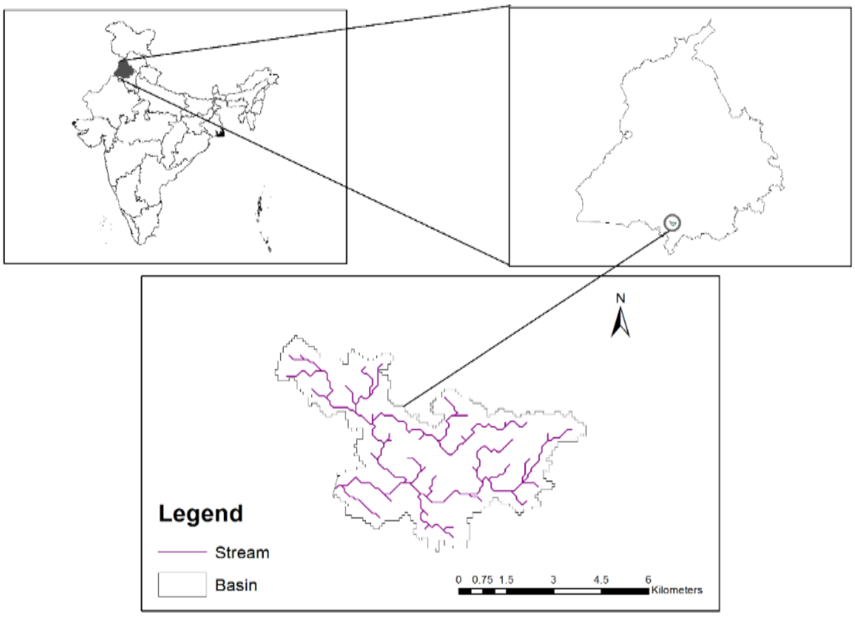

Fig 1. Shows the study area (Power Plants)

Fig 2. Power Plants

The Land use layer was obtained from the database of 'Global Land Cover Facility' and is available at http://ftp.glcf.umd.edu/index.shtml. The information on soil types was obtained from FAO Digital Soil Map of the world. The information available on land use practices and soil classification as constitutes a primary requirement for the Hydrologic Rainfall Runoff modeling platform used in the present study. The landuse of the study area is completely agricultural land and soil type is sandy soil. Rainfall data for the last fifteen years (2000 to 2014) obtained from Indian Meteorological Department, Mansa, Punjab was used for the simulation process.

2.1. SWAT MODEL

SWAT (Soil and Water Assessment Tool) a hydrological model developed by USDA Agricultural Research Service is identified for modelling stormwater runoff and sediment flow for the study area. It is an open source model. It is a physical based catchment scale model. It is operated on daily, hourly and monthly time steps. It is a theoretical and long term simulation model. The SWAT is generally simulated to observe the impact of management practices on surface runoff and sedimentation. The intended of the SWAT model is modular and requires input data i.e. geographic elevation, landuse, properties of soil, climate data and vegetation in the catchment area. The model simulates hydrological processes which include runoff, snow melt and snow cover, percolation, evapotranspiration, groundwater flow, losses from reservoir and ponds. (Arnold et al., 1998). A complete details of SWAT can be found in Arnold et al. (1998) and Neitsch et al. (2011b). During simulation, SWAT model divides the watershed into different sub-watersheds on the basis of landuse and soils information. The sub-watersheds is further divided into HRUs (hydrologic response units). SWAT results obtained is assessed by further carrying out calibration and uncertainty analysis using SWAT-CUP.

2.2. SWAT-CUP

SWAT Calibration and uncertainty Procedures (SWAT-CUP) aimed to do calibration and uncertainty analysis for the SWAT different boundary conditions. Presently the SWAT-CUP can simulate SUFI2 (Mamo and Jain, 2013 and Abbaspour, et al., 2007), Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), and Parameter Solution (ParaSol) (Mamo and Jain, 2013 and van Griensven and Meixner, 2006) and Markov chain Monte Carlo (MCMC) procedures. In this present study, SUFI2 technique is used to estimate different SWAT components related to flow rate. SUFI2 technique takes uses the range of the parameters as constraints and 7 of the model evaluation coefficients as Objective Functions (OF) during calibration, they are 1) A multiplicative form of the square error (mult); 2) A summation form of the square error (sum); 3) Coefficient of determination (r2); 4) Nash-Sutcliffe (1970) coefficient (NS); 5) Chi-squared χ 2 (Chi2); 6) Coefficient of determination R2 multiplied by the coefficient of the regression line (br2); and 7) sum of square of residual (SSQR). During calibration, objective functions are used one by one at a time. The advantage of SUFI2 is that the model estimation coefficients can be improved by using different objective functions because all the objective functions exist in SUIF2. Details documentation on SWAT-CUP can be seen in Abbaspour et al., 2007.

2.3. MODEL SETUP

Firstly, the 90 m resolution Digital Elevation Model (DEM) was imported in ArcSWAT which automatically delineated the catchment into sub-watersheds and natural streams. The whole catchment was divided into 156 sub-watersheds. Comprehensive topographic reports of the watershed were generated after the watershed delineation. Reclassification of the SWAT model was done when the landuse and soil map was provided to the model. The whole watershed was categories into three slope using the SWAT interface. Then the hydrologic response unit was created when landuse, soil and slope classes was overlaid. Location table of weather data, daily precipitation data files were uploaded to link the model. Maximum and Minimum Temperatures, Wind Speed, Relative Humidity and Solar Radiation was generated by the model because the data was not available. When the essential database files was generated them the SWAT model was initially run on daily basis using default parameters value.

2.4. MODEL PERFORMANCE EVALUATION

The Model performance was evaluated based on the following applied quantitive statistics. They are Coefficient of Determination (R^2), p-factor and r-factor, Nash Sutcliffe Efficiency (NSE) and percent bias (PBIAS).

Moriasi et al., 2007 compared simulated results with observed data using different model evaluation techniques due to unavailability of any standard evaluation model. Step by step procedure for calibration and validation for the model and different model evaluation statistics was reported by Moriasi et al., 2007. They further reported that flow rate is acceptable if the RSR < 0.70 (see also Singh et al., 2004), NSE > 0.50 (see also Santhi et al., 2001) and $-25\ \% <$ PBIAS $< 25\ \%$. If the coefficient of determination (R^2) ranges between 0 and 1 where highest specify less error variance, generally it explains the in-situ variance proportion by the model. Nash-Sutcliffe coefficient measures the effectiveness of the model by relating the best fit of the model to the variance of the observed data. The range of Nash-Sutcliffe efficiencies is between $-\infty$ and 1. The model discharge is perfectly matches with the observed data when the NSE value 1 whereas when the NSE is 0 means the model predicts is accurate with the mean of the observed data. If the NSE is less than 0 means that the observed mean is the better predictor than the model (Moriasi et al., 2007).

PBIAS shows that whether the simulated data tend to be larger or smaller than the corresponding measured values. If the value of PBIAS = 0.0 % then it is optimum, if positive then the model is showing underestimation, whereas if negative values then the model shows overestimation (Gupta et al., 1999). p-factor quantified the measured values which accounts for all uncertainties. It is the percentage of measured data bracketed by the 95% predication uncertainty (95PPU). Whereas r-factor quantify the strength of calibration/uncertainty analysis. r-factor is the average thickness of the 95PPU band which is divided by the standard deviation of the observed data. Value of p-factor is in the range of 0 to 100% while that of r-factor is between 0 and ∞. Details description can be found in SWAT_CUP 2012 user manual.

3. RESULTS AND DISCUSSION

3.1. MODEL CALIBRATION AND VALIDATION

Calibration and validation of the model is done to increase the efficiency of the model. In the present study, SUFI2 semi-automated modeling techniques are used. Daily flow data for the study area was available from 2000 to 2014, the first seven years data i.e. 2000 to 2006 was used for calibration process and data from 2007 to 2014 was used to perform validation process.

3.1.1. MODEL CALIBRATION AND VALIDATION USING SUFI2 ALGORITHM

The predictive performance obtained from calibration process for the watershed is summarized in Table 1 and the plots of simulated and measured daily flow is shown in figure 2. Parameters were converging into very fine values using semi-automated calibration technique, which is further used as model constraints. The default objective functions obtained from the calibration process was NSE, 100 numbers of iteration was done for the process. After validation process, the plot of measured and daily flow is shown in figure 3 and the summary of predictive performance is shown in Table 2.

Table 1: Model performance evaluation coefficients for Calibration of daily flow (SUFI2)

Goal_type = NSE			**Best_sim_no = 72 Best_goal = 0.83**		
Variable	p-Factor	r-Factor	R^2	NSE	PBIAS
FLOW_OUT_56	0.46	0.31	0.86	0.73	18%

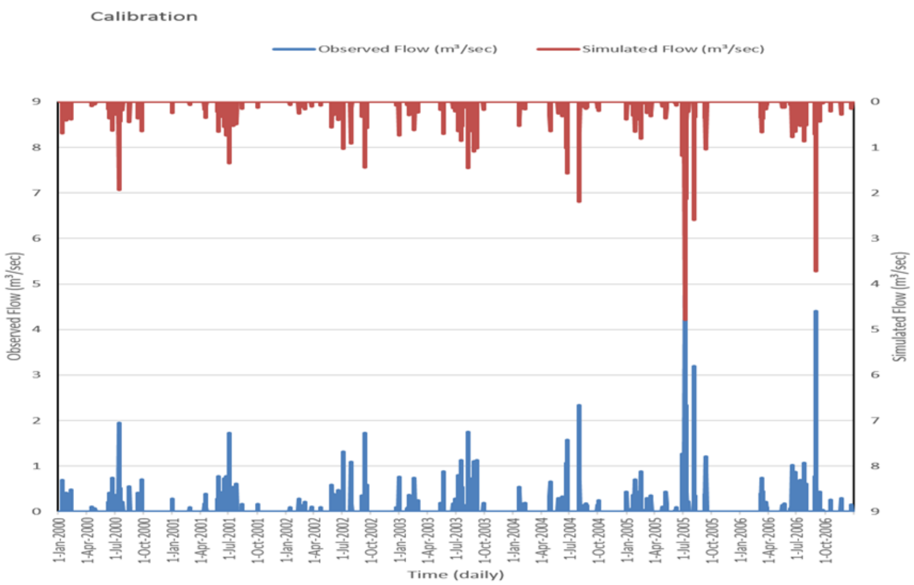

Fig 3.Simulated and observed daily flow superimposed with daily rainfall (SUFI2)

Table 2: Model performance evaluation coefficients for Validation of daily flow (SUFI2)

Goal_type = Nash_Sutcliff		**Best_sim_no = 89 Best_goal = 0.83**			
Variable	p-Factor	r-Factor	R^2	NS	PBIAS
FLOW_OUT_56	0.54	0.29	0.89	0.76	14%

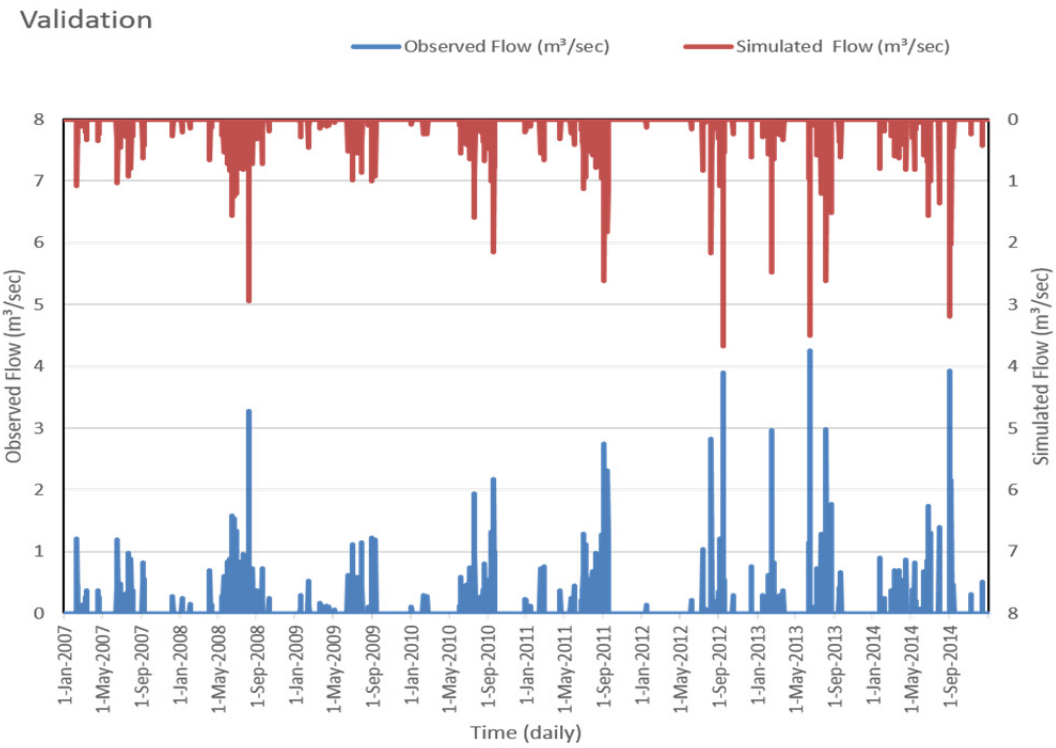

Fig 4. Daily flow validation plot (SUFI2)

3.2. PARAMETER SENSITIVITY ANALYSIS

One-at-a-time sensitivity analysis: shows the sensitivity of a variable to the changes in a parameter if all other parameters are kept constant at some value.

A one to one Sensitivity analysis is performing on this study with changing the value of calibrated 13 parameters (CN2, ESCO, SOL_K, SOL_AWC, SOL_Z, CH_N2, ALPHA_BF, ALPHA_BF, GW_DELAY, GWQMN, GW_REVAP, REVAPMN, RCHRG_DP and SURLAG). Table 3 shows the values of sensitivity index (SI) for different input parameters. 6 out of 13 parameters were found to be sensitive parameters; they are CN2, ESCO, SOL_AWC, GWQMN, SOL_K and GW_REVAP, as per the classification proposed by Lnehart, et al., 2002.

Table 3: The range and optimal value of model parameter.

Sn.no.	Parameters	Lower Limit	Upper Limit	Optimal Value
1	v_CN2.mgt	.03	0.15	0.03
2	v_ALPHA_BF.gw	0.00	1.00	0.70
3	v_GW_DELAY.gw	0.00	31.00	0.47
4	v_GWQMN.gw	10.00	50.00	15.80
5	v_ESCO.hru	0.10	1.00	0.834
6	r_SOL_AWC.sol	0.13	0.20	0.14
7	r_SOL_K.sol	1.00	10.00	5.99
8	r_SOL_Z.sol	-0.80	0.80	0.78
9	R__CH_N2.rte	0.00	0.10	0.88
10	v__GW_REVAP.gw	0.02	0.20	0.13
11	v__REVAPMN.gw	0.00	20.00	17.7
12	v__RCHRG_DP.gw	0.00	1.00	0.69
13	v__SURLAG.bsn	0.05	5.00	1.02

3.3. ESTIMATION OF DAILY SEDIMENT LOAD

Suspended-sediment data was calculated at the outlet of the watershed from where the runoff is entering into the power plant. Amount of sediment flowing with the runoff was calculated in SWAT. Flow rate was calibrated and validated (as discussed in previous section), these flow was used to calculate the sediment that is flowing into the power plant.

The sensitivity parameters obtained from validation process was used in SWAT to obtain the amount of sediment flowing into the plants area. Figure 4 shows the plot of sediment and flow rate on daily basis that is entering into the power plant. Based on the above analysis, it was found that during peak rainfall, flood water and sediment entry into the power plant will be at the rate of 4.78m^3/sec and 2kg/sec respectively which is not good from the power plants points of view. For a long run, this amount of sediment and runoff will gets accumulated in the plant area which will interrupt in the operation of the plant.

The operation of the power plants has to shut down for 2 to 3 months if the above condition continues. The main reasons of shutting down of power plant is the huge amount of flow that is flowing into the plant which submerge all the equipment installed at an average depth of 6 to 7 m. Along with the flow, sediment will also continue to flow and gets deposited at the depth. Excavation of sediment from such a depth is itself a challenging task and also involves huge investment cost. Safety measures like retaining wall were suggested at the locations for stopping the flow and sediment from where it is entering into the power plants area. In addition to this, soak pit and collection ponds were also recommended at some typical locations.

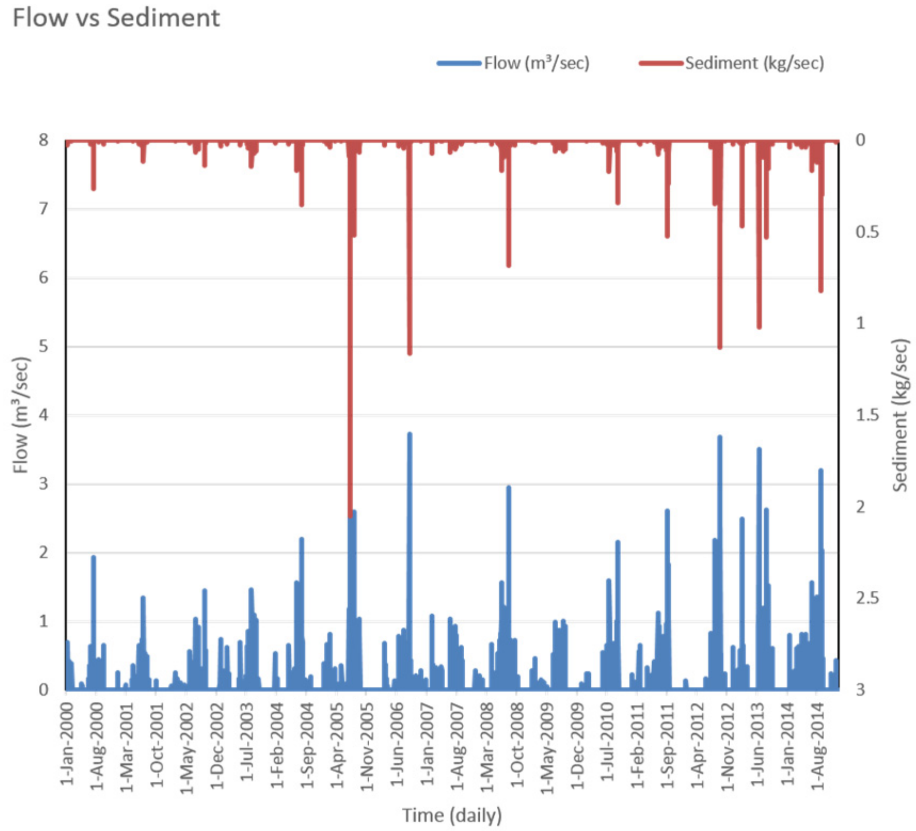

Fig 5. Daily sediment load superimposed on daily flow

4. SUMMARY AND CONCLUSIONS

In the present study, SWAT 2012, a process based partially distributed hydrological model having an interface with ArcGIS software was used for modelling runoff and suspended-sediment was calculated for the power plant in India. SWAT model was setup and calibrated and validated for daily discharge using the observed data from 2000-2006 and 2007 to 2014 respectively using SUIF2. The results obtained from the model were evaluated graphically and statistically.

Shutting down of power plant causes huge economic losses to the management and to the country as well. Proper hydrological study of the power plants site should be carried out before designing. Safety measures should also be taken into considerations during the designing of the power plants for extreme situation like above.

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