



Article Assessment of the Implementation Effect of a Gully Consolidation and Highland Protection (GCHP) Project Based on the GeoWEPP Model

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Abstract: The Gully Consolidation and Highland Protection (GCHP) project is an important governance measure for controlling source erosion and reducing soil erosion in the Loess Plateau, which has been explored and developed continuously in recent decades. However, there is no international precedent for research on the implementation effect of the GCHP project, and it is still relatively weak. In order to quantify the erosion of a small watershed under the construction of a gully head landfill, this study selected Yangjiagou (YJG) as the research area. The spatial analysis function of ArcGIS was used to process DEM and soil type data, the GeoWEPP model was used to simulate soil erosion, and the changes of runoff and sediment yield before and after gully head landfill were analyzed. The results showed that compared with the simulated original soil erosion amount, the annual runoff decreased by 13.13%, and the sediment yield decreased by 37.61% after gully head landfill, indicating that the GCHP project positively influenced soil erosion control. After the gully head landfill measures are taken, the flow path becomes shorter, so the flow scour capacity is weakened. Soil and water control is very effective in the short term, but if long-term maintenance is not carried out, the intensity of soil and water loss is likely to be aggravated. This study provides an effective verification method for the feasibility of a soil loss control scheme on the Loess Plateau and provides a reference for promoting ecological priority and efficient management in the Loess gully area. Ultimately, it will serve the ecological protection and high-quality development of the Yellow River Basin.

Keywords: Loess gully; gully erosion; GeoWEPP model; GCHP; Loess Plateau

1. Introduction

The Loess Plateau is located in the middle reaches of the Yellow River Basin and is one of the regions with the most severe soil erosion in the world [1,2]. The Loess Plateau is a valuable land resource suitable for farming and living, and also an important grain and fruit-producing area and population settlement [3]. With the rapid development of urbanization, the problems of gully erosion and soil erosion caused by large-scale urban construction, transportation network expansion, and agricultural development are becoming increasingly severe. Especially under the double action of high-intensity human activities and frequent



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). rainstorms, the Loess Plateau has become fragmented, seriously threatening the homeland security, livelihood security, and ecological security of the plateau area [4,5]. At the same time, scientific land regulation and soil and water conservation measures play a positive role in the management of small watersheds, ecological environment protection, and agricultural economic development and are considered the main manmade driving factors for the change in hydrological processes in the Loess Plateau. However, the ultimate effect of these artificial measures remains to be evaluated and verified by science.

At present, the use of hydrological models to quantitatively study the pattern and process of soil erosion and to explore the coupling mechanism of soil erosion and various influencing factors is a hot topic in soil erosion research. For example, Mosbahi et al. [6] applied the SWAT model to predict the surface runoff generation pattern and erosion hazards in the Sarrath River catchment, and the results showed that only 10% of the watershed was vulnerable to soil erosion and differences in soil cover types and gradients mainly caused the spatial differences in erosion. Safwan et al. [7] used the WEPP model to predict soil erosion in Lattakia Governorate and compared the results with those of RUSLE, which showed a good correlation between the two models. Admas et al. [8] used the GeoWEPP model to simulate soil erosion, sediment, and runoff in the Megech watershed, and the results showed that the sediment in the studied watershed varied between 10.3 t \cdot ha⁻¹ \cdot year⁻¹ and 54.8 t \cdot ha⁻¹ \cdot year⁻¹. Among them, GeoWEPP is a process model established to make full use of GIS data. It can not only simulate the basic water erosion process, but more importantly, it allows non-GIS professionals to formulate soil and water conservation plans under the condition of obtaining spatiotemporal data that match real erosion. It has been widely applied in soil erosion simulation.

Gully erosion has attracted increasing attention from scientists, and gully development leads to loss of crop yields and available land, as well as an increase in farmers' tillage workload. Studies have shown that gully erosion is often the primary sediment source [9–12]. Gully erosion has long been neglected because it is challenging to study and predict [13]. The gully process has a three-dimensional nature and is affected by a variety of factors and processes [14–17]. Although gully erosion is usually triggered or accelerated by land use changes and extreme climate conditions, it is often caused by a long antecedent history. The Gully Consolidation and Highland Protection (GCHP) project is the main measure to control valley headcut erosion and reduce soil and water loss in the Loess Plateau. Quantitative estimation of soil erosion before and after the implementation of the GCHP is of great significance for determining key water and soil protection areas and formulating corresponding prevention and control measures. However, although past research has provided indispensable theoretical support and experience accumulation for the GCHP project, most of the simulations are based on land use changes, and the land use changes of the GCHP project are much smaller than the terrain changes, so the knowledge extension and expansion of engineering terrain are lacking, which makes the support for the ongoing gully head landfill insufficient.

In this study, Yangjiagou (YJG), Dongzhi Town, Qingyang City, Gansu Province, was selected as the research area. The GeoWEPP model was used to simulate soil erosion in the watershed, and based on primary data such as DEM and soil type, the changes in runoff and sediment yield before and after the gully head landfill project were compared and analyzed to reveal the influence and effect of the GCHP project on soil erosion in the watershed of the Loess Plateau.

2. Study Area

YJG watershed is mainly located northwest of Dongzhi Town, Xifeng District, Qingyang City, Gansu Province. The longitude is $107^{\circ}41'49'' \sim 107^{\circ}41'27''$, the latitude is $35^{\circ}35'26'' \sim 35^{\circ}35'46''$, and the altitude is $1130 \sim 1361$ m. The overall watershed shows a trend of high in the south and low in the north, with a length of approximately 7.47 km from north to south. The watershed area is approximately 0.87 km², with the plateau area accounting for roughly one-third of the total area. The plateau terrain is flat, and the soil is fertile [18].

watershed has a typical temperate continental climate with four distinct seasons, cold and dry in winter and hot and rainy in summer. Spring and autumn are more moderate. The mean annual total precipitation sum in the YJG area is approximately 400~600 mm, the average annual runoff is about 2.04×10^4 m³, and the average annual runoff modulus is about 6016 m³·km⁻² [19]. YJG vegetation is divided into artificial planting and natural vegetation. Artificial vegetation mainly includes three parts: trees, crops, and artificial grass. Herbaceous plants are mostly distributed in gully slopes and valleys, crops and economic orchards are mostly distributed on the plateau, and artificial arbour forests are distributed in gully areas [19]. At present, the cultivation techniques in the basin are mainly conservation tillage and mechanized dry farming. The specific location of YJG is shown in Figure 1.



Figure 1. Location of YJG area. (a) China, (b) Nanxiaohegou basin, and (c) YJG.

3. Method and Data

3.1. GeoWEPP Model

GeoWEPP is a combination of WEPP and GIS. Geographic information is loaded through the interface of the GeoWEPP model, and spatial databases such as topographic maps, land use maps, soil maps, channel information, and vegetation coverage rates can be accessed after entering the system. The annual runoff and sediment yield can be predicted according to the digital climate data input of the existing meteorological database, which is convenient for evaluating the feasibility of the watershed protection method. The GeoWEPP is a model for analyzing the physical process of soil erosion developed on the theoretical basis of hydrology, hydrodynamics, random meteorological generation, and other disciplines. It draws on the advantages of the distributed hydrological model for spatial variability of the erosion process and continuous simulation analysis and can approximate the underlying surface conditions. The dynamic changes of runoff, sediment production, sediment transport, and sediment deposition in soil erosion can be reflected by space and time changes [20]. The latest version developed so far (ArcGIS10.X) only applies to less than 40 hectares of catchments and has only one land use map and soil type per slope. The watershed version of the WEPP model is based on the slope version and divides the watershed into overland flow elements (OFE) for simulation operation. Different OFE elements represent different soil conditions and crop management practices. The process of soil erosion was decomposed into scouring, transport, and deposition [21]. The scouring mainly occurred in the slope and channel. Sediment is mainly transported in river channels, which is a summary of soil erosion and the transport process. Sediment in the gully region is formed by slope erosion and then transported downstream with runoff. Deposition mainly occurs at the bottom of the watershed [22]. The study catchment area should be less than 40 hectares and comprise three parts: channel, slope, and storage facility. Generally, there are sediment deposits at the outlet of the catchment. It is required that there should be less than ten slopes, and the slope length should be less than 100 m. After soil erosion, sediment is transported from the slope to the gully and flows out from the drainage outlet through the gully. The equation of sediment motion for the watershed version of the GeoWEPP model is as follows:

$$\frac{dG}{dx} = dL + dF,\tag{1}$$

where *x* is the downward distance of a point along the slope (m); *G* is sediment transport $(kg \cdot s^{-1} \cdot m^{-1})$; *L* is sediment inflow from adjacent slopes $(kg \cdot s^{-1} \cdot m^{-1})$; *F* is the amount of erosion of the channel by the flow or the amount of sediment deposited in the flow $(kg \cdot s^{-1} \cdot m^{-1})$. When the sediment loss of the gully is greater than the flow transport amount, transport is the primary method. When the sediment loss of the channel is less than the sediment transport, the sediment is mainly deposited [23].

The GeoWEPP model is composed of three modules: TOPWEPP, TOPAZ, and CLI-GEN [24]. The TOPWEPP mainly extracts soil properties, land use types, vegetation, and other information from the drawn and land use distribution maps. The TOPAZ module is used to extract the topographic data of the research area from the elevation map and transform it into the parameter types required by the model. The model has two main climate generators: BPCDG and CLIGEN. BPCDG is mainly used to input the breakpoint file, which requires highly detailed rainfall data. The time separation rates of the meteorological and hydrological data collected were on a daily scale and were not precise enough. Models also need to be used to simulate future scenarios. In general, this type will not be adopted. The CLIGEN module primarily generates the model's required climate data. The GeoWEPP model technical block diagram is shown in Figure 2. The model simulates multiple rains and requires a relatively short run (approximately 4~5 min).



Figure 2. Research flowchart of the GeoWEPP Model.

3.2. Data Collection

In order to meet the needs of soil erosion simulation and comparative analysis of control effects in Yangjiagou, the data of meteorological, hydrological, soil, topography, vegetation, and other natural factors in similar periods of the watershed were systematically collected. Among them, the meteorological data mainly include precipitation and temperature data; hydrological data mainly include runoff and sediment data; spatial data mainly include DEM, land use, and soil type.

Thirty regolith samples were collected from Yangjiagou, and soil parameters (percentage content of sand, clay and gravel, organic matter content, cation exchange capacity, etc.) needed for model establishment were obtained. Combined with existing reports and the Soil Records of Qingyang, soil types were determined, and GIS software obtained soil maps in the study area. According to the images taken by UAV, PhotoScan software was used to splice the positive image, and ENVI was used to supervise and classify the land use vector maps of Yangjiagou. The slope was derived from DEM, calculated by hydrologic analysis (Figure 1). Vegetation is naturally formed, and the engineering of GCHP studied in our study was mainly in the gully head area. Compared with the whole basin, the area proportion was small, so the impact of vegetation was small and could be ignored.

The meteorological data came from the meteorological station set up by the Institute of Earth Environment, Chinese Academy of Sciences in Nanxiaohegou watershed. The measured hydrological data came from the measured data in Yangjiagou. The location of the river measurement station is shown in Figure 1. The frequency of sediment measurement was once a day and only suspended mass was measured. During the data collection period, the climate changed normally, and no extreme climatic event occurred, and the sediment data from 2018 to 2021 were collected and used. The DEM data were actually vectorized by GIS software referred to as the 1:50,000 contour map. The land use map and land use parameters were drawn by GIS software based on the images obtained by field survey and UAV high-altitude flight. Soil parameters were obtained by experiments on regolith samples taken from Yangjiagou (Figure 3). A 5 cm diameter soil drill (DIK-1815, Labcan Scientific, Shanghai, China) was used as the tool. The regolith samples were collected from 0 cm (the surface soil) to 200 cm in depth at an interval of 50 cm (sampling was repeated three times at each point to reduce errors). The total number of roots in the $0 \sim 50$ cm soil layer accounted for more than 90%, while that in the 50~200 cm soil layer was less than 10%. Pretreatment (such as an air-drying method) was carried out before testing [25]. The particle size composition of the soil was determined by the Malvern laser particle size analyzer, and the organic matter content and cation exchange capacity of the soil were determined by the dichromate potassium oxidation method and hexamine cobalt trichloride leaching-spectrophotometry.



Figure 3. (a) Land use and (b) soil type in YJG.

3.3. Gully Head Landfill Method

Gully head landfill refers to the gully part of the Loess Plateau area as artificially large-scale mechanical landfill work, landfill gully into natural slope shape or step form.

Before and after gully head landfill, the change in terrain is the most obvious. In order to intuitively express the response of the gully head landfill to soil erosion, only the terrain factors are changed when the gully head landfill is set, and other data remain unchanged. In this paper, only the simplest landfill method was used to simulate the situation of gully head landfill by changing the contour line. The main steps were as follows: the spatial analysis tool of GIS was applied to extract the contour lines of the research area with an interval of 3 m; combined with the image map of the study area, the area with relatively serious erosion at the gully head was filled, and the landfill area was determined; the contour lines were re-edited by the GIS editing tool, which reached the scenario setting of gully head landfill; the re-set contour line was converted into DEM through GIS software, and the terrain data after gully head landfill were obtained.

Figure 4a shows the contour line before gully head landfill treatment, and Figure 4b shows the contour line after the treatment of the gully head landfill.



Figure 4. Contour comparison (a) before and (b) after landfill.

The extent of the landfill area is generally determined when the head of a gully destroys a road or the edge of a town. The area of straightened contours downslope, which must be landfill, is included. However, Figure 4b only shows only the area with the largest elevation.

4. Results and Analysis

4.1. Accuracy Analysis of Climate Data Generated by CLIGEN

Among the factors affecting soil erosion, rainfall and temperature account for a large proportion, and the climate parameters to be input in the GeoWEPP model simulation process are simulated data generated by the CLIGEN climate generator based on the actual monitored climate data. Therefore, to ensure the accuracy of the model simulation results, it is necessary to verify the generated simulated climate data and rainfall data. In order to ensure the accuracy of the data, the measured climate data of the YJG meteorological station and the simulated data of the CLIGEN climate generator were selected for comparative analysis.

It can be seen from Figure 5 that the simulated monthly maximum temperature and the simulated monthly minimum temperature have little error with the measured value, and the measured value is slightly lower than the simulated value, r > 0.995.



Figure 5. Comparison of simulated and measured temperature values.

The difference between the monthly average precipitation simulated by CLIGEN and the measured value is minimal. As can be seen from Figure 6, the rainfall trend of the monthly series is consistent, and its Pearson correlation coefficient (*r*) reaches 0.995. From the effect of precipitation and temperature simulated by the CLIGEN climate generator, it can simulate the distribution trend of individual meteorological factors well.



Figure 6. Comparison of simulated and measured rainfall values.

4.2. Evaluation of Simulation Accuracy of Watershed Runoff by GeoWEPP Model

Before using the model, it is necessary to evaluate the applicability of the model in the YJG watershed. This paper used only 13 times of runoff generated in the watershed to calibrate and verify the model at the rainfall scale. The comparison between the simulated and measured values of the watershed runoff during the calibration and verification periods is shown in Figure 7. It can be seen that the simulated value of runoff depth is consistent with the measured value, and the error is small.



Figure 7. Comparison of measured and simulated runoff value in YJG. (a) Comparison of measured and simulated runoff; (b) calibration periodic correlation analysis; (c) validation periodic correlation analysis.

The data of the simulated value and the measured value were analyzed. According to the statistical results of relative error, Nash–Sutcliffe efficiency coefficient, and correlation coefficient (Table 1), the Nash–Sutcliffe efficiency coefficient is above 0.90, and the relative error is within the allowable range. The three parameters of model adaptability evaluation of the watershed are all in the ideal numerical range, and the changing trend of erosion and runoff in the whole simulation period is basically the same, indicating that the model has a good fitting effect and can reflect the characteristics of runoff and soil erosion in the study area. It can be used for soil erosion prediction in the YJG watershed.

Table 1. Model applicability verification.

	Relative Error	Correlation Coefficient	Nash-Sutcliffe Efficiency Coefficient
Model calibration period (1–6)	13.248	0.997	0.994
Model validation period (7–13)	43.876	0.958	0.958

4.3. Assessment of Implementation Effect for GCHP

The soil type and land use of the YJG watershed remained unchanged. The data of the gully landfill were converted into ASCII format by ArcGIS for model reading, and then the data and DEM were simulated and analyzed. After the gully head landfill treatment, information on 153 slopes and 74 gullies was extracted, and the simulated subcatchment area was 0.87 km². The soil erosion threshold was defined as 0.01 t/(ha·yr), and the soil erosion distribution is shown in Figure 8.



Figure 8. Soil erosion distribution graph. (a) Original soil erosion; (b) soil erosion after GCHP.

After the implementation of gully head landfill, further erosion of the plateau by the gully head was cut, preventing geological disasters such as collapse, landslide, and edge cracking induced by the dissected valley. The erosion at the gully head decreased significantly, and the figure's original deep red area turned light red. However, some local soil erosion appeared red on both sides, indicating that a new gully head and gully were produced, but the original main erosion source had been improved. According to the simulation results in Table 2, the annual runoff was reduced to 495,952 m³, and the sediment yield was reduced to 7.3 t. In addition, the analysis was only compared with the simulated original soil erosion amount. As a result, the annual runoff decreased by approximately 13.13%. Compared to the amount of sediment eroded before the project, the sediment yield decreased by about 35.96%.

Name	Annual Runoff/m ³	Annual Sediment/t
Measured value	481,198.56	9.756
Simulated value	570,882	11.4
Simulated value after GCHP	495.952	7.3

Table 2. Comparison of measured and simulated values.

On the whole, the annual runoff and sediment yield were reduced. Generally, using a gully head landfill affects fixing the gully and maintaining the plateau. The possible reasons for such a result are as follows: after the gully head landfill measures are taken, the water flows path changes. As seen from Figure 8, after the landfill, the water flow path becomes shorter and more numerous, reducing the scouring ability of the water flow and only generating little runoff. On the other hand, the time is short due to the simulated rainfall situation, and the generated runoff is insufficient to produce significant erosion changes.

Runoff is a significant cause of soil erosion and slope instability [22]. After gully head landfill, many new shallow gullies will develop around the gully head over time (as shown in Figure 9), the number of flow paths increases, the length becomes shorter, and the coverage of sub-watersheds decreases, but the number of covered watersheds in the gully head area increases. Figure 10 shows the results of the hydrological analysis. For ease of comparison, the same background map was used, and Figure 10b was generated under the simulation scenario of the ditch head landfill. Simple gully head landfill measures can reduce runoff and soil erosion in a short time. Huo and Yang [23] used the SWAT model to find that the drainage area decreased due to the shortening of the flow path, and so did the runoff and the sediment amount. Xu and Chen [24] confirmed by comparing DEMs from

different periods that over a long period (maybe years to decades), if these small water flow paths develop and expand uncontrolled, then a new gully channel may be incised [25], causing severe erosion in the future. Ramke [26] suggested that the drainage design in the landfill site requires attention, which may be very beneficial in preventing the reformation of ditches.



Figure 9. Simple gully head landfill. (**a**) Initial stage of gully head landfill; (**b**) after one year of gully head landfill.



Figure 10. The river network before landfill (a) and after landfill (b).

4.4. Simulation of Erosion and Sediment Yield in Small Watershed under Gully Head Landfill Scenario

In order to simulate and analyze the effect of the GCHP project, the identified and verified GeoWEPP model was used to simulate the soil erosion under the current soil and water conservation measures and the GCHP (gully head landfill) engineering measures in the YJG watershed. The basic parameters of the model under the two schemes are consistent.

Figure 11 and the calculated data show that the gully head landfill project plays a protective role in the soil erosion of small watersheds in the Loess Plateau and can reduce runoff and sediment generation simultaneously. The runoff and erosion of the 3rd, 4th, 5th, 9th, and 10th times decreased but did not change much because the rainfall intensity was small (\leq 3 mm/h). Therefore, when the rainfall intensity is small, whether there is a GCHP project has little effect on the soil erosion of the whole basin. This change is more apparent when the rainfall intensity reaches a certain level (such as the second and sixth rainfalls).



Figure 11. Comparison of runoff and erosion before and after gully head landfill in YJG.

5. Discussion

Previous studies have verified the applicability of GeoWEPP in the small watershed of the Loess Plateau [26,27]. This paper used the measured temperature data to calculate the climate data parameters required by the model. After verification, the simulated values of the maximum and minimum temperatures were consistent with the distribution trend of the measured values, consistent with the assumption in the CLIGEN module that the daily maximum and minimum temperatures were subject to the independent normal distribution. The correlation between the simulated and measured values reached 0.99. The monthly precipitation factor mainly verified the simulation accuracy of rainfall probability. Comparing the simulated value with the measured value, the trend of monthly average precipitation was consistent. The Pearson correlation coefficient (*r*) was greater than 0.995, indicating that it can effectively simulate the distribution trend of monthly rainfall. The rainfall probability factor data analysis shows that the relative error of monthly rainfall probability was less than 0.1, indicating that the rainfall situation between years was basically consistent. From the above analysis, CLIGEN simulated climate data were reliable and valuable.

The soil erosion forecasting model is a cutting-edge field of soil erosion scientific research. Researchers at home and abroad have favored the research and development of soil erosion forecasting models integrated with GIS. Based on DEM, soil type, soil parameters, land use, and meteorological data of YJG, TOPAZ software was used to extract watershed topographic parameters from DEM. The GeoWEPP model based on physical process coupled with WEPP and GIS was used to study the soil erosion characteristics of YJG. The soil erosion amount before and after the implementation of the GCHP project was quantitatively evaluated. The simulation results show that compared with the simulated original soil erosion amount, under the implementation conditions of the GCHP project, the annual runoff decreased by 13.13%, and the sediment yield decreased by 35.96%. This shows that the measures of the GCHP project have good soil and water conservation functions. The research results are consistent with the research results of Jin et al. [28]. The GCHP project in Qingyang City controls 10,900 km² of the soil and water loss area, accounting for 47% of the city's soil and water loss area, and has achieved remarkable results. However, the GCHP project is not completely reliable for soil and water control. If

the engineering design is inappropriate or lacks follow-up management, it will likely lose the protective effect, which will aggravate soil erosion.

This study provides a clearer understanding of the changes in the spatiotemporal pattern of soil erosion and the implementation effect of the GCHP project, but there are still some shortcomings in the research process. For example, this study only studied the gully head landfill project in the GCHP project, and different engineering measures can be added in the subsequent research. Additionally, the study could be improved by modifying vegetation types to study soil erosion under different land use types to explore the best land use mode of the GCHP project. The YJG watershed is a small branch of the Nanxiaohe basin, and the spatial scale can be extended in the follow-up work to study the influence of the existing measures of the GCHP project on medium and large-scale watersheds.

6. Conclusions

Taking the YJG watershed as the research area, a typical scenario of the gully head landfill was built with the help of RS and ArcGIS software. The numerical simulation of the scenario was carried out by the GeoWEPP model and compared with the original natural gully. The conclusions are as follows:

- (1) The GeoWEPP model has good applicability in the YJG watershed. The relative error, correlation coefficient, and Nash–Sutcliffe efficiency coefficient were 13.248, 0.958, and 0.958, respectively, indicating that the GeoWEPP model has high accuracy in the simulation of erosion and sediment yield in the YJG watershed and can be used for various simulation analyses of erosion and sediment yield in the watershed.
- (2) According to the comparison of the simulation results, the sediment yield in the YJG area was reduced by 35.96%, and the annual runoff volume decreased by 13.13% after landfill, indicating that the gully head landfill effectively prevented the further erosion of the loess plateau and reduced the erosion area. Generally speaking, it alleviates the soil erosion problem in the YJG area.
- (3) The results of the hydrological analysis showed that new shallow gullies would develop around the gully head after the GCHP as time went on. Compared with the original water flow path, the length and quantity of gully heads become shorter and more. The development of fissures and sinks on the edge of the tableland provides advantageous channels for water flow. If necessary maintenance is lacking, new gullies will easily develop in the long run, thus promoting greater soil erosion in the watershed. In the gully region of the Loess Plateau, there is a mutual feedback effect between the GCHP (gully head landfill) and soil hydraulic erosion. In order to reduce the shrinkage rate of the plateau surface and slow down the development of soil hydraulic erosion in the watershed, the use of ecological measures to control the surface of the bare area of the gully head landfill area (e.g., the landfill area is covered with grassland) can be implemented, which is an important research direction for future GCHP projects.

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