Original Research Article

Assessment of groundwater recharge in shallow aquifers using Soil and Water Assessment Tool: A case study of the Thuthapuzha subbasin

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ABSTRACT

Aim: To study the spatial and temporal variability of shallow groundwater recharge using the Soil-Water Assessment Tool (SWAT) model on a watershed scale.
Place of Study: Thuthapuzha subbasin
Methodology: Groundwater recharge is a significant factor of groundwater simulations, which may aid in realistic groundwater resource management and decision-making. The study assessed the spatial and temporal variability of shallow groundwater recharge in the Thuthapuzha subbasin using a semi-distributed hydrological model called SWAT. Land use map, soil map, topographic data (Digital Elevation Model [DEM]), and basic meteorological data are the general input data necessary to run the SWAT model.
Results: The average annual groundwater recharge in the Thuthapuzha subbasin was obtained as 201.26 mm/year over the 28 years from 1992 to 2019. According to the long-term water balance of the whole watershed, runoff accounts for 60% of the average annual precipitation. Evapotranspiration accounts for 27% of the average yearly precipitation in the research region. Meanwhile, groundwater recharge is barely 8% of the average annual rainfall. The topography and land use in the study region were found to influence the spatial variability of groundwater recharge. The groundwater recharge also showed monthly and annual fluctuations. While the major rainy season (South-West monsoon) lasts from June to September, July to September period shows the highest recharge. The comparison of recharge obtained from the SWAT model with the recharge estimated using the rainfall infiltration factor (RIF) method shows a good correlation ($R^2 = 0.68$).
Conclusion: SWAT modeling is a feasible option over field-scale approaches for assessing groundwater recharge and its response to various influences on a catchment scale.

Keywords: Groundwater recharge, Modelling, Rainfall Infiltration Factor, River basin, SWAT model, water balance

1. INTRODUCTION

The hydrologic process through which water from the land surface enters the dynamic groundwater flow system is known as groundwater recharge. Precipitation that is momentarily ponded over the land surface and penetrated at the land surface contributes to groundwater recharge after losing some water to evapotranspiration and runoff. Quantitative knowledge of regional and temporal variability in groundwater recharge on a watershed scale can help with groundwater resource planning and management [1]. Groundwater is a public resource that is susceptible to exploitation on an individual and community level, and India is the world's largest extractor [2]. The average annual per capita water availability in India has decreased from 5177 cubic meters in 1951 to 1508 cubic meters in 2014. It is expected to decline further to 1,465 and 1,235 cubic meters by 2025 and 2050. In addition, if it goes below 1000-1100 cubic meters, India may be categorized as a water-stressed country [3].

Groundwater, which meets more than 85 percent of India's rural domestic water requirements, 50 percent of its urban water demand, and more than 50 percent of its irrigation requirements are depleting fast in many areas due to its largescale withdrawal for various sectors [4]. Also, the rainfall infiltration rates into the soil and consequently the natural recharging of aquifers have been reduced as a result of increased demand for groundwater resources, rapid urbanization, land-use land cover changes, and climate change [5]. Kerala is a state in India where around half of the urban population and 80% of the rural population rely on open wells to meet domestic water demands. However, the majority of observatory wells have recorded an average annual fall in water level of half a meter in the recent decade. Hence, determining the rate of natural groundwater recharge is a crucial step in establishing a watershed management strategy that protects groundwater resources from climate change and other stresses [1]. Also, groundwater recharge is an important part of groundwater simulations, which may help with realistic water resource management and decision-making. In many models, it is regarded as an intermediate outcome, inputs, boundary conditions, or simply internal variables [6, 7].

A variety of methods can be used to estimate groundwater recharge. One of these techniques is to use hydrological models, which are advanced tools for calculating recharge and associated hydrological processes at a regional scale. Hydrological models have the advantage of being able to replicate the impacts of flowing water over many sectors [8]. In this study, a semi-distributed hydrological model, ArcSWAT (Soil-Water Assessment Tool) is applied to estimate spatial and temporal variability of shallow groundwater recharge in the Thuthapuzha subbasin of the Bharathapuzha river basin. The Soil and Water Assessment Tool (SWAT) model [9, 10] is a physically-based, computationally efficient, semi-distributed, small watershed to river basin-scale hydrologic model, that operates on a daily time step [11, 12]. It is a free and open-source model that simulates the quality and quantity of surface and groundwater to anticipate the environmental impact of land use, land management techniques, and climate change [13]. The key model components include weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, fertilizer, and pesticide loading, and water transfer. SWAT is a flexible approach for combining numerous environmental processes to achieve more effective watershed management and is one of the most common hydrological models used all around the world [11, 14].

2. MATERIAL AND METHODS

2.1 Study area

Thuthapuzha sub-basin, is a sixth-order sub-basin of the Bharathapuzha river basin, Kerala's second-largest river basin. It is located in Palakkad and Malappuram districts, with latitude and longitude ranges of 10°50′–11°15′ North and 76° 05′–76°40′ East (Fig. 1). The total geographical area of the Thuthapuzha subbasin is 916.66 km2. The average annual precipitation in the subbasin is 3830 mm [15]. This is more than the Bharathapuzha River

Basin's average annual rainfall (1822 mm) and Kerala's average annual rainfall (2817 mm) [16, 17]. The study area is underlain by Precambrian crystalline rocks like charnockite, charnockitic gneiss, hornblende biotite gneiss, garnet biotite gneiss, chondrites, migmatites, etc [18]. The major crops cultivated in the river basin include rice, rubber, coconut, pepper, banana, etc. Mannarkkad, Thachanpara, Sreekrishnapuram are some of the areas within the subbasin which often face water scarcity problems [19].

Fig. 1. Location of the study area

2.2 ArcSWAT Model Description

The SWAT version ArcSWAT 2012.10.24 is used in this study. ArcSWAT is an ArcGIS plugin for the SWAT model that provides a graphical user interface. The model divides the watershed into several sub-watersheds or subbasins. When distinct regions of the watershed are dominated by land uses or soils with properties that differ enough to affect hydrology, the use of subbasins in a simulation is specifically useful [20]. Subbasins are spatially distributed, and streamflow and associated contaminants are routed from one subbasin to another. However, the smallest spatial units, known as hydrologic response units (HRUs), are not distributed, may not be continuous, and don't have any routing among them. HRUs are portions of a subbasin that have unique land use/management/soil and slope properties based on user-defined thresholds for each category within a given subbasin. The majority of the SWAT simulation happen at the HRU level [21]. Water balance is the driving force behind everything that happens in the watershed, regardless of the type of study conducted using the SWAT model. SWAT simulates the hydrological cycle in the land phase using the following water balance equation) [19]:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

Where, SWt is the final soil water content (mm), SWo is the initial soil water content on the day i (mm), t is the time (days), Rday is the amount of precipitation on the day i (mm), Qsurf is the amount of surface runoff on the day i (mm), Ea is the amount of evapotranspiration on the day i (mm), Wseep is the amount of water entering the vadose zone from the soil profile on the day i (mm), and Qgw is the amount of return flow on the day i (mm).

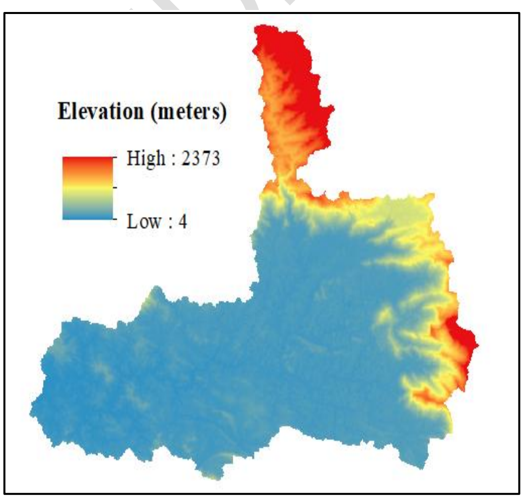
One of the primary outcomes of SWAT modelling is the calculation of groundwater recharge in both unconfined (shallow) and confined (deep) aquifers [22]. Water that percolates and flows through the root zone of the soil is characterized as groundwater recharge to an unconfined aquifer in SWAT. If time goes on, this water will eventually come into contact with the phreatic surface of the saturated zone [6]. The basic goal of SWAT modelling is to compute the water balance. When the rainfall occurs, the water ponded over the land surface is infiltrated into the soil profile and redistributed. The infiltrated water in the soil profile becomes deep percolation when the water content within the strata exceeds its field capacity resulting in vertical downward movement of water through the soil profile. Water that enters an unsaturated vadose zone, recharges the shallow groundwater, after passing through the lowest soil layer. The residue going downwards as recharge is computed using a soil moisture balance in a series of soil layers, considering evapotranspiration and runoff. The Penman-Monteith equation is used to obtain potential evapotranspiration. On any given day, the recharge has computed the equation given below [23]:

$$W_{rchrg,i}=(1-\exp[-1/\delta_{gw}])W_{seep+exp[-1/\delta gw]}W_{rchrg,i-1} \quad (2)$$

where W rchrg,i is the amount of recharge entering the aquifers on the day i, δgw is the delay time of the overlying geological units (days), Wseep is the total amount of water that exits the bottom of the soil profile on the day i (mm H_2O), and Wrchrg, i-1 is the amount of recharge that enters the aquifer on day i-1(mm H_2O)

2.3 Input Data

The general input data required to run the SWAT model are land use, soil map, topographic data (Digital Elevation Model [DEM]), and basic meteorological data (rainfall, wind velocity, relative humidity, temperature, solar radiation). The DEM of the Thuthapuzha river basin has been created for this study using topographic data from the SRTM Digital Elevation Model (30 m resolution), as shown in Fig. 2. The study area has an elevation range of 4 to 2373 meters. The land use land cover map (Fig. 3) has been prepared in consultation with Kerala State Remote Sensing and Environment Centre using LISS-III imagery of IRS P6 of 2008 [24]. The Directorate of Soil Survey & Soil Conservation of Kerala State provided the details about the physical properties of the soil and the soil map required for the SWAT model. The soil map was digitized and converted to a grid file for use in the SWAT model using ArcGIS 10.2 [24]. The daily rainfall data, maximum and minimum temperature, relative humidity, wind speed, and solar radiation data were collected from the Regional Research station (Pattambi), Central Water Commission (CWC), and India Meteorological Department (IMD). Daily river discharge data of the Pulamanthole (basin outlet) gauging station was obtained from the website of India Water Resource Information System (India-WRIS) developed by the Ministry of Jal Shakthi, Government of India. The river discharge data is used for performing sensitivity analysis, calibration, and validation of the SWAT model.



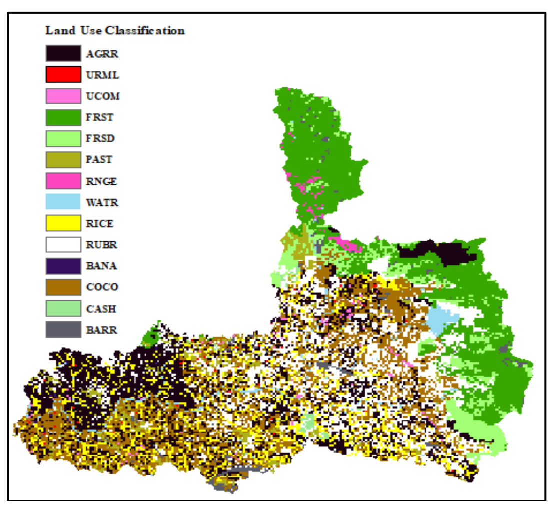


Fig. 2. DEM of the study area **Fig. 3. Land use map of the study area**

The watershed is delineated using the Digital Elevation Model (DEM) and divided into 36 subbasins. Then, by combining slope classes, soil, and LULC data, 362 HRUs were created using multiple HRU options (12 % land use over subbasin area, 15 % soil class percentage over the land-use area, and 15 % slope class over soil area respectively as HRU thresholds). Wind speed, precipitation, humidity, maximum-minimum temperature, and solar radiation data were imported and written. The SWAT model simulation was performed for 28 years (1989-2019). The first three years of the simulations were a warmup period and the model does not give output for these years.

2.1 Calibration and validation of SWAT model

Using observed streamflow data, the SWAT model has been calibrated and validated. The data is split into two groups, including calibration data from 1992 to 2012 and validation data from 2013 to 2019. The runoff has been simulated using the SWAT model together with the appropriate input data and default settings. The simulated runoff was then transferred to SWAT-CUP for calibration and validation against the monthly streamflow data collected from the Pulamanthole gauging station. The SUFI-2 method was used to optimize the parameters (Sequential Uncertainty Fitting version 2). Initially, a sensitivity analysis for the runoff is performed, and the parameters are optimized using data from 1992 to 2012. The model's adjusted parameters are then calibrated using data from 1992 to 2012. The calibrated SWAT model for the Thuthapuzha subbasin is further validated using the data for the period 2013-2019 with the same parameters and with no changes to the input data.

The performance of the model was assessed using statistical indicators to see how closely the model's simulated values matched the observed values. The coefficient of determination (R2), the Nash-Sutcliffe efficiency (NSE). The value of R2 ranges from 0 to 1, with higher values suggesting lower error variance and values larger than 0.5 are generally considered acceptable [25, 26]. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with 1 being the best value [27, 28].

3. RESULTS AND DISCUSSION

According to the calibration and validation outputs, the SWAT model was successful in simulating monthly river discharge. Table 1 shows the NSE, R2 values obtained after calibration and validation with observed stream discharge. Based on these variables, model performance on a monthly basis has shown a good agreement. The SWAT model allows for the measurement of the amount of groundwater recharge throughout the whole watershed by simulating runoff in the research area. Hence, once the runoff calibration and prediction are finished, recharge estimation is also completed.

Table 1. Model performance evaluation

Statistical indicators	NSE	R^2
Value after calibration	0.84	0.84
Value after validation	0.81	0.82

Table 2 presents the estimated annual recharge over the entire watershed from 1992 to 2019, based on a calibrated SWAT model, assuming no changes in land uses during that period. The 28 years average annual groundwater recharge over the Thuthapuzha subbasin is estimated from the SWAT model is 201.26 mm/yr. Fig. 4 shows the bar diagram of the average annual water balance obtained using the SWAT model during the whole simulation period. The long-term water balance of the entire catchment shows that the runoff is 60 % of the average annual precipitation. The evapotranspiration accounts for 27 % of the mean annual precipitation that occurs in the study area. Meanwhile, groundwater recharge is only 8 % of normal yearly rainfall. In a nutshell, according to SWAT model simulation, runoff is the greatest water-consuming, while recharge is the least water-consuming process in the watershed under consideration. This is due to the nature of the physiography of the study area, which features a continuous sloppy terrain that favours surface runoff over infiltration.

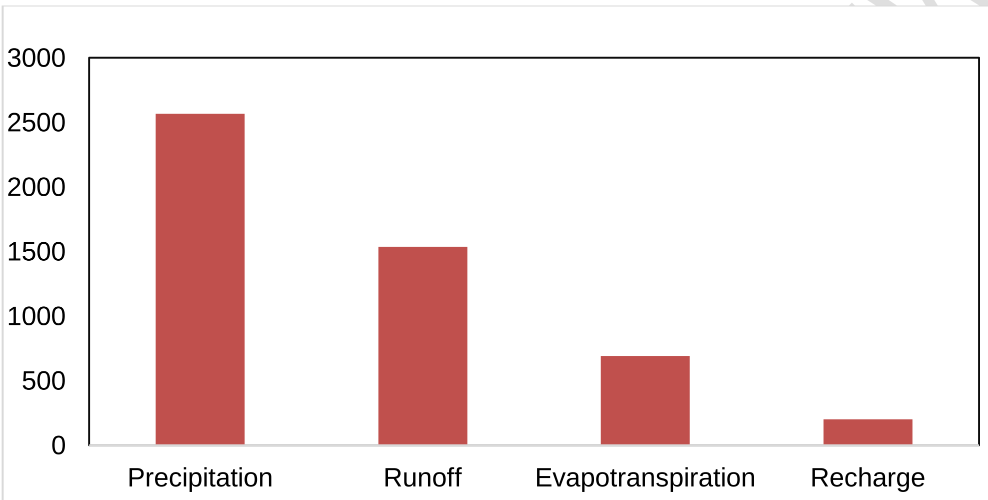


Fig. 4. Average annual water balance components in mm (1992-2019)

Table 2. Annual recharge estimated from SWAT model and RIF method

Year	**Recharge from SWAT (mm/year)**	**RIF method**		
		Rainfall(mm)	**RIF**	**Recharge (mm/year)**
1992	152.42	2986.00	0.075	223.95
1993	114.27	2443.30	0.075	183.25
1994	200.82	3263.40	0.075	244.76
1995	198.91	2650.80	0.075	198.81
1996	174.44	2097.70	0.075	157.33
1997	185.54	3064.60	0.075	229.85
1998	230.97	2688.50	0.075	201.64
1999	174.83	2550.60	0.075	191.30

2000	155.04	2039.96	0.075	153.00
2001	166.48	2409.90	0.075	180.74
2002	148.21	2052.90	0.075	153.97
2003	112.88	1994.60	0.075	149.60
2004	177.54	2555.20	0.075	191.64
2005	275.76	2813.50	0.075	211.01
2006	263.87	3029.30	0.075	227.20
2007	336.99	3676.60	0.075	275.75
2008	143.48	1907.80	0.075	143.09
2009	192.54	2461.40	0.075	184.61
2010	261.45	2632.70	0.075	197.45
2011	283.44	2754.90	0.075	206.62
2012	143.76	1929.90	0.075	144.74
2013	293.61	2749.60	0.075	206.22
2014	248.24	2523.50	0.075	189.26
2015	146.43	2253.10	0.075	168.98
2016	126.49	1328.20	0.075	99.62
2017	206.72	2044.80	0.075	153.36
2018	260.51	2979.70	0.075	223.48
2019	259.69	3040.60	0.075	228.05

3.1 Spatial and temporal groundwater recharge variability

As previously stated, the annual average recharge over the entire watershed as simulated from the SWAT model is 201.26 mm/yr, accounting for only 8% of the mean annual precipitation that would reach the shallow aquifer. However, in the planning of water conservation and artificial recharge structures, it is vital to understand the spatial variability of groundwater recharge. The spatial distribution of groundwater recharge over the whole basin is depicted in Fig. 5. The spatial variability of groundwater recharge is dependent on both topography and land use in the study area, according to a comparison of recharge distribution with the DEM and land use map of the study area. The region under rice cultivation at low elevation shows the highest recharge (348.7 mm/yr). Within the subbasin, there is also a decreasing tendency in recharge from forest land use at high altitude (108 mm/yr) to that in low altitude (283.33 mm/yr). Similar results were reported by [29].

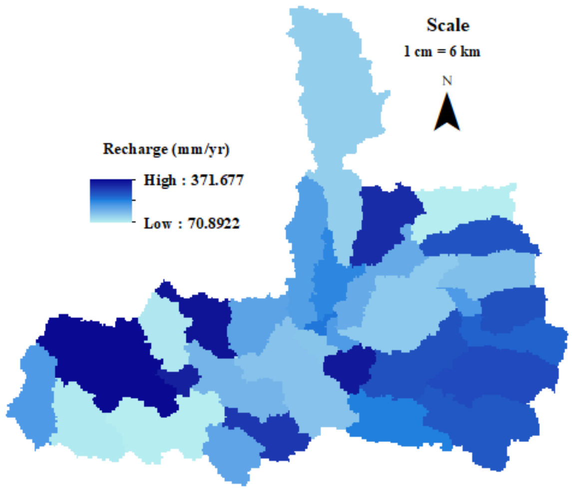


Fig. 5. Spatial variation of Average annual groundwater recharge from 1992-2019

The groundwater recharge obtained from the SWAT model exhibits monthly and yearly variations, assuming no change in land-use land cover in the simulation period. Table 3 shows the monthly average recharge values from the year 1992 to 2019. According to these findings, while the major rainy season (South-West monsoon) occurs from June to September, higher recharge occurs in July to September. In addition, the higher recharge occurs in October during the Northeast monsoon season (October to November). The recharge from January to May months is small, ranging from 0.79 to 1.1 mm.

In general, the recharge over the Thuthapuzha subbasin is affected temporally by the seasonal occurrence of the rain and spatially by the amount of rainfall distribution, land use - land cover, and topography of the area.

3.1 Comparison with recharge estimated from RIF method

The net annual groundwater recharge (mm) simulated from the SWAT model was compared with the recharge estimated from the rainfall infiltration factor (RIF) method [30,31]. It is an indirect method for estimating the groundwater recharge [32].

Recharge can be calculated using the RIF method as,

$$Rif = r \times RIF \quad (3)$$

Where, Rif is the annual groundwater recharge (in mm) computed using the RIT method; r is the total observed annual rainfall (in mm) and RIF is the rainfall infiltration factor.

The rainfall Infiltration factor for the study area is 0.075 [33]. The groundwater recharge from 1996-2019, calculated using the RIF method is shown in Table 2. The annual average groundwater recharge over 28 years in the Thuthapuzha subbasin is estimated to be 201.26 mm/year from the SWAT model and 186.20 mm/year from the RIF method. The plot of recharge simulated from swat vs. recharge estimated from the RIF method showed moderately correlated with a correlation coefficient of 0.68. This shows that the independently estimated recharge values by the RIF method closely match the simulated recharge simulated from the SWAT model for the study area. The predicted annual recharge values follow the recharge calculated from the RIF method closely. From Table 2, it is clear that in both methods, maximum recharge is obtained in the year 2007, the year which shows the highest annual precipitation among 28 years. This suggests that groundwater recharge is dependent on the magnitude of rainfall received.

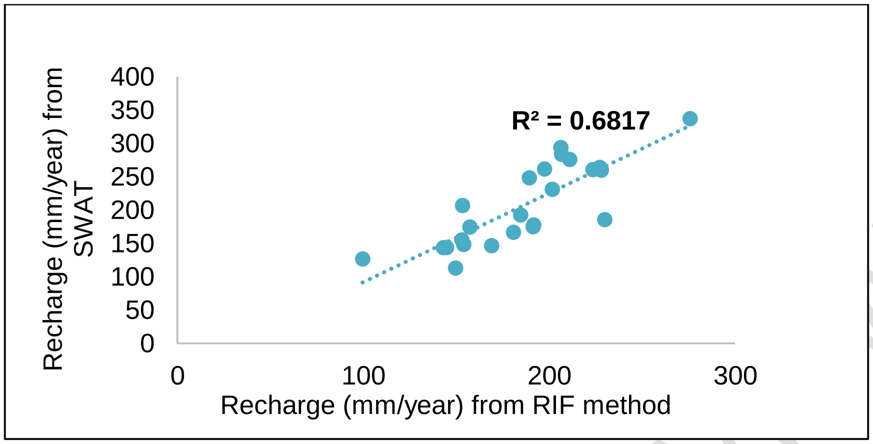


Fig. 6. Recharge obtained from SWAT model versus RIF method

4. CONCLUSION

The study suggests that a watershed-based approach as with SWAT is needed to understand the spatial and temporal variation in groundwater recharge. Field methods like the water level fluctuation method may have many constraints. The recharge simulation using the SWAT model gives a better understanding of groundwater recharge over a watershed or catchment with a better understanding of other mass balance components like surface runoff and evapotranspiration. Also, the effect of land use as well as the topography of the area on groundwater recharge can be easily evaluated using hydrologic modelling. The predicted recharge value is validated with the recharge estimated using the RIF method and found in good agreement with a correlation coefficient of 0.68.

The estimated recharge is closely related to the type of land use, rainfall received, and the nature of the topography. The soil type has been found less impact on the recharge, as the majority of the area contains sandy clay loam soil which is of moderately to well-drained type. With the SWAT model, recharge can be generated on daily, monthly, and yearly time steps. This data can be later used as input for groundwater modelling. Also, different water conservation methods can be planned considering the spatial as well as temporal variation of groundwater recharge obtained from the SWAT model. Also, future climate change impacts on groundwater recharge can be predicated using the calibrated SWAT model. But, the effect of geological features on groundwater recharge cannot be assessed using the SWAT model.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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