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Trends and effects of rainfall on groundwater recharge in Namakkal district of Tamil Nadu: analysis using the Mann–Kendall test and transfer function model

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Abstract Persistent rainfall determines the potential groundwater availability; hence, their association is assessed in this paper. The Mann–Kendall test is used on time series data, and a linear transfer function model is fitted. The Mann–Kendall test shows a negative trend in the groundwater level during the north-east monsoon and an increasing trend in all seasons. The rising trend of rainfall raised groundwater availability throughout the year except during the north-east monsoon. The linear model specifies that rainfall affected the monthly average groundwater level which led to the recharge of the dynamic groundwater level.

Keywords Trend, rainfall, groundwater, Mann–Kendall test, Sen's slope

JEL codes Q25, Q54

Worldwide, groundwater is the most preferred source of water supply, and its rising demand has lowered the water level and made groundwater decline a serious problem. Water in aquifers is not frequently at a persistent level; the water level depends on recharge resulting from the infiltration of precipitation. Rainfall controls the groundwater table. When rainfall is less than normal for a long period, the water flow in rivers and streams slows down, and the water level falls in reservoirs and lakes and, ultimately, wells.

The rate of recharge determines the groundwater table, but the relationship between rainfall and groundwater recharge is not clear, mainly because the changes in groundwater storage have not been observed in a sustained manner and the availability of data is inadequate (Taylor et al. 2013). Groundwater assumes significance in the context of declining contribution of surface water sources, especially when the area irrigated by tanks has been declining steadily since the 1960s (Sivasubramaniyan 2016). The largest component of groundwater use is the water extracted for irrigation (Roopal 2016).

Tamil Nadu is one of the water-starved states in India; more than 60% of its wells show a fall in the groundwater level, and its annual replenishable groundwater resource of the state is estimated at 23.07 billion cubic metres (BCM). The current level of utilization expressed as net groundwater draft of 13.59 BCM is about 60% of the available recharge, while 8.88 BCM (40%) is available for use. The uncontrolled use of the borewell technology has led to the extraction of groundwater at such a high rate that often recharge is not sufficient. The attention to water conservation and re-use, water use efficiency, groundwater recharge, and ecosystem sustainability has been inadequate.

With this view, the Central Ground Water Board, South Eastern Coastal Region is monitoring the water levels in a set of groundwater monitoring dug wells and piezometer wells in Tamil Nadu and Puducherry to study the behaviour of the groundwater table. Analyses of rainfall and water extraction data from satellite records by researchers in India find that diminishing monsoon rainfall has been disturbing groundwater storage (Nature India 2017). Data is required on groundwater resources and levels to assess whether its utilization is sustainable (Valerie et al. 2019). Standardized recharge and rainfall time series demonstrate a clear relationship between rainfall and recharge. Annual recharge is higher (or lower) than the mean value when annual rainfall is also higher (or lower) than the mean rainfall. This trend is confirmed by the observed relationships between the annual groundwater storage balance (the difference in storage between January and December the same year) and the annual rainfall.

Currently, changes in groundwater storage are strongly correlated to rainfall. The increasing pressure on the limited resources requires immediate action for sustainable groundwater resource management. In this context, this study investigates the future scenario of groundwater in Tamil Nadu and proposes policy options to sustain groundwater resources.

Study area and data

Namakkal, a district in Tamil Nadu, is situated in the north-western and western agroclimatic zones, and its climate is hot and dry. The meteorological department follows the standard of four seasons with some local adjustments: winter (January and February); summer (March, April, and May); monsoon (rainy) season (June to September); and a post-monsoon period (October to December). The weather turns hot in March and the temperature reaches the maximum during April and between October and December (District Survey Report, Namakkal District 2019). The river Cauvery is one of the major water sources for the overall socio-economic progress of Namakkal district.

In the context of groundwater levels, the district is categorized as an over-exploited area (Central Groundwater Board, India 2017). Rainfall is the only source of moisture, but the distribution of rainfall is uneven and erratic, and agriculture is mainly rain-fed. The district receives rain under the influence of both the south-west and north-east monsoons. Both the temporal and spatial variability of rainfall influence the cropping pattern, agricultural productivity, and livelihood sustainability. The annual and seasonal rainfall received and its variability affect crop growth and yield and directly influence success or failure. To select suitable crops and take the appropriate mitigating measures, it is essential to study the characteristics of rainfall and the variability of annual and seasonal rainfall.

This study is uniquely based on the secondary data of the monthly groundwater level (mbgl) and rainfall (mm) data of Namakkal district for the period from 2010 to 2018. The data is obtained from the Central Ground Water Board; the State Ground and Surface Water Resources Data Centre, Tamil Nadu; and from the Series of Season and Crop Report (Department of Economics and Statistics, Tamil Nadu 2009–10 to 2017–18).

Trend analysis may be the best approach to assessing the responsiveness of the groundwater level to treatment rainfall in situations where treatment was gradual and widespread. Statistical trend analysis is a hypothesis-testing process (Donald et al. 2011); the null hypothesis (H_O) is that there is no trend and each test has its own parameters for accepting or rejecting H_O.

Mann–Kendall test and Sen's slope estimator

The studies that use trend analysis focus mainly on the null hypothesis of no trend (the type I error). Only a few studies report the competency of the Mann–Kendall test (Mann 1945; Kendall 1975; Gilbert 1987) to successfully recognize the trends. The Mann–Kendall test has been commonly used to statistically detect the monotonic (upward or downward) trends in the hydrometeorological time series, but the trend may or may not be linear (Partal and Kahya 2006; Kumar et al. 2010).

The non-parametric Mann–Kendall test is commonly employed to detect monotonic trends in data series—environmental, climate, or hydrological (Thorsten 2020). The null hypothesis, H_0, is that the data comes from a population with independent realizations and it is identically distributed. The alternative hypothesis, H_a, is that the data follows a monotonic trend. The Mann–Kendall test can be used in place of a parametric linear regression analysis, which can be used to test whether the slope of the estimated linear regression line is different from 0.

Richarde et al. (2015) apply the non-parametric Mann–Kendall and use Sen's methods to determine whether there was a positive or negative trend in rainfall data with statistical significance. A detailed statistical analysis applied to the river flow and rainfall time series of all gauges indicates that rainfall is highly temporally variable and that annual rainfall fell between 1960 and 2000. The Mann–Kendall test statistic is determined by the ranks and sequences of time series rather than the original values, and it is robust when dealing with non-normally distributed data, censored data, and time series with missing values (Hirsch 2011). Fan Wang et al. (2020) describe the Mann–Kendall test as follows.

For a given time series $\{X_i, i = 1, 2, \dots n\}$, the test statistic S

$$\sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\ (x_j - x_i) \quad \dots(1)$$

where X_i and X_j are the values of sequence i, j; n is the length of the time series and

$$sgn\ (\theta) = \begin{vmatrix} 1\ if \boldsymbol{\theta} > 0 \\ 0\ if \boldsymbol{\theta} > 0 \\ -1\ if \boldsymbol{\theta} < 0 \end{vmatrix} \quad \dots(2)$$

The statistic *S* is approximately normally distributed when $n \geq 8$, with the mean and the variance of statistics *S* as follows:

$$E(S)=0 \quad \dots(3)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i-1}^{m} T_1 i\, 9i-1)(2i+5)}{18} \quad \dots(4)$$

On running the Mann–Kendall test on the selected data, if the p-value is less than the significance level α (alpha) = 0.05, H_0 will be rejected. If H_0 is rejected, a trend is indicated in the time series; if H_0 is accepted, no trend is detected. If the null hypothesis is rejected, the result is said to be statistically significant.

Sen's slope estimator

The standard method of estimating the slope of a regression line is based on a least squares estimate, but the method is not valid when the data elements do not fit a straight line, as it is also sensitive to outliers. For estimating the magnitude of a time series trend for the set of pairs (i, x_i) where xi is a time series, the non-parametric procedure, Sen's slope (Sen 1968), is more robust.

$$\text{Sen's slope} = Median\left(\frac{x_j - x_i}{j-i} : i < j\right) \quad \dots(5)$$

where β is Sen's slope estimate. β>0 indicates an upward trend in a time series. Otherwise, the data series presents a downward trend during the time period.

Transfer function model

Rainfall influences aquifer recharge. To find out whether rainfall accelerates aquifer recharge in the study area, we mathematically estimate the relationship between monthly rainfall and monthly average groundwater level. Stochastic time series multivariate models can be constructed by the transfer function modelling technique involving two or more input variables and their dynamic relationships with the output. The main feature of this model is that the time evolution of rainfall and groundwater level would be linked to their previous and current values for both variables.

Yi and Lee (2004) find that x_t and y_t can follow linear processes and a linear relationship can be proposed between both time series. The residual e_t will also be a time series, likely to follow an autoregressive moving average with exogenous variables (ARMAX) model as an extension of linear regression to the time series area.

We constructed transfer function models for the data on the rainfall and groundwater levels based on time series methods using the steps necessary to model the stochastic time series process (Knotters and Bierkens 2000).

$$y_t = y_t * + N_t \quad \dots(6)$$

$$y_t * = \sum_{i=1}^{p} a_i\, y *_{t-1} + \sum_{j=o}^{q} b_j\, x_{t-j-k} \quad \dots(7)$$

$$N_t - \mu = \sum_{i=1}^{r} c_i\, (N_{t-i} - \mu) + \sum_{j=1}^{s} d_j\, \varepsilon_{t-j} + \varepsilon_t \quad \dots(8)$$

Where, y_t is the groundwater level at time t; y_t* is the groundwater level attributed to the rainfall value; N_t is the unexplained part, or noise term; x_t is the average rainfall attributed to the time step t–1 to t; k is the delay factor of relation between input and output; μ is the expected value of the noise term; a_i is the autoregressive parameter of the transfer function model of order i = 1, … p; b_j is the moving average parameter of the transfer model of order j = 1, …; c_i is the autoregressive parameter of the noise model of order i = 1, … r; d_j is the moving average parameter of the noise model of order j = 1, … s; and e_t is the white noise with mean zero and constant variance ε^2.

The transfer function model orders such as p, q, r, and s were kept for comparing different models with different parameterization methods. By applying the selected model orders in Equations 4–6, the resulting model is

$$y_t = y_t^* + N_t \qquad \dots(7)$$

$$y_t^* = a_1\,(y^*_{t-1}) + x_t \qquad \dots(9)$$

$$N_t - \mu = c_1\,(N_{t-1} - \mu) + \varepsilon_t \qquad \dots(10)$$

If the model order of the autoregressive parameter of the noise model is taken to be same as the autoregressive parameter of the transfer model—i.e., $c_1 = a_1$—the transfer function model of Equations 7–8 can be reduced to a special case of the transfer function model, also known as the ARX model:

$$y_t - \mu = a_1\,(y_{t-1} - \mu) + b_0\,(x_t) - \varepsilon_t \qquad \dots(11)$$

As a good prediction model, the residuals are used to examine the goodness of fit of the model that meets the requirements of a white noise process. If the model is not suitable, a new model should be identified. The steps of parameter estimation and diagnostic checking are repeated many times until an optimal model is selected. The last selected model is used to forecast the value.

Effect of rainfall on groundwater recharge

The periodic data on rainfall and groundwater level are important to study the fluctuation trends and access the groundwater potential. Table 1 precises the statistical range of both ground water level and rainfall for all the season.

Table 2 Mann–Kendall trend test and Sen's slope—south-west monsoon

Particulars	Rainfall	Groundwater level
Kendall's tau	0.167	0.444
S value	6.000	16.000
Var(S)	92.000	92.000
p-value	0.602	0.118
Sen's slope	7.800	0.514

The seasonal values of rainfall and groundwater levels were plotted for each of the four seasons to obtain the seasonal trend in the variables by applying the Mann–Kendall test. Sen's slope is considered in measuring the magnitude of change in the study variables.

The season-wise resultant graphs are presented with the line of best fit and the equation of the line as in the graphs. The positive Sen's slope (Table 2) represents the increasing trend (Figure 1) of rainfall in the south-west monsoon and winter (Figure 3). The decreasing trend (negative Sen's slope (Table 3 and Table 4) is observed in the north-east monsoon season (Figure 2). The rainfall trend is considerably stable during summer (Figure 4). Sen's slope and the Kendall tau statistic show a negative trend in the north-east monsoon. The groundwater level shows an increasing trend in all the four seasons. The rising trend of rainfall—robust by a relatively steep slope of the best-fit line—raises groundwater availability significantly (Figure 1 and Figure 3).

The congruent increasing trends of winter rainfall and groundwater level lead to the rising trend of

Table 1 Descriptive statistics of groundwater level (mbgl) and rainfall (mm)

Statistic	South West Monsoon		North East Monsoon		Winter		Summer	
	GWL (mbgl)	Rainfall (mm)	GWL (mbgl)	Rainfall (mm)	GWL (mbgl)	Rainfall (mm)	GWL (mbgl)	Rainfall (mm)
Minimum	3.50	0.00	4.35	57.50	4.35	0.00	6.06	63.70
Maximum	16.82	258.80	12.47	429.00	13.75	26.80	15.83	237.50
Median	11.56	35.40	11.08	251.60	9.69	6.90	11.94	138.15
Mean	10.76	56.98	10.36	257.54	9.50	8.66	11.13	137.98
Variance (n-1)	8.56	3185.04	5.87	10812.06	9.35	101.92	9.60	3063.66
Std deviation(n-1)	2.93	56.44	2.42	103.98	3.06	10.10	3.10	55.35

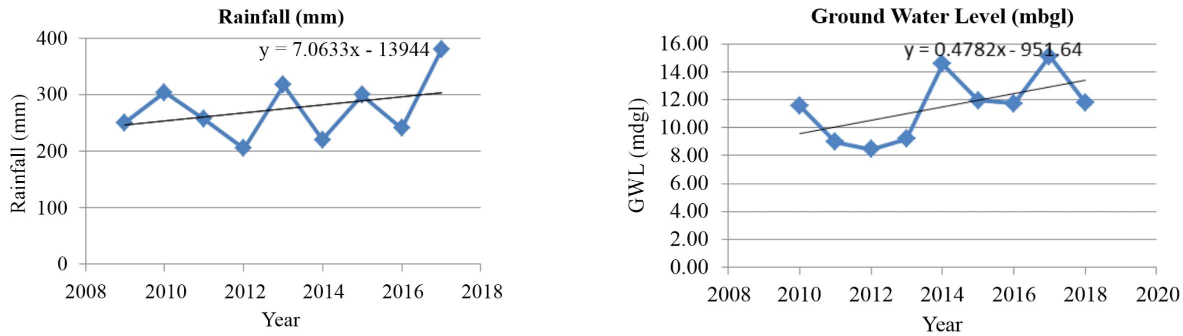

Figure 1. South West Monsoon (June - September)

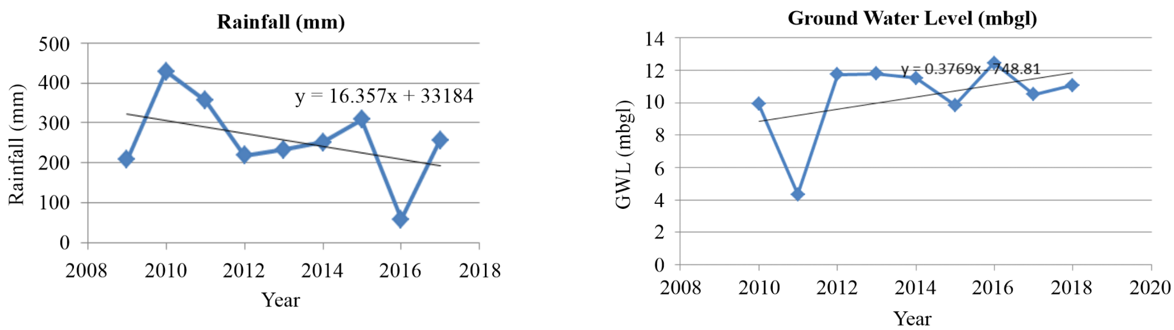

Figure 2. North East Monsoon (October - December)

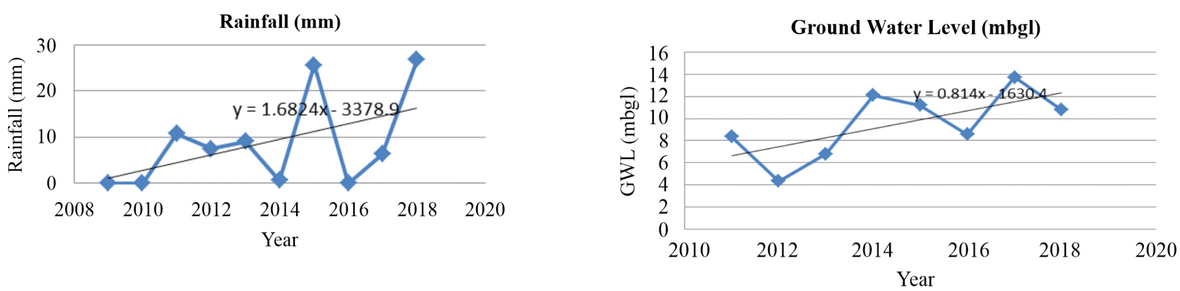

Figure 3. Winter (January - February)

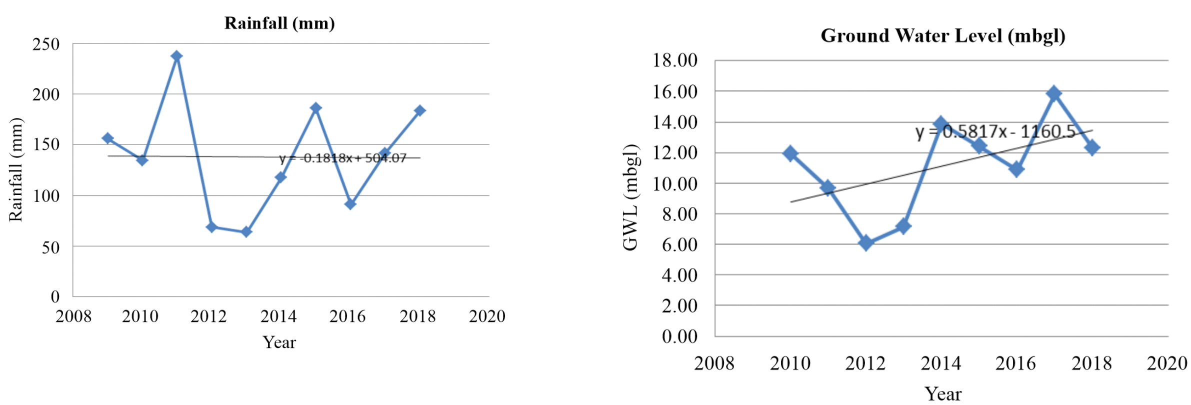

Figure 4. Summer (March - May)

Table 3 Mann–Kendall trend test and Sen's slope—north-east monsoon rainfall

Particulars	Rainfall	Groundwater level
Kendall's tau	–0.056	0.167
S value	–2.000	6.000
Var(S)	92.000	92.000
p-value	0.917	0.602
Sen's slope	–14.346	0.162

Table 4 Mann–Kendall trend test and Sen's slope—winter rainfall

Particulars	Rainfall	Groundwater level
Kendall's tau	0.322	0.429
S value	14.000	12.000
Var(S)	121.333	65.333
p-value	0.238	0.174
Sen's slope	1.600	0.847

groundwater availability in the summer (Table 5). The trends of the variables in all seasons are statistically insignificant, but Sen's slope was positive for groundwater level for all the seasons. Overall, the patterns show that rainfall stimulates an increase in the level of seasonal groundwater and that the groundwater level reflects the effect of rainfall.

Linear transfer function model

We conduct the unit root test to check the variables—monthly rainfall and groundwater level—for stationarity. The Dickey–Fuller test and the KPSS test statistics (p-value at significance level at alpha=0.05) prove that both monthly rainfall and groundwater level have stationarity. To identify the time series model structure, we conducted autocorrelation and partial autocorrelation analyses on the level of rainfall and groundwater. As estimated, the autocorrelation function plot shows that the monthly rainfall and water level data have significant autocorrelation due to seasonality.

Table 5 Mann–Kendall trend test and Sen's slope—summer

Particulars	Rainfall	Groundwater level
Kendall's tau	0.022	0.333
S value	1.000	12.000
Var(S)	125.000	92.000
p-value	1.000	0.251
Sen's slope	1.014	0.608

The time delay of the influence of the monthly rainfall on the monthly average groundwater level is considered, and the linear transfer function model is employed for the number of times with different numbers of the parameters of the respective models. The cross-correlation between rainfall and groundwater level data is significant, and the time delay parameter k was fixed as zero ($k = 0$) in the linear transfer function model for order fixation.

The time delay of the influence of the monthly rainfall on the monthly average groundwater level is considered, and the linear transfer function model is employed for the number of times with different numbers of the parameters of the respective models. The order for autoregression and moving average for transfer function model is assigned as numerator and denominator and the model is estimated. The results of the various models of the monthly average groundwater levels using monthly rainfall are given in Table 6.

The construction of each model is indicated by orders of autoregressive (r) and moving average (s) and time delay (k) of the model denoted as r- s -k.

The developed transfer function models were evaluated by means of specified statistics: R-squared (high R^2), root mean square error (low RMSE), mean absolute percent error (low MAPE), and Bayesian information criteria (low BIC). These criteria are desirable for the adequacy of a model.

Table 6 shows only nine comparatively well-performed models; the table depicts that the model with $r=1$, $s=2$ and $k=0$ process has the maximum number of lowest values of all the selected criteria RMSE, MAPE, BIC with the highest coefficient of determination R^2. Hence, the ARMAX (1,2,0) model is selected and validated with respective R^2 for forecasting the data series.

The results from the linear model reliably specify that the impact of rainfall in the last two months starting from a given month affected the monthly average groundwater level, which led to the recharge of the dynamic groundwater in the district in that period. This result is in line with the finding in Mohanasundaram

Table 6 Selection of ARIMA models

Model selection criterion/r-s-k	1 1 0	1 2 0	1 3 0	2 1 0	2 2 0	2 3 0	3 1 0	3 2 0	3 3 0
R-squared	0.810	0.819	0.814	0.810	0.818	0.802	0.814	0.818	0.804
RMSE	1.331	1.348	1.357	1.349	1.338	1.344	1.359	1.357	1.313
MAPE	8.271	8.239	8.385	8.245	8.441	8.263	8.574	8.415	8.244
Normalized BIC	1.026	0.902	1.138	1.027	1.105	1.214	1.140	1.233	1.264

et al. (2017), which use transfer function models to develop a statistical relationship between monthly rainfall and groundwater levels in the Adyar River basin in Chennai.

Pre-whitened rainfall and water levels were correlated, and a lag of one month was observed between rainfall and groundwater levels. The impacts of declining monthly rainfall in the north-west monsoon (October to December) are possibly being reflected in the increasing trend of monthly average groundwater levels in the winter (December to February). By the same token, the observations from model simulation studies also substantiate the observations from the Mann–Kendall test statistic and Sen's slope estimator—an increase in the rainfall induces the availability of groundwater in all seasons.

Conclusions

The periodical fluctuations in rainfall and groundwater level in Namakkal district of Tamil Nadu were statistically discovered and the relationship between these two variables established by their time series data. The Mann–Kendall test performed on the time series data of seasonal rainfall and groundwater levels in the district showed an increasing trend during the 2009–2018 period. The positive Sen's slope also represented the increasing trend of rainfall in the south-west monsoon and winter; in the north-east monsoon, a decreasing trend (negative Sen's slope) was observed. The Sen's slope and Kendall tau statistic show a negative trend in the north-east monsoon.

In the case of the groundwater level, an increasing trend is seen in all the four seasons. The rising trend of rainfall is robust, by a relatively steep slope of the best-fit line, and it raised groundwater availability significantly. The patterns show that rainfall stimulates an increase in the level of seasonal groundwater and that the groundwater level reflects the effect of rainfall. Although the time delay of the influence of monthly rainfall on monthly average groundwater level is considered, the linear transfer function model is employed for the number of times with different parameters of the models.

The developed transfer function models were evaluated by the means of specified statistics: R-squared (High R^2), root mean square error (low RMSE), mean absolute percent error (low MAPE), and Bayesian information criteria (low BIC). These criteria are desirable for the adequacy of a model. Among the nine well-performed models, the model with the r=1, s =2 and k=0 process has the maximum number of lowest values of all the selected criteria RMSE, MAPE, BIC with highest coefficient of determination R^2. This model is selected and validated with respective R^2 for forecasting the data series.

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