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Hydrological modeling of Upper Ribb watershed, Abbay Basin, Ethiopia

Andualem T.G.[1], Guadie A.[1], Belay G.[1], Ahmad I.[1] and Dar M.A.[2,3*]
[1]Department of Hydraulic and Water Resources Engineering, Debre Tabor University, Debre Tabor, Ethiopia
[2]Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[3]Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam
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*to whom all correspondence should be addressed: e-mail: mithas.ahmad@tdtu.edu.vn
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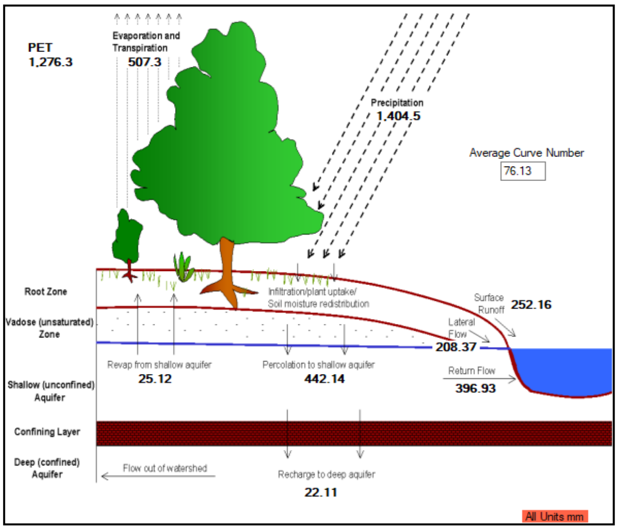
Graphical abstract



Abstract

Hydrological modeling of a watershed is necessary for water resources planning and management. The hydrology of Upper Ribb watershed has been analyzed using spatially semi-distributed Soil and water assessment tool (SWAT) model. This study aimed to determine the water balance components and its relation to the rainfall which reaches to the surface of the earth. Different spatio-temporal (land use, soil, digital elevation model, climate data, river discharge) data were used for hydrological modelling of Upper Ribb watershed. The applicability of SWAT model in Upper Ribb watershed has been evaluated using coefficient of determination (R^2) and Nash Sutcliff efficiency (NSE) parameters. The calibration results revealed the observed data showed a very good agreement with the simulated data with the R^2 and NSE values of 0.90 and 0.84 respectively. Similarly, the validation results of streamflow were acceptable with the R^2 and NSE values of 0.80 and 0.82 respectively. The monthly average streamflow from Upper Ribb watershed were found 13.39 m^3/s. The major portion of the rainfall contributes to the surface runoff due to the major percentage of the watershed is covered with agricultural lands. The groundwater flow was high in forested areas, while evapotranspiration was found very high in water bodies (Ribb reservoir). In this study area the rainfall showed a direct relationship with the streamflow. The ratio of streamflow and evapotranspiration with rainfall was 0.61 and 0.36 respectively. Due to the presence of high amount of surface runoff and evapotranspiration the deep recharge which contributes to the ground water is not that much significant.

Keywords: Runoff, water balance, SWAT, Upper Ribb watershed.

1. Introduction

Hydrological studies are essential for water resources management. Hydrological modelling could be done by using different hydrological models (Moradkhani and Sorooshian, 2009; Hromadka, 1990; Devia *et al.*, 2015). Malago *et al.* (2015) tried to identify the hydrological process with the spatial and temporal calibration of model input parameters.

Hydrological models are used to simulate basin/catchment scale water resources (Jones *et al.*, 2006; Kebede *et al.*, 2006). Precipitation is one of the major components for hydrological modeling of a certain catchment (Blöschl and Sivapalan, 1995). The other water balance components have been derived from the precipitation data used for analysis (Kirchner, 2009).

A process based, semi-distributed and continuous SWAT model have been adopted for hydrological modeling of catchments (Krysanova and Arnold, 2008; Setegn *et al.*, 2008; Setegn *et al.*, 2010; Yesuf *et al.*, 2015; Andualem and Bogale, 2015; Gebrie and Jemberie, 2016; Demeke and Andualem, 2018). SWAT model is one of the widely adopted river basin model giving a continuous temporal and spatial results of the hydrological components of the basin (Gassman *et al.*, 2014; Arnold *et al.*, 1998; Neitsch *et al.*, 2004; 2005; Gassman *et al.*, 2007). SWAT model provides annual, monthly and daily streamflow results which is very essential to compare the water balance components viz. precipitation, evaporation, groundwater flow, subsurface flow, baseflow and surface runoff.

Now a day's climate change became a major factor in the extreme rainfall events occurred in the world (Gentilucci *et al.*, 2019). Most of the developing countries found in Africa such as Ethiopia are more prone to the effects of extreme rainfall events. The different climatic variations (Gentilucci *et al.*, 2018) are resulting extreme weather events which are further producing high environmental problems such as flooding in the downstream areas' and drought in the upstream. The climate change effects are having major impacts in the country's agricultural productivity, socio-economic development and social welfare. In Ribb watershed especially in the downstream parts of the study area extreme rainfall events are reducing agricultural productivity and displacing the peoples living in the area. Therefore, studying the water balance of the area considering the different climatic variables (Figure 1). The evaluation of climate change and its effects on water resources have been studied by using SWAT model (Krysanova and Srinivasan, 2014; Legesse *et al.*, 2003).

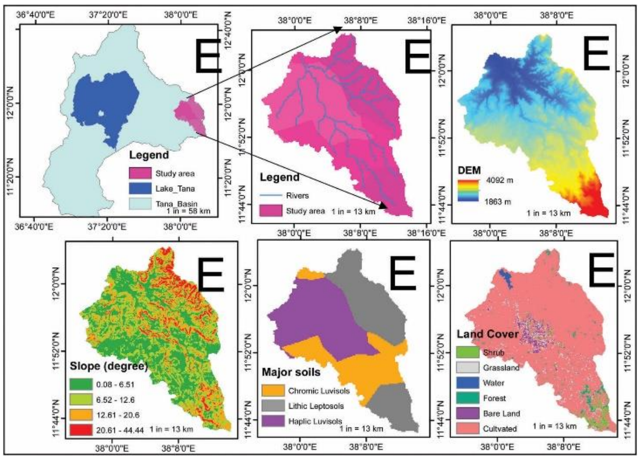


Figure 1. Location of Upper Ribb watershed

Estimating the water budget for Upper Ribb watershed is necessary for effective water resources planning at Ribb Dam which is found at the outlet of this catchment. The dam is constructed for two main purposes viz., flood protection for Fogera flood plain area and to irrigate 20,000 hectrare of land with a reservoir capacity of 238 Mm^3 water. Therefore, an attempt has been made to determine the hydrological components and its interaction with the rainfall it reaches to the surface for sustainable development water resources using a physically based SWAT model.

2. Methodology

2.1. Description of study area

Study area is found in Amhara region, Tana Sub-basin; which is located between $11^0$40' and 12^0 8' N latitude, and $37^0$52' and $38^0$14' E longitude. Upper Rib watershed has an area of 674.14 km^2. The topography of the area ranges between 1851 and 4090 m.a.s.l. This watershed contributes to Rib reservoir which has a storage capacity of 238 Mm^3 for irrigating 20,000 ha of land.

The rainfall in Upper Rib watershed is unimodal type (rainy season from May to September), with the average monthly rainfall varying from 0 mm (January) to 21.53 mm (August). Mean annual precipitation in this study area is 1404.6 mm. The minimum temperature varies between 9.21 °C (in December) and 14.65 °C (in May). The major soils which are found in the study area are Chromic Luvisols (57.53% coverage), Eutric Leptosols (42.15% coverage) and Eutric Fluvisols (0.17% coverage).

2.2. Model description

Streamflow and sediment yield simulation at a catchment scale has been done by using a physical process-based; SWAT model (Arnold *et al.*, 1998; Neitsch *et al.*, 2005). For the computation of soil yield at the Hydrological Response Unit (HRU) level; Modified Universal Soil Loss Equation (MUSLE) were employed to SWAT model. For detaching and transporting of sediment throughout the contributing catchment the model used runoff energy (Williams and Berndt, 1977). Routing of sediment in the channels consists channel degradation using stream power and deposition of sediment in the channel using fall velocity (Arnold *et al.*, 1995; Smith and Williams, 1980).

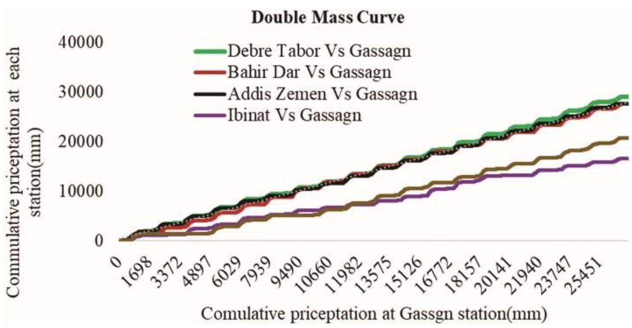


Figure 2. Double mass curve

2.3. Model input and data analysis

SWAT model is a data intensive model which requires meteorological data (precipitation, minimum and maximum temperature, relative humidity, solar radiation, wind speed), soil, land use, topography and hydrological data (river flow and sediment). The required meteorological data required were collected from National Meteorological Agency of Ethiopia. Twenty years (1997–2015) meteorological data of Debre Tabor, Bahir Dar, Addis Zemen, Gassay, Ebinat and Amed Ber stations were used for this study. The consistency and homogeneity of the data were checked by using double mass curve and rainbow respectively after filling the missing data (Figure 2 and 3).

The river daily discharge and sediment concentration data of Upper Ribb river was collected from Ministry of water, irrigation and electricity, hydrology department for Addis Zemen gauging station, Ethiopia.

The digital elevation model (DEM) and soil data having a 30 m resolution was obtained from ministry of water, irrigation and electricity. The land use/cover map of the study area were prepared from downloaded satellite image of the year 2018. The satellite image was classified using

ERDAS Imagine 2014 and the results were verified by using ground truth points (Andualem *et al.*, 2018).

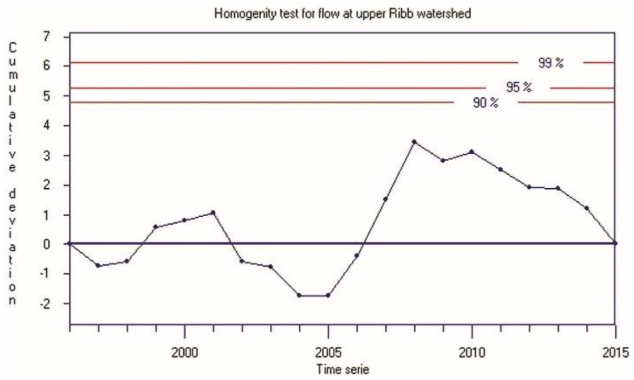


Figure 3. Commutative deviation of annual streamflow at Addis Zemen gauging station

Watershed delineation, HRUs, weather write up, sensitivity analysis, calibration and validation of streamflow and sediment yield had been done using SWAT model. HRUs were developed using land use, soil and slope with threshold levels of 10%, 10%, and 10% respectively. Sensitivity analysis of streamflow and sediment parameters were done for identifying the parameters used for calibration of the model results. The period from 1998 to 2009 was used as a calibration period considering one-year warmup period (1997). After calibrating and getting acceptable results the model was validated (Bitew *et al.*, 2012; Gassman *et al.*, 2007) for six years period from 2010 to 2015. For this study coefficient of determination (R^2) and the Nash-Sutcliffe efficiency coefficient (NSE) (Krause *et al.*, 2005) were used for checking the performance of the model. The values of R^2 and NSE were calculated using equations 1 and 2 respectively.

$$R^2 = \frac{\left(\sum_{i=1}^{n}(Oi-\bar{O})*(Pi-\bar{P})\right)^2}{\left(\sum_{i=1}^{n}(Oi-\bar{O})*\sum_{i=1}^{n}(Pi-\bar{P})\right)^2} \quad (1)$$

$$NSE = \frac{\left(\sum_{i=1}^{n}(Oi-\bar{O})-\sum_{i=1}^{n}(Pi-\bar{P})\right)^2}{\sum_{i=1}^{n}(Oi-\bar{O})^2} \quad (2)$$

Where: n is the number of observations during the simulation period, Oi and Pi are the observed and predicted values at each comparison point, $\bar{O}$ and $\bar{P}$ are the arithmetic means of the observed and predicted values.

Table 1. Global sensitive flow parameters

Parameter type	Parameter name	T-STAT	P-Value	Sensitivity
HRU	V__ESCO.hru	3.76	0.01	1
	R__SOL_AWC (..).sol	3.55	0.01	2
HRU	V__EPCO.hru	2.55	0.04	3
HRU	R__CN2.mgt	-1.95	0.09	4
Groundwater	V__ALPHA_BF.gw	1.77	0.12	5
Routing	V__CH_N2.rte	1.36	0.21	6
Groundwater	V__GW_DELAY.gw	-1.3	0.24	7
Groundwater	V__GW_REVAP.gw	0.77	0.47	8
Groundwater	V__REVAPMN.gw	0.72	0.49	9
Groundwater	V__GWQMN.gw	0.64	0.54	10
HRU	V__CANMX.hru	0.6	0.56	11
Groundwater	V__RCHRG_DP.gw	-0.49	0.64	12

3. Results and discussion

3.1. Streamflow modeling

3.1.1. Sensitivity analysis

The sensitive and significant streamflow parameters (Table 1) were identified using SWAT CUP (Calibration and uncertainty program) model.

In Upper Ribb watershed ESCO, SOL_AWC and EPCO were found very sensitive flow parameters (Table 1). T-STAT and P-values had been used for evaluating the level of sensitivity and significance of the parameter. Parameters with high absolute T-STAT value considered as highly sensitive and with a P-value close to 0 considered as highly significant.

3.1.2. Streamflow calibration

Calibration was done after identifying the sensitive parameters using Addis Zemen gauging station flow record. The period considered for calibration was from 1998 to 2009; while the first-year simulation (year 1997) were taken as a ‘‘warm up’’ period. The fitted values of streamflow parameters were determined through calibration (Table 2).

The calibration results of streamflow showed a good agreement with R^2 and NSE values of 0.90 and 0.84 respectively (Table 3 and Figure 4). Jemberie *et al.* (2016) showed a similar result at other parts of the basin (Deddissa sub-basin) with R^2 and NSE values of 0.80 and 0.76 respectively. The results of Andualem and Gebremariam (2015) in Gilgel Abay watershed also found a similar result with values of R^2 (0.88) and NSE (0.80). The monthly average streamflow had been found 13.39 m^3/s in the calibration period (Table 3).

Table 2. Calibrated flow parameter values

Parameter name	Fitted value	Minimum value	Maximum value
R__CN2.mgt	0	-0.2	0.2
V__ALPHA_BF.gw	0.5	0	1
V__GW_DELAY.gw	15	0	50
V__GWQMN.gw	1500	0	5000
V__CH_N2.rte	0.9	0	1
V__EPCO.hru	0.7	0	1
V__ESCO.hru	0.5	0	1
V__GW_REVAP.gw	0.074	0.02	0.2
V__REVAPMN.gw	250	0	500
V__RCHRG_DP.gw	0.7	0	1
V__CANMX.hru	3	0	10
R__SOL_AWC.sol	0.9	0	1

Table 3. Monthly average flow and model performance indicators

Land use year	Calibration (1998–2009)				Validation (2010–2015)			
	R^2	NSE	Flow (m^3/s)		R^2	NSE	Flow (m^3/s)	
			Observed	Simulated			Observed	Simulated
2018	0.9	0.84	16.89	13.39	0.8	0.82	12.85	12.66

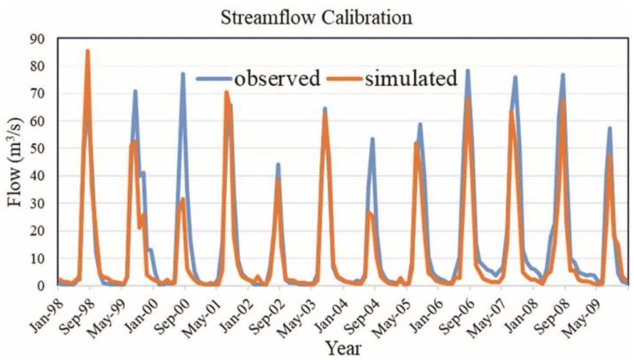


Figure 4. Monthly calibration of flow for 2018 land cover from (1998–2009)

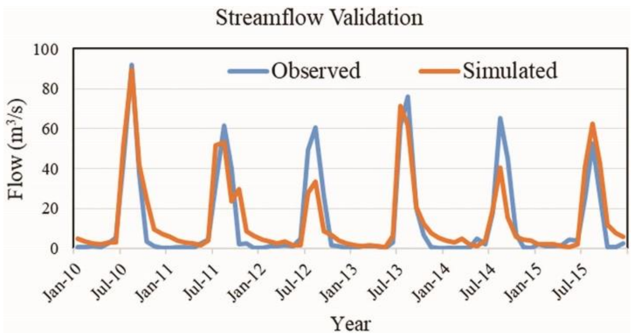


Figure 5. Monthly Validation of flow for 2018 land cover from (2010–2015)

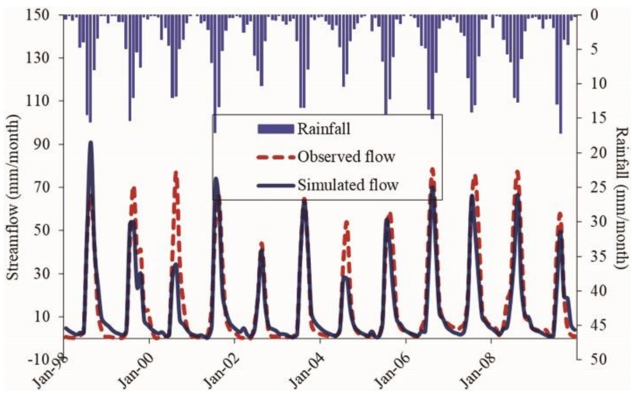


Figure 6. Comparison of observed and simulated monthly flow superimposed with monthly rainfall for the calibration period (1998–2009) for 2018 LULC

3.1.3. Streamflow validation

Streamflow validation has been done for the period between 2010 and 2015 with the calibrated flow parameters without changing their values. The validated results of flow for Upper Ribb watershed had showed good agreement with the observed data recorded at the gauging station with R^2 and NSE values of 0.80 and 0.82 respectively (Table 3 and Figure 5). As it had seen from Table 3; all R^2 and NSE values are greater than 0.8 (closer to 1). Therefore, the model had good performance which could be applicable in the study watershed.

3.2. Rainfall-runoff relationship

The relationship between the recorded rainfall, runoff and sediment yield in the Upper Ribb watershed has been done. Rainfall has showed a direct relationship with runoff; when the rainfall has increased the runoff also increased. During dry season the runoff has been decreased with the rainfall (Figure 6).

3.3. Water balance analysis

The water balance components of Upper Ribb watershed was determined from the spatially semi-distributed model results. The major components which are found in Upper Ribb watershed were precipitation, surface runoff, lateral flow, deep recharge and evapotranspiration.

The hydrological cycle components of Upper Ribb watershed has been presented in Figure 7. The major components of the hydrologic cycle in Upper Ribb watershed were evapotranspiration (507 mm), rainfall (1404.5 mm), surface runoff and lateral flow.

The results of this study revealed that high groundwater contribution has been found in forest areas followed by grassland while high amount of evapotranspiration was found in water bodies. On the other hand, high amount of surface runoff was found in agriculture lands (Table 4).

Table 4. Relation between water balance components and land cover

Land cover	Area (km^2)	AWC (mm)	Surface runoff (mm)	Groundwater (mm)	ET (mm)
Grassland	33.97	140.58	199.70	624.40	535.34
Water	5.41	182.60	0	0	1773.97
Forest	12.29	112.01	138.16	740.62	490.37
Agriculture	622.44	134.19	259.48	606.83	495.13

Table 5. Monthly average water balance components

Month	Rainfall (mm)	Surface runoff (mm)	Lateral flow (mm)	Water yield (mm)	Evapotranspiration (mm)	Potential evapotranspiration (mm)
January	10.65	0.24	0.42	7.06	15.97	91.38
February	8.79	0.55	0.31	2.46	16.00	95.17
March	45.96	2.53	1.94	5.64	63.05	107.69
April	44.47	0.88	2.30	4.03	60.43	113.63
May	85.32	7.11	7.11	15.22	46.50	101.40
June	141.77	14.83	14.08	31.9	40.94	90.58
July	410.26	95.24	64.59	187.63	58.81	77.53
August	396.22	92.33	72.20	261.55	63.72	81.01
September	146.62	21.86	30.85	171.50	54.25	88.50
October	68.31	11.79	10.01	111.19	38.34	95.04
November	38.04	4.73	3.85	58.25	26.90	83.46
December	8.06	0.07	0.70	23.15	22.29	250.15
Annual	**1404.47**	**252.16**	**208.36**	**879.58**	**507.2**	**1275.54**

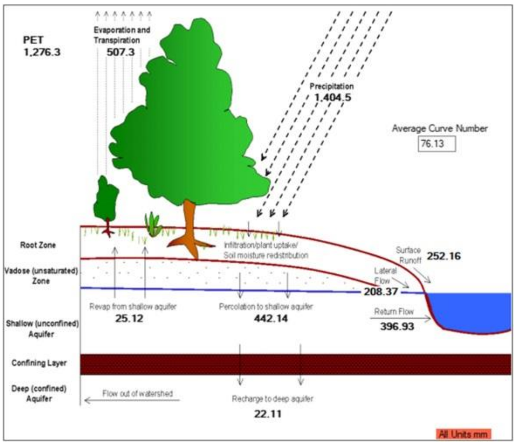


Figure 7. Schematic representation of hydrological components of Upper Ribb watershed

The monthly average and annual water balance components showed that rainfall has a direct relationship with each of the water balance components. From the annual rainfall value of 1404.47 mm about 507.2 mm and 252.16 mm water goes as evapotranspiration and surface runoff respectively (Table 5 and Figure 8).

As shown in Table 6 about 36% of the precipitation goes as evapotranspiration and only about 31% and 2% of rainfall contributes to groundwater as percolation to the soil and deep recharge respectively. The ratio between total flow, and baseflow and surface runoff also computed in Upper Ribb watershed (Table 6). SWAT had shown good capability of analyzing and detecting of the different water balance components. The water supply components were derived from the different climatic variables as one of the inputs for SWAT model. Therefore, SWAT model has a strong relationship between climate change and climatic variables.

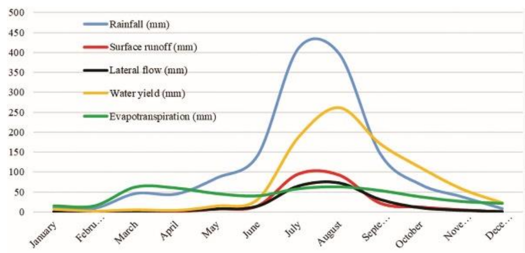


Figure 8. Water balance components of Upper Ribb

Table 6. Ratio between water balance components

Component	Baseflow/TF	SURQ/TF	Streamflow/RF	Percolation/RF	Deep recharge/RF	ET/RF
Ratio	0.71	0.29	0.61	0.31	0.02	0.36

SURQ = Surface runoff, ET = Evapotranspiration, RF = Rainfall, TF = Total Flow

4. Conclusion

During this study the hydrological parameters of Upper Ribb was determined using spatially semi-distributed SWAT model. Coefficient of determination, R^2 and the Nash-Sutcliffe efficiency, NSE had been used to measure the performance of the model. The statistical analysis of calibration results of the model at Upper Ribb watershed showed very good agreement between observed and simulated monthly values of streamflow. SWAT model has a great importance to evaluate the streamflow and/or runoff potential of the basin. SWAT had also a capability of detecting climate change effect on water balance components and other weather parameters. The monthly average streamflow from Upper Ribb watershed were found 13.39 m^3/s. The major portion of the rainfall were surface runoff due to large area was covered with agricultural lands. The evapotranspiration from rainfall was about 36% which is a significant loss. Due to the presence of high amount of surface runoff and evapotranspiration the deep recharge which contributes to the ground water is not that much significant. The rainfall showed a direct relationship with water yield and surface runoff.

Conflicts of interest

There is no conflict of interest between authors.

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