Analyzing the Temporal Variation of Groundwater Level in Attanagalu Oya Basin Using Numerical Models

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Abstract

Scarcity for drinking water becomes one of the enormous threats around the world due to the increase in population, climatic fluctuation and pollution. Sri Lanka is considered as a country with little or no water scarcity when reckoning the whole country as one unit. However, several local regions have been identified with temporal water scarcity. Attanagalu Oya basin which covers almost the entire Gampaha district is a major hydrologic feature in determining the groundwater characteristics of the region. In this study, the temporal groundwater variation of the Attanagalu Oya basin was quantitatively analyzed. Using the data obtained from data loggers and field surveys, a numerical model for the groundwater in the basin was designed by using two software modelling approaches, a self-written Fortran code and Visual MODFLOW by USGS. Fortran code is mainly used for runoff modelling and Visual MODFLOW is for subsurface modelling. The quantitative variation obtained from the model was then examined temporally and spatially to correlate the upstream to downstream flow and monsoonal recharging impacts. The possible reasons for the observed deterioration and variations in the groundwater quantity can be contemplated as keys to providing recommendations for sustainable management of the groundwater resources in the basin.

Keywords: Fortran, Hydrologic feature, Quantity, Scarcity, Runoff, MODFLOW.

1. Introduction

Water is one of the most important natural resources which is essential for the existence of all living beings. Groundwater is the water that exists mainly in subsurface pore spaces at the zone of saturation. Groundwater resources are mainly recharged by precipitation (rainfall).

Sri Lanka is an island located near the southern tip of India, with a mainland area of 65,610 km^2.

Rainfall in Sri Lanka has multiple origins with monsoonal, convectional and expressional sources, while monsoonal rain accounts for a major share of the annual rainfall [1]. According to the rainfall pattern, Sri Lanka is divided into three zones as wet zone, dry zone and intermediate zone.

Groundwater is the primary source of domestic water supply in Sri Lanka. About 80 % of the island's rural drinking water comes from residential open dug wells and tube wells [2]

Gampaha district is having the second most population in Sri Lanka and due to the rapid urbanization and industrialization, the need for the water is ultimately increasing there.

As Attanagalu Oya Basin is the only major source in that region, it fulfils the most water demands including agriculture, domestics and industries. The primary problem associated with the Attanagalu Oya basin is the deterioration of the water quantity and quality due to excessive consumption by domestic, agricultural and industrial sectors. Uncontrolled disposal of industrial effluents (both solid and liquid) and use of agro-chemicals are observed as the main causes for the impairment of water quality in the basin.

Groundwater systems that are affected by natural processes and human activities, must require an appropriate targeted management execution to maintain the condition of groundwater resources within acceptable limits, while providing desired economic and social benefits [3].

Groundwater modelling has been the most commonly used tool for decision-making processes involved in groundwater management policies and thereby, aids the determination and mitigation of such adverse effects beforehand successfully. Groundwater models provide additional insight into the complex system behaviour (when appropriately designed) and can assist in developing conceptual understanding [4]. Hydrological modelling and forecasting are carried out to perform a proper water resource management to predict water related issues and to overcome them.

At present, there is an inadequacy of data for policymaking and groundwater management of Attanagalu Oya basin to mitigate seasonal scarcities of groundwater. Even though, there are plenty of qualitative research projects carried out to study mainly the groundwater deterioration of the region, still, the quantitative studies are lacking. This research is mainly intended to develop a regional scale quantitative groundwater model, through which, the regions with temporally varying stress levels of groundwater scarcities can be identified and to assist in making an appropriate management plan for groundwater resources.

2. Methodology

2.1 Study Area

The Attanagalu Oya Basin is situated in the Gampaha district in Western Province of Sri Lanka, between two major river basins, Kelani and Maha Oya. It has an extent of 727 km^2. The main river drains from east to west, directly towards Negombo Lagoon. The river's source is at 40 miles from the sea at an elevation of about 400 feet above the mean sea level. Northeast monsoon provides 26% and Southwest monsoon provides 30% of the annual rainfall. Intermonsoons also considerably contribute for the rest.

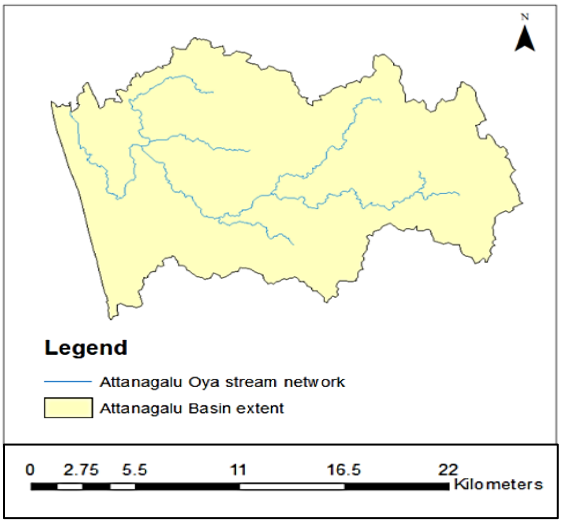

Figure 1: Study location

Dominant portion of the Attanagalu Oya basin falls within the wet zone, with an annual rainfall of 2000 - 2600 milliliters occurring during two monsoonal periods. The temperature ranges from 23 – 31 ^{o}C and the Relative humidity is, on average, 73% during the daytime and 90% at night.

2.2 Project progressive flow

The flow of the concept was planned to be constructed under five main focuses as depicted in Figure 2.

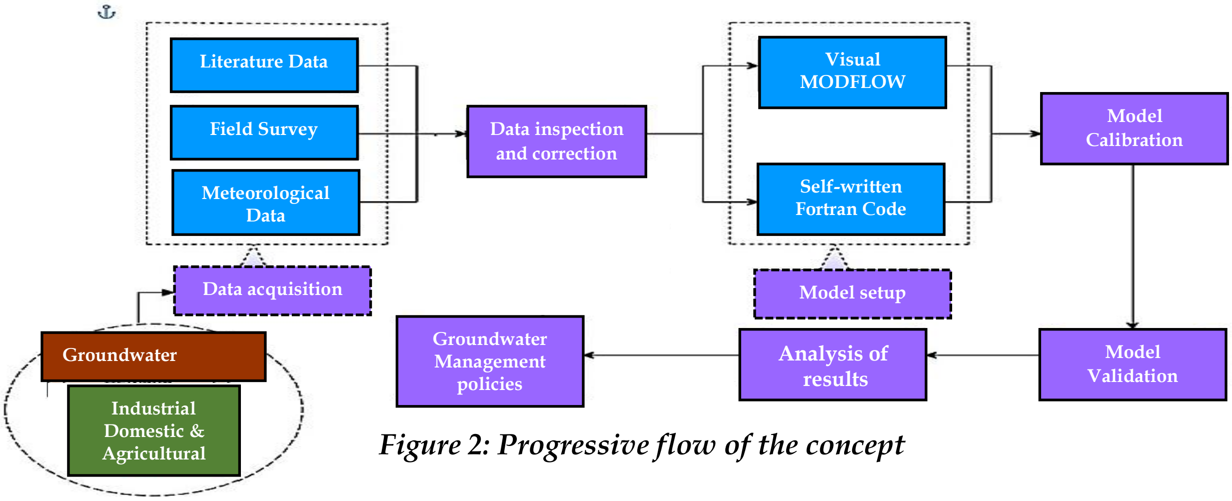

Figure 2: Progressive flow of the concept

1. Data Acquisition
2. Model Setup
3. Model calibration and validation
4. Model applications and analysis
5. Development of Groundwater Management policies

2.2.1 Data Acquisition

Data were collected as per the requirements from the Meteorological department, Field surveys and Literature studies related to Sri Lankan Hydrogeology as shown in Table 1. Also, field surveys were conducted at the locations indicated in Figure - 3 below.

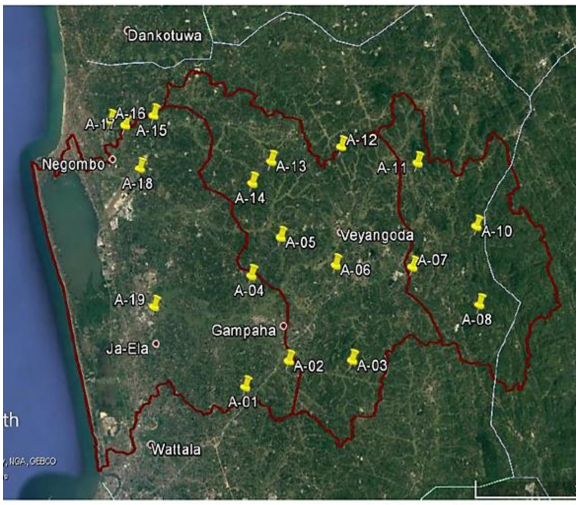

Figure 3: Field survey locations

2.2.2 Model Setup

The concept of model setup has following components.

1. Surface Runoff modelling
2. Subsurface modelling

Table 1: Input data sets for the modelling

Required Data	Source(s)
Daily Rainfall data (2013-2018)	Meteorological Department
Daily minimum and maximum temperature data (2013-2018)	Meteorological Department
Hourly River flow data	Irrigation Department
Catchment boundary and terrain (2 m Resolution)	CRIP Project (Digital Elevation Model)
Observed well heads in the region	Field surveys in consecutive stages
Hydraulic conductivity of soil & aquifer property	Literature
Land use map of the study area	Sentinel 2 satellite images using ArcMap image classification

Surface Runoff Modelling

The present study employed a distributed hydrological runoff model developed by Kashiwa et al. (2010) under the structure proposed by Kazama et al. (2004) for simulating the natural runoff, in which natural hydrological process is included (there is no consideration of irrigation and reservoir control) [5]. In this model, the catchment is divided into land flow planes and channel segments. The hydrological processes considered in this model are precipitation, snowmelt, infiltration, evapotranspiration, surface runoff, groundwater flow and water balance in each layer. In the land, for each grid cell, three layers are considered in the vertical direction: groundwater layer, subsurface layer and the third one to account for the snow melting contribution (not considered in this study). The methodology used for flow estimation includes a direct flow and base flow models.

Direct flow is calculated using kinematic wave concepts which pursues meteoric water runoff using a momentum equation and a continuity equation. With an assumption of a rectangular grid section, the continuity equation can be transformed as follows:

$$\Delta h = \frac{\Delta t}{B\Delta x}(Q_{in} - Q_{out}) + (r - E)\Delta t \qquad (1)$$

Where Δh is the variation of depth, Δt and Δx are time and mesh intervals of flow direction. B is the width of flow path. Q_{in} and Q_{out} are inflow and outflow volume respectively and r and E are precipitation and evapotranspiration respectively.

Hargreaves equation is used to calculate potential evapotranspiration. Base flow is calculated with the storage function method because of its simplicity.

An algorithm, accommodating all the required equations mentioned above was self-written using the Fortran Language. It was also used to modify the input data into appropriate input file formats. Daily rainfall and daily maximum and minimum temperature data were formalized to create binary files of evapotranspiration. The final stage of the Fortran programming was the simulation of a surface runoff model using the binary files of evapotranspiration and precipitation as the primary input files.

In this study, the model uses a grid system with a 1 km spatial resolution and runs in 100 s time steps.

Subsurface Modelling

In the process of establishing a subsurface model, the basic engine used was MODFLOW 2005 powered by United States Geological Survey (USGS). The model setup procedure was done through the third-party software Visual MODFLOW Flex Version 6.1 by Waterloo Hydrogeologic.

In addition to the Meteorological data, following sets of stratigraphic data were acquired to create input files for MODFLOW.

- DEM – Digital Elevation Model o. the region

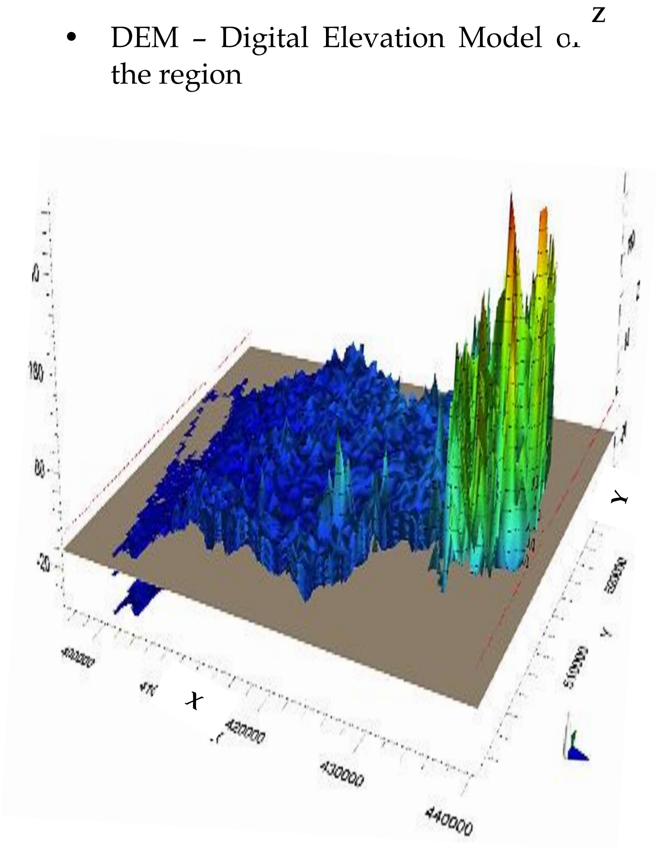

Figure 4: Stratigraphy of the basin

- Topsoil layer
- Sand Layer
- Clay layer
- Weathered Rock and rock layer

2 m resolution Lidar DEM (Digital Elevation Model) of Attanagalu Oya Basin was obtained from the Climate Resilience Improvement Project (CRIP). This datum was highly accurate, but the processing power of the available computers could not handle such high-resolution data, which would ultimately result in a larger number of grids. Therefore, the data were resampled

to 75 m sized cells. The resulting grid covering the entire Attanagalu Oya basin consisted of 421 rows and 614 columns.

In defining the model structure, each of the above layers was categorized into respective horizons together with their physical type. Normally the topsoil which has higher possibility to undergo periodic erosion was categorized as 'Erosional', whereas the bottom-most layer of rocks was the 'Base' of the model. The rest of the layers were verified as 'Conformable' as an option available in the software.

The hydraulic conductivities in the directions of x, y and z, namely Kx, Ky and Kz were also defined to each of the horizons.

Boundary conditions

It is a necessary condition to define at least two boundaries to the model structure. A polyline type data was defined as Head Boundary condition in both upstream and downstream positions. The upstream head boundary was assigned to be 125 m and the downstream head boundary was 15 m based on the wellhead observation surveys carried out.

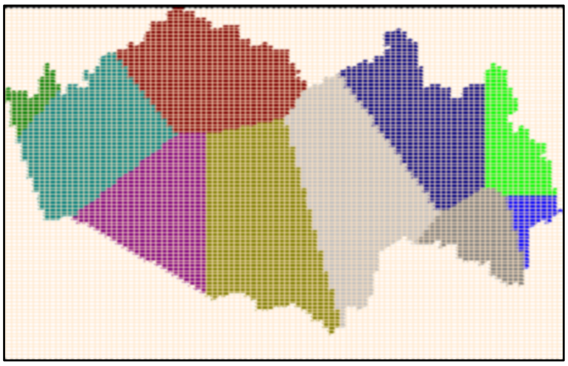

Figure 5: Thiessen Polygon of Recharge

The surface infiltration data were obtained from the surface runoff model. The recharge to the basin has been distributed throughout the basin by creating a Thiessen polygon using ArcMap Software (Figure – 5).

Finite Difference Grid

A finite-difference grid type was selected with 100 rows and 100 columns. The vertical grids were maintained as uniform thickness layers consisting of 10 layers for the entire model domain.

Cell height - 1578.75 m
Cell width - 2302.5 m

Numerical Conversion

Once the basic conceptual modelling was completed, the model was then converted to numerical model.

Since the model runs throughout a considerable period, it is necessary to approach a transient (non-steady) flow. Here, the transient flow for one stress period (365 days) includes 10 Time Steps with a multiplier of 1.2. Running of the numerical engine was the last stage of the subsurface modelling, where the output is created.

3 Results

3.1 Results of Surface Runoff Model

The surface runoff model was created by using the self-written Fortran code. The output files were in binary format, containing direct outflow (RQ), base flow (RKQ) and the depth of direct flow (RH) and depth of base flow (RS) for each day of a particular year. The binary files that were created for each day of every year (from 2013 to 2018) can be visualized using ENVI software.

Annual variation of cumulative rainfall, Evapotranspiration, Infiltration (Recharge) and Surface Runoff as per the obtained output of the runoff model can be depicted as follows.

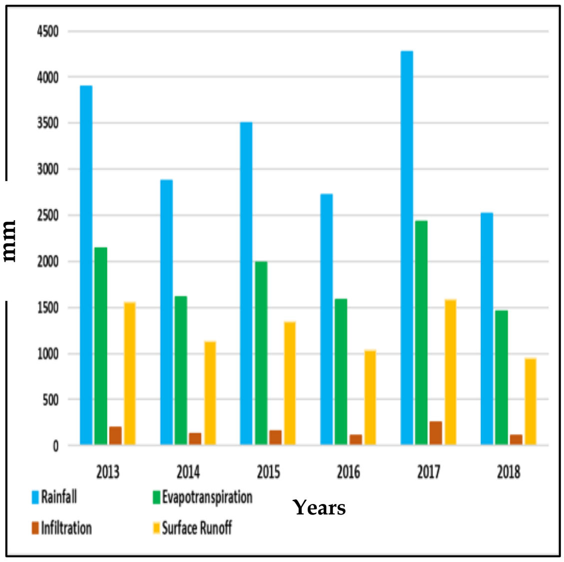

Figure 6: Histogram view of annual cumulative variations

3.1.1 Model Calibration

The simulated results of the model for the outputs of 2013, 2014, 2015, 2016, 2017 and 2018 are calibrated with the observed data available for the year 2015. The calibration results as in Figure – 10, were obtained with the respective statistical degree of closeness values shown below.

Coefficient of determination (R^2) = 0.737421

Nash-Sutcliffe efficiency (E) = 0.553873

The calibrated model can be further analyzed at specific time period to uniquely identify the suitability of the model to be accurately used either to the low flow or to the high flow.

Table 2: Finite Calibration of the Model

Period (Days)	E	R^2
81 – 200	0.594742	-0.08372
250 – 300	0.795863	0.720927
15 – 62	0.219159	0.133645
200 – 235	0.081744	-0.34548

The first two rows of the above table show the water table variations for the periods where the simulated values are higher than the observed values. In the last two periods, the observed values exceed the simulated values. By comparing the R^2 and E values individually, it can be inferred that this model is highly suitable to a low flow scenario (when there are higher simulated values than the observed values).

3.2 Results of Subsurface Model

Water table variations as in Figure - 8 show a smooth increment while moving towards the upstream region. The contour values indicate that the obtained water table values lie within the range of head boundary conditions given to the subsurface model.

It can be clearly seen that the water budget in Figure - 9 falls in the negative numerical range throughout the region. It indicates that quantitatively, there is a higher discharge from the subsurface, exceeding the recharge quantity, causing water stress. The regions in the downstream have a higher negative water budget as compared to the upstream regions.

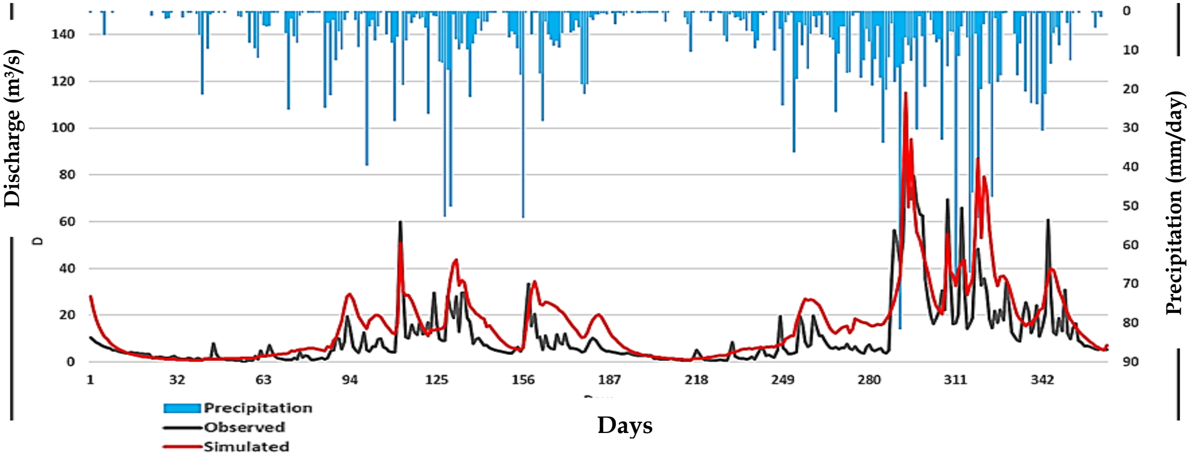

Figure 7: Model Calibration

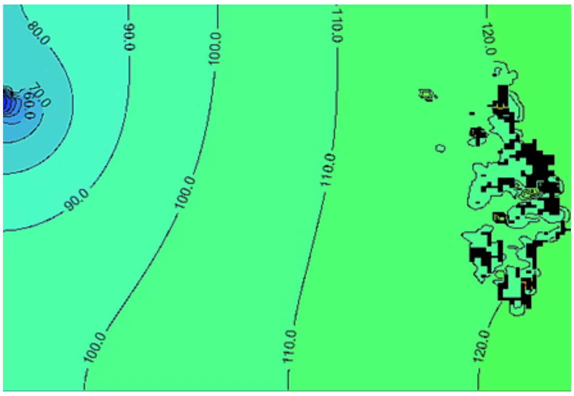

Figure 8: Water table variations

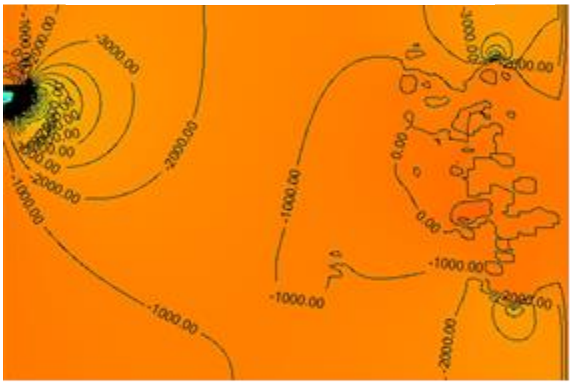

Figure 9: Water budget variations

Drawdown is the reduction in hydraulic head observed at a well in an aquifer, typically due to pumping as a part of an aquifer test or well test. Drawdown is inversely proportional to water budget, and hence the downstream regions with higher negative water budgets have positive drawdowns.

2.2.1 Chart based comparisons

Yearly variations of In – Out as shown in Figure – 10, give the difference between the volumes of periodic recharge and discharge, occurring at each time step throughout the stress period (365 days). It can be clearly seen that in each time step, the In – Out volumes are considerably small, which implies that the total annual recharge is almost the same as that of the total annual discharge in the basin with a percentage of discrepancy 0%.

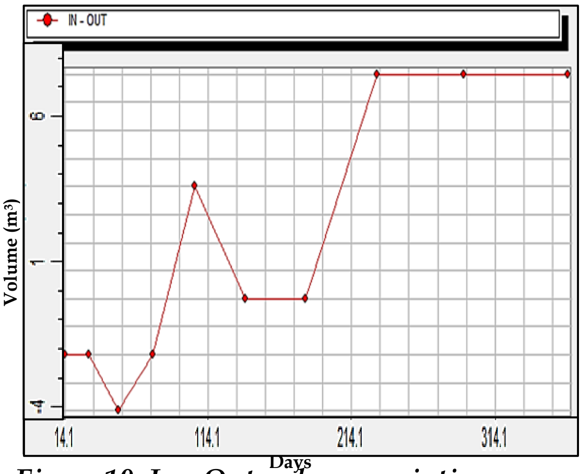

Figure 10: In - Out volume variations

Table 3: Subsurface recharge and discharge volumes

Year	Recharge (R) (m^3)	Discharge (D) (m^3)	R-D (m^3)
2013	130,557,144	130,557,136	8
2014	148,667,040	148,667,040	0
2015	140,226,784	140,226,752	32
2016	128,066,392	128,066,384	8

Furthermore, the annual recharge and discharge volumes of subsurface water for the study period can be tabulated from the subsurface model as in the table below.

3. Discussion

Fortran can be used to model the subsurface water level too. But, the model visualization cannot be done as that available in the Visual MODFLOW. Perhaps, the comparative variations of relative groundwater level can be predicted. Assuming the initial water level be zero on the starting date of the model (01.01.2013), the day-by-day variations of relative groundwater level can be plotted as below in Figure - 11.

In this model, the external pumping data were not considered. Only the natural

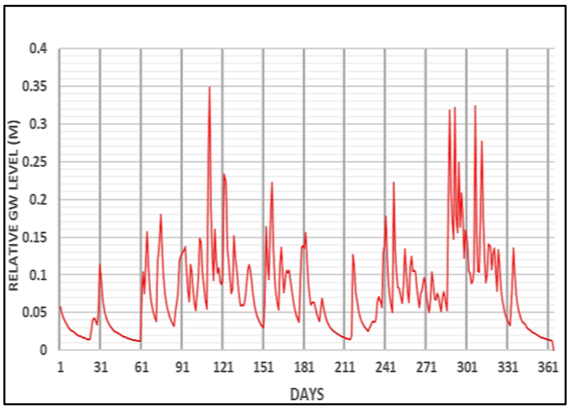

Figure 11: Relative variation of groundwater level

recharge and discharge were considered. It is quite complicated to accurately quantify the daily pumping of water from domestic, industrial, and agricultural wells throughout such a large basin.

An appropriate groundwater management policy can be implemented by carefully studying the model together with the interpretation of the following information.

- Water quality parameters
- Future variation of population density
- Demand for water (Industrial/ Agricultural / Domestic)

Further studies on groundwater modelling of the region should be continued with more field surveys and observation well data to achieve satisfactory levels of valid results.

4. Conclusions

From the surface runoff model obtained using Fortran coding, it can be cognitively concluded that out of the total annual rainfall in the Attanagalu Oya basin, almost 50% of the water goes out as Evaporation and Transpiration. Out of the remaining portion, approximately 40% goes out as surface runoff and only 5-10% of the remaining water infiltrates into the ground. When concerning the subsurface model, the water budget seems to be negative throughout the basin. Most significantly the downstream region has closely packed contour lines with a higher negative phase budget. This shows that the water discharge in the downstream is excessively high since the downstream area is densely populated, highly urbanized and industrialized.

In this model, though, the external pumping data were not taken into account, still, it can be clearly emphasized with reference to the Table - 3, that the groundwater source is eventually declining in the Attanagalu Oya basin because, the cumulative addition of annual pumping quantity of water from the wells would ultimately lead to further depletion of groundwater and thus, it makes sense in the higher negative phase water budget and reduction of the water table in the basin.

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