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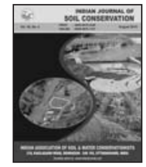

Estimation of natural groundwater recharge using MIKE11 NAM Model

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ABSTRACT

The MIKE11 NAM model is used for the estimation of natural groundwater recharge in the Andhiyarkhore intermediate catchment in Chhattisgarh state. NAM is a part of the rainfall-runoff module of the MIKE11 River modelling system which simulates the rainfall-runoff processes occurring at the catchment scale. Thirteen years data (1995 to 2007) of rainfall, runoff and evaporation are used for modeling. The correlation coefficient for the calibration period was 0.71 and Nash-Sutcliffe coefficient was 0.5 and the total water balance error during the calibration was 0.3% which is very less, which indicates a good match and the developed model is performing well to simulate the runoff. This calibrated model can be used for estimation of runoff and groundwater recharge for the future years or for gap filling in the runoff time series and also estimation of groundwater recharge during previous years.

1. INTRODUCTION

Groundwater is the part of precipitation that seeps down through the soil until it reaches rock material that is saturated with water (USGS, 2013). Water in the ground is stored in the spaces between rock particles. Groundwater slowly moves underground, generally at a downward angle (because of gravity), and may eventually seep into streams, lakes, and oceans. Water movement in aquifers is highly dependent on the permeability of the aquifer material. Permeable material contain interconnected cracks or spaces that are both numerous enough and large enough to allow water to move freely. In some permeable materials groundwater may move several meters in a day; in other places, it moves only a few centimeters in a century. Groundwater moves very slowly through relatively impermeable materials such as clay and shale (USGS).

Groundwater recharge is a hydrologic process where water moves downward from surface water to groundwater. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface (Wikipedia, 2013). Recharge occurs both naturally (through the water cycle) and through anthropogenic processes (*i.e.,* artificial groundwater recharge), where rainwater and stash or reclaimed water is routed to the subsurface. Alternatively, groundwater recharge may be expressed as the process whereby the amount of water present in or flowing through the interstices of the sub-soil increases by natural or artificial means. Groundwater recharge is the component of infiltration into the subsurface that joins groundwater through unsaturated zone, the river bed or lake ground (Seiler and Gat, 2007). The principal source for replenishment of moisture in the soil water system and recharge of ground water is rainfall. Other sources include recharge from rivers, streams, canals, irrigation water, *etc.* The natural groundwater recharge is the recharge through rainfall infiltration and/or rivers, streams, *etc.* On the other hand, artificial recharge is the recharge through artificial means like tanks, wells, pits, shafts, *etc.* Groundwater recharge maintains the supply of freshwater to wells, streams, springs and wetlands, which support the humans, plants and animals that are part of the ecosystem.

A detailed review has been carried out on the estimation of groundwater recharge. The chloride tracers and Soil Moisture Deficit (SMD) method both were used for the estimation of groundwater recharge in Zimbabwe (semi-arid climate) and it was concluded that the amount of recharge depends upon rainfall, vegetation and soil type;

and the timing of recharge corresponds to the heaviest rainfalls of monsoons when rates of incoming precipitation (400 mm yr^{-1}) temporarily exceed the intense evapotranspirative flux (Houston, 1990). Using neutron probe measurements and saturated volume fluctuation (groundwater fluctuation) methods the groundwater recharge in the semi-arid Karoo aquifers of South Africa was estimated (Van Tonder and Kirchner, 1990). Taylor and Howard (1999) carried out a study of the impacts of tectonic setting on the hydrological characteristics of deeply weathered terrains in Uganda (equatorial tropical climate) using groundwater recharge estimates from SMD and stable isotope tracer methods. The groundwater recharge in semi-arid Niger was estimated by using an isotope tracer method and the study revealed that the unexpected groundwater level rise (in spite of the severe droughts of the 1970s and 1980s) in the Continental Terminal in southwest of Niger may be explained by a change in land-use. During 1950s and 1960s the recharge in the study area was 5 mm yr^{-1} and increased to 20 mm yr^{-1} since 1990 (Leduc *et al.*, 2001).

The groundwater recharge in northern Nigeria was estimated by using chloride mass balance method at the plot scale, and then extrapolated the groundwater recharge results to a regional scale. The estimated groundwater recharge was to vary from 14 - 49 mm yr^{-1} based on the point-source data in northern Nigeria (Edmunds *et al.*, 2002). In Ching-Shui Watershed in Taiwan the groundwater recharge was estimated by using water balance model. The area of ChingShui watershed is about 421.4 km^2, and the length of the river is about 47 km. The annual rainfall in this area is around 2100 mm, and 78% occurs from April to October. The coefficients of groundwater recharge by precipitation in the ChingShui watershed estimated from established soil moisture budget model and base flow model were 12.40 and 9.92%, respectively (Yeh *et al.*, 2005). A surface water balance model was developed to estimate groundwater recharge by using commonly available geographic information system (GIS) data layers in combination with tabular climatological data. This model was based on the modified Thornthwaite-Mather soil-water-balance approach, with components of the soil water balance calculated at a daily time-step. Recharge calculations were made on a rectangular grid of computational elements that may be easily imported into a regional groundwater-flow model (Westenbroek *et al.,* 2010). Engott (2011) used soil-moisture budget model to estimate the spatial distribution of groundwater recharge on the Island of Hawaii. This study is supposed to produce the best available estimation of the spatial distribution of groundwater recharge on the Big Island and aid responsible parties and agencies in making informations about water-resources decisions and policies.

2. MATERIALS AND METHODS

Study Area

The Andhiyarkhore intermediate basin falls in the Chhattisgarh state. The basin extends between $21^{0}45^{'}33^{''}$ and $22^{0}30^{'}16^{''}$ N latitude and $81^{0}01^{'}57^{''}$ and $81^{0}37^{'}39^{''}$ E longitude (Fig. 1). This basin covers an area of 2005.56 km^2. The basin falls in three districts, namely, Kawardha, Durg and Bilaspur. The basin area of 1664.71 km^2 falls in Kawardha district, 340.73 km^2 in Durg district and 0.229 km^2 in Bilaspur district. The largest part of the study area is used for agriculture (1015 km^2) which is about 50.61% of the total basin area. The wasteland is the second most dominant land use/land cover in the study area covering an area of 490.86 km^2. The area covered by the settlement is 205.09 km^2, forest occupies an area of 289.58 km^2, and the water bodies cover the area of 4.84 km^2 of the basin. There are five rain gauge stations in the basin, namely, Pandariya, Mungeli, Kawardha, Saroda and Bemtara. The most of the rain occurs during the monsoon season that is June to September. The Pandariya rain gauge station covers maximum area (948.11 km^2). The second largest thiessen's polygon area is 602.28 km^2 for Kawardha rain gauge station. Bemtara rain gauge station has the area of 275.66 km^2 while the Saroda rain gauge station has an area of 114.44 km^2. Mungeli rain gauge station has the minimum area of thiessen's polygon that is 63.80 km^2 (Fig. 2).

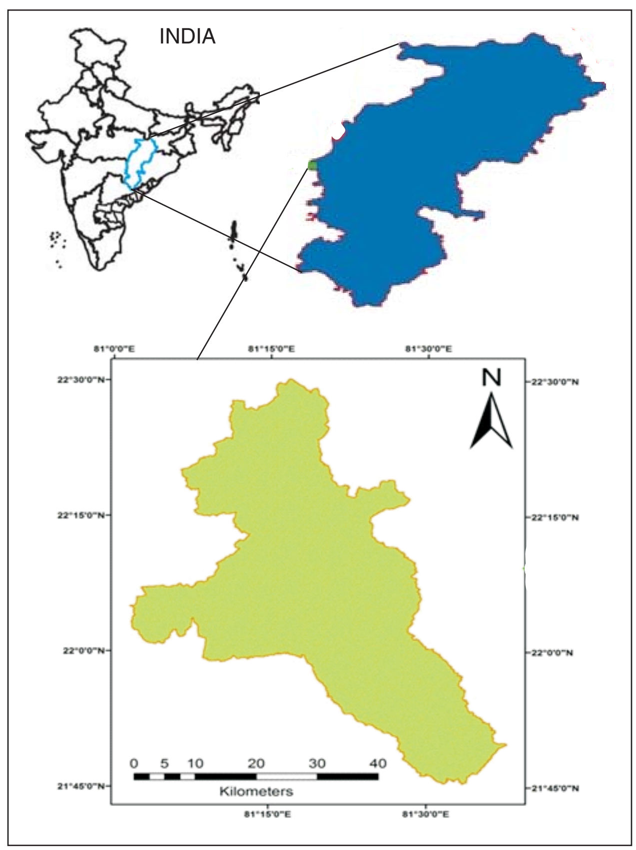

Fig. 1. Index map of the Andhiyarkhore intermediate catchment

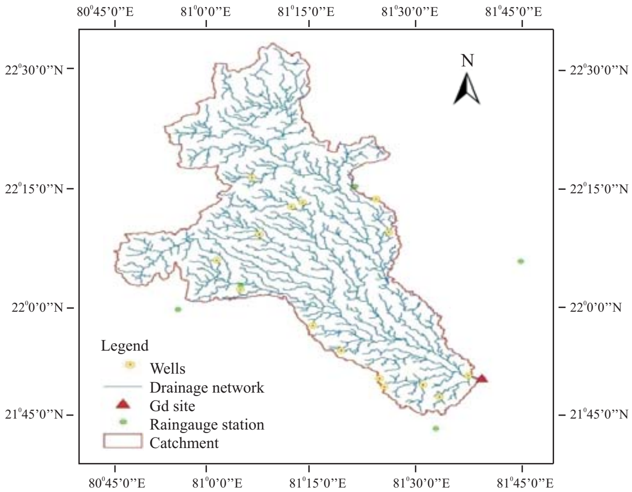

Fig. 2. Map showing raingauge stations, gauge-discharge sites, wells and drainage network

Rainfall-Runoff Model (MIKE 11 NAM)

"Nedbor Afstromnings Model" (NAM) is a part of the rainfall-runoff module of the MIKE11 River modelling system which simulates the rainfall-runoff processes occurring at the catchment scale. NAM model simulates the runoff and the results are obtained in a water balance form. The basic data input requirements for the NAM/MIKE 11 rainfall-runoff (RR) model are, meteorological data, stream flow data for the model calibration and verification, definition of the catchment parameters, and definition of the initial conditions. The basic meteorological data requirements are precipitation time-series, potential evapotranspiration time-series, temperature and radiation time-series if snow accumulation and melt is to be modelled. This can either be applied independently or used to represent one or more contributing catchments that generate lateral inflows to a river network. In this manner it is possible to treat a single catchment or a large river basin containing numerous catchments and a complex network of rivers and channels within the same modelling framework. NAM model simulates the runoff and the results are obtained in a water balance form. It also gives the total groundwater recharge taking place in the basin. Based on the meteorological input data, NAM produces catchment runoff as well as information about other elements of the land phase of the hydrological cycle, such as the temporal variation of the evapotranspiration, soil moisture content, groundwater recharge and groundwater levels. The resulting catchment runoff is split conceptually into overland flow, interflow and base flow. The basic data input requirements for the NAM/MIKE 11 Rainfall Runoff (RR) model are, meteorological data, stream flow data for the model calibration and verification, definition of the catchment parameters, and definition of the initial conditions. The basic meteorological data requirements are precipitation time-series, potential evapotranspiration time-series, temperature and radiation time-series if snow accumulation and melt is to be modelled.

NAM module of MIKE11was used to estimate all the basin water balance components *i.e.,* runoff, actual evapotranspiration, and groundwater recharge. There is no minimum time limit to run the model, however, one monsoon season data will be sufficient to run the NAM model. As the model requires so many parameters so its calibration is quite difficult.

For this purpose, thirteen years (1995 to 2007) data of rainfall, evaporation and runoff are used. The rainfall of Kawardha, Mungeli, Saroda, Bemtara and Pandariya stations are used. The observed runoff data of Andhiyarkhore gauging site is used for the comparison of results. The catchment area of 2005.56 km^2 was assigned to the model. The total data period of 13 years was divided into two parts *i.e.,* 1995 to 2003 for the calibration and 2004 to 2007 for the validation purpose. The details of the parameters used in the calibration of the model are given in Table 1.

3. RESULTS AND DISCUSSION

Model Calibration

The model was calibrated for the period 1995 to 2003 using auto-calibration. In auto-calibration, model fixes the surface and root zone parameters and groundwater parameters automatically. The calibrated results of observed and simulated runoff are shown in Fig. 3. The correlation coefficient for the calibration is 0.7 and Nash-Sutcliffe coefficient is 0.5 which indicates a good match.

Table: 1
Parameters used in the model calibration

Parameter	Unit	Description	Value used	Range
U_{max}	mm	Maximum water content in surface storage	19.1	5-20
L_{max}	mm	Maximum water content in lower zone/root storage	290	50-300
CQOF		Overland flow coefficient	0.668	0.1-1
CKIF		Interflow drainage constant	551.8	200-1000
TOF		Overland flow threshold	0.39	0-0.99
TIF		Interflow threshold	0.0604	0-0.99
TG		Groundwater recharge threshold	0.0989	0-0.99
CK1	Hrs	Timing constant for overland flow	33.6	10-50
CK2	Hrs	Timing constant for interflow	30.5	10-50
CKBF	Hrs	Timing constant for baseflow	2845	100-4000

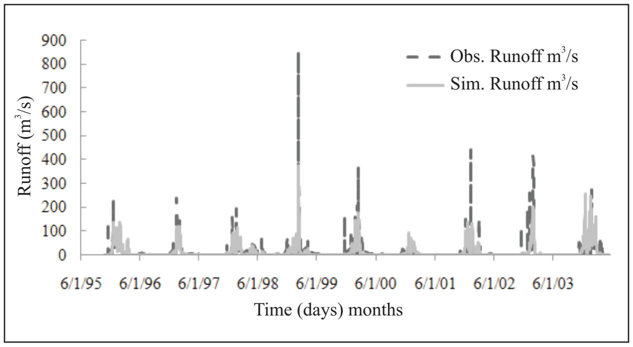

Fig. 3. Comparison of observed and simulated runoff during model calibration

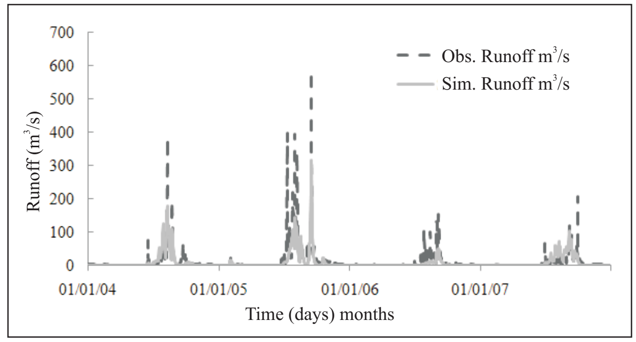

Fig. 4. Comparison of observed and simulated runoff during model validation

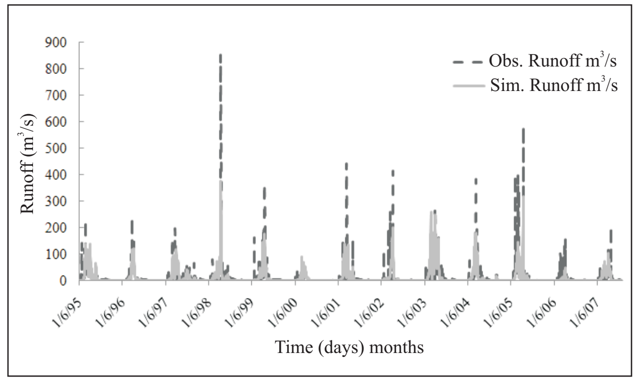

Fig. 5. Observed and simulated runoff during 1995 to 2007

The total water balance error during the calibration is 0.7% which is very less. Here the calibration criteria are sufficient which are due to the large variability in the rainfall distribution in the catchment. Further, negligible water balance error also points towards a good match (Santhi *et al.,* 2001, Van Liew *et al.,* 2003, Krause *et al.,* 2005, Moriasi *et al.,* 2007). It is seen from Fig. 3 that magnitude of some peaks is not matching but the accumulated observed volume is almost matching with the computed volume (0.5% difference). However, the time to peak is matching.

Model Validation

The model was validated for the period 2004 to 2007 using the model calibrated parameters. The validated results of observed and simulated runoff are shown in Fig. 4. The correlation coefficient for the calibration is 0.75 and Nash-Sutcliffe coefficient is 0.56 which indicates a good match. In this case, correlation coefficient is little improved. It is further seen from Fig. 4 that magnitude of peaks is not matching closely; however, the time to peak is matching.

The difference between total accumulated observed and simulated runoff during calibration and validation was observed 0.5 and 23.9%, respectively. This indicates that the difference between total accumulated observed and simulated runoff was more during the validation period.

The coefficient of determination for the calibration and validation period of the model was 0.5 and 0.56, respectively which indicate that the developed model is performing well to simulate the runoff but the overall difference between total accumulated observed and simulated runoff is causing significant error during the validation period. Since the observed runoff data series was not sufficiently long, the period of calibration was extended up to December, 2007. The model was then calibrated and the calibrated results of observed and simulated runoff are shown in Fig. 5. The correlation coefficient obtained for this period was 0.71 and Nash-Sutcliffe coefficient was 0.5 and the total water balance error during the calibration was 0.3% which is very less, which indicates a good match and the developed model is performing well to simulate the runoff.

This calibrated model can be used for estimation of runoff and groundwater recharge for future years or for gap filling in the runoff time series and also estimation of groundwater recharge during previous years.

Groundwater Recharge

Groundwater recharge in the basin is estimated using the NAM water balance model. The rainfall, runoff and evaporation data of years 1995 to 2007 was used for the estimation of groundwater recharge in the basin. These data were used as an input to the model which was processed by model and gives the result in the water balance form. The result also includes the groundwater recharge in millimeter. The recharge was estimated on annual basis. The equation used by the model for the estimation of groundwater recharge is given as:

$$G = \begin{cases} (PN - QOF)\dfrac{\frac{L}{L_{max}} - TG}{1-TG} & , \text{for } L/L_{max} > TG \\ 0 & , \text{for } L/L_{max} \le TG \end{cases}$$

Where, TG = root zone threshold value for groundwater recharge ($0 \le TG \le 1$), L = water content in lower storage, L_{max} = maximum water content in lower storage, QOF = overland flow and PN = excess water. The annual estimated recharge in the basin is presented in Table 2. The groundwater recharge in the basin was maximum in the year 2003 (350.7 mm) and minimum in the year of 2006 (69.5 mm). The average annual recharge estimated in the basin is 40311.7 ha-m. The amount of annual recharge in different years is given in Table 2.

Table: 2
Annual Groundwater recharge in Andhiyarkhore basin

Year	Recharge (mm)
1995	225.6
1996	160.3
1997	199.3
1998	204
1999	186.1
2000	125.7
2001	209.6
2002	198.6
2003	350.7
2004	224.8
2005	246.7
2006	69.5
2007	167.8

4. CONCLUSIONS

The present study was carried out in the Andhiyarkhore intermediate catchment, Chhattisgarh (India) to estimate the natural ground water recharge. The groundwater recharge of Andhiyarkhore catchment is estimated using the water balance of MIKE11 NAM model. The review of literature indicates that the estimation of the natural groundwater recharge is a complex and difficult due to interaction of the recharge phenomenon with so many processes affecting the recharge rate. The data for the period 1995 to 2007 was used for the estimation of groundwater recharge in the basin. The correlation coefficient obtained for the calibration period was 0.71 and Nash-Sutcliffe coefficient was 0.5 and the total water balance error during the calibration was 0.3% which is very less, which indicates a good match and the developed model is performing well to simulate the runoff. The estimated average annual groundwater recharge in the basin is 40,311.7 ha-m.

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