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. 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 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. The 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.*

Keywords: *Groundwater recharge, MIKE11 NAM, calibration, validation*

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 of 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 metres 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, 2013).

Groundwater recharge is defined in many ways by various researchers but the only essence is to augment the groundwater. 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 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 can also be defined as the amount of water that joins the groundwater table vertically and horizontally either through infiltration from ground surface or any surface water body including artificial recharge structures. 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). Groundwater recharge is defined as the downward flow of water reaching the water table and replenishing groundwater resources (WHO, 2006). Groundwater recharge is the water that has soaked into (infiltrated) the ground, and moved through pores and fractures in soil and rock to the water table. Rainfall is the principal source for replenishment of moisture in the soil water system and recharge of ground water. Other sources include recharge from rivers, streams, canals, irrigation water etc. Moisture movement in the unsaturated zone is controlled by suction pressure, moisture content and hydraulic conductivity relationships. Recharge to groundwater may be natural or artificial. The groundwater recharge through rainfall infiltration and/or rivers, streams, etc is called the natural groundwater recharge. On the other hand, recharge through artificial means like tanks, wells, pits, shafts, etc is termed as artificial recharge. Groundwater recharge maintains the supply of freshwater to wells, streams, springs and wetlands, which support the humans, plants and animals that are the part of the ecosystem. In natural places (having no nearby rivers or lakes), almost all water-supply needs are met by groundwater, and recharge is critical to maintain the abundance and quality of groundwater. Groundwater contributes to wells as well as flow to streams, springs, and wetlands year-round, sustaining them during droughts and dry summer months.

A detailed review has been carried out on the estimation of groundwater recharge. The chloride tracers and an SMD method both are used for the estimation of groundwater recharge in Zimbabwe (semi-arid climate) and it can be concluded that the amount of recharge depends upon rainfall, vegetation type, and soil; and the timing of recharge corresponds to the heaviest rainfalls of monsoons when rates of incoming precipitation (400mm/a) 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 5mm/a and increased to 20mm/a 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/a 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 Ching–Shui watershed is about 421.4 km, 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 Ching– Shui 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 is 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 are 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 informed about water-resources decisions and policies.

Study Area

The Andhiyarkhore intermediate basin falls in the Chhattisgarh state. The basin extends between

21^{0}45’33” and 22^{0}30’16” north latitude and 81^{0}01’57” and 81^{0}37’39” east longitude. This basin covers an area of 2005.56 sq. km. 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 highest part of the study area is used for agriculture (1015 km^2) which is about 50.61% of the total basin area. The waste land 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 205.09km^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 has maximum area of impact that is 948.11 km^2. The second highest Thiessen’s polygon area is for Kawardha rain gauge station that is 602.28 km^2. 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 63.80km^2. The basin map is shown in Figure1.

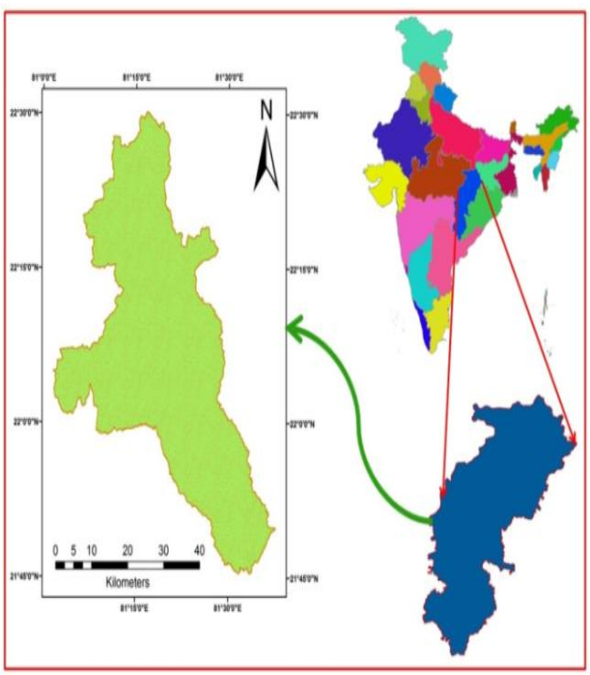

Fig. 1 Location of the Andhiyarkhore intermediate catchment

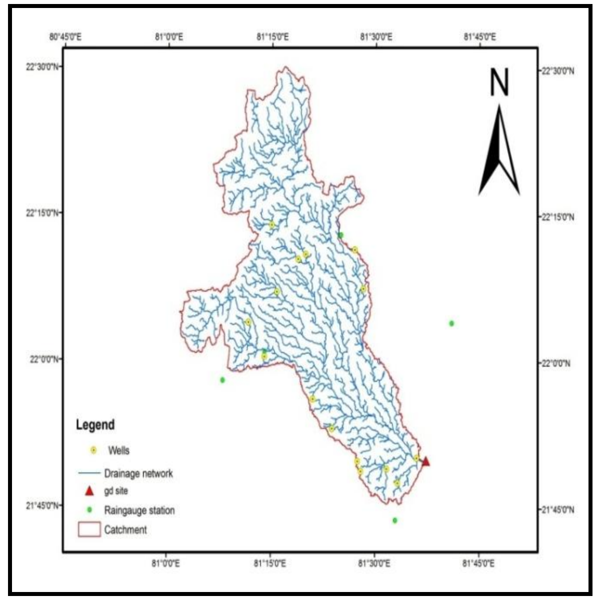

Fig. 2 Catchment showing various details like raingauge stations, GD site, wells, drainage network

Material and Methods

Rainfall-Runoff Model (MIKE 11 NAM)

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. 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 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 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.

Results and Discussion

NAM module of MIKE11 is used to estimate all the basin water balance components, i.e. runoff, actual evapotranspiration, and groundwater recharge. 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 sq.km 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.

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. The total water balance error during the calibration is 0.7%.

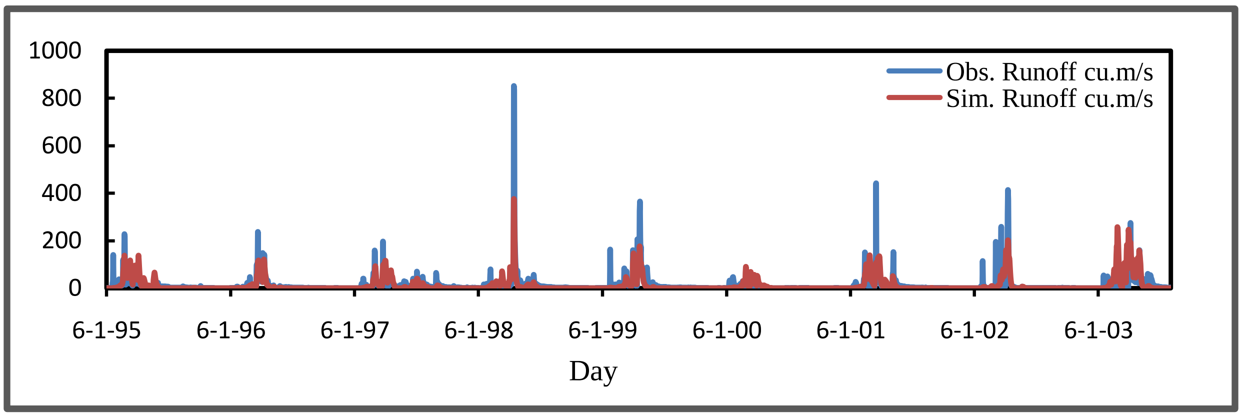

Fig. 3 Comparison of observed and simulated runoff during model calibration

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.

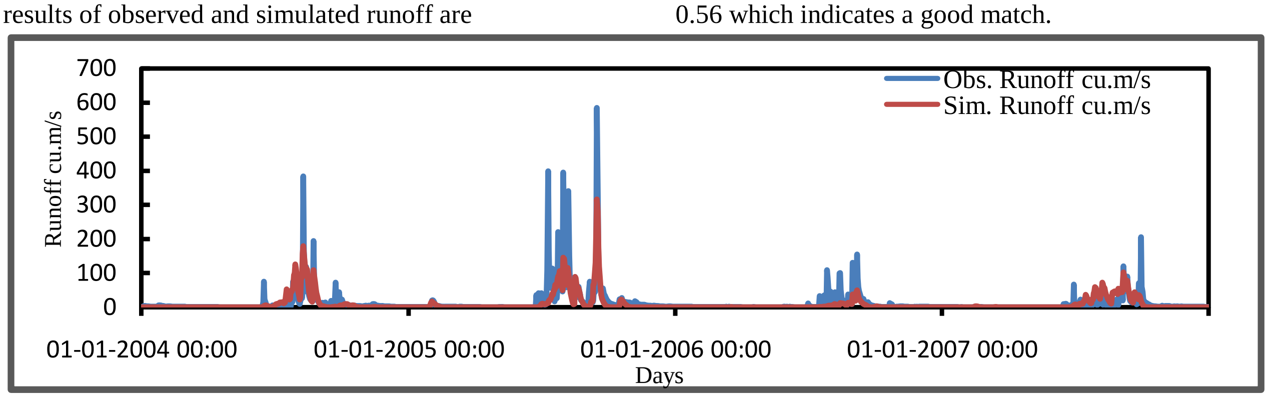

Fig. 4 Comparison of observed and simulated runoff during model validation

The difference between total accumulated observed and simulated runoff during calibration and validation was observed is 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.

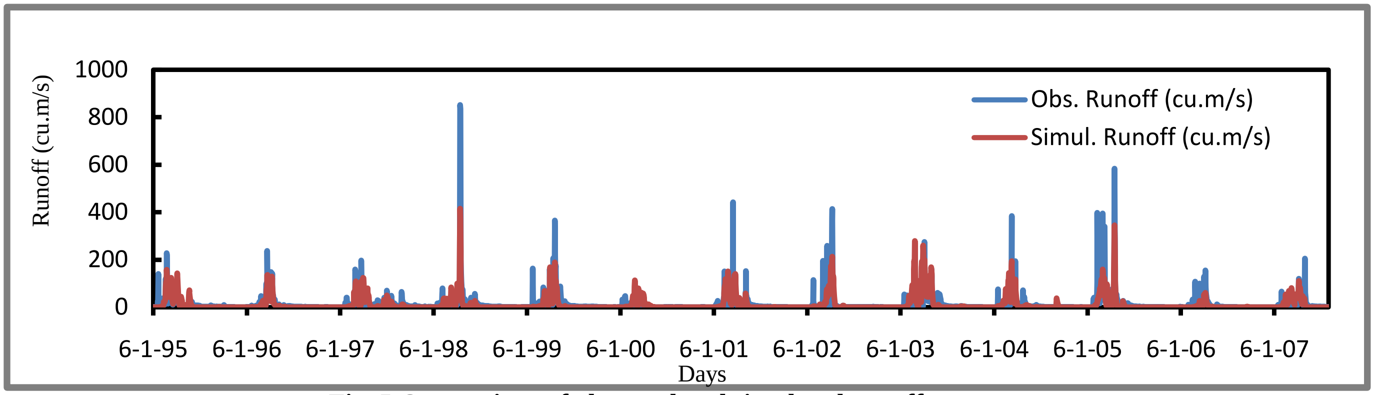

Fig. 5 Comparison of observed and simulated runoff

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:

$$G = (PN - QOF)\frac{(L/_{Lmax}) - TG}{1 - TG} \quad \text{if L/Lmax > TG}$$

$$G = 0 \quad \text{if L/Lmax} \leq \text{TG}$$

Where, TG is the root zone threshold value for groundwater recharge ($0 \leq TG \leq 1$), L is water content in lower storage, L_{max} is maximum water content in lower storage, QOF is overland flow, PN is excess water. The annual estimated recharge in the basin is shown in Fig. 6.

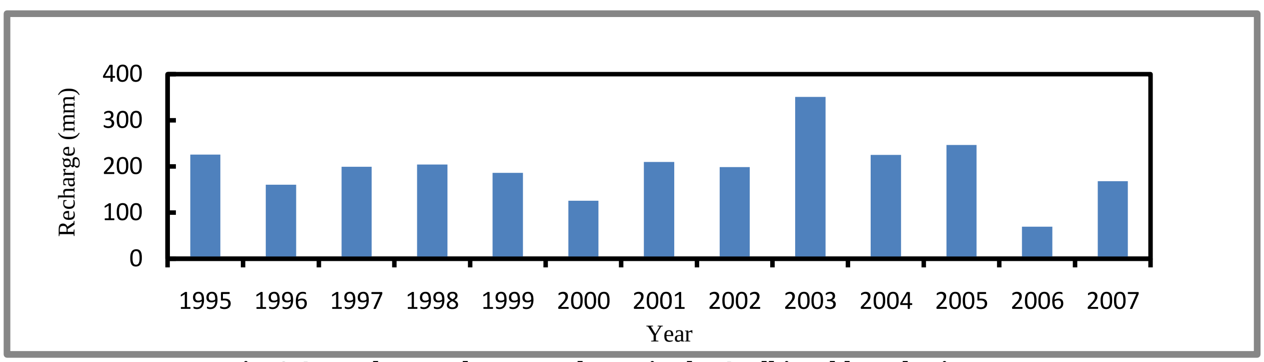

Fig. 6 Annual groundwater recharge in the Andhiyarkhore basin

The groundwater recharge in the basin was maximum in year 2003 that is 350.7 mm and minimum for the year of 2006 that is 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 1.

Table 1 Annual groundwater recharge in the 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

Summary and 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 ground water 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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