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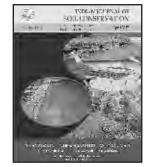

Assessment of natural groundwater recharge in Sonar sub-basin using HELP3 model: A case study

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ABSTRACT

Groundwater is one of the most significant natural resources of the country. The unconstrained exploration and non-judicious use of groundwater is causing a fall down in water table in different areas of the country. However, the situation is more severe in arid and semi-arid areas of the country. Therefore, in order to replenish depleting ground water resources, there is a need for site explicit artificial groundwater recharge by isolating suitable sites in different regions of the country. In this study, an effort was made in this course to estimate groundwater recharge for Sonar sub-basin in central India. The study was conceded out for a period of 38 years during 1972-2010. The HELP3 (Hydrologic Evaluation of Landfill Performance version 3.0) model based on water balance method was used for study. The groundwater recharge was assessed for 12 identified sites located in Sonar sub-basin on the basis of soil types and geology. The soil profile prepared for HELP3 model using well-logs was used to estimate site-specific groundwater recharge as well as for whole Sonar sub-basin. The study reveals that about 4.627% of cumulative average annual precipitation is added to groundwater recharge, which is not adequate to replenish groundwater. Therefore, it is essential that this depletion to groundwater, if not rejuvenated artificially, will cause water table to fall down which will affect hydrological processes and socio-economic life of people residing in Sonar sub-basin.

1. INTRODUCTION

Groundwater recharge is an important part of vadose zone soil-water budget which is driven by precipitation. Based on amount of precipitation and its intensity, temperature and land use/cover and other interception losses, precipitated water is imperiled to various hydrological processes such as interception, evaporation and surface runoff. Part of this water can infiltrate into soil, where it can be taken up by plant roots and subsequently transpired through vegetation canopy. The enduring water will continue to percolate deeper into soil column, ultimately becoming groundwater recharge after crossing water table into saturated groundwater zone. HELP3 is 2-D model adept of modeling hydrological process by routing precipitation falling on land to constituents of evapotranspiration, runoff, storage and vertical infiltration trailed by percolation (recharge) for a layered soil column on a daily basis. The lateral movement of water as overland flow and sub-surface runoff (base flow) is accounted for an output from model, but 2-D flow is not explicitly modeled. The model algorithms are described in facet by Schroeder *et al.* (1994) and limitations are discussed by Berger (2000). Schroeder *et al.* (1994) carried out daily point simulations of recharge using soil water balance hydrology model HELP3 which simulates surface and shallow sub-surface processes, including snow storage, snowmelt, interception, infiltration, runoff, evaporation, transpiration and drainage. The water balance method is prominent because it is practical almost wherever weather, soil and geology data is available to assess residual term (groundwater recharge) of water balance. A major drawback of water balance method is that recharge is estimated as residual term in an equation where other budget terms usually are estimated with substantial error, which can result in large errors in recharge estimate Nimmo *et al.* (2003).

Toews and Allen (2009) found that however, HELP3 does not allow water to be rerouted upwards once it has passed the evaporative zone depth (EZD). For this study, water passing EZD was implicit to result in groundwater recharge. HELP3 has been used in several recent studies by Allen *et al.* (2010); Crosbie *et al.* (2011); Jyrkama and Sykes (2007); Liggett and Allen (2010); Scibek and Allen (2006) to project future groundwater recharge rates from climate scenarios. Limitations of the HELP3 model, particularly for application in arid regions, are discussed by Berger (2000) and Scanlon *et al.* (2002). Kung (1990) and Selker *et al.* (1992) stated that in addition, the soils in unsaturated zone rarely exhibit homogeneous properties, often consisting of layered sands, silts and clays, resulting in non-uniform moisture distributions. Simmers (1990) explained that instability in wetting front and subtle changes in permeability structure can also lead to flow fingering. Even in relatively homogeneous materials, unpredictable occurrence of preferred pathways due to plant roots, cracks and fissures, complicates the hydraulic characterization of soils in unsaturated zone. Freeze and Banner (1970); Schuh *et al.* (1993) showed that large variations in recharge can also occur, even across uniform soils, due to topography, resulting in depression-focused recharge. Shallow groundwater levels also influence recharge process by limiting the amount of water entering ground surface. Lerner (2002) reported that recharge rates can be comprehensively wedged by human activities such as urbanization, which influence the recharge rates through increased impervious cover; leakage from water distribution systems, sewers and septic tanks; and over-irrigation of parks and lawns. Singh *et al.* (2016) illustrated that estimation of recharge rate using aquifer parameters is one of the most intricate and challenging tasks related to groundwater hydrology therefore, estimation of groundwater recharge requires modeling. Singh *et al.* (2016) reported that due to poor saturated hydraulic conductivity, soil matrix flux potential and soil sorptivity accompanied with poor recharge rate in Sonar sub-basin, followed by falling groundwater table in Sonar sub-basin. Consequently, there was a need for modeling to assess natural groundwater recharge occurring in sub-basin and for identifying suitable sites for artificial recharge, if obligatory to replenish depleting groundwater resources.

2. MATERIALS AND METHODS

Study Area

The Sonar sub-basin drains an area of about 1538 sq km (94% in Sagar and 6% in Raisen) in North-Central part of Madhya Pradesh. The Sonar is a tributary of Ken river and the sub-basin extends between 23°21'14" to 23°50'05" N Latitude and 78°35'48" to 79°10'50" E Longitude. The sub-basin has a perimeter of 284 km and basin length of 72.12 km. The climate of basin is semi-arid to sub-tropical. Rugged and rippled terrain with low rocky ridges, narrow valleys and plains exemplifies the landscape of the basin. Large portion of basin is under rain-fed agriculture. The forests are dry deciduous type. Drought incidence met is one in every five years. Limited soil depth of 30-50 cm existed in Sonar sub-basin was measured by auger-hole test. Average annual rainfall and evapotranspiration is 1100 and 1852 mm, respectively. The average number of rainy days in a water year is 45. The average annual minimum and maximum temperature fluctuates between 18 to 33°C. The average annual relative humidity varies between 27 to 85%. The average annual wind speed differs from 4.13 in Nov to 8.45 km h^{-1} in July. The sub-basin was distributed into 12 major soil groups based on soil type and geology, thus soil samples were collected to determine various soil properties, *viz.,* infiltration rate, hydraulic conductivity, soil texture, total porosity *etc.* The soil analysis was carried out at Soil and Water laboratory at National Institute of Hydrology (NIH), Roorkee, Uttarakhand. The index map showing location of Sonar sub-basin, soil map, drainage map, land use map, theissen's polygon map, geology map, hydro-geology map, slope map and digital elevation model (DEM) maps were prepared using Arc GIS 9.2 at NIH, Roorkee and used for presenting and entering input data in spatial format to HELP3 model. The length of Sonar river from Utharia (remotest point) to Garhakota (gauging station) is 95.21 km. There are four tributaries on the left side and two on the right side. The number of 1st, 2nd, 3rd, 4th and 5th order streams is 146, 38, 9, 2 and 1, respectively and the basin trunk order is five. The drainage density is 0.61 km sq km^{-1} and bifurcation ratio being 3.64.

Estimation of Groundwater Recharge using HELP3 Model

The HELP3 model was developed by U.S. Army Engineer Waterways Experiment Station for U.S. Environmental Protection Agency to simulate water movement through landfill designs. The model uses a solution technique that calculates water budget analyses and accounts for surface storage, runoff, infiltration, percolation, evapotranspiration, soil moisture storage and lateral drainage.

Climatological input data

The climatological data can be entered into model using three different options; default data, manual data or synthetically generated data. However, manual option was chosen to enter daily site-specific weather data (precipitation, mean daily temperature, solar radiation, wind speed and relative humidity) for Sonar sub-basin in model. The leaf area index ranging from 0 for bare ground to 5.0 for excellent grass cover based on FAO database for different types of vegetation and stages of growth, EZD for different vegetation and stages of growth from FAO database in mm, starting and ending date for growing season during *rabi*, *kharif* and *zaid* crops were taken from Department of Agriculture, Govt. of Madhya Pradesh in Julian days were defined for Sonar sub-basin in this model.

Soil and geology input data

The data inputs for soil and geology include general information about soil type (soil texture, hydraulic conductivity, field capacity, wilting point, porosity, initial soil water content) and layer types (vertical percolation layer, lateral drainage layer, barrier soil layer and impermeable layer) and design criteria (thickness of soil profile and boundary conditions like areal extent of soil group and corresponding geology) for each layer. The HELP3 includes default values for soil types and soil properties for different layers; however, it was attuned and manually entered for this case study. In addition, user specified weather, soil and geology data inputs were used for this study. The model within calculates other relevant parameters utilizing the data entered *i.e.* SCS curve number for computing surface runoff from sub-basin required for groundwater recharge assessment. The actual evapotranspiration in HELP3 were computed using crop and weather data inputs by FAO Penman-Monteith method as given in Eq. 4. The changes in soil water storage were computed based on soil and weather data input with initial soil moisture condition defined for HELP3 model and daily crop water requirement computed by model based on defined vegetation in sub-basin and growing season.

Boundary conditions

The Sonar sub-basin is distributed into 12 parts based on spatial variations in soil and vertical extent of geology (prepared using well-logs) in basin. These spatial variations in soil properties existing in Sonar sub-basin were basis for horizontal boundary condition and well-log data based thickness of soil profile layer was considered to state vertical boundary condition for model domain.

The water balance method calculates potential recharge as a residual of all other water balance components and is expressed as:

$$R = P - D - Et_a - \Delta W \quad ...(1)$$

Where, R = Potential recharge, P = Precipitation, D = Net runoff, Et_a = Actual evapotranspiration and ΔW = Change in soil water storage.

The daily surface runoff was calculated in the model using SCS curve number method. The runoff equation is,

$$Q = \frac{(P - I_a)}{P - I_a + S} \text{ for } P \geq I_a \quad ...(2)$$

Where, Q = Runoff (mm), P = Precipitation (mm), S = Potential maximum soil moisture retention after runoff begins, I_a = initial abstraction (mm) or amount of water loss before runoff begins, such as infiltration, or rainfall interception by vegetation. Generally, it is assumed that I_a = 0.2S, although it has been found that I_a = 0.3S in Indian condition is more widely accepted for heavy soil, where the curve number (CN) reflect actual conditions. The CN is then related as:

$$S = \frac{1000}{CN} - 10 \quad ...(3)$$

CN has a range from 0 to 100; lower numbers indicate low runoff potential while larger numbers for high runoff potential. The *CN* is related to soil type, soil infiltration capability, land use, antecedent soil moisture content and depth of seasonal water table.

The reference evapotranspiration were calculated by the HELP3 model using FAO Penman-Monteith method as given below:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)} \quad ...(4)$$

Where, ET_o = Reference evapotranspiration (mm day^{-1}), R_n = Net radiation at crop surface (MJ m^{-2} day^{-1}), G = Soil heat flux density (MJ m^{-2} day^{-1}), T = Mean daily air temperature at 2 m height (°C), u_2 = Wind speed at 2 m height (m s^{-1}), e_s = Saturation vapour pressure (k Pa), e_a = Actual vapour pressure (k Pa), e_s - e_a = Saturation vapour pressure deficit (k Pa), Δ = Slope vapour pressure curve (k Pa $°C^{-1}$), γ = Psychometric constant (k Pa $°C^{-1}$).

However, the actual evapotranspiration (Et_a) were calculated based on crop coefficient taken from FAO database for landuse (crops, trees and shrubs *etc.*) existing in Sonar sub-basin. The HELP3 model used these input data values to estimate site specific daily potential groundwater recharge in Sonar sub-basin. The changes in root zone soil moisture were calculated based on weather data, leaf area index, evaporative root zone depth, landuse and starting and ending season of trees and crops.

3. RESULTS AND DISCUSSION

The soil properties for 12 identified sites in Sonar sub-basin measured in Soil and Water laboratory at NIH, Rookee are given in Table 1. The soil porosity measured in laboratary showed large variation from 0.3 (Basa reserve forest) to 0.52 (Jaitpura kachhia). The soil porosity values indicated that most of basin had clay to clay-loam soil (*i.e.* 0.52-0.42) except Basa reserve forest, Ramkheri and Dadhoniya, having sandy loam soil texture with soil porosity values of 0.3, 0.34 and 0.39, respectively. The highest saturated hydraulic conductivity was for Basa reserve forest (55.5×10^{-5}cm s^{-1}) followed by

Ramkheri (49.4×10^{-5}cm s^{-1}), Dhadoniya (19.5×10^{-5}cm s^{-1}), Bijaypura (18.9×10^{-5}cm s^{-1}), Swakara (18.9×10^{-5}cm s^{-1}) and Akala (15.4×10^{-5}cm s^{-1}). Other remaining sites have saturated hydraulic conductivity less than 8×10^{-5} cm s^{-1}. The soil moisture at field capacity ranging from 50.1 to 20.2% vol. of soil and wilting point ranging from 8.2 to 18.2% vol. of soil at 12 sites in Sonar sub-basin is given in Table 1. The recharge rate measured using Guelph permeameter at 12 sites is given in Table 1 showed that highest recharge rate was at Basa reserve forest (0.26 cm^3 s^{-1}) followed by Ramkheri (0.19 cm^3 s^{-1}) and lowest recharge rate was for Dhana (0.04 cm^3 s^{-1}) followed by Khamariakhurd (0.098 cm^3 s^{-1}) and Kothikha (0.099 cm^3 s^{-1}); however, other sites show recharge rate in range of 0.10 cm^3 s^{-1} to 0.13 cm^3 s^{-1}. The cumulative rainfall measured by five rain gauge stations from 1972 to 2010 observed at 12 sites of Sonar sub-basin is shown in Table 2 with corresponding cumulative groundwater recharge estimated by HELP3 model. The values of cumulative groundwater recharge (m) were highest for Basa reserve forest (16.38%) followed by Ramkheri (10.33%), Dhadoniya (9.31%), Bijaypura (7.51%), Sawkara (6.53%), Dhana (6.28), Akala (4.0%), Khamariakhurd (3.82%), Kukwara (1.99%), Indalpur (1.01%), Jaitpura Kachhia (0.91) and Kothikha (0.53%). The average annual groundwater recharge for Sonar sub-basin was 5.72%. The cumulative annual groundwater recharge during 1972-2010 for Sonar sub-basin was found to be 1381.59 MCM or 1.183 m, which is only 4.627% of the average annual precipitation. Therefore, it approximates to an average annual groundwater recharge of 0.1217 m yr^{-1} for Sonar sub-basin. The cumulative rainfall vs. cumulative runoff plot as given in Fig. 11 from 1972-2010 show that rainfall-recharge is not having a linear relationship (R^2 = 0.178). The Fig. 10 shows the annual precipitation, annual runoff, annual evapotranspiration and corresponding annual groundwater recharge from 1972-2010 for Sonar sub-basin. The Fig. 2 shows the location of the Sonar sub-basin in Central India. The drainage pattern with stream order for Sonar sub-basin is given in Fig. 3. The Thiessen's polygon map shows representative areas corresponding to five rain gauge stations located at Sagar (74 sq km), Garhakota (177 sq km), Rehli (468 sq km), Deori (519 sq km) and Kesli (301 sq km). The land use as shown in Fig. 1 and Fig. 4 in Sonar sub-basin are agriculture (63%), forest land (23%), waste land (13%), settlement (0.4%) and water body (0.06%). There were three types of stratigraphy

Table: 1
Soil and aquifer characteristics with recharge rate in Sonar sub-basin

Name of site	(A)	(ϕ)	(K_{fs})	(WP)	(FC)	(Q)
Dhana	16900	0.48	7.16	15.2	45.3	0.0486
Dhadhoniya	1500	0.39	19.50	10.4	24.2	0.1096
Bijaypura	9600	0.42	18.90	11.0	22.2	0.1025
Akala	1800	0.45	15.40	12.8	25.0	0.1168
Swakara	10800	0.42	18.90	10.8	22.0	0.1029
Jaitpurakachhia	7100	0.52	3.27	18.2	54.0	0.1351
Ramkheri	1100	0.34	49.40	9.6	20.2	0.1946
Basa reserve forest	1500	0.30	55.50	8.2	18.1	0.2622
Indalpur	21300	0.50	4.16	16.4	50.1	0.1554
Khamariakhurd	6900	0.47	6.44	15.0	48.6	0.0983
Kothikha	5600	0.51	3.80	17.6	52.0	0.0990
Kukwara	32600	0.49	5.10	16.0	49.1	0.1041

Area of Soil group (A) in ha, Soil porosity (ϕ) in fraction, Saturated hydraulic conductivity (K_{fs}) in $\times10^{-05}$ cm s^{-1}, Soil moisture at wilting point (WP) in % Vol., Soil moisture at field capacity (FC) in % Vol., Recharge rate (Q) in cm^3 s^{-1}.

Table: 2
Cumulative groundwater recharge for Sonar sub-basin during period 1972-2010

Name of site	Rainfall (m)	Recharge (m)	Recharge (%)	Area (km^2)	Gross recharge (MCM)
Dhana	32.6	2.05	6.28	169	723.32
Dhadhoniya	21.8	2.03	9.31	15	30.45
Bijaypura	12.4	0.93	7.51	96	89.38
Akala	21.8	0.87	4.00	18	15.71
Swakara	21.8	1.42	6.53	108	77.87
Jaitpurakachhia	32.8	0.30	0.91	71	106.5
Ramkheri	24.6	2.54	10.33	11	1.14
Basa reserve forest	24.6	4.03	16.38	15	30.45
Indalpur	34.8	0.35	1.01	213	74.98
Khamariakhurd	32.6	1.25	3.82	69	133.17
Kothikha	34.8	0.19	0.53	56	60.48
Kukwara	12.4	0.25	1.99	326	38.14
Total/Average		16.20	5.72		1381.59

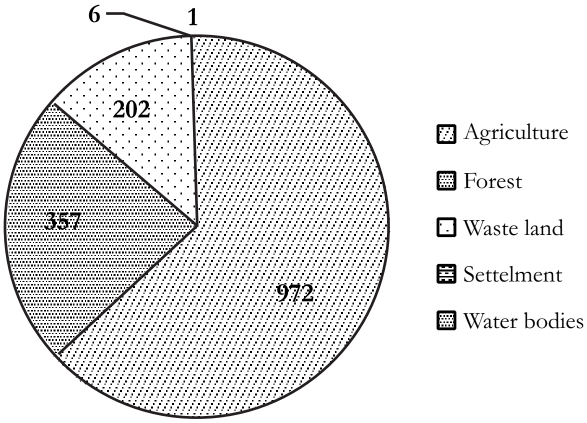

Fig. 1. Land use in Sonar sub-basin

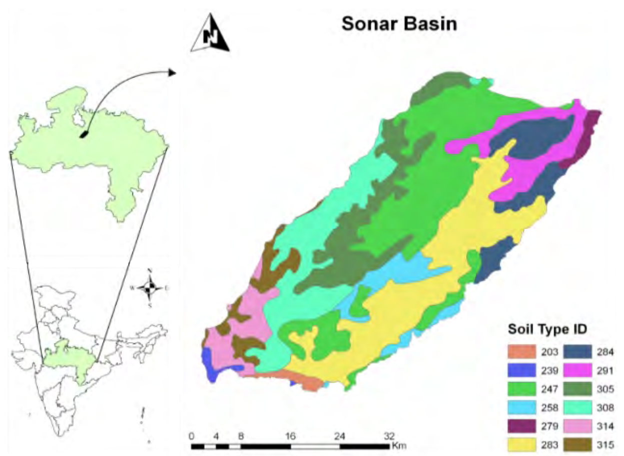

Fig. 2. Location of Sonar sub-basin in Central India

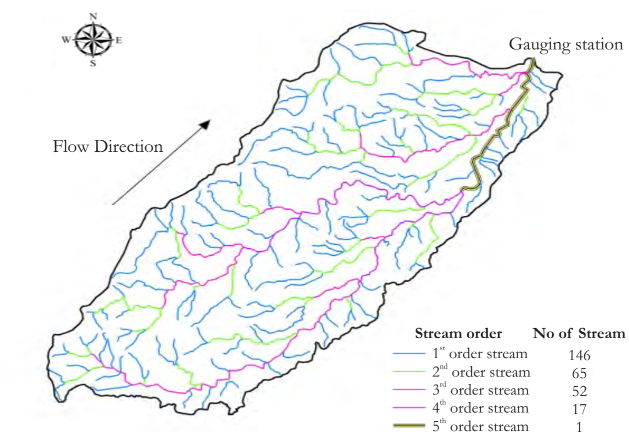

Fig. 3. Drainage and stream order of Sonar sub-basin

in Sonar sub-basin *i.e.* Deccan trap, Lameta group and Vindhyan super group. The geologic formation as shown in Fig. 5 present in Sonar sub-basin are basaltic flows (1064 sq km); Limestone, calcareous, sandstone (20 sq km), Bander (Nagod) limestone (0.18 sq km), Ganurgarh (Simrawal) shale (220 sq km), Sandstone (200 sq km), Sandstone/Shale (22 sq km) and Sirbu shale (12 sq km). The Sonar sub-basin is

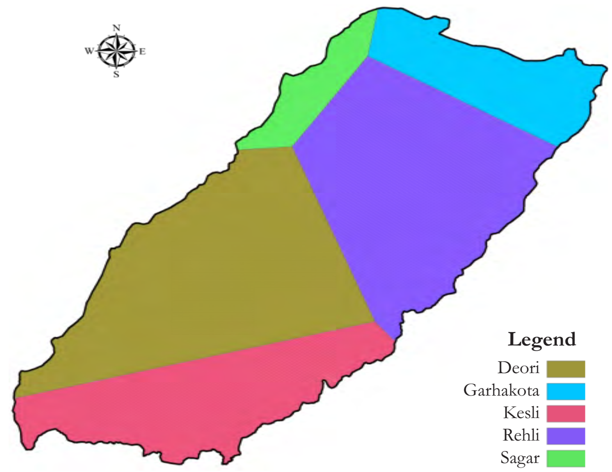

Fig. 4. Theissen's polygon of Sonar sub-basin

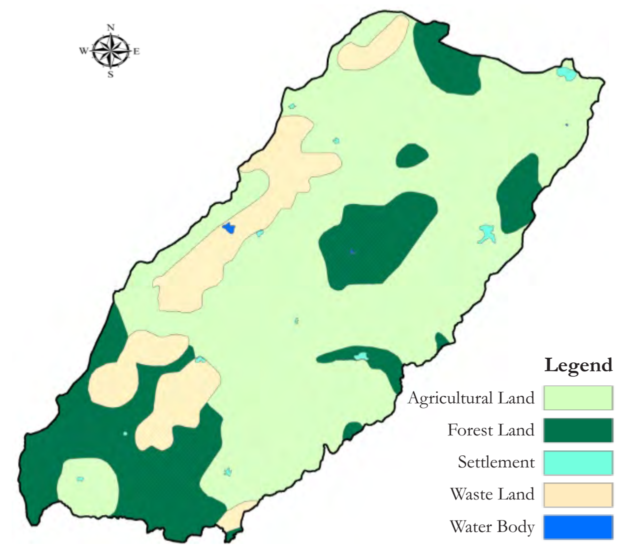

Fig. 5. Land use/cover of Sonar sub-basin

classified into two hydro-geological categories as shown in Fig. 6 based on the permeability of rocks and groundwater potential *i.e.* cumulative high permeability and good to excellent groundwater potential (139 sq km) and low to moderately high permeability and poor to moderately good groundwater potential (1399 sq km). There is a large variation in slope existing in Sonar sub-basin (from 0.1 to 40%) as shown in Fig. 7. The DEM shown in Fig. 8 shows that elevation of Sonar sub-basin from 362 m to 677 m above msl.

The cumulative groundwater recharge estimated for Sonar sub-basin shows a large variation within basin. The Basa reserve forest, Ramkheri, Dhahoniya, Bijaypura Swakara and Dhana show excellent to good groundwater recharge due to forest and agriculture dominated land use, sandy-loam soil texture, permeable geology, less slope and slope length for more opportunity time for water to enter into soil and good hydraulic conductivity. Akala and Khamariakhurd show

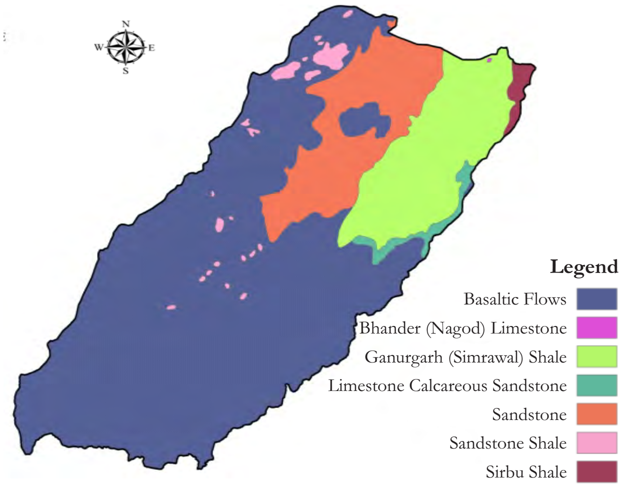

Fig. 6. Geology of Sonar sub-basin

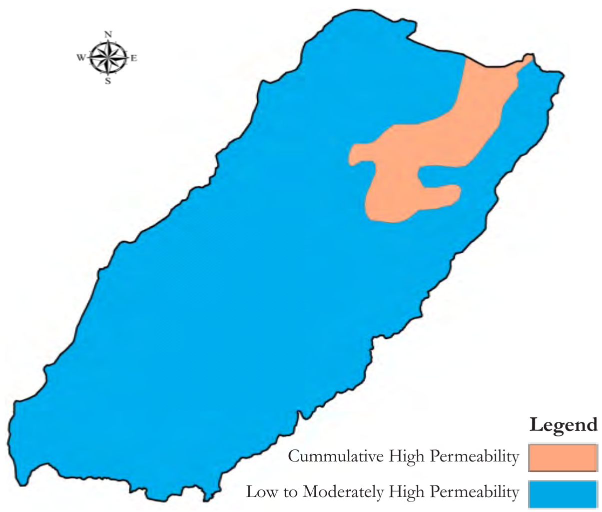

Fig. 7. Hydrogeology of Sonar sub-basin

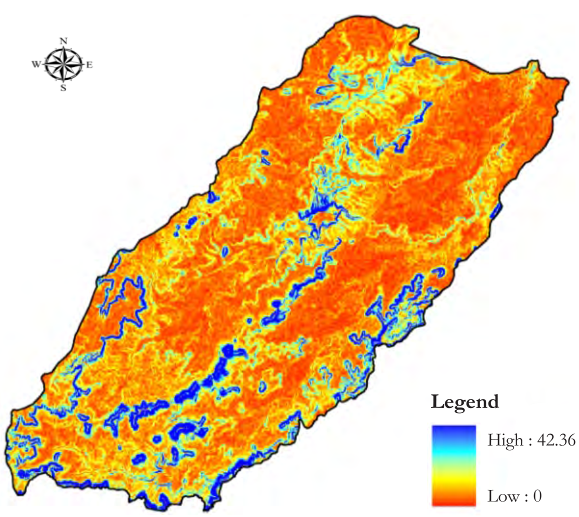

Fig. 8. Slope map of Sonar sub-basin

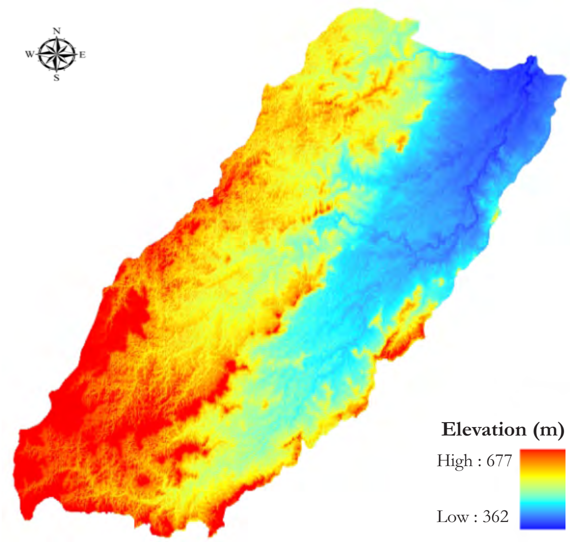

Fig. 9. DEM of Sonar sub-basin

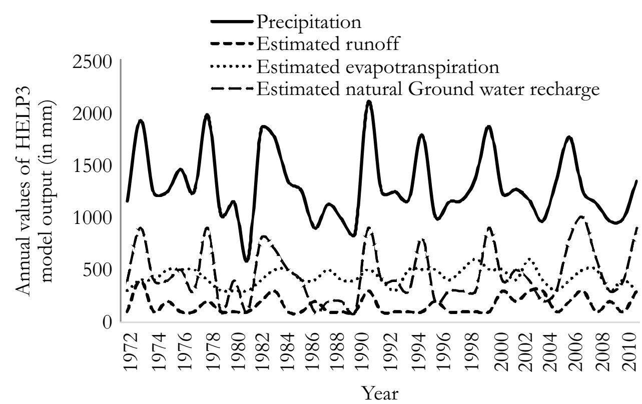

Fig. 10. Estimated values of different parameters for Sonar sub-basin

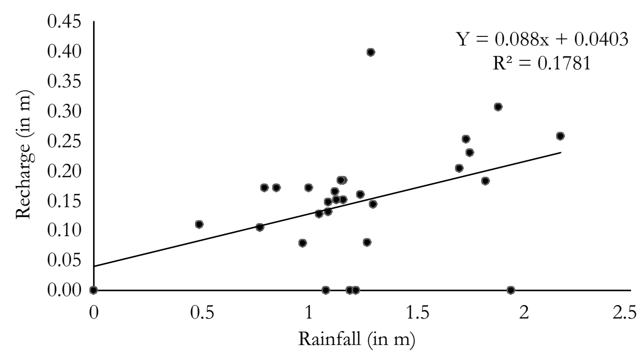

Fig. 11. Rainfall-recharge relationship for Sonar sub-basin

moderate groundwater recharge due to dominance of waste and settlement, loamy to clayey soil texture, less permeable geology, higher slope and slope length resulting in less opportunity time for water to enter into soil and moderate hydraulic conductivity and Kukwara, Indalpur, Jiatpurakacchhia and Kothikha shows low groundwater recharge rate due to dominance of settlement, clayey soil texture, less permeable geology, very high slope and poor hydraulic conductivity of identified sites in Sonar sub-basin. It is also essential to mention that groundwater draft is also an important factor which should be considered while accounting for groundwater recharge. The groundwater draft available block wise from the Department of Water Resource, Govt. of Madhya Pradesh was used for better understanding of reasons for falling groundwater in Sonar sub-basin in correlation with HELP3 groundwater modeling. However, it is a limitation of HELP3, as this model does not account for groundwater draft while estimating groundwater recharge. Generally, it was observed that soil texture, geology, land use, hydraulic conductivity and slope were most important parameters affecting site specific recharge in Sonar sub-basin.

4. CONCLUSIONS

This study showed that groundwater recharge potential of Sonar sub-basin is not sufficient being 4.627% of cumulative average annual precipitation during 1972-2010, which may be one of the reasons for falling water table in Sonar sub-basin. The increasing population has exaggerated this situation due to changes in landuse from forest to agriculture or settlements. The over exploitation of groundwater for irrigation, industrial and domestic needs is due to unavailability of surface reservoirs and canal network in Sonar sub-basin. The decrease in spatial extent due to illegal encroachment and already less area occupied by surface water bodies (<1% of geographical extent of basin) as justified from land use has aggravated this situation. The increase in rainfall intensity resulting in less time for water to enter into soil followed by frequent prolonged dry spell and drought in Sonar sub-basin is caused due to uncertainties accompanied with climate change of the region. This underlined the need for implementing site specific artificial recharge in Sonar sub-basin. The large variation in site-specific recharge estimates showed that natural ground water recharge is influenced by a number of factors which may be meteorological, pedagogical and different surface and sub-surface properties.

REFERENCES

Allen, D.M., Cannon, A.J., Toews, M.W. and Scibek, J. 2010. Variability in simulated recharge using different GCMs. *Water Resour. Res.*, 46(10): doi:10.1029/2009WR008932.

Berger, K. 2000. Validation of the hydrologic evaluation of landfill performance (HELP) model for simulating the water balance of cover systems. *Environ. Geol.*, 39(11): 1261-1274.

Crosbie, R.S., Dawes, W.R., Charles, S.P., Mpelasoka, F.S., Aryal, S., Barron, O. and Summerell, G.K. 2011. Differences in future recharge estimates due to GCMs, downscaling methods and hydrological models. *Geophysical Research Letters*, 38(11): doi:10.1029/2011GL047657.

Freeze, R.A. and Banner, J. 1970. The mechanism of natural ground-water recharge and discharge: 2. Laboratory column experiments and field measurements. *Water Resour. Res.*, 6(1): 138-155.

Jyrkama, M.I. and Sykes, J.F. 2007. The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). *J. Hydrol.*, 338(3): 237-250.

Kung, K.S. 1990. Preferential flow in a sandy vadose zone: 2. Mechanism and implications. *Geoderma*, 46(1-3): 59-71.

Lerner, D.N. 2002. Identifying and quantifying urban recharge: a review. *Hydrogeo. J.,* 10(1): 143-152.

Liggett, J.E. and Allen, D.M. 2010. Comparing approaches for modeling spatially distributed direct recharge in a semi-arid region (Okanagan Basin, Canada). *Hydrogeo. J.* 18(2): 339-357.

Nimmo, F., Pappalardo, R.T. and Giese, B. 2003. On the origins of band topography, Europa. *Icarus*, 166(1): 21-32.

Scanlon, B.R., Christman, M., Reedy, R.C., Porro, I., Simunek, J. and Flerchinger, G.N. 2002. Intercode comparisons for simulating water balance of surficial sediments in semiarid regions. *Water Resour. Res.*, 38(12): doi:10.1029/2001WR001233.

Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W. and Peyton, R.L. 1994. The hydrologic evaluation of landfill performance (HELP) model: engineering documentation for version 3. *Environmental Protection Agency, United States*.

Schuh, W.M., Meyer, R.F., Sweeney, M.D. and Gardner, J.C. 1993. Spatial variation of root-zone and shallow vadose-zone drainage on a loamy glacial till in a sub-humid climate. *J. Hydrol.*, 148(1): 1-26.

Scibek, J. and Allen, D.M. 2006. Modeled impacts of predicted climate change on recharge and groundwater levels. *Water Resour. Res.*, 42(11): doi:10.1029/2005WR004742.

Selker, J., Parlange, J.Y. and Steenhuis, T. 1992. Fingered flow in two dimensions: 2. Predicting finger moisture profile. *Water Resour. Res.*, 28(9): 2523-2528. doi: 10.1029/92WR00962.

Simmers, I. 1990. Natural groundwater recharge estimation in (semi-) arid zones: Some state- of-the-art observations, in Proc. of the Sahel forum on the state-of-the-art of hydrology and hydrogeology in the arid and semi-arid areas of Africa (G.E. Stout and M. Demissie eds.) pp. 373-386.

Singh, G., Singh, S., Singh, R.M., Kumar, R. and Mishra, C.D. 2016. Estimation of recharge rate using aquifer characterization based on *in-situ* saturated hydraulic conductivity for Sonar sub-basin in Madhya Pradesh, India. *Indian J. Soil Cons.*, 44(3): 249-255.

Toews, M.W. and Allen, D.M. 2009. Evaluating different GCMs for predicting spatial recharge in an irrigated arid region. *J. Hydrol.*, 374(3): 265-281.