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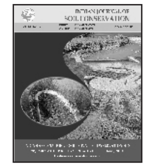

Estimation of recharge rate using aquifer characterization based on *in-situ* saturated hydraulic conductivity for Sonar sub-basin in Madhya Pradesh, India

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ABSTRACT

Estimation of recharge rate using aquifer parameters is one of the most complex and difficult tasks related to ground water hydrology. *In-situ* soil properties are the key hydraulic parameters for flow and transport related phenomena in any aquifer study. In this study, an attempt was made to determine aquifer characteristics such as *in-situ* saturated hydraulic conductivity, soil matric flux potential, soil sorptivity and recharge rate under field conditions in the Sonar sub-basin. Various sites were identified based on soil groups and geology existed in the sub-basin. A total of 60 observations were collected from 12 sites during dry season (March-April). The procedures for estimating steady flow rate during field application of the Guelph Permeameter method were evaluated by approximate procedures that use the first three or four consecutive values of the rate of fall of the water level equal or differing by less than a given percentage. A weighted mean of observations from all sites were evaluated for average values of *in-situ* saturated hydraulic conductivity, soil matric flux potential, soil sorptivity and recharge rate. The results obtained showed wide variation in saturated hydraulic conductivity, soil matric flux potential, soil sorptivity and recharge rate for the Sonar sub-basin in the South West and some parts of North East found better.

1. INTRODUCTION

Quantification of the rate of ground water recharge is a basic pre-requisite for efficient ground water resource management (Sophocleous, 1991). This constitutes a major issue in regions with large demands for ground water supplies, such as in semi-arid areas, where such resources are the key to agricultural development. The Guelph Permeameter (GP) is a popular auger-hole method for *in-situ* measurement of soil hydraulic properties (Reynolds, 2008; Reynolds and Elrick, 2002; Soil Moisture Equipment Corp., 2008; Reynolds, 2010; Reynolds, 2011). In essence, the technique involves augering an unlined well into unsaturated zone, ponding one or more constant heads of water in the well, and measuring the steady 3-dimensional discharge of water out of the well into the surrounding unsaturated soil. From the ponded head and discharge data, estimates of field saturated soil hydraulic conductivity (K_{fs}), soil matric flux potential (φ_m), soil sorptivity (β) and recharge rate (Q) were obtained. The GP theory is applicable to all types of unsaturated porous media; however, practical difficulties can arise in gravelly materials where augering can be problematic and in uncohesive materials where the well collapses during the augering process or upon wetting. Although well collapse can be avoided by inserting a removable well screen or by back-filling pea-gravel or coarse sand around the GP outflow tube (Reynolds, 2008), these procedures are both time consuming and impractical for wells deeper than about 1-2 m. Paige and Hillel (1993); Gupta *et al.* (1993); Kanwar *et al.* (1989) and Lee *et al.* (1985) addressed this problem for different methods under different field conditions. Paige and Hillel (1993) compared the performance of three K_{fs} measuring methods (GP, instantaneous profile method, and core method) for two soils in western Massachusetts. Gupta *et al.* (1993) conducted a similar study with four *in-situ* methods (double-ring infiltrometer, rainfall simulator, GP and Guelph Infiltrometer) in Ottawa, Canada. Kanwar *et al.* (1989) compared the performance of the GP and a velocity permeameter in a glacial till soil of Central Iowa. Lee *et al.* (1985) made a comparative study to evaluate the performance of an air-entry permeameter, GP and falling-head soil core permeameter in southern Ontario, Canada. Since no such work for estimation of ground water recharge has been done in Sonar sub-basin, an attempt has been made in the present analysis for better understanding of ground water status in this region.

2. MATERIALS AND METHODS

Study Area

The study area covers the Sonar sub-basin Sagar district having an area of 1538 km^2 and extends between 23°21'14" to 23°50'05" N latitude and 78°35'48" to 79°10'50" E longitude, which can be viewed in the Survey of India toposheets No. 55M, 54L and 54P. The basin has a perimeter of 284 km and basin length of 72.12 km as given in Fig.1. The area falls under semi-arid to sub-tropical region. Landscape of the region is rugged, undulated terrain with low rocky outcrops, narrow valleys and plains. Large portion of this region falls under rainfed agriculture. The forest type is of dry deciduous type. Drought frequency encountered in the region is one in every five years. Limited soil depth is found in the region. Average annual rainfall of the region is about 1100 mm. The number of rainy days on an average is 45. The average annual potential evapotranspiration is 1852 mm. The mean temperature varies from 18 to 33ºC annually. The mean relative humidity varies from 27 to 85%. The mean wind speed in the region varies between 4.13 km h^{-1} in Nov. to 8.45 km h^{-1} in July.

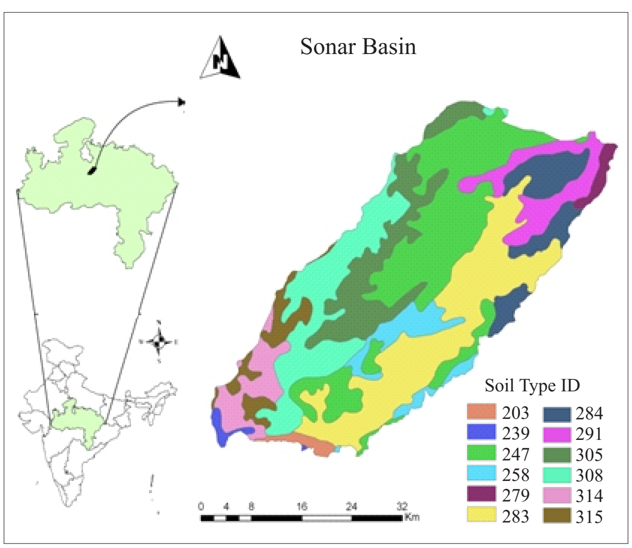

Fig.1. Index map showing location of study area

Measurement of *in-situ* Saturated Hydraulic Conductivity using a GP

There are different methods for determination of hydraulic properties of soil as given in Fig. 2. The GP as shown in Fig. 3 is an in-hole mariotte bottle device for measuring the rate of water influx into most types of soil or other porous medium. It can be used to estimate one or more hydraulic properties of the material, including the saturated hydraulic conductivity (K_{fs}), soil sorptivity (β), soil matrix flux potential (φ_m) and recharge rate (Q).

The GP method measures the steady state rate of water movement, Q (cm^3s^{-1}), necessary to maintain a constant depth of water, H (cm), in an uncased cylindrical well of radius, a (cm), above the water table. A GP measures saturated hydraulic conductivity by applying a constant pressure within a borehole or shallow hole. Like the tension infiltrometer (tensiometer), it applies a constant head using a mariotte bottle, infiltrates water into an unsaturated material, and requires steady state flow conditions before the measurements. It differs from the tension infiltrometer in that it applies a positive pressure, instead of a tension, and does not utilize the (Weir, 1987) solution to calculate the saturated hydraulic conductivity.

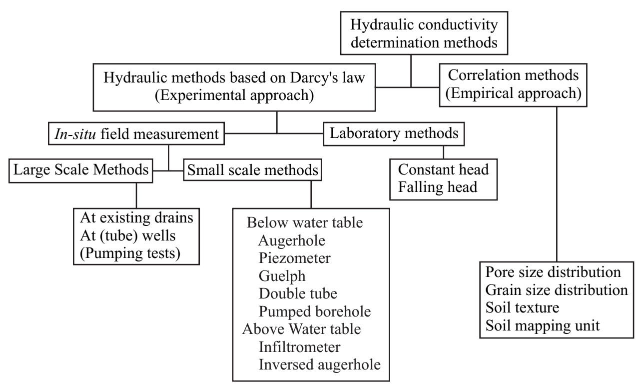

Fig. 2. Different methods for determination of hydraulic conductivity

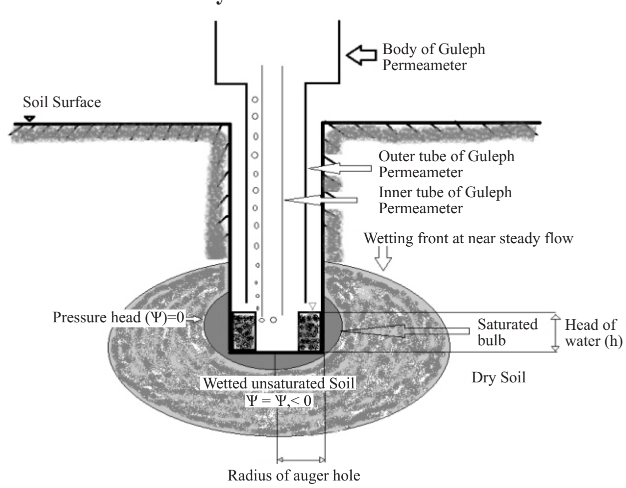

Fig. 3. Guleph Permeameter saturated bulb and wetting front surrounding the auger hole

Principle and Theory for GP Method

The GP description of steady state, constant head discharge of water, Q (cm^3s^{-1}), from an uncased well into unsaturated soil is given by Reynolds, 2008; Reynolds and Elrick, 2002; and Reynolds *et al.,* 1985.

$$Q = \frac{2\pi K_{fs}}{C_A} H^2 + \frac{2\pi K_{fs}}{\alpha^* C_A} + \pi a^2 K_{fs} \quad ...(1)$$

Where, K_{fs} (cm s^{-1}) is field-saturated soil hydraulic conductivity, α^* (cm^{-1}) is soil sorptive number for ponded infiltration, H (cm) is the steady water head (ponding depth) in the well, a (cm) is well radius and C_A is a shape function with the approximate analytic form:

$$C_A = \sinh^{-1}\left(\frac{H}{a}\right) - \left[\left(\frac{a}{H}\right)^2 + 1\right]^{1/2} + \left(\frac{a}{H}\right) \quad ...(2)$$

The first term on the right of Eq. (1) represents discharge due to the hydrostatic pressure of the ponded water in the well, the second term represents discharge due to the capillary suction of the surrounding unsaturated soil and the third term represents gravitational discharge out through the base of the well. Extensive numerical simulations by Reynolds (1986) showed that although the GP shape function depends primarily on the H/a ratio (as implied by Eq. (2), it also depends somewhat on soil capillarity (as parameterized by α^*). As a result, the working GP shape function is often represented by empirical C_{GP} vs. H/a expressions, such as (Reynolds, 2008; Zhang *et al.,* 1998):

$$C_{GP} = \left[\frac{(H/a)}{Z_1 + Z_2 (H/a)}\right]^{Z_3} \quad ...(3)$$

Where, for negligible to moderate soil capillarity ($\alpha^* \geq$ 9 m^{-1}), Z_1= 2.074, Z_2=0.093 and Z_3=0.754; for strong soil capillarity ($\alpha^* \approx$ 4 m^{-1}), Z_1=1.992, Z_2=0.091 and Z_3=0.683; and for very strong soil capillarity ($\alpha^* \approx$ 1 m^{-1}), Z_1=2.081, Z_2=0.121 and Z_3=0.672. The constants (Z terms) are usually obtained by regression-fitting Eq. (3) to numerically determined C_{GP} vs. H/a relationships in Reynolds (1986) and elsewhere. Note also from Eq. (3) that the C_{GP} vs. H/a relationship is effectively independent of soil capillarity for $\alpha^* \geq 9\ m^{-1}$ (Reynolds, 1986; Reynolds and Elrick, 1987).

The field saturated hydraulic conductivity and matrix flux potential can be calculated using following equation.

$$K_{fs} = \left[\frac{CAR}{\left\{2\pi H^2 + C\pi a^2 + \left(\frac{2\pi H}{\alpha^*}\right)\right\}}\right] \quad ...(4)$$

$$\varphi_m = \left[\frac{CAR}{\left[\left(2\pi H^2 + C\pi a^2\right) + 2\pi H\right]}\right] \quad ...(5)$$

Where, C is a dimensionless shape factor, A is the cross sectional area of GP reservoir (cm^2), R is the steady state fall of water level in GP reservoir (cm s^{-1}), π is a constant (≈ 3.14), H is the steady depth of water in well of bore hole (cm), and a is the radius of well (cm).

$$\alpha^* = \left[\frac{Soil\ Texture}{Structure\ Parameter}\right] (cm^{-1}) \quad ...(6)$$

The different soil groups selected for determination of *in-situ* saturated soil hydraulic conductivity were categorized into four different classes based on the soil structure and texture characteristics of soil. Therefore, different soil groups were categorized into four classes based on characteristics for determination of micro-capillary length factor which will be used for calculation of *in-situ* saturated soil hydraulic conductivity at various locations in the Sonar sub-basin.

3. RESULTS AND DISCUSSION

The results obtained from study show that there is a large variation in soil saturated hydraulic conductivity which was found maximum for Basa reserve forest ($5.55\times10^{-04}cms^{-1}$) and minimum for Jaitpurakachhia ($3.27\times10^{-05}cms^{-1}$) as given in Fig. 5(a); however, relative permeability shows that aquifer belongs to semi-pervious category. The soil matrix flux potential was maximum for Bijaypura ($1.58\times10^{-03}cm^2min^{-1}$) and minimum for Kukwara ($1.39\times10^{-04}cm^2min^{-1}$) as given in Fig.5(b). The soil sorptivity was found maximum for Basa reserve forest (5.34×10^{-02}cm $min^{-1/2}$) and minimum for Swakara (6.35×10^{-03}cm $min^{-1/2}$) as given in Fig. 5(c). The recharge rate was found maximum for Basa reserve forest (2.62×10^{-01} cm^3s^{-1}) and minimum for Dhana (4.8×10^{-02} cm^3 s^{-1}as given in Fig. 5(d). The simple mean values of soil saturated hydraulic conductivity, soil matric flux potential, soil sorptivity and recharge rate for Sonar sub-basin were 17.29×10^{-05}cm s^{-1}, $8.99\times10^{-04}cm^2$ min^{-1}, 2.19×10^{-02}cm $min^{-1/2}$ and $1.27\times10^{-01}cm^3s^{-1}$, respectively. The weighted mean value of *in-situ* saturated soil hydraulic conductivity, soil matric flux potential, soil sorptivity and recharge rate for sonar sub-basin were 8.95×10^{-05} cm min^{-1}, $1.73\times10^{-04}cm^2s^{-1}$, 2.12×10^{-02}cm $min^{-1/2}$ and $1.09\times10^{-01}cm^3s^{-1}$, respectively. Fig. 4 shows the average steady rate of water movement in soil, only two sites Basa reserve forest and Ramkheri have much higher average steady rate of water movement in soil. The sites Dhadhoniya, Bijaypura and Swakara were found to have slightly more than average steady rate of water movement in soil, whereas all other sites have much less than average steady rate of water movement in soil. However, most of sites have poor

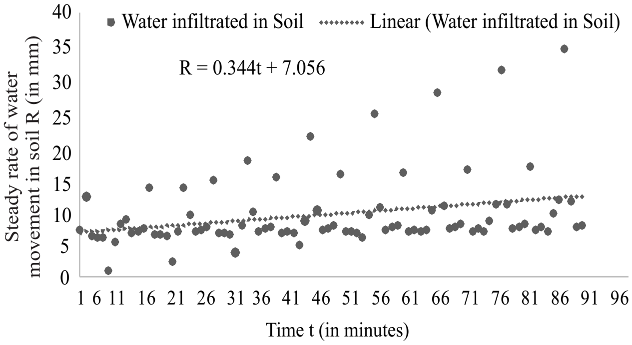

Fig. 4. Steady rate of water movement in soil for Sonar sub-basin

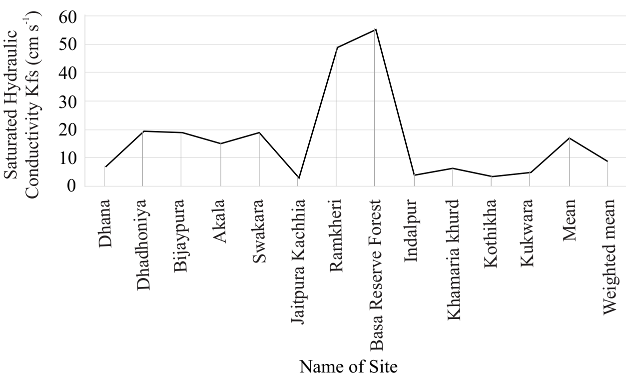

Fig. 5(a). Saturated hydraulic conductivity in Sonar sub-basin

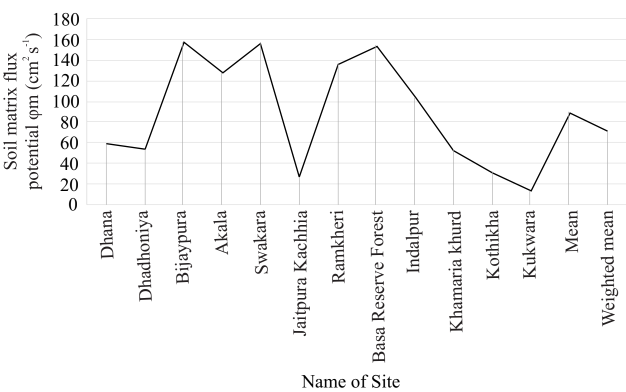

Fig. 5(b). Soil matrix flux potential in Sonar sub-basin

saturated hydraulic conductivity, soil matrix flux potential and soil sorptivity which shows that there is insufficient natural ground water recharge in Sonar sub-basin. The hydraulic conductivity values obtained from different sites located in Sonar sub-basin can be beneficially used for selecting sites for economical construction of dug wells and tube wells. The sites Basa reserve forest and Ramkheri shows good potential for recharge because they have high saturated hydraulic conductivity, soil matrix flux potential and soil sorptivity therefore, these sites can be used for augmenting artificial ground water recharge.

The results obtained through single head inner and combined are shown in Table 1 and Table 2, respectively

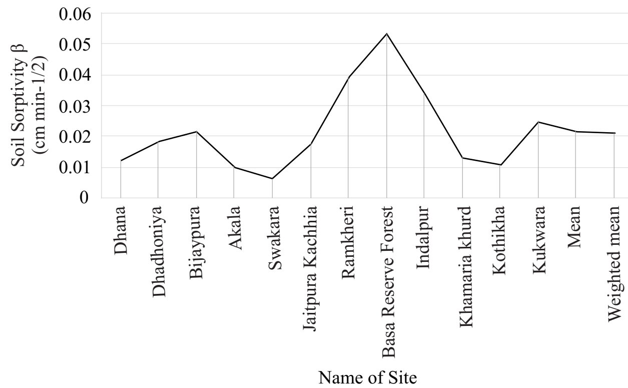

Fig. 5(c). Soil sorptivity in Sonar sub-basin

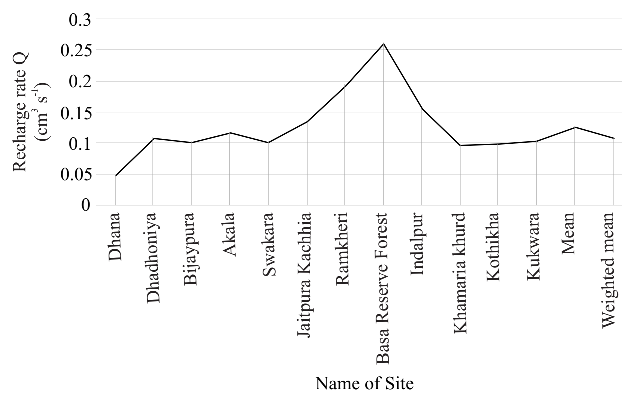

Fig. 5(d). Recharge rate in Sonar sub-basin

Table: 1
Values of aquifer parameters for single head and inner reservoir in Sonar sub-basin

Name of site	S	(R)	(α*)	(C)	(Q)	(K_{fs})	(φ_m)
Dhana	3	0.1678	0.12	0.8031	0.006	1.1	9.16
Dhadhoniya	4	0.1568	0.36	0.8031	0.0056	1.7	4.70
Bijaypura	3	0.2489	0.12	0.8031	0.0089	1.63	13.60
Akala	3	0.2679	0.12	0.8031	0.0096	1.75	14.60
Swakara	3	0.2989	0.12	0.8031	0.0107	1.96	16.30
Jaitpurakachhia	3	0.0695	0.12	0.8031	0.0025	0.455	3.79
Ramkheri	4	0.9092	0.36	0.8031	0.0327	9.84	27.30
Basa reserve forest	4	0.9997	0.36	0.8031	0.0359	10.8	30.00
Indalpur	2	0.1254	0.04	0.842	0.0045	0.393	9.84
Khamariakhurd	3	0.1009	0.12	0.8031	0.0036	0.661	5.52
Kothikha	3	0.0988	0.12	0.8031	0.0035	0.647	5.39
Kukwara	4	0.0896	0.36	0.8031	0.0032	0.97	2.69

Single Head, Inner reservoir, Head (H)=5 cm, Borehole radius (a)=3 cm

Table: 2
Values of aquifer parameters for single head and combined reservoir in Sonar sub-basin

Name of site	S	(R)	(α*)	(C)	(Q)	(K_{fs})	(φ_m)
Dhana	3	0.208	0.12	1.2875	0.122	13.20	110.00
Dhadhoniya	4	0.4086	0.36	1.2875	0.2398	36.80	102.00
Bijaypura	3	0.5689	0.12	1.2875	0.3339	36.20	302.00
Akala	3	0.4562	0.12	1.2875	0.2677	29.00	242.00
Swakara	3	0.5634	0.12	1.2875	0.3307	35.80	299.00
Jaitpurakachhia	3	0.0957	0.12	1.2875	0.0561	6.09	50.70
Ramkheri	4	0.9879	0.36	1.2875	0.5798	89.00	247.00
Basa reserve forest	4	1.112	0.36	1.2875	0.6527	100.00	278.00
Indalpur	2	0.2341	0.04	1.2902	0.1374	7.93	198.00
Khamariakhurd	3	0.1922	0.12	1.2875	0.1128	12.20	102.00
Kothikha	3	0.1093	0.12	1.2875	0.0641	6.95	57.90
Kukwara	4	0.1002	0.36	1.2875	0.0588	9.02	25.10

Single Head, Combined reservoir, Head (H)=10 cm, Borehole radius (a)=3 cm

indicate the similar conditions with a little variation from average values obtained for Sonar sub-basin. The higher values of soil sorptivity for sites Basa reserve forest and Ramkheri as in Fig. 5(c) indicate ease of sorption and desorption of water through capillary movement, hence are more appropriate for growing crops with high water requirement whereas other sites having lower values are suitable for growing crops with comparably less water requirement. The soil matric flux potential as given in Fig. 5(b) indicates available water to plants; therefore, soil having higher values like sites Bijaypura, Swakra, Basa reserve forest, Ramkheri and Indalpur shows good potential for growing crops with less chances of crop failure due to water scarcity than other sites. The Fig. 6 shows that South West part of the basin has higher *in-situ* saturated hydraulic conductivity as compared to other parts. The Fig. 7 indicates that South West and North East part of basin has higher soil matric flux potential. Hence they have more plant available water and hence suitable for growing most of the crops but in other parts there is a need for adopting suitable moisture conservation practices as well as provision for water harvesting for providing supplemental irrigation to crops during period of water scarcity. Similarly, Fig. 8 shows that south west part of basin has higher soil sorptivity signifying ease of soil sorption and desorption as compared to other parts. The higher value of sorptivity also implies that there is better potential for recharge and higher water availability in soil for growing crops. However, for other sites, there is a need for adopting suitable agronomic and mechanical measures for ensuring water availability during periods of dry spell or drought conditions. The similar conditions are also depicted by Fig. 9 showing good potential for recharge in South West part of basin supporting previous discussion for *in-situ* saturated hydraulic conductivity, soil matric flux potential and soil sorptivity for Sonar sub-basin. The weighted mean as well as simple mean as given in Table 3 reduced recharge rates at most of sites indicates that there is insufficient natural ground water recharge in basin indicating a need for

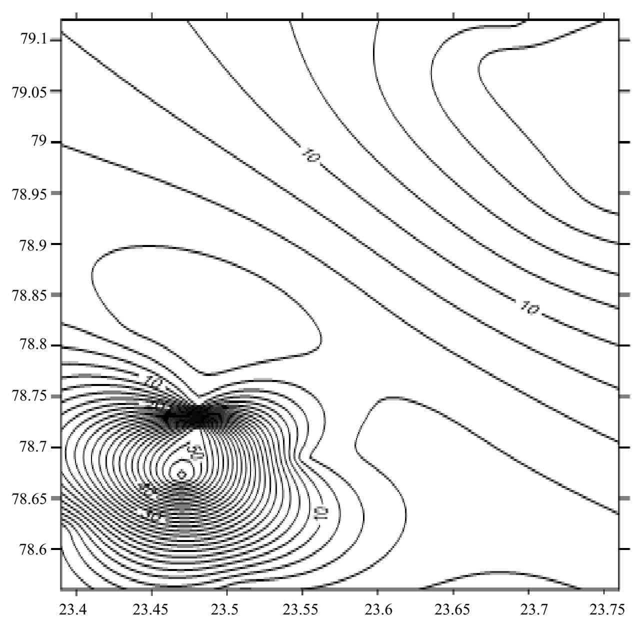

Fig. 6. Variation of hydraulic conductivity in Sonar sub-basin

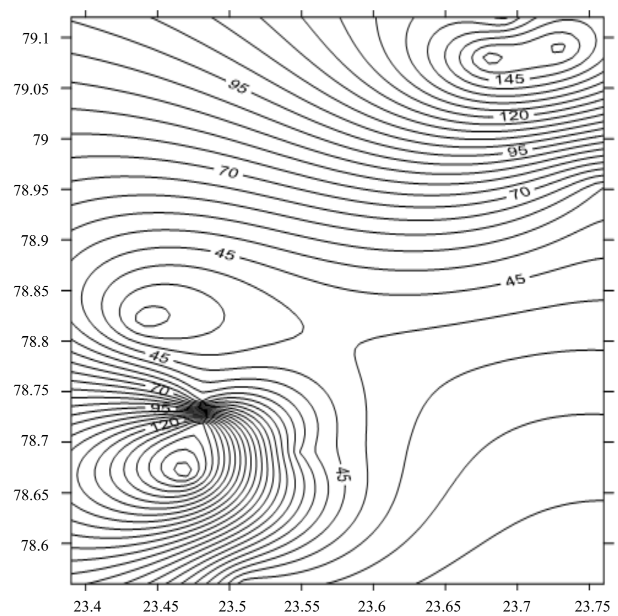

Fig. 7. Variation of soil matric flux potential in Sonar sub-basin

augmenting artificial methods to recharge depleting ground water resources in basin. The soil matric flux potential and soil sorptivity indirectly signifies availability of water for plant growth hence can be used for crop planning and selection of crop and cultivar suited for such conditions. The result obtained will help in adopting suitable soil and water conservation methods for efficient management of available water resources. The risk involved in timely availability of water especially during critical crop growth stages can be managed by adopting rain water harvesting in surface reservoirs as well as *in-situ* moisture conservation. The conjunctive use of water is required to attain sustainability.

The detailed description of all parameters for single head, inner reservoir test used in this study are: S is the soil texture-structure category/class (dimensionless), R is the steady state rate of water level change in inner reservoir at head H (cm min^{-1}), α^* is the microscopic capillary length factor (cm^{-1}), C is the shape factor at head H (dimensionless), Q is the recharge rate at head H (cm^3s^{-1}), K_{fs} is the soil saturated hydraulic conductivity ($\times10^{-05}$cm s^{-1}), and φ_m is the soil matric flux potential ($\times10^{-05}cm^2min^{-1}$). In case of combined reservoir test, R is the steady state rate of water level change in inner reservoir at head H (cm min^{-1}) and rest all other parameters are same as explained above.

4. CONCLUSIONS

The results indicate the importance of this study for understanding characteristics of aquifer that influence the availability of ground water and planning for conjunctive

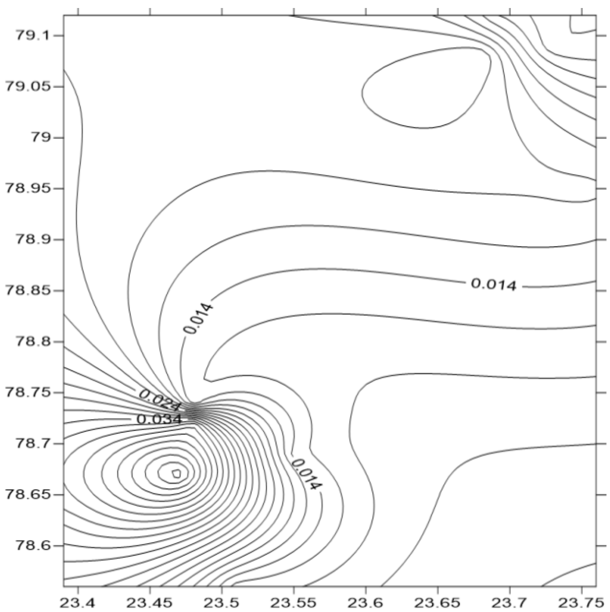

Fig. 8. Variation of soil sorptivity in Sonar sub-basin

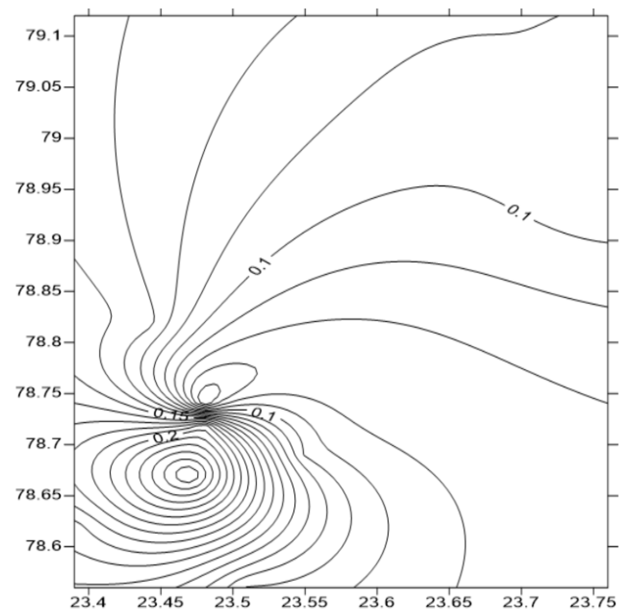

Fig. 9. Variation of recharge rate in Sonar sub-basin

Table: 3
Aquifer characteristics for various sites and their recharge rate in Sonar sub-basin

Name of site	Area of soil group (A)	Saturated hydraulic conductivity (K_{fs})	Soil matric flux potential (φ_m)	Soil sorptivity (β)	Recharge rate (Q)
Dhana	16900	7.16	59.70	0.0125	0.048625
Dhadhoniya	1500	19.50	54.20	0.01845	0.109628
Bijaypura	9600	18.90	158.00	0.02195	0.102525
Akala	1800	15.40	128.00	0.01015	0.11685
Swakara	10800	18.90	157.00	0.00635	0.102925
Jaitpurakachhia	7100	3.27	27.30	0.0177	0.135175
Ramkheri	1100	49.40	137.00	0.0395	0.19465
Basa reserve forest	1500	55.50	154.00	0.05335	0.26225
Indalpur	21300	4.16	104.00	0.03385	0.1554
Khamariakhurd	6900	6.44	53.70	0.01325	0.098325
Kothikha	5600	3.80	31.70	0.01095	0.099075
Kukwara	32600	5.10	13.90	0.02505	0.10415
Mean		17.29	89.87	0.02192	0.127465
Weighted mean	116700	8.95394	71.33633	0.02121	0.10966

Area of Soil group (A) in ha, Saturated hydraulic conductivity (K_{fs}) in $\times10^{-05}$cm s^{-1}, Soil matric flux potential (φ_m) in $\times10^{-05}cm^2s^{-1}$, Soil sorptivity (β) in cm $min^{-1/2}$, Recharge rate (Q) in cm^3s^{-1}.

use management in the Sonar sub-basin. The insufficient natural ground water recharge against excessive exploitation has created severe problems like unavailability of water during periods of prolonged dry spell, uneconomical construction of dug wells and tube wells, crop failure and reduction in crop productivity. These compelled the study to focus on recognizing the root cause of all these problems; hence it was decided to go for this case study. The results obtained show areas having higher *in-situ* soil saturated hydraulic conductivity, soil matric flux potential, soil sorptivity and recharge rate signifying good potential for augmenting artificial ground water recharge for combating such situations. The conjunctive use of surface and ground water resources will prevent situation from getting worse. There is a need of planning for adoption of artificial ground water recharge in areas having poor ground water potential and creating surface reservoirs to reduce dependability on ground water. For the sustained socio-economic development of the region, formulation and policy implementation related to water use are also needed.

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