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Understanding area specific recharge process from Vadoze zone resistivity variations – a case study in basalt watershed, Ujjain district, Madhya Pradesh

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ABSTRACT

Spatial variability in parameters used in groundwater resource estimation and budgeting over an area always compromised with averaging and distribution. Among the parameters, the natural recharge spatial variability found to influence critically in resource assessment. To understand the spatial variability in principal recharge component, an attempt is made to relate the vadoze zone characteristics by integrating results of natural recharge, injected tritium tracer studies, infiltration and electrical resistivity tomography over black soil covered basaltic Ghatiya watershed in Ujjain district, Madhya Pradesh. Analysis of recharge function at three sites representing upper (recharge area), middle and lower (discharge parts) is found to be a function of vadoze zone resistivity characteristics and an exponential function of infiltration rate. The relationship may help in getting the dependency in spatial distribution of recharge with limited spot recharge measurements and resistivity characteristics of vadoze zone of intervening areas and infiltration indices.

INTRODUCTION

The vadoze zone, also termed the unsaturated zone, is the part of earth between the land surface and the top of the phreatic zone, i.e., the position at which the groundwater is at atmospheric pressure. It comprises a complex arrangement of solid, liquid and gaseous phases, mostly interconnected. Water in the vadoze zone has a pressure head less than atmospheric pressure, and is retained by a combination of adhesion and capillary action. The porous matrix of the vadoze zone is the result of mechanical, chemical and biological weathering of the parent rock. The upper part of the vadoze zone is the most dynamic region, which controls the downward transport of mass and energy. The geologic framework of the vadoze zone is very complex, with a high degree of heterogeneity and anisotropy in its physical, hydrologic, and geochemical properties (Wilson et al., 1995). In hard rock granite terrain the vadoze zone may extend up to few tens of meters, with the soil depth restricted from few centimeters to few meters depending upon the rooting depth. Basaltic rocks of Deccan traps, occupy the most extensive tract of Western Peninsula covering large parts of Maharashtra, Gujarat, Madhya Pradesh and Andhra Pradesh. Deccan basalts popularly known as Deccan Traps consist of vast pile of bedded lava flows. These lava flow beds have two district horizons. The lower one is massive and the upper comprises vesicular basalts. The massive part of basaltic rocks is hard and compact, whereas the vesicular part is characterized by vesicles as cavities filled with secondary minerals. The massive traps are fractured and jointed at places. The weathering/ fracturing of massive and vesicular basalts are favorable zones for surface and sub-surface storage. Black soils, locally called black cotton soils, and internationally known as 'tropical black earths' or 'tropical chernozems' have been developed by the weathering of the Deccan lava. The zone that contains clayey soil (black soil), followed by weathered pulverized fractured vesicular/ massive basalt, between the ground surface and the fluctuating ground water levels is marked as vadoze zone. The black color is attributed to the presence of titaniferous magnetite, compounds of iron and aluminum, accumulated humus and colloidal hydrated double iron and aluminum silicate. In general, these soils have clayey texture; average clay content being 50% and the range being 40-50%. Except in cases where there is stratification, the clay content down the profile is uniform. In general, these soils are rich in iron, lime, calcium, potash, aluminum and magnesium carbonates but poor in nitrogen, phosphorus and organic matter. Because of their high clay content, black soils develop wide cracks during the dry season, but their iron-rich granular structure makes them resistant to wind and water erosion. They are also highly moisture-retentive, thus responding well to irrigation.

Natural groundwater recharge, which is an important process that refills aquifers, generally occurs through the vadoze zone from precipitation. Natural groundwater recharge estimation is a basic pre-requisite for proficient groundwater resource management. The various sources of natural recharge are: rainfall, return flow from applied water irrigation, seepage through streams and ponds. Infiltration of monsoon precipitation through unsaturated zone is the principal source of natural recharge to shallow aquifers. Sustainable exploitation of groundwater resources necessitates improved understanding of recharge processes (Scanlon et al., 2002). The task of estimating recharge is challenging in areas that are undergoing development, the prevailing heterogeneities of aquifers and variability in rainfall patterns (Scanlon et al., 2006).

Several conventional methods are available for recharge estimation such as groundwater balance, water table fluctuation, soil water balance and chloride mass balance (Sophocleous, 1991; Moon et al., 2004; Dewandel et al., 2006; Batelaan and Smedt, 2007; Sibanda et al., 2009). These methods require analysis of huge volume of hydrological data such as precipitation, surface runoff, evapo-transpiration, and change in groundwater storage accumulated over a considerable time span, which is generally inadequate or lacking or unreliable in many areas. The water level fluctuation is linked with several factors such as base flow, precipitation, and irrigation return flow, seepage from surface water bodies' viz., lakes and ponds. In addition, measuring the water level in the area with dense network of pumping wells is a difficult task, mostly influenced by pumping wells and, thus, the measurement may not reflect the actual peizometeric head.

Isotope tracer technique, a direct method for estimation of groundwater recharge and soil moisture transport, obviates the above mentioned difficulties to some extent and therefore, it has been extensively used in various geological terrains throughout the world by many researchers. The development of piston flow model for soil moisture transport (Munich et al., 1967; Munich, 1968; Zimmerman et al., 1967a, b; Rao, 1984; Datta et al., 1980); use of environmental tritium and stable isotopes for recharge estimation (Allison and Hughes, 1978; Sukhija and Rama, 1973; Dincer et al., 1974; Sharma and Hughes, 1985); use of injected tritium for soil moisture transport and natural recharge measurement effected by rainfall in catchment scales (Datta et al., 1973; Gupta and Sharma, 1984; Sharma and Gupta, 1987; Athavale et al., 1980, 1983, 1992, 1998; Athavale and Rangarajan, 1988; Rangarajan and Athavale, 2000; Rangarajan et al., 2005, 2009; Muralidharan et al., 1988); understanding the process of recharge (Sukhija et al., 2003); estimation of recharge and its dependency on sub-surface geo-electrical parameters (Ramesh Chand et al., 2004; Singh et al., 2004; Hodlur et al., 2003); lithologically constrained rainfall (LCR) method for estimating spatial and temporal natural recharge distribution (Subash et al., 2011) are some of the developments/ uses of isotope tracer and geophysical techniques. In the present study, we have evaluated and studied the process of recharge to the basaltic aquifer in Ghatiya watershed located in Malwa Deccan Plateau of Central India through tracer and geophysical techniques.

Study area

Ghatiya watershed covering an area of 70 km^2 is located in Ujjain district in the State of Madhya Pradesh (Fig-1). The watershed area comprises black soils with argillaceous materials overlying flood basalts, forming part of Malwa Deccan Plateau region. The average seasonal rainfall of the watershed area is around 700 mm with very high annual variability. The watershed area drained from west to east has elevation of 520 m amsl in the west to 480 m amsl in the east. Geomorphologically, the watershed comprises plateau basalts, pediments, denudational hills, shallow pediplains and moderate pediplains (Fig-2). The thickness of the top black soil varies from 0.5 m in the western part to 3.0 m in the eastern part. The thickness of weathered zone varies from few meters to 20 m. The drainage pattern is sub-dendritic to structural controlled

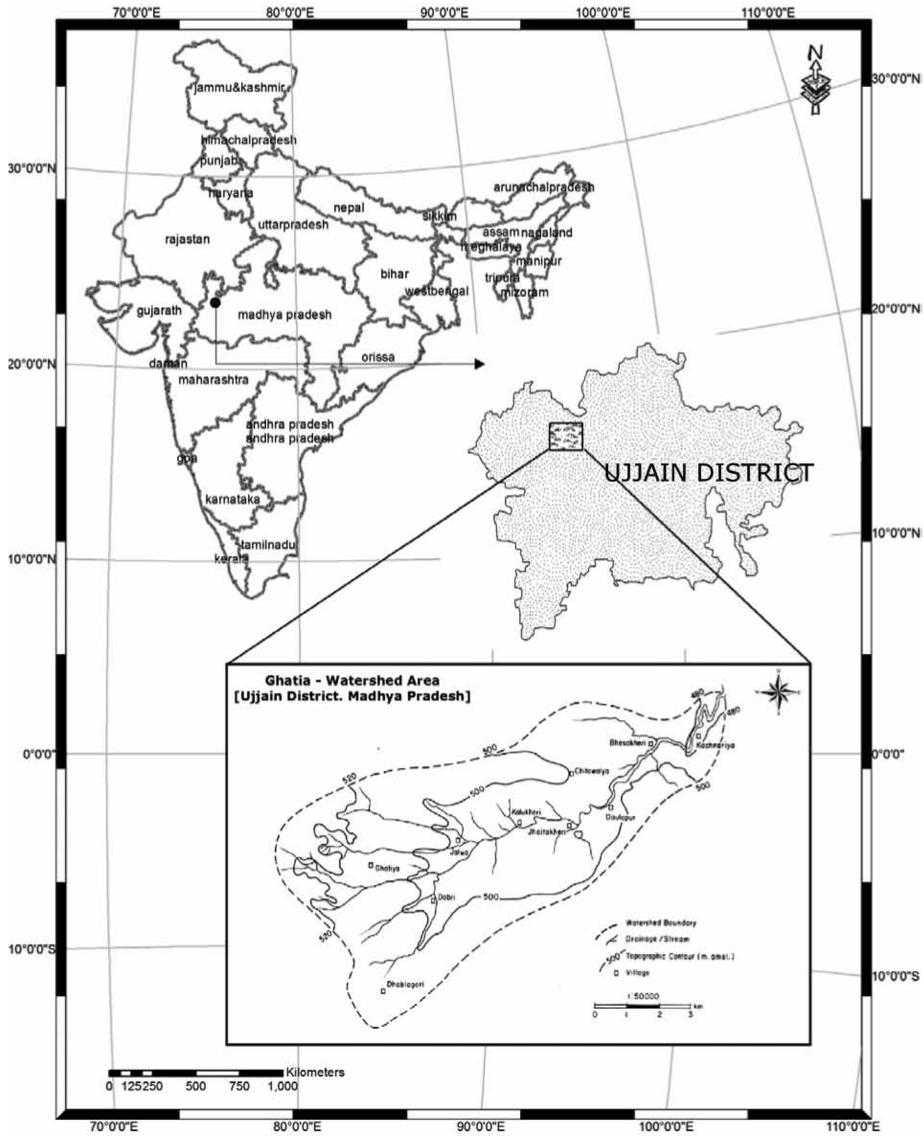

Figure 1. Ghatia Watershed, Ujjain district, M.P

nature. Most part of the watershed area is irrigated using groundwater as the main source for Rabi crops. Significant groundwater recharge takes place over the watershed area as reflected by water level rise observed immediately after monsoon. After a good monsoon year, the groundwater level reaches very shallow level quickly. It is observed that the decline of static water level is also rapid during post monsoon period. Most of the open wells in the watershed area generally dry up during pre monsoon months. The major Rabi crops sown in the watershed area are Soya Bean and Wheat. The major irrigation problem of the watershed is inadequate groundwater availability even for intermittent irrigation requirement of Rabi crops. Due to non-availability of water resources, the agriculture is practiced in a limited area adjoining the major streams. In order to improve the sustainability of groundwater resources for drinking and agriculture, integrated geohydrological studies have been carried out to map the various parameters that influence the groundwater regime and to suggest effective measures for improving the sustainability of the resource to stabilize the agriculture.

INTEGRATED STUDIES

Natural Recharge

Tritium, the radioisotope of hydrogen (max energy: 18 KeV, half life: 12.43 years), is an ideal tracer

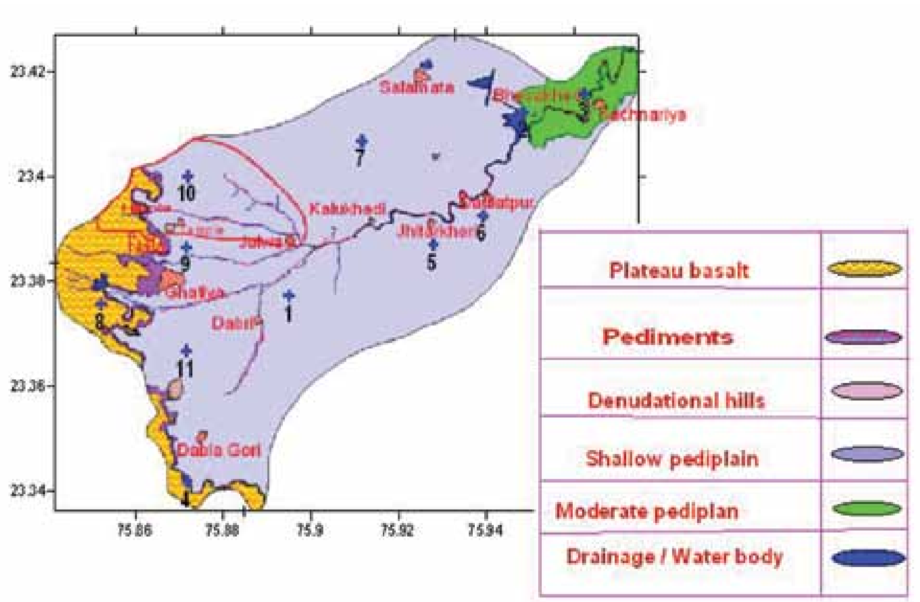

Figure 2. Geomorphological map of Ghatia Watershed with experimental sites

for soil moisture movement studies. Both the environmental tritium method and injected tritium method have been practised for evaluating natural recharge rates of groundwater in India. The tritium injection method of estimating recharge is based on the assumption that soil moisture moves downwards in discrete layers. Any fresh layer of water added near the surface, due to precipitation or irrigation, would percolate by pushing an equal amount of water beneath it further down, and so on, such that the moisture of the last layer in the unsaturated zone is added to the groundwater (Athavale et al., 1980). In this technique, tritium is added at certain depth (50-60 cm) in the soil to avoid the root zone loss. The tracer then moves downwards along with the infiltrating moisture due to subsequent precipitation. Soil samples are collected as cores, using hand auger from the injection site after a chosen interval of time and subsequently the moisture content and tracer concentration are measured in the laboratory at various depth intervals. The displaced position of the tracer in the tritium depth profile is indicated by the peak in its concentration.

The recharge or the amount of water added per square centimeter of the soil, was calculated by determining the peak of tritium profile and the moisture content of the zone between the injection depth and depth of the displaced tritium spiked layer

$$Rr = \left[\frac{m_d}{(100+m_d)} \right] Y_w h \qquad \text{...... (1)}$$

R_r = Recharge
m_d =dry weight percent of soil moisture
γ_w = wet-bulk density of the soil in situ
h = displacement of tracer, i.e. the distance between injection depth and the centre of gravity of the profile.

Recharge coefficient (Rc) is the fraction of the precipitation or irrigation entering into the groundwater over the specific time interval and its formula is

$$R_c = R_r + \Delta t/(P+I) \text{ x } 100\% \qquad \text{.... 2}$$

P is precipitation during ‘Δt’, mm; and I is irrigation during ‘Δt’, mm. (Bingguo Wang, et.al, 2008).

Tritium tracer studies were carried out at 10 sites within the watershed area and recharge rates were assessed.

Natural recharge measurements over black soil covered basaltic terrain were studied in few watersheds/basins to estimate the natural ground water replenishment using Injected Tritium Technique (Athavale et al. 1983 and Rangarajan et al. 1994). The

Table-1: Natural Recharge Values in Basalt Terrain

S. No.	Basin/ Watershed	No. of sites	Range of recharge values (mm)	Mean recharge (mm)	Standard deviation (mm)	Coefficient of variation (%)
1	Jam basin, Nagpur district, Maharashtra (400 sq km)	25	9 - 265	131	234	178
2	Kukadi basin, Ahmednagar district, Maharashtra (1050 sq km)	19	0 – 135	46	73.5	160
3	Godavari basin, Aurangabad district, Maharashtra (1080 sq km)	24	0 - 208	53	55.8	105
4	Ghatiya watershed, Ujjain district, Madhya Pradesh (70 sq km)	10	51 – 320	171.0	39.2	22

results of earlier studies and the present Ghatiya watershed have been summarised and presented (Table-1).

The study results have shown high coefficient of variation of recharge rates measured within the basin area. In order to understand the ambiguity in adopting mean recharge as a function of recharge estimation over the area, the natural recharge sites were subjected with supporting studies in the Ghatiya watershed to understand the variation in natural recharge parameter from site to site when all the sites are experiencing the same rainfall and pattern.

Infiltration test

Part of rain water enters the soil surface and percolates into deeper layers during rainy days. However, the rate at which water enters into the soil surface is essentially controlled by the texture of the soil and time period of water availability. The maximum rate at which the soil is capable of absorbing water is its infiltration capacity. Usually, infiltration begins at a higher rate and decreases to a fairly steady level in time-domain. Several mathematical expressions describe infiltration rate behaviour, based on the physics of the fluid flow through porous media (Green and Ampt, 1911; Philip, 1957), while many defined as an empirical function (Kostiakov, 1932; Horton, 1940; Holtan, 1961; Smith et al., 1970). Among the physical expressions, Philip's two-parameter equation is the most attractive for its ease of computation; also the time can be expressed as an explicit function of cumulative infiltration or *vice versa* (Swartzendruber and Youngs, 1974).

The field investigation method generally followed for estimation of infiltration capacity of soil is the double-ring infiltrometer, which generally consists of two mild steel ring plates of fixed height and diameter. The double-ring infiltrometer used in our experiment had a height of 20 cm and diameters of 20 and 40 cm. The two circular ring plates were driven into the soil, one inside the other, uniformly without any tilt and undue disturbance of the soil, to a depth of 5 cm; the smaller ring was placed inside the larger ring keeping a uniform annular space between the two. Two point gauges are usually fixed, one in the centre and the other in the annular space between the two rings, in order to maintain the height of water added in the rings during the test (Rolland Andrade and Muralidharan, 2011). The infiltration rate (mm/h) at the various time intervals was measured at 10 tracer test sites in the study area and the stabilized infiltration rate was determined.

2D Resistivity Imaging Survey

The electrical resistivity method can be deployed for two different objectives: (a) to estimate the thickness and probable lithological sequences of any site through the vertical electrical sounding technique, and (b) to identify variations in lateral resistivity within the sub-surface at any site through the profiling technique. Resistivity is prone to transient change due to the addition or movement of moisture over an area for a considerable time. Resistivity measurements are normally carried out by applying electric current by means of two current electrodes (C1 and C2), and measuring the resulting voltage difference through

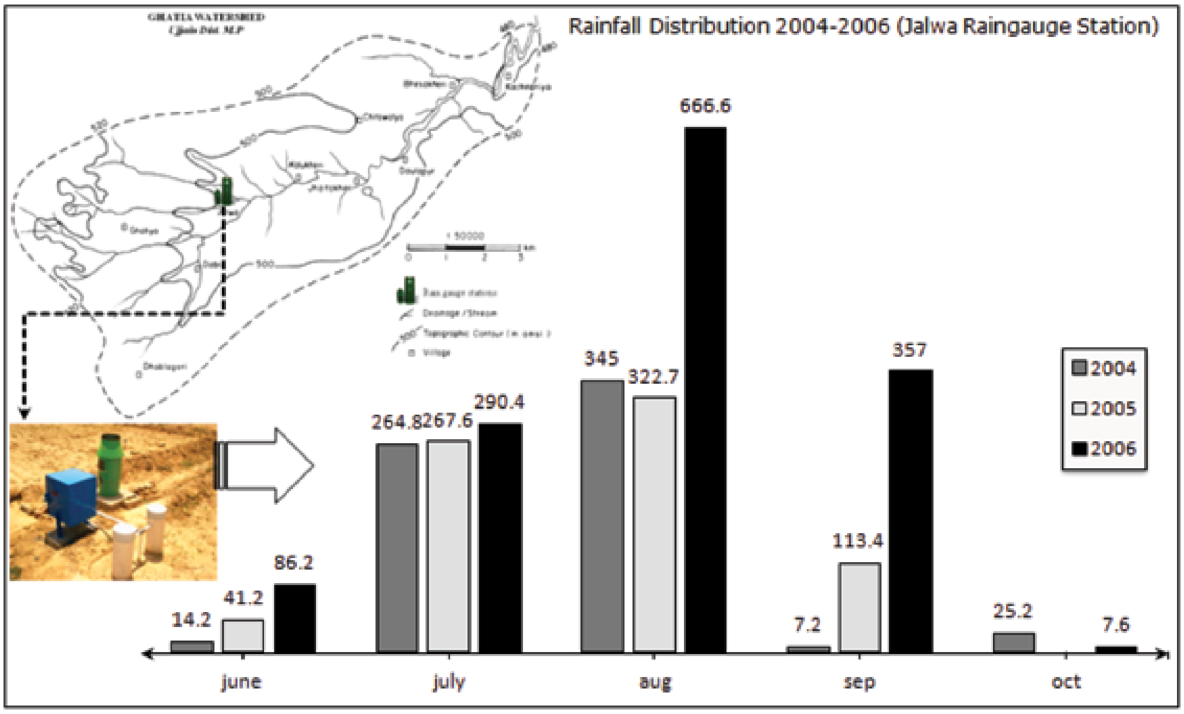

Figure 3. Seasonal rainfall at Jalwa rain gauge station within Ghatiya watershed (2004-06)

potential electrodes (P1 and P2). From the current (I) and voltage (U) values, an apparent resistivity (ρ_a) is calculated.

Scientific advances in the field of instrumentation in recent years have brought into use two-dimensional (2D) electrical resistivity imaging/ tomography surveying to map the sub-surface along a profile line with variable depths. This gives us a realistic model of the sub-surface in terms of resistivity changes pertaining to the sub-surface lithological variation, moisture migration, etc., in both the vertical and horizontal directions along a profile line. Two-dimensional resistivity imaging is generally carried out with a large number of electrodes (e.g., 40, 80, 120) connected to the relay system (electronic switching unit) to automatically select the electrode configuration for each measurement through a multi-core cable and a laptop (microcomputer). The resistivity imaging system is basically a combination of both electrical profiling and sounding that directly gives the resistivity image (true resistivity pseudo-section) all along a profile line of the area in two directions (x-spatial distance and z-depth). Based on the configuration selected during the survey, resistivity data are generated all along the profile. Using the RES2DINV inversion program, the apparent resistivity data collected are inverted and transformed into a 2D resistivity pseudo-depth model of the sub-surface. The resistivity imaging along a profile line length of 80 m at all tracer test sites has been carried out and the results are analyzed for characterizing the vadoze zone resistivity.

RESULTS AND DISCUSSIONS

The annual rainfall over the watershed area for the period 1995 to 2006 reflected a high variability with a poor rainfall of 322.8 mm in 2000 to a very high rainfall of 1627 mm in 2006. Further, a detailed analysis of rainfall revealed that nearly 65% of monsoon rainfall is contributed through few rainy day events, with excess rainfall, as against the normal monsoon. The rainfall data analysis of study area showed that rainfall during 2004, 2005 was marginally less than normal, whereas it was much above normal during 2006 (Fig-3). So, on an average the study area received below normal precipitation for the period 2003 to 2005 and received above normal precipitation in 2006. Water level in observation wells has shown a rise of few meters during the monsoon of 2004, 2005. Whereas, abnormal water level rise was observed during the monsoon of 2006. The rainfall

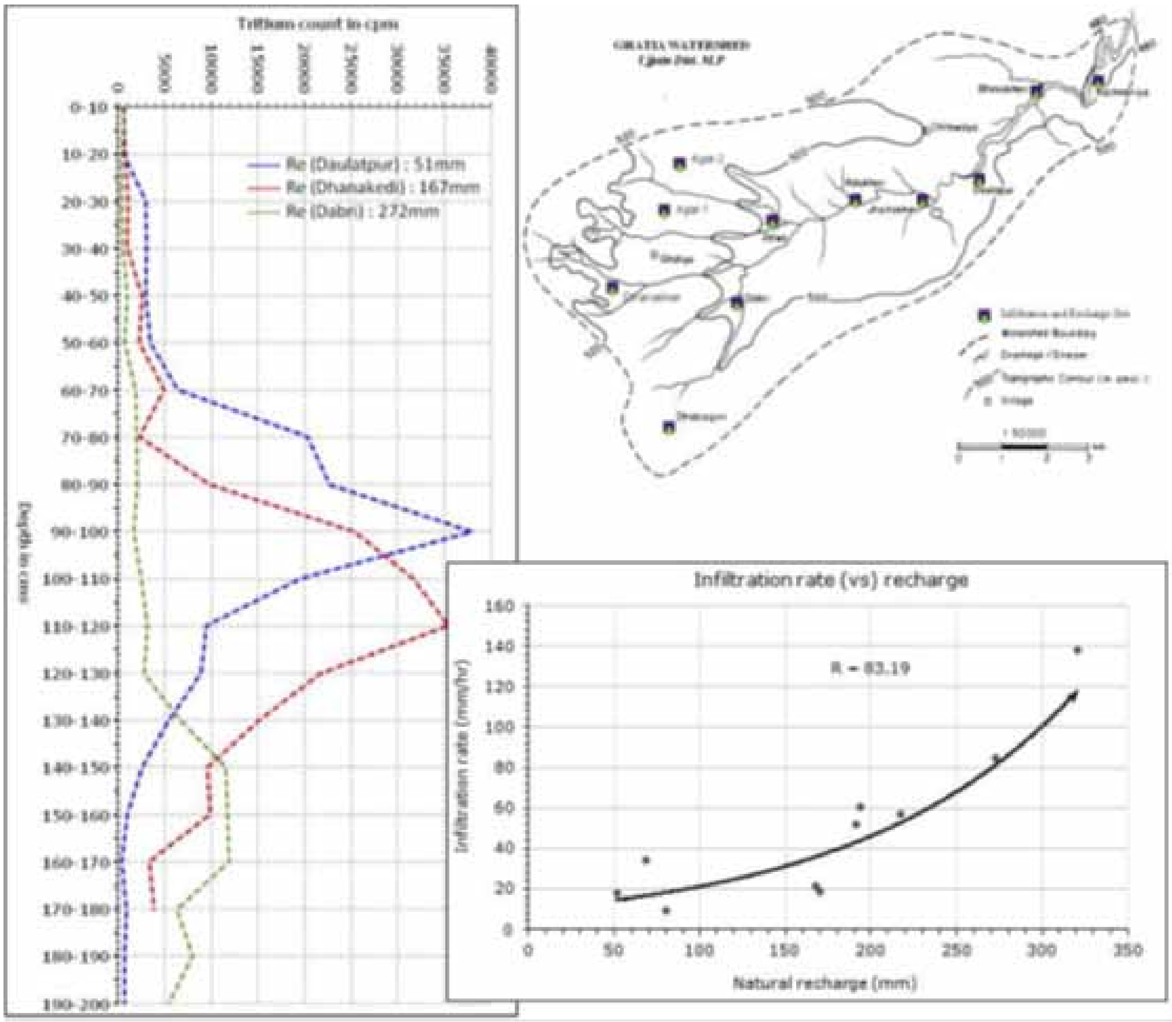

Figure 4. Tritium and infiltration sites in the study area with tritium profile and the correlation between infiltration (vs) recharge rates

and water level monitoring analysis reflected a very high groundwater recharge in Ghatiya watershed during 2006 when compared to 2004 and 2005.

Infiltration tests using double ring infiltrometer were carried out under constant head conditions and the rates calculated were in the range of 0.24 m/d to 3.3 m/d, indicating a large variation in black soil hydraulic properties. The recharge measurements estimated using injected tritium tracer technique has also shown a large variation within the watershed area. The recharge calculated and analyzed over the entire watershed varied from 51 mm to 320 mm for the rainfall of 616 mm during 2004 (Table-1).

Typical tritium profiles of 2004 with varying recharge rates observed over the watershed area is shown in Fig-4. In order to understand the relation between infiltrations and recharge rates, a correlation was attempted between these two parameters measured at several sites. An exponential relation was observed between recharge rate and infiltration rate with a correlation coefficient of 83.19% (Fig-4). The exponential relation shows that the infiltration capacity of top surface is ultimately controlling the percolation, which causes the recharge below the root zone. As per the relation obtained, it is explicitedly seen that the relation signifies that the recharge vector is higher in the infiltration rate range of 20–60 mm/hr and decreases as the infiltration rate increases. As the relation obtained is from field measurements, it is inferred that to augment the recharge, the traditional deep ploughing of surface by the agriculturist before the rainy season may not be required for black cotton soil covered areas. If adopted, this would considerably reduce the operational costs.

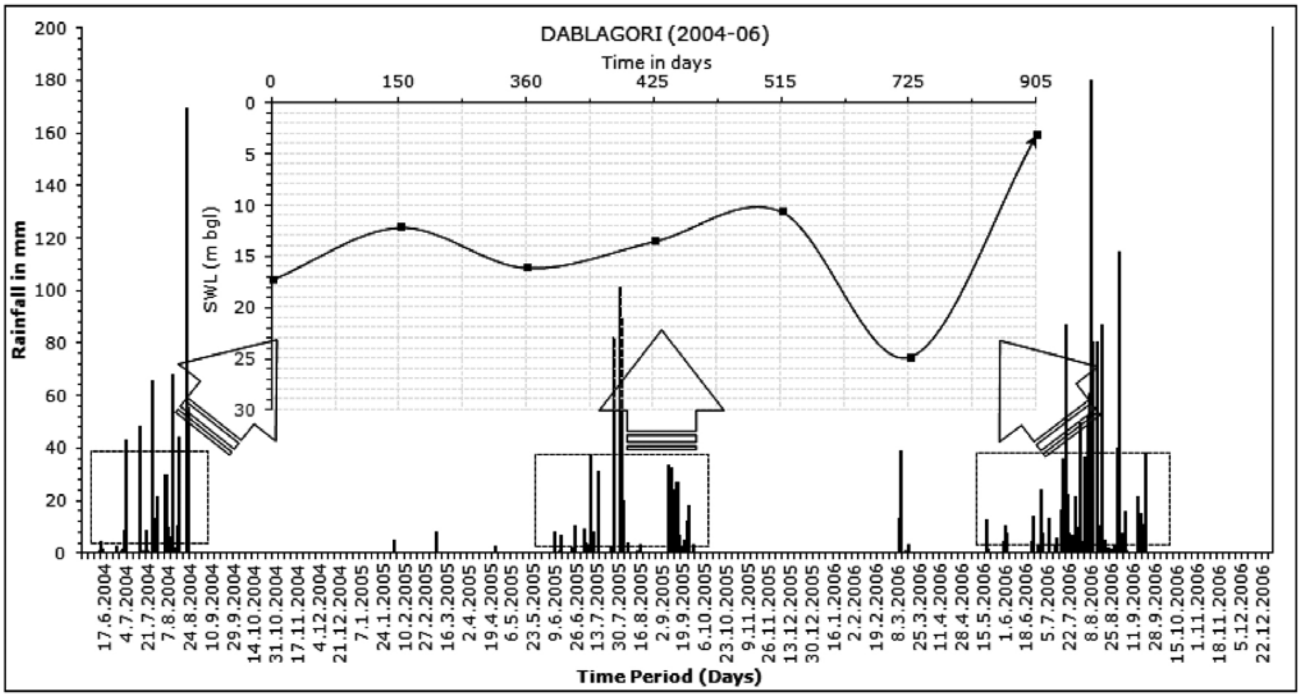

Figure 5. Daily rainfall with water level data at a site in the watershed

In 2006, the water table became very shallow at many of the dug well sites (up to 0.5 m below ground level). Water level monitoring over the three years of study clearly brought out the relation of rise in water level with respect to rainfall, which indicated indirectly the varying degree of recharge quantum. One of the monitored dug wells of Dablagori village is presented as an example of water level rise observed in a dug well and its relation with the rainfall (Fig-5). The moisture influx measurements have also shown very high recharge rate due to higher monsoon rainfall in 2006 due to which the tracer has moved beyond a depth of 240 cm (beyond collected soil core depth).

After establishing that the study area exhibits large spatial variation in infiltration and natural recharge rates, the bulk properties of sub-surface layers that constitute the vadoze zone (such as soil, highly weathered and moderately weathered and fractured vesicular basalt with partial saturation above the water table), through which the recharge processes occur during the monsoon was studied using resistivity imaging. Based on 2D resistivity survey interpretation, the geo-electrical properties of the sub-surface have been studied. It helped in establishing a relation between the natural recharge rate and resistivity of moisture infiltrating zone, as anticipated.

The survey carried out at 3 natural recharge sites shows various levels of natural recharge rates. The data analyzed using RES-2D inversion program generated true resistivity 2D image for the natural recharge sites. As the depth of investigation was aimed at mapping shallow vadoze zone resistivity variations, resistivity survey was carried out with 1 m electrode spacing at each investigated site. Calibration of resistivity imaging results was done by conducting survey with small inter-electrode spacing near dug wells, where the litho-stratification could be deciphered and thickness could be ascertained.

Basalts are electrically conductive in nature due to mineralogical composition. Since chemical composition variations are, in general, limited in a basaltic terrain of smaller dimension like in Ghatiya, only the physical conditions of basalt flow units control the conducting nature. Further, within a flow unit, various constituents of the physical division (namely vesicular, massive and amygdaloidal nature) would contribute together to the electrical characteristics, depending on the degree of saturation. It is often difficult in distinguishing these flow parts individually while interpretation of geo-electrical response. However, if the flow unit of considerable thickness is at very shallow depth level, closer spacing of observations may help us in picking up the representative contribution. Knowing these inherent constraints, the imaging studies were carried out with 1m electrode separation, to explore very shallow depth in which the tracer migration was expected.

The resistivity images generated at the three selected sites are presented in Fig-6. The shallow resistivity images to a depth of 6 m at all the three sites clearly mark different physical conditions within a flow unit along with top soil cover. At Site-1 (Dabri) with highest recharge rate of 272 mm, the first geo-electric layer of 10-20 Ohm-m resistivity near the top having a thickness of more than 2.5 m represents the top soil cover and highly weathered basalts with saturation followed by semi-weathered to fractured basalt**.** The injected tracer at this site due to monsoon moved beyond the first geo-electric layer and the volume moisture measured for the depth range of 200 cm showed higher moisture content (20-25%) within the tracer peak activity displaced zone of 150 cm. However, it reduced in depth range 150 to 200 cm. This signifies that the first layer of 2.5 m thickness delineated by the resistivity imaging is in a favorable condition for allowing the deep percolation of moving moisture front, which resulted in higher recharge rate. The resistivity ranges below the first geo-electric layer, has moderately favorable condition to accept the recharged water to form a water table aquifer extending to a depth of 5 m. Below 5 m, massive basalt part of the flow unit has been encountered.

At Site-2 (Dhanakhedi), the first geo-electric layer in which the injected tracer moved to a depth of 1.2 m is represented by weathered basalt with resistivity of 15 to 30 Ohm-m from 0.5 m to 1.5 m with a thin cap of soil cover. However, the resistivity imaging reflected the heterogeneity of the area at the surface itself by indicating that the left half of the area has exposed weathered basalt with moderate resistivity, while the right half of the profile line has a conductive soil cover with adequate thickness. The recharge site being at the center of the profile line, the observed volume moisture percentage in the range of 17-20 % in the tracer displaced zone (Fig-4) explains the lower order of recharge rate of 167 mm measured

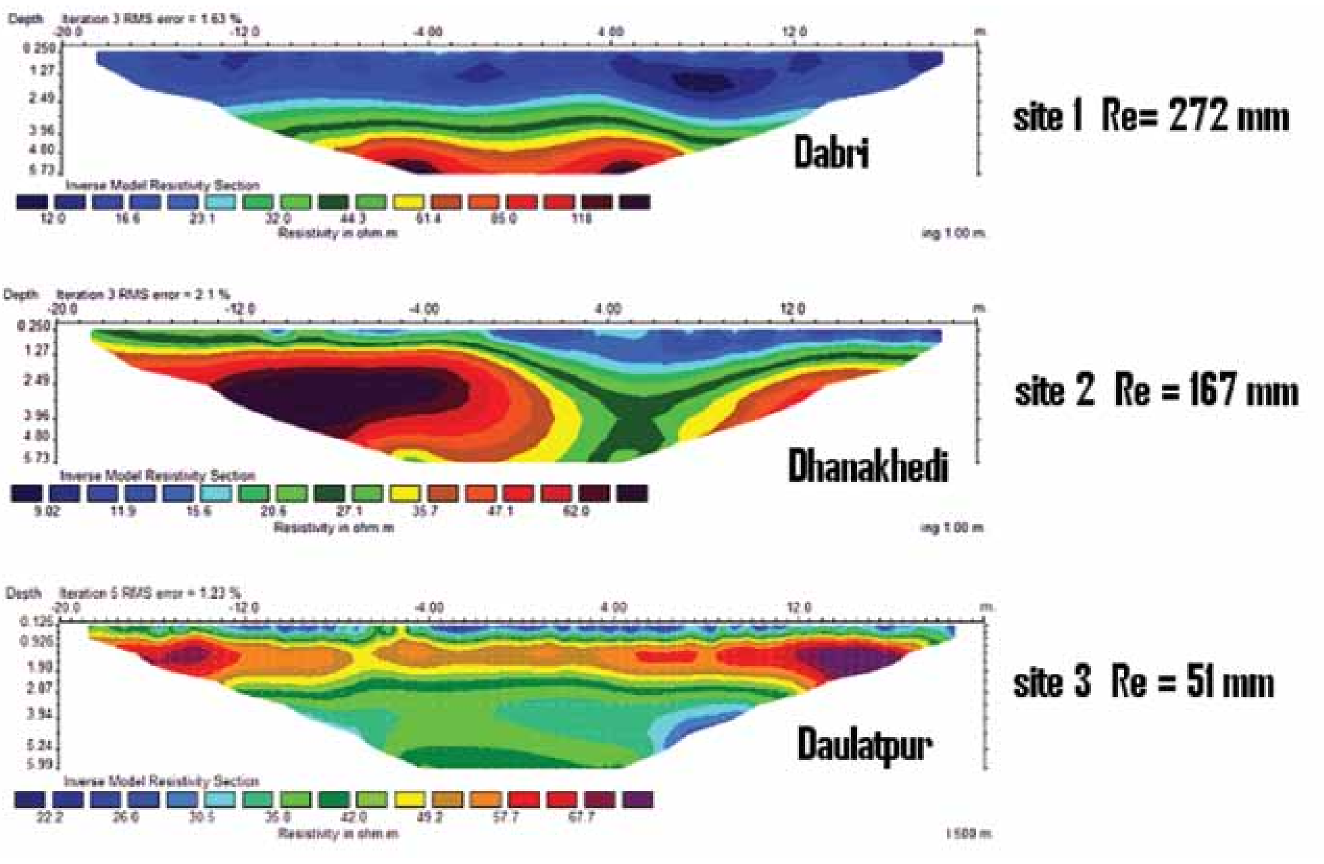

Figure 6. Resistivity imaging at natural recharge sites in Ghatiya watershed

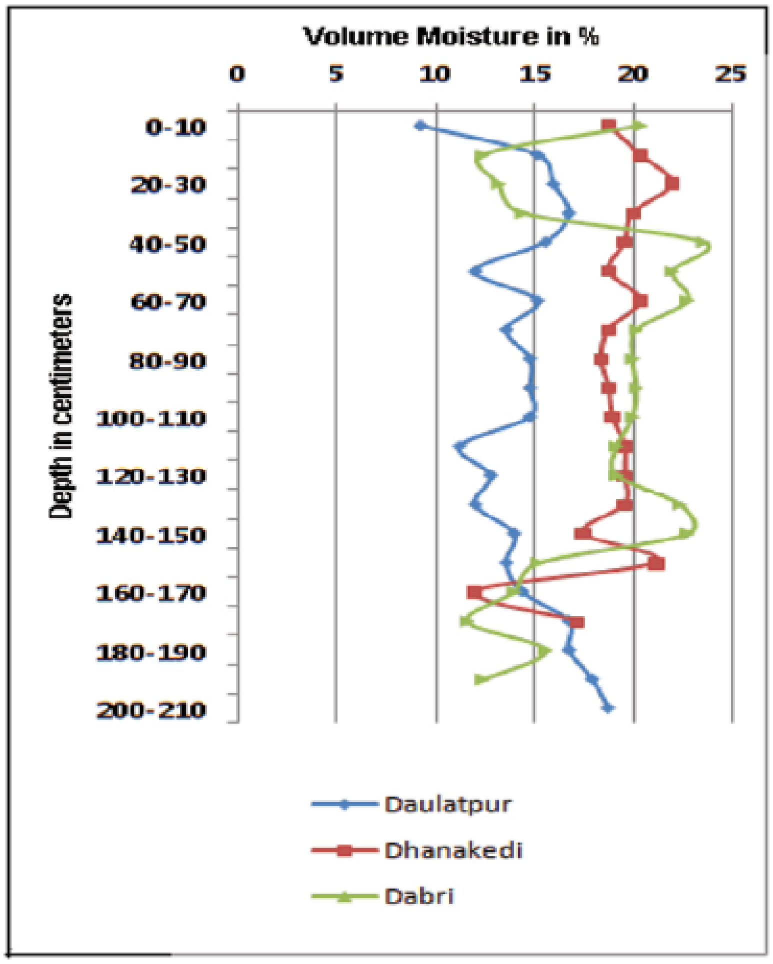

Figure 7. Depth volume moisture percentage at tracer injected sites

at this site. The volume moisture depth profile in Fig.7 shows an increasing trend from 100 cm depth onwards in which the tracer peak has been observed.

The resistivity imaging survey conducted at Site-3 (Daulatpur) has shown that the top layer in which the injected tracer movement of 0.9 m and a recharge of 51 mm is comparatively resistive, than the other two sites, at the shallow level itself with resistivity range of 25-40 Ohm-m. The tracer front could not move beyond 0.9 m probably due to existence of resistive stratum of > 45 Ohm m, which probably prevented the further downward movement of the tracer. However, after this thin resistive layer, presence of a conductive layer from a depth of 1.7 m onward to the investigated depth of 6 m suggests the presence of another basaltic flow unit. The geophysical signature of the top of this second flow layer (conductive in nature) is validated with the depth moisture profile, which clearly shows that the moisture content progressively increased from the depth of 170 cm. The poor recharge rate of 51 mm is attributable to the presence of resistive zone from 90 cm to 108 cm, which might have retarded the movement of tracer further downwards.

Using these three integrated examples, an attempt was made to characterize the variance in recharge rate with geophysical characteristics of the site. Fig-8 shows relationship of recharge rate, average volume moisture and the resistivity ranges of tracer displaced zone. The exercise helped in distinguishing three hydro-geologic processes, which could be characterized from resistivity ranges of shallow part of vadoze zone.

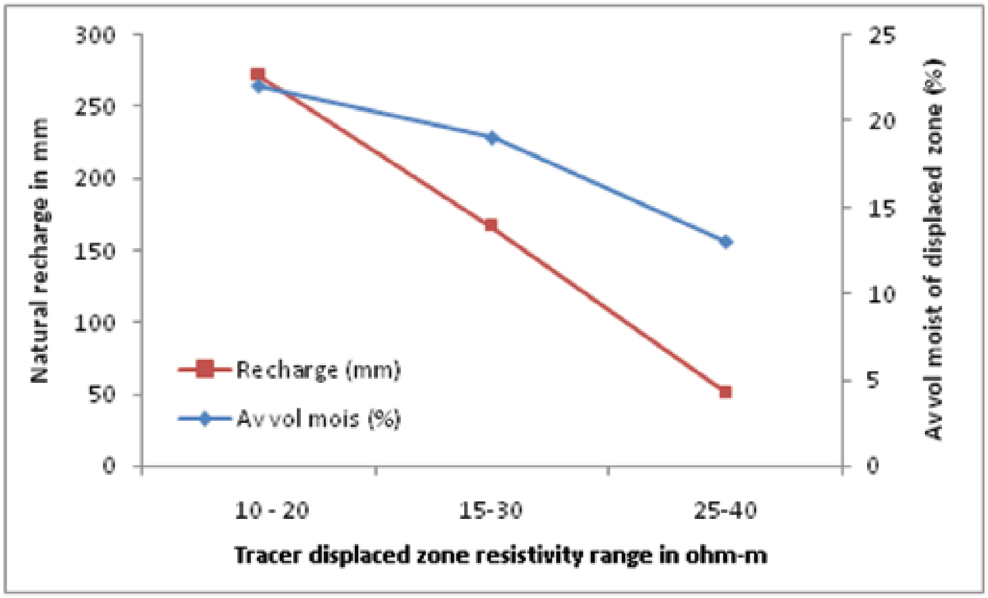

Figure 8. Relationship between resistivity, recharge and volume moisture

CONCLUSIONS

The results and the relationship found in site specific recharge with infiltration and the vadoze zone resistivity over the representative basaltic terrain of Indian subcontinent revealed that the natural recharge calculated and analyzed over the Ghatiya basaltic watershed in Ujjain district, Madhya Pradesh varied from 51 mm to 320 mm for the seasonal rainfall of 616 mm. The spatial variability in natural recharge is being characterized with hydraulic properties of soil and vadoze zone in terms of its infiltration capacity and thickness. Exponential relation between infiltration and natural recharge rate, depicts that natural recharge is a function of hydraulic characteristics of top shallow soil depth. Transient change in resistivity variation due to texture indicated that the natural recharge rate variation is attributable to the resistivity characteristics of the vadoze zone. It is also observed that as the resistivity of the tracer displaced zone increases, recharge and volume moisture decreases. The relationships could be used to estimate recharge over an area experiencing similar rainfall to certain extent over black soil covered basaltic terrains. High density measurement of natural recharge evaluation using injected tritium tracer can be minimized through established of this relation of infiltration with recharge for the black soil covered basaltic terrain by conducting short duration infiltration tests with more coverage of the area. One could better establish the varied nature of this relationship in time and space. The research study pointed out that in order to evaluate reliable estimation of recharge for a large basin or watershed, soil hydraulic conductivity followed by resistivity characteristics have to be adopted. It is opined that the outcome of this applied research may facilitate in reducing the ambiguity in groundwater resources estimation in basaltic terrains for a sustainable management of groundwater.

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REFERENCES

Allison, G.B., Huges,M.W. 1978. The use of environmental chloride and tritium to estimate total local recharge to an unconfined aquifer, Australian Journal of Soil Research, v.16, pp: 181–195.

Athavale, R.N., Murti, C.S., Chand, R. 1980. Estimation of recharge to the phreatic aquifers of the Lower Maner basin, India, by using the tritium injection method, Journal of Hydrology, v.45, pp: 185–202.

Athavale, R.N., Ramesh Chand and Rangarajan, R. (1983) – Ground water recharge estimates for the two basins in the Deccan trap basalt formation, Hydrological Sciences Journal, v.28, pp: 525-538.

Athavale, R.N. and Rangarajan, R. 1988. Natural recharge measurements in hard rock regions of semi arid India using tritium injection, Proceedings of International workshop on 'Estimation of Natural recharge to ground water', Antalaya, Turkey, 1987, pp:175-194.

Athavale, R.N., Rangarajan, R., Murlidharan, D. 1992. Measurement of natural recharge in India, Journal of Geological Society of India v.39, pp: 235–244.

Athavale, R.N., Rangarajan, R., Muralidharan, D. 1998. Influx and efflux of moisture in a desert soil during a one year period, Water Resources Research v.34, pp: 2871–2877.

Batelaan, O., Smedt, F. 2007. GIS-based recharge estimation by coupling surface– subsurface water balances, Journal of Hydrology, v.337, pp: 337–355.

Bingguo Wang, Menggui Jin, John R. Nimmo, Lei Yang, and Wenfeng Wang. 2008. Estimating groundwater recharge in Hebei Plain, China under varying land use practices using tritium and bromide tracers, Journal of Hydrology, v.356, pp:209– 222.

Datta, P.S., Goel, P.S., Rama, F.A., Sanghal, S.P. 1973. Groundwater recharge in western Uttar Pradesh, Proceedings of the Indian Academy of Science, v.78, pp:1–12.

Datta, P.S., Gupta, S.K., Sharma, S.C. 1980. A conceptual model of water transport through unsaturated soil zone, Mausam v.31, pp: 9–18.

Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J.C., Krishnamurthy, N.S. 2006. A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. Journal of Hydrology, v.330, pp: 260–284.

Dincer, T., Al-Murgin, A., Zimmerman, U. 1974. Study of infiltration and recharge through the sand dunes in arid zones with special to the stable isotopes and thermonuclear tritium, Journal of Hydrology v.23, pp: 79–109.

Green, W.H., and Ampt, G.A. 1911. Studies on soil physics, 1. The flow of air and water through soils, J. Agric. Sci., v.4, pp:1–24.

Gupta, S.K., Sharma, S.C. 1984. Moisture transport through the unsaturated zone. Tritium tagging studies in Sabarmati basin, W. India, Hydrological Sciences Journal, v.29, pp: 177–189.

Hodlur, G.K., U.K. Singh, U.K., Das, R.K., Rangarajan, R., Ramesh Chand and Singh, S.B. 2003. Geophysical expression of natural recharge in different geological terrains, Groundwater, v.41, pp:857-866

Holtan, H.N. 1961. A concept for infiltration estimates in watershed engineering. Washington, D.C.: US Dept Agriculture, Agric. Res. Ser. Paper, v.41, pp: 1–51.

Horton, R.E. 1940. An approach toward a physical interpretation of infiltration capacity, Soil Sci. Soc. Am. Proc., v.5, pp: 399–417.

Kostiakov, A.N. 1932. On the dynamics of the coefficient of water percolation in soils and the necessity for studying it from a dynamic point of view of purposes of ameliorations, Trans. 6th Comm. Int. Soil Science Soc., Russian Part A, pp:17–21.

Moon, S.-K., Woo, N.C., Leeb, K.S. 2004. Statistical analysis of hydrographs and water-table fluctuation to estimate groundwater recharge, J. Hydrol. V.292, pp:198– 209.

Munich, K.O., Roether, W., Thilo, L. 1967. Dating of groundwater with tritium and C-14, Isotope Hydrology, IAEA, Vienna, pp: 305–320.

Munich, K.O. 1968 Moisture movement measurement by Isotope tagging, In: Guide book on Nuclear techniques in Hydrology, IAEA, pp:112-117.

Muralidharan, D., Athavale, R.N. and Murthi, C.S. 1988. Comparison of recharge estimates from injected tritium technique and regional hydrological modelling in the case of a granitic basin in semi-arid India, In: Proceedings of International workshop on "Estimation of Ground water Recharge", Ed: I. Simmers, Antalaya, Turkey, March 7-15, 1987, pp:195-220

Philip, J.R. 1957. The theory of infiltration, 4. Sorptivity and algebraic infiltration equations. Soil Sci., v.84, pp: 257–264.

Ramesh Chand, G. K. Hodlur, G.K. and Ravi Prakash, M., Mondal, N.C. and singh, V.S. 2004. Reliable natural recharge estimates in granitic terrain, Current Science, v.88, pp: 821-824.

Rangarajan, R., Athavale, R.N., Muralidharan, D., Deshmukh, S.D., Prasada Rao, N.T.V. 1994. Natural recharge measurements in Jam river basin for four hydrological cycles using tritium tagging method, Technical report no: NGRI-94-GW-152.

Rangarajan, R., Athavale, R.N. 2000. Annual replenishable groundwater potential of India—an estimate based on injection tritium studies, Journal of Hydrology, v.234, pp: 38–53.

Rangarajan, R., D. Muralidharan, S.D. Deshmukh, G.K. Hodlur and T. Gangadhar Rao. 2005. Redemarcation of recharge area of stressed confined aquifers of Neyveli groundwater basin, India through tritium tracer studies, Environ. Geology, v. 48, pp: 37-48.

Rangarajan, R. Mondal, N.C., Singh, V.S. and Singh, S.V. 2009. Estimation of natural recharge and its relation with aquifer parameters in and around Tuticorin town, Tamil Nadu, India, Current Science, v. 97, pp: 217-226.

Rao, S.M. 1984. Nuclear Techniques in Hydrology. Ph. D. thesis, 1984, 187 pages

Rolland Andrade and Muralidharan, D. 2011. The influence of litho-stratification on the infiltrating water front in a granite terrain, Hydro. Sciences Journal, v.56, pp: 907-915.

Scanlon, B. R., Healy, R. W., and Cook, P. G. 2002, Choosing appropriate techniques for quantifying groundwater recharge, Hydrogeology Journal, v. 10, pp:18–39

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I. 2006. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes, v.20, pp: 3335–3370.

Sharma, M.L., Hughes, M.W. 1985. Groundwater recharge estimation using chloride deuterium and oxygen-18 profiles in the deep coastal sands of Western Australia. Journal of Hydrology, v.81, pp: 93–109.

Sharma, P., Gupta, S.K. 1987. Isotopic investigation of soil water movement: a case study in the Thar Desert, western Rajasthan, Hydro. Sciences Journal, v.32, pp: 469–483.

Sibanda, T., Nonner, J.C., Uhlenbrook, S. 2009. Comparisons of groundwater recharge estimation methods for the semi-arid Nyamandhlovu area, Zimbabwe, Hydrogeol. J. v.17, pp: 1427–1441.

Singh, U.K., Das, R.K. and Hodlur, G.K. 2004. Significance of Dar-Zarrouk parameters in the exploration of quality affected coastal aquifer systems, Environmental Geology, v.45, pp:696-702

Smith, D.B., Wearn, P.L., Richards, H.J., Rowe, P.C. 1970. Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium, Isotope Hydrology, IAEA, Vienna, pp:73–87.

Sophocleous, M.A. 1991. Combining the soilwater 664 balance and water-level fluctuation methods to estimate natural ground water recharge: practical aspects, J. Hydrol. V.124, pp: 229–241.

Subash Chandra, Shakeel Ahmed and Rangarajan, R. 2011. Lithologically constrained rainfall (LCR) method for estimating spatio-temporal recharge distribution in crystalline rocks, Journal of Hydrology, v.402, pp: 250-260.

Sukhija, B.S., Rama, F.A.Sc. 1973. Evaluation of groundwater recharge in semi-arid region of India using environmental tritium, Proc. Indian Acad. Sci. LXXVII, Sec. 'A' (6), pp:279–292.

Sukhija, B.S., Reddy, D.V., Nagbhushanam, P., Hussain, S. 2003. Recharge processes: piston flow vs. preferential flow in semi-arid aquifers of India, Hydrogeol. J. v.11, pp: 387–395.

Swartzendruber, D., and Youngs, E.G. 1974. A comparison of physically-based infiltration equations. *Soil Sci*., 117, 165–167. Scanlon BR, Healy RW, Cook PG. 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology Journal, v.10, pp: 18–32.

Wilson LG, LG Everett, and SJ Cullen. 1995. *Handbook of Vadoze Zone Characterization and Monitoring*. CRC Press, Inc., Lewis Publishers, Raton, Florida. Wilson LG, LG Everett, and SJ Cullen. 1995. *Handbook of Vadoze Zone Characterization and Monitoring*. CRC Press, Inc., Lewis Publishers, Raton, Florida

Zimmerman, U., Munich, K.O. and Roether, W. 1967a. Downward movement of soil moisture traced by means of Hydrogen Isotopes, Geophysical Monograph, No. 11, Washington, U.S.A, American Geophysical Union, pp:28-36.

Zimmerman, U., Ehhalt, D., Munich, K.O. 1967b. Soil water movement and evapotranspiration, changes of isotopic components of soil water, Isotopes in Hydrology, IAEA, Vienna, pp:567–585.

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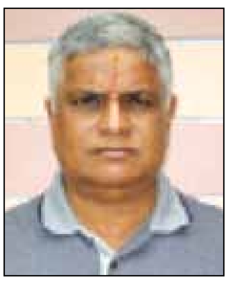

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