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GROUNDWATER RECHARGE MODELING – AN OVERVIEW

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ABSTRACT

Groundwater recharge must be well understood for the effective utilization of water resources. In this article some of the recent studies in groundwater recharge modeling are detailed and discussed. The topics covered include (1) Recharge modeling in deterministic framework, (2)Recharge modeling in stochastic framework, (3) Recharge modeling using electromagnetic surveys (4) Mountain front recharge (5) Natural recharge estimates for India. Groundwater recharge modeling is a potential field for future research due to the recent problems such as groundwater contamination and global climate change.

INTRODCUTION

The interaction between groundwater flow systems, water supply wells, and natural or artificial groundwater recharge creates a complex velocity flow field in aquifers. This velocity field can be represented as a result of the interaction of vertical line sinks (wells) and horizontal areal sources (recharge). The flow is three dimensional rather than two-dimensional and is transient rather than steady. The role of groundwater flow modeling is to provide an estimate of the flow velocities or head predictions. Velocity estimates, however, are usually based on hydraulic head differences and therefore are much more sensitive to numerical modeling errors than are estimates of the hydraulic head alone. Satisfactory predictions of transport often require that the velocity field be calculated on a fine spatial grid. Therefore analytical solutions have some advantage over numerical procedures. A brief review of recent studies on ground water recharge modeling is presented in the following sections.

1. Recharge Modeling in Deterministic Framework

The effect of compressibility for flow caused by a well (vertical line sink) has been shown to be significant for very early stages of pumping, causing delayed response of draw-down in an unconfined aquifer. Dagan's (1967) method does not take into account the phenomenon of delayed gravity response, and therefore it is limited in its application to relatively large distances from the pumping well and to sufficiently large values of time. The distribution of hydraulic head and velocity components of the transient groundwater flow in a compressible unconfined aquifer of finite thickness under constant uniform circular recharge (Fig. 1) are obtained from the linearized mathematical model by the use of integral transforms by Zlotnik and Ledder (1992). In this study only the saturated zone is considered. A problem is formulated for the increase in hydraulic head over the initial level within the limits of linearized theory on the small time scale and large time scale. Approximate solutions are derived on the two different time scales from the complicated exact solution by the method of matched asymptotic expansions. The velocity vector is then obtained as the gradient of the hydraulic head. By treating the compressibility (σ), the ratio of storativity to specific yield, as a small parameter, further analysis of the solution of hydraulic head in a compressible aquifer was

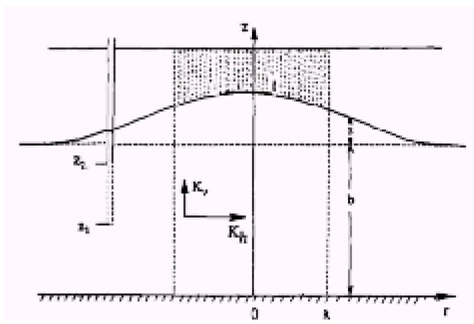

Figure 1: Schematic diagram of groundwater recharge in an unconfined aquifer of finite thickness (Zlotnik and Ledder, 1992)

performed by asymptotic methods, resulting in approximations to the exact solutions for head, vertical velocity and radial velocity on small and large time scales and also in the limit of very large time. It was found that Dagan's solution (1967) for the hydraulic head always over predicts the growth of the groundwater mound. The solutions obtained from this analysis generalize Dagan's (1967) solution for the hydraulic head, which was derived by neglecting the compressibility. Zlotnik and Ledder (1993) have also carried out similar studies for unconfined aquifers with rectangular recharge. Results obtained show that applicability of the Dupuit assumption for computation of velocity components in an unconfined aquifer is limited to a far-field zone given approximately by $|x| > 1.5X$, $|y| > 1.5Y$, where X and Y are the half width and half-length, respectively, of the rectangular contaminant source.

Aquifers subject to natural recharge from rainfall exhibit groundwater velocities, which vary with distance and with the recharge intensity. This in turn generates an evolving transport dispersion coefficient that increases with distance even in a homogeneous aquifer with constant dispersivity. Serrano (1992) gave the form of the dispersion equation under recharge and variable velocity with coefficients given as variable functions of distance. Field scale solute transport parameters are described in terms of regional hydrologic and aquifer hydraulic properties, such as recharge rate, transmissivity, hydraulic gradient, aquifer thickness and soil porosity. A new stable analytical solution of this equation is presented along with numerical comparisons with the classical convection dispersion equation and sensitivity tests on the effect of hydrologic-hydraulic variables on the contaminant evolution. It was found that the recharge rate substantially affects the contaminant distribution and may partially explain the scale dependence of dispersion parameters. Transmissivity and hydraulic gradient values also determine the velocity distribution and therefore the rate of migration.

There is a growing need to delineate the complete catchment feeding individual wells in order to control pollution in general and specifically to control the leaching of nitrates. Protection zones around pumping wells are commonly defined as time-of-travel zones, either to allow for attenuation of pollutants in the aquifer or to provide a monitoring zone. The classical analytical method used to map catchments and time-of-travel zones of pumping wells (Bear and Jacobs, 1965) does not take recharge into account. Lerner (1992) has presented an approach for generalized catchment shapes for aquifers with recharge (Fig. 2). They can be scaled to field situations through two or three nondimensional parameters. A semianalytical path line-tracing model was used to generate the shapes. It contains new expressions for pore water velocities in two infinite strip, recharged aquifers, one with two fixed head boundaries, the other with one impermeable boundary. The resulting catchments differ significantly in both shape and size from catchments estimated by the no-recharge method. The area of the whole catchment is ***Q/R,*** which represents the ratio of abstraction to recharge**.** In nondimensional terms this is ***Q/4a*R,*** which equals ***q'***. The area inside an isochrone, A_I, can be nondimensionalized as $A_I' = A_I/4a^2$. Provided that saturated thickness

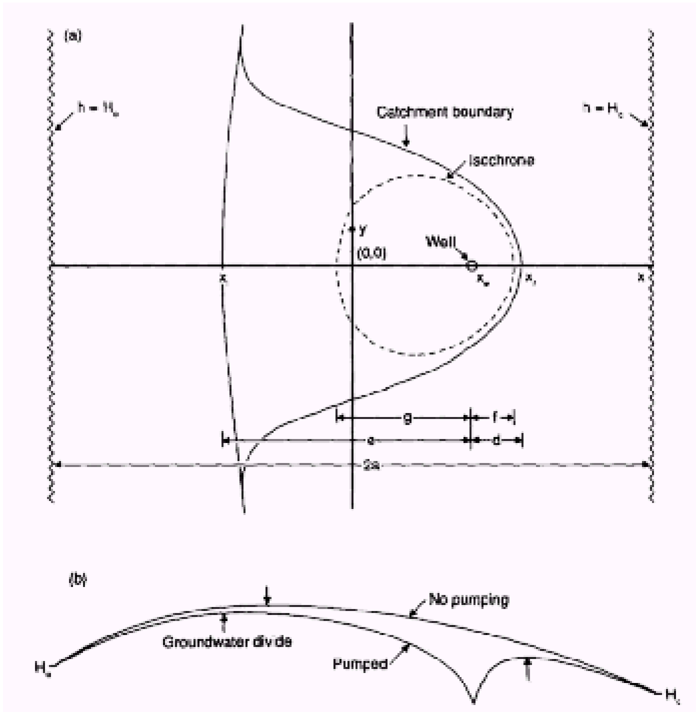

Figure 2: Schematic of a well catchment and isochrone in an infinite strip bounded by two constant heads. (a) Plan view showing coordinate system and key dimensions (b) Cross section showing water table elevation with and without pumping (Lerner, 1992)

does not vary significantly across the aquifer, the shapes and sizes of catchments and isochrones in recharged aquifers can be generalized and described by a maximum of four nondimensional variables. Only two variables are needed for catchments in strip aquifers with one impermeable and one fixed head boundary: ***q'***, and x_w', the well position. Generalized results were also presented for time-of-travel zones, which are noticeably smaller than those calculated by the no-recharge method. Comparison with an equivalent recently released model from the U.S. Environmental Protection Agency (GPTRAC, part of WHPA, *Blandford and Huyakorn,* 1991) showed that the latter gave poor estimates of catchments and time-of-travel zones.

Effects of an organic mat filter on artificial recharge with turbid water were studied by Schuh (1991). Total recharge was 81% larger for a sandy basin with an organic mat filter than for the same basin with a clean, fully renovated surface, but without the mat. Surface impedance was larger for check areas without organic mat, while areas with the mat exhibited impedance increases to greater depths. A substantial decrease in hydraulic impedance and a corresponding increase in infiltration rate were measured between 90 and 400 hours and indicated that despite large sediment influx, soil hydraulic conductivity was larger under the organic mat than for the same basin positions on clean sands using clean water. The large decrease in impedance is attributed to microbial transformation of O_2 to CO_2, which increased water-filled large porosity.

The spatial, statistical structure of the fluid velocity field in the case of uniformly recharged heterogeneous aquifers is investigated, and the spatial covariances of the velocity field are derived by Rubin and Bellin (1994). The resulting first two moments of the velocity are nonstationary and are functions of a parameter ξ which characterizes the degree of flow nonuniformity and is related to the recharge. The displacement variances are computed and tested favorably using numerical simulations. Simple relations are developed which relate the transport parameters found for the case of uniform-in-the-average flows to nonuniform flows using a simple, nonlinear transformation of the travel time, based on ξ.

A distributed parameter ecohydrological model (TOPOG_IRM) was applied by Zhang et al. (1999) to a 1.6 km^2 pastoral catchment in southeast Australia for estimating soil moisture and groundwater recharge. The main objective of TOPOG_IRM is to provide a realistic description of the key processes, which control the soil moisture dynamics, evapotranspiration, and to investigate hydrological and ecological responses at a catchment scale. The spatial patterns of the soil moisture content appear to be controlled mainly by the soil types, and the results indicated that there is little lateral movement of water in the catchment. Average groundwater recharge was found to be 5% of the annual rainfall, and the soil types dominated its spatial patterns.

Can shallow temperature measurements on vertical profiles be used to determine the recharge? A relationship between water flux and temperature was determined by different studies. In other words, infiltration results in convective transfer, which can be observed on vertical temperature profiles. A group of annual cycles allows us to determine the average value of vertical water seepage: in the presence of infiltration the apparent diffusivity deduced from the damping of the amplitude of the temperature between two different depths differs from the apparent diffusivity deduced from the temperature phase shift between the same pair of depths, and the average water flow can be easily deduced from this difference.

Tabbagh et al. (1999) have determined recharge in unsaturated soils using temperature monitoring. They have used soil temperature measurements with the following details. The sensors are placed at 0.1, 0.2, 0.5, and 1.0 m depths; the time steps correspond to one (at 12 local solar time) or three times (at 6, 12, and 18 local solar time) a day. This sampling step is too large for the diurnal variation to be correctly described, which is also damped out below 0.2 m. They concluded that the determination of average values of the recharge is possible for a several-year-long cycle; the year-by-year results, deter-mined using Fourier analysis, still need to be checked by comparison with other information and measurement techniques. For the determination of recharge over shorter periods of time it would be better to reconsider the sampling step of the data in both time and space domains.

2. Recharge Modeling in Stochastic Framework

Traditionally, the movement of groundwater in aquifers is modeled in the deterministic fashion, which assumes that the information required in the modeling, such as aquifer parameters and boundary conditions, is known with certainty. A unique solution can therefore be obtained, associated with the set of deterministic conditions. In reality, hydrological events are better described as random phenomena. The boundary conditions such as river stage, precipitation recharge, pumping rate, etc., are uncertain, or unknown, especially when predictions into the future are to be made. The aquifer properties, such as hydraulic conductivity, transmissivity, and storativity, are also random parameters, due to the lack of information and/or the intrinsic randomness of the geological process. Groundwater flow is therefore more realistically modeled via the stochastic approach.

The governing equation for hydraulic head distribution in a transient two-dimensional aquifer system with spatially random transmissivity and spatiotemporally random recharge is

$$\frac{\partial}{\partial x_i}\left[T(\mathbf{x})\frac{\partial H}{\partial x_i}\right] + R(\mathbf{x}, t) = S_y\frac{\partial H}{\partial t}$$

where $\mathbf{x} = (x_1, x_2)$ is a vector point in the horizontal plane, $T(\mathbf{x})$ is the transmissivity at location $\mathbf{x}$, $R(\mathbf{x}, t)$ is the transient recharge at time t and location $\mathbf{x}$ (positive for accretion), $H(\mathbf{x}, t)$ is the transient hydraulic head at time t and location $\mathbf{x}$, and S_y is specific yield, representing the volume of water produced per unit area per unit decline in head, treated here as a known constant. Summation over repeated indices is assumed.

Pore water velocity vector for two-dimensional transient flow is

$$v_i(\mathbf{x}, t) = -\frac{T(\mathbf{x})}{bn}\frac{\partial H(\mathbf{x}, t)}{\partial x_i} \qquad i = 1, 2$$

in which $v_i(\mathbf{x}, t)$ is the pore velocity at vector location $\mathbf{x}$ and time t, $T(\mathbf{x})$ is the transmissivity, b is the aquifer thickness, and n is the porosity. Here both the porosity and aquifer thickness are assumed to be known constants.

By compiling the relevant articles on groundwater modeling in stochastic framework published in *Water Resources Research*, Dagan (1986) suggested that this new science has passed the infancy stage, which is characterized by an exponential growth in the number of publications, and is entering maturity. Cheng and Lafe (1991) presented boundary element solution for solving stochastic boundary value problems in groundwater flow based on integral equation formulation. The aquifer considered has deterministic hydraulic conductivity but is subject to random boundary condition and domain recharge. Using the distribution of fictitious sources and dipoles, stochastic integral equations for the mean and covariance of head and flux are derived. An iterative boundary element technique is applied for numerical solution. Two one-dimensional examples are examined and compared with exact solution. A two-dimensional problem is then presented.

Two-dimensional aquifer flow under naturally variable recharge and its application to optimal estimation in groundwater is investigated by Hantush and Marino (1993) in stochastic framework. The governing stochastic equation is solved quasi-analytically using the Galerkin finite element method and matrix exponentials. The continuous-time stochastic solution relates head perturbations to random initial head and a convolution of the pertinent stochastic recharge process. Based on the quasi-analytical solution, continuous time autocorrelation matrices for aquifer head are developed conforming to (1) white noise recharge fluctuations in time and (2) fully correlated recharge fluctuations in time. Results obtained from quasi-analytical solution compared well with those obtained using closed-form solution. Application to optimal state feedback estimation is demonstrated by adopting Kalman filtering and forecasting to a numerical experiment consisting of two-dimensional aquifer flow instigated by variable leakage. Filtering results demonstrate that under scarce measurements, statistical conditioning on available measurements can result in an estimated aquifer hydraulic response that captures the actual variability that may exist under natural field conditions. Forecasted aquifer heads, however, are sufficient for a relatively short period; they converge asymptotically to their respective average values.

Li and Graham (1999) have carried out Stochastic analysis of solute transport in heterogeneous aquifers subject to spatiotemporal random recharge. It extends their previous study (Li and Graham, 1998) to deal with the unconditional moments of head, velocity, and concentration under transient flow conditions, which are assumed to be caused by a spatiotemporally random recharge. Semianalytical solutions are derived for the unconditional covariances for transient velocity with a constant mean recharge using a Fourier transform approach. Results demonstrate that the velocity covariance derived for the steady state random recharge field is a limiting case of the spatiotemporally variable velocity covariance with an infinite temporal correlation scale. Another limiting case indicates that introduction of temporally random but spatially uniform recharge has no effect on the velocity covariances (over that induced by the mean recharge on the mean head gradient). Thus for this limiting case there is no increased effect on the ensemble mean concentration plume spreading or the concentration prediction uncertainty. The equations for mean concentration and macrodispersive flux under zero mean transient recharge are decoupled in the Laplace-Fourier domain and solved using a fast Fourier transform algorithm, which significantly reduces the computational demand. The first-order concentration variance is solved using three different approximate techniques: an approximate Fast Fourier Transform (FFT) technique, a finite element method, and a direct numerical integration. The simulation results show that introduction of a spatiotemporally random recharge enhances both longitudinal and lateral mean concentration plume spreading compared to the no recharge case. They concluded that, transient recharge produces less spreading and less concentration prediction uncertainty than the steady state spatially random recharge case.

3. Recharge Modeling using Electromagnetic Surveys

Groundwater recharge is one of the most difficult components to measure in the water balance studies. For this reason, electromagnetic methods have been used to infer its variability from measurements of apparent electrical conductivity.

A Helicopter-Borne Electromagnetic Survey was used by Cook and Kilty (1992), to estimate groundwater recharge at 20 sites using unsaturated zone chloride methods. Interpolation between drill sites was accomplished with the aid of a helicopter-borne electromagnetic survey. Correlations between recharge and apparent electrical conductivity were only significant (R^2=65%) at the highest frequency (56,000 Hz). Using these single-frequency data, variations in recharge were mapped over an area of 32 km^2. Recharge, as inferred from the electromagnetic data, appears to be lognormally distributed, and varies from less than 1 to more than 50 mm per year. Within the study region in Australia, spatially averaged recharge can be estimated from the electromagnetic data, with an accuracy of approximately -60%, +140% (90% probability). This is comparable to the estimation accuracy when surface electromagnetic methods are used. Aerial electromagnetic methods appear very useful for identifying areas of high and low recharge over large regions.

Earth Resources Satellite-1, Synthetic Aperture Radar's (ERS-1 SAR) capability to estimate surface soil moisture is examined by Cognard et al. (1994) on a small agricultural watershed, Naizin watershed situated in the central part of French Brittany. During 1992 and 1993, almost all possible SAR images were acquired together with two types of ground truths: intensive ground measurements during 14 field campaigns and point automatic measurements over the entire period. Even on a field scale, the relation between radar signal and soil moisture is not stable. However, it is possible to establish good relation between the mean regional radar measurements and mean soil moisture at the same scale. Mean radar signal, soil moisture measured at 10 cm depth using dielectric probes and the concurrent rainfall data are shown in Fig. 3 for the year 1992. From the comparison of the ground truth data with the ERS 1 images, the following results are obtained. On a field scale the relation between the radar signal and the surface soil moisture depends strongly on the type of crops: Correlation is poor for the different crops except for wheat. On a basin scale, it is observed that during the period of low vegetation density, there is a linear correlation between the mean radar data and the point automatic measurements.

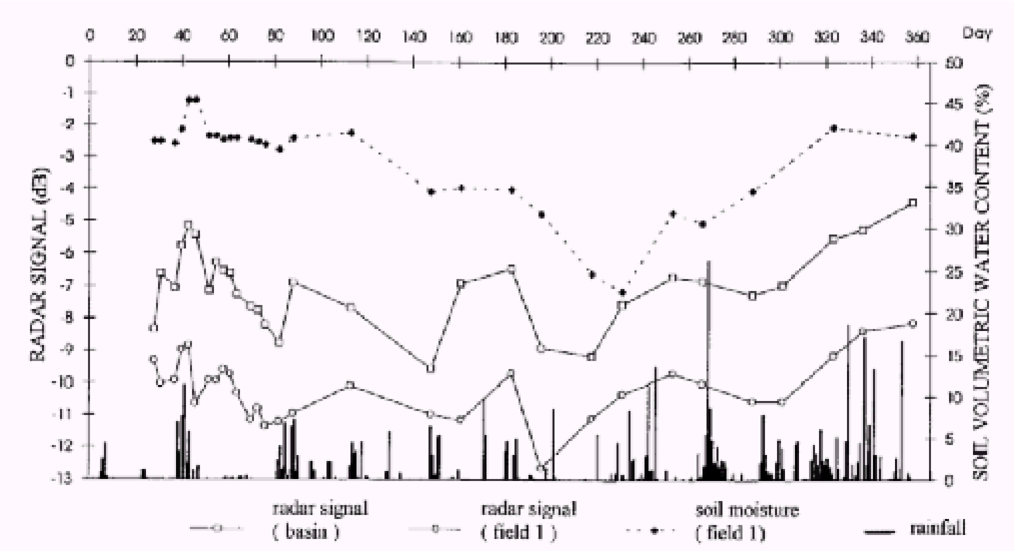

Figure 3. Mean radar signal, soil moisture measured at 10 cm depth using dielectric probes and the concurrent rainfall data for the year 1992 (Cognard et al., 1994)

4. Mountain Front Recharge to Regional Aquifers

Mountain front recharge is defined by *Wilson et al.* [1980] as recharge which occurs along the portion of the regional aquifer boundary that parallels a mountain area (Fig. 4). According to this definition the components of this type of recharge are (1) the infiltration of streamflow from the washes and rivulets between the bases of the mountains and the regional aquifer boundary and (2) the subsurface inflow from the mountain mass to the basin-fill sediments.

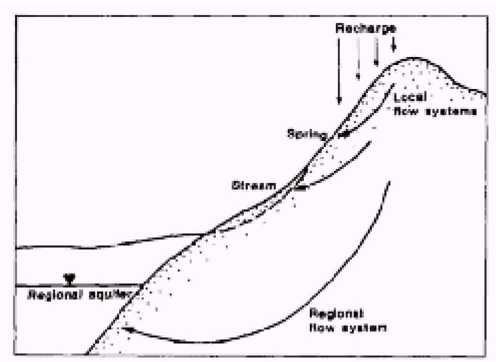

Figure 4. Local and regional flow systems in the mountains (Chavez et al., 1994a)

The two main mechanisms of natural recharge to regional aquifers in arid and semiarid areas are channel recharge and mountain front recharge. While mountain front recharge is a vital component of the groundwater system in many of these areas, it constitutes only a minor fraction of the total amount of water delivered to the area by precipitation and therefore cannot be estimated reliably by “gross” water balance calculations. Estimates of mountain front recharge to regional aquifers are required for management purposes, particularly in order to determine the safe yield from wells in groundwater basins where overall recharge is small and development may readily lead to overdraft conditions. Such basins are common in arid and semiarid regions. Estimates of mountain front recharge also provide prescribed flux values for digital models of regional groundwater flow.

Prior estimates of mountain front recharge can be obtained with the aid of environmental isotopes and hydrochemical mass balance calculations. These methods are associated with large uncertainties. An alternative approach to estimation of mountain front recharge is the use of hydroclimatic models. Such models are particularly useful in areas where reasonable records of rainfall and streamflow exist but where there is almost no data on groundwater.

Chavez et al. (1994a,b) developed model for the estimation of mountain front recharge to regional aquifers in a series of two papers. In paper 1 of this two-part series, they developed analytical models of the seasonal surface runoff and streamflow based on a conceptual model of hydrologic processes that should approximate some types of field conditions, in particular, hard rock mountainous watersheds where deep percolation occurs exclusively through fractures. In paper 2 (Chavez et al., 1994b), the parameter estimation problem is posed in the framework of maximum likelihood theory, where prior information about the model parameters and a suitable weighting scheme for the error terms in the estimation criterion are included. Various optimization methods are combined for parameter estimation. The issues of model and parameter identifiability, uniqueness, and stability are addressed, and strategies to mitigate identifiability problems in the modeling are discussed. The seasonal streamflow model is applied to a mountainous watershed in southern Arizona, and maximum likelihood estimates of mountain front recharge and other model and statistical parameters are obtained. The analysis of estimation errors is performed in both the eigenspace and the original space of the parameters.

5. Natural Recharge Estimates for India

Natural recharge is a vital parameter to be known for ground water budgeting, management and modelling. Percolation of a portion of the rainfall, through the vadose zone, is the principal source of natural recharge to the aquifer systems in India.

About 80% of India falls under semi-arid tropics and about 80% of the annual rainfall is received as pulses and occurs during the four monsoon months from June to September. The seasonal rainfall shows a large variation from 11,000 mm per year at Cheerapunji located near Shillong to 200 mm per year near Jaisalmer (Fig. 5). The average annual precipitation of the subcontinent is 1194 mm per year. Isohyetal map of Inida is shown in Fig. 5.

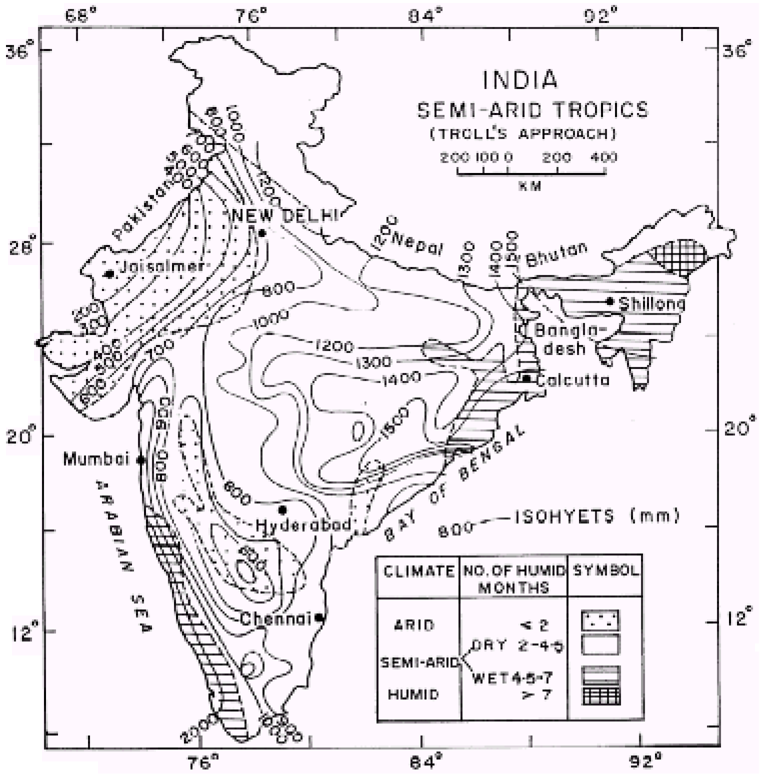

Figure 5. Isohyetal map of India, showing semiarid areas (Rangarajan and Athavale, 2000)

Rangarajan and Athavale (2000) presented an estimate based on injected tritium studies for the annual replenishable groundwater potential of India. Natural recharge measurements, using the tritium injection method, have been carried out in India during the last 25 years.

Tritium Injection Method: Tritium, the radioisotope of hydrogen (Maximum Energy: 18 KeV, Half-life: 12.43 years), is an ideal tracer for soil moisture movement studies. The tritium injection method assumes a piston flow model for movement of water infiltrating the vadose zone. It means that the soil moisture moves downwards in discrete layers. In this method, the moisture at a depth below the shallow root zone (0.6–0.8 m) in the soil profile is tagged with tritiated water. The tritium labelled layer of moisture is displaced down-wards as a result of percolation of rainwater. The peak in its concentration distribution indicates the displaced position of the tracer. The moisture content of the soil column between the tagged depth and the displaced depth of the peak in the soil core, corresponds to the natural recharge to ground water over the time interval between injection of tritium and collection of soil core. The methodology provides spot measurements of natural recharge.

The natural recharge data are grouped into four main hydrogeological provinces (Fig. 6), namely granitic, basaltic, sedim-entary and alluvial and the regression equations between rainfall and natural recharge are derived for each province. Various research groups have carried out natural recharge measurements for the last 25 years in 35 watersheds, river basins and administrative blocks of India. All these 35 areas are shown in Fig. 6.

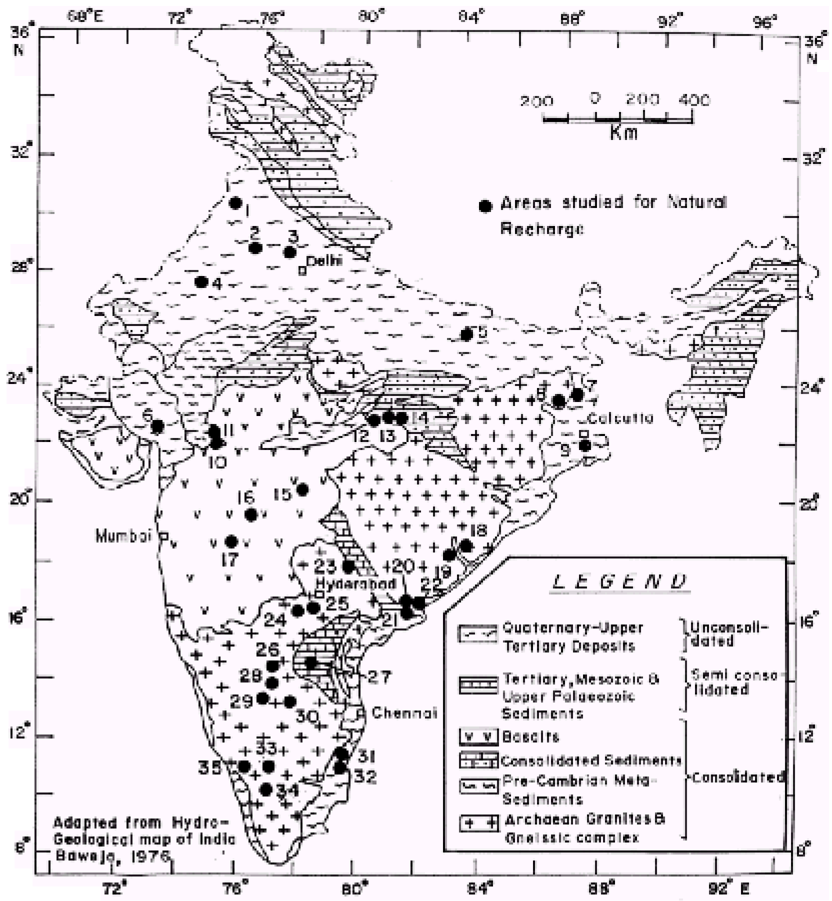

Figure 6. Hydrogeological map of India showing areas studied for annual groundwater recharge (Rangarajan and Athavale, 2000)

A linear relation between rainfall and natural recharge exists for all the four major hydrogeological units of granites, basalt, sediments (mainly sandstone) and alluvium. The regression equation derived for each of the hydrogeological provinces indicates a certain minimum rainfall requirement to initiate ground water recharge. These minimum values are 255 mm per year for granite, 355 mm per year for basalt, 220 mm per year for sediments and 40 mm per year for alluvial areas. The rainfall–recharge plots can be used for arriving at an estimate of natural ground water recharge, during a particular year, in any part of the country. Annual natural recharge values for 17 major river basins were presented in Table 1. The recharge rates range from 24 to 198 mm per year or 4.1 to 19.7% of the local average seasonal rainfall.

The results presented in the study by Rangarajan and Athavale (2000), may be considered as minimum recharge as they represent the natural recharge due to precipitation alone and does not account for seepage from ponds, lakes, stream bed, canals and return flow from surface water irrigation. The annual replenishable ground water potential of India, for normal monsoon year based on tritium injection studies, is calculated as 476×10^9 m^3 per year.

Table 1. Annual natural groundwater recharge in various river basins of India (input = area x recharge) (Rangarajan and Athavale, 2000)

S. no.	Major river basins and area ($\times 10^{10} m^2$)	Major soil types	Major rock types	Average annual rainfall (mm)	Natural recharge estimation using regression equations	
					Recharge ($mm\ yr^{-1}$)	Input ($\times 10^9\ m^3\ yr^{-1}$)
1.	Ganga (86.15)	Alluvial	Alluvium	1160	165	142.1
2.	Brahmaputra (18.71)	do	do	1220	173	32.3
3.	Barak and others (7.82)	Red and Yellow	do	2860	414	32.3
4.	Between Ganga and Mahanadi (8.1)	do	Granite, Alluvium	1470	210	17.0
5.	Mahanadi (14.16)	do	Granite, Gneiss	1460	207	29.3
6.	Between Mahanadi and Godavari (4.97)	Red and Black	Granite, Gneiss, Basalt, Sandstone, Alluvium	1110	141	7.0
7.	Indus (32.13)	Mountainous,	Sandstone, Alluvium	560	76	24.4
8.	Luni and others (32.18)	Desert	Alluvium	380	50	16.1
9.	Sabarmati and Mahi (5.93)	Alluvial	do	1590	228	13.5
10.	Narmada (9.88)	Black	Basalt	1210	153	15.1
11.	Tapi (6.69)	do	do	780	74	4.9
12.	Godavari (31.28)	Black, red Gneiss	Basalt, Granite	1100	134	41.9
13.	Krishna (25.90)	do	do	810	87	22.5
14.	Pennar and others (14.49)	Red Sandstone, Limestone	Granite, Gneiss	820	92	13.3
15.	Cauveri (8.80)	do	Granite, Gneiss, Alluvium	990	133	11.7
16.	Below Cauveri (3.51)	Deltaic Alluvium	do	910	120	4.2
17.	Below Tapi (11.21)	Lateritic Gneiss	Basalt, Granite	2790	429	48.1
		Total				476.0

CONCLUSIONS

Groundwater recharge modeling needs further investigation in many fields which will be more adaptable to the data availability. Optimal planning for conjunctive use of surface and subsurface water resources for sustainable development.

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