ICIWRM – 2000, Proceedings of International Conference on Integrated Water Resources Management for Sustainable Development, 19 – 21 December, 2000, New Delhi, India

Advances in groundwater research for integrated resource management and sustainable development

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Abstract
Increasing water demand, zonal disparity in water supply and disproportionate use of groundwater resulted in widespread decline in water table and productivity of wells, increasing pumping cost and energy requirement, and expanding areal extent of groundwater quality degradation. In this context, case studies on advanced radioisotopic (^{3}H, ^{14}C) and stable isotopic (^{2}H, ^{18}O) investigations, conducted in the Indo-Gangetic Alluvial Plains; Sabarmati River Basin and Rajasthan, have been described and technology packages have been suggested.The studies indicate that groundwater recharge from rainfall varies widely from region to region and within the parts of a region, depending on the frequency, intensity and distribution of rainfall, evaporation and landuse, and significant stratification exist at many places. Groundwater contamination is mostly derived from slow infiltration of agricultural and urban surface run-off, through stagnant water pools, alongwith indiscriminately used agrochemicals and land-disposed anthropogenic wastes. The levels of contaminants in groundwater vary spatially and temporally due to different degrees of evaporation/recharge and adsorption/dispersion of contaminant species in the soils. Abstraction induced mixing of highly contaminated groundwater with fresh water takes place along specific flow-pathways.The inherent specificity and complexities of the groundwater system calls for consolidation of existing efforts and reorientation of future research to problem-solving inter-disciplinary approaches, cutting across other areas such as environment, physical sciences, earth and atmospheric sciences, applicable at the local level. Advanced 'packages' and programmes of training in isotopic surveying is very essential for detailing hydrogeologic characteristics of the flow field and pollutants dynamics in the groundwater, under natural and exploited conditions.

INTRODUCTION

Groundwater is used in India directly or indirectly for agricultural, domestic, industrial and other purposes. However, in many parts of the country, disproportionate use of groundwater, has resulted in lowering of groundwater levels, decline in productivity of wells, increasing pumping costs, more energy requirement, more seepage from canals, intermixing of contaminated water with fresh water, etc.. Human impacts on the groundwater resource and its sustainability is governed by economic motives and competition for development and is inextricably characterised by other factors, such as, specificity of groundwater occurrence, demand and use, complexity of its interaction with other resources, and with its physical and socio-economic environment, population density, settlement pattern, etc.. Obviously, to optimise the water-use in the long term and to protect it from depletion and degradation, a responsible water management policy can be evolved only after assessing the nature of the geohydrological problems, by identifying the knowledge gaps and by obtaining comprehensive and accurate data on groundwater occurrence and regeneration.

Some of the important aspects, with which the water resources managers and developers are confronted, relate to understanding the groundwater flow regime, recharge and contamination characteristics, residence time in the aquifer, stratification, groundwater recharge areas and hydrodynamic zones to locate wells of high yield and efficiency, groundwater-surface water interactions and intermixing pathways, etc.. In this context, among the advances in groundwater research, the isotope techniques occupy a special place, since such methods only can give a direct insight into the water movement and distribution processes within the hidden aquifer system. In India, isotope techniques have been used extensively for over three decades, and a lot of potential applications addresses to the aforesaid aspects. While the artificial radioisotopes are of interest in short range studies (but not necessarily of short duration), the scope of naturally occurring stable isotopes have applications in both short and long range studies of short and long duration. In this brief background, use of radioactive isotopes (^{3}H, ^{14}C) and stable isotopes (^{2}H, ^{18}O) for groundwater research has been described through some case studies.

ISOTOPIC CHARACTERISATION OF GROUNDWATER PROVENANCE

Natural replenishment of any groundwater reservoir and management of the resource are governed by the rainfall recharge characteristics, the residence time of the recharged water in the aquifer system from the recharge zone to the discharge zone and the groundwater flow velocity. Conventionally, groundwater recharge for a region is estimated either using data on water table fluctuations or empirical formulae based on amount of rainfall alone. The other methods, viz., inventory, storage, lysimetric, etc., require a large amount of hydrological data over a long period. Non-availability of long-term data and uncertain nature of data on evapotranspiration, runoff, etc. in many areas restrict the use of water balance equation for groundwater recharge estimation. These conventional approaches are grossly inadequate and provide incorrect estimation of recharge and groundwater residence time (defined as the total storage devided by the recharge), because recharge fluxes are very small component of total water fluxes.

Groundwater Recharge Estimation

Regional groundwater recharge has been estimated by tracing the downward movement of an artificially injected tritium tagged soil moisture layer below the root zone, through the unsaturated soil. The tritium tagging method, first used in the Indo-Gangetic Alluvial Plains, has been extensively applied to many other areas in India, well-distributed over seventeen major river basins (Datta et al, 1973, 1980, 1997, 1998, Datta and Goel,1977, Goel et al, 1977, Sharma and Gupta, 1987, Datta, 1997).The average value of recharge has been estimated to be 20% in western Uttar Pradesh, 18% in Punjab, 15% in Haryana, 14% in Sabarmati Basin, Gujarat, less than 8% in Delhi area, 8-14% in the desert areas around Jodhpur and the Jaisalmer region, and 31% in Pushkar Valley, Rajasthan. This method may work well in the case of shallow unconfined aquifers in humid regions, but applicability in semi-arid and arid regions has temperature effects. The results indicated that higher potential evaporation during monsoon months in Sabarmati basin may reduce the net groundwater recharge for a certain amount of water input, as compared to that in the Ganga, the Ramganga and the Yamuna basins (Datta et al, 1979) and winter rains

have relatively higher efficiency in inducing groundwater recharge. It has been also observed that in these river basins, under the prevailing meteorological and soil regimes, insignificant recharge from vertical percolation results when the annual water input (rainfall + irrigation) is less than 40 cm (Datta et al, 1979). A strong inverse relationship has been observed between fractional recharge and intensity of groundwater irrigation in Punjab (Datta and Goel,1977). A recent study indicates that sloppy topography and vegetation cover reduces infiltration in sand dunes considerably (Datta et al, 1994, 1998).
Besides the tritium method, the ^{18}O isotope being a conservative tracer, and groundwater ^{18}O composition being a proxy indicator of the rainfall isotope composition, helps in evaluating the recharge characteristics. The isotopic composition remains constant in the direction of groundwater flow unless affected by physical processes such as mixing with water of different isotopic composition. In Delhi area, while the weighted mean δ^{18} O value of rainfall is -6.1λ (Datta et al, 1996), the groundwater isotopic composition ranges from -2.8 to -8.6λ (Fig.1), suggesting selection effect in groundwater recharge in favour of depleted rainfall and heterogeneous groundwater system.

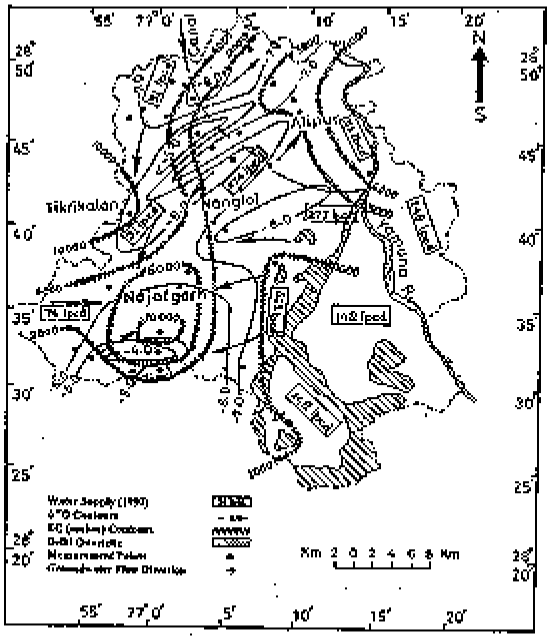

Figure 1. Map showing the groundwater isotopic composition in Delhi area.

Similarly, with respect to the rainfall mean $\delta^{18}O$ value of -2.5λ (Datta et al, 1994), occurrence of isotopically highly depleted groundwater (Fig.2), $\delta^{18}O$ ranging from -4.0 to -5.7λ in Churu, Nagaur, Sikar, Ajmer, Pali and other parts (Chandrasekharan et al, 1986), $\delta^{18}O$ ranging from -5.1 to -7.6λ at deeper level in Jalore district and $\delta^{18}O$ ranging from -1.8 to -6.3λ in the Pushkar Valley (Datta et al, 1994, 1998) suggest groundwater inhomogeneity in its lateral extent, different sources of origin and possible occurrence of palaeowaters which got recharged during relatively cooler and humid period. Integration of recharge data obtained from tritium tagging method with the ^{18}O isotope studies indicate that average groundwater recharge from rainfall varies widely from region to region and within the parts of a region, both in space and time, depending on the frequency, intensity and distribution of rainfall, evaporation, topography, depth to water table and soil clay content (Datta et al, 1980, 1998, Goel et al, 1977, Sharma and Gupta, 1987, Datta, 1997). Therefore, in view of these observations, expressing average recharge in terms of percentage of rainfall may give erroneous assessment and these estimates should be revised time to time with changes in landuse pattern.

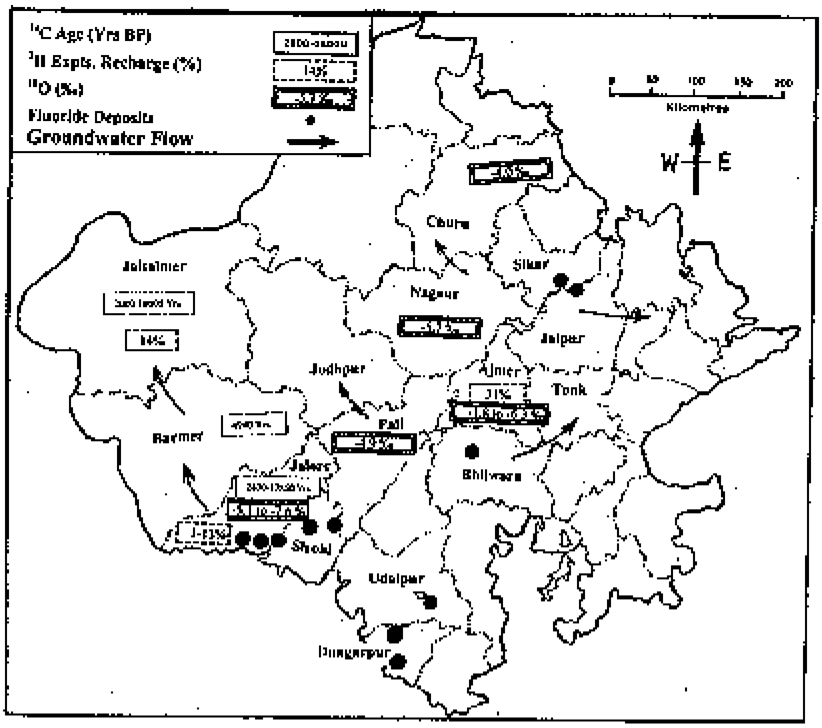

Figure 2. Map of Rajasthan showing ^{14}C age, ^{18}O composition and recharge (%) of groundwater.

Groundwater residence time, regional flow and stratification

The residence time of groundwater is defined as the length of the time the water has been isolated from the atmosphere. Groundwaters in Gujarat and Rajasthan have been dated by the naturally occurring ^{14}C ($T_{1/2}$=5730 yr), incorporated continuously in groundwaters as recharge and dissolved as various inorganic carbonate species. Both inorganic reactions (calcite dissolution) and biogenic processes can modify ^{14}C input values. The dissolved carbon isotopes can get further retarded in the aquifer through sorption and/or isotopic exchanges in the presence of carbonate mineral. Therefore, an understanding of the evolution of the carbon geochemistry and its effect on ^{14}C concentrations are essential for the interpretation of ^{14}C data in terms of groundwater ages. Apparent radiocarbon age of the groundwaters in the Watrak-Shedi sub-basin of the Sabarmati river basin (Datta et al,

1980) and of deep seated (> 150m) groundwaters in the Jaisalmer, Barmer and Bikaner districts of the Thar Desert have been observed to be about 2,000 yrs to 18,000 yrs BP (Fig.2). The age of 2,000 yr corresponds to younger waters in the recharge area. The data further indicates that the older water in the discharge areas resided within the aquifer system for almost a period of 18,000 years after getting recharged from the recharge area (Datta et al, 1980). Most of the 1st and 2nd aquifer groundwaters in the Thar Desert have residence time of 4,000-8,000 yrs B.P., indicating that recharge might have taken place during relatively wet phase, through different and distant recharge areas (Gupta and Nijampurkar, 1974).

Such evidences, suggest that the Gujarat and Rajasthan states are becoming increasingly dependent on water that recharged the deep groundwater bodies with significant amounts of fresh water, many thousands of years back in the past during pre-Holocene period, under a different climate. The aquifers being exempted from any recent recharge can be discarded as a potential groundwater resource for being a no recharge - noflow system. For large groundwater systems which contain water recharged under different climatic conditions, water age represents either the present situation or the reconstruction to the time before an intensive exploitation has been started. For such systems which had periods of negligible or no recharge, the tracer age is always larger than the water age and the tracer age may yield lower flow velocities then the real values observed for the flow field that existed before an intensive exploitation. From interpolation contouring of the apparent radiocarbon ages, regional velocity of groundwater flow in the confined aquifer in the Watrak-Shedi sub-basin of the Sabarmati Basin was estimated to be 6-7 m/yr in the NE-SW direction. As compared to the Sabarmati Basin, at Pokharan (Jaisalmer district) in Lathi Basin, the groundwater velocity of around 1-6 m/yr based on age (Datta et al 1980), and velocity of around 0.5 m/yr in deep seated aquifer (Bhandari et al, 1978), based on single point dilution method, also suggest relatively very slow or restricted movement of groundwater. Higher velocity in the Sabarmati Basin suggests relatively rapid circulation of groundwater, controlled by more exploitation of aquifer. Radiocarbon dates of groundwater also indicate significant stratification in groundwater, with little mixing between individual layers. ^{18}O isotopic depletion increasing with depth to groundwater table (Fig.3) also indicates stratified groundwater system in the vertical extent of the aquifers in Delhi area, Pushkar Valley, Rajasthan and Jaisalmer District, Rajasthan .

Groundwater - surface water interaction and intermixing

Ionic mass balance in river/canal and groundwater bodies, in hydraulic connection with each other, has often been used to estimate the influent/effluent seepage. Changes in discharge and flow rate in surface water courses, and considerable seasonal variations in groundwater ionic concentrations, usually give fluctuating and erroneous estimate of seepage. In a study in Delhi area, by developing a simple mixing model (Datta and Tyagi, 1995), based on spatial and depth variations in $^{18}O/^{16}O$ ratio of groundwater and canal/river water and equal inflow of groundwater through the screens of the tubewells, it was computed that canal/river water contributes to the groundwater recharge upto 5-10m depth of the aquifer adjacent to the canal/river. It was also observed that there is decreasing contribution of river/canal seepage component to groundwater with increasing depth of the aquifer. Seepage contributions were estimated to range between 20% to 50% and is determined by the flow in the surface water courses. Straight line relationships between groundwater ^{18}O and Cl in Delhi area indicate that groundwater intermixing takes place along specific flow-pathways (Fig.4). By using simple mixing equations, the lateral component of recharge is estimated to range from 25-70%, influenced by the flow-pathways of intermixing and the extent of the hydrodynamic zones (as indicated by small isotopic gradients in Fig.1).

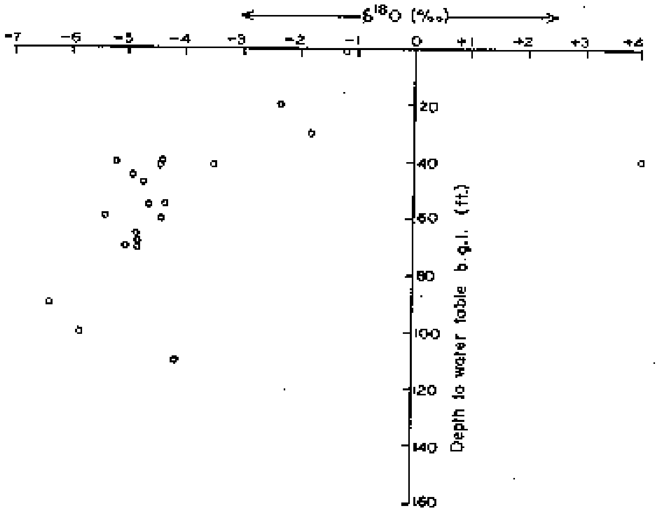

Figure 3. Variation of ^{18}O(%) with depth to groundwater table in Pushkar (Ajmer) Lake Valley, Rajasthan.

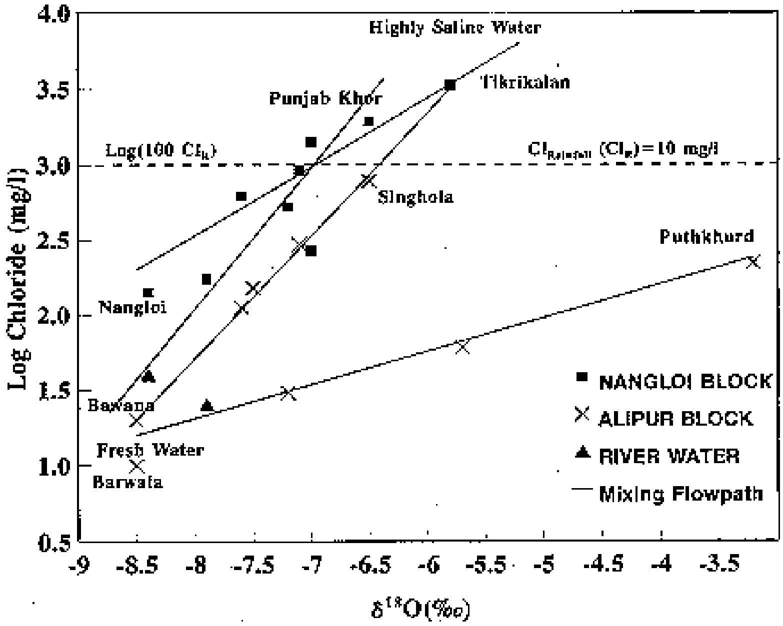

Figure 4. Groundwater $\delta^{18}O$-Cl relationship in Delhi.

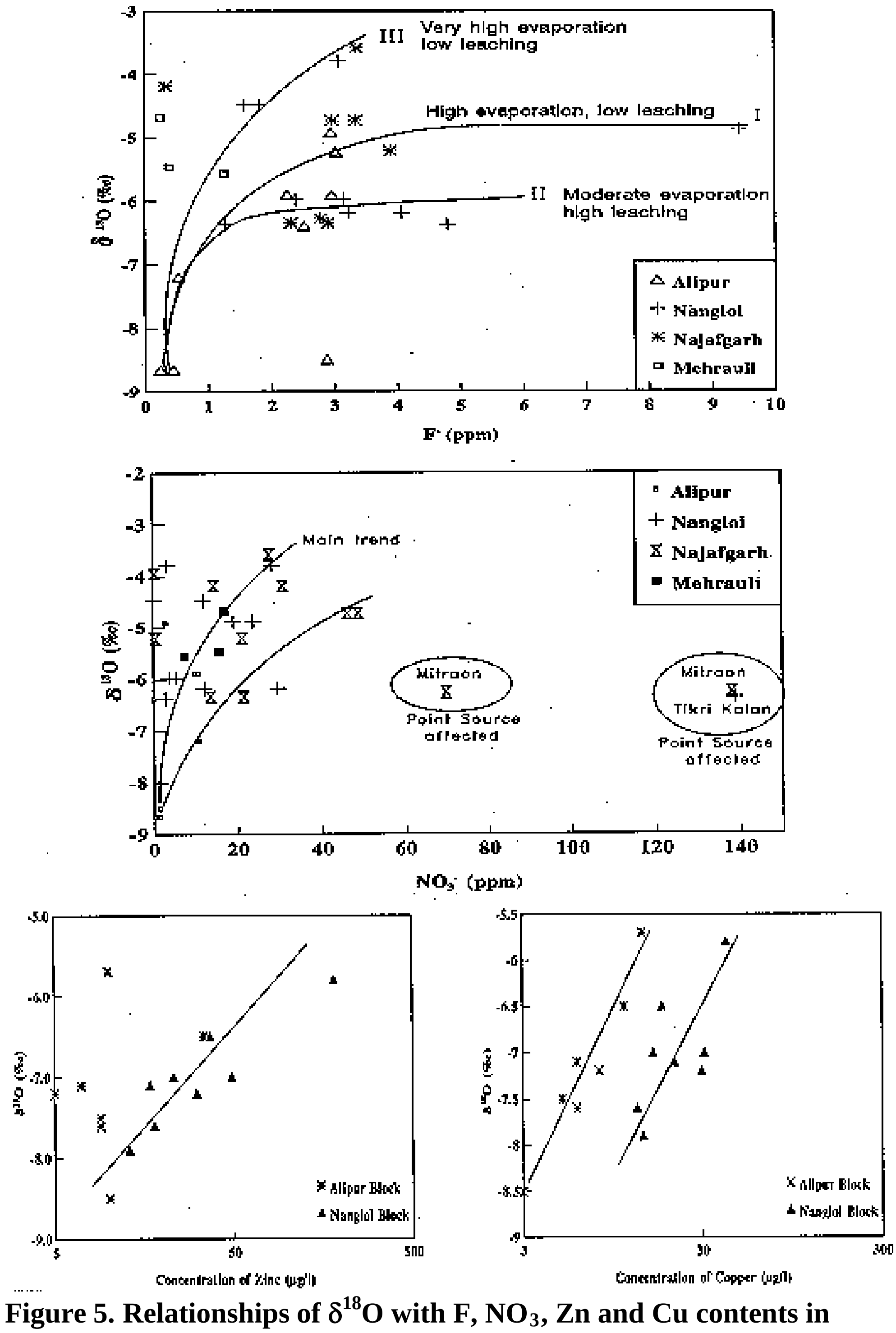

Figure 5. Relationships of $\delta^{18}O$ with F, NO_3, Zn and Cu contents in groundwater in Delhi area.

GROUNDWATER CONTAMINATION CHARACTERISTICS

Groundwater in considerable parts of the investigated areas is affected by salinisation and is moderately to highly contaminated with toxic chemical constituents, such as nitrate, fluoride, heavy metals, etc. (Datta et al 1996, 1997, 1998, 1999). Highly skewed distribution of contaminants in groundwater suggests contributions from both point and non-point sources. Characterisation of the extent of contamination and the processes governing such contamination is not possible based on the contaminants concentration data alone. At any location in the saturated aquifer, the combined effect of geochemical dissolution of minerals, the processes of adsorption/dispersion of contaminants species in the soils, changes in contaminants concentration in recharging waters over time (related to changes in landuse practices), as well as variable lateral intermixing of contemporary recharge with relatively old groundwater results in variation in contaminants contents and increase in areal extent of contaminated groundwater.

Relationships of ^{18}O with the chemical contaminant species clearly indicates that groundwater contamination is mostly derived from infiltration of rainfall, irrigation water and surface run-off water alongwith indiscriminately used agrochemicals and/or land-disposed industrial wastes (Fig.5) (Datta et al 1996, 1997, 1998, 1999). Hence, depending on the recharge characteristics, evaporation along the groundwater flowpath and during the period of stay of water on the land surface, the combined effects of the aforementioned processes, superimposed with lateral mixing along specific flow-pathways, are likely to result in ^{18}O enrichment and increase in contaminants levels of groundwater, with different trends in $\delta^{18}O$-contaminants relationships from location to location (Datta et al 1996, 1997, 1998, 1999). Barring a few points with very low contaminants levels, large variation in contaminants content with relatively little change in isotopic composition in the upper part of the trend clearly suggests leaching, while the lower part indicates different degrees of evaporation and mixing (Fig.5). It is well known that the land surface in the areas characterised by high evaporation and water scarcity, has a tendency to accumulate more wastes in the proximity of water supply sources. Therefore, management of groundwater in such areas must consider not only the source and level of contaminants but also the pathways between the contaminants source and the water-supply well, the velocity of groundwater along the pathways and the attenuation capacity for the contaminants in the aquifer.

CONCLUDING REMARKS

Groundwater resource characteristics and distribution differ from region to region and are geographically bound entities. Although, at some places high intensity rainfall may be the main contributor to the groundwater, yet, recharge from flood is not a rapid process and vertical recharge may be small or negligible.

Groundwaters are, generally, mixtures of varying proportions of different sources and the aquifer in an area does not necessarily constitute a homogeneous system in its vertical and lateral extent. Therefore, each area/region should be treated seperately, through proper choice of technology and research packages (which include inventory, survey as well as experimental projects). It is desirable to formulate mechanism, specifically to control contamination of groundwater due to diffused and non-point sources, through coordination among the provisions in the statutes on groundwater quality, waste disposal practices, removal of waste dumps, etc, and through preventive measures to carry away the wastes from the vicinity of the tubewells, wells and handpumps. Capacity building, educating the public, government and non-government personel, particularly women, in conservation of the quality and quantity of water and sustained management of the water supply system are of utmost importance.

Inherent uncertaianty, inhomogeneity and complexities of the hidden natural groundwater system suggest that sustainable solutions demand development of a community based network on water quality monitoring and surveillance system, based on adequate infrastructure and technology for obtaining basic hydrogeologic information of the groundwater system, both under natural and exploited conditions. It is desirable to bridge many gaps by continued systematic research, based on isotope techniques, on generating, refining and monitoring the hydrogeological parameters, such as, characteristics of the groundwater flow field, recharge, dynamics of pollutants, their depth variation and seasonal fluctuations, in relation to the changes in meteorological conditions and landuse pattern. Newer technologies should have more knowledge intensive mandate, with an objective to protect the resource base and to enhance the use-efficiency. This calls for consolidation of efforts and significant reorientation in the ways research is organised, managed and conducted in order to enable existing and future technical research to become more appropriate and applicable at the local level. Research organisation should be shifted from the existing compartmentalised disciplinary mode to problem-solving interdisciplinary approaches, clearly distinguishing from multi-disciplinary mode. From the point of resource management, the focus should shift to the development of: (a) more knowledge intensive technological 'package', suitable for long-term needs of the users, planned in association with the users, and (b) programmes of training in appropriate isotope tracer technology, realising the significance and importance of close inter-linkages with other disciplines such as water resources, environment, physical sciences, earth and atmospheric sciences, etc.

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