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Advances in Isotope Techniques for Environmentally Sustainable Resource Management and Crop Production

P.S. DATTA
Nuclear Research Laboratory, Indian Agricultural Research Institute,
New Delhi 110 012

ABSTRACT

Management of water resources, for environmentally sustainable crop production, requires a comprehensive understanding of the complex interaction of the water resource with its physical environment. In this context, isotope techniques provide a potential tool which give a direct insight into the water movement and distribution processes within the hydrological cycle and plants system. Advances in the use of radioactive isotopes (^{3}H, ^{14}C, ^{234}U, ^{238}U, ^{239}U) and stable isotopes (^{2}H, ^{3}He, ^{18}O, ^{13}C) for water resource management has been described through case studies, conducted in the Indo-Gangetic Alluvial plains, in the Sabarmati River Basin of Gujarat and in some arid parts of Rajasthan.

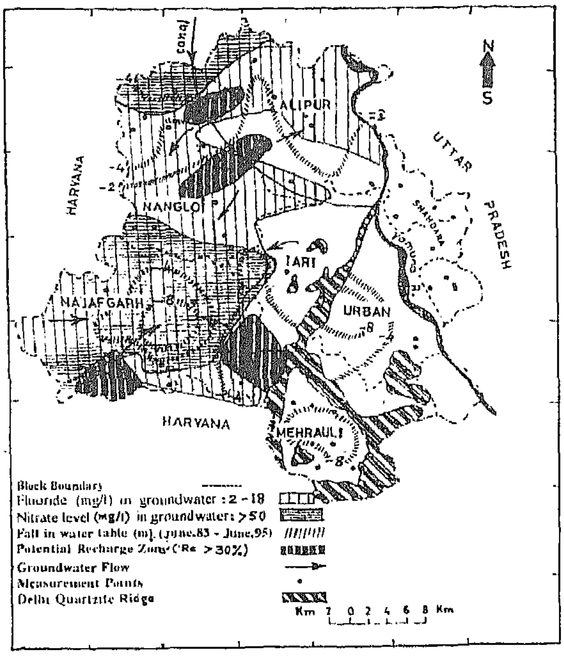
Introduction

The sustainability in crop production is determined by a complex interaction of natural resources (water as the leading input) with their physical environment. By the yardstick of irrigation efficiency, obviously, groundwater is the most important water resource for the future. However, in many parts of the country, disproportionate use of groundwater has resulted in a number of environmental problems, such as lowering in 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. The environmental consequences of agricultural technologies and the management of natural resources to adopt these technologies, however, have not received adequate attention. Hence to optimise the water-use in the long term and to conserve it as required, a responsible water management policy is expected to make every effort to obtain comprehensive and accurate data on groundwater and its regeneration. Some of the important aspects, with which water resources managers and developers are confronted, include groundwater renewal characteristics, flow velocity and direction, its interaction with each other as well as with surface water bodies, quality of water and causes of quality deterioration. These parameters must be measured under both the steady and non-steady conditions.

The isotope techniques occupy a special place, in this context, since such methods only can give a direct insight into the water movement and distribution processes within the hidden groundwater aquifiers and plants system. In India, isotope techniques have been used extensively, for over three decades, to understand the water cycle, soil water movement, groundwater flow regime, recharge and contamination characteristics, residence time (age) in the aquifer, groundwater-surface water interactions, water translocation in vascular plants and water-use-efficiency, groundwater hydrodynamic zones, flow-pathways and mixing processes in groundwater system. In this brief background, use of radioactive, isotopes ^{3}H, ^{14}C, ^{234}U, ^{238}U, ^{239}U) and stable isotopes (^{2}H, ^{3}He, ^{18}O, ^{13}C) for groundwater resource management has been described through case studies, conducted in the states of Punjab, Haryana, Delhi and Uttar Pradesh of the Indo-Gangetic Aluvial Plains, in the Sabarmati River Basin of Gujarat and in some arid regions of Rajasthan.

Groundwater recharge characteristics

Advanced techniques using ^{3}H and ^{18}O isotopes provide an independent and reliable estimates of groundwater recharge. The tritium injection technique has been extensively used during the last twenty five years and mean recharge values for twenty two areas, well-distributed over the seventeen major river basins are now available. The studies indicate that average groundwater recharge from rainfall varies widely (1-50%) 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 and soil clay content. The average value of recharge is 20% in western Uttar Pradesh (Datta *et al.*, 1973), 18% in Punjab (Datta and Goel, 1977), 15% in Haryana [Goel *et al.*, 1977], 14% in Sabarmati Basin, Gujarat (Datta *et al.*, 1980) and less than 8% in Delhi area (Fig. 1) (Datta,



- **Recharge is less than 5% in most parts, where fall in water table due to over exploitation ranges from 2 - 8 m.**
- **Groundwaters in almost 50% of the area are severely contaminated with high levels of fluoride and nitrate, contributed by agrochemicals and anthropogenic wastes.**

Fig. 1. $^{18}O/^{16}C$ isotope signature based characterisation of groundwater recharge and contamination in Delhi area

1997). A comparison of the results for the Sabarmati basin with those of the Ganga, the Ramganga and the Yamuna basins in the Indo-Gangatic Plains indicated a relatively higher efficiency of winter rains in inducing groundwater recharge [Datta *et al.,* 1979]. Higher potential evaporation during monsoon months in Sabarmati basin may be expected to reduce the net groundwater recharge for a certain amount of water input (Datta *et al.,* 1980a).

The radiocarbon concentrations of confined groundwaters in Gujarat and Rajasthan indicated significant amounts of fresh water recharge even in areas far away from the principal recharge areas of aquifers [Borole *et al.,* 1979]. A strong relationship between recharge amount and depth to water table suggests that in water-logged areas recharge can be enhanced by lowering the water table. A conceptual model was developed to reproduce the isotope tracer profile in the soil zone and to simulate layer by layer movement of soil water and mechanisms of infiltration in the unsaturated zone [Datta *et al.,* 1980a]. A significant correlation (r=0.94] was observed between the number of recharge pulse (estimated by the model) and the number of days with rainfall greater than three times the estimated pulse size. Such models are also useful in predicting groundwater pollution, caused by return seepage of irrigation waters (containing fertilizers, insecticides, pesticides, etc.) and industrial wastes.

Groundwater - surface water interaction

In outcrop areas, rain water during its entry through the recharge zone of an aquifer gets labelled with the characteristics abundances of ^{238}U as well as $^{234}U/^{238}U$ atomic ratio (AR). Groundwater Uranium AR changes with time either due to decay of ^{234}U ($T_{1/2}$ 2.48 x 10^5 yr) or by mixing with another groundwater body having different Uranium AR. Seasonal variation of ^{238}U concentration (dpm/l) and its isotopic ratio ($^{234}U/^{238}U$) in river water, representing varying components of overland and subsurface flow, were used as tracers for the first time to study to estimate-effluent seepage of groundwater into Sabarmati river, Gujarat [Borole *et al.,* 1979]. The study indicated that about 7% of annual discharge through the river upstream of Ahmedabad was derived from effluent groundwater discharge, the maximum contribution being 25% at some points of the river. Regional flow velocities of groundwater were found to control the effluent seepage of the groundwater system.

In another study in Delhi area, by developing a simple mixing model, based on the spatial and depth variations in $^{18}O/^{16}O$ ratio of groundwater and canal/river water, and considering equal inflow of groundwater through the screens of the tubewells, it was computed that canal/river water contributes to the groundwater recharge upto 5-10 m depth of the aquifer adjacent to the canal/river (Datta and Tyagi, 1995). Seepage contributions are estimated to range between 20% to 50% and is determined by the flow in the surface water courses. There is decreasing contribution of river/canal seepage component to ground-water with increasing depth of the aquifer. Straight line relationships between groundwater ^{18}O and Cl in Delhi area indicate that groundwater intermixing takes place along specific flow-pathways (Fig. 2) [Datta *et al.,* 1996]. The lateral component of recharge is estimated to range from 25-70%, influenced by the flow-pathways of mixing and the extent of the hydrodynamic zones (as indicated by small isotopic gradients) [Datta *et* et al., 1994).

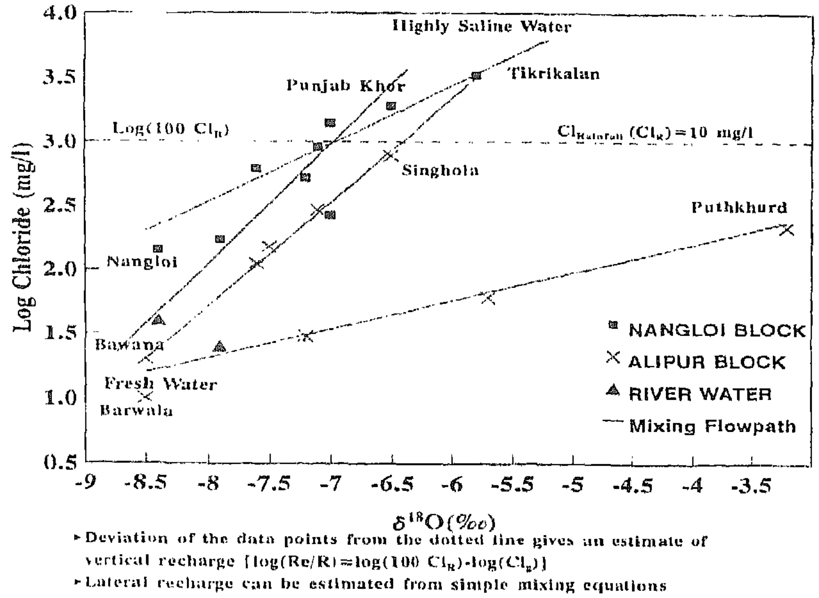


Fig. 2. Groundwater δ^{18}O-Cl relationships in Delhi

Regional groundwater flow

Regional groundwater flow velocity was estimated in he Watrak-Shedi sub-basin of the Sabarmati river basin, Gujarat, by ^{14}C ($T_{½}$ = 5730 yr) dating of groundwaters (Borole *et al.*, 1979). Apparent radiocarbon age of the groundwaters ranged from 1,850-17,880 yr, with age of 2,000 yr corresponding to young waters in the recharge area. From interpolation cotouring of the apparent ages, regional velocity of groundwater flow in the confined aquifer was estimated to be 6-7 m/yr in the NE-SW direction, and transmissivity for the 30-80 m depth group of aquifers was computed to be 700 m^2/day which was in agreement with the value estimated by pump test. Radiocarbon dates and ^{18}O isotopic data of groundwater also indicated significant stratification in groundwater in Delhi area [Datta and Tyagi, 1995], Pushkar Valley, Rajasthan (Datta *et al.*, 1994a), Sabarmati Basin, Gujarat (Borole *et al.*, 1979; Datta *et al.*, 1980b) and Jaisalmer District, Rajasthan (Datta *et al.*, 1980b).

Groundwater contamination characteristics

Widespread decline in the groundwater level and growth of salinisation and pollution are the critical factors controlling future groundwater quality and availability. Groundwater in considerable parts of the investigated areas is affected by salinisation and is moderately to highly contaminated with toxic chemical constituents (Fig. 1), such as nitrate, fluoride, heavy metals, etc. (Datta, 1997; Datta and Tyagi, 1995; Datta and Tyagi 1996; Datta *et al.*, 1996; Datta *et al.*, 1997). The spatial distribution and relationships of the stable isotope ^{18}O and chemical contaminant species clearly indicate the direction of groundwater movement and mixing of multiple sources of highly saline/contaminated groundwater with relatively fresh groundwater or river water along specific flow-pathways (Datta, 1997; Datta and Tyagi, 1995; Datta and Tyagi, 1996; Datta *et al.*, 1996; Datta *et al.*, 1997). The studies also indicate 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. 3a and Fig. 3b) (Datta, 1997; Datta *et al.*, 1996; Datta *et al.*, 1997).

Resource use efficiency

Water uptake and translocation in terrestrial vascular plants occur with negligible discrimination between $H_2{}^{18}O$ and $H_2{}^{16}O$. ^{18}O of atmospheric oxygen does not exchange directly with oxygen of water molecule in the plant, although, it can appear as $H_2{}^{18}O$ by metabolic reaction in plant through O_2 consumption by non-photosynthesising tissues and also by O_2 production in photosynthetic system. Studies on the extent of isotopic enrichment of water in the vegetative parts and wheat grain indicated that the ^{18}O composition varied considerably with respect to that of irrigation water, depending upon the genotypes (Pande *et al.*, 1995). Sharp enrichment in ^{18}O composition of grain water appeared to be related to both desiccation of grain depleting $H_2{}^{16}O$ as well as cessation of irrigation water entry into the grain. This genotypic characteristic of $^{18}O/^{16}O$ ratio could be helpful in resource management and useful for identification of suitable genotypes having better water extraction capacity, an important component of crop productivity.

The increasing biomass during the southwest monsoon period rapidly consumes atmospheric-CO_2 for photosynthesis, through the enzyme Rubisco which has a capacity to discriminate

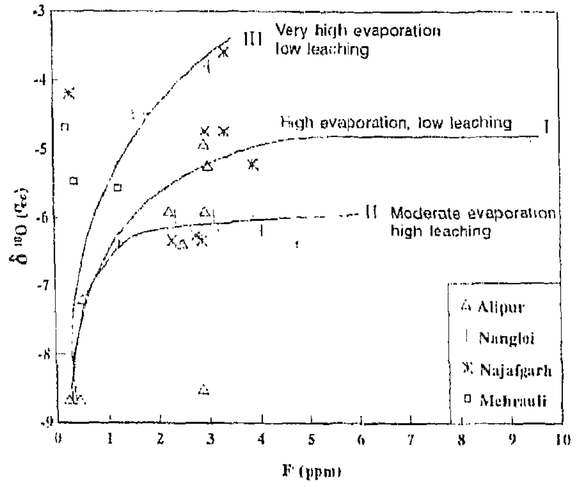


Fig. 3a. $\delta^{18}O$-F relationship in the groundwater of Delhi area, indicating infiltration of irrigation water (evaporated and enriched in ^{18}O) alongwith fluoride

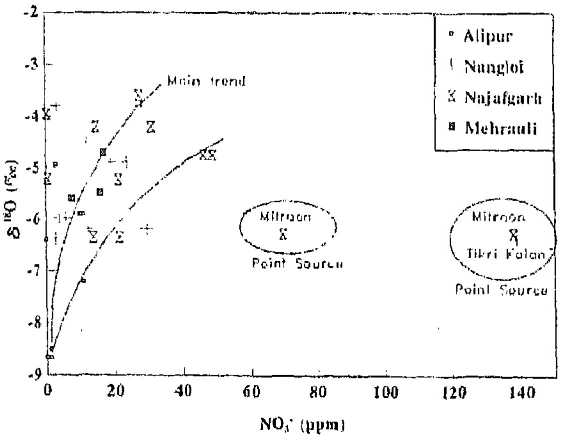
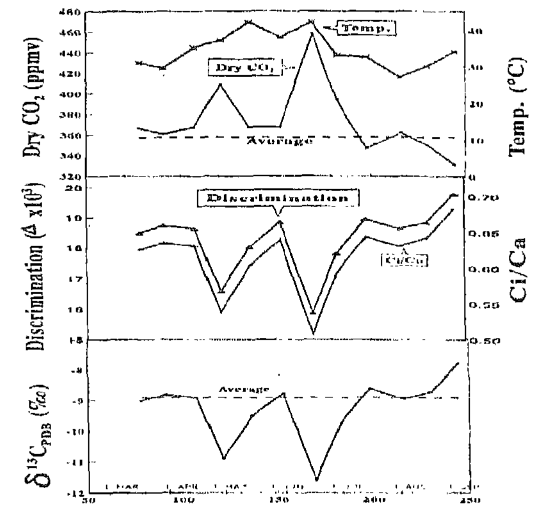


Fig. 3b. $\delta^{18}O$-NO_3 relationship in the groundwater of Delhi area, indicaitng infiltration of irrigation water (evaporated and enriched in ^{18}O) alongwith fertilizer nitrate

between ^{12}C and ^{13}C. This causes associated changes in the $^{13}C/^{12}C$ ratio of air-CO_2 (Datta *et al.*, 1995). The signatures of ^{13}C isotopic discrimination in plants were observed to be negatively correlated with water-use-efficiency (ratio of above ground dry matter to water use). In this background, the magnitude of the above mentioned effects was assessed, in relation to the water-use-efficiency, by estimating the seasonal variations in the $^{13}C/^{12}C$ ratio of air-CO_2 and the discrimination in vegetation dry matter at IARI Farm, New Delhi



▸ Isotopic (^{13}C) discrimination (Δ)in vegetation decreases with increase in air-CO_2 level and depletion in air-CO_2's ^{13}C level.

▸ Δ is relatively less in hot summer months, indicating higher Water Use Efficiency (WUE $\propto$ 1/discrimination).

Fig. 4. Seasonal variations in water use efficiency and $^{13}C/^{12}C$ signatures in air-CO_2 at IARI farm, New Delhi

(Fig. 4). Discrimination was observed to be relatively less during the summer months (April end to June end), indicating enhanced water-use-efficiency of vegetation during warmer months when water availability was less. Conversely, during cooler months when water availability is more, water use-efficiency is expected to decrease, while absolute CO_2-assimilation might increase. Regular monitoring of carbon isotopic discrimination characteristics in plant tissues and air-CO_2 will be useful to assess how plants allocate water and carbon resources to their different structures and functions.

Conclusions

Isotope techniques based ground-surveying is very essential for crop productivity linked water management and ultimate detailing various processes and parameters. The time and reliability problems can be vastly reduced by the integration of ground-surveying with satellite-surveying. To protect the resource base and to enhance the use-efficiency of the inputs, there is need : (a) for the development of an advanced technological package, suitable for long-term needs of the users, planned in association with the users; and (b) for programmes of training in appropriate newer technologies having more knowledge intensive mandate.

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