Groundwater vulnerability to changes in land use and society in India

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Abstract In many parts of India, the freshwater pollution crisis has become evident at different times in response to population growth, agricultural intensification, urbanization, industrialization and *ad hoc* management approaches. Average groundwater recharge from rainfall varies widely (<8–20%). Groundwater in many places is polluted by salinity, F (<1–46.0 mg L^{-1}), NO_3 (<20–1600 mg L^{-1}), and heavy metals Zn (3–41 µg L^{-1}), Cu (5–182 µg L^{-1}), Fe (279–1067 µg L^{-1}), Pb (31–622 µg L^{-1}), Ni (<1–105 µg L^{-1}), Cd (<1–202 µg L^{-1}). Slow infiltration of agricultural/urban surface runoff mixing with available pollutants in cross-sector wastes is responsible for groundwater pollution. Over-exploitation problems have induced the intermixing of highly polluted water with freshwater along specific flow-pathways and this has increased the lateral extension of the groundwater pollution problem. Groundwater vulnerability to pollution has been assessed using the integration of information on groundwater recharge, contamination characteristics, isotope fingerprinting, the Software PHREEQC for aqueous and mineral saturation index, and GIS. The freshwater crisis across India associated with groundwater pollution can be better managed by the strict enforcement of regulatory measures restricting unplanned water abstraction and waste disposal, guided by overarching ethical considerations.

Key words groundwater; recharge; pollution; exploitation; vulnerability; land-use; society; isotope; India

INTRODUCTION

Over recent decades, water demand, consumption and pollution has increased in India in conjunction with a rapidly growing population, land-cover changes, agricultural intensification, industrialization and urbanization. Agriculture occupies 60–80% of the area of the Indian States and accounts for the economic livelihood of ~70% of the population and 80–95% of freshwater utilization; compared with municipal and industrial water consumption account for 11 and 19%, respectively. According to the 2011 population census, which suggested a ~1.6% annual growth rate in India’s national population, the respective populations of Delhi, Uttar Pradesh, Punjab, Haryana, and Rajasthan increased to 17 million (M), 199 M, 27 M, 25 M and 68 M, whilst population density (persons km^{-2}) increased to 9340, 828, 550, 573 and 201, respectively. India experienced a 42.67% growth in industry during the period 1987–2007. For 2009, wastewater generation from the industrial sector was 55 000 × 10^6 m^3 d^{-1}, of which 68.5 × 10^6 m^3 was discharged into rivers/streams without prior treatment. The solid waste produced in Delhi, UP, Haryana and Rajasthan was almost 9448 × 10^3 kg d^{-1}. The Government of India (GoI, 2009) reported that >70% of India’s surface water is polluted. There is substantial disparity in surface water supply, with some areas getting 650 Lpc/d (per capita per day) whilst others receive only 25 Lpc/d. Thus, a freshwater crisis currently exists in many parts of India. On the basis of projected population growth by 2025, per capita water availability is likely to drop from 1588 m^3 in 2010 to <1000 m^3, taking India into “water scarcity”.

India is characterized by an erratic spatial and temporal distribution of annual rainfall (annual average 1170 mm; <150 mm in the northwest declining to 2500 mm in the northeast States and west coast), ~80% of which falls in brief spells during the monsoon months (June–September). Mean maximum temperature remains at 30–40°C in summer (March–May) and falls by 5–10°C with the onset of the monsoon season. The significant disparity of rainfall, floods and droughts in the different parts of India either aggravates or masks the water crisis, as driven by the demand for large quantities of high quality water by rural users and low to moderate quantities by urban users. The weather and man-made pressures have driven India’s farmers, households and industry to depend increasingly on a dynamic supply of 432 billion m^3 of groundwater with the future hope of managing 10 812 billion m^3 in reserves, which according to the World Bank (2010) would support ~60–85% of irrigated agriculture and >80% of domestic supplies.

For the improved protection of groundwater supplies, planners and decision makers are concerned with developing an improved understanding of groundwater recharge, water quality and the principal causes of its deterioration, sources of pollution and the management of the main sources of the pollution problem. However, in India, few detailed local studies of groundwater vulnerability to pollution have been made using available approaches such as probabilistic models and statistical or overlay/index methods. In this context, this paper describes a groundwater vulnerability method based on extensive field studies over three decades, taking account of the spatial and temporal variability of land use, hydrogeology, recharge and pollution characteristics, age (residence time), intermixing flow paths, influent/effluent seepage and potential pollutant sources fingerprinted using radioactive (^{3}H, ^{14}C) and stable (^{2}H, ^{18}O) isotopes in sedimentary aquifers of the Ganges Plains (Fig. 1) in the States of Punjab, Haryana, Uttar Pradesh, Delhi, Rajasthan and Gujarat, characterized by high groundwater usage.

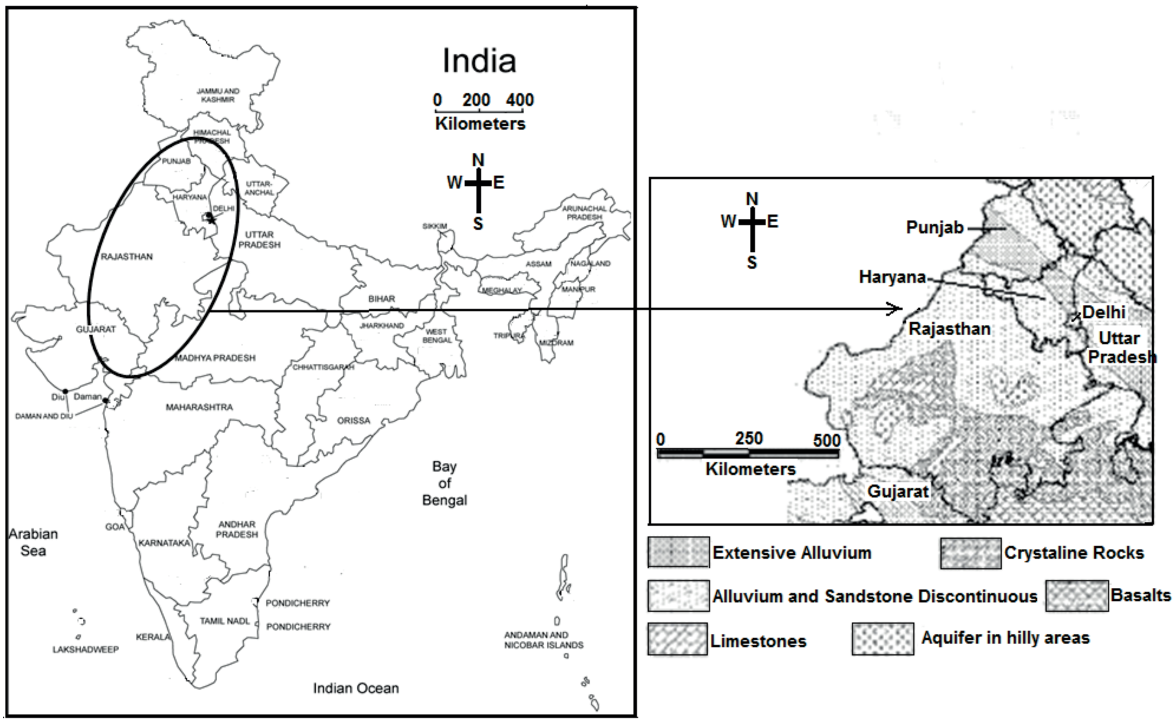

Fig. 1 Maps of India and the investigated areas showing the geological features in the States of Punjab, Haryana, Uttar Pradesh, Delhi, Rajasthan and Gujarat. (Data source: CGWB, India).

MATERIALS AND METHODS

Short range (but not short duration) recharge has been estimated by tracing the downward movement of an artificially injected ^{3}H tagged layer of soil moisture below the root zone, a method developed by Datta *et al.* (1973, 1980), Datta & Goel (1977) and Goel *et al.* (1977). Recharge and pollution characteristics, intermixing flow pathways, and influent/effluent seepage were assessed by considering natural abundances of stable (^{2}H, ^{18}O) and radioactive (^{3}H) isotopes in groundwater as proxy indicators of rainfall isotopic composition. ^{2}H and ^{18}O levels were estimated as δ (per mille ‰) = $(R_{sample}/R_{standard} - 1) \times 1000$ deviations from Standard Mean Ocean Water, where (R) is ^{18}O/^{16}O or ^{2}H/^{1}H. To analyse variations in groundwater quality during the pre- and post-monsoon season, and to assess processes responsible for the pollution, hydrochemistry data were integrated with a range of additional information provided by the saturation index (estimated using USGS Software PHREEQC for low-temperature aqueous and mineral geochemistry calculations such as speciation, one-dimensional transport with reversible and irreversible reactions, and ion-exchange equilibria) and GIS. ^{3}H levels are expressed as Tritium Units (1TU = one ^{3}H atom in 10^{18} atoms of ^{1}H). Groundwater ^{14}C-age was estimated using the ^{14}C half-life (5730 years) and the percentage of

Modern Carbon (pMC), and corrected for the exchange of carbon in water with the surrounding aquifer matrix carbon. Land use was classified as industrial, agricultural and rural. Readers are referred to the cited references for further details on the scientific methods of water sampling and isotopic or chemical analyses.

RESULTS AND DISCUSSION

Groundwater provenance, occurrence and recharge characteristics

Datta *et al.* (1991) and Gupta & Deshpande (2005) reported that available data on the δ-values of ^{18}O and ^{2}H in Indian rainfall fall along the world meteoric line ($\delta^2H = 8\delta^{18}O + 10$) with depleted and relatively enriched isotopes generally associated with heavy rainfall and rainfall deficient years, respectively. Different regions/locations have regional/local meteoric lines, with slopes of <8 due to evaporation and subsequent enrichment of rainwater during the fall. In India, data on groundwater $\delta^{18}O$ (URL: http://www.prl.res.in/%7Ewebprl/web/announce/ind-gw.pdf) suggests three broad groups: <–4‰ (northwestern areas and the Gangetic Plains), –4‰ to –2‰ (southeast coast Plains) and >–2‰ (Western Ghats and the Deccan Plateau). In northwestern India and Gangetic Plains, groundwater $\delta^{18}O$ (–4.2‰ to –7.6‰) is highly depleted compared to the present day weighted mean rainfall $\delta^{18}O$, but with spatial variations evident. Sinha & Navada (2008) measured ^{3}H (5–20 TU) and reported ^{3}H with an age of <50 years in shallow groundwater near a river course in the Jalore area compared with depleted δD and $\delta^{18}O$ and negligible ^{3}H (1.4 to 3 TU) in deep groundwater (>50 m) more distant from the surface watercourse. In northwest India, the groundwater ^{14}C-age of 2000–22 000 years BP (Fig. 2) reported by Borole *et al.* (1979), Kulkarni *et al.* (1989), Rao (2003) and Datta (2009) suggests modern recharge in shallow aquifers and in some places, palaeo-water recharge during past periods of humid climate.

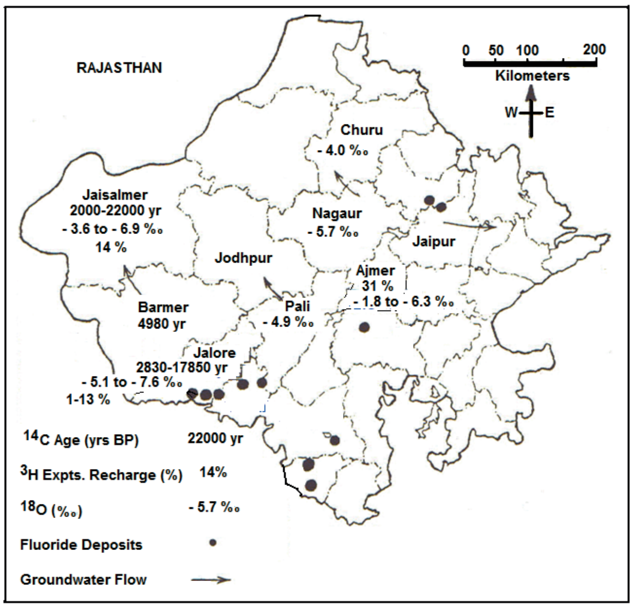

Fig. 2 Map of Rajasthan State showing the groundwater ^{14}C-age and recharge in different parts. Data Source: Rao (2003) and Datta (2009).

Datta *et al.* (1973, 1979, 1980, 1980b, 1996, 2001), Datta & Goel (1977), Goel *et al.* (1977), Sharma & Gupta (1987) and Datta (2000, 2005), and observed that ~73% of contemporary recharge takes place during the monsoon months, and varies widely region to region and within regions, both in space and time, depending on the rainfall intensity, evaporation, and soil properties, resulting in a wide range of $\delta^{18}O$ (–2.8 to –8.6‰) values in groundwater. The average annual groundwater recharge (Fig. 3) in the north alluvial plains is high (18% in Punjab, 15% in Haryana, 20% in Uttar Pradesh) due to plenty of rainfall and thick unconsolidated formations conducive for recharge, but very limited (<5% in Delhi, 1–14% in Rajasthan, and 8–14% in Gujarat) elsewhere. Datta *et al.* (1979, 1980) observed that winter rains have relatively higher efficiency in inducing recharge, but higher potential evaporation during monsoon months is likely to reduce the net recharge. Insignificant recharge occurs if the annual water input (rainfall+irrigation) is <40 cm. Extensive (but inefficient) irrigation canal system seepage contributes ~35% of groundwater recharge. Simple mixing models of canal/river water and adjacent groundwater developed by Datta & Tyagi (1995) and Datta & Kumar (2011), based on the Yamuna River/canal water $\delta^{18}O$ (–8‰ to –9.7‰) and adjacent shallow groundwater $\delta^{18}O$ (–5.6‰ to –9.6‰) values, suggest significant canal/river water seepage to groundwater down to 5–10 m depth in the adjacent aquifer in the Delhi area, with 2% to 96% river water seepage to groundwater under the flood plains along different specific reaches. However, since canal and river water are generally polluted, the seepage contributes to groundwater contamination.

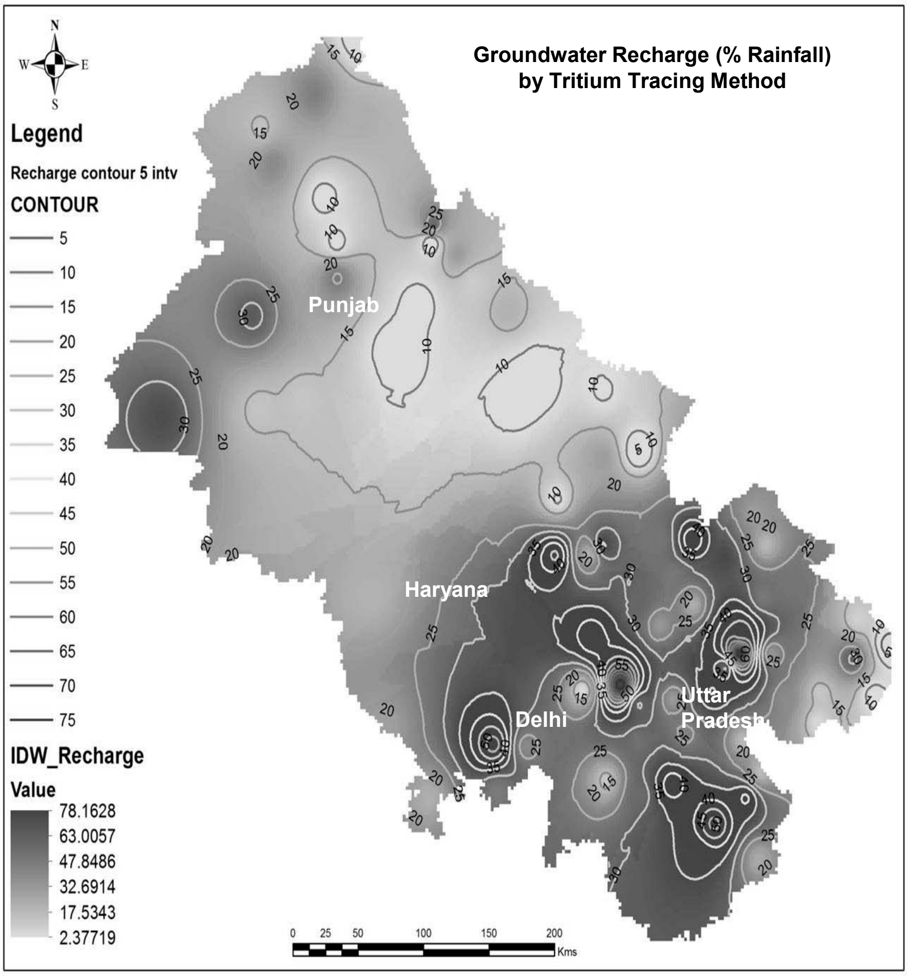

Fig. 3 Groundwater recharge and development characteristics in Northwest India. Data sources: Datta *et al.* (1973, 2001), Datta & Goel (1977), Goel *et al.* (1977), Datta (2000, 2005, 2008).

Groundwater vulnerability to extraction and pollution

As reported by Chatterjee & Purohit (2009), over the last two decades, the development of groundwater resources (Fig. 3) was ~106% in Delhi, 94–145% in Punjab, 84–109% in Haryana, 60–70% in Uttar Pradesh, 41–51% in western states, 17–30% in central states, and 24–60% in southern states. The same authors reported that over-abstraction is 100–260% in some areas in Punjab, Haryana, Gujarat and Rajasthan. Rohilla *et al.* (1999), Datta *et al.* (2001), Datta (2005) and Chatterjee & Purohit (2009) reported that over the last 2–4 decades, water table levels were reduced by between 2–8 m and 30–40 m in different parts of the highly urbanized Delhi area, 7–10 m in Rajasthan, 2–8 m in Haryana and Gujarat, and 0.2–3.0 m in Uttar Pradesh. In 77% of the area of Punjab, the water table has been lowered by a depth of 25–30 cm year^{-1}. Considerable water table lowering (>4 m) has also been observed in other States by Chatterjee & Purohit (2009). In northwest India, groundwater withdrawal has been estimated at 13.2 km^3 year^{-1} based on water table fluctuation data of the Central Ground Water Board (CGWB), reported by the GoI (2010). Groundwater depletion was estimated at 4.0±1.0 cm year^{-1} (17.7±4.5 km^3 year^{-1}) for the aquifers of Punjab, Haryana and Rajasthan including Delhi, over the period 2002 to 2008 by Rodell (2009). NASA's Gravity Recovery and Climate Experiment (GRACE) data for recharge are close to the 15.5±2.5 km^3 year^{-1} reported by Datta *et al.* (1973), Datta & Goel (1977) and Goel *et al.* (1977). Héctor *et al.* (2011) reported, however, that India is the largest groundwater user in the world with an estimated usage of ~230 km^3 year^{-1}, and with 29% of groundwater assessment blocks being classified as semi-critical, critical, or overexploited.

It is evident that groundwater supplies in the states of Haryana, Punjab, Rajasthan, Gujarat and Delhi are vulnerable to over-abstraction and their over-exploitation is not commensurate with recharge rates. This may be because, generally, in rural areas, users manage groundwater by their own wells; and in urban areas, it is managed largely by municipal utilities. Moreover, the absence of strict regulation and systematic registering and metering of wells, plus electricity subsidies in rural areas encourage indiscriminate groundwater pumping by users, with competition to extract as much water as possible. Datta (2005) documented that variations in social, economic and political factors combined with scarce information on the population demands on groundwater supplies, make it difficult to assess exactly the aggregate impact of over 20 million pumping decisions, population growth, land use, and industrialization on groundwater supplies, with a view to developing a single template for improved management.

Datta & Tyagi (1995), Tyagi *et al.* (2009) and Kumai *et al.* (2011) reported that in north-western parts of India, brackish and saline to highly salinity groundwater (EC: 3000–16 000 µmhos cm^{-1}) exist at all depths; EC: 200–3000 µmhos cm^{-1} is observed in shallow groundwater, and salinity increases with depth. Datta *et al.* (1996, 1996a, 1997), Gupta & Deshpande (2005) and Kumai *et al.* (2011) reported that groundwater in many parts of Punjab, Haryana, Gujarat, Rajasthan, Delhi and other states is severely affected by F (1.5–45.8 mg L^{-1}) and NO_3 (25–1800 mg L^{-1}) levels, exceeding the WHO maximum permissible limits in drinking water. A comparison of these levels with those reported by various surveys in other countries, based on UNEP (2010), indicates that in Africa 20–50% of wells contain nitrate levels greater than 50 mg L^{-1} to several hundred mg L^{-1}; and the mean nitrate levels have increased in the last decade in watersheds in the Americas, Europe, Australasia and the eastern Mediterranean. WHO (2004) reported very high fluoride levels, >8 mg L^{-1}, in groundwater of some villages in China and in some African countries (e.g. United Republic of Tanzania); and >1.5 mg L^{-1} to 3–9 mg L^{-1} in groundwater at many places in central Australia. Datta *et al.* (1999) also reported trace to excessive amounts of heavy metals, such as Zn (3–41 µg L^{-1}), Cu (5–182 µg L^{-1}), Fe (279–1067 µg L^{-1}), Mn (<1–76 µg L^{-1}), Pb (31–622 µg L^{-1}), Ni (<1–105 µg L^{-1}) and Cd (<1–202 µg L^{-1}) in groundwater in some parts of Delhi, Haryana and Uttar Pradesh near industrial sites. Datta & Kumar (2011) reported that total and faecal coliform bacteria counts vary from 1–570 000 MPN/100 ml and 1–420 MPN/100ml, respectively. In the coastal area of Gujarat, Kumari *et al.* (2011, 2013) reported the impacts of sea water intrusion on groundwater quality. As a typical example, a summary of some quality parameters levels (mg L^{-1}) in groundwater of different states of India is given in Table 1.

Datta & Tyagi (1995, 1996), Datta *et al.* (1996) and Kumari *et al.* (2011) reported that unplanned excessive application of nitrogen fertilizers (applications have increased ~100-fold since 1947–1948) and agro-chemicals, indiscriminate disposal of wastes from steel, aluminum, brick and tile industries, barn yard and silo wastes, applications of un-treated sewage water to land, or discharges of this waste to canals/river and unlined drains, and leaching from landfills has exposed groundwater to the risks of severe degradation. The lateral extension of polluted groundwater induced by variable intermixing of polluted groundwater with relatively less

Table 1 Some quality parameters levels (mg L^{-1}) in groundwater of different states of India.

	Sabarmati Basin, Gujarat		Rajasthan	Delhi, Punjab, Haryana, Uttar Pradesh
Parameter	Premonsoon	Postmonsoon	Premonsoon	Premonsoon
pH	7.1–9.1	7.1–9.3	7.6–9.0	6.5–9.0
EC (µmhos cm^{-1})	210–2890	240–2350	250–13560	200–16000
HCO_3	73.2–439.2	36.6–1000.4	116–1440.0	28–220.0
F	0.4–2.5	0.3–5.6	0.2–16.5	1.5–45.8
Cl	58.4–1993.2	36.6–850.2	21.0–3930.0	5.7–4400.5
NO_3	1.6 –630.7	2.7–131.7	2.9–150.9	<25–1800.0
Na	90.0–1050.3	63.9–808.4	28.0–2897.0	10.0–1370
Ca	1.9–58.9	10.2–80.2	11.0–496.5	1.3–220.2
Mg	0.9–128.7	2.4–62.4	19.0–492.0	1.7–105.1

contaminated freshwater along specific flow-pathways has been noted by Datta *et al.* (1996a,b), Datta & Tyagi (1995, 1996) and Datta (1997).

Depth variation in groundwater ^{14}C-age and δ^{18}O values reported by Datta & Tyagi (1995) in the Delhi area, by Datta *et al.* (1994, 1980) in the Pushkar Valley and Jaisalmer District, Rajasthan and by Borole *et al*. (1979) and Datta *et al.* (1980) in the Sabarmati Basin, Gujarat, are indicative of vertical stratification. From the ^{18}O and Cl iso-contours in groundwater, Datta *et al.* (1994) and Datta & Tyagi (1995) delineated hydrodynamic zones on the basis of small isotopic gradients and reported two main flow systems occurring vertically in the Delhi region: (i) the uppermost rapidly circulating, low salinity, local flow – more vulnerable to overexploitation; and (ii) a relatively slow circulating intermediate zone – more vulnerable to salinity and depletion. In order to check groundwater vulnerability to depletion and pollution, recharge zones need to be clearly identified and managed in terms of land-use changes, agro-chemical application rates and waste disposal. To make groundwater less vulnerable to N pollution, fertilizer applications to crops need to be regulated, as suggested by Datta *et al.* (1997), on the basis of minor modifications in irrigation water application and improved agronomic practices. On the premise of natural decontamination of percolating water along recharge paths, a predictive model by Soni *et al.* (2009) suggested that it is possible to decontaminate an unconfined aquifer in 6–10 years, by planned withdrawal of polluted water and an allowance for rainfall recharge.

CONCLUDING REMARKS

It is challenging to assess the exact aggregate impact of millions of individual pumping decisions on groundwater vulnerability to depletion and pollution. Further systematic monitoring and scientific research is needed for providing reliable and timely information on the groundwater supply and pollution issue in each region at regular intervals. It is essential to recognize the inextricable linkages between increasing water demand, inadequate availability and the disparity of surface water supply. Groundwater vulnerability to pollution can be managed by land use zoning and locating potential high risk polluting activities in areas of very low aquifer sensitivity. This approach is already being adopted in the European Union, using, for example, designated Groundwater Safeguard Zones in England and Wales.

The lack of an ethical framework has permitted indiscriminate water extraction and its wasteful utilisation and these need to be restricted by strictly enforcing targeted regulatory measures. To enhance water-use efficiency, "use" and "consumption" should be distinguished, with emphasis on pricing for water extraction, and the costs and benefits of water allocation for different purposes, including by communities, in both recharge and discharge areas and the need for exploitation of transboundary aquifers in different Indian States. Community-focused water use should distinguish two key groups: (1) irrigation, where consumptive use is high; and (2) practically all other uses (e.g. domestic, industrial, etc.) with relatively smaller water needs.

Acknowledgements The draft manuscript benefitted from the editorial and peer review, and data sources, such as the Central Ground Water Board, Ministry of Water Resources, Govt. of India; Physical Research Laboratory, Ahmedabad, India; UNEP, GEMS/Water; World Health Organization, etc. are acknowledged.

REFERENCES

Borole, D.V., Gupta, S.K., Krishanswami, S., Datta, P.S. & Desai, B.I. (1979) Uranium isotopic investigations and radiocarbon measurement of river–groundwater systems, Sabarmati Basin, Gujarat, India. *Isotope Hydrology* vol.1, IAEA-SM-228/11, IAEA, Vienna, 118–201.

Chatterjee, Rana & Purohit, Raja Ram (2009) Estimation of replenishable groundwater resources of India and their status of utilization. *Current Science* 96(12), 25 June, 2009.

Datta, P.S. (2005) Groundwater ethics for its sustainability. *Current Science* 89(5), 10 September, 1–6.

Datta, P.S. (2008) *Water: A Key Driving Force*. ISBN No. 81-7480-139-1, Vigyan Prasar, New Delhi. 100 p.

Datta, P.S., Bhattacharya, S.K. & Tyagi, S.K. (1994) Assessment of groundwater flow conditions and hydrodynamic zones in phreatic aquifers of Delhi area using oxygen-18. *Proc. International Workshop on Groundwater Monitoring and Recharge in Semi-arid Areas*, Hyderabad, IAH/UNESCO. S IV12–S IV24.

Datta, P.S., Bhattacharya, S.K. & Tyagi, S.K. (1996a) ^{18}O studies on recharge of phreatic aquifers and groundwater flow-paths of mixing in Delhi area. *J. Hydrol.* 176, 25–36.

Datta, P.S., Deb, D.L. & Tyagi, S.K. (1996b) Stable isotope (^{18}O) investigations on the processes controlling fluoride contamination of groundwater. *J. Contam. Hydrol.* 24(1), 85–96.

Datta, P.S., Deb, D.L. & Tyagi, S.K. (1997) Assessment of groundwater contamination from fertilizers in Delhi area based on ^{18}O, NO_3^- and K^+ composition. *J. Contam. Hydrol.* 27(3–4), 249–262.

Datta, P.S., Desai, B.I. & Gupta, S.K. (1980) Hydrological investigations in Sabarmati basin–I. groundwater recharge estimation using tritium tagging method. *Proc. Ind. Natn. Sci. Acad., Phys. Sci.* 46(1), 84–98.

Datta, P.S., Desai, B.I. & Gupta, S.K. (1979) Comparative study of groundwater recharge rates in parts of Indo-Gangetic and Sabarmati alluvium plains. *Mausam* 30(1), 129–133.

Datta, P.S. & Goel, P.S. (1977) Groundwater recharge in Punjab state (India) using tritium tracer. *Nordic Hydrol.* 8, 225–236.

Datta, P.S., Goel, P.S., Rama & Sangal, S.P. (1973) Groundwater recharge in western Utter Pradesh. *Proc. Ind. Acd. Sci.*, 78, Sec. A, 1–12.

Datta, P.S., Gupta, S.K. & Sharma, S.C. (1980a) A conceptual model of water transport through the unsaturated soil zone. *Mausam* 31(1), 9–18.

Datta, P.S. & Kumar, S. (2011) Significance of ^{18}O and hydrochemical composition to characterize water dynamics in hyporheic zone of Yamuna river flood plains in Delhi Area. *Proc. 3rd Int. Multi-disciplinary Conference on Hydrology and Ecology: Ecosystems, Groundwater and Surface water – Pressures and Options,* Vienna, Austria, 2–5 May 2011.

Datta, P.S., Manjaiah, K.M. & Tyagi, S.K. (1999) ^{18}O isotopic characterisation of non-point source contributed heavy metal (Zn and Cu) contamination of groundwater. *Proc. International Symposium on Isotope Techniques in Water Resources Development and Management*, May 10–14, 1999, Vienna, IAEA-SM-361/35, 190–198.

Datta, P.S., Rohilla, S.K. & Tyagi, S.K. (2001) Integrated approach for water resources management in Delhi region: Problems and perspectives. In: *Regional Management of Water Resources* (ed. by A.H. Schumann *et al.*). IAHS Publ. 268, 1–8. IAHS Press, Wallingford, UK.

Datta, P.S. & Tyagi, S.K. (1995) Groundwater inter mixing model and recharge conditions in Delhi area as derived from oxygen-18 and deuterium. *Sub-surface Water Hydrology*, Kluwar Academic, Netherlands, pp. 103–119.

Datta, P.S., Tyagi S.K. & Chandersekharan, H. (1991) Factors controlling stable isotopic composition of rainfall in New Delhi, India. *J. Hydrology* 128, 223–236.

Goel, P.S., Datta, P.S. & Tanwar, B.S. (1977) Measurement of vertical recharge to groundwater in Haryana state (India) using tritium tracer. *Nordic Hydrol.* 8, 211–224.

GoI (Government of India) (2009) State of Environment Report for India 2009, Minstry of Environment and Forests.

GoI (Government of India) (2010) Groundwater Scenario of India 2009–10, Central Ground Water Board, Ministry of Water Resources. http://www.cgwb.gov.in/documents/Ground Water Year Book%2 02009-10.pdf.

Gupta, S.K. & Deshpande, R.D. (2005) Groundwater isotopic investigations in India: What has been learnt? *Current Science* 89(5), 825–835.

Héctor, G,, Romani, S., Sengupta, B., Tuinhof, A. & Davis, R. (2011) India Groundwater Governance Case Study. *Water Unit, Transport, Water and ICT Dept. Sustainable Development Vice Presidency Water Paper June 2011*. www.worldbank.org/water.

Kulkarni, K.M., Rao, S.M., Singhal, B.B.S., Parkash, B., Navada, S.V. & Nair, A.R. (1989) Origin of saline groundwaters of Haryana State, India. In: *Regional Characterization of Water Quality* (ed. by S. Ragone. IAHS Publ. 182. IAHS Press, Wallingford, UK.

Kumari, Rina, Datta, P.S., Singh, Chander Kumar & Mukherjee Saumitra (2011) Characterization and evaluation of processes governing the groundwater quality in parts of the Sabarmati basin, Gujarat using hydrochemistry integrated with GIS'. *Hydrol. Processes*, doi: 10.1002/hyp.8284.

Kumari, Rina, Datta, P.S., Singh, Chander Kumar & Mukherjee Saumitra (2013) Isotopes and ion chemistry to identify Salinization of coastal aquifers of Sabarmati River Basin. *Current Science* 104(3), 335–344.

Rao, S.M. (2003) Use of isotopes in search of Lost River. *J. Radioanalytical and Nuclear Chem.*, 257(1), 5–9.

Rodell, M., Velicogna, I. & Famiglietti, J.S. (2009) *Nature* 460, 999–1002 (20 August 2009).

Sharma, P. & Gupta, S. K. (1987) Isotopic investigation of soil water movement: a case study in the Thar Desert, western Rajasthan. *Hydrol. Sci. J.* 32(4).

Sinha, U.K. & Navada, S.V. (2008) Application of isotope techniques in groundwater recharge studies in arid western Rajasthan, India: some case studies. Geol. Soc. London Special Publication 288, 121–135, doi:10.1144/SP288.10.

Soni, V., Mehrotra, R., Datta, P. S. & Chander, S. (2009) A process for organic water. *Current Science* 96(8), 1100–1103.

Tyagi, S.K., Datta, P.S. & Pruthi, N.K. (2009) Hydrochemical Appraisal of groundwater and its suitability in the intensive agricultural area of Muzaffarnagar District, Uttar Pradesh, India. *Environ. Geol.* vol. 56(5), 901–912.

UNEP (2010) *Clearing the Waters: A focus on water quality solutions*, ISBN: 978-92-807-3074-6. United Nations Environment Programme. Available from URL: http://www.unwater.org/Clearing_the_Waters.pdf (March 1, 2013).

World Bank (2010) *Deep Wells and Prudence: Towards Pragmatic Action for Addressing Groundwater Overexploitation in India*, World Bank.

WHO (2004) *Fluoride in Drinking-water: Background document for development of WHO Guidelines for Drinking-water Quality*. WHO/SDE/WSH/03.04/96. World Health Organization. Available from URL: http://www.who.int/water_sanitation_health/dwq/chemicals/fluoride.pdf (28 February 2013).