ISOTOPE FINGERPRINTING OF GANGES BASIN GROUNDWATER FOR ITS PROTECTION FROM VULNERABILITY TO DEPLETION AND POLLUTION

Keynote Address

PROF. P.S. DATTA

NUCLEAR RESEARCH LABORATORY
IARI, NEW DELHI

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RECENT GLOBAL CONCERNS

Climate Change and Water Scarcity.

Amplification of overall uncertainties by superposition of model upon model, each with its own assumptions & inaccuracy.

TWO CATEGORIES OF PHENOMENA

Universal: e.g., increasing greenhouse gases, particulate and aerosol in the atmosphere.

Disjunct: Local or regional, e.g., flood flow, groundwater depletion and contamination, soil erosion, sedimentation, and biotic succession.

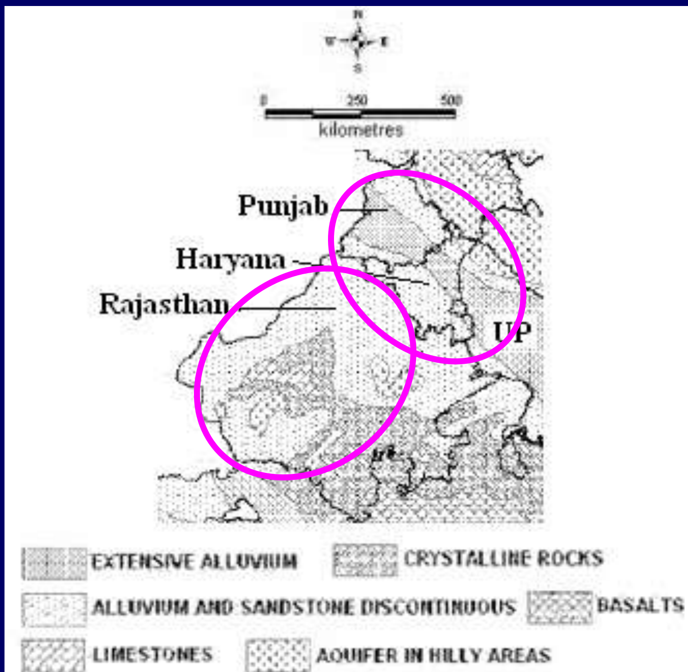
VULNERABILITY OF GROUNDWATER

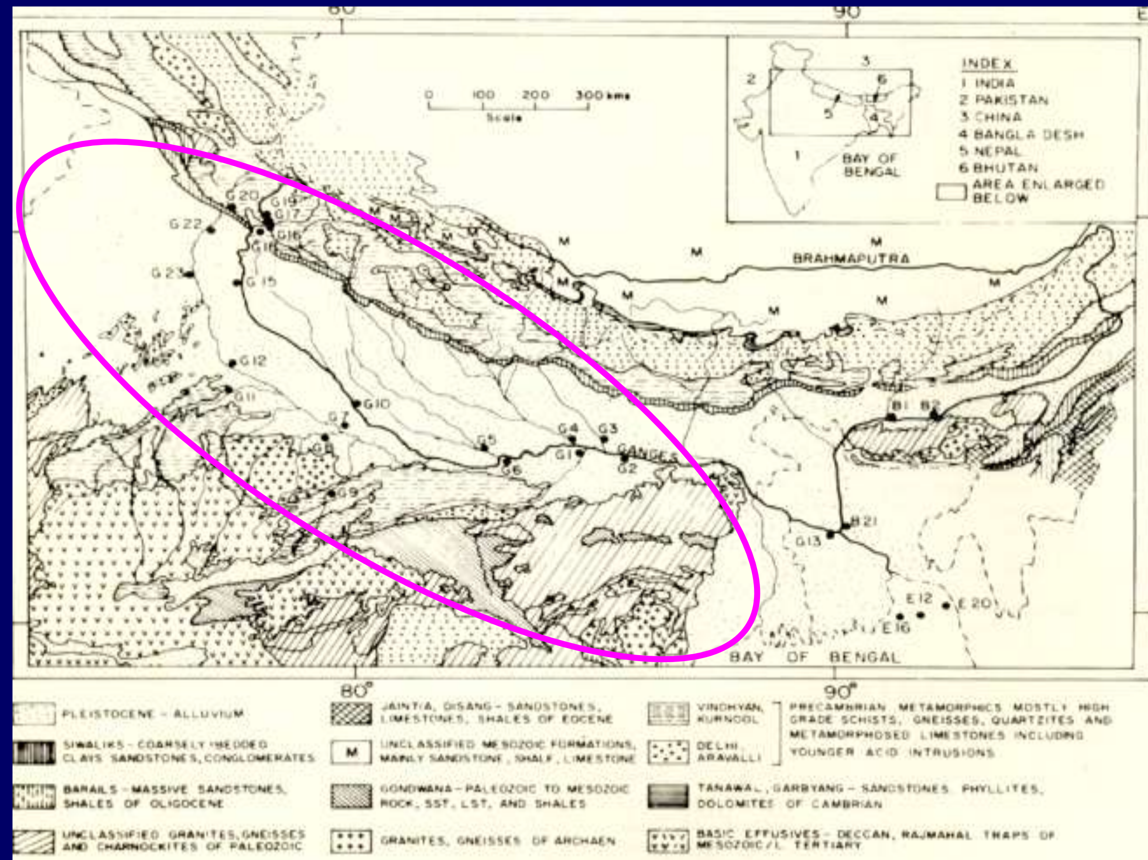
- Multidimensional concept which expresses aquifer - social condition relationship that leads to Aquifer's intrinsic static characteristics beyond human control.
- Major research aspects: methods, measuring and assessing, finding indicators.

RATIONALE OF GROUNDWATER PROTECTION

Generally imply the GW conservation, in terms of quantity and quality, so as to permit efficient long-term exploitation of aquifers, especially as a secure and reliable source of water supply.

THE INVESTIGATED AREA AND THE GEOLOGICAL FEATURES





Rural land area: 93%.
Farmers depend on GW.

The alluvium (> 500m thick) has the most productive and extensive GW under unconfined and semi-confined conditions and under unconfined conditions in the fractured zones of consolidated formations.

REGION'S WATER PROFILE

- Economy is mostly based on agriculture which accounts for 70-80% of freshwater withdrawals.
- Groundwater development: 145% in Punjab, 109% in Haryana, 70% in UP and 300% in Delhi.
- Total Replenishable GW: 171 Km^3
- Irrig. GW Withdrawal: 131 Km^3
- Domestic + Industrial Withdrawal: 11 Km^3
- Utilisable GW: 138 Km^3
- Per Capita Water Availability: 1040 m^3 (in 2008)
- Predicted Per Capita water availability by 2025 ~1000m^3/annum (chronic 'water scarcity').

SOME HARD FACTS

Rapid growth in population, urbanization, industrial activities, landuse changes and competition for economic development increasing water demand and anthropogenic wastes.

Unplanned disposal of wastes and indiscriminate application of agro-chemicals, resulting in excessive accumulation of pollutants on/in the soil.

Due to leaching of contaminants, seepage from rivers and drains, GW quality attained various configurations.

Zonal disparity and inadequate availability of surface water supply leading to indiscriminate GW withdrawal.

SYMPTOMS OF THE PROBLEM

· Lowering of groundwater levels
· Decline in productivity of wells
· Intermixing of polluted water with fresh water
· Expanding areal extent of groundwater pollution

CONCERN OF RESOURCES MANAGERS

- Search adequate quantity of good quality GW.
- Assess quantity and recharge characteristics.
- Evaluate water quality and degradation causes.
- Identify GW flow pathways of inter-mixing
- Protect water from depletion and degradation.
- Evolve a Partnership/Participatory approach.

Why Isotopes?

Water memorises its origin and path

Isotopic fingerprints are imparted during:

1. **Phase change:** **fractionation during evaporation and condensation – temperature & humidity dependent.**
2. **Mixing of different water/vapour masses.**
3. **Selection of rain events during runoff and groundwater recharge.**

Stable Isotopes in Water (^1H_2O)

$^1H_2{}^{18}O$	$\delta^{18}O$(‰)
$^1H^2H^{16}O$	δD (‰)

$$\delta (‰) = (R_x/R_s - 1).1000$$

R=Ratio ($^{18}O/^{16}O$; $^2H/^1H$)

How Do Isotopes Help ?

Isotopes fingerprints in atmosphere, streams and groundwaters represent an integration of source inputs to the system that extend over large spatial and temporal scales.

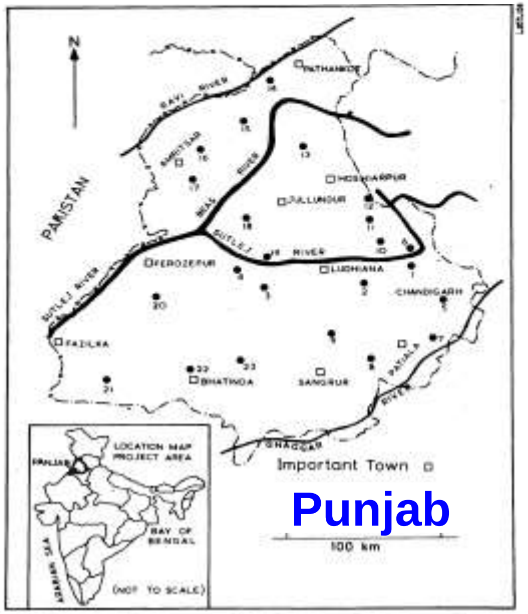
- ***Integrate*** **processes in space and time,**
- ***Indicate*** **the magnitude of key processes,**
- ***Record*** **responses to change condition,**
- ***Trace*** **origin and movement of key elements.**

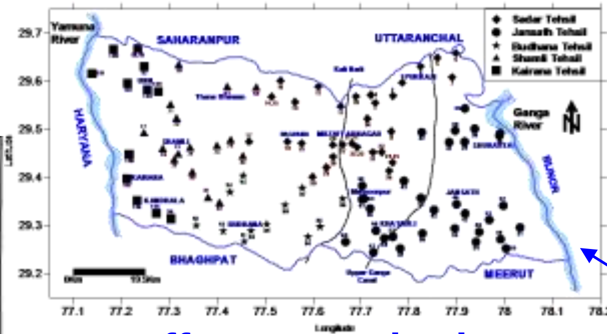
POTENTIALS OF ISOTOPE TECHNIQUES

- Temporal & spatial variations in the environmental isotope composition of rainfall, river and local groundwater provide information on:
  - Beneficial Effects [recharge & mechanism to shallow aquifers]
  - Reconstructing paleo-climate conditions during the GW recharge
  - Non-Beneficial Effects [water-logging and salinization problems]
  - Contribution of new channels to groundwater in different zones
  - Contribution from each source at a given location
- Rainwater Harvesting: To locate the altitude of recharge & understand the recharge process of perennial/non-perennial springs in mountainous catchment for suggesting suitable conservation/protection measures and planning suitable artificial recharge measures.
- Modelling techniques for safe abstraction of groundwater defining the hydraulic boundaries of an aquifer, regional groundwater velocity etc., and validating groundwater numerical models.
- Identify sources, mechanisms, extent of salinization/pollution of GW and prediction of the fate of contaminants in groundwaters.

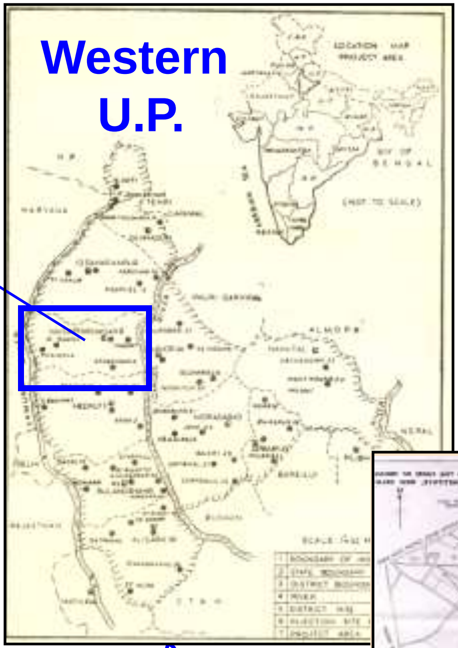
SCHEMATIC MAPS SHOWING LOCATIONS OF THE ISOTOPE STUDIES

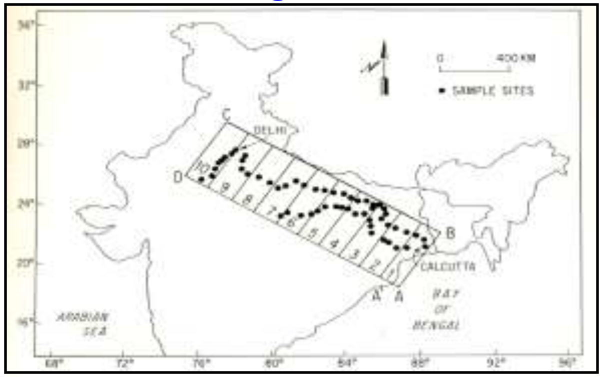
SCALES OF INVESTIGATIONS



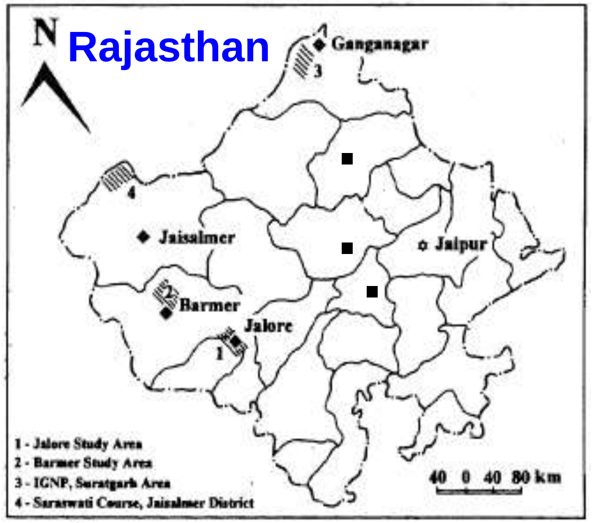


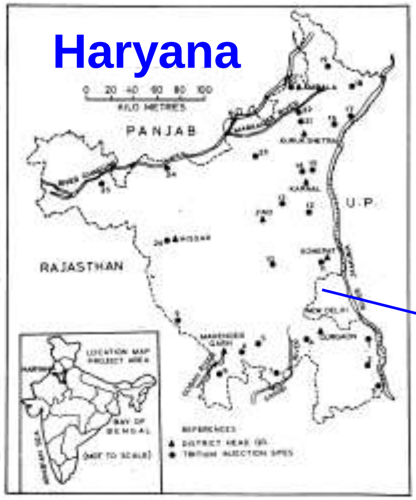
Muzaffarnagar District, U.P.

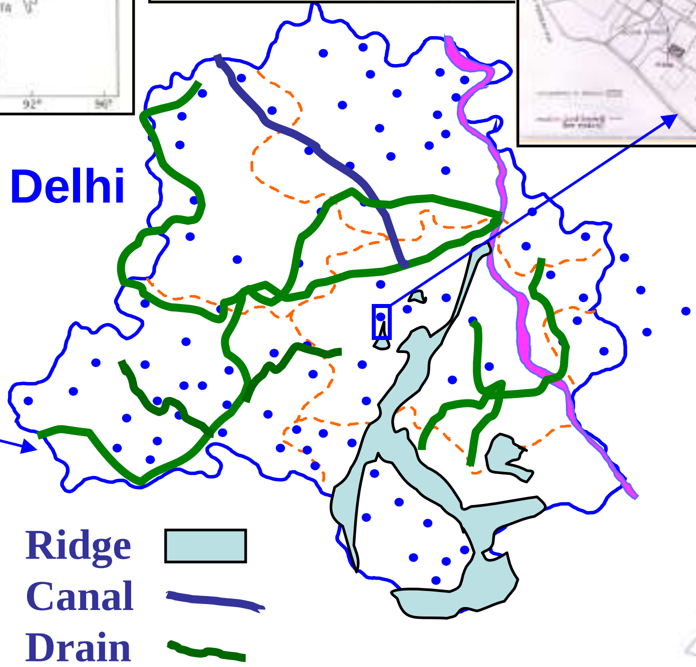




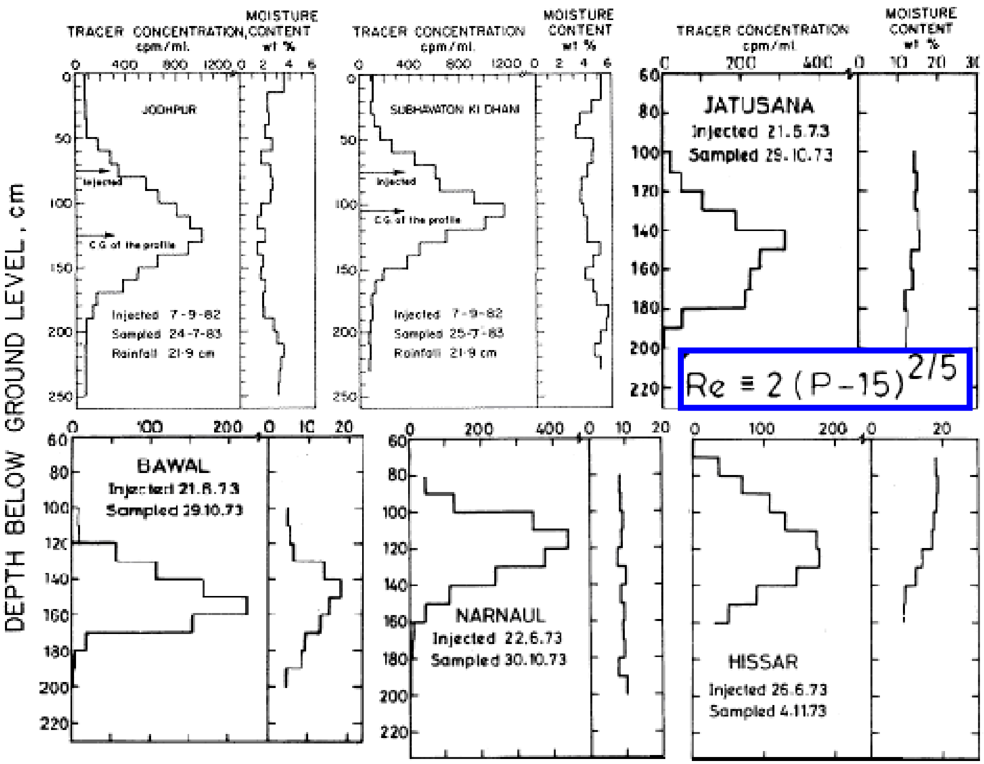
IARI Farm

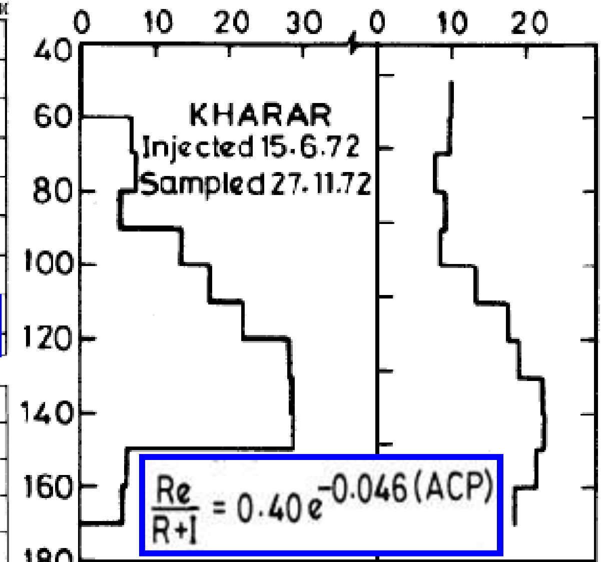


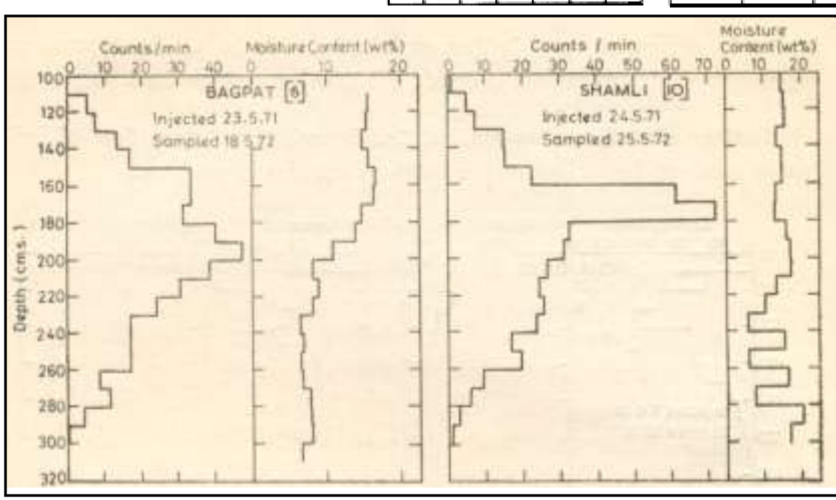




SOME TYPICAL ^{3}H TRACER PROFILES







Punjab, Haryana & Western U.P.

(Datta et al 1973,1977)

Recharge (%) to Groundwater

$Re/R = \theta\nu \times d \times 100$

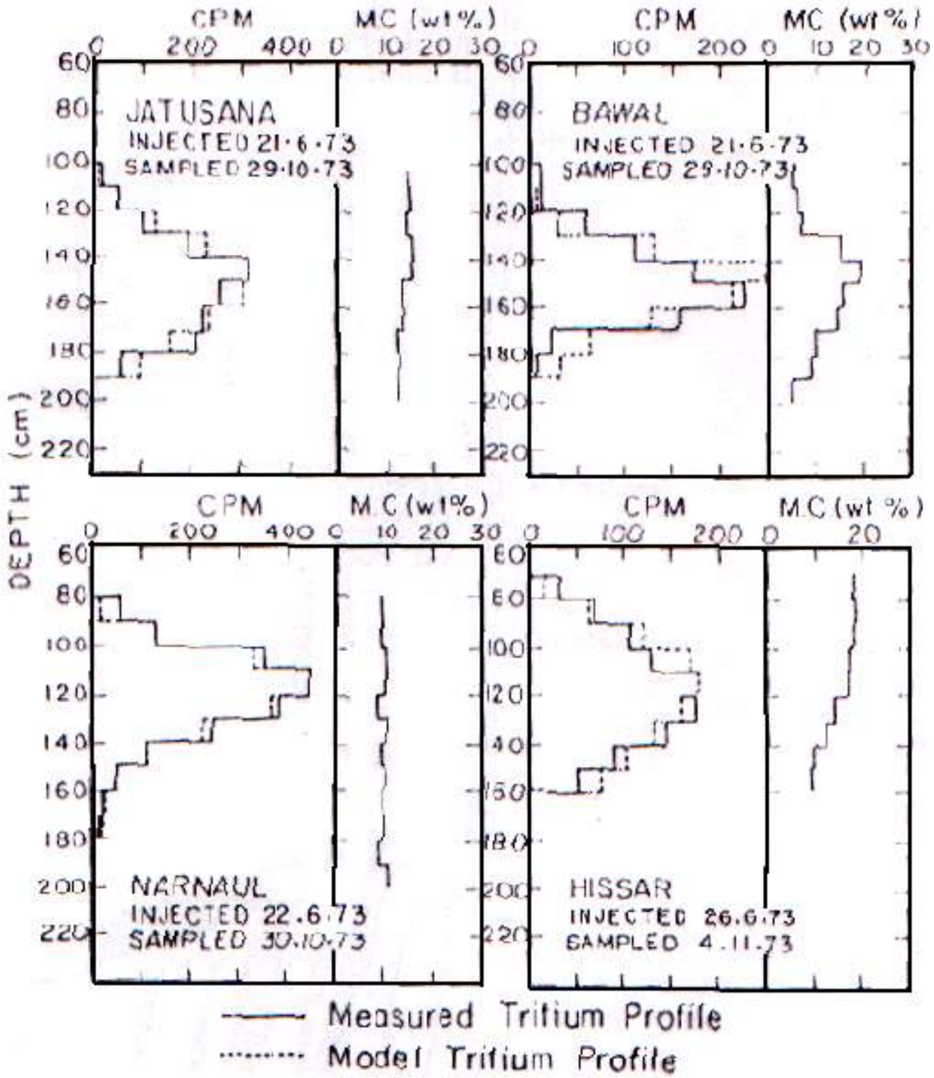
Re – Recharge

$\theta\nu$ - Moisture content (vol %) from the depth of injection to the depth of tritium peak shift

d - Shift of tritium peak (cm)

R - Rainfall and/or Irrigation (cm)

Observed and Model Profiles of Tritium Tracer Movement at Some Places in the Indo-Gangetic Plains



Recharge takes place in pulses depending on water table fluctuations and soil physical properties.

Relatively higher efficiency of winter rains in inducing groundwater recharge.

Higher potential evaporation in monsoon months is likely to reduce net groundwater recharge.

Datta et al. (1979, 1980); and Gupta (1983)

A wide range (1-50%) of annual recharge from rainfall, average being 20% (UP); 16% (Haryana); 18% (Punjab), 6% (Rajasthan) and <8% (Delhi), depending on the frequency, intensity and distribution of rainfall.

Estimated Recharge in Punjab, Haryana, Rajasthan including Delhi by ^{3}H method:

14.8 $\pm$ 2.5 km^3/yr

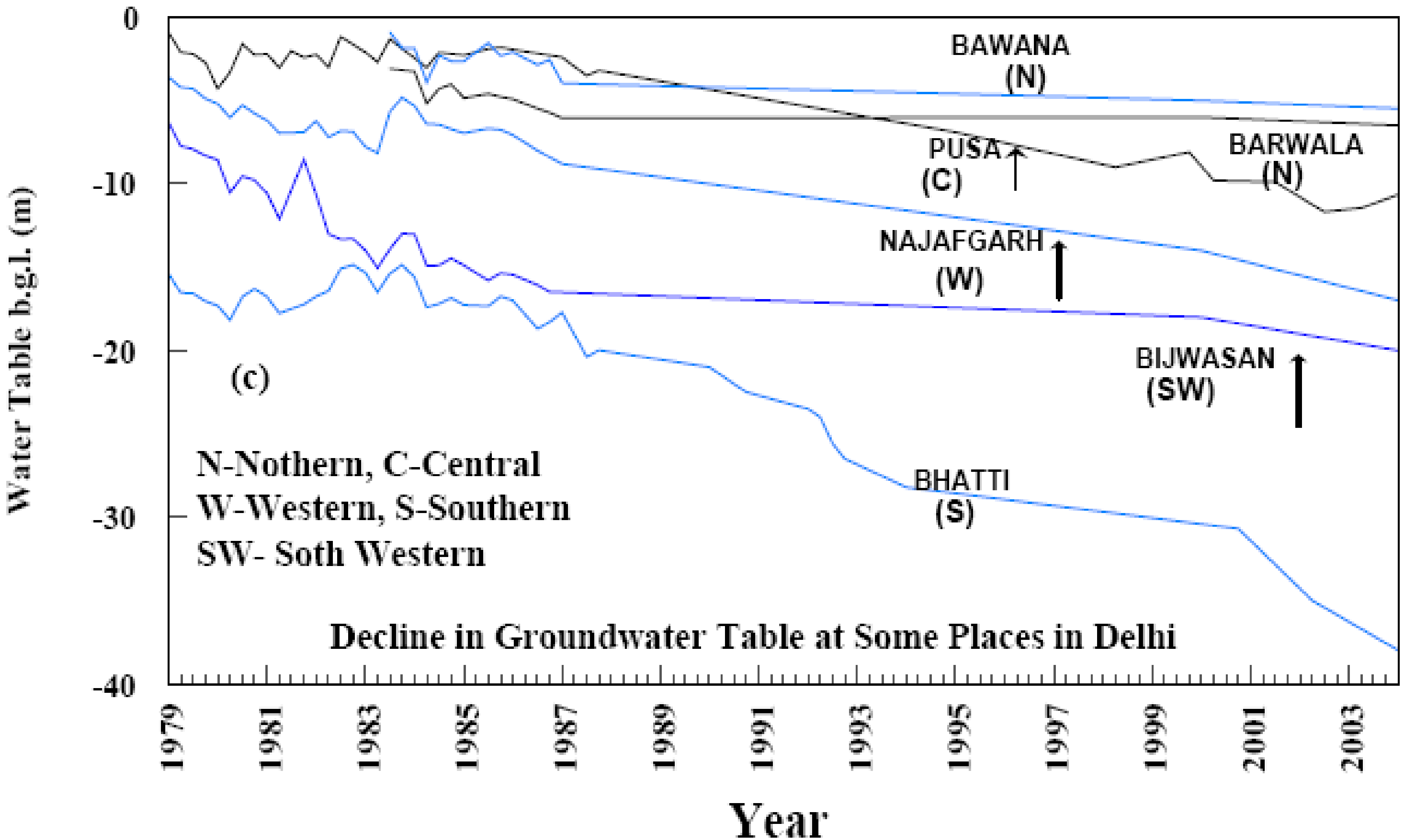
(Datta et al 1973,1977, 2009)

NASA/GRACE Estimated GW Withdrawal:

17.3 $\pm$ 4.5 km^3/yr (2009)

GW has become vulnerable to water table decline by 2-8 m to 30-40 m in different parts during 1960-2003.

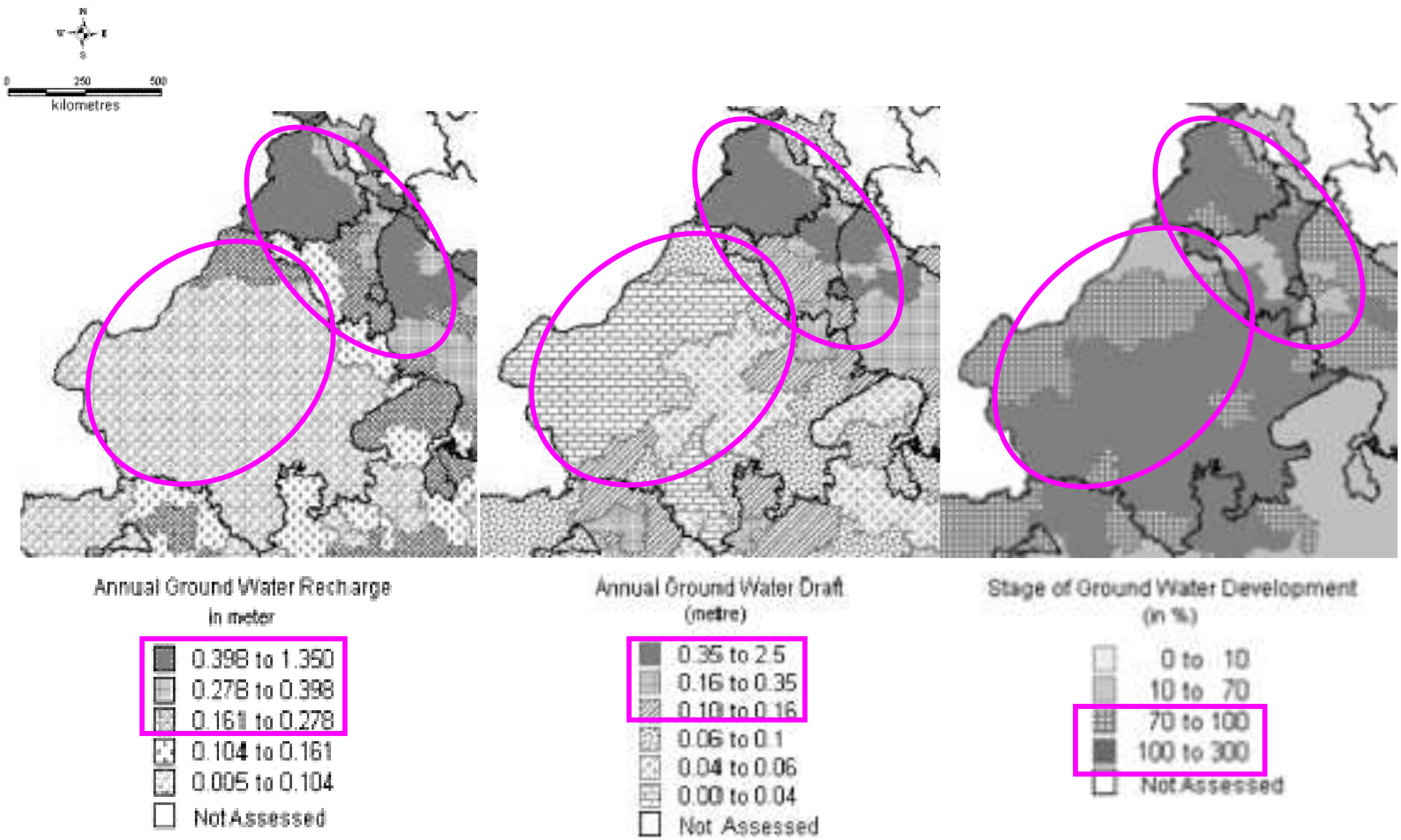
Datta et al. (2001); and Datta (2005)



Delhi GW has become vulnerable to water table decline by 2-8 m to 30-40 m in different parts.

Datta et al. (2001); and Datta (2005)

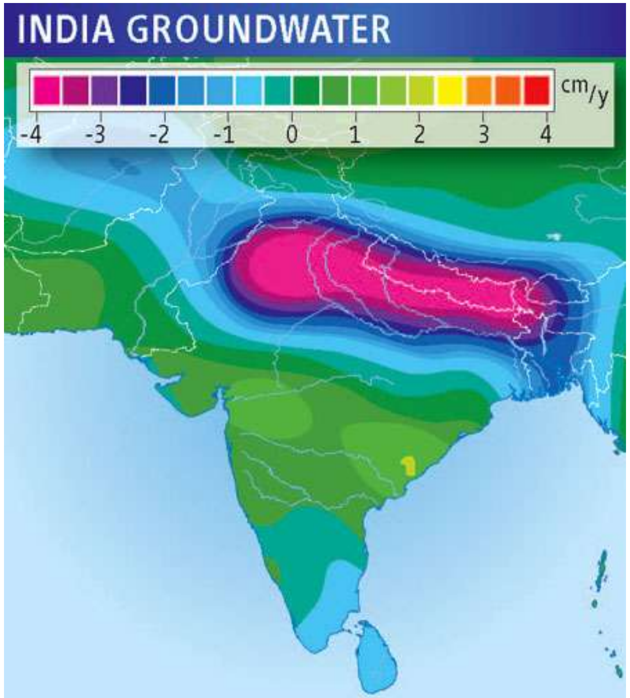
GROUNDWATER RECHARGE, DRAFT AND DEVELOPMENT



(CGWB, Chatterjee and Purohit, 2009)

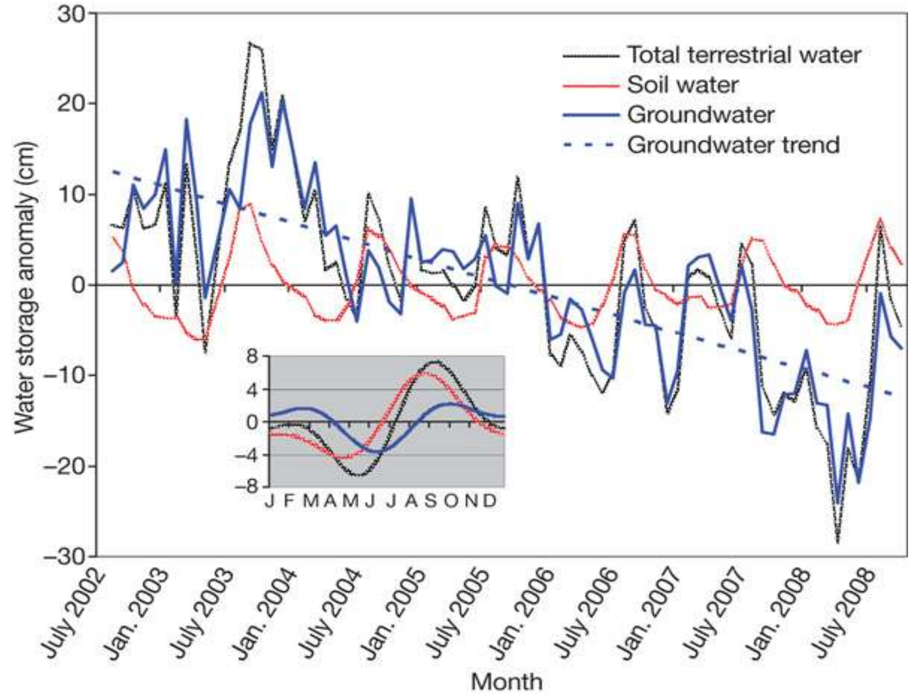
GRACE, NASA OBSERVATIONS

Decline in GW Level



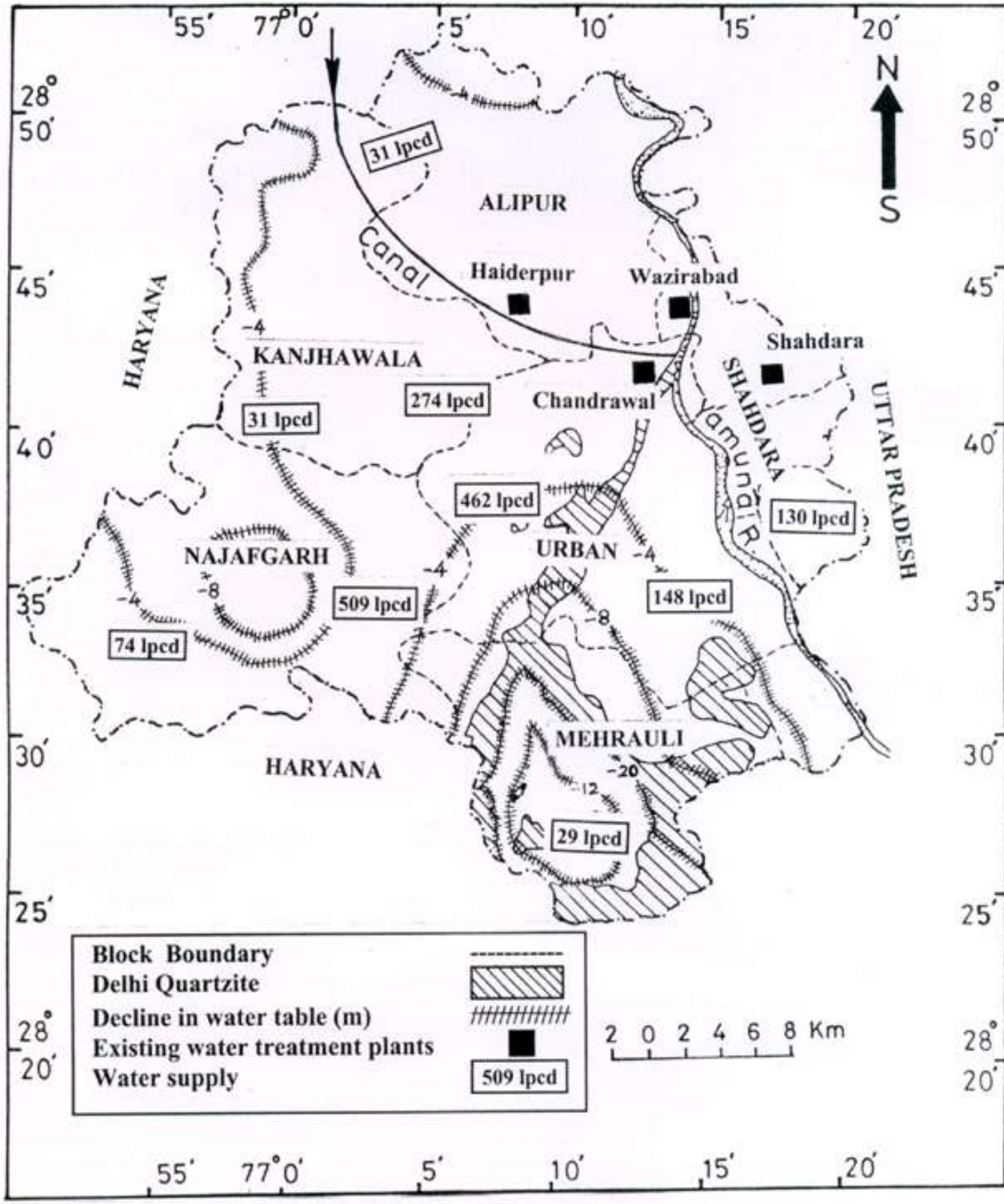
Richard A. Kerr, *Science*NOW Daily News
10 August, 2009

Monthly time series of water storage anomalies in northwestern India.



M. Rodell *et al. Nature* 460, 999-1002 (2009)
doi:10.1038/nature08238

Estimated Withdrawal: 17.3 ± 4.5 km^3/yr



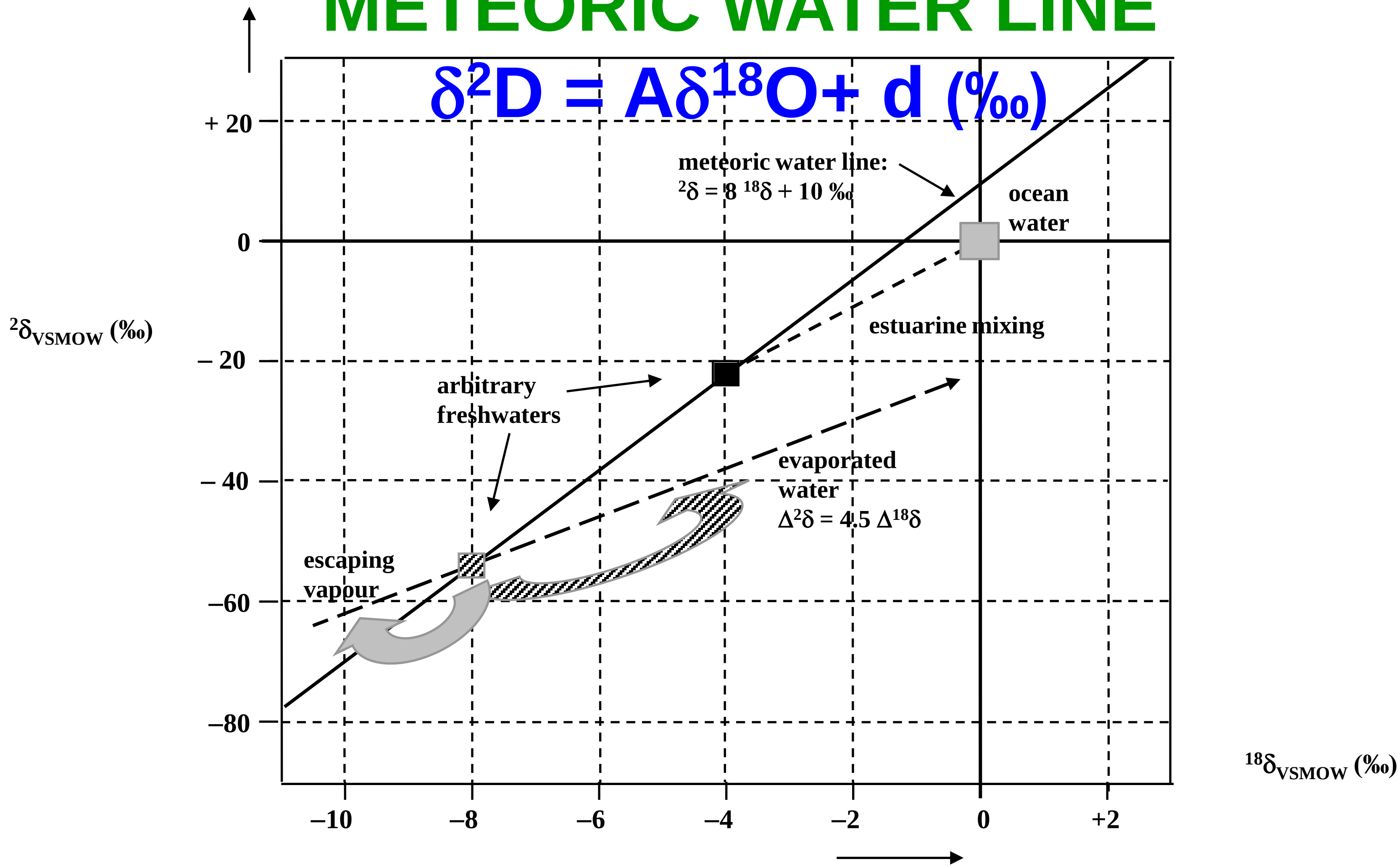
WATER SUPPLY & GW TABLE DECLINE IN DELHI

Zonal disparity in water supply causes more GW abstraction and decline in water table

Datta et al (2000)

METEORIC WATER LINE

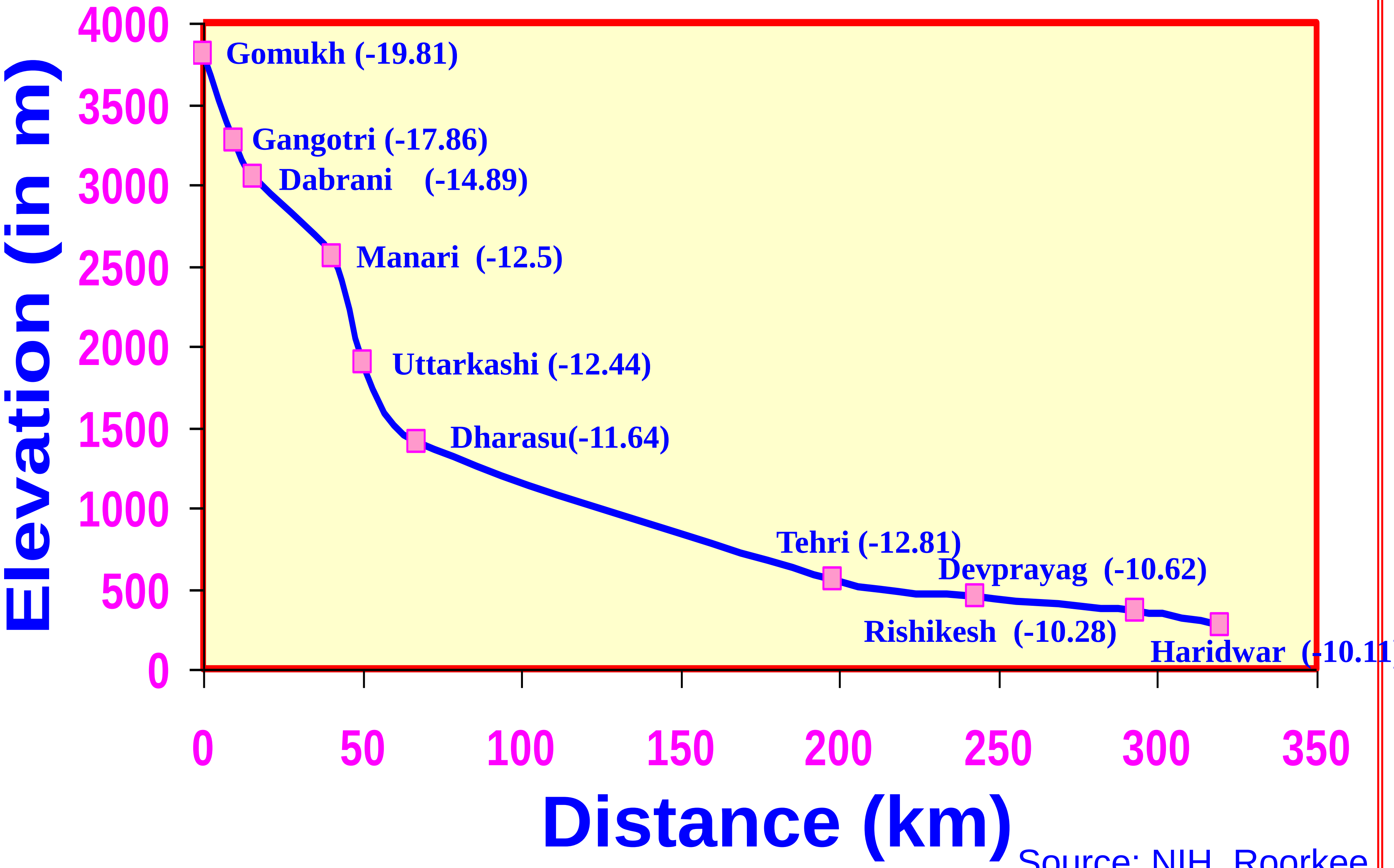
$$\delta^2D = A\delta^{18}O + d\ (‰)$$



'A' is Governed by Processes and 'd' by Source/ Origin/nature of water/vapors

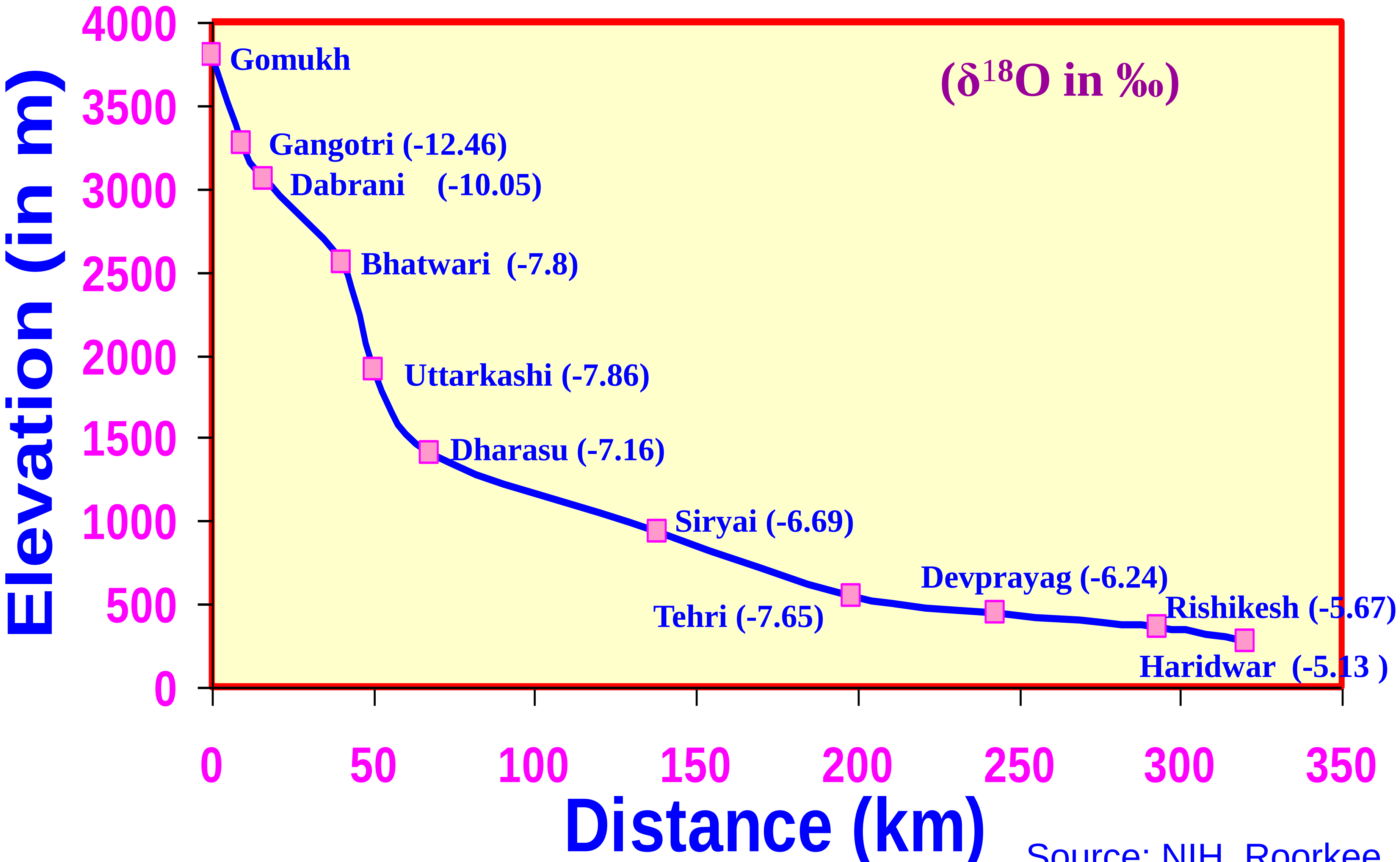
A & d remains constant in Equilibrium Fractionation (temp.) e.g. condensation from clouds and vary in Non-Equilib./Kinetic Fractionation (humidity) e.g., evaporation, mixing with water of different isotope signature, etc.

ALTITUDE VARIATION IN PPT δ^{18}O (‰)



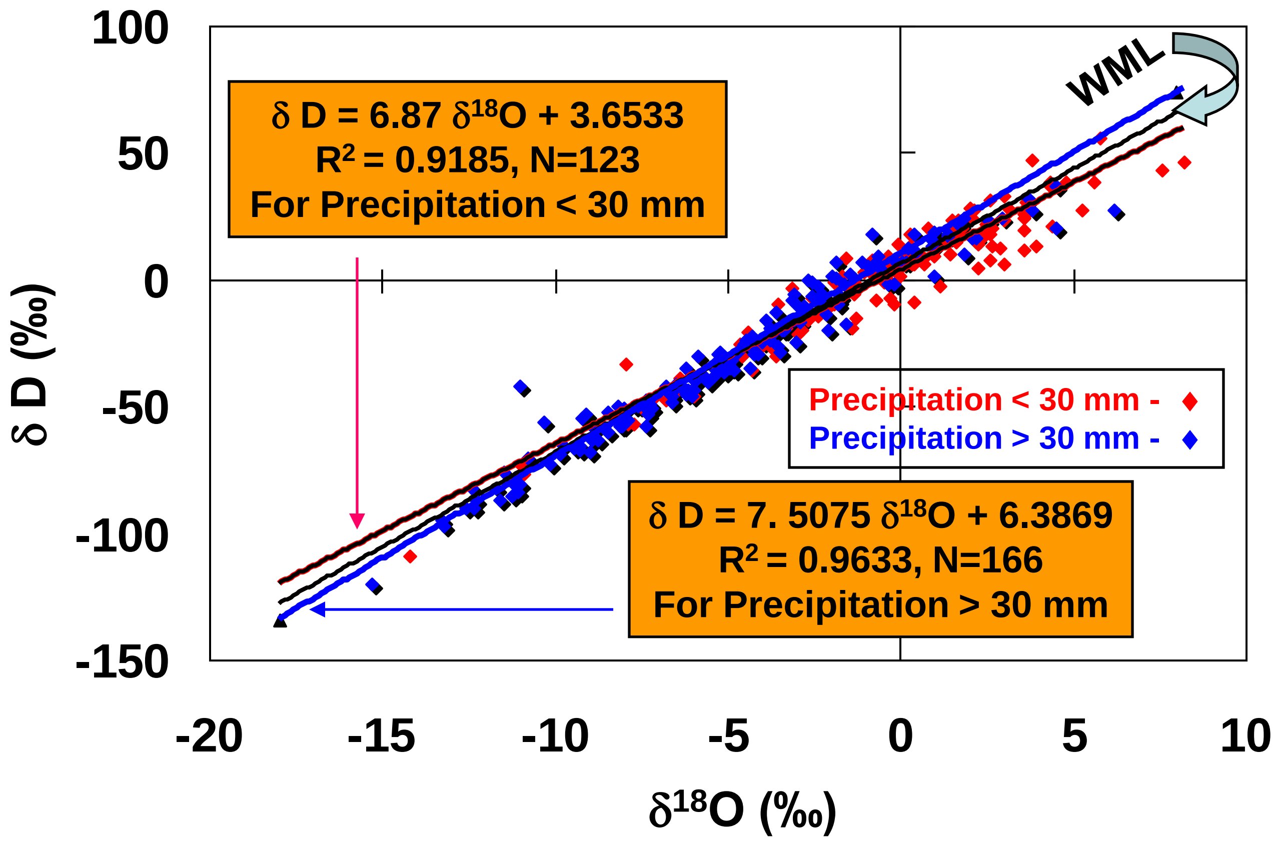
Source: NIH, Roorkee

ALTITUDE VARIATION IN GW $\delta^{18}O$ (‰)



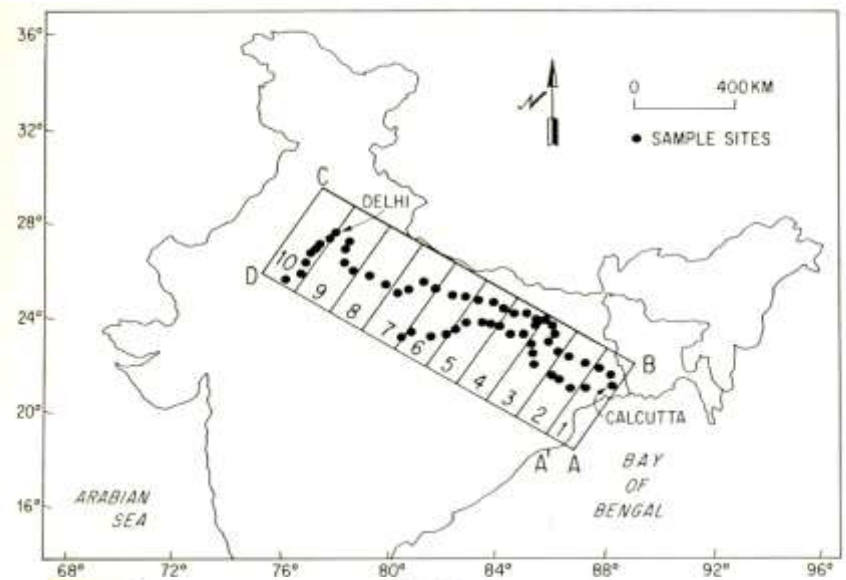
Source: NIH, Roorkee

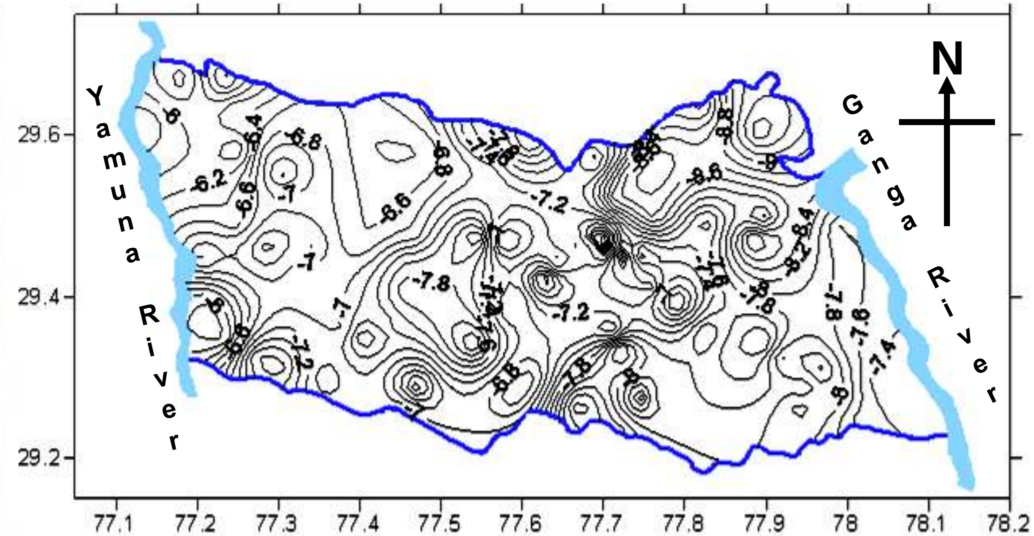
Relationship between δD and $\delta^{18}O$ in Rainfall at New Delhi (1961-2005)



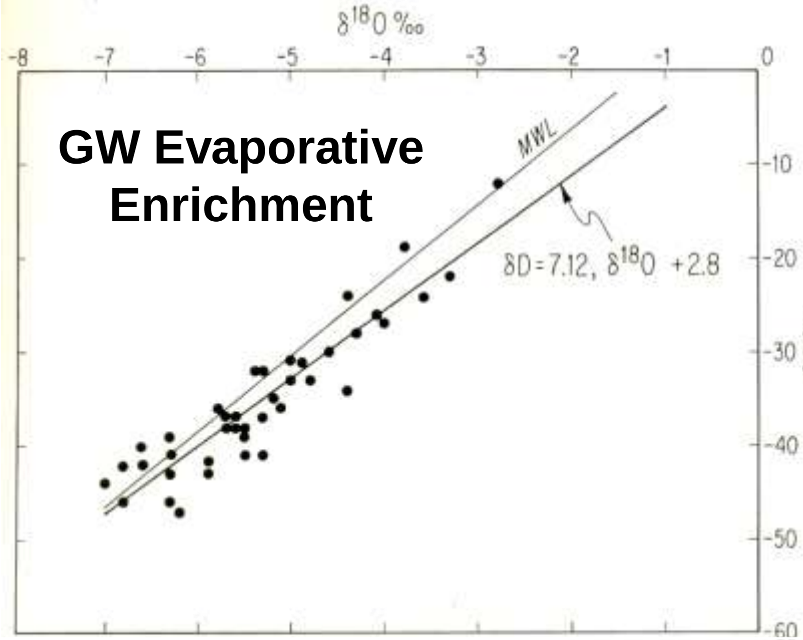
Datta et al (1999, 2009)

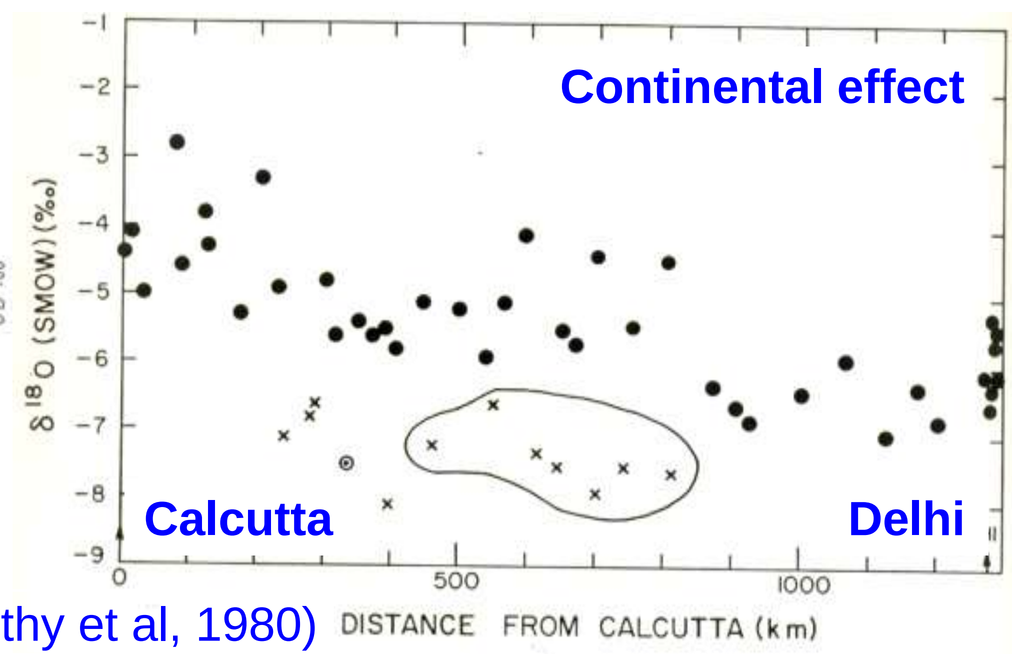
SPATIAL VARIATION IN GW $\delta^{18}O$ (‰)



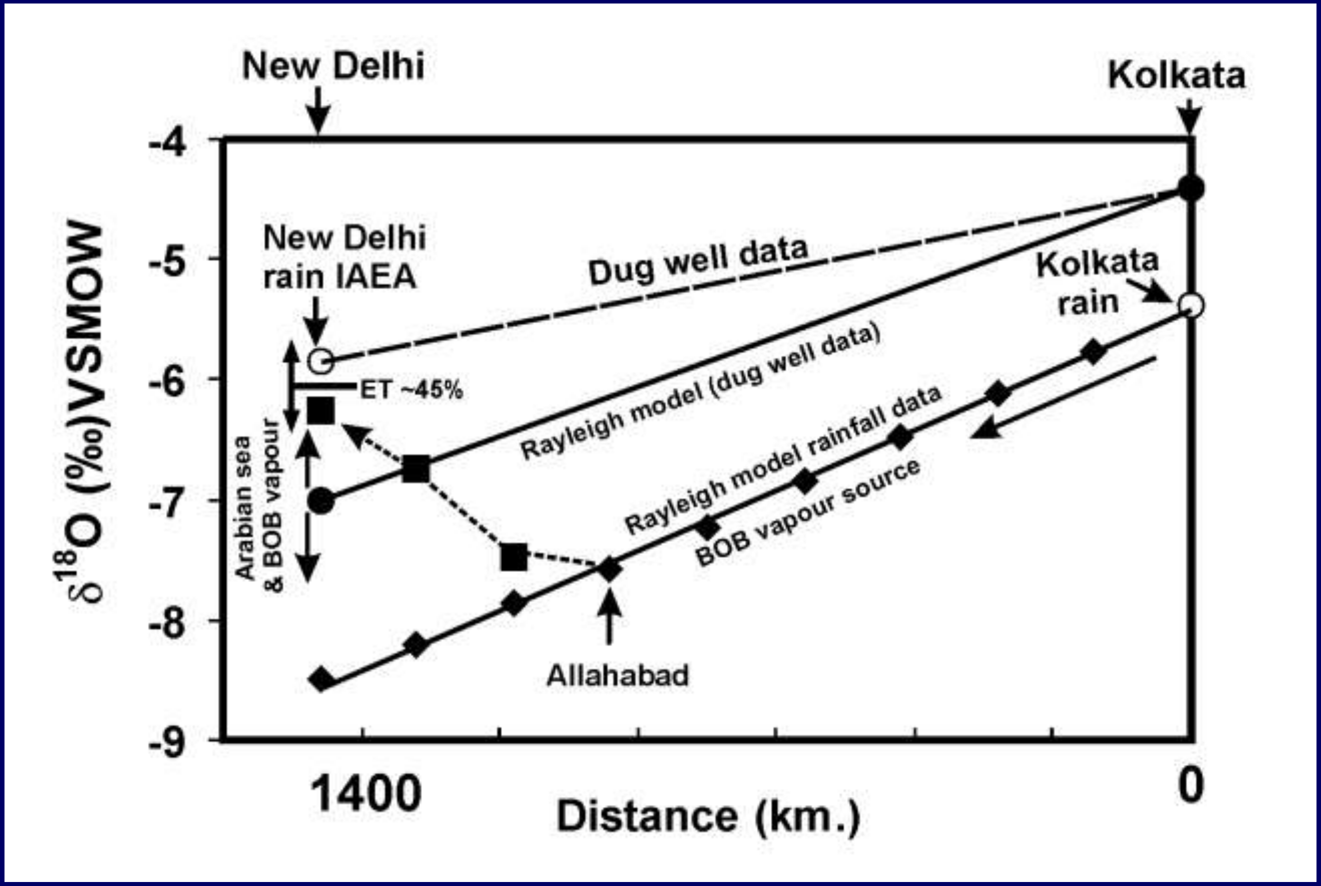


Muzaffarnagar District, U.P.





(Tyagi and Datta, 2009) (Krishnamurthy et al, 1980)

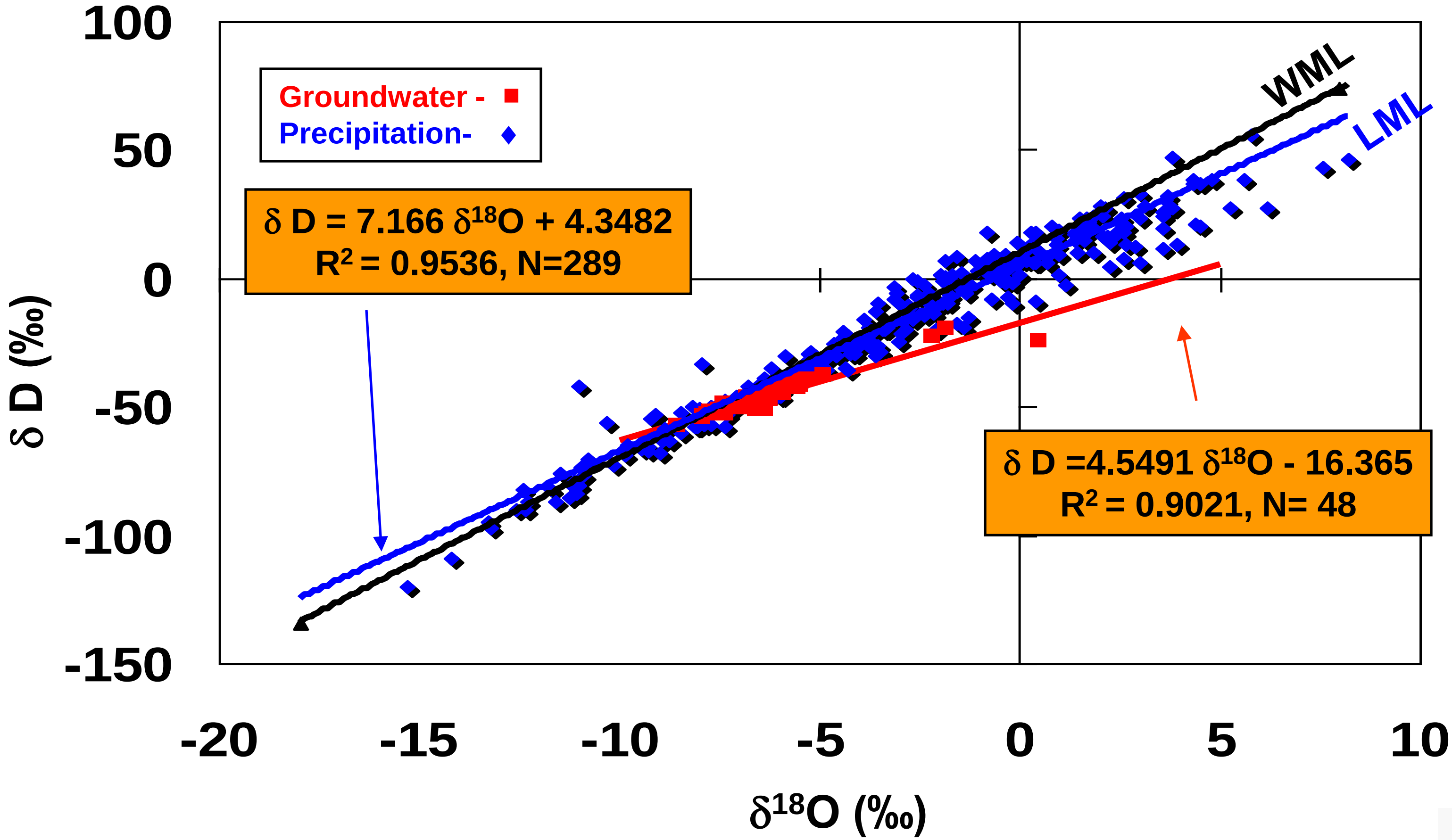


√ **RAIN IN NEW DELHI CAN NOT BE EXPLAINED BY SIMPLE CONTINENTAL EFFECT ALONG KOLKATA-NEW DELHI TRACK**

√ **~20% VAPOUR FROM ARABIAN SEA IS NECESSARY TO MIX WITH BAY OF BENGAL VAPOUR TO EXPLAIN NEW DELHI RAIN**

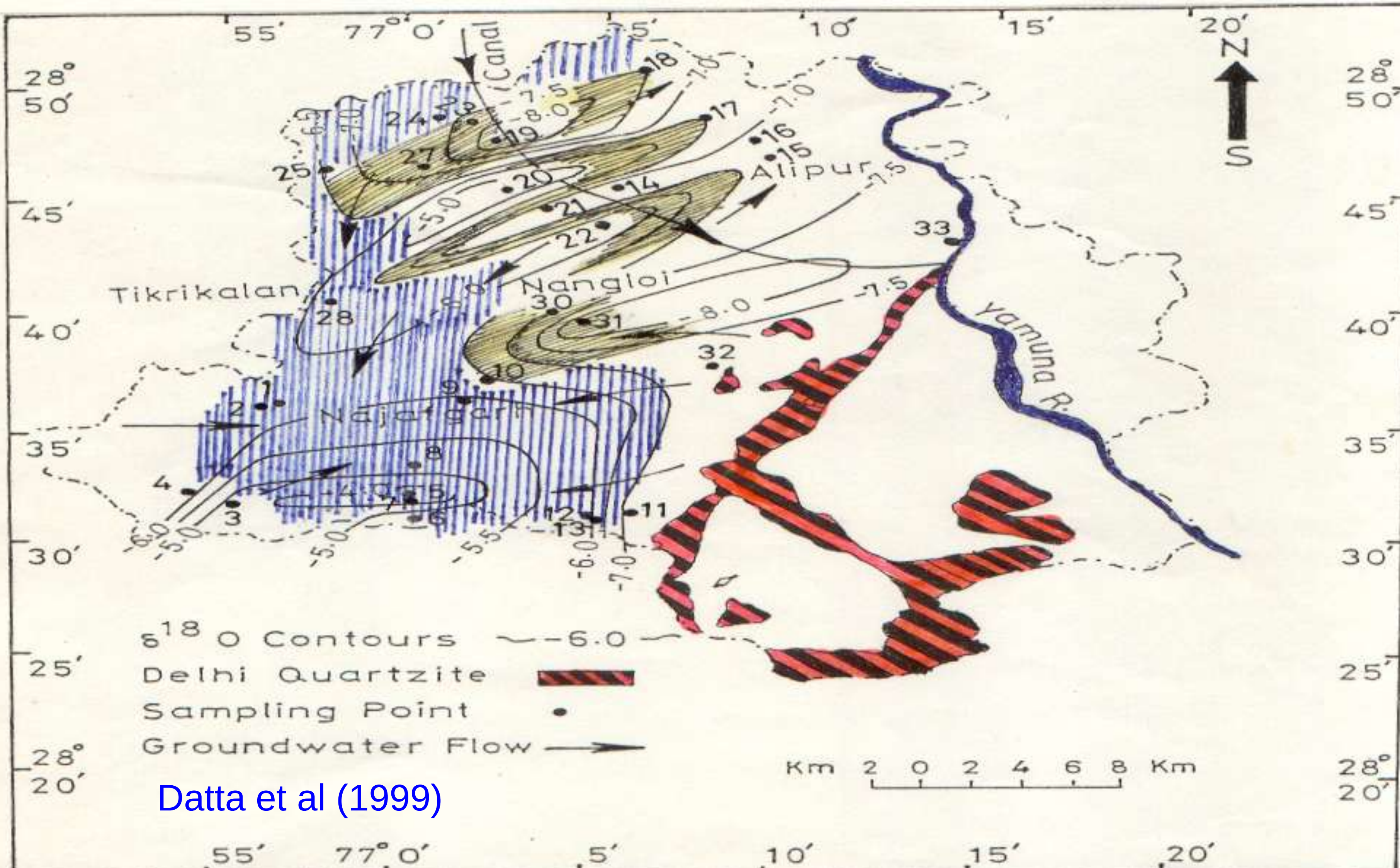
[Sengupta and Sarkar, EPSL, 250, 511-521, 2006]

δD and $\delta^{18}O$ Relationship in Rainfall (1961-2005) and Groundwater in New Delhi



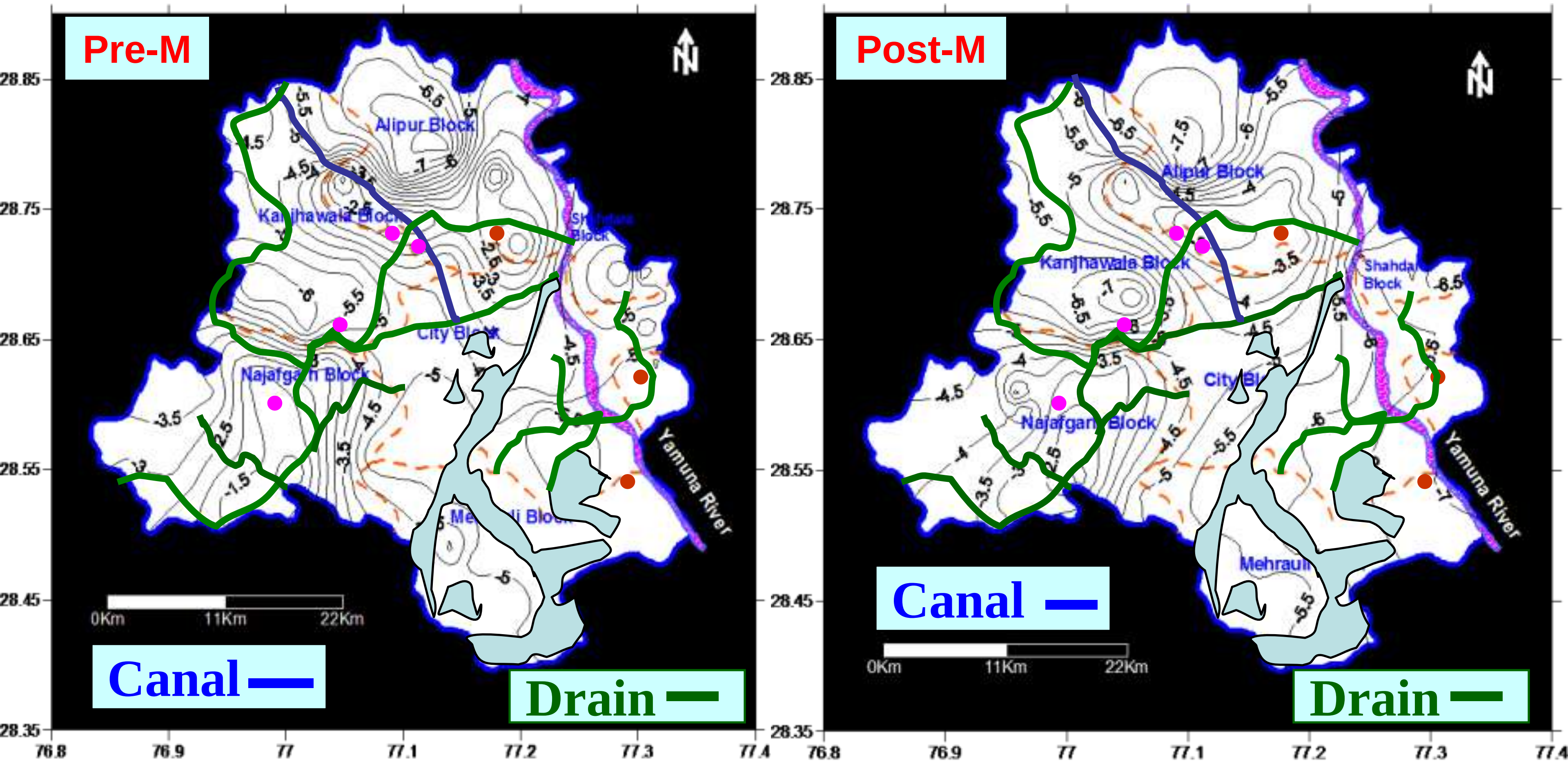
Datta et al (1999, 2009)

$^{18}O/^{16}O$ Isotope Signatures in Groundwater of Delhi Area



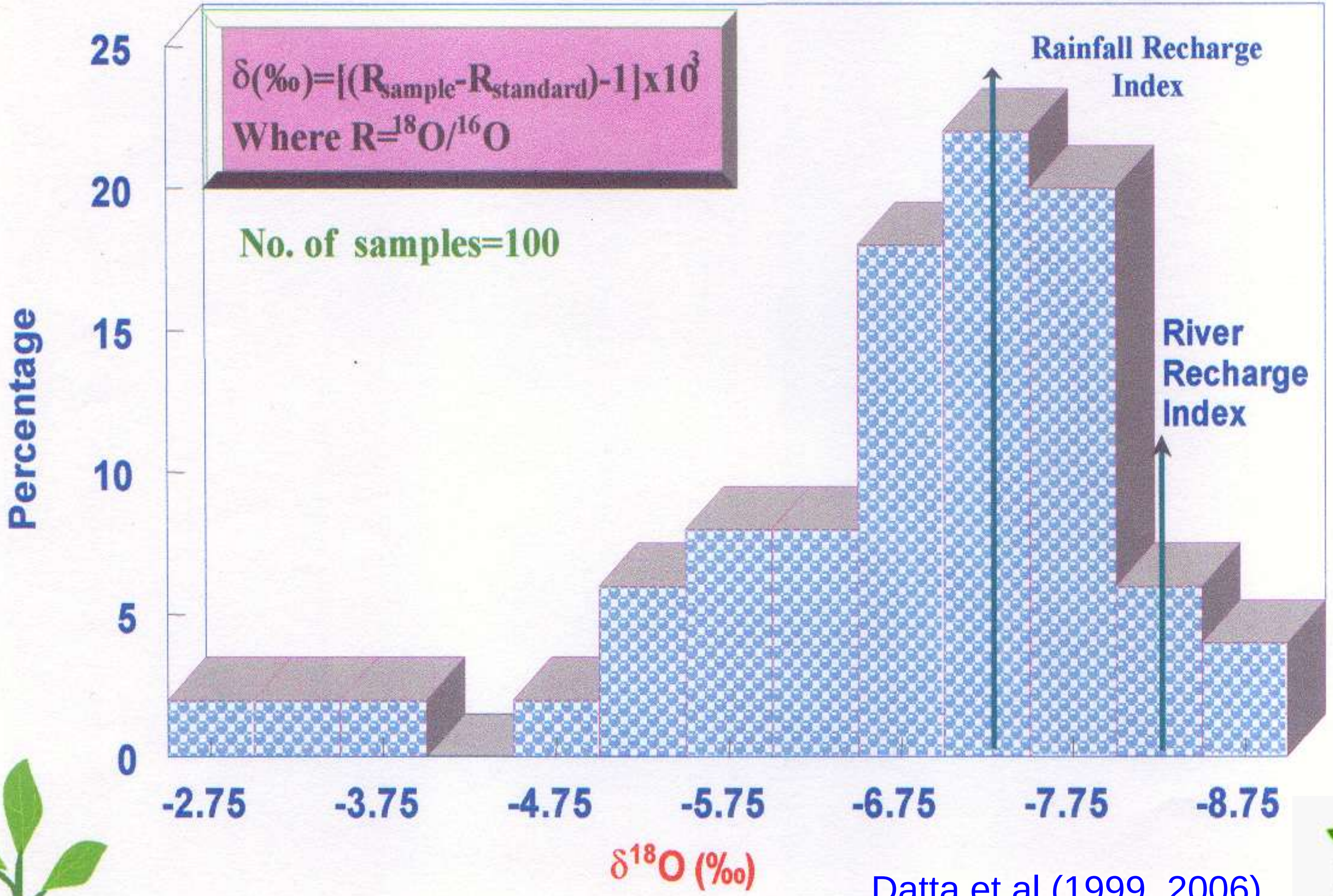
- **Plume-like features** (yellow hatched symbol) **give a clear visualisation of groundwater flow-paths of mixing.**
- **Small isotope gradients** (blue hatched symbol) **indicate the zones of high permeability and high groundwater potential.**

$\delta^{18}O$ (‰) distribution in groundwater of Delhi region



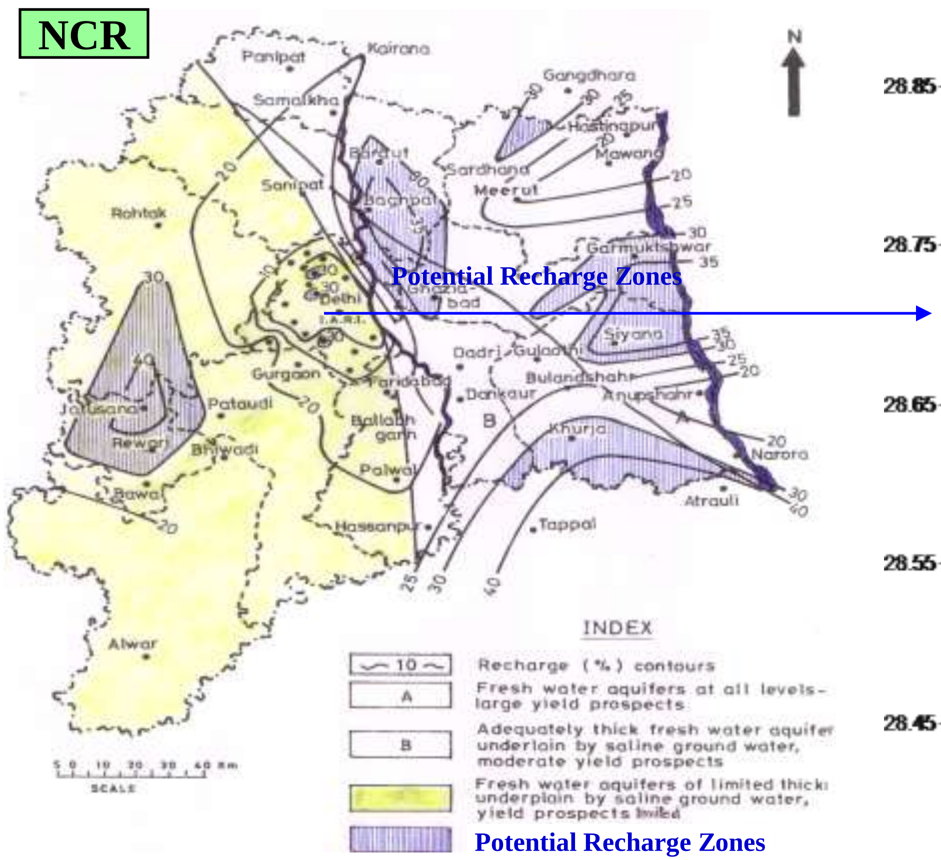
Groundwater in Pre-monsoon is isotopically enriched, indicating depression focused recharge from isotopically enriched rainfall. Post-monsoon GW is relatively depleted, suggesting dilution effect due to lateral flow from surrounding areas.

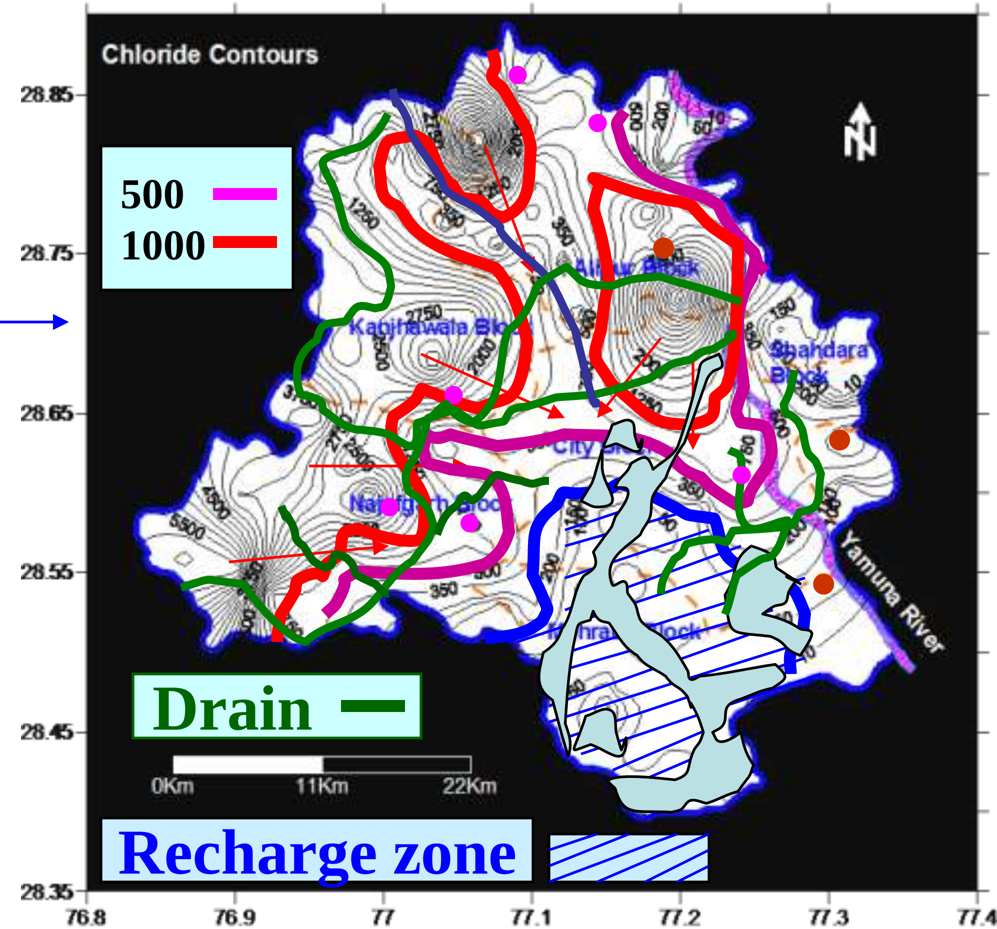
^{18}O isotope content frequency distribution in groundwater of Delhi region



Datta et al (1999, 2006)

Isotopic Characterisation of Potential Groundwater Recharge Zones in the NCR



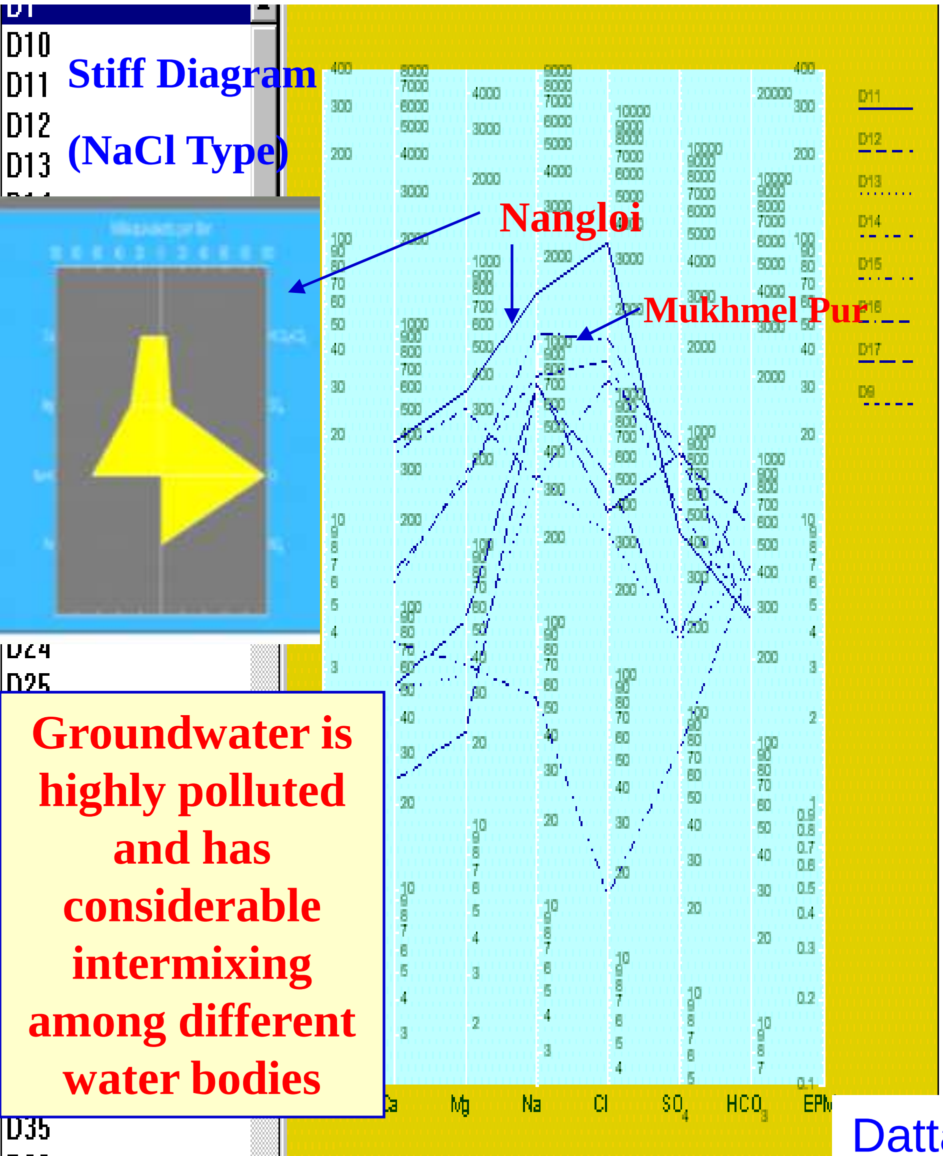


Occurrence of Saline GW and High Chloride (mg/l) Plumes Dynamics in Groundwater of Delhi Region

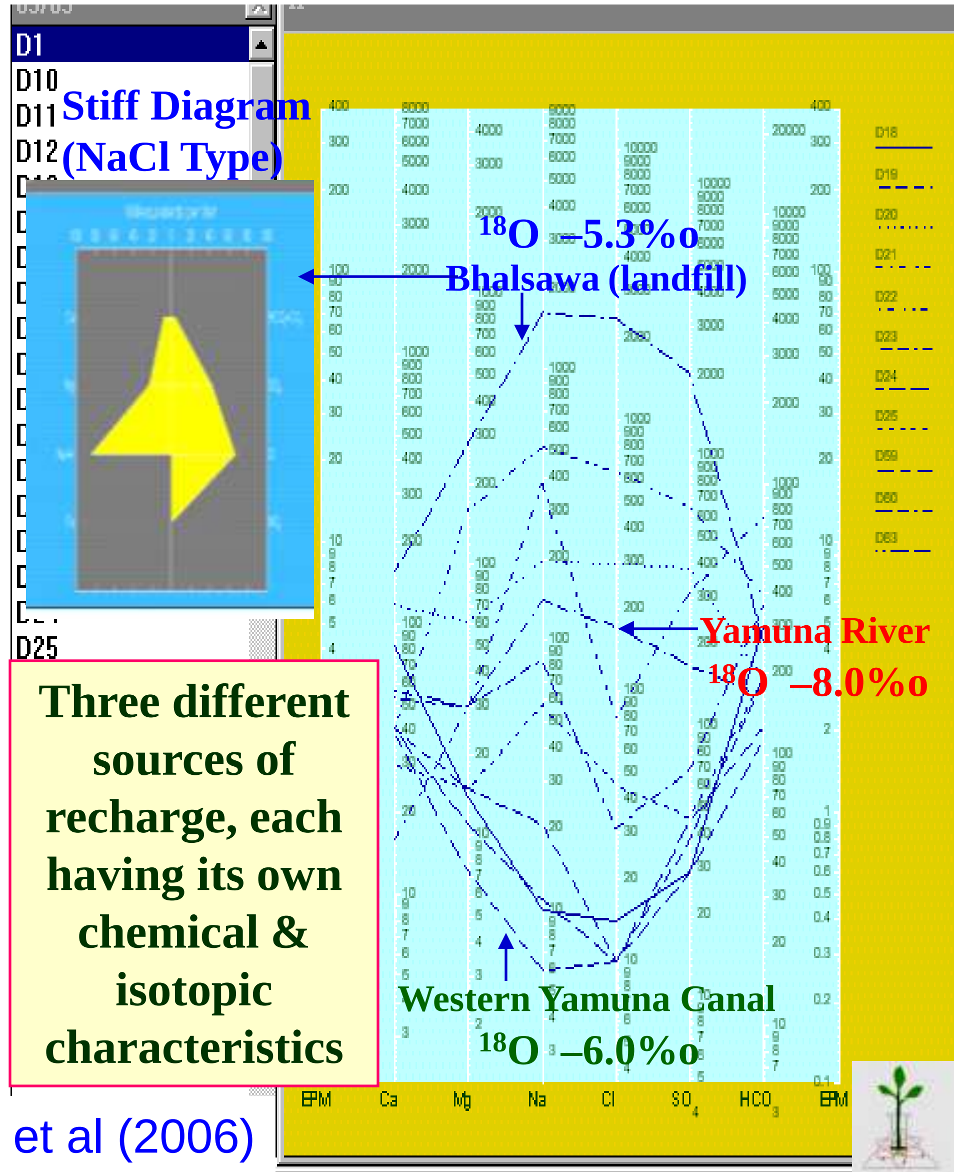
(Datta et al, 1996, 2006)

Multi-ionic Diagram indicating Groundwater Intermixing and Pollution Charactristics

Kanjhawala Block and Alipur Block

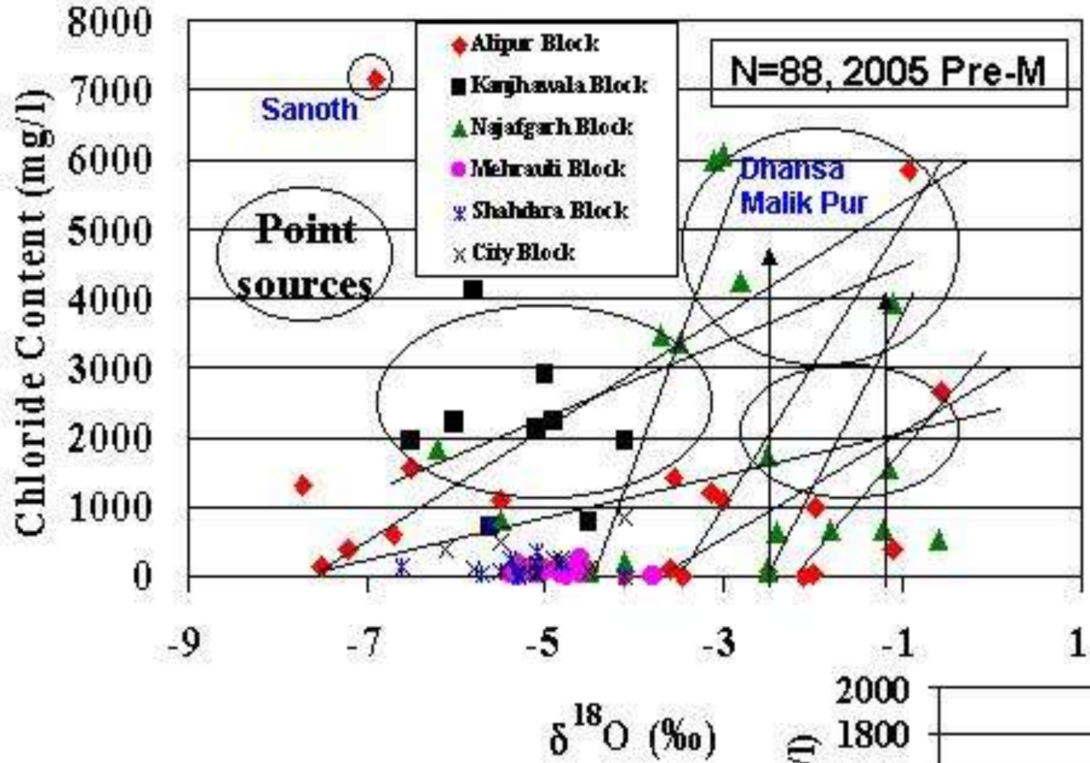


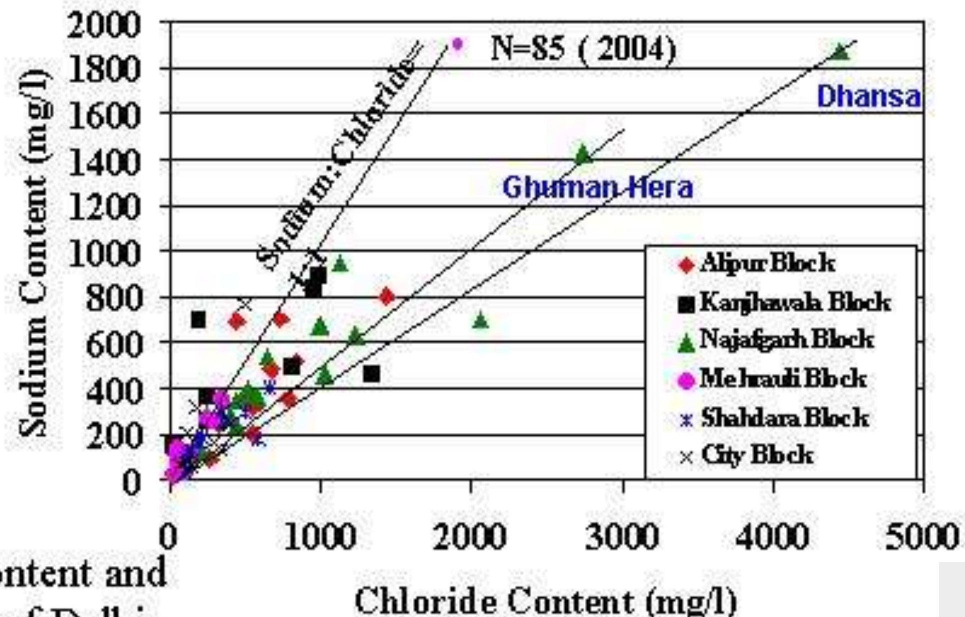
Groundwater is highly polluted and has considerable intermixing among different water bodies



Three different sources of recharge, each having its own chemical & isotopic characteristics

Datta et al (2006)

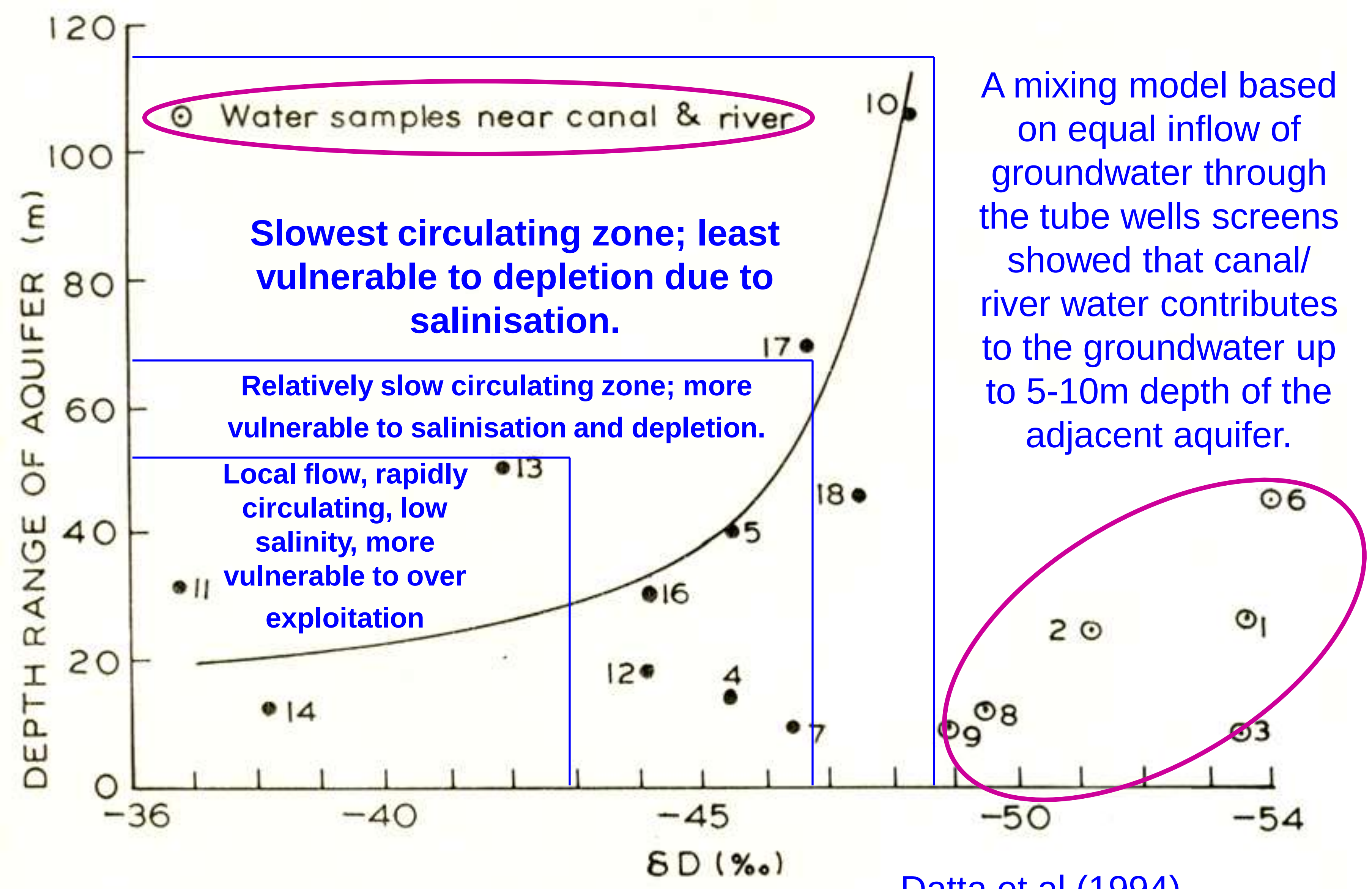




Datta et al (1996, 2006)

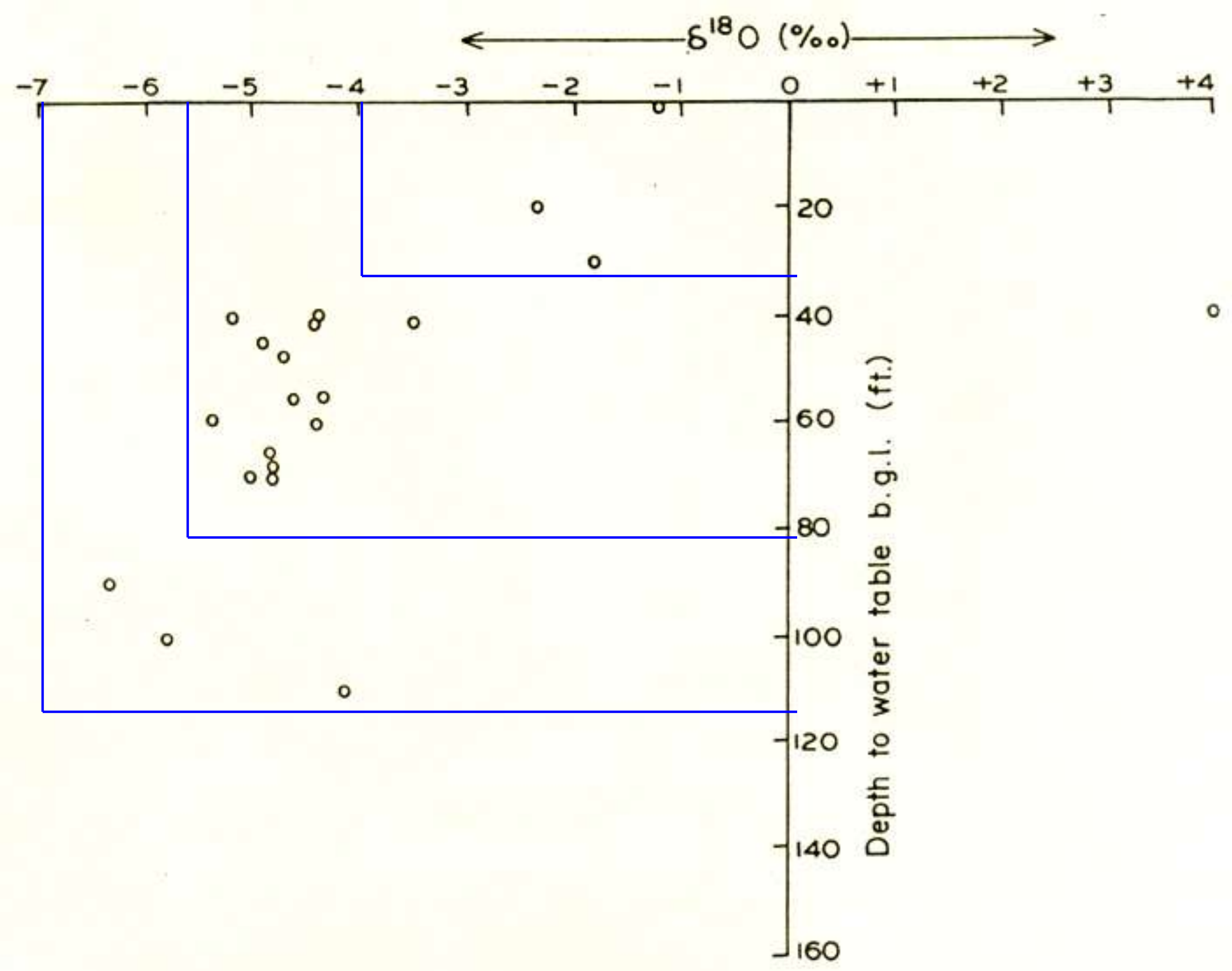
Figure-4 Relationship between Chloride content and d18O and Sodium content in groundwater of Delhi

GROUNDWATER STRATIFICATION IN DELHI



A mixing model based on equal inflow of groundwater through the tube wells screens showed that canal/ river water contributes to the groundwater up to 5-10m depth of the adjacent aquifer.

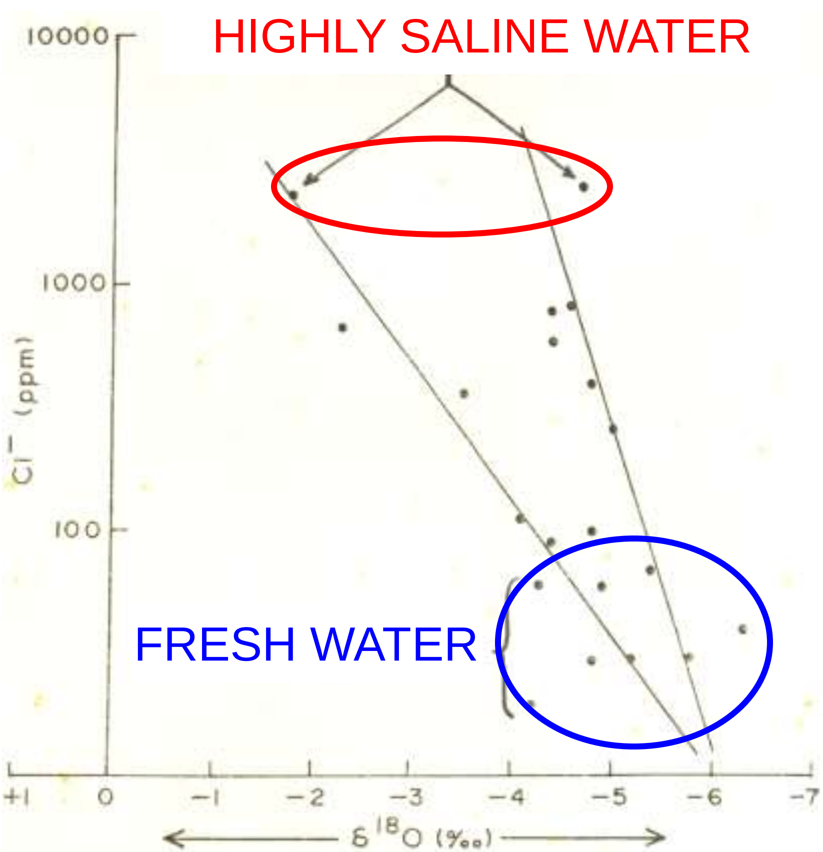
Datta et al (1994)

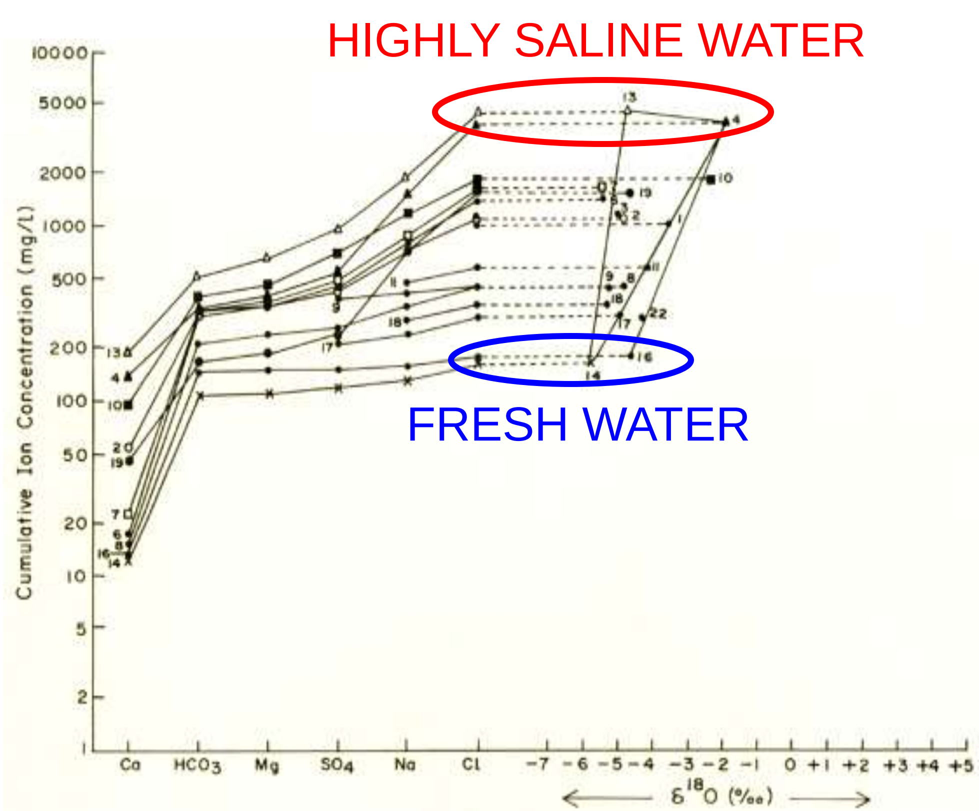


GROUNDWATER STRATIFICATION IN PUSHKAR VALLEY, RAJASTHAN

Datta et al (1998)

GW FLOWPATHWAYS OF INTERMIXING IN PUSHKAR VALLEY, RAJASTHAN



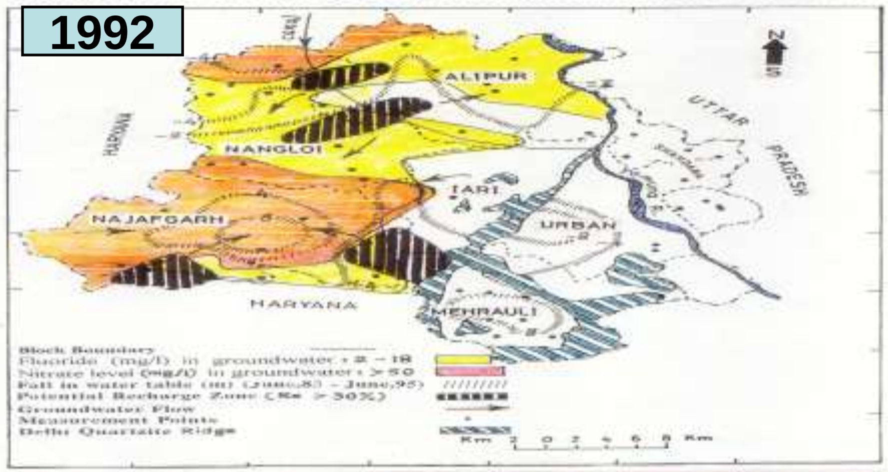


Most of the GWs are generated from the intermixing of three end member GWs forming the triangle

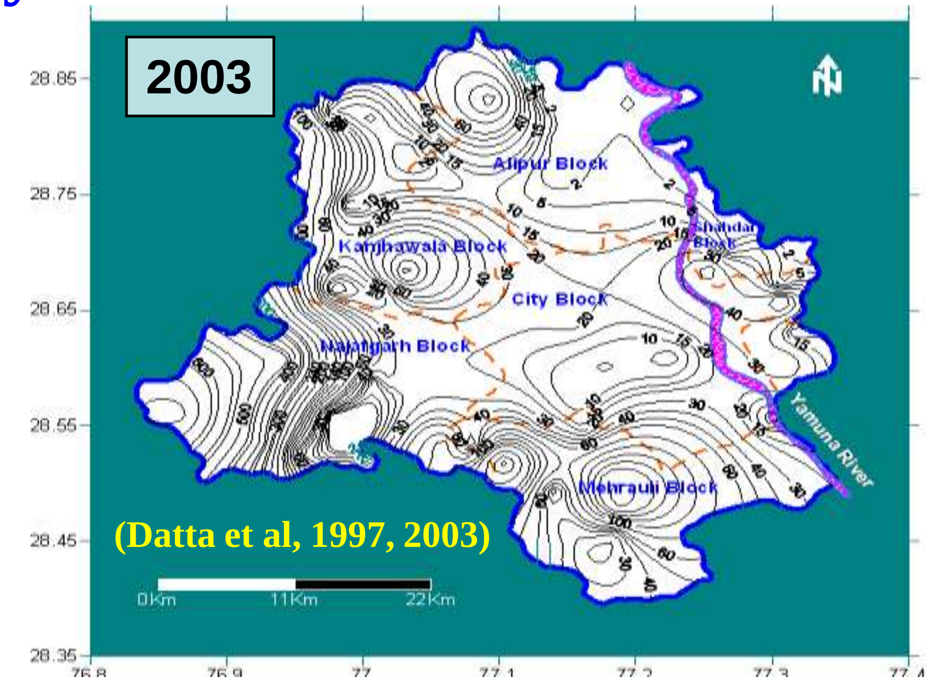
Datta et al (1998)

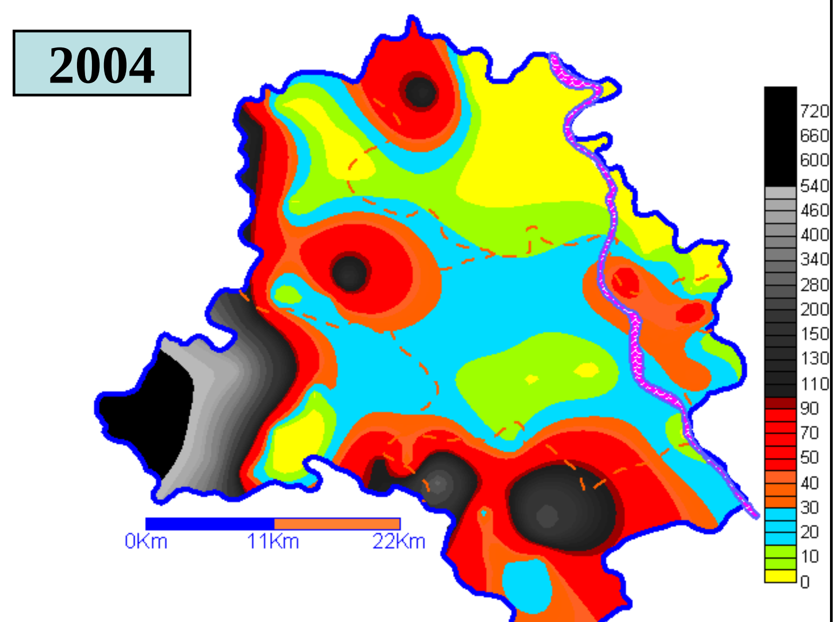
Groundwater Vulnerability to Nitrate in NCT Delhi

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

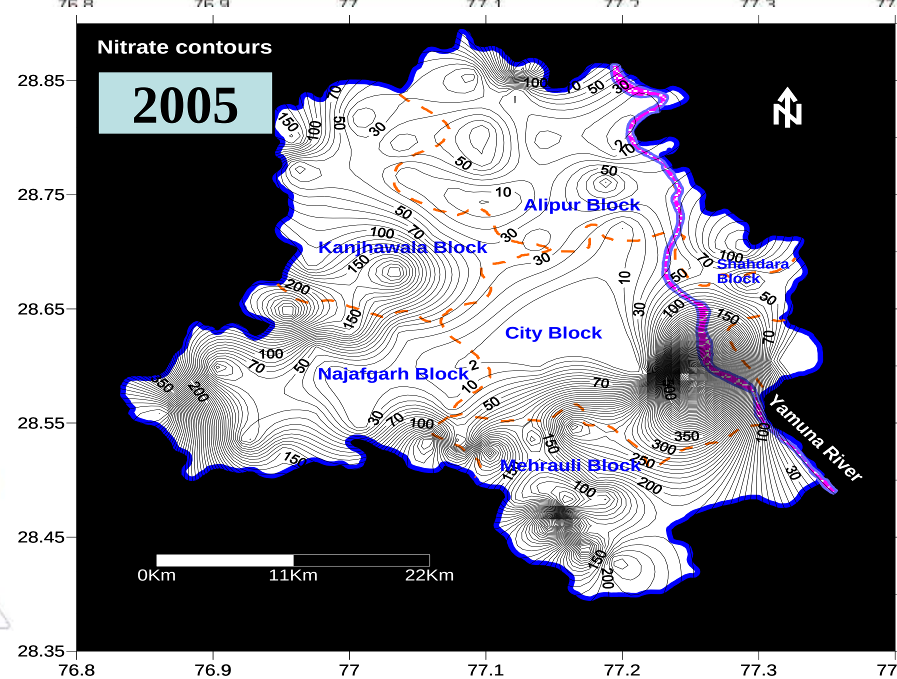


- Recharge is less than 5% in most parts, where fall in water table due to over exploitation ranges from 2 - 8 m.
- Groundwaters in almost 50% of the area are severely contaminated with high levels of fluoride and nitrate, contributed by agrochemicals and anthropogenic wastes.



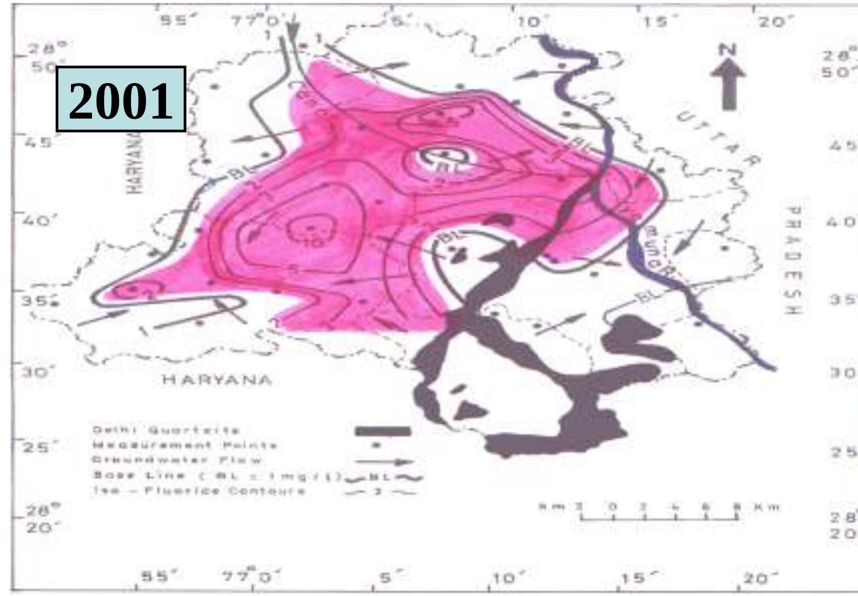


High Nitrate Plumes Movement

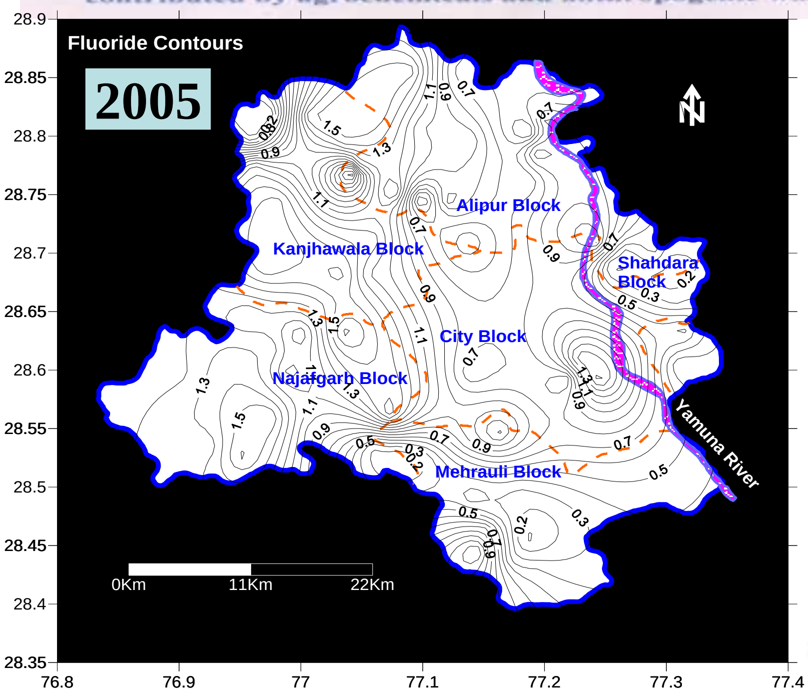


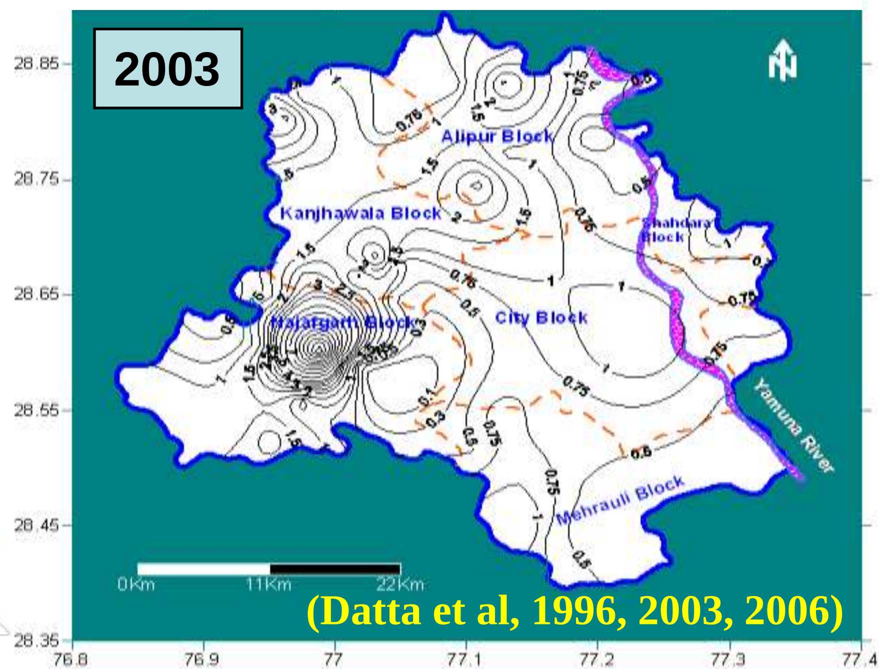
Groundwater Vulnerability to High Fluoride (>1.5 mg/l) in Delhi

- 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.



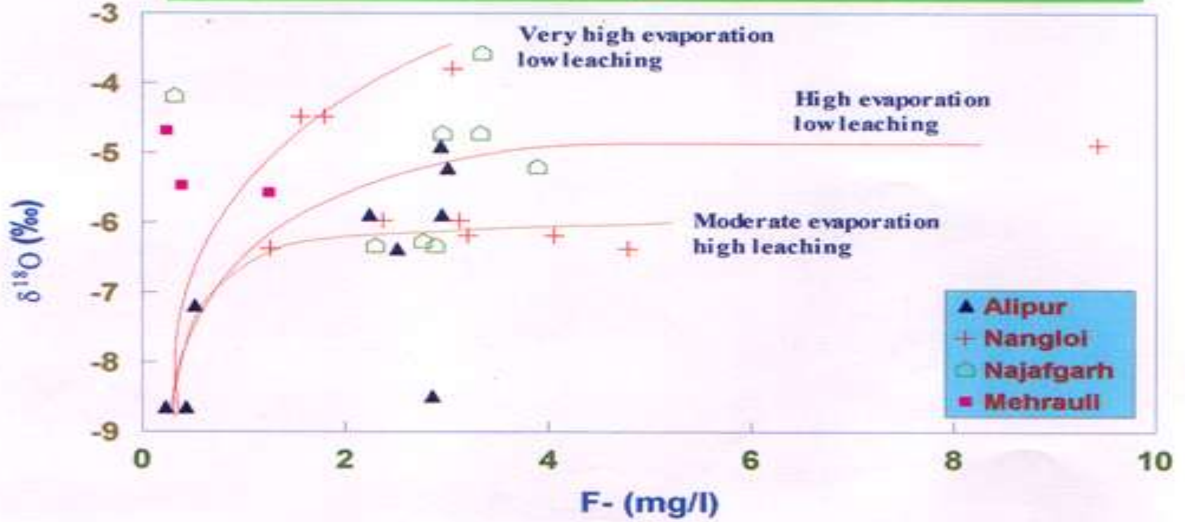
High Fluoride Plumes Movement

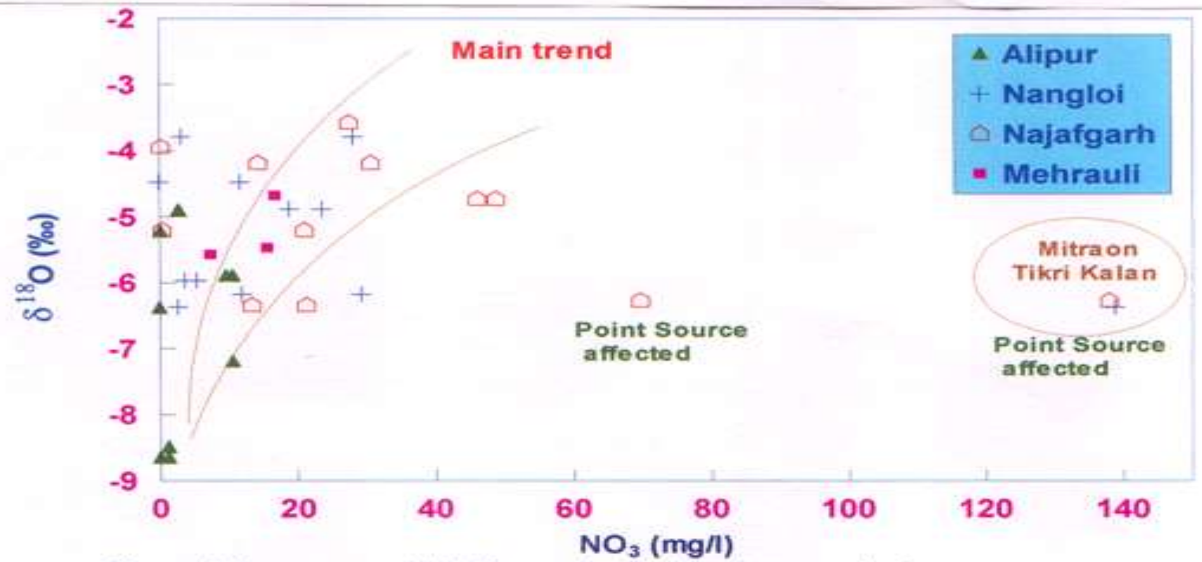




(Datta et al, 1996, 2003, 2006)

Isotopic characterization of fluoride and nitrate contamination of groundwater in Delhi





- Non point sources contributing contamination to groundwater
- Leaching of salts with irrigation water and surface run-off water lead to groundwater pollution.
- 50% of the area is affected by fluoride pollution and 33% by nitrate pollution.
- High nitrate groundwaters can meet considerable nutrient requirement of different crops.

Concentration of nitrate and fluoride in groundwater is governed by nitrate and fluoride content of water recharging from the unsaturated zone, degrees of evaporation/recharge additions from groundwater flowing into the area from surroundings and amounts of fertiliser applied.

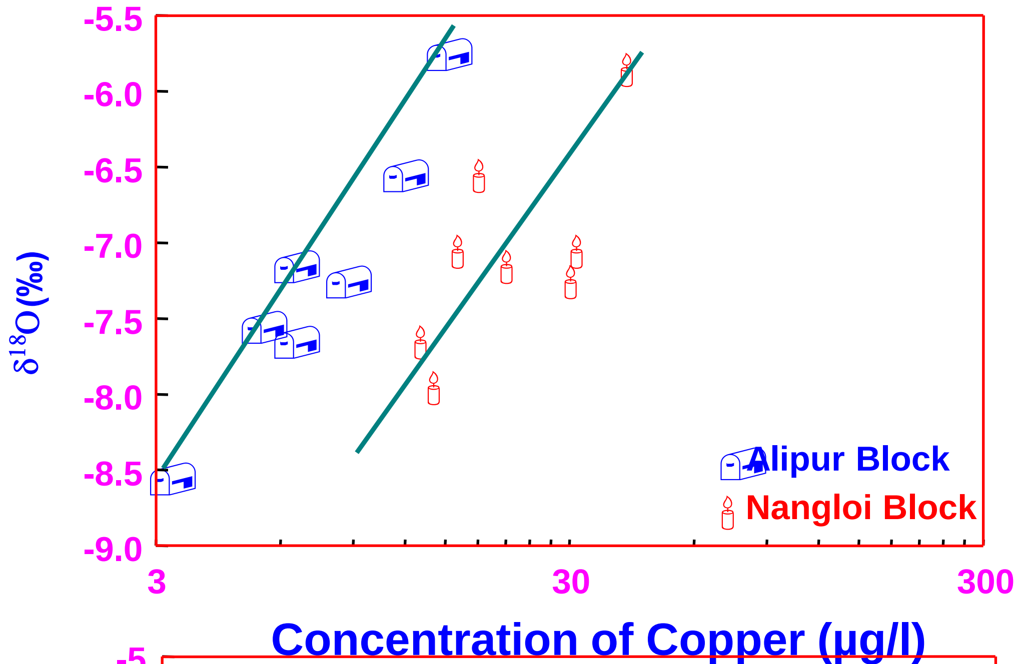
(Datta et al, 1996).

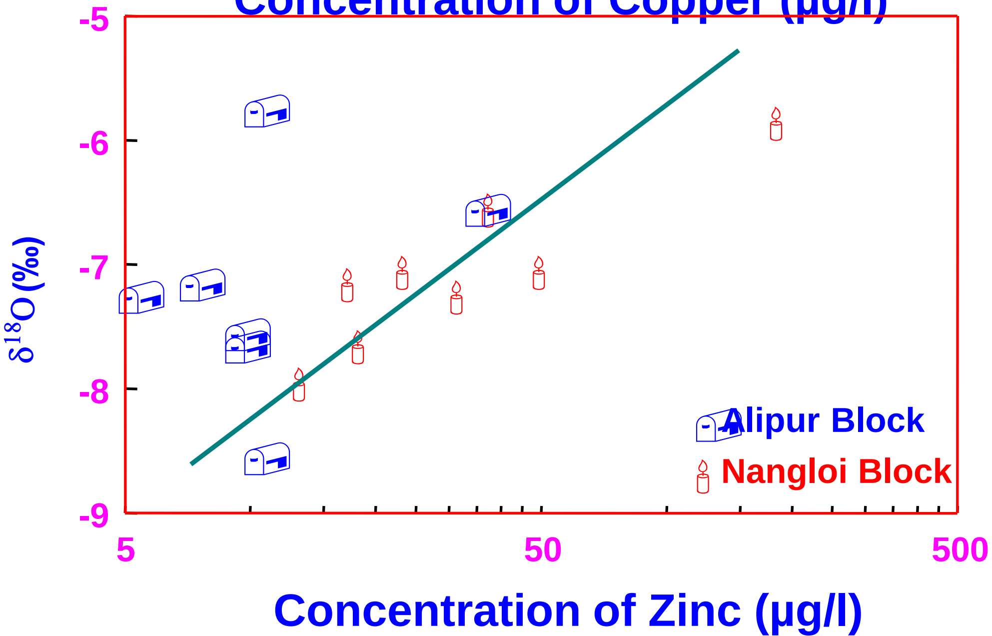
Isotope signature based characterization of (Cu & Zn) contamination of groundwater in Delhi

Peri-urban Soils having Zn (0.2-2.3ppm) & Cu (0.2-5-2ppm) >MPL

Clay minerals & SOM Complex 65%

Crop uptake 1-2%

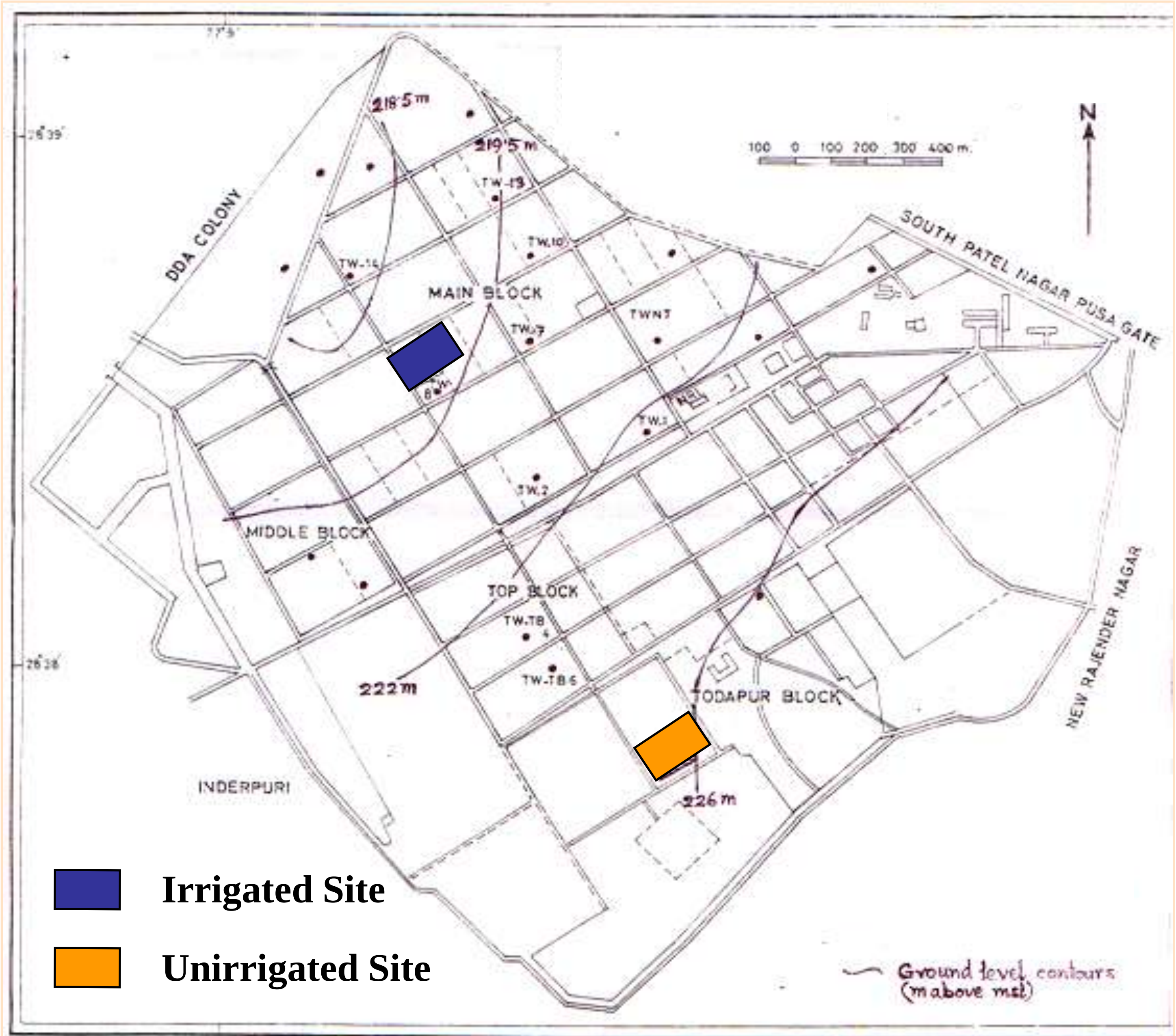




^{18}O isotopic enrichment with increasing Zn and Cu levels indicate leaching of anthropogenic wastes and agrochemicals etc. along with agricultural and urban surface run-off.

(Datta et al, 1999)

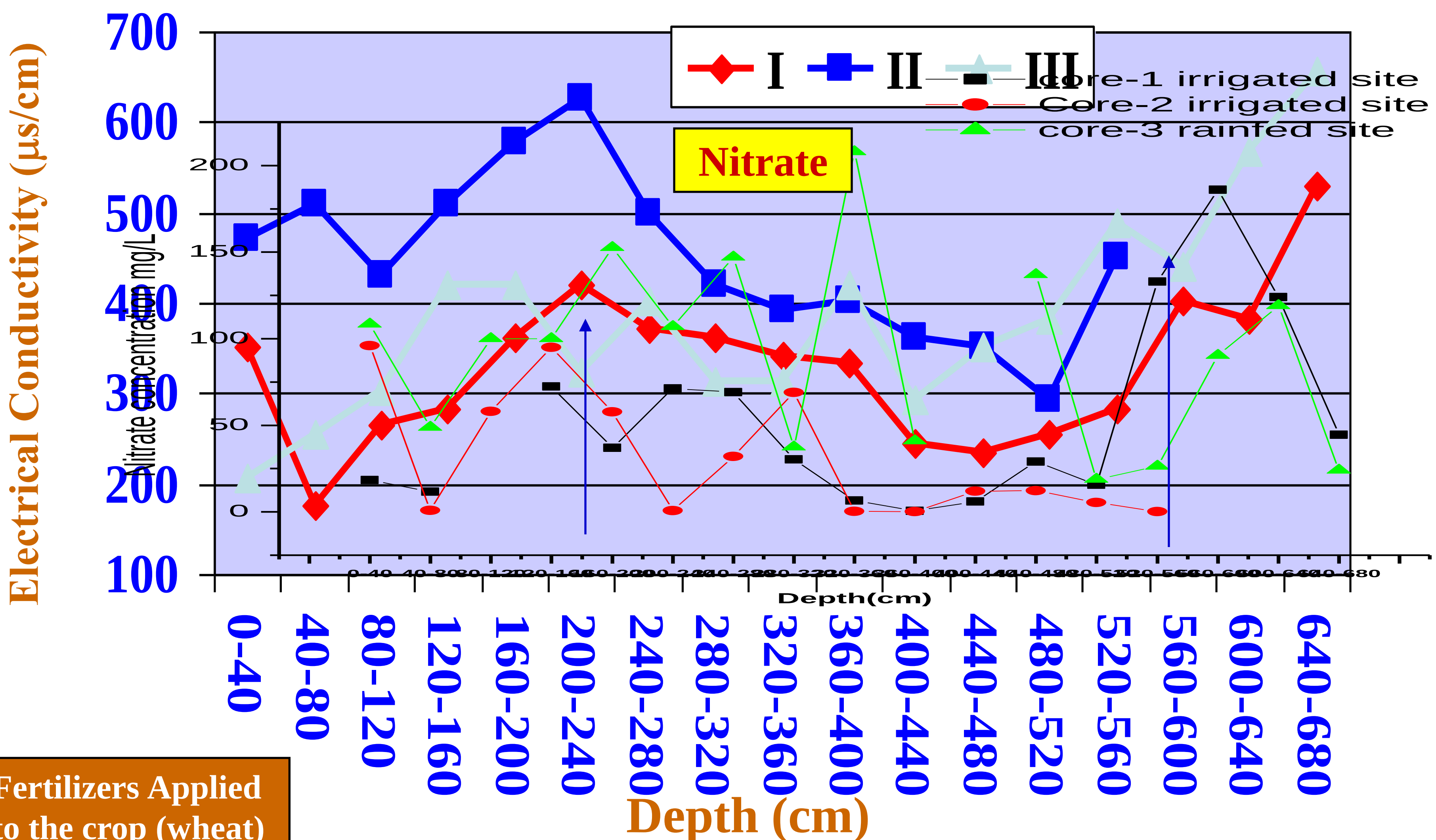
IAEA/CRP Sites at IARI Farm, New Delhi



Deep Drainage of Nitrate and Salinity in IARI Farm

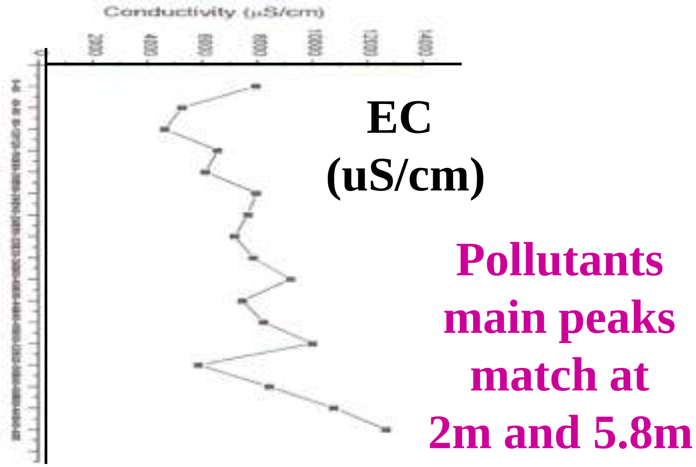
I&II-Irrigated Site, III-Unirrigated Site

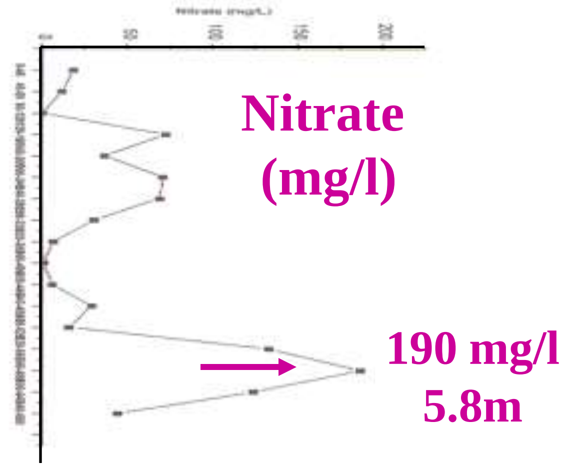
Sampling Date-April,2003

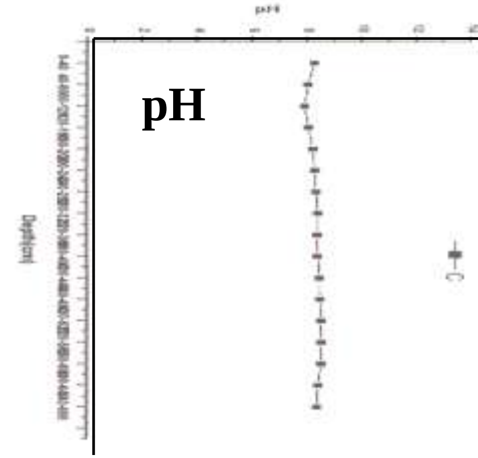


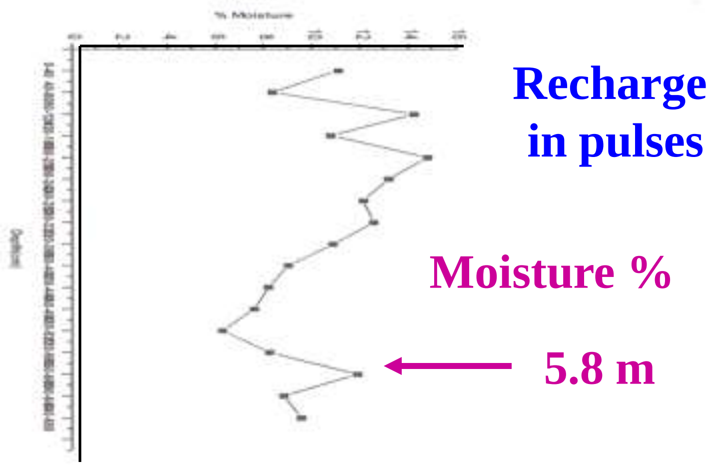
Fertilizers Applied to the crop (wheat)
I- N-60
II- N-180
III-NIL

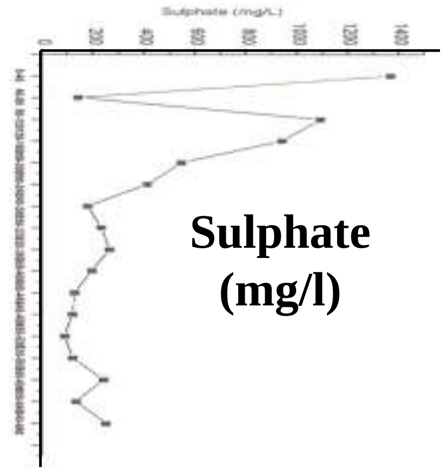
In irrigated site, Nitrate and EC peaks match at 2.2m & 5.6m
Drainage of Nitrate in Irrigated and Rainfed sites are different

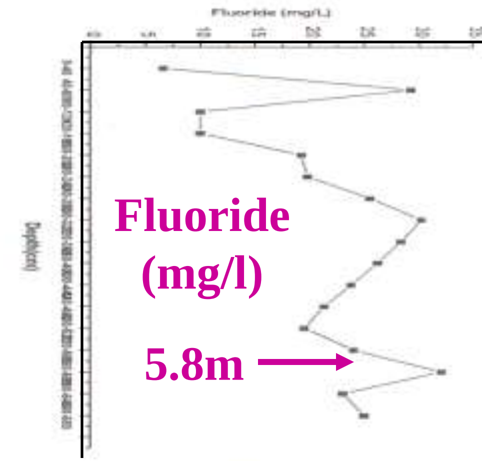




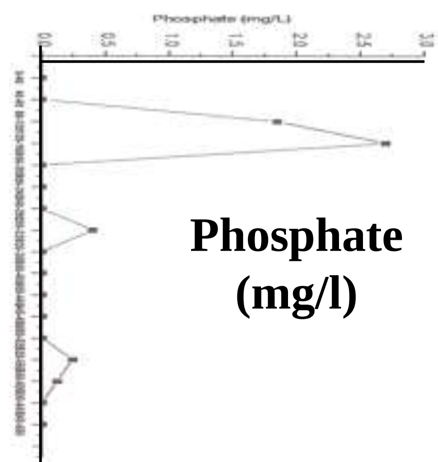


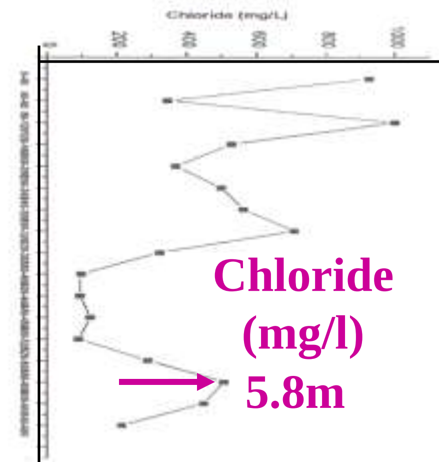


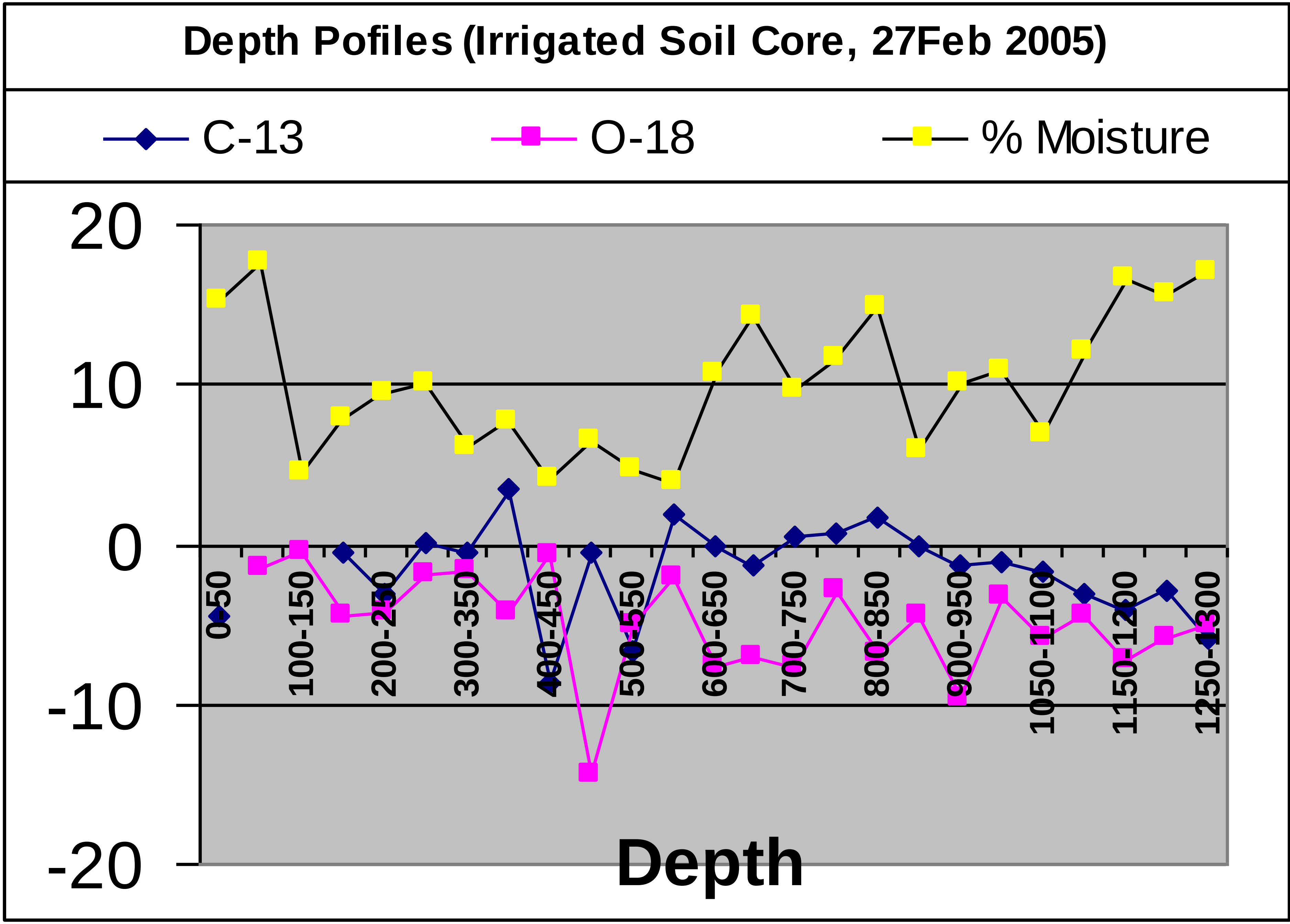




Depth Profile indicating Deep drainage of Pollutants in the Unsaturated Zone at IARI Farm





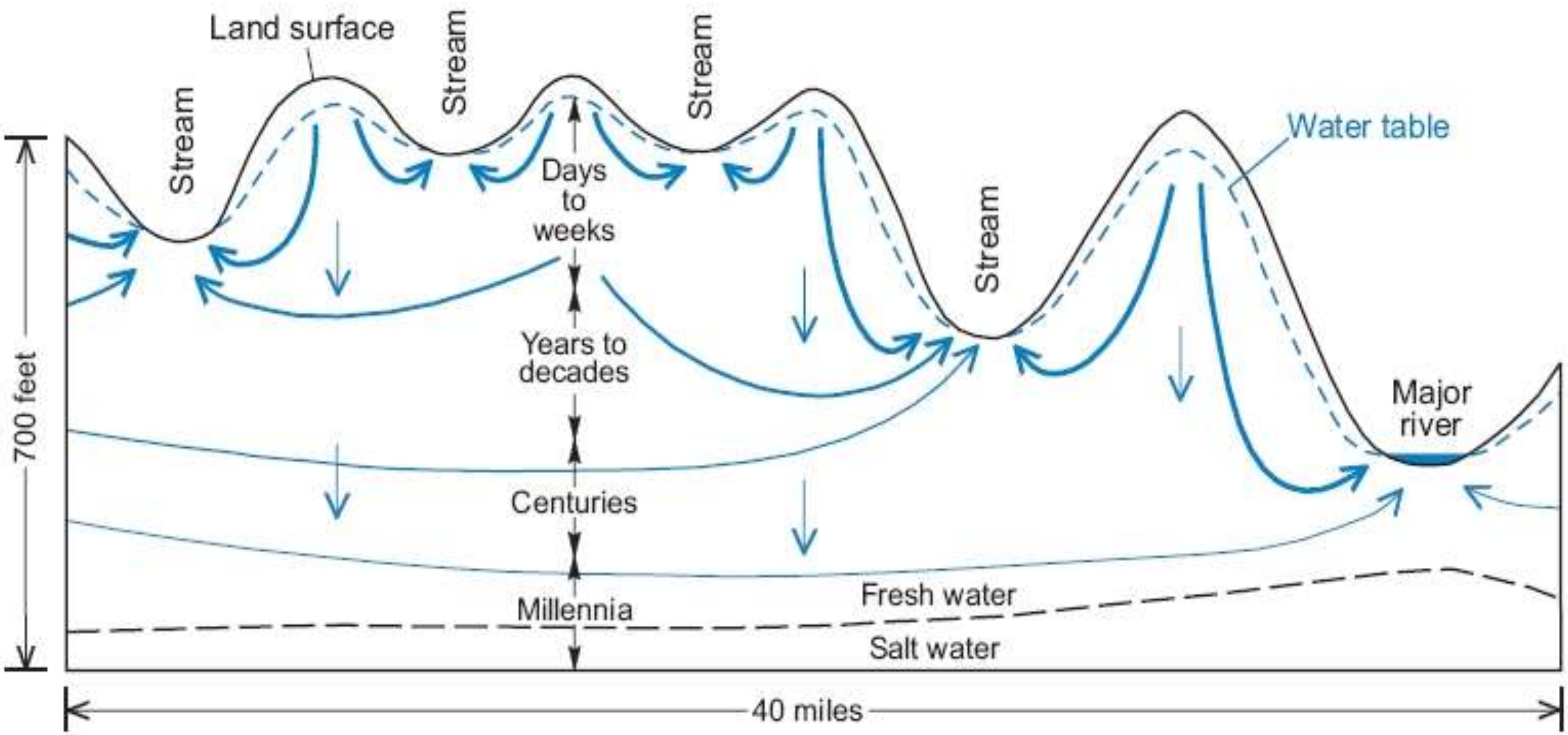

Depth Pofiles (Irrigated Soil Core, 27Feb 2005)
C-13
O-18
% Moisture
20
10
0
-10
-20
0-50
100-150
200-250
300-350
400-450
500-550
600-650
700-750
800-850
900-950
1050-1100
1150-1200
1250-1300
Depth

SOME ASPECTS TO REMEMBER

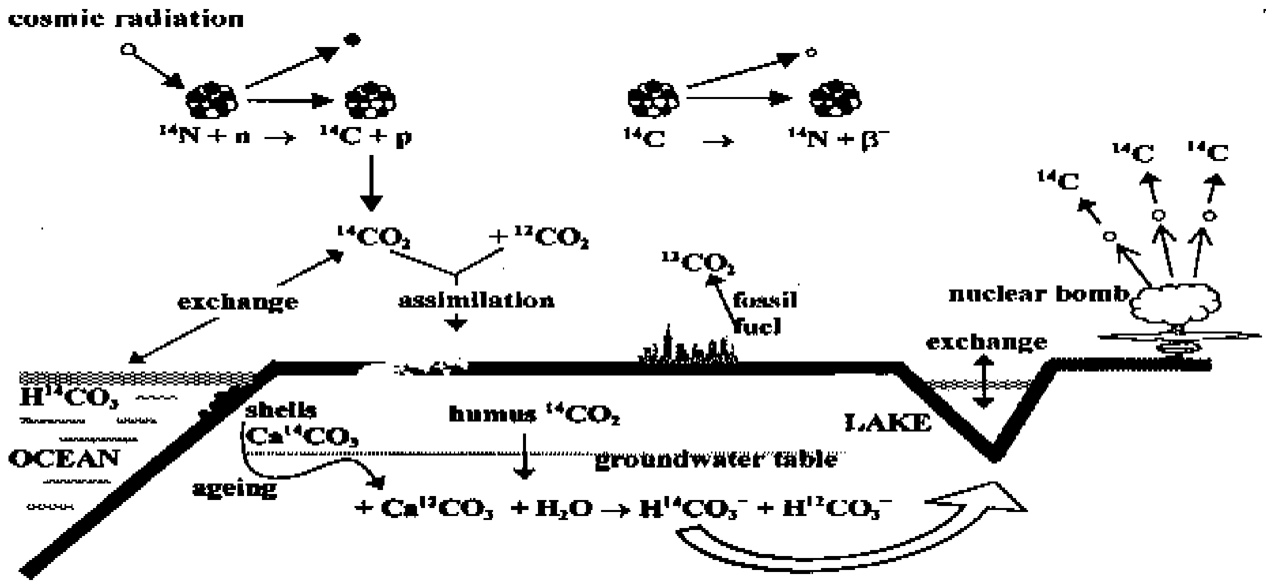
At different scales of investigations, the characteristics of pollutants level and transport in groundwater are altogether different and are associated with variations in one or two parameters at one scale and several parameters at another scale.

A broad qualitative understanding of most of the aforementioned effects are known, little is known about the interactions between solute and soil matrix, which control the behavior of pollutants.

HOW OLD IS THE WATER WE ARE DRINKING?



Groundwater flow paths (indicated by the blue arrows). The thickness of the lines reflect the relative amount of groundwater flowing through the groundwater system.



Origin and distribution of ^{14}C in nature.

- **The production and distribution of ^{14}C in nature occurs through series of chemical and biological processes which has become stationary throughout much of geologic time.**
- **As a consequence, the concentration of ^{14}C in the atmosphere, oceans and biosphere reached a steady-state value which has been almost constant during a geologic period which is long compared to the life span of a ^{14}C nucleus.**

Radioactive decay follows the laws of Exponential decay:

$$N = N_0 e^{-\lambda t}.$$

Where,

- N_0 **= number of atoms at *time* 0, starting point of *age*,**
- N **= number of atoms at *age* or *time* t,**

$$\lambda = \frac{\ln 2}{t_{1/2}}$$ **= disintegration constant,**

$t_{1/2}$ **= radiocarbon half-life**

$$\frac{1}{\lambda}$$ **= radiocarbon mean or average life.**

Radiocarbon date/Age: $$t(BP) = \frac{1}{\lambda} \ln \frac{N}{N_0}$$

APPLICATIONS OF GROUNDWATER AGE DATA

Mapping vulnerability of the shallow aquifers

Renewability of the groundwater

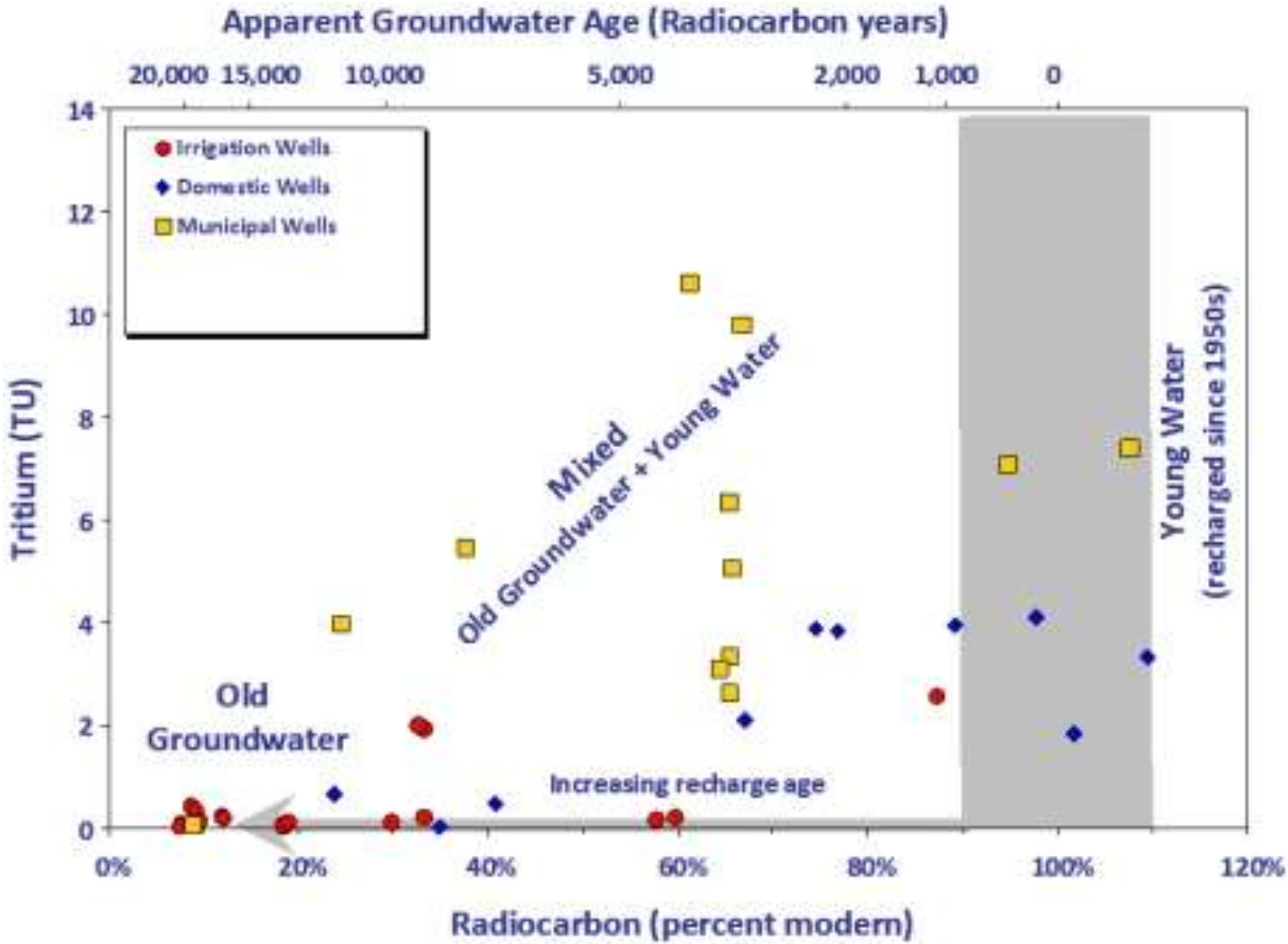
Prevention of over exploitation and contamination

Estimation of the recharge rate and flow velocity

Identification of the GW flow paths of inter-mixing

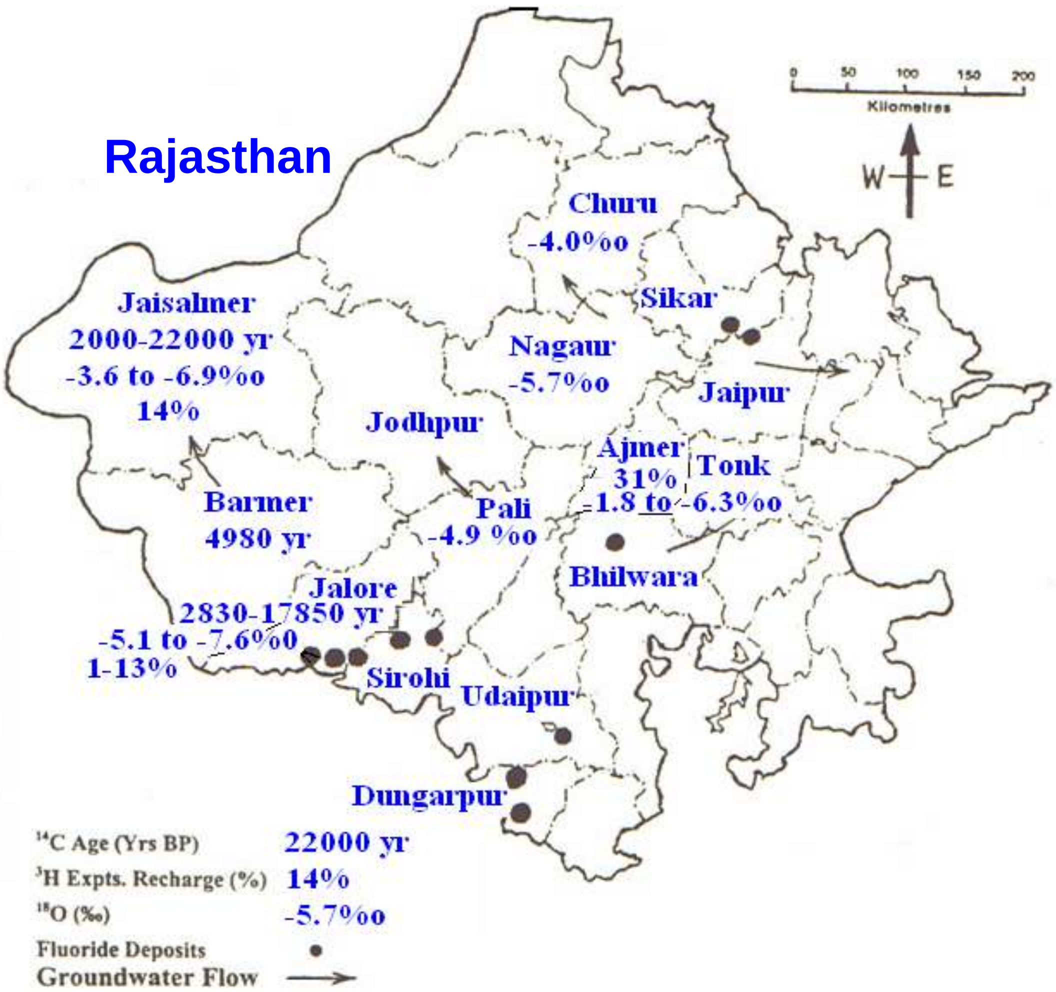
Study of the pre-Holocene (late Pleistocene) climate

Evaluation of GW pollution & travel time of GW plumes



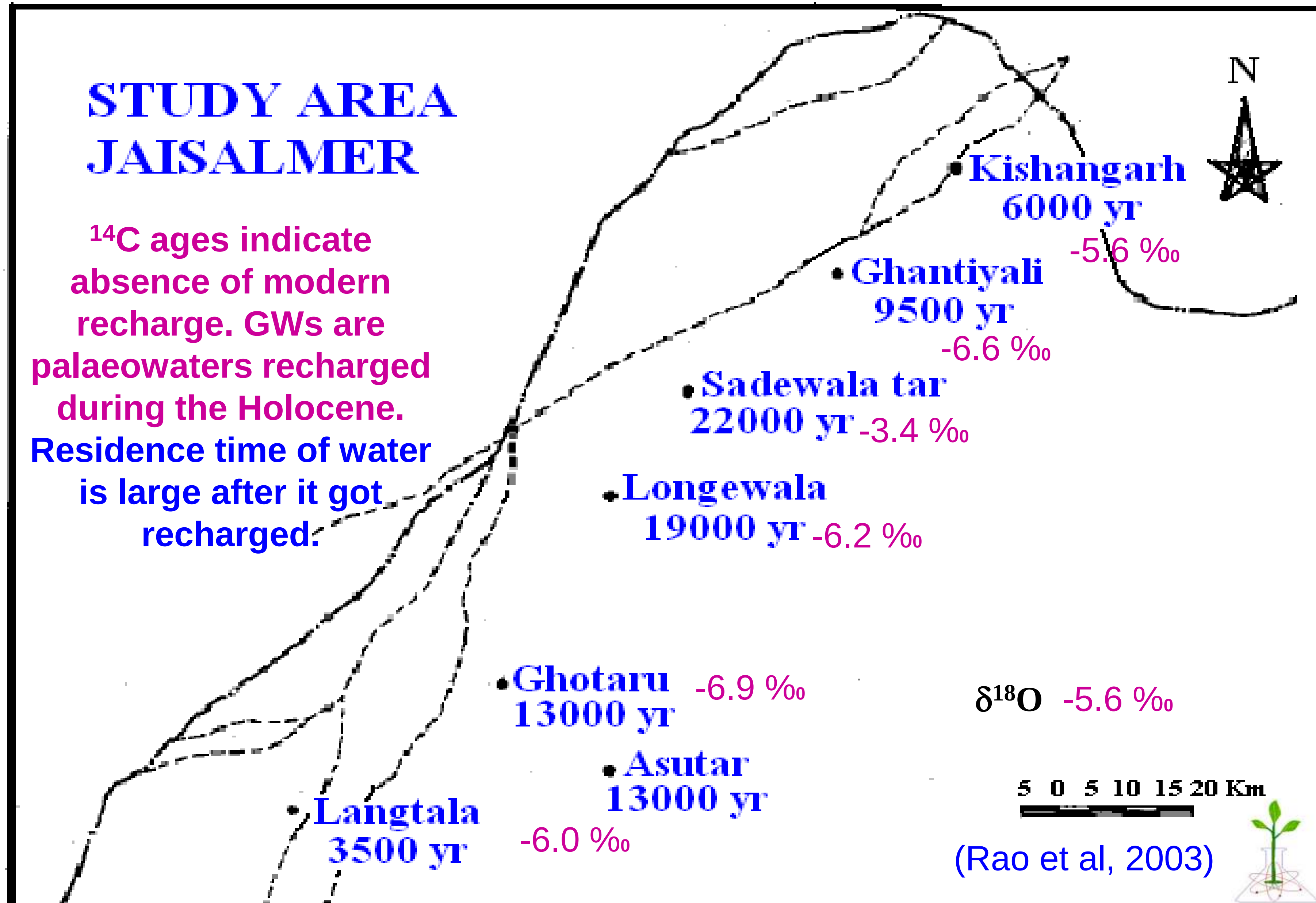
Apparent Groundwater Age (Radiocarbon years)
20,000
15,000
10,000
5,000
2,000
1,000
0
Irrigation Wells
Domestic Wells
Municipal Wells
Tritium (TU)
14
12
10
8
6
4
2
0
Mixed
Old Groundwater + Young Water
Young Water
(recharged since 1950s)
Old
Groundwater
Increasing recharge age
0%
20%
40%
60%
80%
100%
120%
Radiocarbon (percent modern)

Characterization of Groundwater Provenance



Isotopically highly depleted groundwater, ^{18}O (- 4.2 to -7.6‰), with ^{14}C-age 2,000 to 18,000 yrs BP, suggest groundwater lateral inhomogeneity, vertical stratification, slow recharge process and occurrence of palaeowaters recharged during humid climate in the past.

^{14}C AGE AND $\delta^{18}O$ OF GROUNDWATER



^{14}C ages indicate absence of modern recharge. GWs are palaeowaters recharged during the Holocene.

Residence time of water is large after it got recharged.

(Rao et al, 2003)

CONCLUDING REMARKS

- Groundwater characteristics and distribution are heterogeneous in vertical and lateral extent. Each area/region should be treated separately.
- Basic scientific information is fragmented and cost for necessary new information is higher.
- Volumetric estimates for each area should be made separately by further research on groundwater potential and how can it be used sustainably and protected from pollution.
- The different timescales of recharge can help to create an integrated system of water supply, if the spatial and temporal extent of variation of groundwater is properly understood.

CONCLUDING REMARKS

- **Further research needed on hydrogeologic characteristic of the GW flow field under natural and stressed conditions, dynamics and depth variation of GW pollutants in relation to well structure and casing conditions, importance of decontamination potential of soil and geohydrology in limiting contamination.**
- **Cases studies suggest the beginning of a trend of increasing groundwater pollution.**
- **Need for Synergy of Technology and Public Policy.**
- **Participatory Research and Knowledge Management.**
- **The scope of the problem may be larger than imagined and assessed so far.**

POLICY ISSUES AND STRATEGIES

Estimate recharge by improved direct methods. Clearly delineate potential GW recharge zones and protection zones in relation to landuse changes.

Balance water extraction by the recharge. Revise all estimates time to time and reconsider.

Management must consider also the GW velocity and pathways between the source and the water-supply well, lateral inhomogeneity, vertical stratification, and occurrence of palaeowaters

Develop uniformity in the methods for selecting wells and more information for deeper wells.

POLICY ISSUES AND STRATEGIES

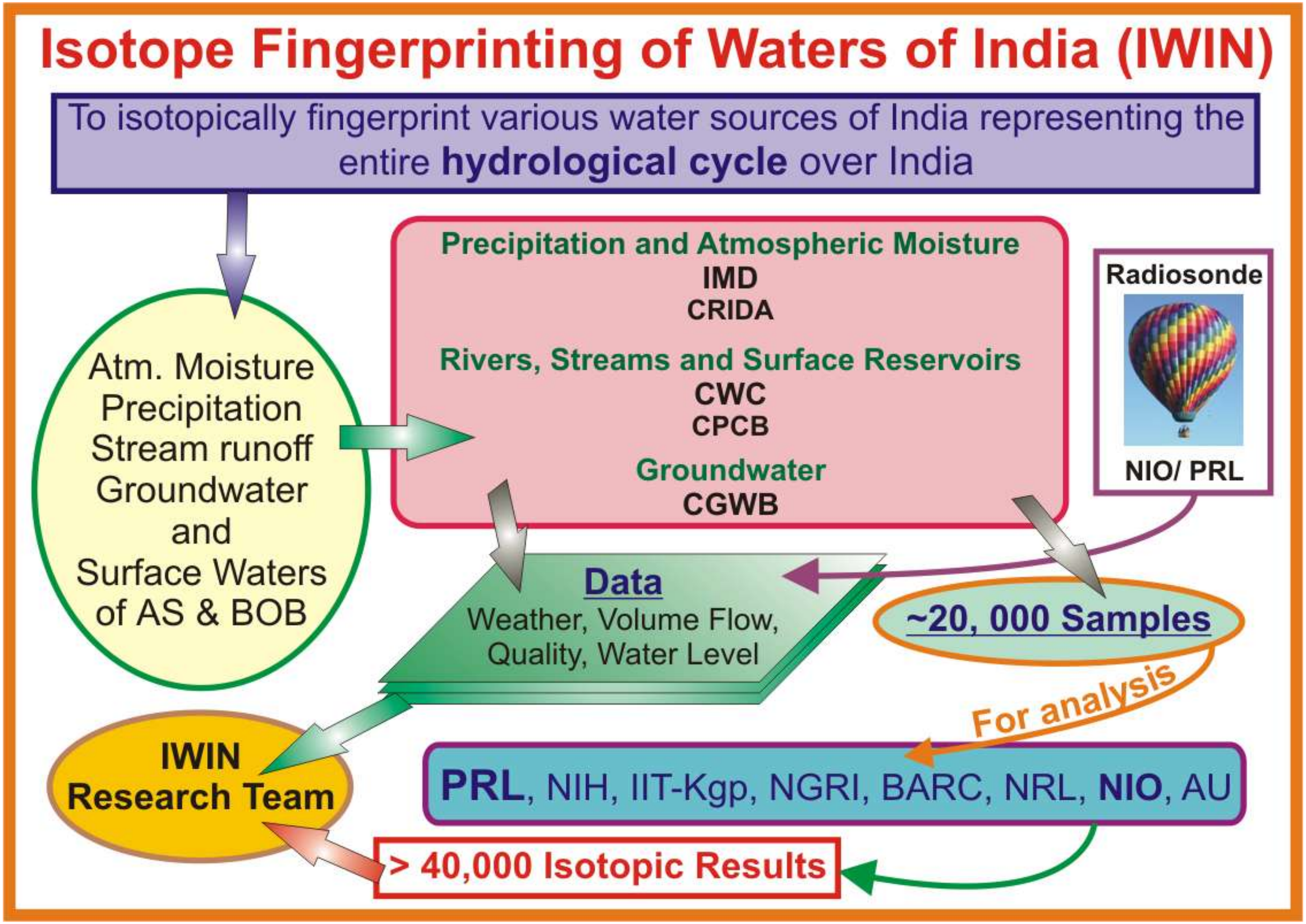
- Change the monitoring strategy from general state descriptions to problem-oriented information on groundwater renewal and recycling.
- Identify pollution sources and containment of spreading from known sources.
- Prepare iso-concentration maps of contaminants levels in groundwater for all tehsils, towns, cities and district headquarters and revise time to time.
- Prepare groundwater vulnerability maps .

POLICY ISSUES AND STRATEGIES

Responsible policy can be evolved only after assessing the nature of these intricate and complex linkages, developing new guidelines on short-term and long-term management goals.

– Control groundwater pollution from non-point sources, through: Coordination among the provisions in the statutes on groundwater quality, waste disposal practices, etc.

– Public need to be made aware of various issues, to link water supply and its quantity and quality with changing water-use and land use.


Isotope Fingerprinting of Waters of India (IWIN)
To isotopically fingerprint various water sources of India representing the entire hydrological cycle over India
Atm. Moisture Precipitation Stream runoff Groundwater and Surface Waters of AS & BOB
Precipitation and Atmospheric Moisture
IMD
CRIDA
Rivers, Streams and Surface Reservoirs
CWC
CPCB
Groundwater
CGWB
Radiosonde
NIO/ PRL
Data
Weather, Volume Flow, Quality, Water Level
~20, 000 Samples
For analysis
IWIN Research Team
PRL, NIH, IIT-Kgp, NGRI, BARC, NRL, NIO, AU
> 40,000 Isotopic Results

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DST

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- ICAR