REPORT OF THE GROUP FOR SUGGESTING NEW AND ALTERNATE METHODS OF GROUND WATER RESOURCES ASSESSMENT

CENTRAL GROUND WATER BOARD
MINISTRY OF WATER RESOURCES
GOVERNMENT OF INDIA

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NEW AND ALTERNATE METHODOLOGIES FOR GROUND WATER ASSESSMENT

1 Background

National Water Policy (2002) states that 'There should be a periodical reassessment of the ground water potential on a scientific basis, taking into consideration the quality of the water available and economic viability of its extraction. Exploitation of groundwater resources should be so regulated as not to exceed the recharging possibilities, as also to ensure social equity.'

In the light of the National Water Policy (2002), annual replenishable ground water resources of the country are being periodically assessed jointly by CGWB and State Ground Water Departments. The last assessment of annual replenishable ground water resources for the entire country was carried out for the year 2004 based on the Ground Water Resource Estimation Methodology (GEC, 1997). Since then there have been changes in ground water scenario in many places of the country. In order to have a fresh look at the methodology for ground water estimation with a view to bring improvements, a group was constituted by Ministry of Water Resources. The composition of the group was as follows -

1. Sh. A.R. Bhaisare, Member (SAM), CGWB — Chairman
2. Shri C.P. Kumar, Scientist F, NIH — Member
3. Shri S.K. Sinha, Scientist D, CGWB — Member
4. Shri Y.B. Kaushik, OIC-SUO, CGWB — Member
5. Shri Rana Chatterjee, Scientist D, CGWB — Member Secretary

Two more members were co-opted in the group –

6. Dr. S.K. Sharma, Consultant (GW), MOWR
7. Shri S.K. Srivastav, Scientist-SF, IIRS (NRSC), Dehradun

After the superannuation of Sh. A.R. Bhaisare, the report has been finalized under the supervision of Sh. S. Kunar, incumbent Member (SAM), CGWB.

The terms of reference of the group was to suggest new and alternate methods of ground water resource assessment for refinement in the existing policy.

In the present report, an attempt has been made to review the various methods for assessment of ground water recharge, present perspective of ground water resources assessment in the country and to suggest the future strategies for refinements of the methodology for assessment of ground water resources.

2 Ground water recharge assessment

Groundwater recharge may be defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir' (Lerner et al.,1990). Reliable estimates of groundwater recharge are needed for a number of reasons, including –

- quantifying groundwater resources which can be utilized without detrimental effects on environment
- assessing the surface water – ground water interactions and total availability of water resources and groundwater vulnerability (for both quantity and quality aspects)
- identifying implications of changes in land use and/or climate on water resources
- ground water management and planning – funding of ground water development projects
- formulation of regional scale artificial recharge and rainwater harvesting programmes
- regulation of ground water development

2.1 Methodologies for recharge assessment

There are several techniques for recharge assessment. These techniques can be broadly classified into three groups – lumped water balance approach, tracer technique and discrete numerical modeling. These three techniques are again sub-divided on the basis of hydrologic sources or zones from which data are obtained, namely surface water, unsaturated zone and saturated zone.

The various recharge estimations techniques and their attributes have been summarized in Table 1 and 2

Table 1 *Various recharge estimation techniques (summarized from Scanlon et al., 2002).*

	Lumped Water Balance approach	*Tracer*	*Numerical Modeling*
Techniques based on surface water	▪ Base flow discharge ▪ Spring hydrograph analysis ▪ Channel-water budget ▪ Seepage meters	▪ Heat tracers ▪ Isotopic tracers (stable isotopes of oxygen and hydrogen)	▪ Rainfall–runoff/ watershed modeling (recharge estimated as balance term in water budget) (SWAT, HELP3, TOPOG_IRM, PRZM-2, SMILE, ANSWERS, PERFECT, etc; Jyrkama *et al.* 2002)
Techniques based on unsaturated zone	▪ Lysimeters ▪ Zero-flux plane ▪ Darcy's law	▪ Applied tracers (bromide, ^{3}H, dyes) ▪ Historical tracers (^{3}H, ^{36}Cl) ▪ Environmental tracers (Cl)	
Techniques based on saturated zone	▪ Water table fluctuation method ▪ Darcy's law	▪ Historical Tracers (^{3}H, $^{3}H/^{3}He$, CFC ▪ Environmental tracers (Cl, ^{14}C)	▪ Ground water flow modeling (recharge estimated by calibrating hydraulic heads) MODFLOW, MIKE-SHE etc.

Table 2 *Comparison of recharge estimation techniques based on recharge attributes (summarized from Scanlon et al., 2002).*

	Techniques based on		
	Surface Water	*Unsaturated Zone*	*Saturated Zone*
Spatial scale	Generally provide regional estimate; seepage meters, heat tracers, channel water budget provide point/small-scale estimate	Generally provide point/ small-scale estimate	Provide regional estimate
Temporal scale	Generally provide event based estimate; longer time-scale estimate possible by summing up event based estimates	Generally provide estimate of longer time-scale	Generally provide estimate of longer time-scale
Range of recharge fluxes[*]	1–4000 mm/a (1–3000 mm/d for seepage meters)	0.1–3,000 mm/a	0.1–1,000 mm/a
Climate	More suitable in humid climate	More suitable in arid and semi-arid climate	More suitable in humid climate
Accuracy/ Reliability	Less reliable (potential recharge is estimated)	Less reliable (potential recharge is estimated)	More reliable (actual recharge is estimated)

[*]*varies depending on the technique used, therefore broad range is given*

Some of the commonly used recharge assessment methods are described below.

Lumped water balance approach

The approach involves the application of the principle of conservation of mass, sometimes referred to as the continuity equation, to account for the quantitative changes occurring in the various components of the hydrologic cycle.

<u>Techniques based on surface water studies</u>

River base flow method

This normally involves the separation of the base flow component from runoff in stream hydrograph at suitably located surface flow gauging stations. Use of base flow discharge to estimate recharge is based on a water-budget approach in which recharge is equated to discharge.

Advantages: The technique is based on surface water studies and is thus suitable for areas where adequate data on river stages are available.

Limitations:

- . Base flow discharge may not be necessarily directly equated to recharge because pumpage, evapotranspiration, and underflow to deep aquifers may also be significant.
- The results tend to be very sensitive to the base flow separation technique used.
- It is often difficult to ascribe the results to individual aquifer areas upstream of the gauging station.
- It cannot be used in ephemeral rivers

Spring Hydrograph Analysis

The spring hydrograph shows a shape similar to that of a surface water stream, a rising limb, peak and a recession limb. It also shows a time-lag between precipitation and peak of the hydrograph. In permeable formations, like karstic limestones, the peak of the spring hydrograph will be broader and flatter with a greater time-lag. In contrast to this, in less permeable formations, the hydrograph has a sharper peak due to small aquifer storage. In karstic aquifers, the peak and the recession limb of the spring hydrograph may have several bumps indicating complex recharge and flow mechanism.

Ground water recharge can be estimated from spring flow data using Eq. (1) based upon the principle of continuity.

$$\int_{t_1}^{t_2} A\,R(t)\,dt = \frac{Q\,(t_2)}{\alpha} - \frac{Q\,(t_1)}{\alpha} + \int_{t_1}^{t_2} Q\,(t)dt \qquad (1)$$

where A is the replenishment area of the spring (L^2), R(t) is the replenishment rate (LT^{-1}), t_1 and t_2 are the instance of time at the end of one dry season and the beginning of the next one , $Q(t_1)$ and $Q(t_2)$ are the spring discharge rate (L^3T^{-1}) at time t_1 and t_2 respectively, Q (t) is the spring discharge rate at any time, t, and α is the recession coefficient (T^{-1}).

The recession coefficient α may be obtained from the following equation

$$\propto = \frac{\log Q(t_1) - \log Q(t_2)}{0.4343\ t_2} \qquad (2)$$

This method has been used, among others, by Korkmaz (1990) and Bhar (1996) for the estimation of recharge in carbonate rock aquifers (Singhal, 2003).

Techniques based on unsaturated zone studies

Lysimeter

Lysimeters consist of containers filled with disturbed or undisturbed soil, with or without vegetation that are hydrologically isolated from the surrounding soil, for purposes of measuring the components of the water balance. All lysimeters are designed to allow collection and measurement of drainage. The various components of the soil water budget are accurately measured by using Lysimeters.

Advantages: Useful for measuring drainage through soils below 1 to 2 m and hence can give an indication of groundwater recharge.

Limitations:

- Most lysimeters have relatively small surface areas (1 m^2) and are shallow (1 m), so the drainage measured may not be fully representative of the flows that would reach a relatively deep water table below a thick subsoil.
- Ideally, for recharge estimation, a lysimeter should be large and deep and extend into the water table (Jones & Cooper, 1998). However, it is seldom practicable.
- Lysimeters are not routinely used to estimate recharge because they are expensive and difficult to construct and have high maintenance requirements.
- They are more suitable for evaluation of evapotranspiration than recharge.

Soil moisture budgets

Groundwater recharge can be estimated by the soil moisture balance approach. Soil moisture budgeting, taking into account evapotranspirational abstraction from precipitation, provides a measure of moisture available for runoff and infiltration. This can be done by Thornthwaite's Book keeping method of moisture balance (Karanth, 1987).

Advantages: The calculation from standard data is simple and can be done in a spreadsheet (Kinzelbach, 2002).

Limitations: Lack of accurate database on potential evapotranspiration, field capacity and wilting point of the soil and surface runoff.

This method is also applicable for small oceanic islands where ground water occurs as a floating lens. The hydrogeological system of these islands are influenced by the topography and tidal fluctuations. The water balance equation used in island conditions (CGWB, 2005) is a type of soil moisture budget viz.

$$P = AEt + R + \Delta V \qquad (3)$$

Where,

P is precipitation, AEt is actual evapotranspiration, R is ground water recharge and ΔV is change is soil moisture. In this equation, runoff has been assumed to be negligible.

Soil moisture flux approach

These include the zero flux plane approach and Darcy flux calculations.

- Zero flux plane approach (ZFP) – In this method, ground water recharge is equated to changes in soil-water storage below the zero flux plane (ZFP), which represents the plane where the vertical hydraulic gradient is zero. The ZFP separates upward (ET) from downward (drainage) water movement. The rate of change in the soil water storage between successive measurements is assumed to be equal to the drainage rate to the water table or the recharge rate.

- Darcy flux approach – Darcy's law is used to calculate recharge (R) in the unsaturated zone according to the following equation:

$$R = -K(\theta)(\frac{dh}{dz} + 1) \quad (4)$$

Where K(θ) is the hydraulic conductivity at the ambient water content, θ, h is the metric pressure head, and z is the elevation. Application of Darcy's law requires measurements of the vertical total head gradient and the unsaturated hydraulic conductivity at the ambient soil water content.

Advantages:

- The ZFP is a useful concept for estimating recharge and actual evapotranspiration, based on measurements of metric potential and soil moisture.

- Darcy method can be applied throughout the entire year unlike ZFP method which can be applied only at certain times of the year

Limitations:

- ZFP technique cannot be applied during periods of high infiltration.
- ZFP technique is relatively expensive in terms of the required instruments and amount of data collection.
- Hydraulic conductivity of the soil is poorly known due to heterogeneity and varies with saturation.

<u>Techniques based on saturated zone studies</u>

Aquifer Response Analysis:

The response of the aquifer to recharge can be quantitatively investigated based on storage and flow concepts.

Storage concept - The response of the aquifer to recharge can be investigated both qualitatively and quantitatively. A qualitative analysis might involve the examination of water level hydrographs for evidence of e.g. summer recharge. Recharge can be estimated quantitatively from water level fluctuations using a relationship of the following form (Kruseman, 1997):

$$R = \Delta h.Sy + Qa + Ql \quad (5)$$

where R = recharge, Δh = change in water table elevation, Sy = specific yield, Qa = groundwater abstraction during the period under consideration, and Ql = the difference between lateral subsurface outflow and lateral subsurface inflow during the same period. It is similar to Water level fluctuation (WLF) method applied in GEC1997.

Flow rate concept - Another type of aquifer response analysis involves the estimation of groundwater recharge using the Darcy's equation. Under steady-state conditions, this gives a good approximation of recharge, provided there are reasonably reliable data on aquifer boundaries, hydraulic gradient and transmissivity.

The subsurface water flux (q) is calculated by multiplying the hydraulic conductivity by the hydraulic gradient. The hydraulic gradient should be estimated along a flow path at right angles to potentiometric contours. The volumetric flux through a vertical cross section of an aquifer (A) is equated to the recharge rate (R) times the surface area that contributes to flow (S):

$$qA = RS \quad (6)$$

The cross section should be aligned with an equipotential line.

Advantages:

- Considerably simple approach.
- Gives the response of recharge on water level.
- Readily available database regarding water level with the Central and State agencies.
- It can be applied on a watershed if groundwater abstraction data are available since in a watershed (in hard rock terrain) lateral inflow and outflow are negligible.

Limitations:

- Highly dependent on the estimation of aquifer parameters like specific yield, transmissivity etc. Slight changes in these parameters lead to considerable changes in the assessment.
- Accurate estimate of ground water abstraction is difficult to get in developing countries like India, in absence of direct measurement of ground water abstraction, various indirect methods are used for quantifying ground water abstraction.

Tracer techniques

Groundwater recharge can be estimated using both environmental (Cl) and applied tracers such as bromide, chlorofluorocarbons (CFCs) and tritium/ helium-3 ($^3H/^3He$), ^{18}O, visible dyes etc. The tracer techniques can be applied to identify ground water recharge from river and other water bodies based on surface water studies. It is also used in both unsaturated and saturated zones to estimate recharge. Lerner et al. (1990) separates the methods into **signature methods** and **throughput methods**.

Signature method - Applied tracers such as tritium are normally used whereby a parcel of water containing the tracer is tracked and dated. Piston flow is generally assumed in most tracer studies. However, tracers can be used to investigate flow processes, including the occurrence of preferential pathways.

In tritium injection technique, the moisture at certain depth in the soil profile is tagged with Tritiated water. The tracer moves downward along with the infiltrating moisture due to subsequent precipitation or irrigation. A soil core is collected from the injection site after certain interval of time and the moisture content and tracer concentration are measured from various depth intervals. The displaced position of the tracer is indicated by the peak in its concentration. Moisture content of the soil column, between injection depth and displaced depth of the soil core, is the measure of recharge to groundwater over the time interval between injection of Tritium and collection of soil profile.

Advantages:

- Applied tracer is a time marker due to its radioactive decay. It can be used to determine water ages.
- Can be used in arid and semi-arid regions where depth to water level is deep and recharge rate is slow.

Limitations:

- The recharge rate is not obtained directly by these methods, but has to be inferred or estimated from the velocities of soil-moisture or ground water movement.
- Require specialized instrumentation and skill.
- Some of the tracer studies are expensive and require a strict sampling procedure.

Throughput method - involve a mass balance of tracer, comparing the concentration in precipitation with the concentration in soil water below the ZFP or in groundwater.

Chloride is probably the most widely used environmental tracer for the *throughput method* (Hendrickx & Walker 1997, Wood 1999). The governing principle is that the amount of Cl into the system is balanced by amount of Cl out of the system for negligible surface runoff. This method is known as Chloride Mass Balance (CMB) method. The principle source of chloride in ground water, if there are no evaporite sources, is from the atmosphere. In this case, the recharge can be expressed as:

$$Ri = rainfall * Cl_{(rainfall)} / Cl_{(groundwater)} \qquad (7)$$

Where, Ri is the recharge from rainfall, $Cl_{(rainfall)}$ is choloride concentration in rainfall and Cl (groundwater) is the chloride concentration in groundwater. The chloride method is a flux method as it estimates directly recharge flux.

Advantages:

- It is particularly effective in arid zones where there is significant concentration through evaporation and also runoff is negligible.
- The method is cost effective and does not require sophisticated laboratories.

Limitations: The mass balance can be complicated by additional chloride inputs from decaying vegetation, localized run-in and from fertilizers, and by losses through dry precipitation and vegetation uptake.

Numerical modeling

Numerical groundwater modeling involves simulation of ground water flow equation in the specified spatial and time domain using discrete approach. Numerical groundwater model is a useful investigation tool for a number of applications including water balance.

Unsaturated-zone modeling is used to estimate deep drainage below the root zone and recharge in response to meteorological forcing. A variety of approaches is used to simulate unsaturated flow, including soil-water storage-routing approaches (bucket model), quasi-analytical approaches, and numerical solutions to the Richards equation (Scanlon et. al. 2002). Examples of codes that use unsaturated flow equations include UNSAT, VISUAL HELP etc.

UNSAT Suite

The UNSAT Suite Plus groundwater software is specifically designed to handle one-dimensional groundwater flow and contaminant transport in the unsaturated zone. This one dimensional model simulates the downward vertical flow of groundwater and migration of dissolved contaminants in the groundwater through a thin column of soil.

VISUAL HELP

Visual HELP is a hydrological modeling software available for modeling landfill hydrology and estimating groundwater recharge rates. It combines HELP model (Hydrologic Evaluation of Landfill Performance) with an interface and graphical features for designing the groundwater model and evaluating the modeling results.

Recharge can be estimated using inverse techniques through simulation of ground water flow in saturated zone. Knowing the boundary conditions, aquifer properties and head distribution, the numerical models can be used to estimate recharge. There are several numerical modeling codes available for unsaturated flow and saturated flow. MODFLOW, MIKE-SHE, SWAT are some of the examples.

MODFLOW

MODFLOW is the Modular three-dimensional finite-difference groundwater flow model originally developed by Michael G. McDonald and Arlen W. Harbaugh of USGS (1988). Because of its ability to simulate a wide variety of systems, its extensive publicly available documentation, and its rigorous USGS peer review, MODFLOW has become the worldwide standard groundwater flow model. MODFLOW is used to simulate systems for water supply, containment remediation and mine dewatering. Groundwater flow within the aquifer is simulated in MODFLOW using finite-difference or finite element approach. Layers can be simulated as confined, unconfined, or a combination of both. Flows from external stresses such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds can also be simulated.

MIKE-SHE

MIKE SHE is an advanced integrated hydrological modeling system. It simulates water flow in the entire land phase of the hydrological cycle from rainfall to river flow, via various flow processes such as, overland flow, infiltration into soils, evapotranspiration from vegetation, and groundwater flow.

MIKE SHE has been applied in a large number of studies world-wide at regional to local scale focusing on e.g., conjunctive use of surface water and ground water for domestic and industrial consumption and irrigation, dynamics in wetlands, and water quality studies in connection with point and non-point pollution.

Soil and Water Assessment Tool (SWAT)

'Soil and Water Assessment Tool' (SWAT) is a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the United States Department of Agriculture-Agricultural Research Service (USDA-ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemicals yields in large, complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2005). SWAT is a physical based model that requires specific information about meteorological parameters, soil properties, topography, vegetation, and land management practices occurring within the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, and others are directly modeled by SWAT using these input data. This technique has been extensively used in USA and Europe.

Advantages:

- Numerical modeling technique can be used for detailed estimation of groundwater recharge as well as for forecasting of future groundwater scenario.
- These techniques can generally be used to estimate any range in recharge rates.

Limitations:

- Models do not produce unique solutions, so should not be relied upon as a sole technique for estimating recharge.
- Reliability of these recharge estimates should be evaluated in terms of the uncertainties in the model parameters.
- This technique requires large number of datasets which are generally not available on a regional scale.

Some of the select methodologies mentioned above have been elaborated with case studies in Annexure I.

2.2 Application of various techniques for recharge estimation

Various techniques of recharge estimation have been widely applied under different climatic and hydrogeological conditions all over the world. A lot of literature is available on the application of these techniques for quantifying ground water recharge (Karanth, 1987, Simmers, 1988, Sharma, 1989, Lerner et. al. 1990, Scanlon et. al. 2002, Xu et. al., 2003, Kinzelbach, 2002 etc.).

Recharge estimation based on hydrograph separation was carried out extensively in eastern US (Scanlon et. al, 2002). Stable isotopes of oxygen and hydrogen are used to identify groundwater recharge from rivers and lakes in Wairau Plain and on the Canterbury Plains, South Island, New Zealand, Rhine river basin, Netherlands (Scanlon et. al. 2002). A wide variety of recharge rates has been measured using Lysimeters in Bunter sandstone and Chalk aquifers, England (Scanlon et. al. 2002). Soil moisture technique has been widely used in watersheds in North America, Europe and Israel (GEC-1997). Soil moisture technique has been applied in sandy aquifer of the island of Mannar, Sri Lanka for recharge estimation (Simmers, 1988). ZFP approach has been used in semi-arid region in Western Australia (Sharma et al. 1991). Mixing-cell models (compartment models, lumped models, and black-box models) have been used to delineate sources of recharge and estimate recharge rates on the basis of chemical and isotopic data in a large karst system in southern Turkey. Hydrochemical and isotopic data were used by Adar et al. (1992) to define a mixing cell model in the Arava Valley, Israel. Tracer techniques (both applied and environmental) have been widely used for recharge estimation in Australia (Sharma, 1989). Recharge characteristics of the aquifers were studied in arid zones in Western Arabia through environmental isotope technique using Oxygen-18, deuterium, tritium. In the small watersheds in the rain forest belt of Nigeria, three independent methods were used for comparative evaluation of recharge methods. The methods include – recharge estimation using water level and porosity, base flow recession analysis and water balance method. The results shows that recharge values obtained from water balance method were consistently higher than values from other methods. The methods can complement each other and to be used based on availability of data of parameters required for computations (Simmers, 1988). The CMB approach was originally applied in the saturated zone by Eriksson and Khunakasem (1969) to estimate recharge rates (30 to 326 mm/year) in the Coastal Plain of Israel. The CMB approach has been most widely used for estimating low recharge rates, largely because of the lack of other suitable methods. Water fluxes as low as 0.05 to 0.1 mm/year have been estimated in arid regions in Australia and in the US. The storage concept using water table fluctuation has been applied over a wide variety of climatic conditions (Scanlon et al., 2002). Recharge rates estimated by this technique range from 5 mm/year in the Tabalah Basin of Saudi Arabia (Abdulrazzak et al. 1989) to 247 mm/year in a small basin in a humid region of the eastern US (Rasmussen and Andreasen, 1959). Numerical modeling techniques have been widely used in Regional Aquifer System Analysis (RASA) by USGS for estimation of recharge.

The various techniques for recharge estimation have also been applied in different parts of India (Baweja & Karanth, 1980, Simmers, 1988, Karanth, 1987, Sharma, 1989, GEC-1997, Kumar, 1997, Chatterjee and Jha, 2006). Separation of base flow in a hydrograph has also been done by solving two simultaneous equations using the chemical quality (Ca/Na ratio) of water in Vedavati river basin project, Karnataka. Lysimetres were used in various water balance projects of Central Ground Water Board for estimation of evapotranspiration (Chatterjee and Jha, 2006). The method of soil moisture budget has been extensively used in water balance studies like Ghaggar project in Rajasthan, climatic water balance study in UNDP, Phase II, Rajasthan, water balance studies in uncropped and cropped deep vertisols and on deep and medium alfisols, Andhra Pradesh, ICRISAT, Hyderabad, studies in typical watersheds in Basaltic terrain, Maharashtra by GSDA, water balance studies in basalts and sedimentaries in Karnataka by Department of Mines & Geology, Karnataka (Baweja & Karanth, 1980) and climatic water balance study in Lakshadweep (CGWB, 2005). The saturated zone storage concept and Darcy's law has been widely used in various water balance projects of CGWB. The storage concept is also used in GEC-1997, the recommended methodology for the state wise estimation of dynamic ground water resources. The Chloride mass balance (CMB) approach was applied in the arid zones in India to estimate recharge e.g. in the Lathi basin, Western Rajasthan (Karanth et. al., 1980). The tritium injection technique was used by NGRI and NIH to estimate recharge rate in several basins all over India (GEC-1997). Numerical modeling techniques have been used for resources assessment in various water balance projects taken up by CGWB, NIH and other organizations (GEC-1997).

Past experiences on application of various methods for recharge estimation show that use of more than one method of recharge estimation is advisable considering the inherent uncertainties in each method. In many cases, different approaches complement each other and help to refine the conceptual model of recharge processes.

2.3 Application of Remote Sensing Technique for Ground Water Resources Assessment

Remote sensing systems provide information about different physical properties of the objects on the Earth's surface by recording reflected/emitted electromagnetic radiations in three regions of electromagnetic spectrum – (1) visible-near infrared-short wavelength infrared region, (2) thermal infrared region, and (3) microwave region. The most important aspect of remote sensing systems is that they provide spatially complete and temporal information about the state of the Earth's surface which helps hydrogeologists improve their understanding of the hydrogeological system, especially in remote and unexplored areas (Hoffmann and Sander, 2007). However, considering that the RS data have limitations with regard to depth penetration, the key for success in ground water investigations lies in understanding/establishing the linkage between surface manifestations (observed on remote sensing data) and the subsurface (ground water) phenomena (Jackson, 2002). This makes the hydrogeological interpretation/analysis as one of the most difficult tasks of all the hydrological applications of remote sensing (Farnsworth *et al.,* 1984). The best possible use of RS data (space-borne, air-borne as well as ground-based techniques), thus, can be made by combining them with field measurements, Geographical Information System (GIS) and numerical modeling (Becker, 2006; Meijerink *et al.,* 2007).

One of the traditional and main hydrogeological applications of remote sensing is in 'ground water exploration,' *i.e.* in delineating the favorable/target areas for follow-up ground-based hydrogeological and geophysical surveys (NRSA 2000, 2008; Hansmann *et al.,* 1992). The approach includes mapping of surface features of hydrogeological relevance – distribution of various lithologies, geologic structures, geomorphology, intrusions, present and past drainage systems, vegetation and surface soil moisture patterns during dry season (*e.g.* Waters *et al.*, 1990; NRSA 2000, 2008; Gupta, 2003). GIS-based spatial models are also commonly used nowadays for delineating favorable areas of ground water occurrence. In India, operational utilization of space-borne remote sensing data in ground water exploration was made by the Dept. of Space (DOS) in collaboration with State Remote Sensing Application Centers during 1987-90 period, wherein district-wise 'ground water potential maps' at 1:50,000 scale were prepared for the entire country (personal communication, Subramanian, 2009). Thereafter, under the Rajiv Gandhi National Drinking Water Mission (RGNDWM) project, initiated in late 1998 by the DOS, 'ground water prospects maps' at 1:50,000 scale are being prepared (NRSA 2000, 2008). The mapping work has been carried out in different phases. In the first two phases, 10 States [Andhra Pradesh (part), Chhattisgarh, Gujarat, Himachal Pradesh, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Orissa, Rajasthan] have been covered. Presently, the third phase is in progress, wherein another 10 States [Arunachal Pradesh, Andhra Pradesh (part), Assam, Jammu & Kashmir, Maharashtra, Punjab, Uttar Pradesh (part), Uttarakhand, West Bengal (part)] are being covered. About 83-95% success rate has been reported by the line Depts. of the State by making use of the RGNDWM maps while implementing the drinking water supply schemes from ground water resources (personal communication, Subramanian, 2009). Many other studies utilizing remote sensing and GIS techniques in ground water potential zoning have been carried out in India and abroad.

Besides ground water potential zoning, some other potential applications of remote sensing in hydrogeological research as reported in literature are following:

- *Mapping and monitoring the spatial distribution of ground water exfiltration and infiltration zones*. Combining the locations of ground water exfiltration with topographic maps and satellite-based DEMs can provide ground water head; however, 'quantifying the magnitude of flux is still a major challenge' (Becker, 2006).

- *Detection of buried channels and palaeo-drainage*. With the presently available sensors operating in microwave region, detection of buried channels is possible up to certain depth (a couple of meters) in hyper-arid conditions with absence of surface cover.

- *Mapping and monitoring of moist soils, swampy/waterlogged zones and vegetation, especially in dry period/climate*. Soil moisture is a key variable that controls partitioning of rainfall into infiltration, runoff, and evaporation (Kerr, 2007). Remote sensing data obtained in optical and thermal infrared regions are suitable for qualitative mapping of moist/swampy/waterlogged zones. The present configuration of microwave sensors, suitable for quantifying the soil moisture, provide only surficial information restricted to 0–2 cm (Wagner *et al.,* 2007) and to areas free of dense vegetation cover (Guntner *et al.,* 2007); coarse spatial resolution of microwave sensors (of the order of few kilometers) is another major constraint.

- *Mapping topographic attributes through satellite-based DEMs. S*tereo-satellite images and SAR Interferometry technique can be used to generate *digital elevation models* (DEMs). While the absolute accuracy of satellite-based (DEMs) is of the order of few meters, relative accuracy is quite good for obtaining certain topographic attributes which when combined with other remote sensing and ground observations provide further insights into understanding hydrogeological processes, e.g. ground water flow patterns, runoff-recharge processes, etc. (Scanlon *et al.,* 2002; Meijerink *et al.,* 2007). One major limitation of satellite-based DEMs is that they provide *digital surface model* (DSM) rather than *digital terrain model* (DTM). Laser Altimetry (or Lidar) has the capability to overcome this problem. The SRTM (Shuttle Radar Topographic Mission) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEMs having 90m and 30m spatial resolutions, respectively, are available in public domain, and can be used to map the runoff and recharge areas based on the guidelines recommended in the GEC (1997) methodology.

- *Site selection for artificial ground water recharge structures.* The lithological, structural, geomorphological, and hydrological factors mapped using remotely sensed data and ancillary information can be integrated for suggesting the type and tentative locations of artificial recharge structures.

- *Using remote sensing data-derived inputs for mapping recharge patterns*. Remote sensing data in conjunction with ground surveys can be used for mapping the parameters controlling the recharge processes (such as geomorphology, lithology, structure, land use/ land cover, slope, soil, drainage, etc) which in turn can be used as inputs for mapping and quantifying the recharge patterns and rates. For example, the land use/land cover and soil maps along with DEMs can be used as inputs in water balance models for estimating recharge as a residual term in the soil water budget equation as discussed earlier. Similarly, parameters controlling the recharge processes can be integrated to derive relatively homogeneous spatial units. The spatial distribution of such homogeneous spatial units provides recharge patterns or relative recharge potential zones (Meijerink, 1996; Reddy 2000; Shaban *et al.,* 2006; Meijerink *et al.,* 2007). With this assumption, point estimates of recharge made using conventional methods can be used to generate areal/distributed recharge maps (*e.g*. Brunner *et al.* 2004; Lubczynski and Gurwin, 2005). In the GEC (1997) methodology, appropriate values of specific yields/ infiltration factors may be provided to such relatively homogeneous spatial units, instead of using only lithology-dependent values, for improving the recharge estimates. The availability of specific yields/ infiltration factors at sufficient number of places may, however, be a constraint. In essence, the remote sensing data have the potential to provide inputs for determining patterns of relative recharge, which can be transformed into an absolute recharge map either by regionalizing the actual measurements at point-scale, or by model calibration.

- *Mapping localized recharge sources*. The spatial and temporal information provided by the remote sensing data can be used to have up-to-date information about the spatial distribution of surface water bodies, streams/tanks/reservoirs, which can be used to estimate the recharge resulting through seepage from such localized sources.

- *Mapping spatio-temporal patterns of ground water use*. Remote sensing data provide information on areal extent of ground water irrigated crops. This information along with appropriate crop coefficients, meteorological parameters and water application efficiency can be used to estimate the crop/irrigation water requirement. Alternatively, field-based information on the quantum of water applied by the farmers for irrigation can be used along with satellite-based crop acreage data to estimate crop/irrigation water requirement. In non-command areas, the total crop water requirement can be approximated as *net ground water draft* (total pumped quantity minus return flow to ground water) for irrigation (Meijerink *et al.,* 2007; Reddy *et al.,* 1998). Remote sensing data obtained in optical and thermal infrared regions of electromagnetic spectrum can also be used along with meteorological data to estimate spatio-temporally distributed *actual evapotranspiration* (AET) rates (*e.g.* Bastiaanssen *et al.,* 1998), a measure of crop consumptive use (Mo *et al.,* 2005). The magnitude of this flux, however, has certain uncertainties and needs to be calibrated (Lubczynski and Gurwin, 2005); nevertheless, the spatial patterns of ground water use can be obtained. The availability of area-specific crop coefficients, uncertainty in the water application efficiency, cloud cover during kharif season are some of the limitations.

- *Detecting and mapping subtle changes in land surface elevation due to ground water withdrawal or recharge*. Differential radar interferometry (D-InSAR) technique is used for this purpose (*e.g*. Chatterjee *et al.,* 2007). It can detect the changes in land surface elevation of the order of fraction of wavelength (5–10 mm in the line-of-sight; Galloway and Bawden, 2006). The limitations, however, are low availability of suitable InSAR images, and temporal decorrelation of radar signal due to change in land cover and atmospheric conditions.

- *Mapping discharge of ground water into rivers, lakes and sea*. Possibility of detection of such phenomena depends on temperature contrast and quantum of ground water discharge; however, quantification of flux is a major challenge.

In the context of country-wide assessment of ground water resources on an operational basis at a reasonable scale, remote sensing data can be utilized to provide/refine certain inputs (such as runoff and recharge areas, sources of localized recharge, spatial recharge patterns or relative recharge potential zones, crop consumptive use patterns, and other terrain related information) required in the GEC (1997) and other methods of ground water resource estimation.

2.3.1 GRACE mission for monitoring terrestrial water storage

The Gravity Recovery and Climate Experiment (GRACE) mission is a unique Earth Observation System launched by NASA and the German Aerospace Centre (DLR) in March, 2002. The mission is aimed at mapping temporal variations in Earth's gravity field which can be used for quantifying seasonal and inter-annual variations in *terrestrial water storage* (TWS). GRACE consists of twin identical satellites, separated from each other by about 220 km, which encircle the Earth in near-circular polar orbit at about 500 km altitude covering the entire globe in a span of 30-days. The basic principle is that the spatio-temporal variations in mass distribution on the Earth induce change in the relative distance between two satellites, which are precisely measured through a microwave ranging system and are in turn used to map the gravity field. These spatio-temporal variations of Earth's gravity field are then processed using certain numerical models to quantify seasonal and inter-annual variations in TWS (Guntner *et al.,* 2007).

The changes in TWS observed by GRACE consist of contributions from different components, such as ground water, surface water, soil moisture, snow and ice, and biomass. The separation of ground water contribution from other components of TWS is a major challenge, and is done using *in situ* observations and land surface/hydrological modeling (Rodell *et al.*, 2009; Tiwari *et al.*, 2009). Several studies have been carried out in large basins in recent years to estimate ground water storage changes – including the High Plains Aquifer, the Mississippi River basin, the Amazon River Basin, and Northern India (Strassberg *et al.*, 2007; Rodell *et al.*, 2007; Zeng *et al.*, 2008; Rodell *et al.* 2009; Tiwari *et al.* 2009). Recently, Rodell *et al.* (2009) and Tiwari *et al.* (2009), based on GRACE observations and hydrological simulations, reported a significant ground water depletion in Northern India. According to Rodell *et al*. (2009) 'ground water is being depleted at a mean rate of 4.0$\pm$1.0 cm/yr equivalent height of water (*i.e.* 17.7$\pm$4.5 km^3/yr) over the Indian States of Rajasthan, Punjab and Haryana (including Delhi), corresponding to a net loss of 109 km^3 of water between August 2002 and October 2008.' Tiwari et al. (2009) reported 'ground water loss at a rate of 54$\pm$9 km^3/yr between April 2002 and June 2008 in Northern India.'

Accuracy estimates for interannual and seasonal water storage variations are of the order of 9 mm (at 1300 km resolution) and 10–15 mm (for area >2 million km^2) water equivalent, respectively (Guntner *et al.,* 2007). The coarse resolution of GRACE data limits its applicability to study ground water dynamics for regions larger than (>900,000 km^2, i.e. at basin/continental/global scale (Guntner *et al.* 2007; Rodell *et al.,* 2007).

3. Ground water resources assessment in India – present perspective

3.1 Existing Methodology for Ground Water Resources Assessment in India - GEC – 1997

As enumerated in the beginning of the report, a methodology for State-wise ground water resources assessment for the entire country has been formulated by a committee of experts drawing members from CGWB, NABARD, State Ground Water Departments, and academic and research institutes. The governing principle of the methodology is the water balance approach which involves estimation of annual ground water recharge and quantification of ground water extraction. The assessment units are categorized based on the percentage of ground water withdrawal to net ground water availability and long term water level trend.

Ground water recharge is estimated season-wise and source wise. Rainfall recharge during monsoon season is estimation by two methods – Water Level Fluctuation (WLF) method and Rainfall Infiltration Factor (RIF) method. In WLF method, specific yield is determined either through field studies or using norms recommended by GEC-1997. In case of RIF method, norms have been recommended for major lithological units of the country. Recharge from other sources like canal seepage, return flow from irrigation, recharge from water bodies and tanks/ ponds are estimated using norms recommended by GEC-1997. In case of rainfall recharge during non-monsoon period, RIF method is used.

Ground water draft is estimated using – (a) unit draft method or (b) cropping pattern method.

Monsoon recharge is estimated based on the following governing equation

$$R = S + Dg \quad (8)$$

Where,
R = possible recharge, which is gross recharge minus the natural discharges in the area in the monsoon season
S = Groundwater storage increase
Dg = Gross Groundwater draft during monsoon season

The ground water recharge from monsoon rainfall is normalized for normal monsoon rainfall. The total recharge during the monsoon season for normal monsoon season rainfall condition is obtained as,

$$R(normal) = Rrf\ (normal) + Rc + Rgw + Rsw + Rwc + Rt \quad (9)$$

Where,
R(normal) = total recharge during normal monsoon season
Rrf = rainfall recharge during monsoon season for normal monsoon season rainfall
Rc = recharge due to seepage from canals in the monsoon season for the year of assessment
Rsw = recharge from surface water irrigation in the monsoon season for the year of assessment
Rgw= recharge from ground water irrigation in the monsoon season for the year of assessment

Rwc= recharge from water conservation structures in the monsoon season for the year of assessment
Rt = recharge from tanks and ponds in the monsoon season for the year of assessment

Similarly, estimation of normal recharge during non-monsoon season is carried out by adding normal non-monsoon rainfall recharge and recharge from other sources during non-monsoon period.

Total annual recharge or annual replenishable ground water resources is the addition of normal recharge during monsoon and non-monsoon seasons.

From annual ground water recharge, Net annual ground water availability is arrived at after keeping an allocation for natural discharge during the non-monsoon season which is about 5 to 10% of the annual recharge.

Stage of ground water development is as follows

$$Stage\ of\ ground\ water\ development = \frac{Annual\ gross\ ground\ water\ draft}{Net\ annual\ ground\ water\ availability} \qquad (10)$$

3.2 Review of GEC-1997

The estimations carried out using the existing methodology in general holds good in most of the cases. However, in some cases, the block level assessment may not match with the field situations in localized areas within the block because of heterogeneity and complexity of hydrogeological setup of the area. Any large scale ground water management programmes should be contemplated based on micro-level hydrogeological studies of the area.

There is an urgent need for further refinements of norms used in recharge and discharge estimations like specific yield, rainfall infiltration factor, canal seepage factor, return flow from irrigation, unit draft etc.

There is also considerable scope for refinement in the ground water estimation by strengthening the database used for resources estimation. The data elements include water level, canal irrigation details, ground water withdrawal details etc.

Though groundwater resources are to be estimated at periodical intervals, the process of groundwater assessment is a **continuous one**. The time period in between two successive assessments needs to be devoted for strengthening of database and field validation of the estimated results. In order to facilitate continuous refinements in the resources estimation and with an objective to define the procedure for groundwater resources assessment, a ***protocol for ground water resources assessment*** has been suggested in Annexure II.

3.3 Aquifer mapping of the Country

Mapping of aquifer systems is of utmost importance for proper assessment of the ground water resources in a region. At present, two dimensional hydrogeological map of India is available on 1: 2,000,000 scale. The map has incorporated the database generated through hydrogeological surveys, investigations, explorations and hydrogeochemical studies undertaken by CGWB.

There is a requirement for mapping the three dimensional aquifer geometry of the regional aquifer systems of the country. 3-D aquifer mapping refers to collection and collation of subsurface lithological information in terms of their vertical and horizontal extension and water bearing properties including quality of formation water.

Techniques used for aquifer mapping can be broadly grouped under two categories

i) Direct methods
ii) Indirect methods

Direct methods

Direct methods involve the proven techniques of drilling of borewell/ tubewell, which provide the point information of disposition of various aquifer units and their geometry. The same is being accomplished through ground water exploration program of CGWB, followed by subsurface geophysical logging to confirm the aquifer disposition and water bearing strata as well as ascertaining the ground water quality in the aquifer.

Indirect methods

Indirect aquifer mapping techniques includes -

- Surface electrical resistivity method
- Seismic refraction/reflection method
- Aeromagnetic method
- Electro-magnetic surveys
- Ground Penetrating radar (GPR) – for shallow aquifer

All the above techniques are applied to get the geophysical anomalies of underlying formation which are correlated with the water bearing properties of rock units and the geochemical characteristics of ground water contained in various formations. The depth of penetration as well as the applicability of various techniques of groundwater varies widely for different hydrogeological environs. For example, seismic refraction methods are best suited in hard rock areas to map the deep seated bed rock topography. Resistivity Imaging is the latest geophysical technique available for obtaining 3-D aquifer geometry of the underlying formations in the area of study.

The advanced geophysical techniques as listed above are comparatively fast as well as the area of coverage is much more as compared to direct method of drilling. In the Indian scenario, such techniques have been used only in isolated project areas, however, the efficacy of these techniques on a larger scale need to studied in detail in collaboration with other developed countries having better experience in the application of these techniques for aquifer mapping.

Once the point informations of the underground aquifer systems are obtained through above methods, these are required to be synthesized, correlated and interpolated to obtained 3-D images. Several commercial software packages such as Rockworks, 3-D Imaging, 3-D Analyst, etc. are available, which can generate a 3D surface form the point data collected during drilling and geophysical informations through various interpolation/extrapolation techniques. The ultimate outputs of the above exercise are cross-sections, fence diagrams and 3D aquifer maps.

4 Recommendations

Based on the review of the various techniques of recharge estimations being practiced in the country and abroad, prevailing hydrogeological settings across the country and availability of data/ informations required for various recharge estimation techniques, following recommendations are made.

- The recharge estimation technique adopted in **GEC-97 is appropriate and suitable for country-wide groundwater resources estimation**, considering the present status of database available with the Central and State agencies.

- Groundwater resources assessment should be done under the supervision of the **State level Committee** following the **protocol** enumerated in Annexure II.

- Groundwater resources estimation is a continuous process and therefore there is an urgent need to **setup Groundwater Resources Assessment Cell** in each State Ground Water Department with dedicated manpower for continuous updation of database like water level, canal details, well census etc., periodical groundwater resources assessment, field validations of the estimates and refinements of norms for various parameters like specific yield, rainfall recharge / infiltration factor, canal seepage factor, recharge factor from irrigation, unit ground water draft etc.

- The **parameter estimation** should be taken up in *project mode* by CGWB and State agencies in collaboration with academic / research institutes.

- **Regional Aquifer System Mapping** of the country needs to be taken up in a phased manner. In the first phase, aquifer mapping of Indus-Ganga-Bhramhaputra basin needs to be taken up. This should be followed by other alluvial basins and hard rock aquifers of the country.

- **Remote sensing data** can be utilized to provide/refine the inputs (such as runoff and recharge areas, sources of localized recharge, spatial recharge patterns, crop consumptive use patterns, etc.) for recharge assessment depending upon the requirement and applicability. In addition, **GRACE mission** data can be used for regional scale assessment of ground water storage changes in select basins.

- Following methods are recommended as **complimentary methods for application** in various hydrogeological setup in the country –

    - Soil moisture (Thornthwaite's Book keeping method) technique can be applied in semi-arid and humid parts of the country. For humid areas, monthly balancing is sufficient. But for semi-arid regions, weekly balancing will be more preferable. Available spreadsheets for the method can be readily used.
    - Applied tracer technique can be used for semi-arid and humid agro-climatic regions of the country.
    - Chloride Mass Balance can be applied in arid and semi-arid regions.

- Application of various **alternate methods for recharge assessment** as enumerated in the previous point be taken up in *project mode* by academic/ research institutes under **R&D scheme of MOWR**.

- **Water Balance projects** be taken up in *project mode* in select basins across the country having different hydrogeological setups through collaborations of organizations like CGWB, State Ground Water Departments and other agencies/ institutes. A combination of various methods including base flow method, soil moisture balance (numerical approach), lysimetric studies, storage and flow rate concept, ground water flow (numerical) modeling techniques etc. to be applied in these water balance projects.

- Regular **interaction and bilateral programmes with International Agencies** are required for keeping updated on the state-of-art of the subject and also on the technology involved in Ground Water Resources Assessment. Some of the premier International Institutions working in the field of ground water estimations are –

    - USGS, USA
    - British Geological Survey, UK
    - IHE, Delft, the Netherlands.
    - Colorado School of Mines, Colorado, US
    - International Ground Water Modeling Centre, UK
    - Centre for Ground Water Studies, Flinders University, Australia.
    - NASA, USA
    - Zuckerberg Institute for Water Research (ZIWR), Israel
    - The Geophysical Institute of Israel, Israel
    - International Groundwater Resources Assessment Centre (IGRAC), Utrecht, The Netherlands
    - Swedish International Development Agency, Stockholm

It is recommended that **project mode activities suggested in the earlier points can be taken up in collaboration with the above mentioned International agencies**.

- The findings of the various projects/ R&D studies related to ground water resources estimation as recommended above be reviewed by the standing committee namely **R&D Advisory Committee on Ground Water Estimation** for further refinements in the assessment methodology.

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ANNEXURES

Annexure I

Estimation of Ground Water Recharge using Stream Base flow Method – A Case example of Asan Watershed, Western Doon Valley, Uttarakhand

Period & Investigator:, S.K. Srivastav, Scientist 'SF', IIRS (NRSC), Dehradun

Area: The watershed of Asan River in the western segment of Dehra Dun Valley (popularly known as Doon Valley) of Uttarakhand State

Methodology:

The base flow component of the stream hydrograph (a graphical representation of discharge as a function of time) of Asan River has been separated using digital filtering method. The discharge data of Asan River for 10 hydrologic years (June 1997 to May 2007), obtained from Uttarakhand Jal Vidyut Nigam Limited, have been used for this purpose. The gauging site is located at the outlet point of the watershed, which is just upstream of the confluence of Asan River with Yamuna River. Two digital filters, namely Eckhardt filter (developed by Eckhardt, 2005) and BFLOW filter (developed by Lyne and Hollick, 1979), have been used through an automated Web Based Hydrograph Analysis Tool (WHAT; developed by Lim et al., 2005). The Eckhardt filter used for base flow separation in WHAT is given as:

$$b_t = \frac{(1 - BFI_{max})*\alpha + b_{t-1} + (1 - \alpha)*BFI_{max}*Q_t}{1 - \alpha*BFI_{max}} \qquad (1)$$

where b_t is the filtered base flow at the t time step; b_{t-1} is the filtered base flow at the t–1 time step; BFImax is the maximum value of long-term ratio of base flow to total stream flow; α is the filter parameter; and Q_t is the total stream flow at the t time step. In the present study, BFI_{max} is assumed as 0.80 as recommended by Eckhardt (2005) for perennial streams with porous aquifers; and α is taken as 0.999 by iterative method based on visual inspection of base flow curve.

The BFLOW filter, developed by Lyne and Hollick (1979), used for base flow separation in WHAT is given as (Lim et al., 2005):

$$q_t = \alpha* q_{t-1} + \frac{(1 + \alpha)}{2} * (Q_t - Q_{t-1}) \qquad (2)$$

where q_t and q_{t-1} are the filtered direct runoff at t and t–1 time step, respectively; α is the filter parameter; and Q_t and Q_{t-1} are the total stream flow at t and t–1 time step, respectively. In the present study, α is taken as 0.998 by iterative method based on visual inspection of base flow curve.

Findings:

The Asan River a tributary of Yamuna River, is a perennial stream. The annual flow in Asan River consists of both direct runoff and base flow. The stream flow during the post-monsoon period (i.e. November to May) consists of base flow generated from the piedmont zone (main aquifer system) only, since in this period the base flow from the hills/mountains are essentially diverted to the piedmont zone through canals for irrigation, which in turn recharges the aquifer by means of return flow. Thus, the estimation of base flow is highly valuable for estimating the ground water recharge in the main piedmont aquifer system.

The stream hydrograph and base flow curve obtained using Eckhardt filter is shown as example in Fig. 1. A summary of base flow estimates obtained using the Eckhardt and BFLOW Filters is presented in Table 1. The estimated base flow during non-monsoon period (November to May, average of 10 hydrologic years mentioned earlier) as obtained using two filters ranges from 257.72 to 270.16 MCM/y (million cubic meters per year), the average being about 263.94 MCM/y. Whereas, in the monsoon period (June to October, average of 10 hydrologic years as mentioned earlier), it ranges from 235.17 to 259.82 MCM/y, the average being about 247.5 MCM/y. The annual base flow (i.e. monsoon base flow + non-monsoon base flow) ranges between 505.53 and 517.54 MCM/y, the average being about 511.44 MCM/y. Since in the monsoon period, hilly/mountainous parts of the watershed also contribute to the total base flow of Asan River, therefore, the minimum annual base flow contribution from the main piedmont aquifer system has been estimated assuming that the minimum base flow rate in the monsoon period will be at least same as that of the non-monsoon period (i.e. 14.07 m^3/s for Eckhardt filter and 14.41 m^3/s for BFLOW filter). With this assumption, the minimum average annual base flow from the piedmont aquifer system is estimated to range between 443.72 and 465.14 MCM/y (average of about 454.43 MCM/y).

Table 1. A summary of base flow estimates obtained using digital filtering methods of hydrograph separation. Stream discharge data of 10 hydrologic years (June 1997 to May 2007) are used.

S.No.		Base flow (MCM/y)		
		Eckhardt Filter	BFLOW Filter	Average
1.	Base flow during non-monsoon period	257.72 (14.07 m^3/s)	270.16 (14.75 m^3/s)	263.94 (14.41 m^3/s)
2.	Base flow during monsoon period	259.82 (19.65 m^3/s)	235.17 (17.79 m^3/s)	247.5 (18.72 m^3/s)
3.	Annual Base flow (i.e. monsoon + non-monsoon)	517.54 (16.41 m^3/s)	505.33 (16.02 m^3/s)	511.44 (16.21 m^3/s)
4.	Minimum Annual Base flow (assuming that minimum base flow rate in the monsoon period to be at least same as that of the non-monsoon period)	443.72 (14.07 m^3/s)	465.14 (14.75 m^3/s)	454.43 (14.41 m^3/s)

MCM/y – million cubic meters per year; m^3/s – cubic meters per second

Assuming the ground water abstraction through wells and evapotranspiration to be negligible, the above estimated average baseflows can be regarded as ground water recharge in the area.

References:

Eckhardt, K. 2005. How to construct recursive digital filters for base flow separation. Hydrol. Process., 19(2): 507–515.

Lim, K.J., Engel, B.A., Tang, Z., Choi, J., Kim Ki-Sung, Muthukrishnan, S. and Tripathy, D. 2005. Automated web GIS based hydrograph analysis tool, WHAT. Jour. Amer. Water Resour. Ass. (JAWRA), 41(6): 1407–1416.

Lyne, V. and Hollick, M. 1979. Stochastic time-variable rainfall-runoff modeling. In: Proc. Hydrol. and Water Resour. Symp., Inst. of Engineers Aust. Natl. Cong. Publ. 79/10, Perth, Australia, pp. 89–93.

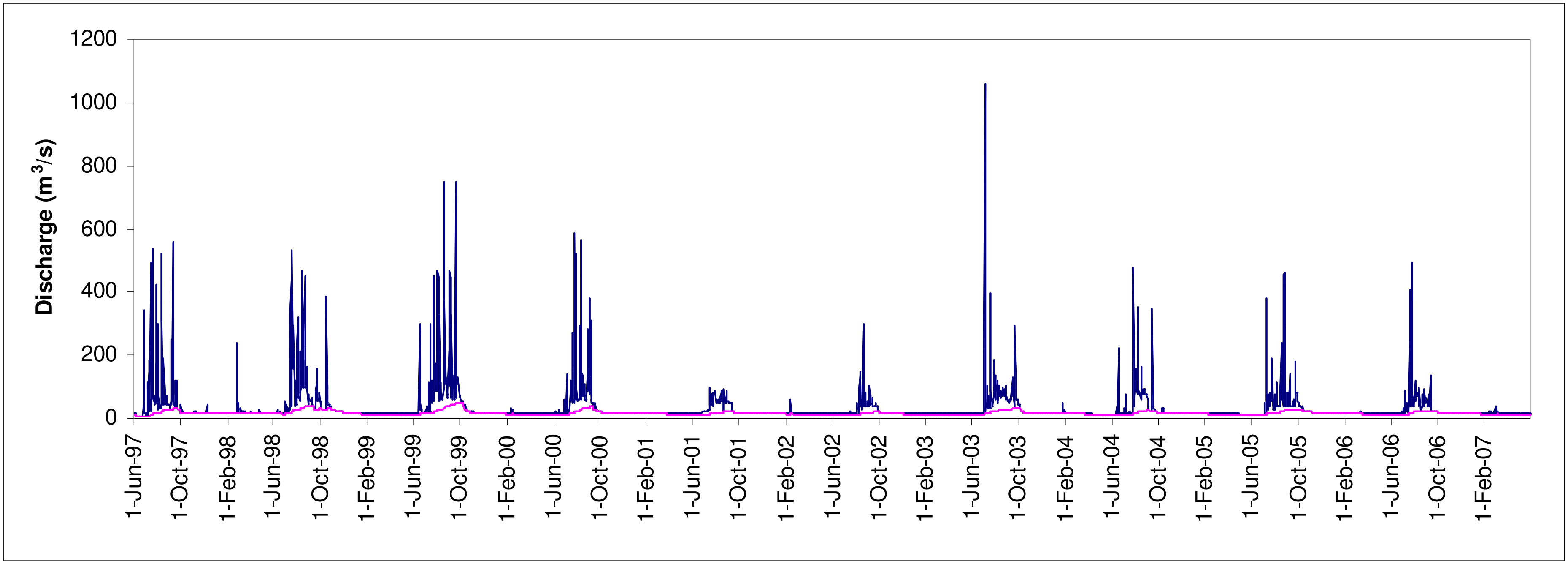

Fig. 1. Base flow (pink color) separation from stream hydrograph (blue color) using Eckhardt filter. The area below the pink line represents the base flow and that between the pink and blue lines represents the direct runoff.

Chloride Method in the Unsaturated Zone – Case study of North East Nigeria, Africa

Period & Investigator: 1992, Ibrahim Baba Goni

Area: North East Nigeria, Africa

Methodology/ Procedure:

In the steady state, the water balance equation used for Chloride technique is given as:

$$Rd = (PCp + Fd)/Cs \quad (1)$$

Where, Rd is the direct recharge flux, P is the long term average annual precipitation, Cp is the concentration of the reference solute in the rainfall, Fd is the net dry deposition fluxes, and Cs is the concentration of the reference solute in the deep interstitial water. If Fd = 0, the fraction of the rainfall contributing to direct recharge is simply given by the ratio Cp/Cs.

In this procedure, mean rainfall is estimated. Chloride concentration in rainfall is analyzed and weighted mean chloride concentrations in rainfall over a minimum of three years for the area are calculated.

Unsaturated zone soils samples were obtained at regular intervals through auguring or other dry drilling techniques. Samples over each interval were mixed and homogenized in a plastic bag and then sub-sampled into a tight container. Care was taken to minimize evaporation loss in this process. Moisture content is measured gravimetrically (by weighing before and after drying), and chloride is determined on samples obtained either by centrifugation or elutriation. Chloride concentration in dry deposition and water samples in water saturated zones were analyzed.

Findings:

Estimated rates of recharge for the seven profiles in the unsaturated zone range from 11 to 22 mm/year (Table 1). Using the concentration of chloride from the saturated zone of 16 mg/l, the same annual rainfall and chloride concentration in rainfall, a rate of 21 mm/year has been estimated. This shows that most of the recharge to the groundwater in the region is from rainfall, with little lateral recharge. Timescales represented by the profiles range from 26 to 71 years, resulting from textural variability.

Table I Unsaturated Zone Profiles and Recharge Estimates from Northeast Nigeria

Profile	Depth (m)	No. Samples (n)	Mean Cl (Cs) (mg/l)	Mean annual recharge RD (mm/year)	Residence time (years)
GM 1	15.50	51	14.1	22.03	35
KA 1	14.75	50	18.3	12.32	40
MD 1	22.50	65	11.5	11.34	71
MN 1	16.50	53	41.6	19.90	32
N-TM	18.75	58	11.7	18.88	52
W-Wgg	19.25	60	18.6	20.28	42
MG	16.26	53	20.7	20.71	26

References:

Goni, Ibrahim Baba. 2002. Chloride Method in the Unsaturated Zone. In 'A Survey of Methods for Groundwater Recharge in Arid and Semi-arid regions'. UNEP.

Cook P.G., Edmunds W.M. and Gaye C.B. 1992. Estimating palaeorecharge and palaeoclimate from unsaturated zone profiles, Water Resource. Res, **28**: p. 2721-2731.

Chloride Mass Balance Method in Saturated Zone – Case study from Western Rajasthan, India

Period & Agency/s involved: 1980, Central Ground Water Board

Area: Lathi basin, Rajasthan

Methodology/ Procedure:

It is assumed that in desert regions, there is a constant movement of salt loaded in wind and dust and therefore it does not enter into the salt balance of soil to any significant degree and that it enters the soil only through precipitation. Therefore, it implies that evaporation causes the soil water to get enriched in dissolved salts which reach the water table whenever there is a surplus water. Under these conditions, rainfall infiltration can be determined from the relative concentrations of stable ions, like chloride present in precipitation and ground water.

$$Pi = \frac{Clp}{Clgw} \quad (1)$$

Where Pi is rainfall infiltration, in per cent
Cl_p is Chloride content in rainwater
Cl_{gw} is chloride content in ground water

Findings:

The average chloride content in rainfall in the Lathi basin is about 4 ppm. The chloride content in groundwater in the recharge area of the Lathi basin ranges from 100 to 150 ppm. From these, the rainfall infiltration was worked out as 3 to 4 per cent. Estimation by this method was found to tally with the recharge values obtained by other methods.

References:

Karanth, K.R., Mehta, M and Jati, K.K. 1980. A Reappraisal of ground water recharge in the Lathi basin, Rajasthan. *Report of Central Ground Water Board, New Delhi.*

Application of Tritium technique for recharge estimation – Case study from Vedavati basin, Karnataka, India

Period & Agency/s involved: 1978, NGRI, Hyderabad

Area: West Survarnamukhi sub-basin, Vedavati basin having an area of 958 km., covered with granite, gneisses, and schists.

Methodology/ Procedure:

The injected Tritium technique was used for estimation of recharge from monsoon precipitation to the phreatic aquifers. In this study, Tritium was injected at 20 sites, well distributed over the basin. Tritium injections were made before the onset of the monsoon. At each injection site, 125 micro-curies of Tritium, contained in 12.5 ml of water were injected at the bottom of a cluster of 5 holes having a depth of 80 cm in the soil profile. The cluster of holes occupies a diameter of 10 cm, with each hole having diameter of 1.25 cm. The holes were back-filled with soil and the injection site was pinpointed with reference markers and triangulation. Vertical soil profiles, down to a depth of 2 to 2.5m, were collected from each site, after the cessation of monsoon season, with a sampling depth interval of 20 cm. The samples were weighed and packed in polythene bags in the field.

About 25 gm of soil from each sample was used for determination of the moisture content, using an Infra-red torsion balance. Moisture from the rest of the soil sample was extracted through partial vacuum distillation. 4ml of the distillate, representing moisture from each 20 cm interval, was used in determining the Tritium activity. The water sample was mixed with 10 cc of the liquid scintillator 'Instagel' in a low potash vial and the vial was kept overnight for dark-setting. The Tritium activity of each vial sample was counted on a manually operated liquid scintillation spectrometer model LSS-20.

The variation of Tritium content and weight percentages of moisture was plotted against depth in the case of the soil profile collected at each site. The spot value of recharge for each site was calculated by first determining the centre of gravity of the Tritium vs. depth profile. The mean displacement of the tracer was taken as the distance between the injection depth and the depth of the centre of gravity. The recharge was calculated from the moisture concentration, tracer displacement and wet bulk density for each site.

Findings:

The arithmetic mean of the recharge values for the entire region was estimated at 39.2 mm. The average monsoonal rainfall, recorded at three rain gauging stations in West – Suvarnamukhi basin, for the period June-November, 1978, was 463 mm. The mean recharge of 39.2 mm, thus amounts to 8.5% of the seasonal precipitation. Taking the effective infiltration area of the sub-basin as 958 sq. km., the average input to the phreatic aquifers, due to direct infiltration of a fraction of the monsoonal precipitation, then works out to be 39.2 mm x 958 sq. km. = 37.6 Million Cubic Meters (MCM).

Reference:

Muralidharan, D., Athavale, R.N. and Murti, C.S. 1988. Comparison of recharge estimates from injected tritium technique and regional hydrological modeling in the case of a granitic basin in semi-arid India. In I.Simmers (ed.) Estimation of Natural Groundwater Recharge. 175-194.

Soil-moisture Balance – Thornthwaite's method – a case study from Kota, Rajasthan

Period & Agency/s involved: 1975, Central Ground Water Board

Area: Kota, Rajasthan

Methodology/ Procedure:

Groundwater recharge can be estimated by the soil-moisture balance approach. The soil-moisture balance for any time interval can be expressed as:

$$P = AE + I + R + Sm$$

Where,
P = rainfall, AE= actual evapotranspiration, Sm = change in soil moisture storage, I= Infiltration, R= surface runoff

In Thornthwaite's (1945) book-keeping method of soil moisture balance, measurements of field capacity and wilting point are to be made to determine the available moisture down to the root zone. Monthly PET and rainfall are tabulated and compared. If rainfall P in a month is less than PET, then AE is equal to P, the period being one of water deficit. If the rainfall is more than PET, the AE = PET, the balance of rainfall raising the moisture level of the soil to field capacity. After meeting the soil-moisture deficit, the excess of rainfall over PET becomes the moisture surplus, also called water surplus. The saturated soil makes available moisture for evapotranspiration if the rainfall is below the PET. The soil moisture is continuously depleted till it reaches wilting point if there is no further rainfall. If any soil moisture is left at the end of the calendar year (or water year), it is carried over to the next year.

The moisture surplus results in surface runoff and recharge to the groundwater body. The runoff can be determined by gauging at the basin outlet, or estimated from the rainfall-runoff curves. The difference between the moisture surplus and runoff gives the ground-water recharge.

Month-by month balancing suits humid and sub humid regions with high rainfall amounts distributed uniformly throughout the month. In arid and semiarid regions, rainfall is mostly of a stormy nature with short wet spells and long dry spells in between. While monthly rainfall is mostly less than monthly PET, in short wet spells the rainfall amount exceeds PET. In these cases, balancing is required to be done on a short period basis, say weekly, or in extreme arid areas, daily. The monthly balancing method can be adopted for weekly balancing also, but daily balancing becomes a laborious and time-consuming process.

Findings:

Table 1 Monthly water balancing by Thornthwaite method for Kota, Rajasthan for the year 1975

Soil Moisture at field capacity: 150.0 mm

Items	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
Rainfall in mm	9.0	12.0	-	1.0	36.0	105.0	186.0	217.0	169.0	1.0	115.0	-	851.0
PET In mm	61.6	80.3	131.4	166.9	225.0	210.3	138.6	120.6	133.3	122.4	75.4	58.3	1524.7
AET In mm	9.0	12.0	-	1.0	36.0	105.0	138.6	120.6	133.3	122.4	75.4	58.3	811.6
Moisture surplus in mm									29.5				29.5

PET = potential evapootranspiration
AET=actual evapotranspiration

Note: The above example has been given for illustration purpose. Ideally for semi-arid & arid regions, weekly water balancing should be carried out.

Reference:

Karanth, K.R. 1987. Ground Water Assessment, Development, and Management. Tata McGraw-Hill Publishing Company Ltd. New Delhi.

Satellite-based estimates of groundwater depletion – Case study of North Western India

Period & Investigators: Period of study - August 2002 to October 2008. Matthew Rodell, NASA Goddard Space Flight Center, Maryland, USA, Isabella Velicogna, & James S. Famiglietti University of California, USA.

Area of Study: The study area encompasses - Rajasthan (342,239 km^2), Punjab (50,362 km^2) and Haryana (45,695 km^2 including the National Capital Territory of Delhi).

Methodology/ Procedure:

The Gravity Recovery and Climate Experiment (GRACE) satellite mission, launched by NASA and the German Aerospace Centre (DLR) in 2002, measures temporal variations in the gravity field, which can be used to estimate changes in terrestrial water storage (TWS). TWS variations observed by GRACE include the combined contributions of groundwater, soil water, surface water (lakes, rivers, canals and rice paddies), snow, ice and biomass.
73 monthly GRACE gravity field solutions generated by the Center for Space Research at the University of Texas at Austin were used in the study.
Gravitational anomalies are filtered and converted into mass in units of equivalent water thickness.
GRACE mass anomalies are corrected for the solid - Earth contributions generated by the high-latitude Pleistocene deglaciation using an independent model. However, the contribution was negligible in this analysis.
To compute the groundwater storage time series, Global Land Data Assimilation System (GLDAS) estimates of soil-water storage variations are removed from GRACE TWS.
The time series of monthly TWS, soil water and groundwater storage in the study region were generated.

Findings:

Glacier retreat contributes to 2.8 $km^3\ yr^{-1}$ (15%) of the estimated TWS.

Reservoir storage reported increasing trend of 0.5 $km^3 yr^{-1}$ during the study period.

The resulting 6-yr time series of monthly groundwater storage anomalies as equivalent heights of water averaged over the three-state region indicates that the mean estimated groundwater storage is 5.9 cm, soil-water storage is 10.3 cm and TWS is 13.8 cm. The rate of depletion of groundwater in the entire region has been estimated in this study to be 4.0±1.0 cm yr^{-1} which is equivalent to 17.7±4.5 $km^3\ yr^{-1}$.

Reference:

Matthew Rodell, Isabella Velicogna & James S. Famiglietti. 2009. Satellite based estimates of groundwater depletion in India. Nature, 2009 , doi:10.1038/nature08238.

Annexure II

Protocol for state-level ground water resources estimation

a) Ground Water Resources assessment should be carried out under the overall supervision of a State level committee headed by Secretary in Charge of Water Resources. Members of the committee would include Heads of various state Govt agencies like Water Resources Department, State Ground Water Departments, Water Supply & Sanitation Department, Dept. of Agriculture, Public Health & Engineering Department, Rural Water Supply Department, Minor Irrigation Department, Department of Industries and NABARD. Regional Director, CGWB would be the Member Secretary of the Committee. The State level Committee may co-opt other members if necessary. This committee will be a Standing Committee responsible for ground water assessment, field validation and strengthening of database required for assessment in the respective States.

b) As a first step, CGWB and concerned State agencies would reconcile the three basic database/ parameters viz. Water level, Specific Yield and Unit Draft and compile the information in a common format. The objective is to identify the data-gaps prior to estimation and strengthening of database in-between consecutive assessments.

c) Next, a preliminary assessment about the ground water situation of each assessment unit would be made jointly by CGWB and State agency based on hydrogeological conditions as per the hydrogeological survey reports and reports of various field investigations carried out by the Centre/ State hydrogeologists and ground water level data/ trends existing with CGWB/ State Govt agencies. This would be a qualitative assessment of whether or not there is depletion of ground water resources.

d) This would be followed by finalization of the values of different parameters to be used for resources assessment based on the norms recommended by GEC-1997 and undertake field studies to collect relevant information.

e) Based on the available database and parameter estimations/ norms, State Ground Water Department and CGWB would jointly carry out resources assessment following GEC-1997 guidelines/ norms and subsequent guidelines regarding Categorization and allocation of ground water resources for utilization.

f) The results of ground water resources assessment shall be reconciled with the results of the preliminary assessment (point c) before categorizing the assessment unit.

g) Upon completion of ground water estimation exercises, field validations need to be carried out based on sample survey. Each state should carry out field validation in at least 10% of the assessment units in different hydrogeological setup. These could be Over-exploited or other category assessment units as decided by the State level Committee. In case of States where Over-exploited assessment units are more than 20% of the total numbers, field validation to be done for 15% of the total number of assessment units.

Field level validations need to be taken up in the following manner –

i. 10% of the villages in the assessment unit should be taken for field validation. The sample villages may be selected based on prevailing hydrogeological conditions and should be representative of the assessment unit.
ii. The sample survey would be conducted based on personal enquiry and field investigations with special emphasis on -
    - Inventory of all the wells in the village, measurement of water levels and informations on their historical trend.
    - Total number of ground water abstraction structures for various uses in the village and their operational status over the years.

h) The results of field validation studies shall be reviewed by the State level Standing Committee and appropriate corrective measures suggested if required.