Aquifer Mapping

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INTRODUCTION

Groundwater is the backbone of India's agriculture and drinking water security. It is a common-pool resource, used by millions of farmers across the country and remains the only drinking water source in most of India's rural households. It also supports important industrial production in many cases.

The scarcity of water resources and ever increasing demands that are placed on the resource make it vital that groundwater resources are identified, quantified and managed in a way that prevents over exploitation and consequent economic loss or environmental damage, while satisfying demand for water supply, industry and agriculture.

The knowledge of the availability of natural resources in time and space, particularly water resources is very important for its management in sustainable way. The precipitation in the country is estimated at 4000 BCM by taking the annual normal rainfall of 1197 mm, which transforms into various surface, sub-surface and ground water sources. The annual surface water flow in the country is estimated at 1869.35 BCM and annual replenishable ground water is 431 BCM. As per the assessment of the ground water resources and categorization of assessment units in the country (as on March 31, 2009) out of the total of 5842 ground water assessment units, 802 units have been categorized as 'Over-exploited' , 169 as 'Critical' and 523 as 'Semi-Critical'.

AQUIFERS

From a resource perspective, the primary unit in ground water investigations is the aquifer, a lithologic or combination of lithologic units capable of yielding water to wells. An aquifer does not have any limited dimension; it can be a small bed, an entire geologic formation or can encompass a stratigraphic unit. The vertical thickness can be varied as well. An aquifer essentially has high porosity and permeability. A unit of low permeability zone that bounds an aquifer is called as a confined bed (Fig.1). The definition of an aquifer can also vary in a ground water rich- or poor- region, e.g., a confining bed may act as an aquifer in a ground water poor region. Aquifers and confining beds come in different connotations.

Aquiclude is a saturated but relatively impermeable material that does not yield sufficient quantity of water to wells e.g., Clays. Aquifuge is a relatively impermeable formation neither containing nor transmitting water, e.g. solid granite. Aquitard is a saturated but poorly permeable stratum that impedes ground water movement and does not yield water freely to the wells, but where sufficiently thick, may constitute an important ground water reservoir, e.g. sandy clay.

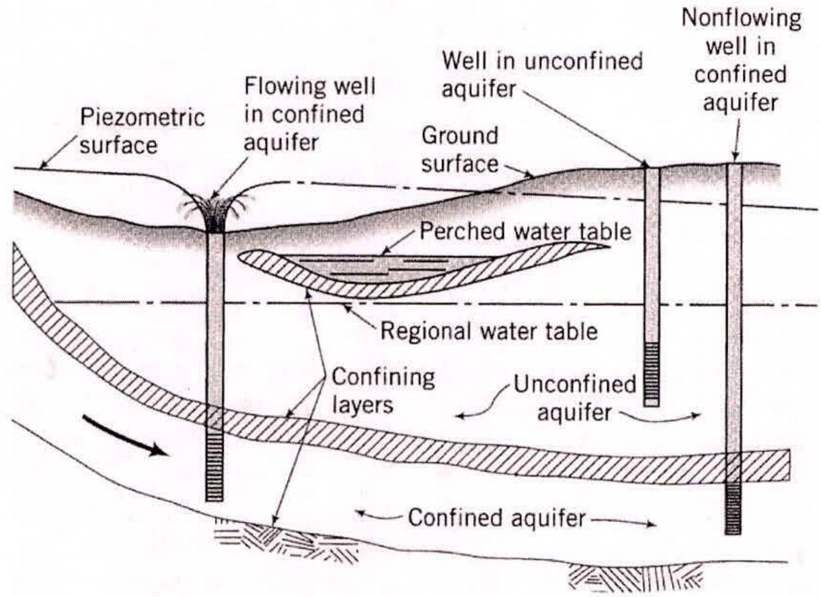

Fig. 1 Schematic diagram of confined and unconfined aquifers

AQUIFER SYSTEM IN INDIA

The ground water condition of the country is compiled in block/district/state level by CGWB and other state agencies and academic institutions involved in the identified regions. The national level information is compiled by CGWB, MOWR. The generalized aquifer system of the country is shown in the map below which gives broad category of aquifers and same needs updating for the large scale maps as per the water stress in the area selected and the variations in Lithological units. The Geological maps prepared by GSI in 1:250,000, 1:50,000 and 1:25,000 scale are used for grouping the geological units into aquifer units and give more details like water level, thickness of the aquifer, recharge-discharge area, water quality, areas of pollution etc. CGWB has prepared Hydrogeological Map of the country on 1:250,000 scale. On this basis, 9 principal Aquifers and 43 Major Aquifer Systems have been identified in the country (Fig.2).

The report of the Expert Group on Groundwater Management and Governance of the Planning Commission (2007), states that, in 2004, 28% of India's blocks were showing high levels of groundwater use. The latest assessment carried out by CGWB in coordination with the states as on March, 2009 indicates about 30% of the assessment units are under Overexploited, critical and Semi-critical category. In addition to quantity, related issues like inequitable distribution of ground water resources and overuse /underuse of the available potential in sustainable way, many parts of the country have reported *water quality* problems, causing drinking water shortage. This is a serious situation warranting immediate attention.

An accurate and comprehensive micro-level picture of groundwater in India through aquifer mapping in different hydrogeological settings will enable robust groundwater management plans at the appropriate scale to be devised and implemented for this common-pool resource. This will help achieving drinking water security, improved irrigation facility and sustainability in water resources development in large parts of rural India, and many parts of urban India as well.

The Detailed Aquifer Mapping Program of CGWB will advance the knowledge of the regional hydrologic system. Depending upon the needs & requirements, it is envisaged to prepare hydrogeological maps on 1:50,000 scale, and in certain cases, even on a still larger scale, as ground water management needs to be taken up at Block and village level through participatory approach. The Aquifer management plans will be implemented through participatory management approach, and the entire exercise is aimed at providing information at local level to the stakeholders.

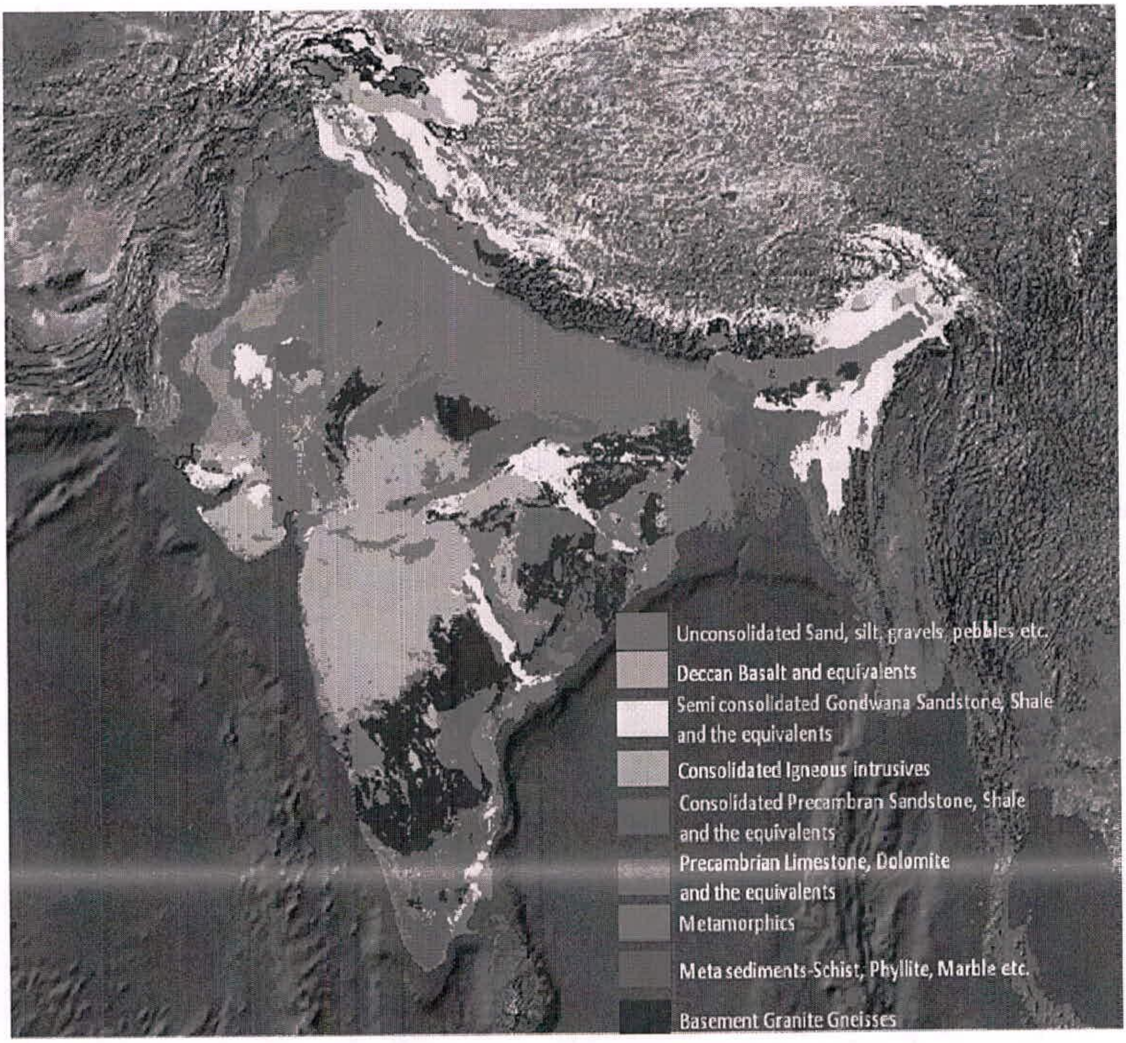

Fig. 2 Principle Aquifers in India

AQUIFER MAPPING PROGRAM OF CENTRAL GROUND WATER BOARD

Central Ground Water Board has designed a programme for groundwater resource management by identifying and mapping aquifers, quantifying the available groundwater resources potential and proposing plans appropriate to the scale of demand, aquifer characteristics and the institutional arrangements for management. This work will be systematically implemented in the country, by involving organisations / institutions across India.

Considerable work and investigations have been carried out by Central and State Agencies, Universities & Research Institutions, NGOs etc. at different scales. Generally, various thematic maps related to ground water domain are available on 1:250,000 scale in the country. These maps have been used in limited way for regional planning and decision support to ground water development rather than management.

For the proposed project on aquifer mapping and creation of micro level aquifer information system, the activities are planned in such a way to facilitate formulation of the ground water management plan for individual aquifer units of optimal size in accordance with the nature of the aquifer, the stress on the resource and prevailing water quality. In areas having adequate data base from the completed studies, aquifer map in 1:50,000 scale will be prepared and aquifer information system will be created with minimal additional field data collection. In identified areas where ground water management issues are significant but existing data is not comprehensive, detailed mapping with integrated hydrogeological, geophysical, geochemical and remote sensing studies will be taken up and used for preparation of large scale aquifer map and aquifer information system for the entire country. At the other end of the spectrum some aquifer management units will require significant investment in detailed mapping with various scientific tools like remote sensing, conventional Hydrogeological, geophysical and hydro chemical studies etc. The accelerated aquifer information data generation will require significant investment in organising the field work with required state of art advance techniques and latest equipments with a dedicated team by involving central, state agencies and creation of aquifer unit wise resource centre with local community participation in implementation of the aquifer management plan.

Objective

The primary objective of the Aquifer Mapping Project is to prepare micro-level aquifer information system with 1:50,000 or larger scale aquifer map and develop Aquifer Management Plans, which will allow institutions and stakeholders to effectively understand and manage groundwater resources at regional and local level.

Resources Available

There are significant resources of data and information that provide the basic knowledge on groundwater and aquifers, and from which it will be possible to develop Aquifer mapping programme in the regional scale at first and then upscale to village/cluster of village level. Beyond the basic topographic and administrative data provided by SOI, the Geological Survey of India provides geological and Lithological information. Using the satellite data, the NRSC prepares various layers such as Land use, Geomorphology and other thematic layers, similarly the soil maps are available with the NBSS. CGWB have produced comprehensive hydrogeological map at a scale of 1: 2 million and 1:250,000, complemented by regional studies and technical reports of state and districts including Hydrogeological Atlas and Ground Water User Maps. Groundwater Prospects Maps for selected areas have been prepared under the Rajiv Gandhi National Drinking Water Mission. In addition, there are several other organisations which have base-line information that shall be integrated under this programme. Especially in areas of extensive groundwater abstraction for urban water resources, industry or major irrigation schemes, comprehensive and detailed technical data, and management tools, including groundwater models may also exist. The State Ground Water Departments are also repository of large volume of State specific data collected over a period of time. Extensive data is also being collected by way of existing and new monitoring networks established under Hydrology Project.

Methodology

Three major steps have been identified for Aquifer mapping, namely:

1. Preparation of Aquifer Maps
2. Preparation of Aquifer Management Plans
3. Participatory ground water management.

1. Preparation of Aquifer Maps: This activity will be carried out in three steps, as detailed below:

- **Identification of Aquifer Management Unit (AMU):** The major aquifer systems of India available in 1:2 Million scale gives the national level distribution of porous and fractured aquifers. There are number of sub-groups transgressing the states and basins and also the country, which are to be properly sub-divided in the lines of water sheds. The multi layered aquifers in porous formation also need grouping in space and depth. Conventionally, geology and geomorphology plays key role in defining the aquifer units. It is proposed to demarcate the aquifers in the country in a scientific way from provinces to regions and local level to an optimal size management unit. Accordingly component of the project will include (a) Lithological model, to include depth and thickness of major aquifers and aquicludes, significant structures, faults and lineaments, and (ii) Attribution of geological model with basic aquifer properties (storage, transmissivity)

  An Aquifer Management Unit is the basic component of both planning and project implementation. Ideally an aquifer management unit will be defined on hydrogeological grounds, including their recharge areas and natural and anthropogenic discharges. This gives the maximum scope for effective management. The identification of AMU will be based on the boundaries of existing regional hydrogeological units, Watersheds and Administrative units.

- **Prioritisation of AMUs:** The prioritisation of AMU, as well as the scale of mapping, shall be based on the evaluation of each AMU. The prioritisation will also indicate further investigations that may be required to fill in the data gaps for each AMU. The Aquifer Management Plans will be accordingly prepared for the prioritised AMUs. The important considerations for prioritisation of AMU's could be: (a) aquifer yield, (b) water quality, (c) demands and stress on the aquifer, (d) Status of ground water development (AMUs with Overexploited/Critical/Semi-critical status will be a priority for mapping and data base creation), and (e) vulnerability of aquifer/environment degradation, viz. sea water ingress, pollution and dried condition of aquifer.

  Once prioritised, an investigative work plan will be drawn up for each AMU. The scope of work required in each AMU is expected to vary across a spectrum, from AMUs where there are sufficiently comprehensive data with which work can focus on digitisation and compilation of the outputs from data generated during previous studies to AMUs where significant investments will be required in digitising detailed records and field data collection.

- **Investigation and data compilation for each AMU:** The prioritised AMUs will be further classified on the basis of the data availability in these units into three categories (i) Priority AMUs with high data availability, (ii) Priority AMUs with moderate data availability, and (iii) Priority AMUs with Low data availability.

  The Work plan for further investigation and analysis shall depend upon this categorisation. Where significant data gaps are identified, additional hydrogeological, geological geophysical, geochemical data collection will be required to supplement existing reports and digital data.

2. Preparation of Aquifer Management Plan: Central ground Water Board shall facilitate the State Government in preparation of Aquifer Management Plans based on mathematical ground water models.

The AMPs shall include, but not limited to:

- The AMPs should also talk about the sustainability of the resource; Sustainability necessarily means the reliability, resilience and the vulnerability of the resource. Reliability is the ability of system to meet demands; resilience is the measure of the ability of the system to recover from failure and vulnerability is the measure of loss/damage incurred because of failure.
- The AMPs should address the issues of climate change and its impact on ground water resource availability through development of mathematical ground water models.
- Feasible areas for ground water development along with yield potential, Type and Depth of drilling / safe yields etc.
- Feasible areas for rainwater harvesting and artificial recharge of groundwater vis a vis subsurface storage space and surplus non committed surface water runoff available for recharge.
- Aquifer wise vulnerability map indicating ground water stress areas in terms of water availability and quality.
- Participatory Groundwater Management protocol, mechanism to involve community and funding options.

3. Participatory Groundwater Management: It is imperative to have the aquifer mapping activity with a road map for groundwater management plan to ensure its transition into a participatory groundwater management programme within the legislative framework for effective implementation of the Aquifer Management Plans (AMPs). This would be implemented through a coordinated effort involving government departments, research institutes, PRIs, civil society organizations and the stakeholders at the village level who would guide collective sharing and use of groundwater based on a careful understanding of the storage and transmission characteristics of different aquifers in each of the hydrogeological settings. Two major issues to be addressed are (i) Management of Groundwater, and (ii) Monitoring leading to sustainability of Groundwater.

AQUIFER MAPPING

Aquifer mapping is a process wherein a combination of geologic, geophysical, hydrologic and chemical field and laboratory analyses are applied to characterize the quantity, quality and sustainability of ground water in aquifers. The aquifer mapping program is important for planning suitable adaptation strategies to meet climate change also. The detailed aquifer map may help in providing protected water supply to all population and also ensuring its sustainability by water conservation and artificial recharge measures. Food security of the country can be achieved by modernizing the irrigation practices suiting the aquifer status prevailing in the area. The major zones of recharge and discharge and the best possible water management plan including the quality protection is feasible with aquifer mapping.

Steps involved in Aquifer Mapping

Aquifer Delineation, Definition & Evaluation	• 1:250,000 Regional hydrogeological map • Literature compilation • Aquifer Unit definition • Development of Conceptual Hydrogeological Model
Initial Evaluation Aquifer Management Unit	• Compilation of Existing data • Groundwater Issues Identification • Data Gap Identification
Data Generation & Aquifer Mapping	• Groundwater Exploration • Geophysical Investigations • Groundwater Monitoring • Water Quality Assessment • Hydrology/Hydrometeorology • Hydrogeology
Aquifer Management Plans	• Modelling tools • Vulnerability map for aquifer Unit • Feasible areas for GW development and Recharge

Remote Sensing

Remote sensing is the small or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, or satellite). Normally this technology gives rise to an imagery which is further processed and interpreted to produce useful data for application in agriculture, archaeology, forestry, geography, geology, planning and other fields.

The conventional approaches for groundwater investigation, which are ground based field surveys and exploratory drilling, are time consuming and uneconomical. The remote sensing technique provides temporal and spatial information on geological and hydrological parameters required for groundwater studies. Repetitive coverage of the earth provides temporal and real time information on static and dynamic resources. The geological and hydrologic information can be inferred by analysis and interpretation of remote sensing data. Hence, remote sensing technique provides vital information on groundwater, which can be supplemented and verified by other field techniques like detailed ground survey, geophysical resistively survey and shallow seismic survey.

Remote sensing data provides only surface information, whereas groundwater occurs at depth and may be a few meters or several tens of meters deep. The depth penetration of EM radiations is barely of the order of fractions of a millimeter in the visible region, to hardly a few meters in the microwave region, at best. Therefore, remote sensing data are unable to provide any direct information on groundwater in most cases. However, the surface morphological-hydrological-geological regime, which primarily governs the subsurface water conditions, can be well studied and mapped on remote sensing data products. Therefore, remote sensing acts as a very useful guide and efficient tool for regional and local groundwater exploration, particularly as a fore runner in a cost-effective manner.

Surface Geological Investigation

Reconnaissance surveys consist of rather extensive studies of the hydrogeology of the region under investigations, using geological maps, aerial photographs, remote sensing data, and ground observations to detect sufficiently permeable strata that by virtue of their relative elevations or depressions, geologic history, and hydrology could be water bearing. Much can be learned from an examination of available maps, reports, and data. There are published geological maps by Geological Survey of India on 1:50,000 scale for most of the parts of India and soil maps by National Bureau of Soil Survey and Land Use Planning. Published geologic maps and reports provide the initial indication of the rock formation, together with their stratigraphic and structural interrelationships. Soil maps together with topographic maps provide an introduction to the distribution of potential recharge areas.

However, even in areas where there is a considerable amount of published information, it is usually necessary to carry out geologic mapping in the field. In view of the importance of unconsolidated sands and gravels as potential aquifers, special attention must be paid to geomorphic landforms and to the distribution of alluvial deposits. Where sand and gravel deposits are sparse, or where these deposits are shallow and unsaturated, more detailed attention must be paid to the lithology, stratigraphy, and structure of the bed rock formations.

Hydrological Investigations

Hydrogeological and groundwater potential maps have been published by Central Ground Water Board. These maps provide a summarized interpretation of the hydrogeologic, geochemical, and groundwater resources data available in an area.

Hydrologic studies may consist of determining water inputs and outputs for the area that could serve as potential recharge sites for the aquifer, such as alluvial fans, beach or dunes, ridges, and other deep permeable soils and outcrops of permeable, consolidated or unconsolidated strata. Net rates of groundwater accretion can then be evaluated as difference between inflow (precipitation, stream seepage, etc.) and outflow (runoff, evaporation from soil, evapotranspiration from vegetation etc.) of water from these areas. Significant accretion of groundwater may occur through less permeable surface material, particularly if they are extensive and rainfall is primarily of low intensity and long duration.

Various other aspects may be investigated, such as, recharge rates and sources, infiltration characteristics of the soils, aquifer parameters, soil moisture changes, and presence of surface and groundwater bodies. The morphometric analysis of groundwater basins provides useful indices for the estimation of groundwater recharge. Besides various hydrometerorological parameters such as rainfall and evaporation have to be studied in relation to water balance.

Seeps and springs are among the hydrologic surface features that may aid in evaluating the groundwater potential of certain areas. Hillside seeps above outcrop of less permeable strata indicate groundwater in overlying formations. Springs also reveal the presence of groundwater. A few large springs may indicate thick transmissive aquifers, whereas frequent, small springs tend to indicate thin aquifer of low transmissivity. In arid areas, presence of trees or other deep rooted vegetation in an otherwise barren landscape may indicate shallow groundwater, for example below ephemeral streams, floodplains, or oases. If the groundwater table in arid areas is close to the surface, evaporation can cause salt accumulation on the surface of the soil. These salt flats, with or without salt tolerant vegetation, should not be confused with playas which are ephemeral lakes formed by surface runoff in low areas with soil of low permeability. Biological indicators of groundwater may even include ants, which are reported to be able tunnel down as much as 30 m to reach groundwater and are used to detect groundwater in the deserts.

Subsurface Geological Investigations

Surface manifestations of hydrogeological environment may not always be sufficient to locate potential aquifers. It is unlikely that subsurface stratigraphic relationships will be fully revealed without direct subsurface investigations. Once again, the initial steps usually involve scanning the available records. Many State and Central government departments drill wells for water supply and other purposes and maintain the geological logs of all borewells drilled by them and other agencies. These data, while varying widely in quality, can often provide considerable information on past successes and failures in a given region.

In most exploration programs, especially those for large scale municipal supplies or industrial use, it is necessary to carry out test drilling to better delineate subsurface conditions. Test holes provide the opportunity for geological, geophysical logging and for the coring or sampling of geological materials. Test holes can also be used to obtain water samples for chemical analysis and to indicate the evolution of the water table at a site. Test drilling programs, together with published geological maps and available well log records, can be interpreted in terms of the local and regional lithology, stratigraphy and structure. Their logs can be used to prepare stratigraphic cross sections, geological fence diagrams, isopach maps of overburden thickness or formation thickness, and lithofacies maps. Hydrogeological interpretations might include water table contours and isopachs of saturated thickness of unconfined aquifers. The results of chemical analysis of groundwater samples, when graphically displayed, can provide important evidence on the natural geochemical environment as well as a direct measure of water quality.

Availability of groundwater in hard rock areas is, in general, controlled by the geomorphic features and geological factors. Geomorphic features control mainly the contact time between the precipitation and the ground surface and thereby influence the infiltration and groundwater recharge. The nature, distribution and structure of geologic formations control the occurrence, movement, quality and availability of groundwater. Therefore, before discussing the various geological exploration methods for groundwater exploration, it is important to understand the role of geomorphic and geologic control on groundwater occurrence in hard rocks.

Geophysical Investigations

Geophysical methods are non-invasive means for sensing the subsurface geological conditions by making use of all possible physical principles till-date. Newton's law of gravitation governs gravity method, coulomb's law for magnetic method, Maxwell's equations for electromagnetic and electrical methods, Hook's law and elasticity theory for seismic methods, laws of heat conduction and convection for thermal methods and so on. Each material in pure form has physical properties like density, magnetic susceptibility, electrical conductivity, elastic and thermal properties etc.

In the present context, satellite, airborne, surface and underground geophysical measurements have been discussed concerning geo-hydrological investigations.

Satellite and Airborne Geophysical Methods

The latest gravity satellite, GRACE has mapped gravity of the entire globe to a very high accuracy. Gravity and tectonics go together. The satellite gravity maps in association with satellite imageries of study region can infer probable fractures/shear zones within hard basement on a regional scale. The follow-up can initially be undertaken with airborne magnetic and later by ground-based geophysical surveys.

In aero-magnetic method, minute changes in geomagnetic field of the order 1nT (10^{-5} Gauss) can be mapped with highly sensitive quantum magnetometers working on a combined nuclear magnetic resonance and optical pumping principles. Latest methods of position location (Differential GPS receivers) and data acquisition and processing procedures have helped achieving such high accuracies in geomagnetic field mapping.

Ground Geophysical Methods

Subsequent to analysis of airborne geophysical data, the ground follow-up is normally undertaken by a wide variety of surface geophysical methods. Usually, the cheaper reconnaissance tools like gravity and magnetic precede other detailed ones like electrical and seismic methods. Out of them seismic methods possess high resolution in sedimentary formations, while electrical methods, in particular, electrical sounding methods can probe the earth in the depth range of 200m with good resolution. Beyond that depth limits either one can undertake dipole-sounding and audio-magnetotelluric soundings.

In routine geohydrological investigations, simple DC resistivity sounding method is undertaken with Schlumberger configuration. The schlumberger configuration is an electrode arrangement, where inner pair of electrodes serve as potential electrodes and outer ones as current electrodes. Through current electrodes DC current/ low-frequency AC is passed through and response of layered earth in the form of potential difference at potential electrode pair is recorded. The input current and recorded response, potential difference are combined into a single parameter, known as apparent resistivity parameter through the usage of relevant formula, which takes care of geometric arrangement of electrodes.

Resistivity methods, resting on a simple Ohm's law and a fundamental theorem in electrical prospecting are also helpful in sensing the shallow subsurface geological and geohydrological conditions up to a depth of 100-150 m. Electrical sounding and profiling methods with collinear and non-collinear electrode configurations can realize them. The four electrode Schlumberger and Wenner configurations are routinely used for carrying out electrical sounding and profiling respectively. Electrical sounding is equivalent to non-invasive drilling at the center point of adopted electrode configuration and is often used to estimate the true resistivity and thicknesses of different strata of subsurface. Electrical profiling on other hand maps lateral resistivity inhomogenities of subsurface. The geoelectrical models gathered by these methods are translated to subsurface geological sections by considering either direct borehole information or published resistivity values for different earth materials.

In hard rock regions, shallow groundwater resources within overburden can be evaluated by vertical electrical sounding (VES) method. The VES data can be interpreted by user-friendly software. However, location of groundwater bearing fractures/shear zones within hard basement cannot be attempted by this method. A variant of VES method, known as circular sounding method can be utilized for mapping saturated fractures/shear zones in a qualitative manner.

Recently, multi-electrode geo-electric tomography, is tackling a wide variety of shallow engineering geophysical problems. The electromagnetic methods, especially, Ground Penetration Radar (GPR), predominantly susceptible to moisture content provide detailed subsurface geological images in the depth range of 20m and under ideal conditions (desert conditions) can reach 30-40m. GPR surveys are usually carried out along profiles spanning the interested region. The frequencies employed for e.m source are in the Giga - hertz (0.5-1GHz) range. Because of this frequency range, the displacement currents predominate over conducting currents in the controlling Helmoltz equation; as a result the governing equation is similar to acoustic equation, governing seismic surveys. The dielectric permissivity of the medium is the key parameter controlling GPR. However, electrical conductivity also plays a vital role in the depth of penetration of e.m wave in the geological medium. Thus both soil moisture content depth-wise and clay/shaliness of medium delimit the deeper penetration of e.m source energy. Usually in the depth range of 15-25m depending on shallow water table and shaliness conditions GPR provides a good resolution often comparable to high-resolution seismics.

Ground gravity surveys are undertaken with gravimeters of different sensitivities at several map scales to suit different geological objectives. For broader regional geology delineation, regional gravity surveys are attempted with geodetic/exploration type gravimeters of sensitivity 0.01-0.1 mGal. For local or detailed surveys gravimeters of higher sensitivity are deployed. Of late micro-gravimeters with sensitivity in the range 0.001-0.05 are being deployed. In gravity surveys, topo-geodetic surveys precede the gravity survey and the position coordinates of gravity stations need to be determined with utmost precision. The micro-gravity surveys along with other geophysical surveys can provide detailed subsurface geological picture including fracture zones at shallow depths. Ground magnetic surveys can be carried out with magnetometers of different least counts. These surveys are usually carried out along with gravity surveys with similar goals of subsurface geological mapping.

In recent years, a new technology has emerged in geophysics encompassing seismic, electrical and electromagnetic methods, viz., geophysical imaging. Resistivity and IP imaging are implemented either in 2D or 3-D versions through the use of multi-electrode systems with microprocessor-controlled systems. These methods have emerged as a powerful tool in aiding civil engineering, geotechnical and hydrological site investigations. A brief account of various geophysical methods for groundwater exploration is as follows,

The differences in ferri-magnetic mineral distribution amongst different rock units form the source of magnetic anomalies in the background of geomagnetic field. The magnetometers of high sensitivity (1 nT) are capable of mapping these magnetic anomalies either in vertical field intensity or total field intensity components. The fracture systems within hard rock (basalts for example) can easily be identified over the magnetic anomaly maps. However, a similar situation does not prevail over granitic terrain. One has to carefully carry out the ground magnetic survey over a proper grid as per norms. The diurnal correction assumes much more importance in such a case. The processed anomalies need to be utilized for respective magnetic anomaly map. By considering dipole sources of magnetic anomalies, depth, size and orientation of fracture(s) with respect to magnetic north, the anomaly patterns need to be carefully analyzed at a given site (latitude and longitude). A forward modeling is worth trying before confirming the presence of fractures within the basement. It is advisable to carry out magnetic surveys over the hard rock, where presence of fracture systems already known to be present to learn specific features/patterns in magnetic anomaly shapes. Hence, one has to validate the method first in order to use magnetic anomaly map for location of subsurface fractures within hard basement.

The nuclear magnetic resonance phenomenon, associated with hydrogen nuclei in the subsurface, provides direct detection of groundwater/soil moisture. SNMR signal strength depends primarily on amount of groundwater and SNMR source excitation values. One can derive depth-wise distribution of soil moisture from SNMR method. But this method assumes 1-D earth model.

Geophysical Well Logging

This discipline is a very vast one involving several geophysical sensors and it is capable of providing the subsurface geology, fluid saturations in strata and their production. All most all known physical principles are exploited in the design of well-logging sensors. Broadly, they can be categorized as wire-line logging and production logging tools. The former one is oriented towards formation evaluation in all aspects and the latter are devoted to assessment of fluids' production capability of different strata.

The wire-line logging tools include electrical, electromagnetic, thermal, acoustic, natural and artificial radioactivity based logging tools. The basic formation parameters assessed are porosity, permeability and fluid saturations. They also address lithology identification, mapping of faults, fractures and shear zones in greater detail in the vicinity of the borehole. In a typical study area several boreholes are drilled at locations recommended by surface geophysical studies and logging is carried out. By cross-correlation of several borehole results, one can reconstruct the subsurface in three-dimensions with much greater resolution, which is non-achievable by any single surface geophysical method or combination of them.

Electrical resistivity and spontaneous polarization logging devices are often employed for hydrological investigations.

The spontaneous potential (SP) curve and the natural gamma ray (GR) log are recordings of naturally occurring physical phenomena in in-situ rocks. The SP curve records the electrical potential (voltage) produced by the interaction of formation water, conductive drilling fluid, and certain ion-selective rocks (shale). The GR log indicates the natural radioactivity of the formations. Nearly all rocks exhibit some natural radioactivity and the amount depends on the concentration of potassium, thorium, and uranium. There are two types of GR logs, (i) the standard GR log, measures only the total radioactivity, and (ii) the natural gamma ray spectrometry log (NGS), measures the total radioactivity and the concentrations of potassium, thorium, and uranium producing the radioactivity. Both the SP curve and GR log are generally recorded in Track 1 (left track) of the log. They are usually recorded in conjunction with some other log - such as the resistivity or porosity log. Indeed, nearly every log now includes a recording of the SP curve and/or GR log. Although relatively simple in concept, the SP curve and GR logs are quite useful and informative.

Water Quality Investigations

By analyzing the distribution of simple chemical components in ground water (such as calcium, sulfate and other ions, or physical parameters such as temperature and dissolved oxygen) we can identify waters of similar composition and flow history, and differentiate between recent recharge and waters with older residence times. Stable isotopes of oxygen and hydrogen can be used to identify sources of water recharged under distinct climatic conditions such as Pleistocene waters over 10,000 years old.

The concept of hydrochemical facies has been used to denote the diagnostic chemical character of water solutions in hydrologic systems. The facies reflect the effects of chemical processes occurring between the minerals within the lithologic framework and the ground water. The flow patterns modify the facies and control their distribution. This definition of hydroehemical facies is a paraphrase of the definition of sedimentary facies: "sedimentary facies are areally segregated parts of differing nature belonging to any genetieally related body of sedimentary deposits."

The term "geoehemieal faeies" has been used to define different sedimentary environments by means of specific mineral indicators of oxidation-reduction potentials and pH. Adams and Weaver (1958) proposed that "geochemical facies" of sedimentary rocks be defined in terms of the thorium-uranium ratio. Keith and Degens (1959, p. 40) used the term "chemofacies" to designate all the chemical elements that are collected, precipitated, or adsorbed from the aqueous environment, or fixed by chemical reactions in the bottom muds, as a basis for differentiating between marine and freshwater sediments.

The term "hydrochemical facies" was used previously for a column heading in a table; however, he did not define the term and used it only to indicate concentration of dissolved solids-that is, low-saline facies, transitional-saline facies, and highsaline facies.

Many Russian scientists have contributed to formulation of the "principle of hydrochemical zones." The concept of hydrochemical facies, as used in this report, is a refinement of this approach and can be considered, in part, as subdivision of major zones. According to the usage by some Russians, hydrochemical zones cover large regions and are segregated according to the predominant anion. For instance, the European part of the Soviet Union is segregated into five hydrochemical zones. The zone (1) of hydrocarbonate (bicarbonate)-siliceous water coincides with the soil-tundra zone, where the average yearly temperature is 0°C. This water is low in dissolved solids. The zone (2) of hydrocarbonate (bicarbonate)-calcium water covers an extensive area in which there are many different geologic deposits, most of which contain calcareous materials. Sulfate and chloride occur in the southern part. Cation exchange also results in the creation of hydrocarbonate-sodium water in this zone. The zone (3) of sulfate and chloride-sulfate water roughly coincides with the central and southern parts of the steppes and is characterized by a predominance of evaporation over precipitation. Calcium is the dominant cation. The zone (4) of chloride water occurs in the area of the Black Sea lowland and in the northern part of the Crimean peninsula; a second area is the Caspian lowland. The first area contains saliferous soils, salt licks, and salt marshes. The Caspian lowland is an area of desert and semi-desert in which the water is the chloride-magnesium-sodium type. Zone (5), in which the water has a low content of dissolved solids of the hydrocarbonate-calcium type, is in the mountainous regions of the Crimea and the Caucasus.

In addition to the geographic hydrochemical zones, several scientists (have discussed three vertical hydrodynamic zones that are characterized by certain chemical types of water. The uppermost zone is characterized by a high degree of water circulation and well-leached rocks and sediments. The water is of the bicarbonate type and has low dissolved-solids content.

In the intermediate zone water circulates less, the dissolved-solids content is higher, and the water is of the sulfate type. The lowermost hydrodynamic zone is a "stagnant" regime in which rocks are unleached and the water is highly mineralized and primarily of the chloride-sodium type. The hydrodynamic zones have been subdivided within the hydrochemical zones by the Russians to produce hydrogeochemical zones. The following vertical succession of hydrogeochemical zones was established by Kravtzov in the coal-bearing measures of the Donetz basin: Hydrocarbonate (bicarbonate) -calcium water, hydrocarbonate-sulfate-sodium mixed water, sulfate-sodium water hydrocarbonate-sodium water, hydrocarbonate-chloride-sodium water, and possibly a zone of highly mineralized chloride-sodium water. The term 'hydrogeochemical zones" is used to emphasize the relationship between the chemistry and movement of water.

The term "hydrochemical facies" includes all the concepts signified by hydrochemical zones, hydrochemical microzones, hydrodynamic zones, and hydrogeochemical zones. Accordingly, one term can be used instead of four.

Procedures and Mapping Techniques

Significant characteristics of hydrochemical facies can be illustrated by methods similar to those used in lithofacies studies trilinear diagrams that show the facies present in an area or in formations, fence diagrams that show the facies distribution, and maps that show isopleths of chemical constituents within certain formations. Trilinear and similar diagrams have long been used to study the chemistry of water. Emmons and Harrington (1913) used two triangles, one for cations and one for anions, with each vertex representing 100 percent of a particular ion or groups of ions, as is often used in petrographic studies. Hill (1940; 1942, p. 1517) published a trilinear diagram which added to the original two triangles a diamond-shaped area in which the two points plotted in the triangles are projected into the diamond and are plotted as a single point. Piper (1944) independently developed a similar diagram that has undergone minor changes and is used in this and other recent papers.

Isotopic Investigations

Stable and radio isotopic are very useful in demarcating various aquifers as they are very useful to understand the surface water and groundwater interactions, aquifer-aquifer interactions, groundwater dynamics and identification of recharge sources and recharge areas of deeper aquifers. Some of the aspects of isotopic characterisation of aquifers are discussed below:

Sources and mechanisms of groundwater recharge

A qualitative and quantitative characterization of groundwater recharge is essential to ensure the sustainable development and management of groundwater resources. Aquifers which receive little recharge exhibit only small fluctuations in groundwater levels; a reliable estimate of recharge rate cannot therefore easily be obtained on the basis of classical approaches alone, such as water level monitoring. Isotope techniques are virtually the only tools which can be used to identify and evaluate present day groundwater recharge under arid and semi-arid conditions.

The isotopic composition of groundwater (expressed as abundance of oxygen-18 and deuterium) is determined by the isotopic composition of recharge. If most of the recharge is derived from direct infiltration of precipitation, the groundwater will reflect the isotopic composition of that precipitation. However, if most of the recharge is derived from surface water (rivers or lakes) instead of from precipitation, the groundwater will reflect the mean isotopic composition of the contributing river or lake. This isotopic composition is expected to be measurably different from that of local precipitation. The difference arises from the fact that recharge via bank filtration may represent water originating from precipitation in a distant area, for instance in a high mountain region. In high mountain regions the isotopic content of precipitation is different to that of precipitation falling on plains. This difference in isotopic composition allows for differentiation of precipitation sources, and hence of recharge mechanisms. In addition to differences in isotopic composition of groundwater resulting from different recharge sources, there can be differences due to how recently recharge occurred. In hydrological settings in which groundwater is very old (>10 000 years), regional climatic conditions at the time of recharge may have been different from those existing today, and this is reflected in the isotope composition of the groundwater.

It is possible to identify, and in some instances quantify, modern recharge — within 40 to 50 years — by measuring isotopes and dissolved gases (e.g. tritium, tritium and helium-3, chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF6)) in soil water in an unsaturated zone or in groundwater from shallow, unconfined aquifers and springs. The tritium–helium-3 method enables bomb tritium from atmospheric testing carried out between 1954 and 1963 to be used to estimate groundwater recharge rates by determining the residence time of different groundwater samples collected at different depths. Even in cases of low vertical flow velocities, identification of the tritium and helium-3 peaks can be used for dating and thus for recharge rate estimation (recharge rate = porosity × vertical flow velocity). In addition, the mere presence of helium-3 derived from the decay of tritium in groundwater with no measurable tritium provides evidence of modern recharge. Tritium and helium-3 data can be modelled to estimate recharge to groundwater and transport parameters of aquifers.

Under certain circumstances, the residence time and thus recharge rate of modern groundwater can also be estimated by measuring the seasonal variations of hydrogen and oxygen isotopes. The applicability of this method is limited to those areas where precipitation shows a pronounced seasonal variation, such as in mountainous areas.

Groundwater in shallow aquifers typically has a residence time of decades to hundreds of years. In contrast, deeper and less permeable aquifers that extend for many kilometres can have through-flow times of thousands of years. If the flow regime is simple and mixing is minimal, such aquifers can serve as archives of information about environmental conditions at the time of recharge. The stable isotopes of hydrogen and oxygen in palaeowaters (groundwater recharged under climate conditions different than today) reflect the air temperature at land surface and the air mass circulation (origin of moisture) at the time of precipitation and infiltration. While palaeotemperatures derived from oxygen–deuterium analyses are useful, recently developed noble gas analytical methods provide greater certainty and precision in palaeotemperature determination.

Groundwater age and dynamics

The radioactive decay of environmental radioisotopes and the transient nature of some of these (bomb tritium, anthropogenic krypton-85, bomb carbon-14 and bomb chlorine-36) make such isotopes a unique tool for determining groundwater residence time. Residence time, also called groundwater age, is the length of time water has been isolated from the atmosphere. Recharge of unconfined aquifers usually results in a vertical gradient of groundwater ages (increasing age with depth), while in confined aquifers the dominating feature is a horizontal or lateral gradient (age increasing with distance from area of recharge). In the former case this gradient is approximately proportional to the inverse of the recharge rate (volume/time), while in the latter case the gradient is approximately proportional to the inverse of the flow velocity. Therefore, the hydrogeologically relevant parameters primarily addressed by groundwater dating with radioactive isotopes are the recharge rate and flow velocity of groundwater in unconfined and confined aquifers, respectively.

One of the approaches to determine groundwater flow rate is to estimate flow velocity by measuring the decrease in the radioisotope concentration along the flow path. If the mean porosity value of the aquifer is known, groundwater flow rate can be estimated. This simple approach requires access to at least two wells along the flow path of an aquifer and knowledge of the initial radioisotope concentration in the recharge area. Under natural conditions, groundwater movement is generally very slow, often in the order of a few metres per year. Water that has moved a few kilometres along the flow path under these conditions is hundreds or thousands of years old; an age beyond the dating range of tritium, tritium and helium-3, and chlorofluorocarbons. Therefore, in large aquifers with long flow paths, the most common radiometric approach to determining groundwater residence times has been carbon-14. Its half-life of 5730 years makes it a suitable tool for the dating of groundwater in an age range of about 2000 to 40 000 years.

Very slow moving groundwater in deep confined aquifers extending over tens and, in some cases, several hundreds of kilometres can reach ages of tens and even hundreds of thousands of years. These ages are beyond the dating range of carbon-14 and require the use of very long-lived radioisotopes. Of the three longlived radioisotopes used in water studies — krypton-81, chlorine-36 and iodine-129 — only chlorine-36 has been found to have wider practical use so far. However, interpretation of chlorine-36 data to ascertain groundwater age is often hampered by insufficient knowledge of in situ production of the isotope owing to reactions in the aquifer matrix. Recent developments in sampling and analytical methods suggest that the use of krypton-81 may grow substantially given that it is a reliable tool to date groundwater in the range of 40 000 to 1 million years old.

Interconnections between aquifers

Both groundwater dynamics and groundwater contamination can be influenced by hydraulic interconnections between aquifers. Environmental isotopes, especially stable isotopes, can be used to investigate such interconnections, provided the isotopic composition of groundwater in the aquifers being measured is different. Thus, isotopes can be used to prove a lack of hydraulic interconnections between aquifers based on contrasting compositions. In some settings, hydraulic connections exist naturally between aquifers, and this can be evaluated through variations in isotopic composition. Intense exploitation of an aquifer can induce leakage from overlying and underlying aquifers. Stable isotope data can be used to estimate the flow of groundwater from adjacent aquifers.

Interaction between surface water and groundwater

Groundwater often consists of a mixture of recharge from surface water (lakes or rivers) and local precipitation. It is important to know the proportions of these recharge components in order to increase the sustainable supply of drinking water through bank infiltration, and to prevent drinking water pollution by infiltration of water from a contaminated surface water source. Different recharge components can be identified through the stable isotope compositions of groundwater because evaporation of water in surface water bodies, in particular under semi-arid and arid conditions, leads to an increase in the proportion of the heavy isotopes deuterium and oxygen-18. A simple isotopic balance equation can then be used to estimate the relative proportions of surface water and precipitation in recharge. The accuracy of this determination generally depends on the magnitude of the difference in isotopic composition of the two components and under ideal conditions is in the order of a few per cent.

River water can show a seasonal variation in isotopic composition, usually observed with reduced amplitude and after a time lag in wells near the river. This time lag as well as the change in mean isotopic composition provides the minimum time (transit time) required for river water and possibly it's dissolved pollutants to reach a groundwater supply well. Isotope composition also provides insight into the fraction of river water in recharge (possibly polluted) relative to other recharge sources. In arid climates, river water may be enriched in deuterium and oxygen-18 relative to groundwater if it was replenished under historical conditions with greater humidity. The fraction of river water in groundwater can be estimated based on the differences in isotopic composition of the mixing components.

CONCLUDING REMARKS

Various investigation techniques, like remote sensing, geological, geophysical, exploratory, water quality and isotopic investigations are used for aquifer mapping. But one thing is to be kept in mind that any one technique used in isolation may lead to incorrect interpretation. Therefore, it is always advisable to use various techniques for aquifer mapping in integrated manner to obtain the best results.