DEVELOPMENTS IN GROUND WATER HYDROLOGY : AN OVERVIEW

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SYNOPSIS

Ground water development has shown phenomenal progress in our country during the past three decades. There has been a vast improvement in the perception, outlook and significance of ground water resource. The objective of this paper is to present the status of developments in hydrological studies related to ground water hydrology including review of the basic concepts and associated methodologies.

1.0 INTRODUCTION

Ground water is a distinguished component of the hydrologic cycle. Surface water storage and ground water withdrawal are traditional engineering approaches which will continue to be followed in future. The uncertainty about the occurrence, distribution and quality aspect of the ground water and the energy requirement for its withdrawal impose restriction on exploitation of ground water. In spite of its uncertainty, ground water has some obvious advantages. These advantages are : ground water is much protected from pollution; it requires little treatment before it use; it is available almost everywhere; it can be developed with little gestation period and can be supplied at a fairly steady rate. It does not require any distribution system and its interference with land resources is minimum. In hilly region, the ground water emerging as springs can serve as a viable source for supply of drinking water. In a canal command area, use of ground water controls waterlogging problems. The role of ground water is conspicuous during period of drought.

2.0 GROUND WATER SITUATION IN INDIA[1]

India is a vast country having diversified geological setting. Variations exhibited by the rock formations, ranging in age from the Archaean crystallines to the recent alluvia, are as great as the hydrometeorological conditions. Variations in the land forms are not insignificant. It varies from sea level at the coasts to the lofty peaks of the snow clad Himalayan mountains attaining staggering altitude upto about 9000 metres. Variations in the nature and composition of rock types, the geological structures, geomorphological set up and hydrometeorological conditions have correspondingly given rise to widely varying ground water situation in different parts of the country.

In the high relief areas of the northern and north-eastern regions occupied by the Himalayan ranges, the various conspicuous hill ranges of Rajasthan, the Central and Southern Indian regions, the presence of very steep slope conditions and geological structures offer extremely high runoff and thus very little scope for rain water to find favourable conditions of storage and circulation as ground water. The large alluvial tract extending over 2000 km in length from Punjab in the West, to Assam in the East often referred to as Sindhu-Ganga-Brahmaputra Plain, is perhaps, the most potential and important region from the view point of ground water resources.

Almost the entire Central and Southern India is occupied by a variety of hard rocks with hard sediments (including carbonate rocks) in the intertectonic and major river basins. Rugged topography, hard and compact nature of the rock formations, the geologic structures and meteorological conditions have yielded an environment which allows ground water storage in the weathered residium and its circulation in the underlying fracture systems. The hard rock terrains, river valleys and abandoned channels, wherever having adequate thickness of porous material, act as potential areas for ground water storage and development. It is observed that sustained yield from fracture system down to 200 m is possible in certain hard rock areas of Peninsular India.

There is a wide variation in the chemical quality of ground water in the country, reflecting the diverse geo-hydrology, hydrometeorology, topographic and drainage conditions and artificially imposed conditions, such as surface water irrigation. The coastal and deltaic tracts, particularly in the East Coast, are covered with vast and extensive alluvial sediments. Though these tracts are productive in terms of water yield yet the overall ground water regime in coastal areas suffer from salinity hazards. Ground water development in coastal areas should be regulated such that contamination of the fresh ground water body with sea water is avoided. Salinity in ground water also exist in inland areas, apart from coastal areas, in parts of Punjab, Haryana, Uttar Pradesh, Rajasthan and Gujarat. This is generally confined to arid and semi-arid regions. In some of the canal command areas where there is progressive rise of water table, it brings about waterlogging conditions resulting in increase of salinity in the top soils and rendering cultivable land barren. Conjunctive use of surface water and ground water should be practiced as an effective method to check the waterlogging conditions in such areas.

3.0 ASSESSMENT OF GROUND WATER RESOURCES[1,2,3]

Ground water regime is a dynamic system in which water is absorbed at the land surface and eventually recycled back to the surface. The ground water movement occurs through the porous unconsolidated sediments and through interconnected openings in the rocks that mantle the earth. The occurrence and movement of ground water depend on the geohydrological characteristics of the subsurface formations. These natural deposits vary greatly in their lithology, texture and structure and differ in respect of their hydrological characteristics. The framework in which ground water occurs is as varied as those rocks and as intricate as their deformation, which has progressed through geologic time. The possible combinations of variety and intricacy are virtually infinite. It has been, therefore, experienced that ground water investigations at a given site almost always exhibit a certain uniqueness.

For estimating regional ground water potential, it has been recommended that the general manner in which the regime functions must be identified. The potential for recharge to the ground water regime in an area depends on the amount and pattern of annual precipitation in relation to the potential evaporation in the area and to the occurrence of any surface or subsurface inflow from adjacent areas. Most of this potential recharge is commonly intercepted by the soil veneer and eventually return to the atmosphere through process of evapotranspiration or dissipate through surface runoff. The amount that actually contributes to ground water recharge varies seasonally and from year to year. It is generally difficult to quantify the recharge to ground water from various sources. Similarly, ground water discharge may be difficult to quantify because of temporal variations, especially if it occurs at a number of scattered locations, either at the land surface in the form of springs, gaining streams, lakes, ponds, marshes or growths of phreatophytes, or at depth through permeable formations.

For quantifying the ground water resource available, two different concepts based on the existing hydrogeological situations are used :

1. Quantity concept - for unconfined (water table) aquifers.
2. Rate concept - for confined aquifers.

(a) Unconfined (water table) aquifers

Ground water resources can be classified as Static and Dynamic. The Static resource can be defined as the amount of ground water available in the permeable portion of the aquifer below the zone of water level fluctuation. The Dynamic resource can be defined as the amount of ground water available in the zone of water level fluctuation. The usable ground water resource is essentially a dynamic resource which is recharged annually or periodically by rainfall, irrigation return flows, canal seepage, influent seepage etc. The most important component of recharge to the aquifer is the direct infiltration of rain water, which varies according to the climate, topography, soil and subsurface geological characteristics. A part of applied irrigation water both from ground water and surface water resources, reach ground water depending on the efficiency of irrigation system and soil characteristics. Influent streams also recharge the ground water body depending on the drainage density, width of streams and on the texture of river bed material. Other sources of recharge are percolation from canal systems, reservoirs, tanks etc.

(b) Confined aquifers

For the confined aquifers which are hydrogeologically separate from shallow water table aquifers, the ground water assessment is done by rate concept. The ground water available in a confined aquifer equals the rate of flow of ground water through this aquifer. The rate of ground water flow available for development in a confined aquifer in the area can be estimated by using Darcy's law.

The 'Ground Water Estimation Committee' constituted in 1982 to improve the existing methodologies for estimation of the ground water resource potential, recommended that for estimating the ground water recharge, water level fluctuation and specific yield approach should be applied as far as possible. The monitoring of water level network stations should be adequate in space (about one station for 100 sq. km. area) and time (about six times in a year) to monitor effects of ground water development on ground water regime. Efforts should be made to install continuous water level recorders wherever possible. It would be desirable that monitoring of water level network stations should be increased in space and time and analysis of the data is carried out keeping in view the hydrogeological situation in the areas. Inconsistencies in observations may be smoothened out taking into account the hydrogeological situation. The ground water contours should preferably be drawn on basin or sub-basin wise and administrative units may be superimposed on such maps to work out the ground water resources on a blockwise basis. The specific yield data may be computed from pumping tests.

During the last decade, a lot of work has been done on the various aspects of the methodology for ground water assessment including refinement of the norms for various parameters. It has been recommended in the National Workshop on Development of Groundwater in Critical and Semi-critical Areas - Alternatives, Options and Strategies (organised by CGWB and NABARD during 11-12 January, 1994 at New Delhi) that there is an impending need for constituting a new committee for updating the methodology for ground water assessment. This will also be in line with the recommendations made in National Water Policy for periodic assessment of ground water.

4.0 GROUND WATER MODELLING[2,4,5]

Ground water modelling is a tool that can help analyse many ground water problems. It begins with a conceptual understanding of the physical problem. The next step in modelling is translating the physical system into mathematical terms. In general, the final results are the familiar ground water flow equation and transport equations. These equations, however, are often simplified, using site-specific assumptions, to form a variety of equation subsets. An understanding of these equations and their associated boundary and initial conditions is necessary before a modelling problem can be formulated.

Mathematical ground water models essentially comprise (i) appropriate differential equations governing the ground water behaviour in a domain of interest and (ii) an algorithm to solve the equations - analytically or numerically. The analytical solutions are generally based upon many restrictive assumptions e.g. homogeneity; isotropy; time and (or) space independent withdrawals, recharge, boundary conditions; regular geometry of the domain. On the other hand the numerical solutions can follow the real world conditions quite closely and in fact, subject to the data availability, the only assumptions which need to be made, are the validity of Darcy's law and the continuity equation. However, the data inadequacy mostly does necessitate many assumptions even in numerical solutions. Nevertheless such solutions can generally provide far more realistic solutions than what can be provided by the analytical solutions.

4.1 Modelling of Flow in Unsaturated Zone

Soil moisture conditions of a basin controls the rainfall-runoff phenomena. It has been shown that performance of rainfall-runoff models is sensitive to the methods used to specify the effective precipitation and the antecedent moisture conditions. Study of soil moisture movement on a continuous basis considering both the storm and interstorm periods will not only determine antecedent moisture conditions but also would enable determination of recharge due to several rainfall events and evaporation losses from soil moisture storage.

Flow of water in the unsaturated zone is a complex phenomenon involving transfers of water, air and vapour through dynamic flow pathways under the influence of hydraulic, temperature, density and osmotic gradients in a compressible porous medium. In hydrological modelling, the physical representation of water flow in unsaturated zone has been made using Richards equation which combines Darcy's law with the equation of continuity. Richards equation is based on the assumptions that the fluid is incompressible and the flow takes place under isothermal condition. Both simulation and laboratory experiments have shown that under certain conditions, the effects of air, vapour and thermal fluxes may be important in the unsaturated zone. Theoretical reasoning would therefore suggest that the use of Richards equation as a simulator of the unsaturated zone should be expected to be inaccurate in some circumstances. Limiting conditions for the use of Richards equation for simulating processes in unsaturated zone in the field have not, however, been established and it is usually assumed, with some justification, that the error resulting from ignoring the multi-phase nature of the flow process may be negligible, relative to the problems of estimating the single-phase flow parameters for field situations. The complexity in physical representation of unsaturated fluid flow would further manifest in greater requirements for parameter and input data. These would include characteristic curves for the transport of air and vapour, thermal capacity and diffusivity, densities of water and air, and upper boundary conditions for air pressures, humidity and temperature in addition to water fluxes.

Another important aspect of soil moisture study which needs to be undertaken is soil moisture forecast. The soil moisture forecast will be useful for water management. A forecast of soil moisture is the prior estimate of the future state of soil water in the zone of aeration. The forecast variables include soil moisture status in the root zone depth, time of occurrence of permanent wilting condition, continuing period of permanent wilting condition, period for which the root zone depth remains in saturated state, time at which root zone attains field capacity, depth fraction of root zone depth that remains at less than field capacity. Roles of a short term forecast i.e. a forecast of future value of an element of the regime for a period ending upto two days from the issue of the forecast and a medium term or extended forecast for a period ending between two and ten days, in water management need to be investigated.

The controlling factors of soil moisture may be classified under two main groups viz. climatic factors and soil factors. Climatic factors include precipitation data containing rainfall intensity, storm duration, interstorm period, temperature of soil surface, relative humidity, radiation, evaporation and evapotranspiration. The soil factors include soil matric potential and water content relationship, hydraulic conductivity and water content relationship of the soil, saturated hydraulic conductivity and effective medium porosity. Besides these factors, the information about depth to water table is also required.

The continuous variation of soil moisture with time and depth can be known by solving the Richards equation. The presentation of the forecast may be in the form of a single value or in the form of probability distribution. Forecasting soil moisture would help in deciding irrigation application, enable prediction of the annual evaporation loss from shallow water table and recharge to ground water storage due to rainfall.

4.2 Modelling of Flow in Saturated Zone

The main objective of saturated ground water modelling exercise is to forecast the response of the aquifer to a proposed man-made excitation (e.g. pumpage, artificial recharge) acting in conjunction with other forms of natural excitation. A critical evaluation of the computed response can determine whether the proposal is acceptable or unacceptable in respect of prestipulated constraints. The response computed directly through the solution of the governing equations comprises water table or piezometric elevations distributed in space and time. The distributions can provide other forms of the response (e.g. stream-aquifer interaction, maximum and minimum depths to water table and/or saturated thicknesses) that a planner may be interested in.

The flow in the saturated zone is governed by a second order linear or non-linear differential equation, depending upon whether the flow is under confined or unconfined condition respectively. The non-linear equation governing unconfined flow can be linearised either by replacing space-time variant saturated thickness by an average space variant saturated thickness (first method of linearisation) or by change of variable from saturated thickness to the square of saturated thickness (second method of linearisation). The differential equations may account for only the horizontal flow (one or two dimensional) or may account for vertical flows also. The numerical solutions may be based upon either the finite difference or finite elements.

The ultimate objective of saturated flow modelling is to be able to forecast the aquifer response to a variety of excitation patterns. Such a modelling is termed as Direct Problem. However, for solving a direct problem, it is necessary to know spatially distributed estimates of the aquifer parameters. It is generally not feasible to carry out test pumping at large enough number of space points to get an adequate spatial distribution of the parameters. The way out is to arrive at such a distribution of the parameters which yields the best possible reproduction of historical water table/piezometric elevations under historical excitation. The inverse problem can be solved by either repeated solutions of the Direct Problem with varying aquifer parameters (indirect method of solving inverse problem) or by solving the governing differential equation directly for the parameters (direct method of solving inverse problem). The indirect methods can be based upon either simulation or rigorous optimization theory.

Most of the saturated flow modelling studies carried out in India have been related to unconfined alluvial aquifers bounded by rivers. The flow has generally been assumed to be two-dimensional horizontal and the non-linear differential equation governing such a flow linearised by the first method. The resulting equation has been mostly solved by finite differences although there have been a few studies employing finite elements. The inverse problem has been generally solved by the simulation based indirect method (i.e. repeated solution of the direct problem). Keeping in view the large areal extent of hard rock aquifers in India, the number of model studies on such aquifers has been rather marginal. Similarly, the number of studies on confined aquifers has been very marginal.

The theory of ground water flow towards partially and fully penetrating wells in unconfined, confined, and leaky aquifers has been developed by numerous authors. Results reported for wells in confined aquifers are derived as solutions to Jacob's differential equation for flow of slightly compressible fluids through deformable porous media. Results in unconfined aquifers are solutions to either the Laplace or Boussinesq equations describing hydraulic head distribution in porous media.

4.3 Spring Flow Modelling

Spring is a ready source of water, a place of natural beauty and a recreational spot. Springs generally provide clean water. They are found in the Himalayas, in the Western Ghats and in other places in India where it is logistically difficult to create storage for water. As such, study of spring flow has relevance to the water supply to rural areas, specially in the hilly region. However, there is no systematic hydrologic study of the springs so far and there is enough scope and need to study springs, particularly in respect of mathematical modelling of spring flow. Exploitation of forested area for food, fibre and minerals and urbanization lead to deforestation and changes in the watershed characteristics. This human interference leads to destruction of the internal hydrological system. As a consequence, the spring flow diminishes which may lead to drying of the spring.

Springs are basically natural outlets of concentrated discharge from an aquifer. A large spring indicates existence of thick transmissive aquifer whereas a small spring indicates an aquifer of low transmissivity. Discharge rate from a spring depends on the extent of the recharge area, the precipitation on the catchment of the spring, aquifer geometry, area of opening of the spring, geology and geomorphology of the area and diffusivity of the aquifer. The discharge of a spring depends on the difference between the elevations of the water table (or piezometric head) in the aquifer in the vicinity of the spring, and the elevation of spring outlet (called as threshold). During dry season, the spring discharge is derived from water stored in the aquifer. Consequently, the water level in the aquifer gradually falls and the spring discharge declines. The recession part of a spring hydrograph, in a semi-log plot (with time on the linear scale), may follow a straight line. Based on such observation, some conceptual linear hydrologic models have been developed to assess the dynamic storage which subsequently appears as spring discharge. These models assume that the spring flow is linearly proportional to the dynamic storage in the spring flow domain. The dynamic storage of ground water at any time during recession is equal to the product of depletion time and discharge of the spring. It is not yet verified that spring discharge from an aquifer conforming to a linear system would follow strictly an exponential decay curve.

5.0 GROUND WATER AND SURFACE WATER INTERACTION[2,6]

Ground water and surface water contained in the hydrological system are closely interrelated. Therefore, the study of the ground water/ surface water interrelationship has always been the subject of great attention on the part of hydrogeologists, hydrologists, and water resources specialists. The study of the character and particularities of the ground water/surface water interrelationship is currently one of the main interests of water sciences. The studies resulted in examination of the processes of ground water flow generation and estimation of ground water discharge including ground water discharge to rivers (base flow). There are many methods for quantitative estimation of streamflow components based on the analysis of streamflow depletion curves, separation of streamflow hydrographs, studying ground water regime and balance under natural conditions, establishing the correlation links between the levels and discharges of ground water and surface water under different natural conditions. During recent decades, the above studies were appreciably intensified primarily due to requirements of practice - the need or regional quantitative estimation of ground water discharge and natural resources (recharge) of fresh ground water.

The separation of streamflow hydrographs, taking into account the character of the hydraulic relationship between ground water and surface water under different hydrogeological conditions and taking into consideration the dynamics of base flow during the seasons of the year, allows us to estimate base flow quantitatively and, therefore, determine the natural ground water resources of the drainage zone in the case of ground water discharge to rivers.

In a ground water basin, it is common to identify several aquifers separated either by less permeable or impermeable layers. A river in general penetrates partially the upper aquifer. When the river stage rises during the passage of a flood, the upper aquifer is recharged through the bed and banks of the river. The lower aquifer is recharged through the intervening aquitard. A single aquifer river interaction problem has been studied analytically by several investigators. A digital model of multi-aquifer system has been developed assuming horizontal flow in the aquifers and vertical flow through the confining layers which separate the aquifers. These assumptions have reduced the mathematical problem to one of solving coupled two-dimensional equation for each aquifer in the system. An interactive, alternating-direction, implicit scheme has been used to solve the system of simultaneous, finite difference equations which describe the response of the aquifer system to applied stresses. The quasi three-dimensional model has been developed to simulate a ground water system having any number of aquifers.

The studies on the ground water/surface water interrelationship made it possible to solve a number of important scientific and practical problems :

1. to estimate base flow and, therefore, sustained low river discharges of different probabilities;

2. to estimate the ground water contribution to total water resources and the water balance of regions;

3. to evaluate quantitatively the natural ground water resources for determining the prospects of their use within large areas and as a component of the safe ground water yield.

The methods for estimating the ground water discharge of the upper hydrodynamic zone are fairly well developed and are being widely employed in hydrogeological practice, while studies on the estimation of the ground water discharge of deep artesian aquifers on their contribution to surface runoff are being carried out insufficiently.

6.0 CONJUNCTIVE USE OF SURFACE WATER AND GROUND WATER[2,6]

In a canal command, because of continuous and intensive application of surface water for irrigation, the water table comes up which may lead to water logging and salinity hazards. These problems can be prevented by withdrawing water from aquifer. If the ground water is not saline, it may be used to irrigate part of the canal command or it may be transported to other areas through the canal conveying surface water to the region. Losses from irrigation schemes to ground water are often significant. In a typical scheme, as much as 40 % of the water released from the reservoir is lost to the ground water. These losses occur in the canals and distributories as well as in the fields. Conjunctive use appears to be a realistic approach for the efficient use of the water. If the water lost from the conveyance system and agricultural field is pumped from the aquifer and supplement the canal water for irrigation, high overall efficiencies could be obtained.

Conjunctive utilization of surface and ground water implies not only their joint use but their coordinated use so that the useful water is more than the sum of the components, and is also used in an efficient economical way. Modern methods of hydrologic analysis can be used for evaluation of surface water resources, safe yield of aquifers and their interactions including the effect of development on availability. Planning models can then be used for efficient economic development and management of these resources in a conjunctive use framework.

While a general conceptual framework is available for the conjunctive utilization problems, case studies are available only at a much simpler level and it is hoped that more realistic studies will be made in the near future because of the importance of conjunctive utilization and the problems of unplanned, uncontrolled and uncoordinated development of different sources of water.

7.0 ARTIFICIAL RECHARGE[2]

It has been recognized that aquifers are not only sources of water but also storage reservoirs that require proper management for efficient use. With respect to management, an aquifer may be considered as a reservoir for long term storage artificially produced and as a water quality control tool because of its filtering characteristic that reclaims artificially recharged waste water. Artificial recharge may be viewed as an augmentation of the natural movement of surface water into underground formation by some method of construction, by surface spreading of water or by artificially changing natural conditions. The purpose of artificial recharge of ground water is to reduce or reverse declining levels of ground water in a basin, to prevent salt water intrusion from sea to coastal aquifer and to store surplus surface water and reclaimed water for future use. The base flow of a stream can be augmented by recharging ground water at locations far away from the stream so that the recharged water will reach the stream during periods of low flow.

The underground fresh water in coastal aquifer can be protected by a hydraulic barrier which can be created by artificial recharge through a line of wells.

The saturated and unsaturated ground water flow equations provide a means of analysing the impact of artificial recharge on ground water system. The complex hydrological conditions that develop during certain type of artificial recharge are (i) large change in saturated thickness and (ii) transport of contaminants in an aquifer. In recent years, numerical models have been exclusively used for solving the complex ground water flow problem.

In a hard rock ground water basin, it is common to find a weathered zone underlain by massive and fractured zones. The weathered zone and the fractured zone provide opportunity for storing surplus water in them. Both the layers can be recharged economically through a single injection well provided the well intercepts both the layers. Assessment of the quantity of water which is recharged to individual layer and determination of the part of the recharged water that is available in the zone of interest at any time are important tasks.

Construction of percolation tanks is a common practice in several parts of India objective of which is artificial replenishment of ground water for lift irrigation in small agricultural tracts. A percolation tank is created by constructing a small earthern dam across a natural stream at a suitable location. It is located upstream of an existing cluster of dug wells. The surface runoff during the short monsoon period is collected in the tanks. Under favourable soil and rock conditions, the water percolates and recharge the ground water. Effectiveness of percolation tanks in recharging ground water has been studied using the isotope method. In choosing among the several sources of available water for ground water recharge, increasing importance has been placed in recent years on the use of reclaimed municipal waste water.

8.0 SEA WATER INTRUSION[2]

In the coastal margins of ground water basin, the lowering of water level or potentiometric head can result in the intrusion of sea water, with a resulting degradation of water quality in the basin or a portion of the basin owing to the intruded sea water. For saline intrusion to occur, permeable formation must be in hydraulic connection with sea water, either directly on the ocean floor or along a river estuary or bay which contains sea water. Another necessary condition of saline intrusion is that there be an inland gradient, that is, there must be a tendency for water to move from the sea water sources to the pumping area. Such an inland gradient normally would result from pumping at rate higher than the recharge to the ground water basin. If these conditions exist, there will be a sea water wedge moving inland. The wedge-shaped intrusion results from the fact that sea water is approximately 1.025 times heavier than fresh water. The greater the depth below sea level, the greater is the pressure differential between sea water and fresh water, and hence there is faster movement of the sea water. In most coastal aquifers, the bodies of sea water and fresh water will maintain, for all practical purposes, separate identities because of the difference in density of the water. An exception to this condition occurs where there is a considerable variation in water levels from pumping and tidal fluctuations and where the formation is very permeable. There a transition or mixed zone of fresh water and sea water is known to occur underground.

Several methods to control saline intrusion have been suggested by hydrologists. These are (a) reduction of ground water extraction, (b) artificial recharge by spreading, (c) physical barrier, (d) dumping trough, (e) hydraulic ridge, and f) combination of pumping trough and hydraulic ridge. The relationship between quantity of water flowing to the sea and the length of the wedge is available in literature. Also mathematical modelling of unsteady flow of saline and fresh water in aquifer is documented. The method of controlling saline intrusion must be chosen considering the special condition of the area.

9.0 GROUND WATER POLLUTION[2]

In terms of biologic or organic quality, ground water is generally better than surface water and in terms of chemical quality (dissolved solids) surface water is generally better than ground water. Although it seems that ground water is more protected than surface water against pollution, it is still subject to pollution, and once pollution of ground water occurs, the restoration to the original, non-polluted state, is more difficult. Flushing processes in ground water reservoir are inefficient and expensive. It is easier to prevent the cumulative and complex process of deterioration than to prevent once pollutant concentration have reached problem proportion.

With the increased demand for water and with the intensification of water utilization, the water quality problem becomes the limiting factor in the development of water resources in many parts of the world. Most essential to developing an appropriate contaminant containment/control programme is that a thorough understanding of the subsurface system be developed. A detailed appraisal of the geologic and hydrogeologic setting must be made and the magnitude of the pollution hazard for a specific incident must be evaluated. As the movement of contaminants, and therefore, the methods of containment/control of the contaminants are largely dependent on the hydrogeologic environment, the effectiveness of the various methods will vary with different geologic settings. Designing a programme for containment or control of ground water contamination is further complicated by the fact that not all the contaminants behave in the same manner in the subsurface. Many contaminants move at different rates in the ground water system and may occupy different levels in aquifers according to their solubility in water, their density, and other physical properties peculiar to the contaminants. All of the processes of migration and alterations present in ground water are also present in the unsaturated zone. However the flow of water through the unsaturated zone is considerably more complex due to the presence of the air water vapour phases. Nevertheless it is important to note that the attenuation mechanisms in the unsaturated zone can provide a powerful barrier to the passage of contaminants to the saturated zone.

The containment and/or control of contaminated ground water can generally be accomplished using one or a combination of several available techniques. The alternatives available for remedial action can be classified into three broad categories (i) physical containment measures, including slurry trench cutoff walls, grout curtains, sheet piling, and hydrodynamic control, (ii) aquifer rehabilitation, including withdrawal, treatment, reinjection (or recharge), and in-situ treatment such as chemical neutralization and biological neutralization, (iii) withdrawal, treatment and use.

The objective of ground water pollution study in a basin is to answer the questions (i) what contaminants are present in the ground water? (ii) what are harmful levels for specific contaminants? (iii) how will the contamination levels in the ground water system change with time? (iv) can the source of contamination be controlled effectively? These questions could be answered by a hydrodynamic transport model. A programme of study of the quality of ground water envisages field observations regarding the source and environment of ground water occurrences, source of pollution and other related aspects having a bearing on the quality of ground water. In fact, determination of safe yield for a ground water resource must consider both its quantity and quality.

While exploiting ground water, it is appropriate to ascertain whether a ground water abstraction zone is liable to contamination and whether a potential source of pollution is contaminating the aquifer. In either case, the present and/or future conditions applicable to the migration of contaminants are determined. For analysis of pollution potential at a particular site, data describing contaminants, their migration characteristics and the characteristics of ground water regime are collected. Whilst inspection of the available data can provide a strong insight into a potential pollution hazard, the use of models may provide more appropriate and rigorous method for integrating all the available data together and for evaluation of the response of the aquifer system to a contamination event. The models are generally derived from the expression of the flow and transport processes in terms of mathematical equations which are then solved by incorporating appropriate parameter values and boundary conditions derived from the collected field data. Analytical solutions for solute transport in homogeneous and isotropic saturated porous media, in which the flow velocity is uniform, are available for simple one and two dimensional cases. Contaminant transport problems have been solved by numerical methods which are well documented. The numerical methods exhibit numerical spatial oscillations while solving the advection dominated transport problems.

10.0 CONCLUDING REMARKS

Although in recent years, intensive studies have been carried out on various aspects of ground water hydrology, there are still many gaps in our knowledge. The following are some of the aspects which are of great relevance for proper utilization of ground water resources and therefore need immediate attention:

(a) There is a need for establishing an integrated National and State Ground Water Data Storage and Retrieval System to collect, store, update, process and disseminate ground water data to enable planning and management of ground water resources.

(b) There is a need for constituting a new committee for updating the methodology for ground water assessment. This will also be in line with the recommendations made in National Water Policy for periodic assessment of ground water.

(c) There is a need for studying unsaturated and saturated flow through weathered and fractured rocks for finding the recharge components from rainfall and from percolation tanks in hard rock ground water basin. The irrigation return flow under different irrigation practices for different soils and different crops needs to be quantified. Also user friendly software should be developed for quick assessment of regional ground water resources.

(d) There is a need for studying soil moisture movement on a continuous basis considering both the storm and interstorm periods. The soil moisture forecast model needs to be made operational on interactive mode.

(e) There is a need for the study of interaction among a stream and several aquifers which are separated by an aquitard considering the changing river width and stage that may occur during passage of flood. A ground water flow model for a multi-aquifer system to cater the need of ground water management should be developed. The assessment of induced recharge due to ground water abstraction in the river basin should be made for planning optimal operation of a ground water reservoir.

(f) A hydrologic study is required to rejuvenate drying springs. Delineation of recharge area of the spring by remote sensing and nuclear methods needs special efforts for controlling human interference. There is a need for finding the true relationship between dynamic storage of ground water and the spring discharge.

(g) There is a need for development of methodology to predict quantity of water artificially recharged by different methods and their temporal and spatial availability in the area of interest. Appropriate method of artificial recharge in hard rock basin and method for retaining the recharged water in the subsurface reservoir need to be established. It remains to be investigated how effectiveness of percolation tanks decreases with time because of siltation, what fraction of the water stored joins the ground water because of evaporation from tank, how much increment in recharge rate could be achieved through construction of recharge shafts. Pretreatment process of the waste water and renovation of waste water with rapid infiltration land treatment system are presently important areas of research.

(h) There is a need to develop numerical scheme to eliminate numerical oscillation while solving the advection dominated transport problems. Assessment of ground water quality in many ground water basins remains as a task yet to be performed.

REFERENCES

1. "Ground Water Estimation Methodology". Report of the Ground Water Estimation Committee, Ministry of Irrigation, Government of India, New Delhi, March 1984, 39 pp.

2. G C Mishra. "Research and Development in Hydrology - Ground Water Hydrology". Proceedings, National Workshop on Thrust Areas of Research in Hydrology, 17-18 June 1993, Roorkee, pp. 72-89.

3. Recommendations of the National Workshop on "Development of Ground Water in Critical and Semi-critical Areas - Alternatives, Options and Strategies" organised by Central Ground Water Board & National Bank for Agriculture and Rural Development, 11-12 January 1994, New Delhi.

4. C P Kumar. "Ground Water Modelling". In. Hydrological Developments in India Since Independence, A Contribution to Hydrological Sciences, National Institute of Hydrology, Roorkee, 1992, pp. 235-261.

5. Deepak Kashyap. "Mathematical Modelling for Ground Water Management - Status in India". Proceedings, Indo-French Seminar on Management of Water Resources, 22-24 September 1989, Festival of France - 1989, Jaipur, pp. IV-59 to IV-75.

6. G B Engelen and G P Jones. "Developments in the Analysis of Groundwater Flow Systems". IAHS Publication No. 163, A Contribution to the International Hydrological Programme of UNESCO (Project A 2.8), 1986, 356 pp.