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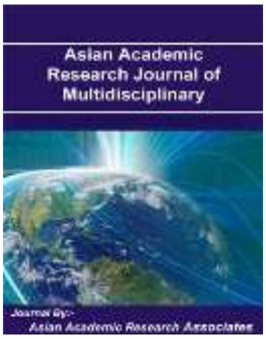

ASSESSMENT AND STRATEGIES FOR DEVELOPMENT POTENTIAL OF DEEPER CONFINED AQUIFERS IN INDIA

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ABSTRACT

The annual replenishable groundwater resources of India have been estimated as 431 BCM. In addition to the annual replenishable groundwater resources in the active recharge zone, there exists a huge groundwater resource in the deeper parts of the unconfined aquifers and also in the deeper confined aquifers in the areas covered by alluvial sediments. There is a need for effective exploration, development and management of water stored in deep aquifers. While the volume of water stored in them is large, it must be used wisely, for its renewal through surface infiltration is low or non-existent. This article presents general groundwater scenario in India and methodology for assessment of development potential of deeper confined aquifers.

INTRODUCTION

Groundwater resources development is viewed as a sequential process with three major phases. First is the exploration stage, in which surface and subsurface geological and geophysical techniques are utilized to search for suitable aquifers. Second is the evaluation stage that encompasses the measurement of hydrogeological parameters, the design and analysis of wells and calculation of aquifer yields. Third is the exploitation or management phase which must include consideration of optimal development strategies and assessment of the interaction between the groundwater exploitation and the regional hydrologic system.

Assume that we have located an aquifer that has some apparent potential represented by an adequate saturated thickness, permeable porous media and high storage coefficient. All these promising indicators are not enough to evaluate and manage the explored aquifer. Instead, the following questions should be raised and answered to evaluate the aquifer potential and to set the proper management strategy for the available groundwater resources:

- Where should the wells be located? How many wells are needed? What pumping rates can they sustain?
- What will be the effect of the pumping scheme on the regional groundwater levels and long-term storage?
- What are the long-term yield capabilities of the aquifer?
- Will the proposed development have any negative influence on other components of the hydrologic cycle?
- Are there likely to be any undesirable side effects of development, such as land subsidence or sea water intrusion that could limit the aquifer yield?

The above-mentioned questions clearly indicate that the aquifer potential term has no significant meaning at the operational management of the aquifer. Therefore, groundwater potential can be considered a superficial term that is used only to qualitatively describe the aquifer ability to store and transmit water efficiently for economic uses. The techniques of groundwater resources evaluation require an understanding of the concept of groundwater yield. Safe yield is the annual amount of withdrawal that does not exceed annual recharge, permanently lower the water table to an uneconomical level, or allow intrusion of poor-quality groundwater.

Groundwater potential for confined non-renewable aquifers is defined as the maximum flow rate from the pumping wells that result in a predefined value of the drawdown. This will dictate determination of the aquifer hydraulic characteristics of the aquifer (transmissivity and storage coefficient) from pumping tests data. With the given input data and the management strategy, the groundwater hydrologist should be able to determine the number of wells with their respective daily discharge rate and the safe well spacing to cause a drawdown of predefined value. The sum of the well discharges represents the annual groundwater potential or the aquifer safe yield.

GROUNDWATER RESOURCES OF INDIA

The National Water Policy (2012) states that *'there is a need to map the aquifers to know the quantum and quality of groundwater resources (replenishable as well as non-replenishable)* *in the country*'. The amount of water which is replenished annually through rainfall and other sources like irrigation etc. is known as the replenishable groundwater. The annual replenishable groundwater resources of the country have been estimated (as on 2009) based on Groundwater Resource Estimation Methodology (GEC-1997). Attempt has also been made to categorize the assessment units into different categories as per the stage of development and water level trends. The present scenario of annual replenishable groundwater resources is not very encouraging as nearly 17% of the assessment units in the country have been placed under over-exploited/ critical category.

The annual replenishable groundwater resources have been assessed as 431 BCM. Keeping an allocation for natural discharge, the net annual groundwater availability is 396 BCM. The annual groundwater draft (as on 31st March, 2009) is 243 BCM. The stage of groundwater development works out to be about 61%. The development of groundwater in different areas of the country has not been uniform. Out of 5842 assessment units (Blocks/ Mandals/ Talukas) in the country, 802 units in various states have been categorized as 'Over-exploited' i.e. the annual groundwater extraction exceeds the net annual groundwater availability and significant decline in long term groundwater level trend has been observed either in pre-monsoon or post-monsoon or both. In addition, 169 units are 'Critical' i.e. the stage of groundwater development is above 90% and within 100% of net annual groundwater availability and significant decline is observed in the long term water level trend in both pre-monsoon and post-monsoon periods. There are 523 Semi-critical units, where the stage of groundwater development is between 70% and 100% and significant decline in long term water level trend has been recorded in either pre-monsoon or post-monsoon. 4277 assessment units are Safe where there is no decline in long term groundwater level trend. Apart from this, there are 71 blocks completely underlain by saline groundwater.

The overexploited areas are mostly concentrated on three parts of the country. In north-western part in Punjab, Haryana, Delhi, Western Uttar Pradesh where though replenishable resources are abundant but there have been indiscriminate withdrawals of groundwater leading to over-exploitation; in western part of the country particularly in Rajasthan where due to arid climate, groundwater recharge itself is less leading to stress on the resource; and in peninsular India like Karnataka and Tamil Nadu where due to poor aquifer properties, groundwater availability is less. In some areas of the country, good continuous rainfall and management practices like groundwater augmentation and conservation measures through government and private initiatives have resulted in improvement in groundwater situation.

Over-exploitation of groundwater resource (stage of groundwater development being more than 100%) refers to the development of groundwater resource which is available below the active recharge zone or zone of fluctuation that is sometimes referred as static or in–storage groundwater reserve. The quantum of water available for development is usually restricted to long term average recharge or in other words to "dynamic resource". Temporary depletion of water table taking place in drought years can be made up in years of high rainfall or in other words, the utilisation of static reserves and consequent depletion in water levels in drought years can be made up during years of high rainfall. This may be studied by comparing the long term rainfall and the water table hydrograph to establish the periodical recharge. In such areas, it would be desirable that the groundwater reservoir be drawn to the optimum limit to provide adequate scope for its recharge during the following monsoon period. An estimate of static groundwater reserve is desirable for planning the optimum utilisation for future development of groundwater resources of an area. The static groundwater resource in an area may be computed as below:

Static Groundwater Reserve (m^3) = (thickness of the aquifer below the zone of water level fluctuation down to exploitable limit, m) * (areal extent of the aquifer, m^2) * (specific yield of the aquifer)

The development of static groundwater resource needs to be done carefully and cautiously. It is recommended that the static groundwater resource may be evaluated basin wise/district wise in each state. Hence, in addition to the annual replenishable groundwater resource, there exists a huge groundwater reserve in the deeper aquifers below the active recharge zone and in the confined aquifers in the areas covered by alluvial sediments of river basins, coastal and deltaic tracts constituting the unconsolidated formations. This article attempts to present methodology for assessment of groundwater potential of deeper aquifers below the first confining layer in the alluvial areas.

GROUNDWATER SCENARIO OF DEEPER AQUIFERS

Hydrogeological Setup

Two broad groups of water bearing formations have been identified in the country depending on occurrence and movement of groundwater viz. porous formations which can be further classified into unconsolidated and semi-consolidated formations having the primary porosity and fissured formation or consolidated formations which has mostly the secondary or derived porosity. The major aquifer systems and their yield prospects are shown in Figure 1.

Figure 1: Hydrogeology of India

In India, prolific deeper aquifers exist in Indo-Gangetic-Brahmaputra basin and coastal tracts. Deeper aquifers with relatively good potential also exist in the faulted basins in Godavari, Mahanadi, Narmada, Tapi, Son and Damodar basins. Hard rock terrains are comparatively devoid of high potential deeper aquifers.

Indo-Gangetic-Brahmaputra Alluvial Plains

This region encompasses an area of about 850,000 sq. km. covering the states of Punjab, Haryana, Uttar Pradesh, Bihar, Assam and West Bengal, accounting for more than one fourth of country's land area, comprises the vast plains of Ganges and Brahmaputra rivers and are underlain by thick piles of sediments of Tertiary and Quaternary age. This vast and thick alluvial fill, exceeding 1000 m at places, constitute the most potential and productive groundwater reservoir in the country. These are characterized by regionally extensive and highly productive multi-aquifer systems. The deeper aquifers available in these areas offer good scope for further exploitation of groundwater with suitable measures. In Indo-Gangetic-Brahmaputra plain, the deeper wells have yield ranging from 25-50 lps.

Coastal Area

India has a main land coastal tract of about 5400 kms. characterized by thick cover of alluvial deposits of Pleistocene to Recent age and constitutes potential multi-aquifer systems in the states of Gujarat, Maharashtra, Goa, Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Orissa and West Bengal. Groundwater prospects and yield potential in these aquifers vary widely depending on the local conditions. However, inherent quality problems and the risk of seawater ingress impose severe constrains in the development of these aquifers.

Aquifers along the coastal tracts of India can be broadly classified as aquifers in porous sedimentary formations and in fissured formations or the hard rock aquifers. The sedimentary tracts, all along the east coast and the coastal plains of Kerala and Gujarat are mostly occupied by 'porous' aquifers while major parts of west coast and parts of Andhra Pradesh and Tamil Nadu coasts are occupied by 'fissured' aquifers. Further, aquifers in the sedimentary tract can be grouped depth-wise into two main groups, viz. shallow aquifers, mostly in the Quaternary alluvium and deeper aquifers in underlying sediments ranging in age from Tertiary to Permo-Carboniferous. Shallow aquifers are mostly separated from underlying deeper aquifers by clay layers. In coastal areas, the aquifers comprising of saline and fresh water represents varied conditions in terms of their dispositions.

Peninsular Shield Area and Faulted Basins

The peninsular shield areas consist mostly of consolidated sedimentary rocks, basalts and crystalline rocks in the states of Karnataka, Maharashtra, and Tamil Nadu, Andhra Pradesh, Orissa and Kerala. Occurrence and movement of groundwater in these areas is restricted to weathered residuum and interconnected fractures having limited groundwater potential. Groundwater occurs mainly in the weathered and fractured zones of rocks, within depth of less than 50 m, occasionally down to 100 m. In these areas, due to absence of multi-layered aquifers and practically non-existence of secondary porosity at depths more than 100 m, chances of deeper potential aquifers are remote.

Faulted / structurally controlled basins in peninsular India having unconsolidated, semi-consolidated and consolidated formations have groundwater potential in deeper aquifers under favourable hydrogeologic situations. In Godavari, Mahanadi, Narmada, Son and Damodar basins, groundwater occur in sedimentary formations. The total thickness of the sediments extent is upto 7000 m. These sedimentary strata under suitable topographic conditions, give rise to auto flowing conditions in wells. Extensive valley fill deposits exist in three discrete fault basins - Narmada, Purna and Tapi valleys. The thickness of valley-fill deposits ranges in thickness from about 50 to 150 m.

Groundwater Development of Deeper Aquifers

In most of the alluvial plains, major groundwater exploitation is from shallow aquifers. However, in parts of Haryana, Punjab and Uttar Pradesh, farmers are pumping groundwater from deeper aquifers recently due to declining water levels, reducing well yields and assured groundwater supply. At places, Public Health department of state governments are also constructing pumping wells for drinking water supply from multiple aquifers including deeper confined aquifers too. Few studies conducted by NABARD in the selected blocks of Sangrur and Rupnagar districts of Punjab regarding sustainability of groundwater use also revealed replacement of shallow tubewells with deeper wells and centrifugal pumps with submersible pumps as common phenomena in the state. However, estimation of groundwater utilization from deeper aquifers is not possible with the existing database, since census data provides information regarding number of wells but do not provide specific information regarding aquifers being tapped.

Several studies have been conducted on the development and management of groundwater resources of deeper aquifer systems in various parts of the world. Similar water balance studies were also carried out in India to decipher the groundwater potential of aquifer systems including deeper aquifers e.g. Rajasthan and Gujarat (UNDP project), Upper Yamuna basin studies, Betwa river basin project etc. However, no specific literature on methodology for assessment of development potential of deeper aquifer is available. Two representative case studies – one each from India and aboard have been illustrated in the report of CGWB (2009).

ASSESSMENT OF DEVELOPMENT POTENTIAL OF DEEPER AQUIFERS

Based on the occurrence, movement, and mechanism of release of groundwater, the geologic material can be classified into various aquifer systems such as unconfined, semi-confined and confined. The groundwater which is available in the zone of water level fluctuation is called dynamic groundwater resources or annual replenishable groundwater resources. Below the zone of water table fluctuation, the groundwater which is available in the perennially saturated portion of the aquifer in the phreatic zone is called as static or in-storage groundwater resources. The water bearing formation below the phreatic zone has been considered as deeper aquifer in the present context. The deeper aquifer broadly constitutes the semi-confined and confined aquifers depending upon the nature or extent of the confining layers.

The dynamic as well as in-storage groundwater resources belong to the unconfined / phreatic aquifer, the thickness of which varies from place to place depending upon depositional history. For computing dynamic groundwater resources and static groundwater resources, detailed methodology has been outlined in GEC-1997. This article presents the suitable method/s for assessment of resource potential of the first confined aquifer in the deeper zone.

There are two types of situations of occurrence of confined aquifers. In hard rock areas, the upper water table aquifer in the weathered zone is connected to the deeper fracture zone, which is semi-confined. In such situations, the assessment procedure applicable for unconfined aquifer accounts for the full recharge, and hence no separate assessment is to be made for the confined aquifer.

In specific alluvial areas, resource from a deep confined aquifer may be important. If the confined aquifer is hydraulically connected to the overlying shallow water table aquifer, it is a semi-confined aquifer, and not strictly a confined aquifer. If there is no hydraulic connection to the overlying water table aquifer, the resource may have to be estimated by specific detailed investigations, taking care to avoid duplication of resource assessment from the upper unconfined aquifers.

A confined aquifer is broadly a porous and permeable geological unit, which is sandwiched between two relatively low permeability layers (unconfined aquifers are only bounded by a low permeability layer below). Because the confining layers above and below these aquifer systems are usually regionally extensive, the recharge and discharge areas of these aquifers may be hundreds of kilometers apart. The groundwater flow dynamics in confined aquifer is different from that in unconfined aquifer. The main source of recharge to any aquifer is rainfall. In case of unconfined aquifer, recharge is both through vertical infiltration and lateral inflow while in confined aquifer, the recharge is through lateral inflow and vertical exchange from top as well as bottom aquifers. The recharge zone in case of confined aquifer is located far apart and the groundwater is under pressure. Under pre-development conditions within a confined aquifer, there is a dynamic equilibrium between recharge and discharge or outflow from a confined aquifer. Water is under pressure within confined aquifer and total volume in storage remains relatively constant.

Confined aquifer systems are more sensitive to development than unconfined systems because of their hydraulic properties. In the wells tapping the confined aquifers, initially water is released from the well storage and subsequently from the compressibility of the fluid and compaction of aquifer material which is controlled by elastic properties of aquifer material. However, in case of unconfined aquifer, the mechanism of release of water is mainly because of de-saturation of aquifer. The quantity of groundwater involved in storage change in confined aquifers is usually several orders of magnitude smaller than that involved in phreatic aquifers.

Assessment of development potential of confined aquifers assumes crucial importance, since over-exploitation of these aquifers may lead to far more detrimental consequences that those of shallow unconfined aquifers. If the piezometric surface of the confined aquifer is lowered below the upper confining layer so that desaturation of the aquifer occurs, the coefficient of storage is no longer related to the elasticity of the aquifer but to its specific yield. In view of the small amounts of water released from storage in the confined aquifers, large scale pumpage from confined aquifers has caused declines in piezometric levels amounting to over a hundred metre and subsidence of land surface posing serious geotectonic problems.

There are several methods mentioned in literature on the assessment of groundwater potential in confined aquifers. The most widely used analytical techniques are based on lumped approach using flow-rate and storage concepts. Numerical modelling techniques are commonly used at local to sub-regional scale using groundwater flow equations.

(a) Groundwater Flow Rate Concept

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

$$Q = T\,I\,L \qquad \text{... (1)}$$

where,

Q = rate of flow through a cross-section of aquifer in m^3/day;
T = transmissivity in m^2/day;
I = hydraulic gradient in m/km;
L = average width of cross-section in km.

The transmissivity may be computed from pumping test data of tubewells. Leakage from overlying or underlying aquifer may also be accounted in the calculation of groundwater available for development in a confined aquifer.

The tubewell draft tapping a deeper confined aquifer may be accounted at the time of quantitative assessment of deeper confined aquifer. The total draft of these tubewells may be taken as gross draft of which 30 percent may be taken recycled and may be added as recharge to water table aquifers. The utilisable recharge may be taken as 85 percent of the total groundwater flow available for development.

For working out optimum development of the confined aquifers, it is recommended that the recharge area of the confined aquifers may be demarcated, the average annual recharge to the confined aquifer in this recharge area estimated, and extent of development of this aquifer is limited to the amount of recharge.

(b) Groundwater Storage Concept

The coefficient of storage or storativity of an aquifer is defined as the volume of water it releases or takes into storage per unit surface area of the aquifer per unit change in head. Hence, the quantity of water added to or released from the aquifer (ΔV) can be calculated as follows.

$$\Delta V = S\,\Delta h \qquad \text{... (2)}$$

If the areal extent of the confined aquifer is A, then the total quantity of water added to or released from the entire aquifer is

$$Q = A\,\Delta V = S\,A\,\Delta h \qquad \text{... (3)}$$

where,

Q = quantity of water, confined aquifer can release (m^3);
S = storativity;
A = areal extent of the confined aquifer (m^2);
Δh = change in piezometric head (m).

Most of the storage in confined aquifer is associated with compressibility of the aquifer matrix. Once the peizometric head reaches below confining bed, it behaves like an unconfined aquifer and directly dewaters the aquifer. The quantity of water released in confined aquifer due to change in pressure can be computed between piezometric head (h_t) at any given time 't' and the bottom of the confining layer (h_0) by using the following equation.

$$Q_p = S\,A\,\Delta h = S\,A\,(h_0 - h_t) \qquad \text{... (4)}$$

where,

Q_p = quanity of water released under pressure (m^3);
S = storativity;
A = areal extent of the confined aquifer (m^2);

Δh = change in piezometric head (m);
h_t = piezometric head at time t;
h_0 = bottom of the confining layer.

While assessing the groundwater potential by flow rate and storage concept, the study area needs to be distributed into smaller units (zones) for accommodating the anisotropy in aquifer parameters (T & S) as well as spatial variations in piezometric heads. In case of piezometric heads, it is desirable to prepare the contours for pre and post monsoon periods separately so as to calculate the flow direction, length of flow as well as the hydraulic gradient. The hydraulic gradients should preferably be computed at optimal number of discrete points to arrive at average gradient for the entire area.

As far as possible, the lowering of piezometric head should be avoided below the upper confining layer to avoid any environmental degradation such as land subsidence and irreversible aquifer damage etc.

(c) Groundwater Modelling Concept

Groundwater modelling technique is one of the advanced methods for assessment of groundwater potential of confined aquifers. The objective is to determine permissible level of pumpage, so that piezometric head should not go below the upper confining layer of the confined aquifer or to a defined level, as the case may be. The methodology involves solving the governing differential equations of groundwater flow either by analytical or numerical approach.

When the system is complex and anisotropy is to be considered, the only choice left is to go for numerical models which involve simulation of groundwater flow equation in the specified spatial and time domain. Modelling technique requires enormous data and true demarcation of aquifer geometry which may not be practical for regional aquifer system. However, groundwater flow models can be simulated for a smaller study area which requires proper planning for data collection. The results of such studies can be extended to other areas with similar hydrogeological conditions. Numerical models are capable of solving more complex equations that describe groundwater flow and solute transport. These equations generally describe multi-dimensional groundwater flow, solute transport, and chemical reactions. The commonly used numerical approaches used in practice for solving groundwater flow equations are Finite Difference Method (FDM) and Finite Element Method (FEM).

The accuracy of model predictions depends upon the degree of successful calibration and verification of the model simulations. Errors in the model used for predictive simulations, even though small, can result in gross errors in solutions projected forward in time. Monitoring of hydraulic heads and groundwater chemistry (performance monitoring) will be required to assess the accuracy of predictive simulations. Numerical modelling requires a complete protocol to be followed starting from establishing the purpose or objectives of modelling, conceptualization, model design, calibration, validation, predictions, sensitivity analysis and finally, post-audit.

The recent concept of groundwater management models are exclusively used to establish the safe limit for exploitation of groundwater from different aquifer systems including confined aquifer. The groundwater management models basically operate on simulation - optimisation platform (SO model) with an objective to arrive at the safest level of development without dropping the heads below given level at specified locations.

Applicability of Various Methods

The applicability of various methods for assessment of groundwater resources in confined aquifers depends on scale of assessment, availability of hydraulic parameters and purpose of the study. The storage concept and rate concept methods are simpler and can be applied on a regional scale, if the required parameters pertaining to confined aquifers are available. The availability and development potential of groundwater in confined aquifers can be approximated using these methods. In the rate concept, the volume of water flowing through a specified column in specified time is approximately equal to the amount available for development during that period. In the storage concept, the volume of groundwater available for development at a particular time can be approximated by lowering the piezometric heads to a desired level.

CONCLUDING REMARKS

- The assessment of groundwater availability and development potential of deeper aquifers would require detailed mapping of aquifer systems to establish the aquifer geometry including delineation of recharge areas of the confined aquifers and estimation of aquifer parameters. Therefore, regional aquifer mapping and establishing aquifer geometry / parameters of the individual aquifers need to be undertaken for the entire country.

- There should be a well established mechanism for monitoring the water level / piezometric heads with optimal network density and frequency for different aquifers.

- The preliminary estimate of the availability and development potential of groundwater in confined aquifers can be attempted using simplistic approach of flow rate concept and storage concept. However, for the purpose of planning groundwater development of confined aquifers, precise assessment of availability and their development potential need to be ascertained by groundwater modelling approach.

- The resources of deeper confined aquifers can be harnessed keeping in view the long term sustainability of the aquifers. An essential consideration in the development of confined aquifer is the chemical quality of water. The primary management tool for groundwater development in confined aquifers is well spacing, restriction on the rate of withdrawal from the aquifers.

- Groundwater availability and potential in confined aquifers need to be assessed in a scientific way before planning for its development, keeping in view the adverse consequences of over-development of confined aquifers.

- Groundwater resources assessment, like other fields of science, requires continuous refinements. The issue becomes more relevant considering the strong linkage between assessment and groundwater management. Some of the suggestions to bring in further refinements in the groundwater resources assessment approach are – strengthening of database, setting up dedicated groundwater resources assessment cell, pilot studies on yearly assessment and assessments in doab (alluvial area) and micro-level unit (hard rock area), and application of alternate methods for recharge estimation.

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