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Analytical Study of Environmental Impacts and Their Effects on Groundwater Hydrology

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Abstract

The hydrology of the groundwater is not just the science of subsurface water but also encompasses the rock strata and structure matrix in which it is contained. It also deals with the natural and man-made activities that affect the quality and quantity of subsurface water and physiology, geology, and minerology of the rock structure as well as the effects of the environment, climate, and other physical and natural forces trying to alter the subsurface water source in either way. Strategies for management and upkeep of groundwater as a resource are also discussed for sustainable and equitable usage by all stakeholders.

Keywords: hydrology, groundwater, subsurface water, aquifers, variations, fluctuations, environment, meteorology, geohydrology

1. Introduction

For thousands of years, man has survived living in arid regions of the world solely by skillfully managing that vital but scarce resource called water [1]. Out of the two, the surface water and the groundwater, the groundwater has always been more important for survival due to its intrinsic quality of natural preservation. Groundwater is a vital source of fresh water for domestic, agricultural, and industrial use. Currently contribution of groundwater is almost 34% of the total annual water supply. Water consumption is increasing day by day due to continuous development of the economy, industrialization, and changes in life patterns, which cumulatively results in shortage of usable water.

To meet the increasing water demands, reliance on groundwater has been rapidly increasing, especially in the arid and semiarid regions leading to water exhaustion and overconsumption of groundwater, causing ecological problems such as decreased water levels, water pollution, seawater intrusion, and deterioration of water quality. The recharge of groundwater occurs both naturally and artificially. The natural recharge occurs through the process of infiltration where water percolates from the surface to the bed of the aquifer. But due to rapid development and stupendous growth of population in the recent past, the areas for natural infiltration have been lessening day by day; hence the scope for natural recharge of the groundwater is also declining [2].

The combination of decreasing water availability and increasing water demand can lead to drastic water shortages. Groundwater exploration involves knowledge of hydrological properties of various geological materials such as porosity, permeability, storage coefficient, transmissivity, and specific yield or in other words holding and discharge capabilities of geological materials.

2. Groundwater variations

In the nature, water resources and water demand are unevenly distributed both spatially and temporally. It is these uneven distributions that make the groundwater hydrology more complex and dynamic in its nature and form. Ironing out of the variations and equitable juxtaposition of haves and have-nots in both demand and resource is the ultimate goal of all hydrological knowledge.

2.1 Spatial variations

These variations in the groundwater levels are with respect to physical location and space. Physical properties including type of soil, groundwater depth, porosity of vadose zone, rainfall patterns, and hydrogeology tend to vary the groundwater recharge spatially. Fluctuations in the groundwater levels are generally greater in the areas of low drainage density than those in regions of moderate to high drainage density. The factors like weathering intensity, presence of fractures, and drainage density control the quantity of groundwater. In such regions groundwater flow and quantity are not controlled by highly weathered dykes in shallow unconfined aquifers. The phenomena like fracturing, weathering, and faulting increase the permeability of rocks and the recharge which controls the fluctuations in groundwater levels. For the fluctuations in groundwater levels in terrains of hard rocks, several studies have been carried out. Fractured and weathered rocks carry the groundwater under unconfined conditions, and the major source for groundwater recharge is rainfall. Due to downward seepage of rainfall, the unconfined aquifers are recharged in the unsaturated zone [3].

2.2 Temporal variations

Variations in the phreatic levels, chemical concentration levels, biological concentration levels, and fluid properties of the groundwater may be described with respect to time as seasonal variations and secular variations.

2.2.1 Seasonal variations

Such variations are periodic. The changes in the water level due to some seasonal happenings such as rainfall, storms, and irrigation pumping are referred to as seasonal variations. Water-level fluctuation in summer and winter is also considered under the same type. The lowest variations in water levels occur in winter season, while the highest occur during late spring. At the end of the irrigation season in an irrigated area, the lowest variations in water levels normally occur where frozen ground is not a factor. **Figure 1** shows the variations in the water levels for frozen ground areas in winter are periodic [4].

2.2.2 Secular variations

Such variations are nonperiodic and show the change in the water level over several years, which cover the dry and wet seasons and the related groundwater

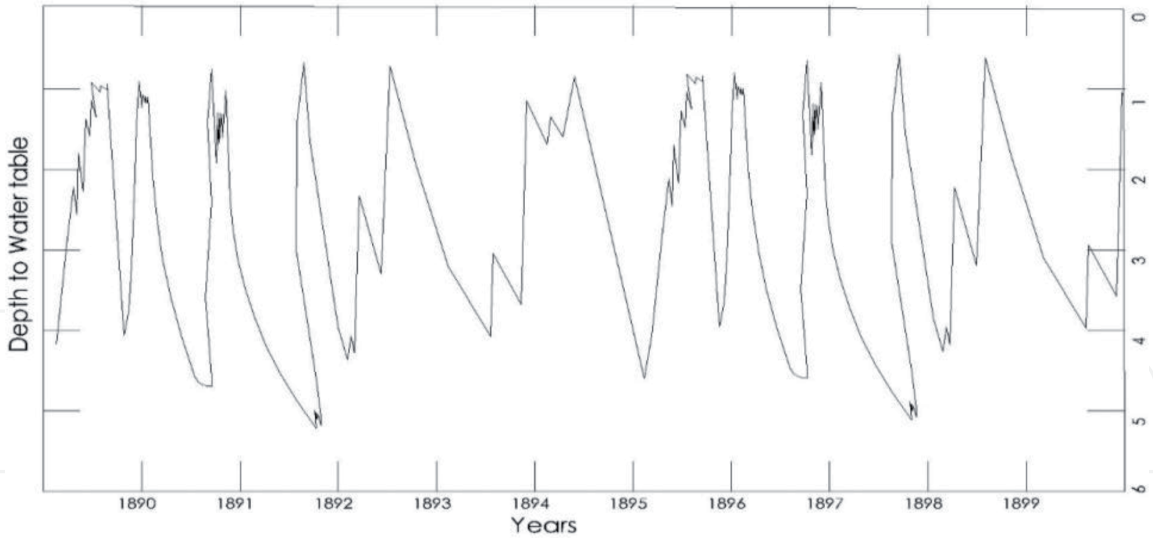


Figure 1.
Seasonal variations [4].

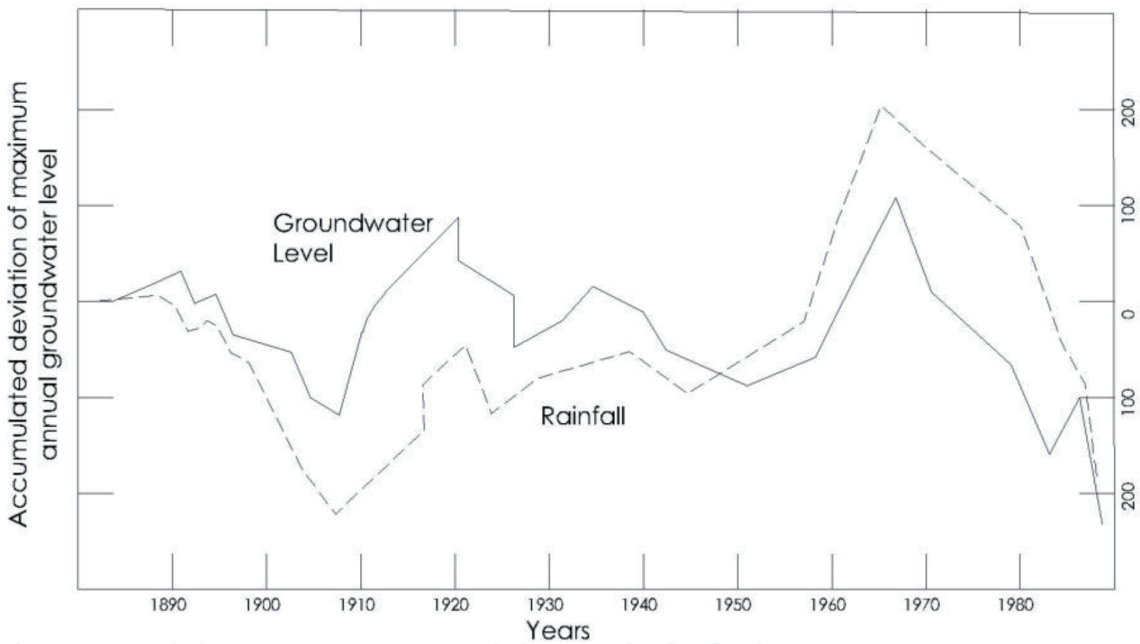


Figure 2.
Secular variations [4].

fluctuations. Long-term fluctuations in water levels are produced when rainfall is above or below the mean, during alternating a series of dry and wet years. **Figure 2** shows the long records of groundwater levels and rainfall and illustrates that rainfall is not an accurate indicator of variations in groundwater levels [4].

3. Impacts of human activities

3.1 Urbanization

Groundwater, as the world's most vital natural resource for the reliable provision of potable water supply, is affected by urbanization. Due to rapid urbanization and increasing industrial activities, the need for fresh water has increased in the past few decades. Almost 50% of the world population lives in urban areas, and

the proportion is expected to increase in the coming decades. Urbanization brings many benefits such as increased job and education opportunities, cultural activity, and economic diversification. However, unplanned urban growth is also leading to challenges such as the overexploitation of water resources. Furthermore, land-use changes and anthropogenic activities such as surface sealing due to streets and buildings, flood control, forest management, and irrigation modify the infiltration and movement of water. The authors [5] have shown that due to urbanization, built-up area increased by 271%, water bodies decreased by 46%, and bare land decreased by 129% in the study area. These modifications linked with urbanization often lead to groundwater resource deterioration [6].

There are many conditions which interrupt the subsurface water balance, and as a result groundwater levels are lowered. A few of such conditions are listed below:

- a. Groundwater recharge is reduced by paving the surface areas and building the storm sewers. When the surface area is paved, it stops the surface water entry into the ground, and as a result the groundwater recharge is reduced. Also when storm sewers are built, they store the amount of surface water, stop the water entry into the ground, and result in reduction of recharge.
- b. Pumping wells increase the groundwater discharge which results in lowering of groundwater table.
- c. Collection of wastewater in sanitary sewers also decreases the groundwater recharge.
- d. Huge reduction in groundwater recharge occurred nowadays due to excess plastic wastage.

3.2 Excessive extraction

Groundwater is our major source of water. Due to climate change, rapid urbanization, industrial activities, and intensive agricultural practices have put a tremendous pressure on groundwater. Groundwater depletion occurs when the pumping rates are excessively higher than the rate of replenishment.

The extreme use of groundwater resources can have serious concerns, such as uplifting and seismic activities, ecological environment deterioration, land subsidence, vegetation degradation, livelihoods for rural poor, and food security implications. In view of the shrinking groundwater resources, it is important to develop effective techniques and methods to study the trend of groundwater storage (increase/decrease) and its recharge-discharge relationship, which can support the mitigating measures of overpumping shallow groundwater to ensure the sustainable utilization of groundwater resources [7].

4. Environmental and natural impacts

4.1 Meteorological phenomena

Fluctuations in groundwater due to meteorological phenomena are caused by atmospheric pressure, rainfall, wind, and frost. As stated by [8], aquifers are inherently very resilient to atmospheric variations above ground, but climate adversely alters the aquifer's groundwater recharge, thus introducing uncertainties in spatial pattern definitions.

4.1.1 Atmospheric pressure

Variations in atmospheric pressure produce fluctuations in wells penetrating confined aquifers. There is an inverse relationship between atmospheric pressure and water levels. It means that increase in atmospheric pressure will decrease the water levels and vice versa. If the changes in the atmospheric pressure are expressed in terms of a column of water, then the ratio between changes in water levels and pressure is known as barometric efficiency of an aquifer. This efficiency is expressed by the following equation:

$$B = \gamma \Delta h / \Delta p_a \quad (1)$$

where B = barometric efficiency of an aquifer, γ = specific weight of water [981 N/m^3 or 62.4 lb/ft^3], Δh = change in piezo-metric levels, and Δp_a = change in atmospheric pressure.

Discussions related to the effect of atmospheric pressure on confined and unconfined aquifers assume that no delay occurs in the balance of pressure between the aquifer and well. But in reality, the time required for movement of a finite volume of water between the surrounding aquifers and well delays the transmission of atmospheric pressure change between the aquifer and well. This delay in time depends on the properties of aquifer (i.e., storability and transmissivity) and conditions of existing boreholes (i.e., well skin effects and well bore storage). Due to imbalance of pressure between an aquifer and a well, at the instance of pressure change, previous investigators have observed that these temporary imbalances in the pressure can be treated as individual step changes in pressure applied at the well [9]. Due to travel time for percolation and surface and subsurface losses, rainfall is not considered as an accurate indicator for groundwater recharge. The travel time for vertical percolation may vary from a few minutes for permeable formations with shallow water tables to several years for low permeable formations with deep water tables. The regions that lie between semi-humid and semiarid zones with seasonal climatic conditions observe zero recharge in the groundwater due to rainfall [4].

4.1.2 Rainfall

In arid and semiarid regions, due to heavy rainfalls, groundwater recharge tends to occur unlike those regions which are a combination of constant rate and periodic behavior. Physical properties including type of soil, groundwater depth, porosity of vadose zone, rainfall patterns, and hydrogeology tend to vary the groundwater recharge spatially [10].

4.1.3 Wind

Wind blowing over the top of wells generates minor fluctuations in water levels. It works on the principle of vacuum pump. When wind is blowing over the top of a well casing, the air pressure within the well lowers down suddenly due to which the water level rises quickly. Once the wind passes, the air pressure within the well rises and water level falls [4].

4.1.4 Frost

It has been observed in the regions of extreme frost that shallow water tables are reduced during the winter season and increased in early spring. These fluctuations are observed due to the presence of frost layer above the water table. Due to

capillary action and transfer of vapors to the frost layer, water moves upward from water table during winter. Thermal gradient and the fact that at 0°C vapor pressure over liquid water is greater than that over ice play an important role in the migration of vapors. When mean air temperature reaches 0°C in early spring, the frost layer begins thawing from the bottom due to which meltwater percolates down in the water table [4].

4.2 Tides and seawater intrusion

Groundwater is an important source of fresh water with high quality for coastal communities worldwide. These sources of fresh groundwater in the coastal communities are highly affected by intrusion of seawater caused by excessive groundwater extraction and rises in sea levels. Globally increasing population will lead to rising demands of fresh water in the coming decades and will result in a decline of groundwater sources gradually. Coastal flooding will also be increased due to rise in sea levels, which may lead to seawater intrusion and coastal erosion, and as a result it will affect the biodiversity and losses of wetland [11].

In response to the tides, sinusoidal fluctuations of groundwater levels occur in the coastal aquifers which are in contact with the ocean. If a simple harmonic motion varies the sea levels, a pattern of sinusoidal waves is propagated inland from the submarine outcrop of the aquifer. The time lag of given maximum increases, and inland amplitude of waves decreases with respect to distance [4].

In coastal regions, tidal forces acting on an adjacent groundwater are a common feature and can be important pore water phenomena in tidal and saturated zones. Near the top of the water table, the entry of saltwater and variations in the concentration of solutes can be increased due to tidal forces in shallow unconfined aquifers. Comparative studies between tidal and water-level variations show that increase in the height of tide will increase the corresponding water levels [12].

Fluctuations produced by the attraction of sun and moon on the crust of the earth are a result of earth tides. The following observations are analyzed based on well record:

- a. Fluctuations occur twice in a daily cycle due to moon about 50 min later each day.
- b. Retardation of cycle on average daily bases matches with that of moon's transit closely.
- c. At the lower and upper peaks, the moon's transits and the troughs of water levels on daily bases are coincided.
- d. Periods of full and new moon coincide with the periods of large regular fluctuations, while the periods of the first and third quarters of moon coincide with periods of small irregular fluctuations [4].

Forces of sun and moon which produce tides act in the same direction at the time of new and full moon, causing ocean tides to be greater than the average range. But at the time of the first and third quarter of moon, the forces of sun and moon which produce tides act perpendicular to each other, causing ocean tides to be smaller than the average range. At the time of coincidence of the moon's transit with time of low water, the tidal attraction will be maximum; therefore, the load on the aquifer is reduced which allows the aquifer to expand slightly [4].

4.3 Earthquakes and landslides

History reveals that there are varieties of effects of earthquakes on groundwater. Fluctuations like sudden rises and falls of water levels in wells, variations in spring discharges, formation of new springs, and venting of mud and water out of the ground are observed due to earthquake shocks. Such fluctuations produced due to earthquake shocks are known as *hydroseisms*.

Seismic waves generated by earthquakes affect the groundwater in two major ways. One is that oscillations are produced in the groundwater levels, and second is that permanent changes occur in the groundwater levels. As groundwater remains in contact with the surface water, some variations in surface water flows are also observed. Half to one year long time variations in water level have been observed due to the response of earthquakes at a great distance from the monitoring locations [13].

Response of groundwater to earthquakes is somehow complex and can be observed by different processes on varying time scales. The impact of earthquake on the groundwater is considered in three parts: before, during, and after an earthquake event. Before an earthquake, in the area of a fault zone, there will be an increase or decrease in pore pressure due to poroelastic deformation caused by variations in stresses. Increase in pore pressure will occur in compressional regime, while decrease in pore pressure will occur in extensional regime. In a confined aquifer of high permeability or in an unconfined aquifer, the variations in pore

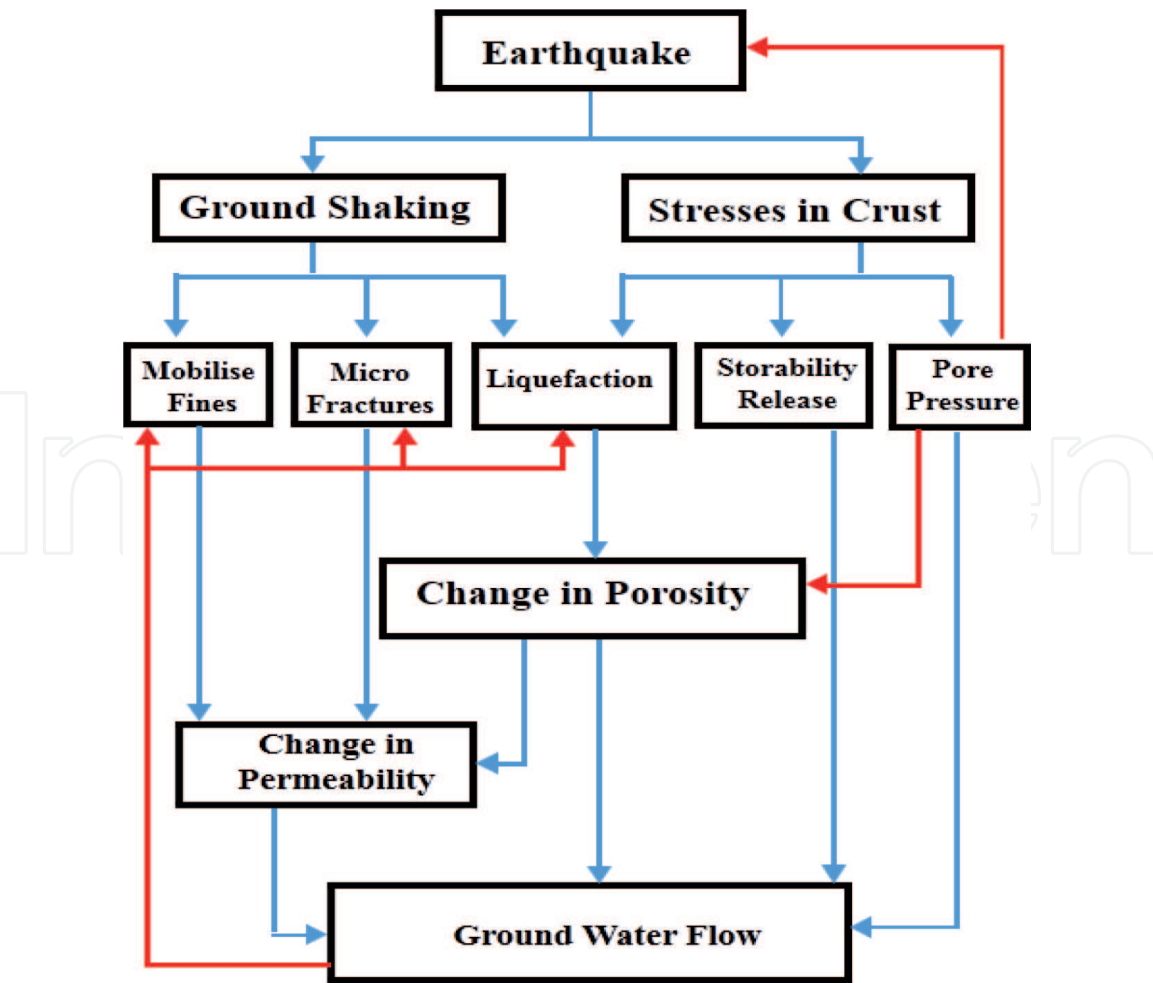


Figure 3.
Relationship between earthquake and groundwater processes.

pressure will be dissipated quickly, and no significant changes in surface water flow or groundwater will be observed. Ground deformation resulted from the passage of seismic waves during an earthquake event will change the pore pressure in an aquifer. These changes occur at different frequencies, and excess pore pressure is not allowed through groundwater flow.

The processes involved between an earthquake and groundwater are shaking of ground, stresses in the crust, mobilization of fines, microfractures, liquefaction, storability release, pore pressure, change in porosity, and change in permeability. Summary of relationships between earthquakes and groundwater processes is described in **Figure 3**.

5. Conclusion: groundwater management strategies

Groundwater resources are not managed properly in different parts of the world. For the proper management of groundwater resources, simple and effective rules and regulation must be adopted. The governing regulations may be based on knowledge and practical experiences of the local region supported by scientific and field information. The groundwater management strategies are recommended to be planned such that:

- a. Groundwater withdrawal will be adjusted as per forecasted supply and demand requirements of the future.
- b. The renewable character of potential aquifers must be considered with optimum aquifer pump rates, well locations, and relative priority of each sub-aquifer unit within the integrated management system of the entire aquifer field.
- c. Water quality, effect of urbanization, intensive agricultural practices, economy, social impact, and local administrative strategies should also be considered.
- d. Recommended groundwater management practices need to scientifically determine different hydrogeological parameters such as porosity, specific yield, and hydraulic conductivity for actual water volume calculations. It is preferable to obtain estimated parameter by field techniques like the aquifer tests and their proper interpretations.
- e. For strategic planning of groundwater reservoirs that may be replenished, the groundwater quality is significant not only for management but also for controlling the excessive exploitation possibilities. Naturally existing groundwater does not have homogenous but heterogeneous properties within the same storage. Generally, the bottom layers are saline, and, therefore, during pumping operations, the up-coning must be avoided.
- f. Private well owners must be convinced to allow for groundwater strategic planning by avoiding haphazard and unnecessary exploitations.
- g. Implementation of artificial recharge system in order to compensate the present deficit. Increasing groundwater recharge could counteract the projected effects of climate changes on the groundwater system.
- h. Construction of new management system helps in monitoring the groundwater system in terms of quantity and quality.

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