GROUNDWATER RECHARGE AND DISCHARGE

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Contents

Biographical Sketch

Summary

Groundwater recharge and discharge are important—although typically inconspicuous—aspects of the global hydrological cycle. Recharge involves the downward movement and influx of groundwater to an aquifer; discharge involves the upward movement and outflux of groundwater from an aquifer. Recharge and discharge activities are usually spatially limited to a small portion of an aquifer. The most common recharge areas are hills, updip outcrops or erosional exposures of confined aquifers, alluvial fans along mountain fronts, and ephemeral stream bottoms in dry regions. Common natural discharge areas include perennial stream valleys in humid regions, swamps, springs, lakes, and the oceans. Climatic factors are the key influences on groundwater recharge; in that only a small percentage of rainfall results in recharge in arid and semiarid climates.

Recharge rates are difficult to calculate. However, numerous estimates have been made by various techniques that include water-balance computations, geophysical measurements that trace the movement of water in the shallow subsurface, and various chemical (notably chloride mass balances) and isotopic methods. Human activity has a great influence upon recharge, discharge, and groundwater flow. Artificial recharge involves the deliberate emplacement of water underground, and allows for the storage of large volumes of water that can be used during periods of hydrological deficit. Groundwater pumping, often necessary for irrigation and municipal water supplies, can lead to significant problems such as land subsidence and the alteration of groundwater flow directions when "overdraft" occurs.

1. Introduction: Overview of Groundwater Recharge and Discharge

Groundwater recharge and discharge are important aspects of the global hydrological cycle and are critical to the analysis of groundwater flow systems and water budgets. *Recharge* is the replenishment of groundwater by the downward infiltration of precipitation, or by water that was temporarily stored on the Earth's surface. *Natural recharge* occurs without influence or enhancement by humans, while *artificial recharge* occurs as the result of deliberate or inadvertent human activity, such as the direct injection of water into the subsurface or irrigation. *Discharge* represents the upward outflow of groundwater from the subsurface that occurs naturally or as the result of human activity, notably well pumping. Both groundwater recharge and discharge are usually spatially limited, and therefore may not be nearly as conspicuous as other aspects of the hydrological cycle.

Practically all groundwater that is used by human beings originates from the atmosphere or has a "meteoric" origin, and the principal source of natural recharge is precipitation that falls directly on the Earth's surface. Groundwater is induced to discharge from wells, and discharges naturally from the subsurface to oceans, springs, lakes, rivers ("gaining streams"), swamps, and other wetlands. Hence, groundwater discharge can represent a significant control over ecosystems. Groundwater may also return to the atmosphere directly by evaporation within the soil and by transpiration through vegetation, but these processes are not formally considered as discharge. Without human intervention discharge rates often approximate to recharge rates, and hence a balance or equilibrium is achieved between influxes and outfluxes to the subsurface water budget (see Section 3.1). However, "overdrafts" resulting from human exploitation of groundwater resources can lead to declining water levels (thereby raising pumping costs), hydrostatic pressure reductions, and other related problems such as land subsidence (see Section 7.3).

1.1. Recharge, Discharge, and the Hydrological Cycle

Almost all groundwater, including deep hydrothermal water, can be traced to local precipitation sources. However, only a small percentage of rainfall or snowfall will infiltrate below the Earth's surface to recharge aquifers. Some of the precipitation is blocked by tree cover (interception), while most is returned to the atmosphere as water vapor (evaporation or "evapotranspiration" if the liquid is converted to vapor through vegetation).

Most of the water reaching the Earth's surface that does not evaporate will return to the ocean directly through surface water runoff. The small portion of water remaining will infiltrate the subsurface where it may evaporate, become temporarily stored in the soil, flow to streams prior to reaching the water table (a process termed "interflow"), or eventually *recharge* the groundwater reservoir by reaching the water table (Figure 1).

The hydrological cycle can be quantified in its simplest form using the following mass balance expression:

$$\text{Precipitation} = \text{Actual Evapotranspiration} + \text{Runoff} + \text{Infiltration} \qquad (1)$$

This is a steady state equation that implies no water is held in storage on the Earth's surface, and that the outflux is equivalent to the influx. The major complication is that a significant amount of water that infiltrates the shallow subsurface is discharged through river basins and subsequently becomes a component of stream runoff (Figure 1).

Therefore, runoff and infiltration are interlinked and are often not independent variables. Evapotranspiration rates act as a major control upon runoff and infiltration, and ultimately upon recharge. The greater the percentage of water that evaporates or transpires through plants, the lower the runoff and recharge. Water management schemes must therefore consider the effects of plants on groundwater replenishment.

Numerous investigations have concluded that the removal of vegetation results in increased recharge. For example, it has been observed that clearing of the native *Eucalyptus* vegetation in semiarid South Australia resulted in an increase of recharge of as much as 50 millimeters per year.

Deforestation resulted in an increase of approximately twice the normal rate of recharge in the east African Victoria Nile basin. However, many would regard deforestation as a deliberate means to increase groundwater recharge as a dubious water management "strategy."

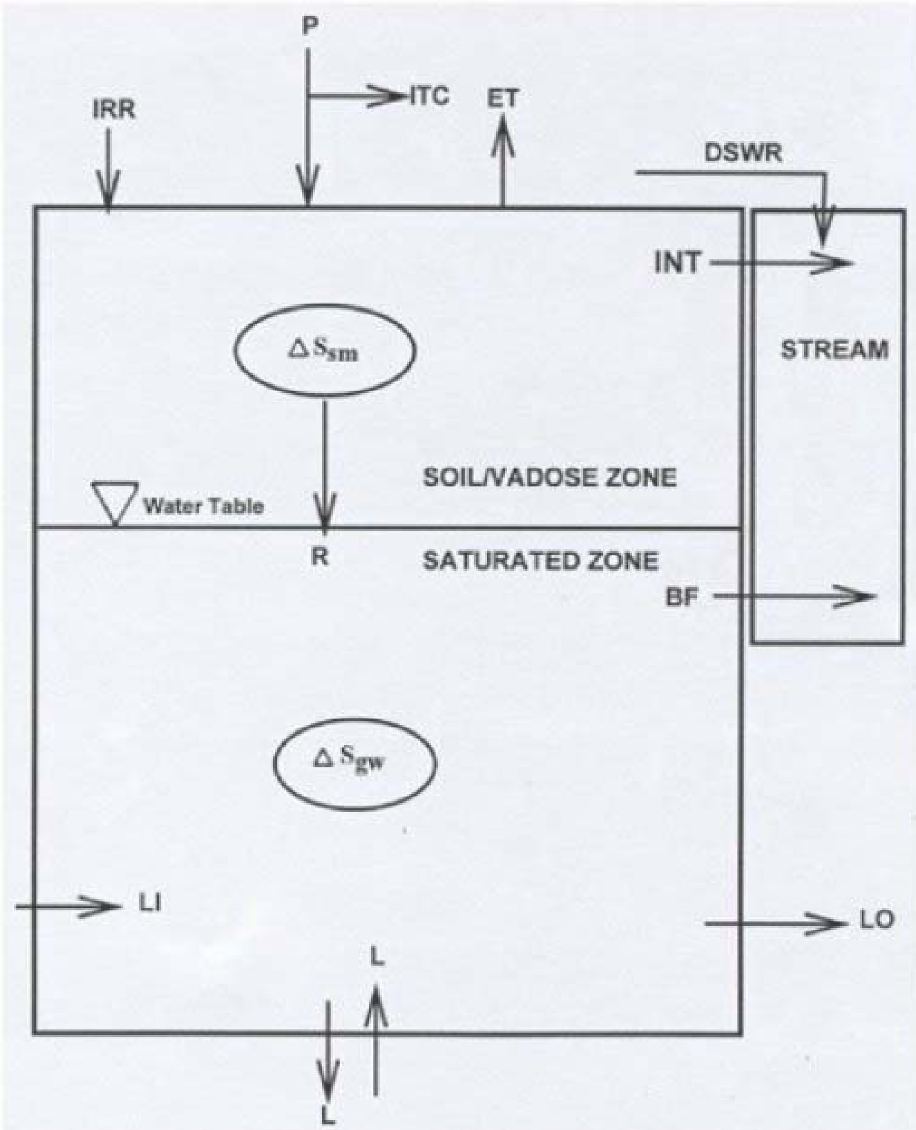

Figure 1. Hydrological fluxes on the Earth's surface and in the shallow subsurface. P = precipitation; IRR = irrigation; ET = evapotranspiration; DSWR = direct surface water runoff; ITC = interception; INF = infiltration; R = recharge; INT = interflow; ΔS_{sm} = changes in soil moisture storage; BF = baseflow; LO = lateral outflow; LI = lateral inflow; L = vertical leakance; and ΔS_{gw} = changes in saturated groundwater storage. (See Eqs. 1–7 and related discussion.)

Groundwater bodies do not typically act as stagnant reservoirs, with the possible exception of some water stored in deep sedimentary basins such as the Great Artesian Basin in Australia. Groundwater will eventually discharge to river basins and oceans as "baseflow": this probably represents the least-observed aspect of the hydrological cycle, although an estimated 2300 km^3 of groundwater discharges directly to the oceans annually. Groundwater also emerges at localized points on the Earth's surface known as *springs* (Section 6.1). Multiple springs or more diffuse outcrops of groundwater on the Earth's surface create the conditions for the formation of swamps and other wetlands.

Groundwater that discharges to lakes, river basins, wetlands, or the oceans (Figure 2) ultimately evaporates and enters the hydrological cycle once again.

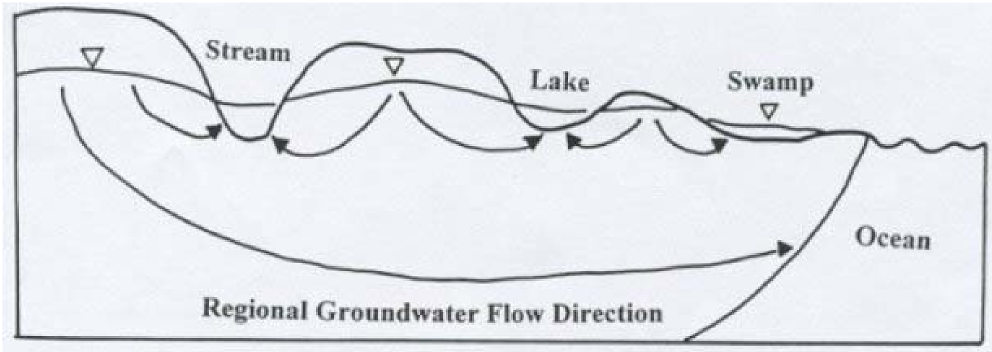

Figure 2. Common discharge areas associated with unconfined aquifers

1.2. Recharge and Discharge in Unconfined and Confined Aquifers

1.2.1. Unconfined (Surficial) Aquifers

Groundwater can directly infiltrate an unconfined aquifer from the Earth's surface and gravitate towards the water table: hence, recharge represents "a net downward vertical influx" of water to the water table. Recharge areas are most rigorously defined as those regions in which there exists a downward component to groundwater flow lines (Figure 3), and this flow is directed *away* from the water table. Not all water that passes below the Earth's surface will reach the water table. Some moisture is stored within a soil horizon where it can return to the atmosphere through evapotranspiration before reaching the water table. In order for water to gravitate, soil pores must become nearly filled with water, or reach *field capacity*. This is necessary in order to overcome the often-high tension or capillary force (upward force opposed to gravity) within the vadose zone. Antecedent rainfall and soil moisture conditions become a factor here, in that soil tension is greater during drying than wetting; hence recharge is enhanced by soils that are wet prior to a given rainfall event. Because of these considerations recharge is usually an intermittent, rather than a continuous, process that is limited to periods of excessive rainfall that leave the soil wet.

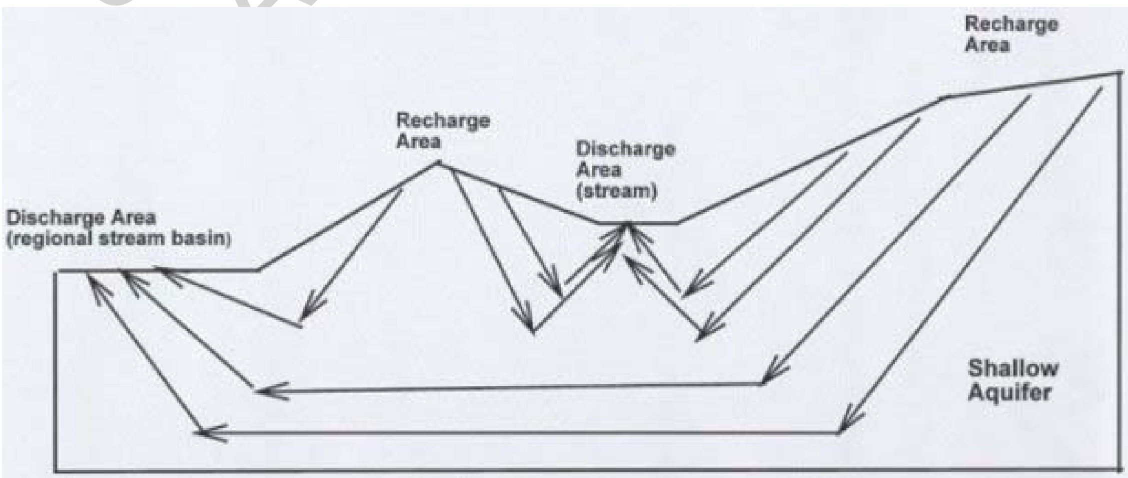

Figure 3. Idealized flow in lines a shallow groundwater flow system. Note that flow lines have a vertical downward component below recharge areas and a vertical upward component in discharge areas: they are near-horizontal throughout most of the extent of the aquifer.

Most (but not all) recharge areas are located below topographically raised areas (for example, hills), making the water table profile a subdued image of the surface topography. Multiple groundwater flow paths can be taken from a given recharge area, including short and shallow paths to local tributaries and longer deeper paths to regional stream basins. In regions underlain by moderately soluble rock such as limestone (like the Mammoth Cave region in Kentucky, USA), recharge is often more diffuse and not limited to any specific set of topographic locations. Artificial topographic features such as landfills can act as local recharge areas, with obvious deleterious effects upon groundwater quality.

Groundwater discharge occurs within unconfined aquifers where groundwater flow lines have a net vertical upward component as they emerge toward the Earth's surface. In contrast to recharge areas, discharge areas are often located in topographic lows such as stream valleys, lakes, and swamps. To reiterate, recharge is defined by the *downward* movement of groundwater while discharge is characterized by the *upward* movement of groundwater. Given a sufficiently deep and expansive aquifer, however, groundwater flow is neither upward nor downward throughout most of the extent of the flow system (Figure 3).

1.2.2. Confined Aquifers

Recharge and discharge processes are generally less amenable to direct observation or study in confined aquifers than in unconfined aquifers. The most common type of recharge area associated with confined aquifers is at an *outcrop* area where the aquifer emerges upon the Earth's surface, either at an updip location or where erosion has removed part of the overlying confining unit (Figure 4). Recharge at these locations is very similar to recharge of unconfined aquifers in that the top of the aquifer is exposed at the Earth's surface. An example of where this occurs is the "Fall Line" of the southeastern United States, where the Cretaceous and Tertiary aquifers of the coastal plain are recharged from a regional outcrop area. Numerous aquifers in the midwestern United States are recharged from outcrop areas along the eastern flank of the Rocky Mountains.

In many cases confining beds are not laterally extensive, and recharge occurs through hydraulic contact with the overlying unconfined aquifer. Recharge to confined aquifers also occurs through the bases of sinkholes, lakes, and storage reservoirs, providing that the bottoms of these features are in contact with the confined aquifer and that the hydraulic head associated with these features is greater than that of the underlying aquifer. If the hydraulic head of the confined aquifer is greater than that associated with sinkholes, lakes, and reservoirs, the latter features become loci for groundwater discharge. From these considerations, it is obvious that the quality of surface water providing recharge—both in terms of its natural water chemistry and any possible pollutants that might be incorporated—can ultimately affect the suitability of groundwater as a drinking-water source.

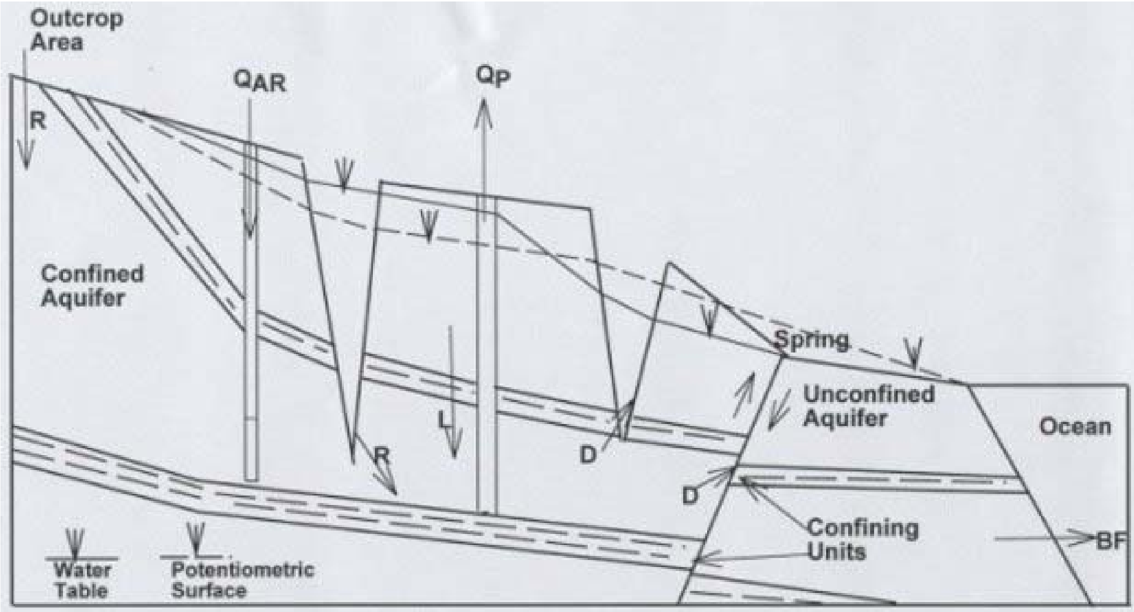

Figure 4. Groundwater recharge and discharge in an idealized confined aquifer. R = recharge; D = discharge; Q_{AR} = artificial recharge; Q_P = pumping; L = leakance; BF = base flow. Note that groundwater in the confined aquifer can recharge the unconfined aquifer when the elevation of the potentiometric surface is greater than that of the water table. If the water table elevation is greater than that of the potentiometric surface, the unconfined aquifer can recharge the confined aquifer.

Groundwater can both enter and leave a confined aquifer deep below the Earth's surface, passing through openings (typically fractures) in the overlying or underlying confining beds. This is a processes termed *leakance* (Figure 4) and is controlled by the hydraulic head values of both the confined aquifer and the overlying and underlying aquifers.

If the hydraulic head is greater in the confined aquifer than in the overlying or underlying aquifers, groundwater can leak or flow through the confining layer to these aquifers.

Conversely, if the hydraulic head of an overlying or underlying aquifer is greater than the head within the confined aquifer, water from these aquifers can then recharge the confined aquifer.

Leakance has been inferred to occur through fractures within Cretaceous shale beds that overlie the Dakota Sandstone east of the Rocky Mountains in the United States. In most cases leakance represents a slow diffusive movement of groundwater between rock formations, and as such it is very difficult to directly observe.

Groundwater can also discharge from a confined aquifer through faults and wells (Figure 4).

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Biographical Sketch

Seth Rose is an Associate Professor in the Department of Geology at Georgia State University in Atlanta, Georgia (USA), where he teaches courses in Hydrogeology and Aqueous Geochemistry. He received an M.Sc. from the University of Florida in Geology and a Ph.D. in Geoscience (minor in Hydrology and Water Resources) from the University of Arizona. He is also a licensed professional geologist in Georgia. His primary research interests include the utilization of chemical and isotopic parameters to better understand the mechanisms of groundwater flow and streamflow in Piedmont Province watersheds of the southeastern United States.