GROUNDWATER RECHARGE

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Contents

Summary

This work attempts to establish a hydrogeological framework for the understanding of natural groundwater recharge processes in relation to climate, landform, geology, and biotic factors. It begins with the concepts of groundwater flow systems, which form the basis for comprehending recharge processes. It then concentrates on the sources and mechanisms of groundwater recharge and stresses the importance of developing correct conceptualizations of recharge. Several recharge estimation methodologies are then outlined, with an emphasis on minimizing uncertainty. The article then discusses developing predictive relationships for recharge based on the major recharge-influencing factors, and regionalizing point recharge data. A discussion of difficulties that face the field of recharge assessment follows, with recommendations as to how to minimize them.

Although there are various well-established methods for the quantitative estimation of recharge, few can be applied successfully in the field. All are characterized by major uncertainties. When estimating groundwater recharge it is essential to proceed from a good conceptualization of different recharge mechanisms and their importance in the study area. Besides this conceptualization the objectives of the study, available data and resources, and possibilities of obtaining supplementary data should guide the choice of recharge-estimation methods. A key to deciding on a methodology is related to the spatial and temporal scale of interest. If the major concern is obtaining good recharge estimates over a limited area, then the need for detailed information is evident. However, small-scale variability in local recharge ceases to be a major problem for regional studies. In addition, the inherent temporal variability of recharge has important implications for the measurement techniques adopted. Different measurement techniques provide recharge estimates with different temporal scales. For example in arid and semiarid areas, where deep drainage fluxes are low and water tables are deep, interpreting groundwater hydrographs and water table rises may be misleading for estimating rates of groundwater recharge; chemical and isotopic methods are likely to be more successful than physical methods in such cases.

1. Introduction and Terminology

The endless circulation of water as it moves in its various phases through the atmosphere, to the Earth, over and through the land, to the ocean, and back to the atmosphere is known as the *hydrologic cycle*. This cycle is powered by the Sun; through phase changes of water (i.e. *evaporation* and *condensation*) involving storage and release of *latent heat*, it affects the global circulation of both the atmosphere and oceans, and hence is instrumental in shaping weather and climate. The efficiency of water as a solvent makes geochemistry an intimate part of the hydrologic cycle; all water-soluble elements follow this cycle at least partially. Thus, the hydrologic cycle is the integrating process for the fluxes of water, energy, and the chemical elements. This cycle is the foundation of hydrological science and occurs over a wide range of space and time scales.

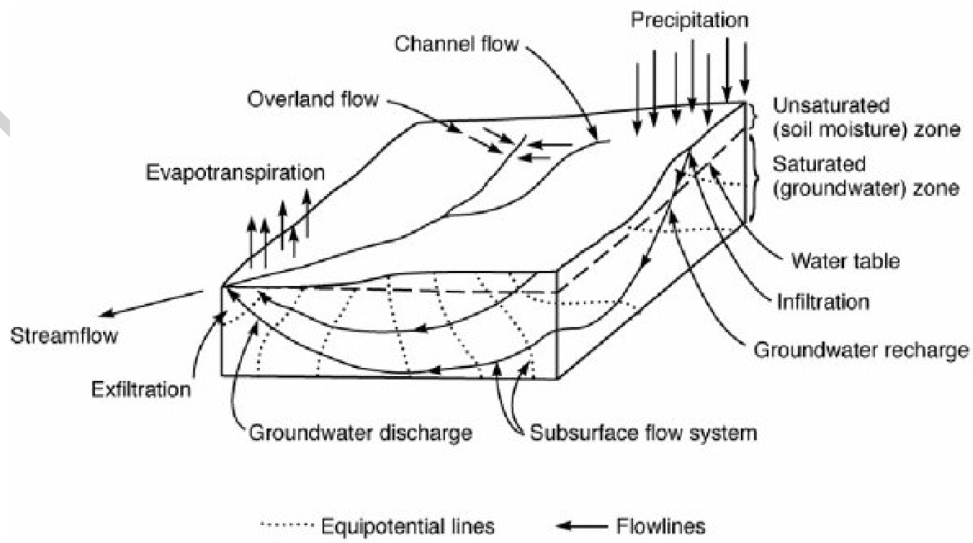

Figure 1. Schematic representation of the hydrologic cycle (from Freeze, 1974)

Figure 1 illustrates different parts of the land-based portion of the hydrologic cycle that affect an individual watershed or catchment.

Water enters the hydrologic system as *precipitation*, in the form of rainfall or snowmelt. It leaves the system as streamflow or *runoff*, and as *evapotranspiration*, a combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants. Precipitation is delivered to streams on the land surface as *overland flow* to tributary channels, and in the subsurface as *interflow* or *lateral subsurface flow* and *baseflow* following *infiltration* into the soil.

A portion of the infiltrated water enters the groundwater or aquifer system by passing through the *vadose* or *unsaturated zone*, and it exits to the atmosphere, surface water, or to plants. As Figure 1 shows, the flowlines deliver groundwater from the highlands towards the valleys, or from the recharge areas to the discharge areas. As the figure also shows, in a *recharge area* there is a component to the direction of groundwater flow that is downward. *Groundwater recharge* is the entry to the saturated zone of water made available at the water table surface. Conversely, in a *discharge area* there is a component to the direction of groundwater flow that is upward (Figure 1). *Groundwater discharge* is the removal of water from the saturated zone across the water table surface. The patterns of groundwater flow from the recharge to the discharge areas form *groundwater flow systems*, which constitute the framework for understanding recharge processes.

2. Groundwater Flow Systems

The route which groundwater takes to a discharge point is known as a *flow path*. A set of flow paths with common recharge and discharge areas is termed a *groundwater flow system*. The three-dimensional closed system that contains the entire flow paths followed by all water recharging the groundwater system has been termed a *groundwater basin*. Groundwater possesses energy mainly by virtue of its elevation (elevation or gravitational head) and its pressure (pressure head). Groundwater can also possess kinetic energy by virtue of its movement, but usually this energy is negligible because of groundwater's low velocities. Groundwater moves from regions of higher energy to regions of lower energy. A measure of groundwater's energy is the level at which the water stands in a borehole drilled into an aquifer and measured with reference to an (arbitrary) reference level or datum, such as sea level. This height at which water stands above a reference datum is called *hydraulic head*, or simply *head*. The hydraulic head, for most practical purposes, is composed of the sum of the pressure head and gravitational or elevation head. Both of these component forms of energy (in other words, elevation energy and pressure energy) are known as *potential energy*. The change in hydraulic head over a certain (arbitrary) distance along the groundwater flow path is called hydraulic gradient or head gradient and constitutes the driving force for groundwater movement. According to *Darcy's law*, which describes the flow of groundwater through an aquifer, the groundwater flow rate is directly proportional to the cross-sectional area through which flow is occurring, and directly proportional to the hydraulic gradient. Gravity due to elevation differences is the predominant driving force in groundwater movement. Under natural conditions, groundwater moves "downhill" until it reaches the land surface, such as at a spring, or the root zone, where it is evapotranspired to the atmosphere.

Therefore, groundwater moves from interstream (higher) areas toward streams or the coast (lower areas). Except for minor surface irregularities, the general slope of the land surface is also towards streams or the coast. The depth to the water table is greater along the divide between streams than it is beneath a floodplain. In effect, the water table is usually a subdued replica of the land surface.

A groundwater flow pattern is controlled by the configuration of the water table, and by the distribution of hydraulic conductivity in the rocks. The water table, in turn, is affected by topography, and is controlled by the prevailing climate. The flow pattern is therefore a function of topography, geology, and climate. These three parameters have been collectively termed the *hydrogeologic environment*. In addition, biotic influences affect most aspects of the hydrologic cycle, including groundwater. Vegetation, for example, regulates the rate at which a land surface returns water vapor to the atmosphere, and humans alter nearly all aspects of water's distribution and behavior on land.

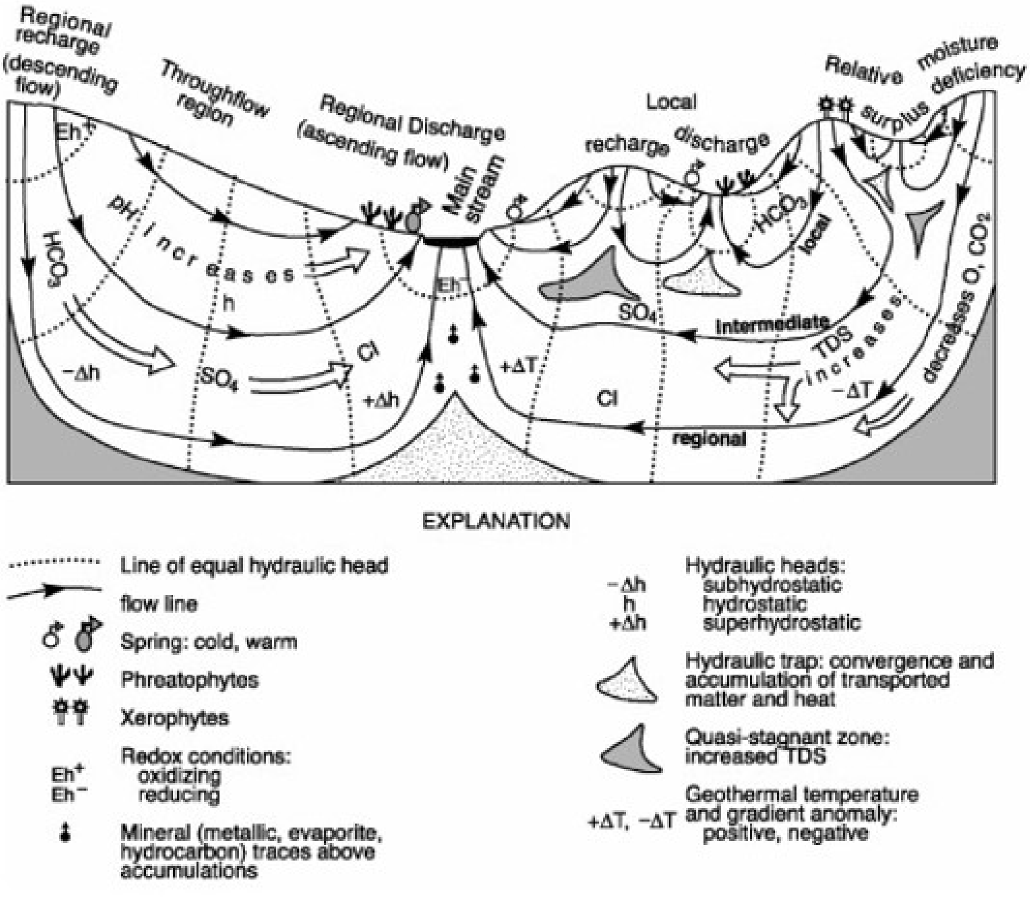

Figure 2. Effects and manifestations of gravity-driven flow in a regionally unconfined drainage basin (adapted from Tóth, 1999)

Based on their relative position in space, three distinct types of flow systems have been recognized (right-hand side of Figure 2):

1. A *local system*, that has its recharge area at a topographic high and its discharge area at the immediately adjacent topographic low.

2. An *intermediate system*, characterized by one or more topographic highs and lows located between its recharge and discharge areas.

3. A *regional system*, that has its recharge area at the major topographic high and its discharge area at the bottom of the basin. Regional flow systems are at the top of this hierarchical organization; all other flow systems are nested within them.

On the basis of a comparative study of variations in selected geometric parameters—such as depth to impermeable basement, slope of the valley flanks, and local relief—the conditions under which local, intermediate, and regional systems may develop were elucidated. If local relief is negligible, and there is a general slope of topography, only regional systems will develop. Because no extensive unconfined regional system can span the valleys of large rivers or highly elevated watersheds, pronounced local relief generally is an indicator of a local system. The greater the relief, the deeper the local systems that develop. Under extended flat areas unmarked by local relief, neither regional nor local systems can develop. Waterlogged areas may develop, and the groundwater may be highly mineralized due to concentrations of salts.

The recognition that groundwater moves in systems of predictable pattern in topography-controlled flow regimes, and that various identifiable natural phenomena are regularly associated with different segments of the flow systems, was only made in the 1960s when the system-nature of groundwater flow was first understood. This recognition of the system-nature of subsurface water flow has provided a unifying theoretical background for the study and understanding of a wide range of natural processes and phenomena, and has thus shown flowing groundwater to be a general geological agent.

A schematic overview of groundwater flow distribution, and some of the typical hydrogeologic conditions and natural phenomena associated with it in a gravity-flow environment, is presented in Figure 2. On the left side of the figure, a single flow system is shown in a region with insignificant local relief; on the right side, a hierarchical set of local, intermediate, and regional flow systems is depicted in a region of composite topography. Each flow system has an area of recharge, an area of throughflow, and an area of discharge. In the recharge areas, the hydraulic heads, representing the water's potential energy, are relatively high and decrease with increasing depth; water flow is downward and divergent. In discharge areas, the energy and flow conditions are reversed: hydraulic heads are low and increase downward, resulting in ascending and converging water flow. In the areas of throughflow, the water's potential energy is largely invariant with depth (the isolines of hydraulic heads are subvertical), and consequently flow is chiefly lateral. The flow systems operate as conveyor belts, with the flow serving as the mechanism for mobilization, transport (distribution), and accumulation of mass and energy, thus effectively interacting with their ambient environment.

3. Flow System Extensions

Studying flow systems in groundwater basins may help gain an understanding of the interrelations between the processes of infiltration and recharge in topographically high parts of the basin and of groundwater discharge through evapotranspiration and baseflow. For example, at least some of the water derived from precipitation that enters the ground in recharge areas will be transmitted to distant discharge points, thus causing a relative moisture deficiency in soils overlying recharge areas. Water that enters the ground in discharge areas may not overcome the upward potential gradient, and therefore becomes subject to evapotranspiration close to its point of entry. Water input to saturated discharge areas generates overland flow, but in unsaturated discharge areas infiltrating water and upflowing groundwater is diverted laterally through superficial layers of high hydraulic conductivity. Further, the ramifications of anthropogenic activities in discharge areas are immediately apparent. Some of these include:

- waterlogging problems associated with surface-water irrigation of lowlands,
- waterlogging problems associated with destruction of *phreatophytes*, or plants discharging shallow groundwater, and
- pollution of shallow groundwaters by gravity-operated sewage and waste-disposal systems located in valley bottoms in semiarid basins, where surface water is inadequate for dilution.

The spatial distribution of flow systems will also influence the intensity of natural groundwater discharge. In the example in Figure 2, the main stream of a basin may receive groundwater from the area immediately within the nearest topographic high, and possibly from more distant areas. If baseflow calculations are used as indicators of average recharge, significant error may be introduced in that baseflow may represent only a small part of the total discharge occurring downgradient from the line separating the areas of discharge from the recharge areas. In groundwater hydrology today, the system concept is fundamental to thinking about a groundwater problem. System thinking is vital to the understanding of practical problems, such as groundwater contamination from point sources, or the impact of a structure such as a dam, waste disposal facility, or gravel pit. Many such studies suffer irreparably from the failure to place the local site in the context of the larger groundwater system of which the site is only a small part.

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Biographical sketch

Marios Sophocleous received his B.Sc. in Natural Sciences and Geology from the School of Physics and Mathematics of the University of Athens, Greece, in 1971, his M.Sc. in Water Resources from the Civil Engineering Department of the University of Kansas in 1973, and his Ph.D. in Geology, with specialization in Hydrogeology, from the University of Alberta, Canada, in 1978. Since 1978 he has been employed at the Kansas Geological Survey, where he became Senior Scientist in 1987. He is editor of the *Journal of Hydrology*, Associate Editor of the *Hydrogeology Journal*, member of the editorial boards of *Computers and Geosciences*, *Natural Resources Research*, and *Current Research in Earth Sciences* (Kansas Geological Survey's peer-reviewed electronic journal), and Adjunct Professor of Geology at The University of Kansas. He was the 1997 recipient of the *Best Practice Paper Award* by the Irrigation and Drainage Engineering Division of the American Society of Civil Engineers. His areas of research include experimental investigations and numerical modeling of soil-water and groundwater flow and pollutant transport, aquifer-recharge processes, stream–aquifer interactions, regional groundwater flow and watershed hydrology, soil–vegetation–atmosphere hydrologic interactions, integrated watershed/groundwater modeling, and water-resources evaluation and management.