Aquifers: Recharge

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INTRODUCTION

Aquifer recharge was defined by Meinzer[1] and Heath[2] as water that moves from the land surface or the unsaturated zone into the saturated zone. This definition excludes saturated flow between aquifers, which avoids double-accounting in large-scale studies, so it might be more precisely called "aquifer-system" or "saturated-zone" recharge. *Recharge rate* designates either a flux $[L^3/T]$ into a specified portion of aquifer, or a flux density $[L/T]$ into an aquifer at a point. Sources of water for recharge include precipitation that infiltrates, permanent or ephemeral surface water, irrigation, and artificial recharge ponds. Recharge may reach the aquifer directly from portions of rivers, canals, or lakes,[3] though usually it first travels by various means through the unsaturated zone.

Recharge varies considerably with time and location. Temporal variation occurs, for example, with seasonal or short-term variations in precipitation and evapotranspiration (ET). This variability is especially evident in thin unsaturated zones, where recharge may occur within a short time of infiltration. In deep unsaturated zones, recharge may be homogenized over several years so that it may occur with essentially constant flux even though fluxes at shallow depths are erratic. Spatial variation occurs with climate, topography, soils, geology, and vegetation. For example, a decrease of slope or increase of soil permeability may lead to greater infiltration and greater recharge. Many applications use a concept of recharge that is time-averaged or areally averaged.

Both the amount of infiltration and the fraction of it that becomes recharge tend to be greater with more abundant water, so the recharge process is most efficient if infiltration is concentrated in space and time. Because ET may extract most or all of the water that infiltrates, water is more likely to become recharge if it moves rapidly below the root zone. Temporal concentration occurs during storms, floods, and snowmelt, when ongoing processes such as ET are overwhelmed. Spatial concentration typically occurs in depressions and channels, where higher water contents promote rapid movement by increasing the hydraulic conductivity (K), the amount of preferential flow, and the downward driving force at a wetting front. Quantitative estimation of recharge rate contributes to the understanding of large-scale hydrologic processes. It is important for evaluating the sustainability of ground water supplies, though it does not equate with a sustainable rate of extraction.[4] Because it represents a first approximation to the rate of solute transport to the aquifer, the recharge rate is also important to estimate contaminant fluxes and travel times from sources near the land surface. Methods for obtaining a quantitative estimate of recharge mostly require a combination of various types of data which themselves may be hard to estimate, so in general it is wise to apply multiple methods and compare their results.

WATER BUDGET METHODS

The water balance for a basin can be stated as

$$\begin{aligned} P + Q_{\mathrm{on}}^{\mathrm{sw}} + Q_{\mathrm{on}}^{\mathrm{gw}} = {} & \mathrm{ET}^{\mathrm{sw}} + \mathrm{ET}^{\mathrm{uz}} + \mathrm{ET}^{\mathrm{gw}} + Q_{\mathrm{off}}^{\mathrm{sw}} \\ & + Q_{\mathrm{off}}^{\mathrm{gw}} + Q_{\mathrm{bf}} + \Delta S^{\mathrm{snow}} \\ & + \Delta S^{\mathrm{sw}} + \Delta S^{\mathrm{uz}} + \Delta S^{\mathrm{gw}} \end{aligned} \tag{1}$$

where P is precipitation and irrigation; Q_{on} and Q_{off} are water flow on and off of the site, respectively; $Q_{\mathrm{off}}^{\mathrm{sw}}$ is runoff; Q_{bf} is baseflow (ground water discharge to streams or springs); and ΔS is change in water storage. Superscripts refer to surface water, ground water, unsaturated zone, or snow, and all parameters are in units of L/T (or volume per unit surface area per unit time). For the saturated zone only, a water balance can be written for a defined area as

$$R = \Delta Q^{\mathrm{gw}} + Q_{\mathrm{bf}} + \mathrm{ET}^{\mathrm{gw}} + \Delta S^{\mathrm{gw}} \tag{2}$$

where R is recharge and ΔQ^{gw} is the difference between ground water flow off of and onto the basin. This equation implies that water arriving at the water table: 1) flows out of the basin as ground water flow;

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2) discharges to the surface; 3) is evapotranspired; or 4) goes into storage. Substitution in Eq. (1) produces a simpler form of the water balance:

$$R = P + Q_{\mathrm{on}}^{\mathrm{sw}} - Q_{\mathrm{off}}^{\mathrm{sw}} - \mathrm{ET}^{\mathrm{sw}} - \mathrm{ET}^{\mathrm{uz}} - \Delta S^{\mathrm{snow}} - \Delta S^{\mathrm{sw}} - \Delta S^{\mathrm{uz}} \tag{3}$$

Water budget methods include all techniques based, in one form or another, on one of these water balance equations.

The most common water budget method is the "residual" approach: all other components in the water budget are measured or estimated and R is set equal to the residual. Water budget methods can be applied over a wide range of space and time scales. The major limitation of the residual approach is that the accuracy of the recharge estimate depends on the accuracy with which other components can be measured. This limitation can become significant when the magnitude of R is small relative to other variables. The time scale for applying water budget methods is important, with more frequent tabulations likely to improve accuracy. If the water budget is calculated daily, P can greatly exceed ET on a single day, even in arid settings. Averaging over longer time periods tends to dampen out extreme precipitation events and hence underestimate recharge. Annual recharge estimated with water budgets range from 23 mm in a region of India[5] to 400 mm at a site in the eastern United States.[6]

Watershed, surface water flow, and ground water flow models constitute an important class of water budget methods that have been used to estimate of recharge (e.g., Ref.[7]). An attractive feature of models is their predictive capability. They can be used to gauge the effects of future climate or land-use changes on recharge rates.

METHODS BASED ON SURFACE WATER OR GROUND WATER DATA

Fluctuations in ground water levels can be used to estimate recharge to unconfined aquifers according to

$$R = S_{\mathrm{y}} \mathrm{d}h/\mathrm{d}t = S_{\mathrm{y}} \Delta h/\Delta t \tag{4}$$

where S_{y} is specific yield, h is water table height, and t is time. The method is best applied over short time periods in regions with shallow water tables that display sharp water-level rises and declines. Analysis of water-level fluctuations can also, however, be useful for determining the magnitude of long-term change in recharge rates caused by climate or land-use change. The method is only appropriate for estimating recharge for transient events; recharge occurring under steady flow conditions cannot be estimated. Difficulties lie in determining S_{y} and ensuring that fluctuations are due to recharge, not to changes in pumping rates or atmospheric pressure or other phenomena. Recharge rates estimated by this technique range from 11 mm over a 26-month period in Saudi Arabia[8] to 541 mm yr^{-1} over 1 yr for a small basin in the United States.[9]

Ground water levels can also be used to estimate flow, Q, through a cross-section of an aquifer that is aligned with an equipotential line. Multiplying K by the hydraulic gradient normal to the section times the area of the section calculates Q. Recharge is determined by dividing Q by the surface area of the aquifer upgradient from the section.

Methods of estimating recharge based on surface-water data include the Channel Water Balance Method (CWBM) and determination of baseflow by hydrograph separation. The CWBM involves measuring discharge at two gauges on a stream; the difference in discharge between the upstream and downstream gages is the transmission loss. This loss may become recharge, ET, or bank storage. Hydrograph separation involves identifying what portion of gauged stream flow is derived from ground water discharge. Rutledge and Daniel[10] developed an automated technique for this purpose and applied the method to estimate recharge at 15 sites. Drainage areas for the sites ranged from less than 52 km^2 to more than 5200 km^2; estimated annual recharge was between about 13 cm and 64 cm.

DARCIAN METHODS

Applied in the unsaturated zone, Darcy's law gives a flux density equal to K times the driving force, which equals the recharge rate if certain conditions apply. Matric-pressure gradients must be measured or demonstrated to be negligible. Some types of preferential flow are inherently non-darcian and if important would need to be determined separately. Accurate measurements are necessary to know K adequately under field conditions at the point of interest. For purposes requiring areal rather than point estimates, additional interpretation and calculation are necessary.

In the simplest cases, in a region of constant downward flow in a deep unsaturated zone, gravity alone drives the flow. With a core sample from this zone, laboratory K measurements at the original field water content directly indicate the long-term average recharge rate.[11]

In the general case, transient water contents and matric pressures must be measured in addition to K.[12] Transient recharge computed with Darcy's law can relate to storms or other short-term events, or provide data for integration into temporal averages.

TRACER METHODS

Increasing availability and precision of physical and chemical analytical techniques have led to a proliferation in applications of tracer methods for recharge estimation. Isotopic and chemical tracers include tritium, deuterium, oxygen-18, bromide, chloride, chlorine-36, carbon-14, agricultural chemicals, dyes, chlorofluorocarbons, and noble gases. In practice, concentrations measured in pore water are related to recharge by applying chemical mass-balance equations, by matching patterns inherited from infiltrating water, or by determining the age of the water. Tracer methods provide point and areal estimates of recharge. Multiple tracers used together can test assumptions and constrain estimates.

The most common tracer for estimating recharge is chloride. Chloride continually arrives at the land surface in precipitation and dust. Chloride is conservative in many environments and is non-volatile. Under suitable conditions,

$$R = P[\mathrm{Cl_p}]/[\mathrm{Cl_r}] \tag{5}$$

where P is precipitation and $[\mathrm{Cl_p}]$ and $[\mathrm{Cl_r}]$ are chloride concentrations in precipitation and pore water, respectively. Chloride mass-balance methods can be applied to unsaturated profiles[13] and entire basins.[14]

Isotopic composition of water provides a useful tracer of the hydrologic cycle. The isotopic makeup of precipitation varies with altitude, season, storm track, and other factors. Recharge estimates using isotopic varieties of water usually employ temporal or geographic trends in infiltrating water.

Non-conservative tracers can indicate the length of time that water is isolated from the atmosphere, that is, its ''age.'' Recharge rates can be inferred from water ages if mixing is small. If ages are known along a flow line,

$$R = \theta L/(A_2 - A_1) \tag{6}$$

where θ is volumetric water content, A_1 and A_2 are ages at two points, and L is separation length. One point is often located at the water table. Preindustrial water can be dated by decay of predominately cosmogenic radioisotopes, including carbon-14 and chlorine-36. The abundance of tritium and other radioisotopes increased greatly during atmospheric weapons testing, labeling recent precipitation. Additional compounds for dating modern recharge include chlorofluorocarbons, krypton-85, and agricultural chemicals.[15,16]

Heat is yet another tracer of ground water recharge. Daily, seasonal, and other temperature fluctuations at the land surface produce thermal signals that can be traced through shallow profiles.[17,18] Water moving through deeper profiles alters geothermal gradients, which can be used in inverse modeling to obtain recharge rates.[19]

OTHER METHODS

Additional geophysical techniques provide recharge estimates based on the water-content dependence of gravitational, seismic, and electromagnetic properties of earth materials. Repeated high-precision gravity surveys can indicate changes in the quantity of subsurface water from recharge events.[20] Similarly, repeated surveys using seismic or ground-penetrating-radar equipment can resolve significant changes in water-table elevation associated with transient recharge.[21] In addition to surface-based techniques, cross-bore tomographic imaging can provide detailed three-dimensional reconstructions of water distribution and movement during periods of recharge.[22]

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