

Ground-Water Recharge in Minnesota

“Ground-water recharge” broadly describes the addition of water to the ground-water system. Most water recharging the ground-water system moves relatively rapidly to surface-water bodies and sustains streamflow, lake levels, and wetlands. Over the long term, recharge is generally balanced by discharge to surface waters, to plants, and to deeper parts of the ground-water system. However, this balance can be altered locally as a result of pumping, impervious surfaces, land use, or climate changes that could result in increased or decreased recharge.

- Recharge rates to unconfined aquifers in Minnesota typically are about 20–25 percent of precipitation.
- Ground-water recharge is least (0–2 inches per year) in the western and northwestern parts of the State and increases to greater than 6 inches per year in the central and eastern parts of the State.
- Water-level measurement frequency is important in estimating recharge. Measurements made less frequently than about once per week resulted in as much as a 48 percent underestimation of recharge compared with estimates based on an hourly measurement frequency.
- High-quality, long-term, continuous hydrologic and climatic data are important in estimating recharge rates.

The first section of this fact sheet introduces the process of ground-water recharge, including definitions of related terminology and clarification of common misconceptions. The second section describes how ground-water recharge rates vary in Minnesota. The third and final section is a more technical overview of several methods used to estimate recharge rates in Minnesota.

What is Ground-Water Recharge?

“Ground-water recharge” broadly describes the replenishment of water to a ground-water flow system (Winter and others, 1998). Recharge, an integral part

of the hydrologic cycle, is the process by which water moves to the water table and then away from that area through saturated materials. Figure 1 shows how water recharges an unconfined aquifer and moves toward a river where it discharges.

The process of ground-water recharge is like refilling a leaky tank. Over the long term, recharge is generally balanced by discharge to surface waters or deeper parts of the ground-water system or by uptake by plants. However, this balance can be altered locally by pumping, impervious surfaces, land use, or climate changes resulting in increased or decreased recharge.

Where Does Recharge Occur?

Recharge to the water table occurs in most areas of the landscape but commonly at varying rates. Given the same precipitation, recharge rates in areas where sediments are sandy are greater than in areas where sediments are finer grained. In addition, surface-water runoff to low lying depressions in the land-surface generally promotes recharge (fig. 1). Surface-water bodies can be a source of recharge in areas where the water level (hydraulic head) in the underlying aquifer is below the lake or river water level.

Water in confined glacial and bed-rock aquifers is typically replenished by leakage of water through overlying

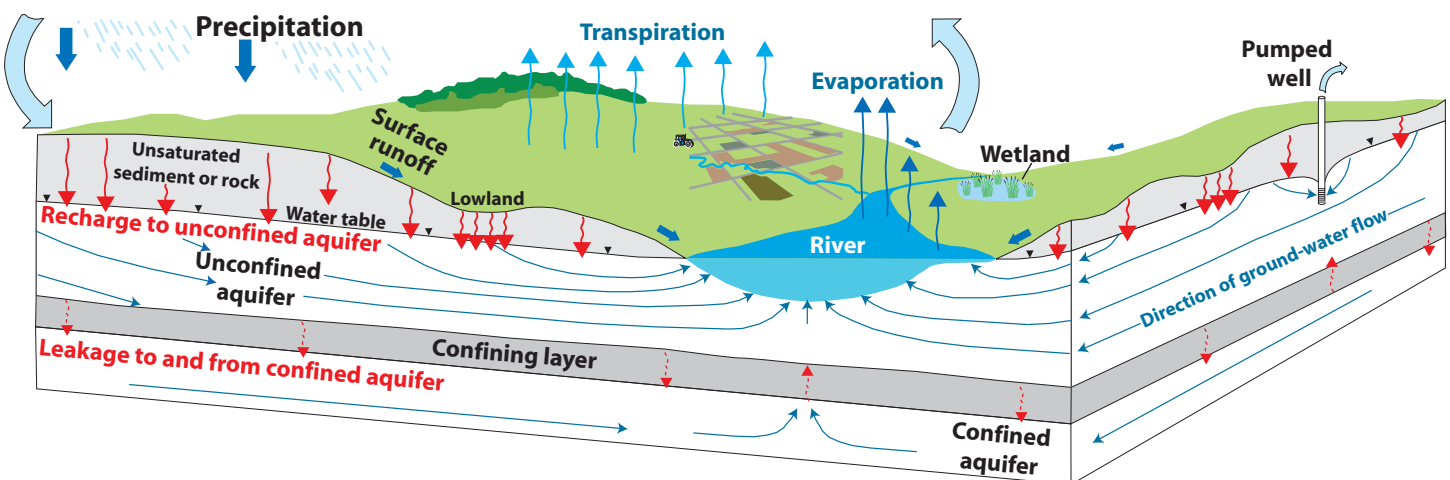


Figure 1. Ground-water recharge is an important part of the hydrologic cycle in Minnesota.

confining layers. Leakage is a process similar to but not the same as recharge (fig. 1). Rates of leakage to confined aquifers are generally less than rates of recharge to unconfined aquifers. Upward leakage also occurs from a confined aquifer in areas where hydraulic head in the confined aquifer is greater than that in the overlying formation; water moves from areas of greater to lower hydraulic head. Confined aquifers also are replenished in areas where the confining layer is permeable or absent.



Photograph by Lee Grim,
National Park Service

Figure 2. Much ground water recharge in Minnesota ends up in streams, lakes, and wetlands.

Why Do Recharge Rates Vary?

Numerous factors, including physical characteristics of the soil, vegetation cover, land use, topography, water content of surface materials, and the presence and depth of the confining layers, influence the spatial variability of recharge rates. Weather patterns, including the timing and intensity of spring snowmelt, spring rains, evapotranspiration (ET) during the summer growing season, and fall rains, play a major role in controlling spatial and temporal variability in recharge rates.

What Happens to the Water After it is Recharged?

In semihumid regions like Minnesota, most water recharging the ground-water flow system moves relatively rapidly to surface-water bodies (fig. 1) and sustains streamflow, lake levels, and wetlands (fig. 2). Smaller portions of the recharged water move to deeper confined aquifers, are extracted by plants, or are withdrawn from aquifers by wells for irrigation, public supply, or industrial and other uses.

Figure 3a illustrates the temporary effect recharge water has on the water table. The water level in a well installed in an unconfined aquifer generally rises rapidly in response to recharge from precipitation. In the absence of recharge, the water table declines in response to movement of water away from the area.

When Does Recharge Occur?

The amount of ground-water recharge varies seasonally in response to precipitation; spring and fall are the times of greatest ground-water replenishment in Minnesota (fig. 3b). Evidence of smaller recharge events also can be seen in the figure 3b hydrograph. During winter, water levels generally decline because recharge rates are negligible due to snow cover and frozen soil. During the growing season, plant transpiration rates generally exceed precipitation rates. A large proportion of the water that infiltrates at land surface, therefore, is returned to the atmosphere before it can reach the water table. Occasionally, as shown in figure 3b, summer rainfall in excess of ET rates results in net recharge.

Ground-water recharge is not...

...equivalent to "infiltration" of water at the land surface. Most water that infiltrates at the land surface is returned to the atmosphere by plant transpiration and evaporation from soil and water surfaces (fig. 1). Recharge is typically only a small fraction of infiltration.

...equated to the process of "percolation;" instead, percolation refers to the movement of water through unsaturated sediments. The percolating water can be viewed as potential recharge, however.

...to be confused with the term "aquifer yield." This term refers to the amount of water that an aquifer can yield to pumping.

...the same as "sustainable yield." Recharge is less than sustainable yield. If all recharge water was utilized, stream, lake, and wetland levels could be adversely affected. Furthermore, it cannot be assumed that pumping at less than the recharge rate will not cause water-level declines and ground-water storage depletions.

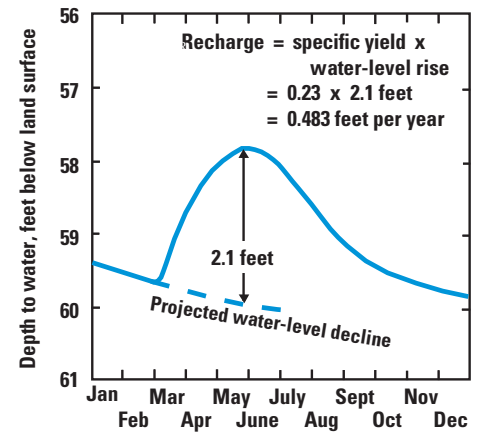


Figure 3a. Example recharge estimation based on the water-table fluctuation method using hypothetical data with only one recharge event in a year (modified from Delin and others, 2007).

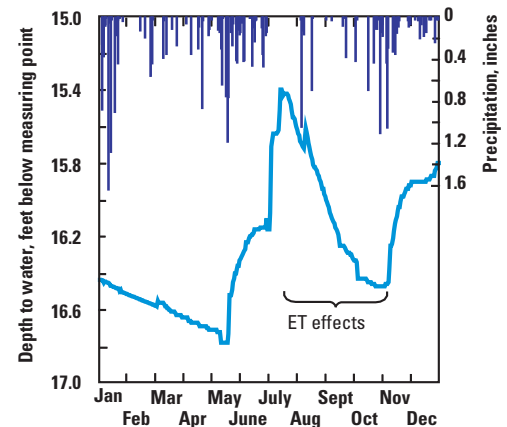


Figure 3b. Hydrograph for calendar year 2000 from a well near Windom, Minn., completed in an unconfined aquifer, showing the effects of evapotranspiration (ET) and of multiple recharge events (modified from Cowdery, 2005).

Why is Knowledge of Ground-Water Recharge Rates Important?

Knowledge of ground-water recharge rates is important to studies of water availability, sustainability, well-head protection, contaminant transport, ground-water and surface-water interactions, effects of urbanization, and aquifer vulnerability to contamination (Scanlon and others, 2002). Estimates of recharge rates are necessary to quantify the amount of water moving through near-surface ground-water systems and are important to understanding the water balance of an area and the ways that human activities, such as landscape practices, affect

that balance. For example, by estimating the seasonal and spatial distribution of recharge rates, one can estimate the total volume of water entering a system. Recharge is a sensitive component of ground-water flow models and is the one that is least understood (Delin and others, 2007).

How are Recharge Rates Estimated?

There is no “recharge gage” analogous to a rain gage, but many methods have been developed for estimating recharge rates. Selection of the appropriate method for a given study is important and can be challenging. Recharge rates are best estimated by use of multiple methods and the results compared. Accu-

rate long-term measurements of stream-flow, ground-water levels, and climate are needed to estimate recharge rates. The final section of this fact sheet provides a general description of several methods that can be used to estimate recharge in Minnesota.

How do Recharge Rates Vary Across Minnesota?

The statewide basin-scale estimates of ground-water recharge rates in Minnesota (fig. 4) are based on the regional regression recharge (RRR) method of Lorenz and Delin (2007). Stream base-flow estimates in selected basins and statewide climate and soil data are incor-

porated in the RRR method. The results illustrate the spatial variability of annual recharge rates to surficial materials across the State. An abbreviated description of the RRR method is in the Regional-Scale Methods section of this fact sheet. The recharge estimates shown in figure 4 are representative of average recharge rates for 1971–2000 because they are based on data from that time period.

Recharge rates to unconfined aquifers in Minnesota typically are about 20–25 percent of precipitation. A crude, preliminary estimate of recharge rate is sometimes made on the basis of this assumption. Recharge rates where glacial clays or till are present, however, generally are less than 10 percent of precipitation. By comparison, leakage rates to confined aquifers generally are less than 1 percent of precipitation.

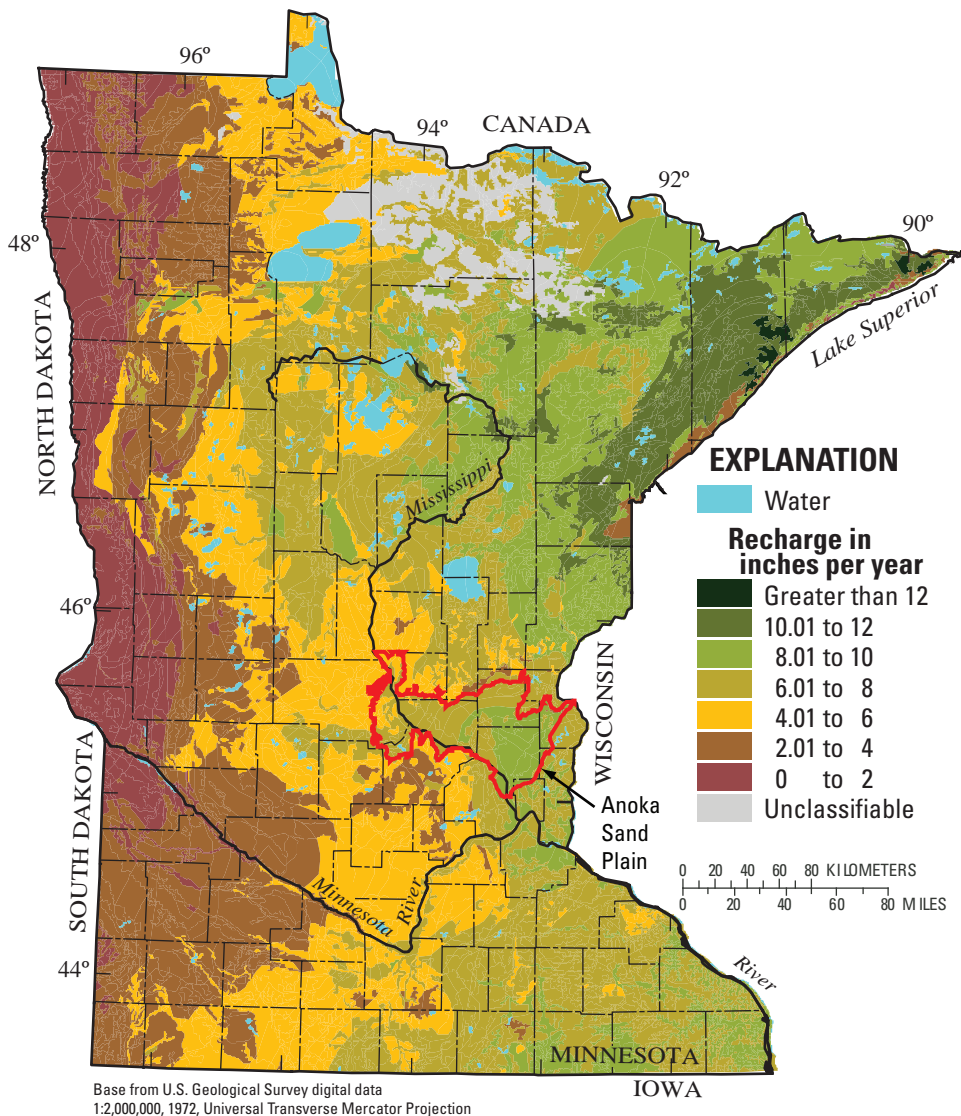


Figure 4. Average annual recharge rate to surficial materials in Minnesota (1971–2000) estimated on the basis on the regional regression recharge method (modified from Lorenz and Delin, 2007).

Spatial trends in recharge in Minnesota (fig. 4) reflect general trends in precipitation. In the western and northwestern parts of the State where precipitation is least (20–25 in/yr (inches per year)), recharge also is least (0–2 in/yr). In contrast, recharge increases in the eastern part of the State to greater than 6 in/yr as precipitation increases to greater than about 30 in/yr.

In addition to being affected by precipitation, recharge rates are locally affected by soil properties. Sandy areas, such as the Anoka sand plain and others in the central and east-central parts of the State, have coarse-textured soils that correspond well with RRR rates in the 6–10 in/yr range (fig. 4). Clay-rich soils, such as those in the western parts of the State, correspond well with RRR rates in the 0–4 in/yr range. The “Unclassifiable” areas in figure 4 represent primarily peatlands, where the organic content is too great to estimate RRR rates accurately.

Fine-scale variability in weather patterns, soil properties, land use, and topography were not included in the RRR model of the State. Low permeability units at or near land surface, ET in areas of shallow ground water, and impervious surfaces could effectively reduce the

estimated recharge rates locally. Focused recharge to depressional areas by runoff from upland areas also may increase recharge locally. In addition, 30-year averages of precipitation and other data were used to construct the RRR model (Lorenz and Delin, 2007). Thus, actual recharge rates may vary during a given year as well as from year to year, depending on weather patterns. Nonetheless, the RRR recharge estimates (fig. 4) can be a useful source of input for regional ground-water flow models and should be helpful to resource managers in developing water-management plans at State and regional scales.

Methods Used to Estimate Recharge Rates in Minnesota

Ground-water recharge rates cannot easily be measured, thus recharge rates must be estimated using indirect methods. Recharge rates in Minnesota have been estimated by means of many methods. A detailed description of all recharge-estimation methods and their limitations is beyond the scope of this fact sheet. The reader is referred to Scanlon and others (2002) for a thorough review of recharge estimation methods and their limitations. The methods commonly used in Minnesota are briefly described below and grouped on the basis of spatial scale: local, representing areas up to thousands of square feet; basin, representing tens to hundreds of square miles, and regional, representing hundreds to thousands of square miles.

Local-Scale Methods

The **water-table fluctuation (WTF) method** may be the most widely used method for estimating recharge rates in humid regions (Healy and Cook, 2002). The WTF method relates changes in measured water-level elevation to changes in the amount of water stored in the aquifer. Recharge is assumed to be equal to the product of water-table rise and specific yield (fig. 3a). Specific yield is the amount of water a unit volume of saturated permeable material will yield when drained by gravity. Several approaches have been used in Minnesota for estimating the peak water-table rise attributed to the recharge event (Delin and others, 2007). The method is relatively easy to

use but is limited by the accuracy with which specific yield can be determined; it is also affected by water-level measurement frequency and accuracy.

Delin and others (2007) showed that water-level measurement frequency is important in applying the water-table fluctuation method. Measurements made less frequently than about once per week resulted in as much as a 48 percent underestimation of recharge based on an hourly measurement frequency (fig. 5).

The **age dating of ground water method** uses estimated ground-water ages (the time elapsed since the water entered the aquifer as recharge) and well-depth information to obtain an estimate of vertical ground-water velocity. The velocity is then multiplied by aquifer porosity to obtain an estimate of recharge rate. This method is limited primarily by the accuracy with which the ground-water age is determined and by the accuracy with which aquifer porosity can be determined. Environmental tracers such as chlorofluorocarbons and sulfur-hexafluoride (as described by Busenberg and Plummer, 1992 and 2000, among others) are used to estimate ground-water age to within about 1 to 2 years.

The **chloride tracer method** is used to estimate recharge rates as the product of precipitation and the ratio of chloride concentration in wet and dry deposition on land surface to chloride concentration in the unsaturated or saturated zones (Scanlon and others, 2002). The unsaturated zone is that part of the subsurface from land surface down to the water table. Chloride is conservative (not prone to change in concentration as a result of chemical reactions), and its mass inflow must be balanced by mass outflow or by a change in storage. In areas where total infiltration is less than total precipitation, because of surface runoff, the chloride tracer method will overestimate actual recharge.

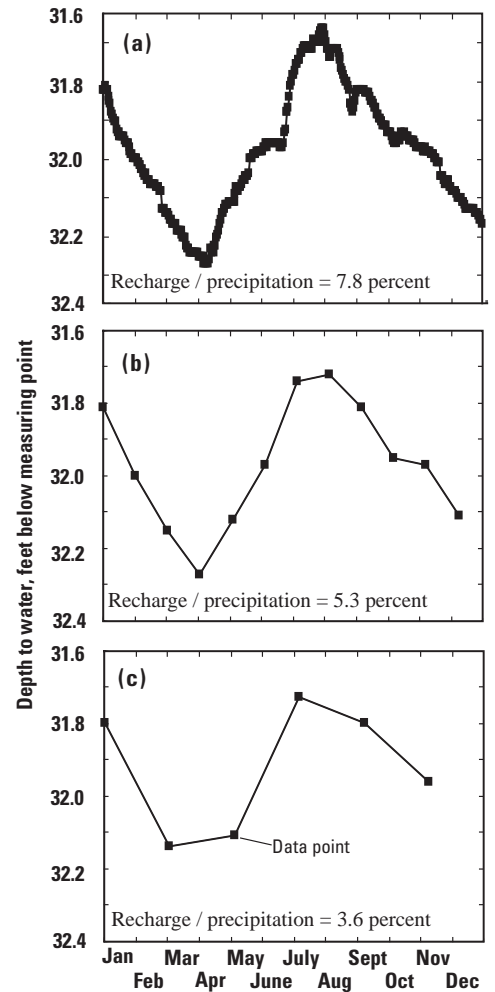


Figure 5. Hydrographs and recharge estimates for a well near Bemidji, Minn., for calendar year 2002 based on the water-table fluctuation method and a water-level measurement frequency of once every (a) day, (b), month, and (c) two months.

The **unsaturated-zone water balance (UZWB) method** (Delin and others, 2000) is based on the premise that soil water moves upward in response to ET above the zero-flux plane boundary in the unsaturated zone and that water below that boundary eventually percolates downward to the water table. Recharge is estimated by measuring the change in water stored below the boundary over time. This method, sometimes called the zero-flux plane method, is limited primarily by the requirement of intensive collection of soil-moisture data from the unsaturated zone.

The **unsaturated-zone drainage method** can be used to estimate recharge rates by directly measuring the vertical flow of water from gravity lysimeters installed in the unsaturated zone. This drainage from the lysimeters represents water that has not yet reached the water table and has been termed “potential recharge” by Scanlon and others (2002). Lysimeters are not routinely used to estimate recharge because they are expensive and difficult to construct, and they also require substantial maintenance.

The **Darcian flux method** is used to estimate recharge rates on the basis of Darcy’s Law, by using estimated hydraulic head gradient and estimated hydraulic conductivity. Several variants of this method can be used with data from saturated and unsaturated materials. In the unit gradient variation of this method, one assumes the matric potential in the unsaturated zone is constant with depth and gravity is the only driving force (Nimmo and others, 2003).

Seepage meters can be used to estimate seepage to or from surface-water bodies (Scanlon and others, 2002). A seepage meter typically consists of a cylinder that is pushed into the bottom of a stream or lake; an attached reservoir, commonly a plastic bag, collects water. A ground-water recharge rate can be estimated from the rate at which water in the cylinder infiltrates, as determined from changes in the reservoir volume. This method is inexpensive and easy to apply; however, numerous measurements may be necessary because of the point nature of the estimate.

Basin-Scale Methods

RORA (Rutledge, 1998) is an automated method for estimating the average recharge rate in a basin from analysis of streamflow records, and is based on the recession-curve-displacement method of Rorabaugh (1960). RORA accounts for the effects of ET, underflow (the flow of ground water beneath and bypassing a stream), and other losses or gains of ground water after a precipitation event.

High-quality, long-term, continuous hydrologic and climatic data are important in estimating recharge rates. High-quality streamflow (fig. 6), ground-water level (fig. 7), and climate data are required for some recharge estimation methods. Missing data add an additional degree of uncertainty to the results.

In the **streamflow-hydrograph separation methods**, base flow is used as a proxy for recharge. Base flow is defined as ground water that discharges to a stream and sustains the flow during dry periods. In using these methods, one assumes that ground-water underflow, ET, and other losses of ground water are minimal. **PART** (Rutledge, 1993), **HYSEP** (Sloto and Crouse, 1996), and **BFI** (Wahl and Wahl, 1988) are computer programs that separate base flow from a streamflow hydrograph on the basis of different criteria.

Regional-Scale Methods

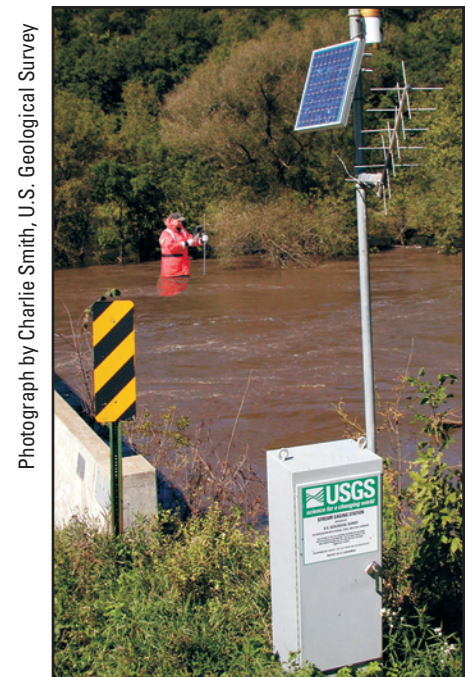
The **regional regression recharge (RRR) method** of Lorenz and Delin (2007) yields an estimate of spatial variability of annual recharge rates within a region. Many other methods are documented in the literature, and the reader is referred to Lorenz and Delin (2007) for a review of these references. The RRR method is based on a regression of RORA recharge rate estimates with climate and soil data for the region. The accuracy of the RRR estimates are representative of the soils data, which are collected over areas ranging from about 2 to 150 square miles. Recharge rates estimated on the basis of the RRR method (fig. 4) compared favorably with results from local- and basin-scale methods in Minnesota. The RRR rates on average were about 41 percent less than UZWB rates, ranged from 35 percent greater to 12 percent less than WTF rates, were about 12 percent less than age-dating-method rates, and were about 5 percent greater than RORA

rates (Delin and others, 2007). RRR rate estimates could be a useful source of input for regional ground-water flow models.

The **water-balance equation** is a common approach for estimating recharge rates at regional scales. A general form of a water budget is:

$$P + Q_{on} = ET + Q_{off} + \Delta S$$

where P is precipitation (including irrigation), Q_{on} and Q_{off} are water flow onto and off the site respectively, ET is evapotranspiration, and ΔS is change in water storage (Scanlon and others, 2002). Many other variations of this equation can be formulated by incorporating subcomponents of each variable. All ground-water and surface-water flow models fit under this method because they are based on a water-balance equation. Although listed here as a regional-scale method, a water budget estimate of recharge can also be made on the basis of local- or basin-scale data.



Photograph by Charlie Smith, U.S. Geological Survey

Figure 6. High-quality, continuous streamflow data are essential for accurate recharge estimation using basin-scale methods. The USGS maintains a nationwide network of stream-gaging stations, with stream water level and flow data served in real-time to the Internet.

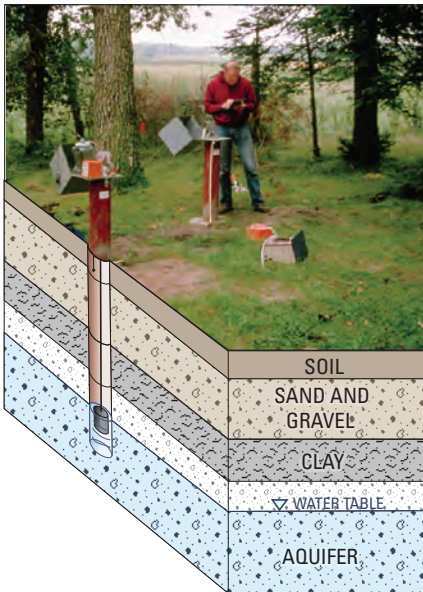


Figure 7. High quality, continuous ground-water level data are essential for accurate recharge estimation with the water-table fluctuation method. In this picture a USGS hydrologist is programming dataloggers to measure ground-water levels in Otter Tail County. The schematic diagram beneath the picture illustrates an observation well completed in a glacial aquifer.

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Information on the ¹U.S. Geological Survey Minnesota Water Science Center can be obtained at following web site <http://mn.water.usgs.gov/> and information on the ²Minnesota Department of Natural Resources Division of Waters can be obtained at <http://www.dnr.state.mn.us/waters/>