GROUND-WATER DEVELOPMENT, SUSTAINABILITY, AND WATER BUDGETS

A ground-water system consists of a mass of water flowing through the pores or cracks below the Earth's surface. This mass of water is in motion. Water is constantly added to the system by recharge from precipitation, and water is constantly leaving the system as discharge to surface water and as evapotranspiration. Each ground-water system is unique in that the source and amount of water flowing through the system is dependent upon external factors such as rate of precipitation, location of streams and other surface-water bodies, and rate of evapotranspiration. The one common factor for all ground-water systems, however, is that the total amount of water entering, leaving, and being stored in the system must be conserved. An accounting of all the inflows, outflows, and changes in storage is called a water budget.

Human activities, such as ground-water withdrawals and irrigation, change the natural flow patterns, and these changes must be accounted for in the calculation of the water budget. Because any water that is used must come from somewhere, human activities affect the amount and rate of movement of water in the system, entering the system, and leaving the system.

Some hydrologists believe that a predevelopment water budget for a ground-water system (that is, a water budget for the natural conditions before humans used the water) can be used to calculate the amount of water available for consumption (or the safe yield). In this case, the development of a ground-water system is considered to be "safe" if the rate of ground-water withdrawal does not exceed the rate of natural recharge. This concept has been referred to as the "Water-Budget Myth" (Bredehoeft and others, 1982). It is a myth because it is an oversimplification of the information that is needed to understand the effects of developing a ground-water system. As human activities change the system, the components of the water budget (inflows, outflows, and changes in storage) also will change and must be accounted for in any management decision. Understanding water budgets and how they change in response to human activities is an important aspect of ground-water hydrology; however, as we shall see, a predevelopment water budget by itself is of limited value in determining the amount of ground water that can be withdrawn on a sustained basis.

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Ground-Water Budgets

Under predevelopment conditions, the ground-water system is in long-term equilibrium. That is, averaged over some period of time, the amount of water entering or recharging the system is approximately equal to the amount of water leaving or discharging from the system. Because the system is in equilibrium, the quantity of water stored in the system is constant or varies about some average condition in response to annual or longer-term climatic variations. This predevelopment water budget is shown schematically in Figure 8*A*.

We also can write an equation that describes the water budget of the predevelopment system as:

Recharge (water entering) =
Discharge (water leaving)

The water leaving often is discharged to streams and rivers and is called base flow. The possible inflows (recharge) and outflows (discharge) of a ground-water system under natural (equilibrium) conditions are listed in Table 1.

Table 1. *Possible sources of water entering and leaving a ground-water system under natural conditions*

Inflow (recharge)	Outflow (discharge)
1. Areal recharge from precipitation that percolates through the unsaturated zone to the water table.	1. Discharge to streams, lakes, wetlands, saltwater bodies (bays, estuaries, or oceans), and springs.
2. Recharge from losing streams, lakes, and wetlands.	2. Ground-water evapotranspiration.

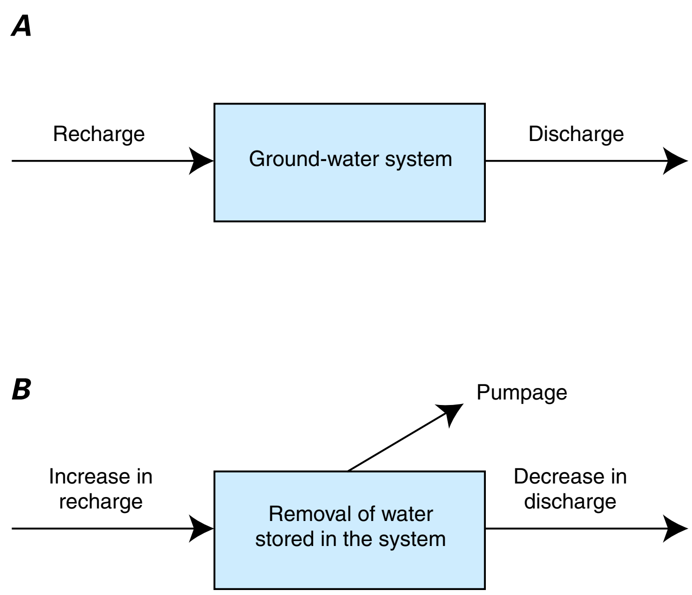

Figure 8. *Diagrams illustrating water budgets for a ground-water system for predevelopment and development conditions.*

(A) Predevelopment water-budget diagram illustrating that inflow equals outflow. (B) Water-budget diagram showing changes in flow for a ground-water system being pumped. The sources of water for the pumpage are changes in recharge, discharge, and the amount of water stored. The initial predevelopment values do not directly enter the budget calculation.

Humans change the natural or predevelopment flow system by withdrawing (pumping) water for use, changing recharge patterns by irrigation and urban development, changing the type of vegetation, and other activities. Focusing our attention on the effects of withdrawing ground water, we can conclude that the source of water for pumpage must be supplied by (1) more water entering the ground-water system (increased recharge), (2) less water leaving the system (decreased discharge), (3) removal of water that was stored in the system, or some combination of these three.

This statement, illustrated in Figure 8*B*, can be written in terms of rates (or volumes over a specified period of time) as:

Pumpage = Increased recharge + Water removed from storage + Decreased discharge.

It is the changes in the system that allow water to be withdrawn. That is, the water pumped must come from some change of flows and from removal of water stored in the predevelopment system (Theis, 1940; Lohman, 1972). The predevelopment water budget does not provide information on where the water will come from to supply the amount withdrawn. Furthermore, the predevelopment water budget only indirectly provides information on the amount of water perennially available, in that it can only indicate the magnitude of the original discharge that can be decreased (captured) under possible, usually extreme, development alternatives at possible significant expense to the environment.

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Regardless of the amount of water withdrawn, the system will undergo some drawdown in water levels in pumping wells to induce the flow of water to these wells, which means that some water initially is removed from storage. Thus, the ground-water system serves as both a water reservoir and a water-distribution system. For most ground-water systems, the change in storage in response to pumping is a transient phenomenon that occurs as the system readjusts to the pumping stress. The relative contributions of changes in storage, changes in recharge, and changes in discharge evolve with time. The initial response to withdrawal of water is changes in storage. If the system can come to a new equilibrium, the changes in storage will stop and inflows will again balance outflows:

Pumpage = Increased recharge
+ Decreased discharge

Thus, the long-term source of water to discharging wells is typically a change in the amount of water entering or leaving the system. How much ground water is available for use depends upon how these changes in inflow and outflow affect the surrounding environment and what the public defines as undesirable effects on the environment.

In determining the effects of pumping and the amount of water available for use, it is critical to recognize that not all the water pumped is necessarily consumed. For example, not all the water pumped for irrigation is consumed by evapotranspiration. Some of the water returns to the ground-water system as infiltration (irrigation return flow). Most other uses of ground water are similar in that some of the water pumped is not consumed but is returned to the system. Thus, it is important to differentiate between the amount of water pumped and the amount of water consumed when estimating water availability and developing sustainable management strategies.

The possibilities of severe, long-term droughts and climate change also should be considered (see Box B). Long-term droughts, which virtually always result in reduced ground-water recharge, may be viewed as a natural stress on a ground-water system that in many ways has effects similar to ground-water withdrawals—namely, reductions in ground-water storage and accompanying reductions in ground-water discharge to streams and other surface-water bodies. Because a climate stress on the hydrologic system is added to the existing or projected human-derived stress, droughts represent extreme hydrologic conditions that should be evaluated in any long-term management plan.

Consideration of climate can be a key, but underemphasized, factor in ensuring the sustainability and proper management of ground-water resources.