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ESSAY

Groundwater: Recharge is Not the Whole Story

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INTRODUCTION

The "hydrologic cycle" describes the earth system that transports water from the oceans to the land: Energy from the sun evaporates water from the earth's oceans; the water vapor in the atmosphere forms clouds; clouds move in the prevailing winds; ultimately, the clouds produce precipitation much of which falls on land; some fraction of the water from precipitation is used by land plants locally, another fraction runs off as streamflow associated with rainfall events, and another fraction recharges groundwater in the underground where it also runs off. Humans living on the land observe the above-ground workings of the hydrologic cycle, but water under ground is not directly observable; so what happens to water in the underground is a mystery to many. Water under ground is the purview of hydrogeology, and the subject of this essay.

Soil and rocks as observed near the land surface contain void space that we refer to as "porosity." All rocks are known to have porosity. If one drills a borehole into the earth to some reasonable depth, say 100 m, water in the hole will stand over time within 30 m of the land surface—this is known as the "normal" condition. If we imagine that we drill similar boreholes nearby, we can define an imaginary surface formed by the elevation of water levels in similar boreholes. This surface represents the top of the water (fluid) saturation in the earth—this is the so-called "water table." Beneath the water table, the soils and rocks in the earth are saturated to depths in which pressure and temperature no longer make this statement meaningful. In other words, beneath the water table in the earth, all rocks are saturated with water (or some other fluid—such as oil or gas) since all rocks are known to have some porosity.

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Near the land surface, groundwater circulates, usually driven by differences in topography (Tóth 1962). Shallow groundwater systems generally contain freshwater. Approximately 50% of the current population of the United States obtains its public and domestic water supply from shallow groundwater wells (Maupin et al. 2014). As one drills deeper into the earth, the influence of the local topography is lost as a driving force, and the natural circulation of water in the earth slows. As the movement of the water slows, the chemistry of the water becomes equilibrated with the rocks in which it is contained; in other words, the water becomes mineralized (Back 1966). The deeper one drills, the more mineralized groundwater becomes. One can reach depths in which the primary driving force on the mineralized water in the rocks is chemical diffusion. In some geologic basins, the deeper groundwater appears to be more or less stagnant. These are places where chemical—even radioactive—wastes might be sequestered indefinitely in the earth.

Getting back to the hydrologic cycle, some fraction of water from precipitation moves down through the soil and ends up recharging groundwater. Recharge moves through the shallow groundwater reservoir and discharges somewhere down stream. One tenet of Newtonian physics is the "conservation of mass." In the case of groundwater, recharge must go somewhere; either it increases the groundwater stock in storage in the system, or it discharges. Because natural systems existed for long periods, they are generally full. Thus, in most instances, recharge to a groundwater system, before the system is perturbed, is balanced by discharge, and the usual form of groundwater discharge is flow to local streams.

In the groundwater system described above, most of the components of the system are hard to observe. We interpret many of the components from partial information. For example, recharge usually occurs as widely distributed precipitation over a portion of a watershed, where it percolates downward through the soils. Although recharge can be determined by careful observations at a local site, how to extend the site-specific results to a much larger area can be problematic.

Discharge from groundwater forms streamflow in between rainfall events — this is the so-called "baseflow" of streams—and hydrogeologists routinely measure it. Often the measured baseflow of streams is the most informative data we have concerning the magnitude of groundwater flow through an aquifer. Even though one often hears hydrogeologists and others speaking about the recharge to groundwater, most often it is the *discharge* from the system that is the most reliable information. Usually discharge measurements constrain recharge estimates. And under undisturbed conditions, in most instances, the recharge is equal to the discharge, and vice versa.

WHAT HAPPENS WHEN ONE PUMPS?

A classic question in groundwater is: *Where does water come from when one pumps a well*? The well creates a new discharge from a groundwater system that is already balanced in the undisturbed state – recharge equals discharge. There are three potential sources of water to the well: (1) the well can induce more recharge, (2) the well can reduce the discharge, or (3) the well can pump from storage in the groundwater system (or some combination of all three).

The well must create pressure gradients in the aquifer that move water into the borehole (such as the one posited earlier). Imagine if we were to drill observation wells near a pumping well; the water levels would form an imaginary, downward facing cone, centered on the pumping well – the so-called "cone of depression." Groundwater is removed from storage from within the cone of depression.

If one seeks a sustainable development, then, at some point, water levels within the aquifer must stabilize—there cannot be a continued removal of groundwater from storage. In a sustainable state, conditions 1 and/or 2 (stated earlier) must be met: In other words, (1) the well induces additional recharge sufficient to offset the pumping, and/or (2) the well reduces the discharge sufficiently to offset the pumping. In many situations, it is impossible for the pumping to induce more recharge. In these instances, the system is sustainable *if* the pumping can reduce the discharge sufficiently to offset the pumping. Usually the reduction in discharge created by pumping determines how much pumping can be sustained. The magnitude of the recharge is only of passing interest, it does not determine how large a pumping rate can be maintained (Theis 1940; Lohman 1972).

If pumping is conducted at a volume such that a sustainable system cannot be maintained, then the water pumped will continue to be supplied from groundwater in storage—this represents "groundwater mining." As a result, water levels in such an aquifer will continue to decline. Pumping can continue until the water table drops to a level so deep that it is no longer economical to lift water from such depths. Or, as one taps into deeper portions of the aquifer, the water will become of such poor quality, that it is no longer usable. This is the current situation in the southern San Joaquin Valley where groundwater levels are declining rapidly. Often a continuously declining water level in an aquifer produces land subsidence as clay interbeds in the aquifer release water and compact.

PUMPING EFFECTS ON AN ADJOINING STREAM

Many, if not most, stream valleys contain alluvial deposits (gravel, sand, silt, and clay) that are commonly highly porous and permeable. This is true of the Central Valley of California. Irrigation developed on alluvial terraces that adjoin many streams in the West. Interestingly, many streams that depend upon melting snowpack in mountain portions of the watershed for most of their runoff did not have flow in their lower reaches late in the summer and fall in their natural state — streams tended to dry-up during the dry season. It is return flow from irrigation in the valleys of these streams that maintains the streamflow during the entire year. Year-round flow in many western streams is a phenomenon that occurred in the last 150 years; we now view this as the norm, but it is a recent occurrence. Year-round flow enhances the habitat for anadromous fish. In California, there is an extensive alluvial aquifer in the Sacramento Valley.

Alluvial deposits in most stream valleys are highly productive aquifers. These aquifers are large reservoirs of groundwater. Typically, wells are developed in the alluvial aquifers. How does pumping of groundwater from an alluvial aquifer affect a nearby stream? Not surprisingly, the effects of pumping depend upon: (1) the magnitude of the pumping, (2) the properties of the aquifer (the porosity and permeability of the alluvial deposits), and (3) the distance of the pumping from the stream.

Our discussion earlier indicates that evaluating the change in discharge is important in assessing groundwater effects. Recharge, on the alluvial terraces of a stream valley, creates discharge to the adjoining stream. When one pumps from the alluvial aquifer one can either (1) reduce the discharge from the aquifer to the stream, or (2) induce recharge from the stream to the aquifer. Whether the well creates recharge or discharge from the stream depends upon the status of the stream—whether it is losing water to the adjoining aquifer, or is gaining flow from it. Mathematically, the analysis of stream depletion is in both instances identical.

Wells that pump water at similar rates of volume from an alluvial aquifer have different effects on an associated stream, depending upon the distance of those wells from the stream. Figure 1 shows the reduction in streamflow from an irrigation well pumping relatively near the stream, that is, less than one quarter mile from the stream. As Figure 1 shows, when a well is located close to the stream, pumping effects occur relatively quickly, but accumulate only slightly from year to year.

In contrast, Figure 2 shows the effects of a well pumping similar at a similar rate of volume, but some distance from the stream. A well relatively far (more than 1 mile from the stream) creates dramatic stream depletion. This well's effect on the stream is not fully felt until water has been pumped from it for 15 or 20 years. Furthermore, the effect occurs at a more or less constant rate during the entire year; there are only small seasonal fluctuations in the rate of depletion. As time elapses, the rate of depletion is approximately equal to the volume of pumping averaged over the entire year, This is important since now the effect of pumping occurs during the entire year, not only during the growing season (Bredehoeft and Kendy 2008).

The differing effects of these two wells, both pumping similarly, illustrate an important principle in hydrogeology: The location of a well relative to an adjacent stream makes a big difference in how the stream is affected. Contrary to surface

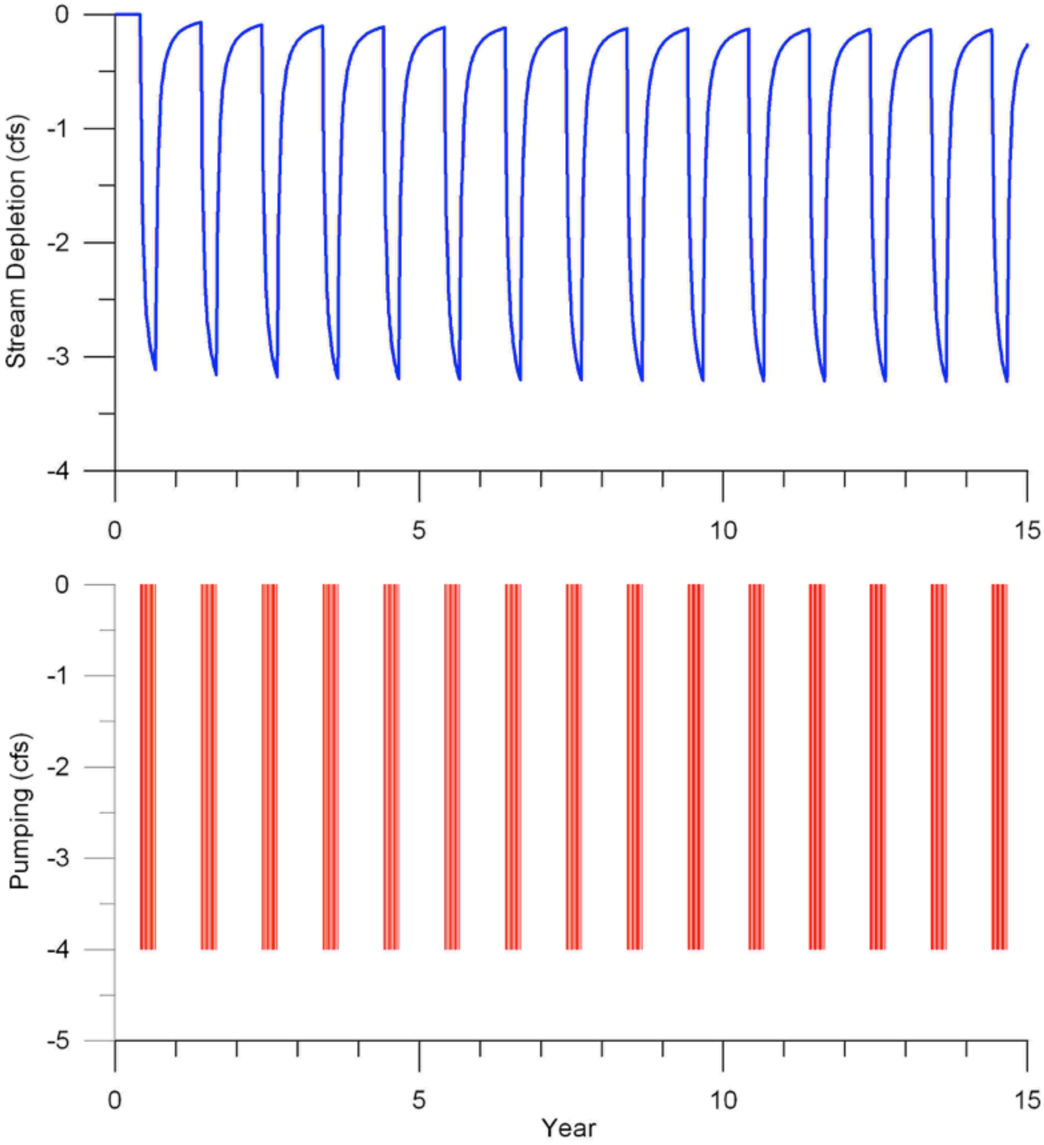

Figure 1 Reduction in streamflow (stream depletion, upper graph) created by a well located less than one-quarter mile from a stream pumping at a rate of 4.0 cfs (0.11 m^3s) for 3 months annually (lower plot)

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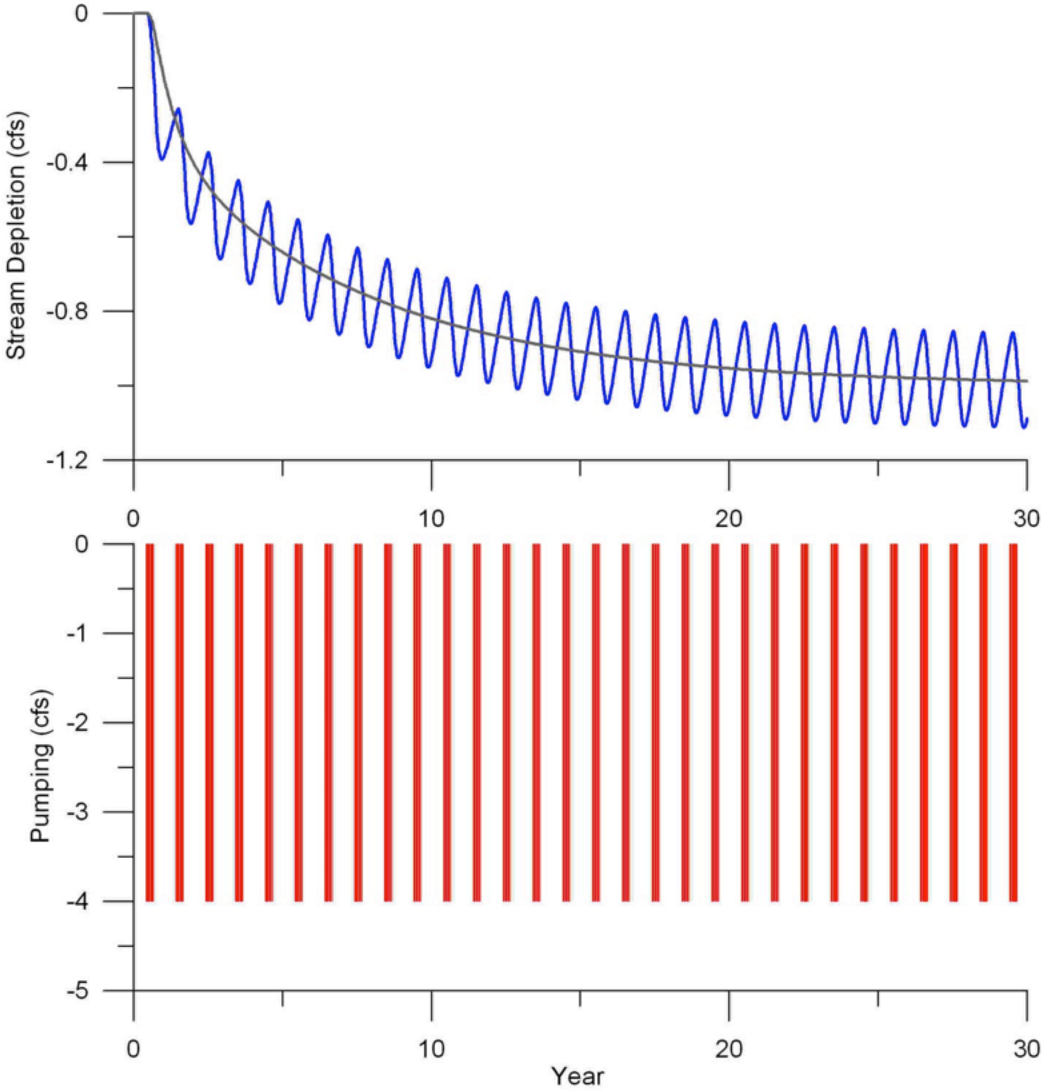

Figure 2 Reduction in streamflow (stream depletion, upper graph) created by a well located more than one mile from a stream and pumping 4.0 cfs (0.11 m^3s) for 3 months annually (lower graph). The smooth black line in the upper graph shows the stream depletion for a well pumping continuously at 1.0 cfs (0.03 m^3s).

water systems, in groundwater systems the placement of wells relative to the boundaries of the system is important in determining how the system will respond. Usually, a simple water budget analysis does not indicate how groundwater systems respond to stress.

GROUNDWATER MODELS

To many, hydrogeologists may seem fixated on the use of models for purposes of analysis, but there is a reason for this. Groundwater systems, because they both store and transmit water, behave with a diffusive response (Bredehoeft 2006). The differential equations that describe groundwater flow are similar to equations for heat and electricity, and in simple situations can be solved by classical methods. But most realistic groundwater problems are sufficiently complex that closed form mathematical solutions are impossible. However, these same real-life problems can be decomposed into a mathematical model that can be solved by computers. In the final analysis, the numerical models solve the partial differential equations of flow that usually simply conserve the mass of water in the system.

”Conceptual models” are now an integral part of the science of hydrogeology and are critical in describing the fluid–rock interactions within the earth’s crust in all its complexity. Once a conceptual model is established, it goes through several stages of development. A domain is created and populated with an initial parameter distribution, boundary conditions, and sources and sinks. During subsequent model runs the parameters are adjusted until the model output reproduces an observed history; this is often referred to as “model calibration.” Optimization procedures help to adjust the parameters until a good history match is achieved. Once the model output matches the observations satisfactorily, the model can be used to project future responses of the system to stresses of interest. For example, one can test various scenarios of development. The models serves to simulate the complex interaction between the sources and sinks in a complex, heterogeneous aquifer system. Further, the model output constrains how the system might be managed. The critical step in modeling is the selection of the conceptual model itself.

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