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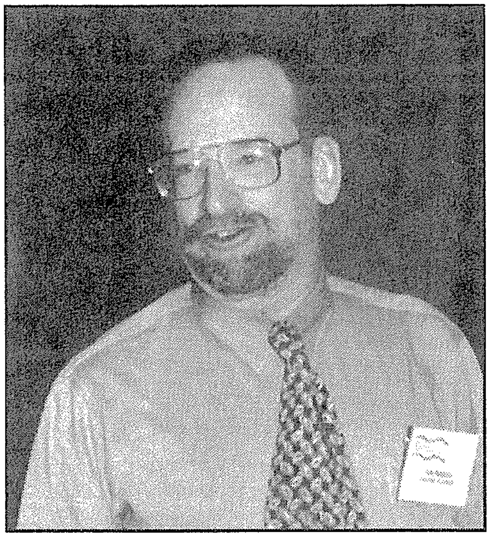

MODELING GROUND AND SURFACE WATER INTERACTIONS

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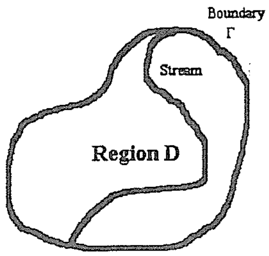
With the advent of the digital computer and its progeny, the personal computer, nearly every inhabitable basin in this country has been modeled by a groundwater model. In this talk, I will describe these models, how they work and what they do.

A groundwater model is usually the numerical solution to a set of field equations such as those shown in Figure 1. A numerical solution is necessary because of the complexity of regions' boundaries and hydraulic properties. A grid structure is superimposed over a plan view of a region (figures 2, 3 and 4) and an approximate solution is obtained for grid cells, rather than for the continuous region. One part of the solution is the water level at each grid point. The other part is a water budget for the region. The water levels at the grid points can be contoured, such as those shown in Figure 5. The contours are actually

For a region D,

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W-S_s\frac{\partial h}{\partial t}=0$$



Subject to:

$$h(x,y,z,0)=H_o(x,y,z) \text{ on D}$$

and

$$\left[K_n\frac{\partial h}{\partial n}+c_b\left(H_b-h\right)-Q\right]\Big|_{\Gamma}=0$$

Figure 1. Modeling ground and surface water interactions.

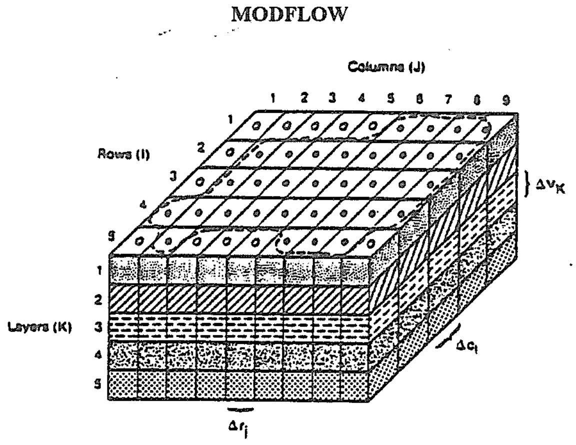


Figure 2. The finite difference formulation.

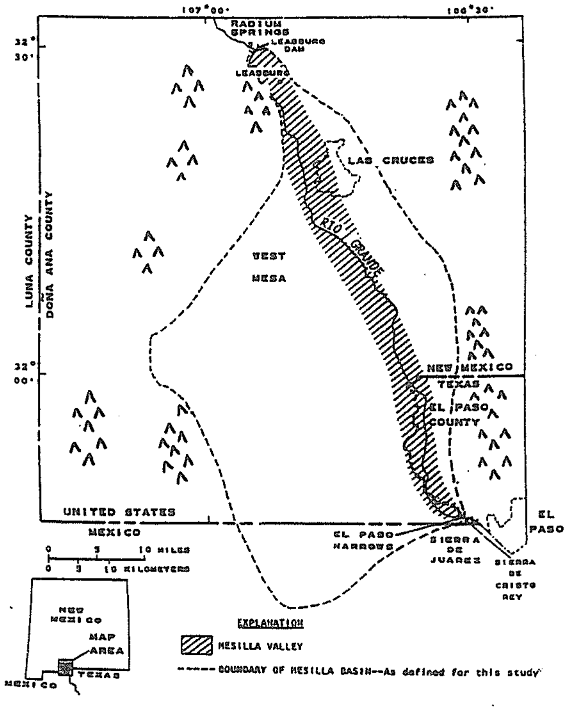


Figure 3. Map of the Mesilla Basin.

drawdown, the change in water level from predevelopment conditions, which is also an output of the model. Thus, the model can be used to predict changes in water levels over time and space. These water level changes can be caused by well pumping or by changes in natural recharge or discharge conditions to and from the aquifer.

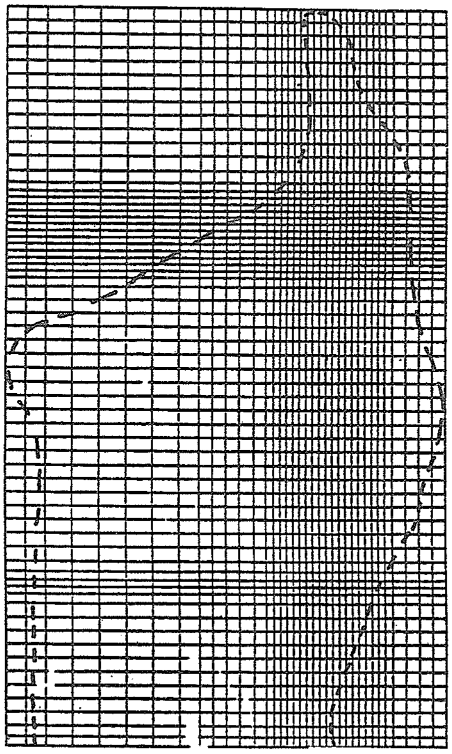


Figure 4. Mesilla Basin model grid.

Groundwater models can simulate certain types of surface water behavior; in particular, the stream stage of baseflow, which, along with runoff, is a component of the streamflow. Figure 6 depicts a stream discharge hydrograph, which is a graph of some measured streamflow versus time. Hydrologists can separate the stream-discharge hydrograph into two component hydrographs: the runoff hydrograph and the baseflow hydrograph. Groundwater hydrologists are usually only interested in the baseflow because this is the portion of streamflow that interacts with the groundwater. The runoff is assumed, in most cases, to flow through the basin too quickly to interact with the groundwater.

Groundwater models are used to determine capture. Under natural conditions, prior to the development of wells, a groundwater system exists in a state of approximate equilibrium.[1] This equilibrium is maintained by a long-term balance between natural recharge and discharge processes[2] in the groundwater basin (see Figure 7). Over the millennia, wet years, in which recharge exceeds discharge, offset dry years, in which discharge exceeds recharge. Below elevations

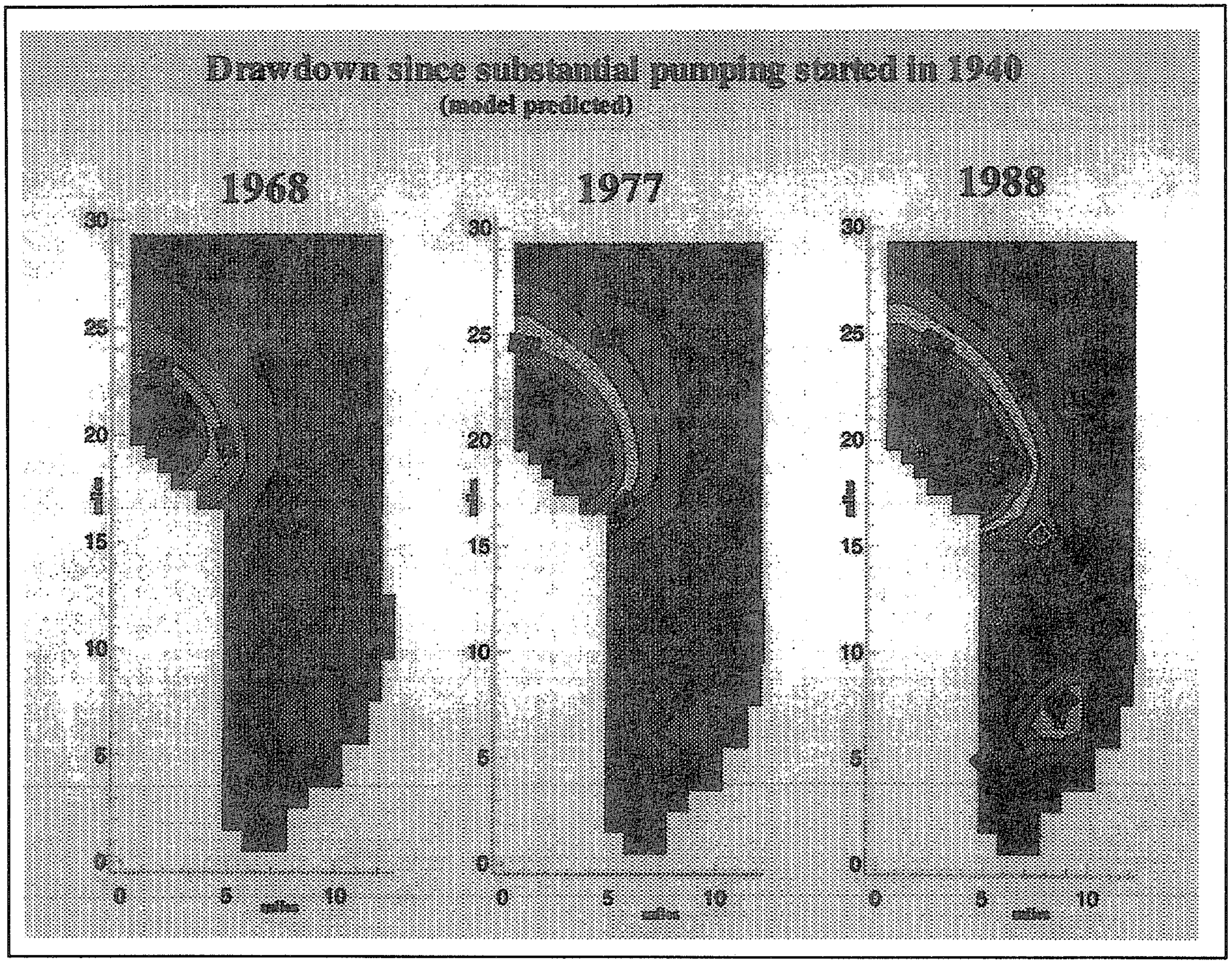


Figure 5. Drawdown since substantial pumping started in 1940 (model predicted).

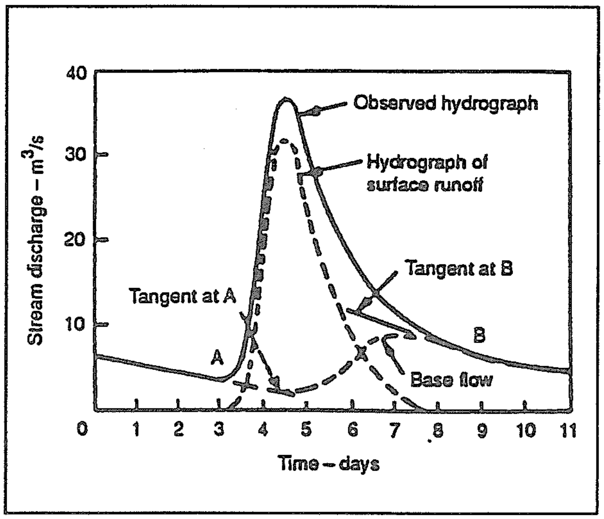
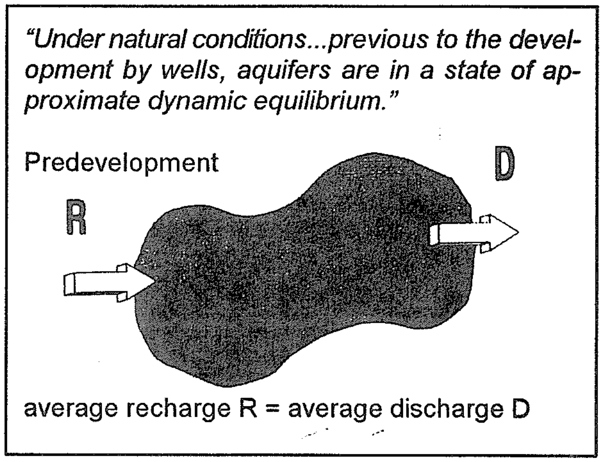


Figure 6. Base flow.


"Under natural conditions...previous to the development by wells, aquifers are in a state of approximate dynamic equilibrium."

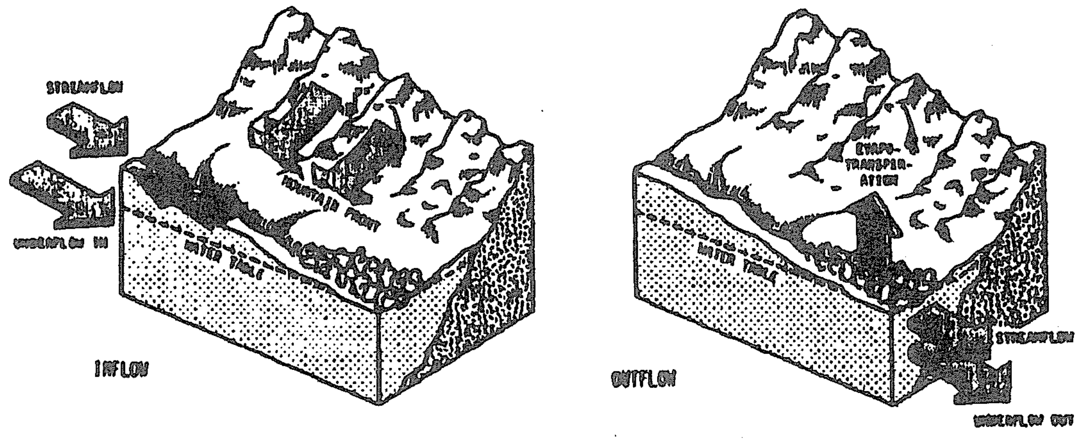
average recharge R = average discharge D

Figure 7. The concept of capture.

of about 4,000 feet in the arid southwest, mountain-front recharge[3], seepage from losing streams [4], and inflow from other groundwater basins comprise the principal mechanisms for aquifer recharge. Discharge from the aquifer typically occurs through evapotranspiration[5] and seepage to gaining streams[6] (Figure 8). Discharge from pumping wells is a new process imposed on the formerly balanced groundwater system. The new discharge process will produce either a decrease in aquifer storage land and/or some combination of an increase in recharge and a decrease in natural discharge. The sum of the induced *increase* in recharge plus the *decrease* in discharge is called capture (figures 9 and 10). Examples of capture include pulling waters directly from the stream, intercepting waters that would have arrived at the stream, and reducing evaporation and transpiration processes in the riparian areas (Figure 11).

Before pumping from a well-induced capture, all water extracted from the well is derived from aquifer storage and is considered "mined" water. The mining process creates a "cone of depression" in the water table near the well, which is simply the manifestation of the impeding action of the aquifer material. The "cone" is inverted with its nadir centered at the well and its base at the level of the surrounding water table (Figure 12). As the water is mined from the aquifer, the cone of depression expands, causing the nadir to deepen and the base to widen.

The cone of depression continues to grow until a source of capture is encountered. If no sources of capture exist in a region, the cone will continue to grow indefinitely until the saturated thickness of the aquifer open to the well cannot yield sufficient water to maintain pumping. If the capture source is a losing stream, the cone of depression induces an increase in inflow to the aquifer from the stream (Figure 11A). If the capture source is a gaining stream, the cone induces a decrease in outflow from the aquifer to the stream (Figure 11B). In either case, the stream loses water. The most debilitating effects occur when a stream capture source lies within a riparian area. If the cone of depression lowers the water table below the root zone, it will reduce evapotranspiration and may damage plant and animal habitat (Figure 11C). Once capture begins, however, the growth of the cone of depression slows. If the volume of water captured equals that pumped from the well, the cone will cease to grow because no water is derived from storage.



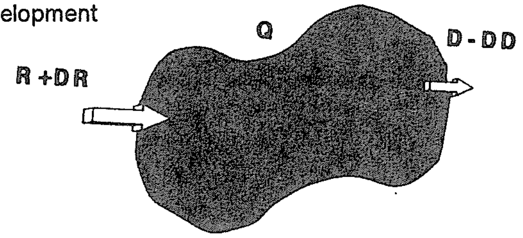
Recharge
Losing Stream
Underflow In
Mountain Front

Discharge
Gaining Stream
Underflow Out
Evapotranspiration

Figure 8. Predevelopment recharge and discharge.

"Discharge by wells is thus a new discharge superimposed upon a previously stable system, and it must be balanced by an increase in recharge of the aquifer, or by a decrease in the old natural discharge, or by a loss of storage in the aquifer, or by a combination of these."

Development



Stress Q is introduced

The system may respond in three different ways:

- increase in recharge -> R+DR
- decrease in discharge -> D-DD
- change in aquifer storage -> DS

Figure 9. Concept of capture continued.

NEW EQUILIBRIUM

$$R + DR - (D - DD) - Q = DS$$

BUT

$$R = D$$

THEREFORE

$$DR + DD - Q = DS$$

$$\boxed{\text{CAPTURE} = DR + DD}$$

Figure 10. Concept of capture continued.

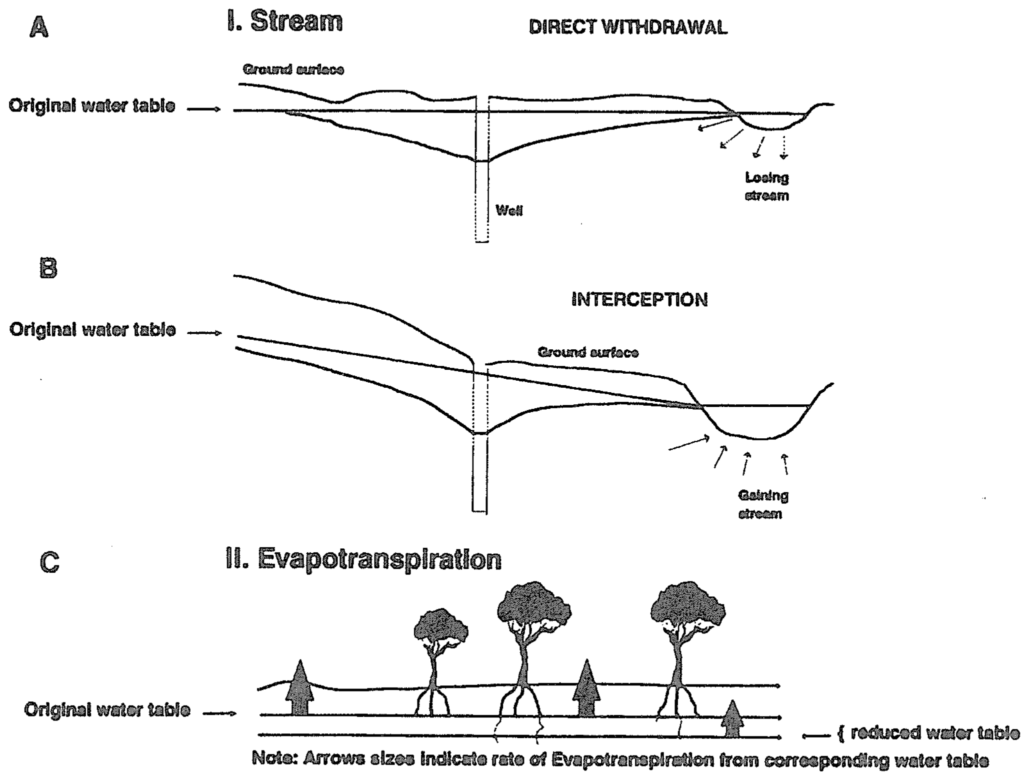


Figure 11. Main sources of capture.

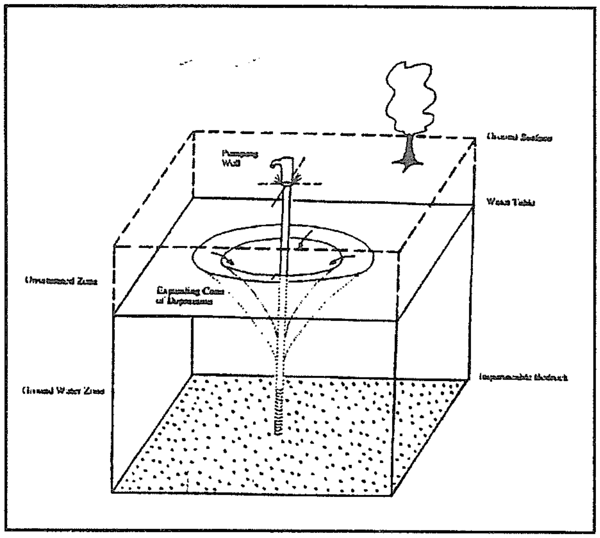


Figure 12. Cone of depression.

Ground and surface water interaction models can give information about capture processes both for entire basin systems and for specific reaches along a river. Figure 13, for example, is a systemwide water budget for the San Pedro River. The San Pedro in southeastern Arizona is a stream that runs north out of Mexico into the United States. It usually has only about four to five second-feet of water in it. The time axis in this figure starts in the 1940s and ends in the 1990s. Four different activities are identified: pumping, aquifer storage, evapotranspiration and net flow to the stream. First, we see a fairly steady rise in the pumping of the system. In the late 1980's, however, we see an interesting downturn. At this time, much of the agricultural property was turned over to the Bureau of Land Management, and Congress started the San Pedro Natural Conservation Area. The Bureau of Land Management ended the agricultural pumping and allowed for recovery. Secondly, we see a storage loss, which is not as great as the volume that has been pumped out. This trend is a clear indication of capture—without capture in the basin, the curves representing volume pumped out and storage loss would simply replicate themselves in terms of the total volume of water removed from the system. Thirdly, the net flow to the stream has started to decline as a result of the reduced pumping because of the retirement of agricultural land. Finally, evapotranspiration rates have also declined, although not as dramatically as the interception processes which reduce the net streamflow.

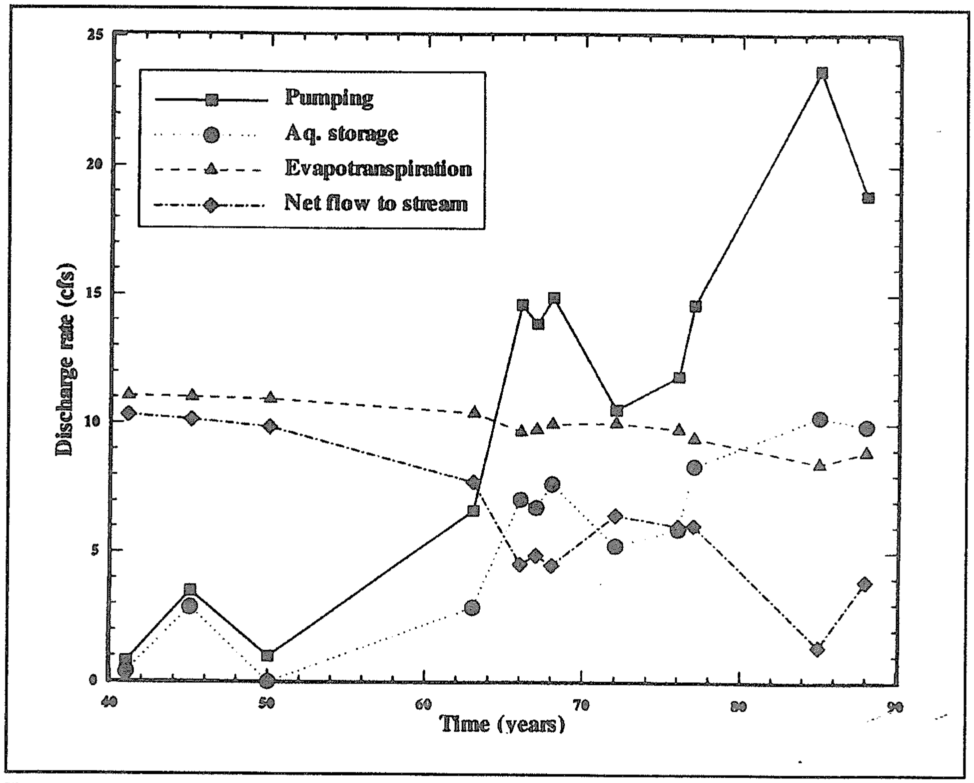


Figure 13. Change in discharge components over time.

Figure 14 shows the interactions between groundwater and the baseflow for four distinct points along the river. The first, Palominas, is an agricultural area very close to the San Pedro River. As the pumping continues from the 1940s, the stream, which was originally a gaining stream, is converted to a losing stream. At one time the water went from the groundwater system into the river, but the pumping has reversed the trend, causing the water to move from the river into the groundwater system—the basic result of large-scale pumping near streams, canals, laterals, and drains. The second area, near Hereford, has a relatively large confining unit between the alluvial system and the regional aquifer sitting below it. In this case, although there is some interaction, the effect is not nearly as dramatic upon the river system. Pumping from these deeper systems eventually causes pumping effects to cross the confining layers. It takes a long time, however, for water to cross; we have been pumping for 40-50 years in the San Pedro system. The pumping that occurred in the San Pedro basin in the early 1940s generally did not have a great effect on the rivers. After the 1950s, however, the use of the high-lift turbine pumps and the continued long-term pumping resulted in pumping effects crossing the confining units. In the third and fourth areas near Lewis Springs and Charleston Bridge, geological outcrops retard ground and surface water interactions.

I'd like to finish this talk by describing how we actually model ground and surface water interactions. Although I will not go into the involved mathematics, I will describe the modeling process conceptually. The first way to model the interaction is with a constant head boundary (Figure 15). It is assumed as a matter of course that the stream is as deep as the aquifer—that it acts as a constant head. The stage or depth of water in the stream, therefore, is constant, regardless of the amount of water withdrawn from the stream by capture from pumping groundwater. Because the stream depth and aquifer thickness are the same, the interactive flow between the stream and the aquifer is horizontal. For a basin in which the groundwater pumping centers are quite far from a large river, the constant head boundary approach is adequate.

The second way to model the interaction is to use a "prescribed stage" boundary (Figure 15). The prescribed stage boundary no longer requires the stream

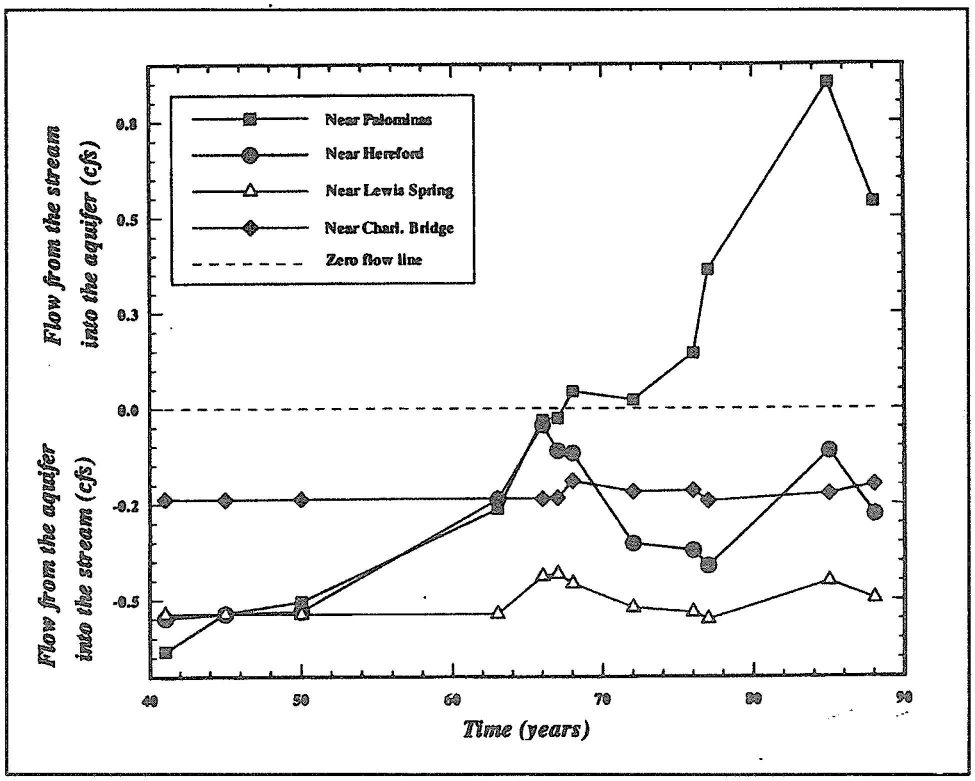


Figure 14. Flow between stream and aquifer at selected locations.

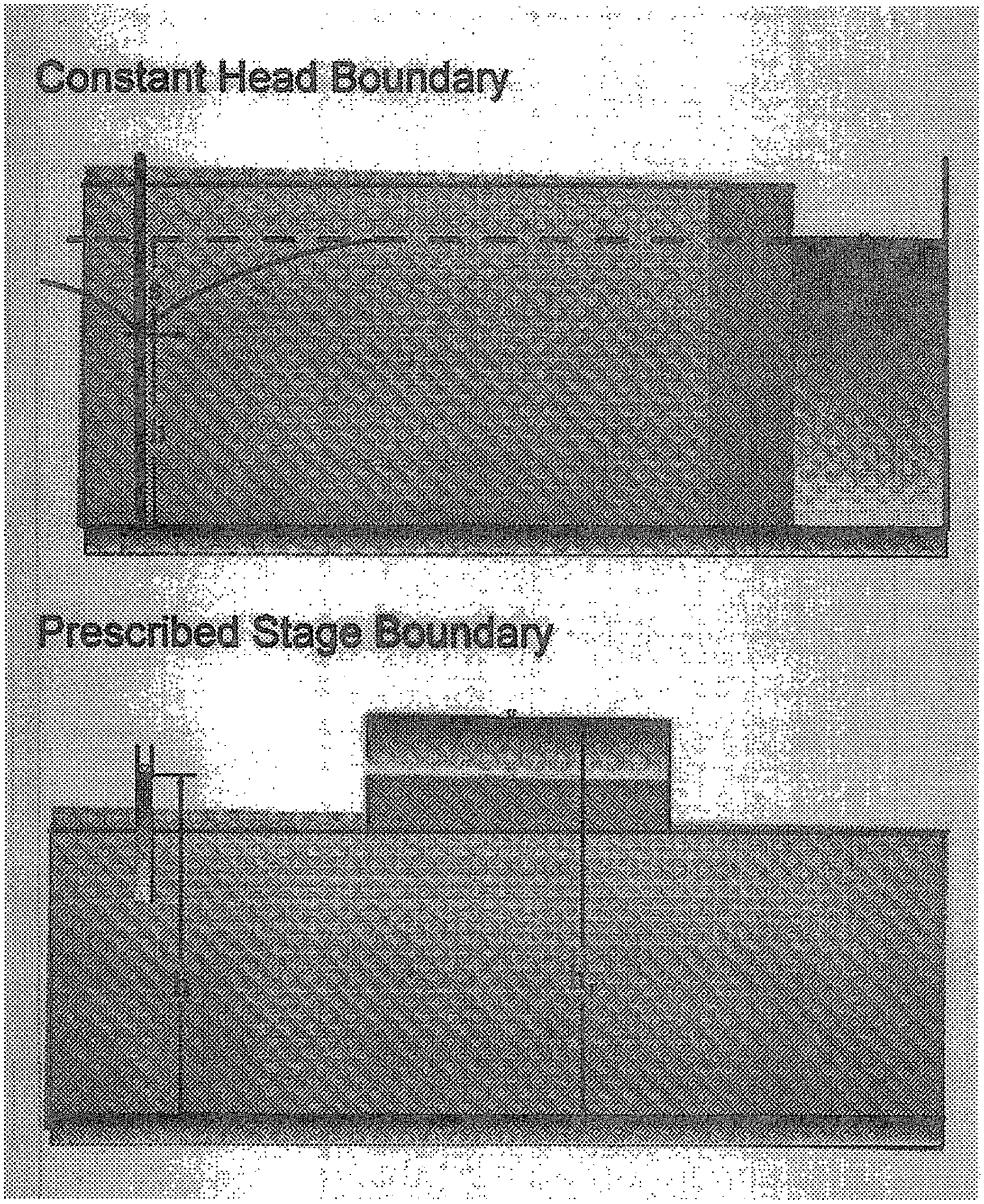


Figure 15. Methods of modeling streamflows.

to be the same depth as the aquifer thickness. In fact, ground and surface water interaction is assumed to occur only through the stream bed. The stream depth is specified, and flow in the aquifer no longer need be horizontal. Because the stage is specified, however, the stream cannot dry out, regardless of how much capture occurs.

The third and final method involves a "calculated stage" boundary (Figure 16). The calculated stage model may have the stream or river dry out and rewet if too much capture occurs. The stage calculated is only for the baseflow portion of the streamflow. The runoff portion is ignored. The interaction will depend on the shape of the stream bed, the slope of the

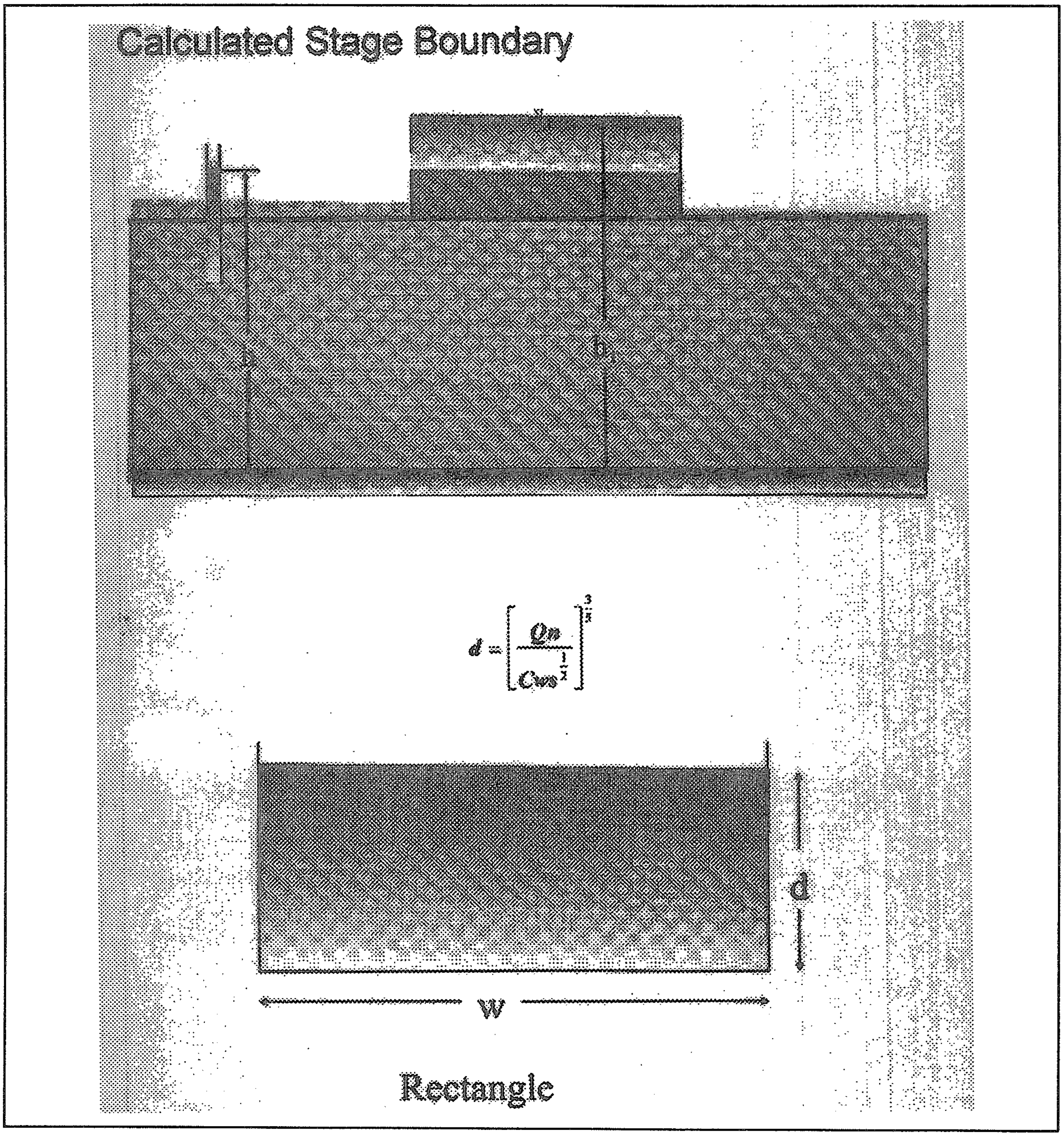


Figure 16. Methods of modeling streamflows.

stream and a friction coefficient called Manning's number.

To summarize, therefore, the advent of computerized modeling techniques can greatly simplify and enhance our understanding of ground and surface water interactions. Depending on the general configuration of the stream in question, computerized modeling techniques can generate surface-water-groundwater interactions, which will be an invaluable tool in studying the changes in the water levels, baseflow and capture processes in the given basin.

Endnotes

1. Charles V. Theis, "The Source of Water Derived From Wells," *Civil Engineering*, May 1940, at 277.
2. Recharge processes occur when subterranean waters flow into the aquifer, and discharge processes occur when subterranean waters flow out of the aquifer.
3. Mountain-front recharge is subterranean water that originates from precipitation at higher elevations. Rain and snowmelt percolate into the aquifer through the alluvial fans at the base of the mountains.
4. In a losing stream, water infiltrates from the stream into the aquifer. The net effect over a reach of the river is a loss of streamflow.
5. Evapotranspiration is water lost to evaporation from soils and transpiration from plants.
6. In a gaining stream, water infiltrates from the aquifer into the stream. The net effect over a reach of the river is an increase in streamflow.