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Assuring a Long Term Groundwater Supply: Issues, Goals and Tools

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Introduction

Groundwater is a hidden, but important resource. We can practicably define groundwater as water beneath the ground surface that can be extracted by wells. Other water in the ground that is not considered to be available for man's direct use is commonly called "subsurface water." Subsurface water includes moisture within the root zone.

Groundwater is contained in geologic strata termed aquifers. Aquifers can be composed of a wide range of materials, including sand, gravel, limestone, and fractured granite. The more permeable the aquifer to water (the greater its hydraulic conductivity), the more easily groundwater flows through it. Groundwater generally moves through aquifers relatively slowly, except in fractures or solution channels. Solution channels form where water dissolves the materials around a fracture, gradually increasing the size of the underground channel. Although underground streams can result, they are the exception, rather than the rule. The chance that a well will intersect an underground stream is slight.

Generally, wells extract groundwater that is contained in the pore spaces or interstices between particles of the aquifer material. The more interconnected pore spaces in the aquifer, the more water can be stored and removed. By knowing the shape, dimensions and effective porosity of an aquifer, one can estimate how much water that layer can hold. But that does not tell us how much groundwater can be removed by wells year after year. How much can be extracted depends on how much is initially in the aquifer, how much new water enters (recharges) and how much water leaves (discharges) in other ways.

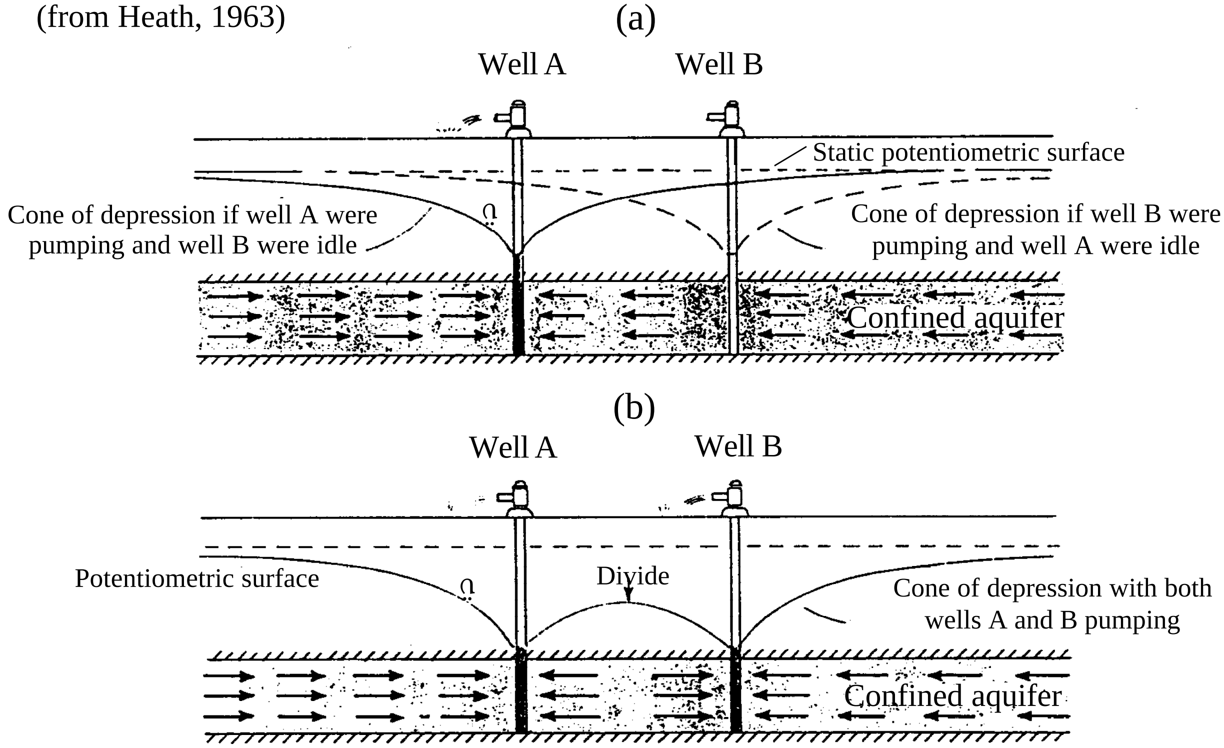
Groundwater is part of the dynamic hydrologic system. Most groundwater is continually in motion. Groundwater flows from locations of recharge to locations of discharge (from locations of high water surface to locations of lower water surface)[1]. In Utah, water commonly enters aquifers in or near the mountains. It then flows through the aquifer to eventually emerge downhill: as discharge from springs and naturally flowing wells; as flow to streams or lakes; as

[1] This is a simplification. Groundwater moves from locations of higher potentiometric head to locations of lower potentiometric head. The potentiometric surface describes the potential energy of the water. The potentiometric surface can also be called the water table in an unconfined aquifer, or the piezometric surface in a confined aquifer.

[2] Groundwater velocity = (hydraulic conductivity of the aquifer)(slope of the potentiometric surface)/(effective porosity of the aquifer)

[3] Steady-state conditions exist when water levels no longer change significantly with time.

Figure 1. (a) Distinct cones of depression resulting from pumping at two separate wells at different times
(b) Composite cone of depression resulting from pumping at both wells simultaneously
(from Heath, 1963)



evapotranspiration, or as discharge from pumped wells. How long a period water exists in an aquifer depends on the distance between the recharge and discharge locations, and the speed with which it moves.[2] Water entering an aquifer near a streambank might discharge to the stream within a few days. Groundwater might also take centuries to move greater distances.

Extracting groundwater through wells causes groundwater levels to drop. A depression in the groundwater surface will form around a pumping well (a cone of depression). The cone can continue to expand until steady-state conditions are attained.[3] The effect of pumping from multiple wells is roughly additive. The cumulative depression resulting from pumping all the wells approximately equals the sum of the depressions from the individual wells (Figure 1). Composite cones of depression can become very large.

The depressed region around a single well can recover shortly after the well stops pumping. Depending primarily on aquifer permeability, and the size of the depression, recovery can take from a few hours to several days. Recovery can take much longer for large composite cones of depression—years to decades.

Consequences of Groundwater Extraction

If recharge to the aquifer (or any part of it) exceeds discharge, groundwater levels (the potentiometric surface) will rise. This commonly happens near rivers at times of high river flow. As groundwater levels rise within an aquifer, the volume of groundwater in storage in the aquifer increases. If groundwater discharge exceeds recharge, groundwater levels will drop. That means that some of the discharged water has been obtained by reducing the total volume of groundwater stored in the aquifer.

Extracting more groundwater than is recharged is termed groundwater mining. Groundwater mining is not inherently bad. Some mining is necessary to make best use of an aquifer. An aquifer undeveloped by man has natural recharge rates and natural discharge rates. Extracting groundwater by pumping changes those rates. The first groundwater that is pumped comes from storage. However, groundwater pumped later can also come from increasing recharge; and from reducing other discharges.

Some beneficial side effects can result from groundwater mining and declining groundwater levels. Dropping groundwater levels increases flow toward the pumping wells and can: (1) increase recharge to the aquifer from rivers, lakes, or adjacent aquifers; (2) reduce discharge from the aquifer to surface water bodies; (3) reduce groundwater contamination by causing water levels to be below the reach of degradable leaching contaminants; (4) reduce undesirable groundwater loss (discharge) due to phreatophytes or evaporation from the capillary fringe; (5) reduce other undesirable groundwater discharges; improve crop yields in previously waterlogged areas; (6) reduce septic tank problems resulting from high water table elevations; or (7) reduce moisture in basements.

However, excessive mining can be harmful. Problems that can result from declining groundwater levels include: (1) increase in energy required to raise a specific volume of groundwater to the ground surface; (2) reduction in well yield or total loss of well functionality due to diminished aquifer saturated thickness in the well screened interval; (3) increased migration of salty or otherwise contaminated water into previously uncontaminated portions of the aquifer; (4) reduction in flow from springs; (5) reduction of flow in rivers due to induced recharge from river to aquifer or reduction in discharge from aquifer to river; (6) dewatering of wetlands; (7) economic hardship due to previously listed problems; and, last but not least, (8) social conflict and litigation.

Goals of Groundwater Management

Within its legal capacity, a water management agency usually tries to assure that water users will have a long-term reliable source of water of adequate quality and quantity. Since groundwater and surface water resources interact and affect each other, agencies generally try to coordinate management of those resources. Coordinated management of ground water and surface water resources is commonly referred to as conjunctive water management. If done carefully (with appropriate consideration of interactions between the two resources), transferring of water rights between parties can improve conjunctive water management. Transfer can be accomplished by sale or trade.

Agencies attempt to assure that groundwater pumping will not cause significant problems, such as are listed above. They commonly use proven equations or computer simulation models to predict the consequences that will result from continuing current pumping rates, or the pumping rates that would result if everyone that wants to use groundwater is permitted to do so.

Computer simulation models contain equations describing how groundwater levels and flows respond to groundwater pumping, changes in recharge rates, or changes in other hydrologic features, such as rivers or lakes. The models also contain estimates of aquifer parameters (such as hydraulic conductivity, effective porosity) and recharge rates, and the locations at which these occur. Computer simulation models are not used to predict the future, until they have been acceptably calibrated for the region of interest and have been proven to acceptably simulate what happened in the past.

Agencies frequently use properly calibrated simulation models to predict what the consequences will be of any increase in pumping rates. An agency might use a model after receiving a request from someone wishing to drill a new well, or increase pumping. If the model predicts that approving the new request will harm those already pumping (or other legal or environmental interests), the agency may deny the new request. This is a common appropriate use of a simulation model.

If the model predicts that continuing current groundwater pumping will cause significant regional problems, it might be the agency's responsibility to attempt to reduce groundwater extraction. Because the aquifer is not a uniform and homogeneous system, reducing pumping in one part of the region might cause more beneficial results than reducing pumping in another region. However, that does not

Table 1. Comparison between simulation models and simulation/optimization (S/O) models (modified from Peralta and Aly, 1993).

Model Type	Input Values	Computed Values
Simulation	Physical system parameters	
	Initial conditions	
	Some boundary flows	Some boundary flows
	Some boundary heads	Heads at "variable" head cells
	Pumping rates	
Simulation/ Optimization (S/O)	Physical system parameters	
	Initial conditions	
	Some boundary flows	Some boundary flows
	Some boundary heads	Optimal heads at "variable" head cells
	Bounds on pumping, heads, & flows	Optimal pumping, heads and flows
	Objective function (equation)	Objective function value

mean that the agency can simply force users in the most hydrologically beneficial region to reduce pumping without forcing others to reduce also. The seniority of water rights, and other issues, must also be considered.

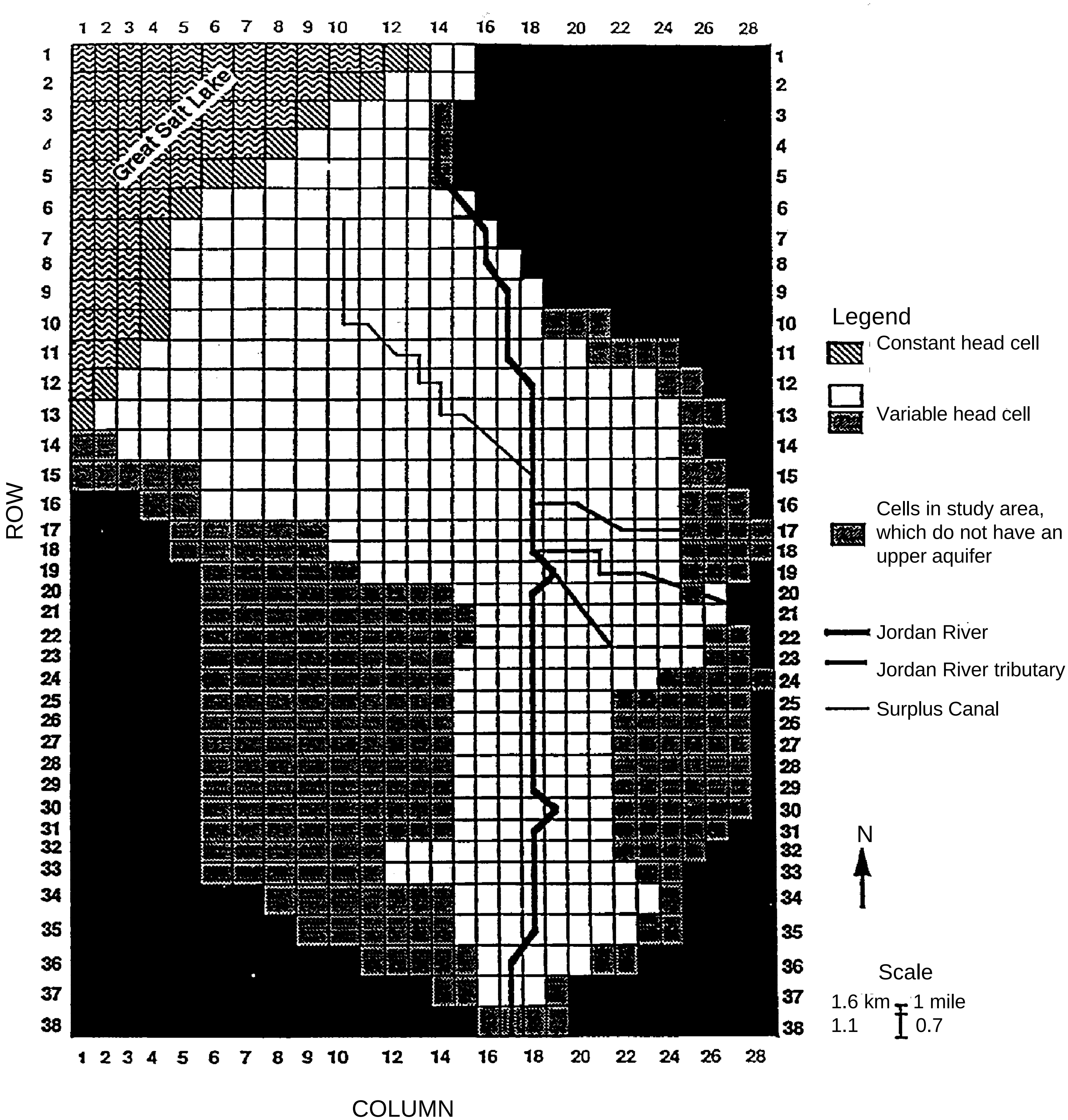
It is not easy to determine how best to reduce current pumping to prevent unacceptable problems, but a computer simulation/optimization (S/O) model can help in ways a normal simulation model cannot (Table 1). An S/O model includes: groundwater flow simulation equations; mathematical optimization capabilities; user-specified upper and lower limits on acceptable future water levels and flows; and mathematical statement of the management objective (the objective function).

For example, an S/O model can compute the set of long-term perennial groundwater yield pumping rates and locations that satisfies as many existing water rights as possible, while assuring that unacceptable consequences are avoided. In that case, the objective function is to maximize the total water provided to those having existing water rights. Since a study area is geographically divided into cells, the value of the objective function is the sum of optimal pumping rates in all cells having current legal groundwater pumping. (Figure 2 illustrates a grid and cell layout used in Salt Lake Valley models by the U. S. Geological Survey and Utah State University.) As an example, the upper limit on pumping rate that the model could consider in any cell might be the current pumping rate. The lower limit on the water level in each cell that the model could consider might be 40 feet below current water levels. Thus any pumping rates selected by the model would not cause water levels in the aquifer to drop below that limit.

A "pumping strategy" is a set of pumping rates (which are usually not distributed uniformly across all aquifer cells). A "perennial yield" pumping strategy is one that can be continued forever (barring unexpected changes in hydrology and recharges) without unaceptable results. This is also sometimes referred to as a "safe sustained yield" pumping strategy.

Implementing a sustained yield pumping strategy means permitting only the same pumping rates (or lesser rates) to be used year after year. Assuming that long-term average climatic and hydrologic conditions do not change significantly, extracting (pumping) groundwater at the same rate year after year will cause the gradual evolution of a particular potentiometric surface. Once attained, no major fluctuations of the water surface will result. For example, the water levels might return to roughly the same values Spring after Spring. Once this particular steady-state surface has evolved, annual recharge equals annual discharge. Until steady-state conditions are achieved, annual recharge is less than annual discharge, and groundwater mining is taking place.

Figure 2. Discretization of study area into cells within a groundwater computer model (modified from Waddell et al., 1987; Gharbi and Peralta, 1994).



The result of implementing a safe sustained yield pumping strategy will be the gradual evolution of acceptable water levels. If the strategy is computed via S/O model, these water levels will be within the ranges (bounds) specified by the user before running the model. For example, they will not be so low as to cause unacceptable drawdowns, flows, economic hardship or loss of water rights. The more such restrictions imposed on the pumping strategy, the less total pumping is possible. This simply reflects the results of having multiple conflicting goals. One cannot achieve more of one goal without hurting achievement of some other conflicting goal.

An Opportunity and Need for Public Cooperation

In pioneer times, a "tragedy of the commons" occurred. The commons was a grassed area in town available for everyone's use. Everybody wanted to use it, because if they didn't, someone else would. The tragedy was that overgrazing stripped the commons of grass. That hurt all users of the commons. There are similarities with groundwater use. Although groundwater is a renewable resource, it can be badly harmed. Dewatered or contaminated aquifers can take decades to recover.

Agencies try to protect the common groundwater resource so as to provide a sustainable water supply adequate for the present and the future. Agencies try to address valid water needs. Different groups of people can have differing valid goals that affect how groundwater should be managed. Sometimes improving the degree to which one goal is achieved reduces the degree to which another goal is achieved. Such goals are termed "conflicting objectives."

When valid management goals conflict, compromise water management strategies need to be identified. Effected groups should clearly express their views to the responsible agency. Those with conflicting goals should agree to disagree, while working with the agency to identify a compromise solution they can live with. Because groundwater is a finite (rather than an infinite) resource, probably, no single group can obtain all they would like, but each can probably achieve enough.

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