PEER REVIEW:

SALTWATER INTRUSION AND THE MINIMUM AQUIFER LEVEL IN THE SOUTHERN WATER USE CAUTION AREA: Hydrologic Evaluation Section, Southwest Florida Water Management District, 21 August 2002 (draft)

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INTRODUCTION

This report includes the Peer Review Committee's findings regarding matters set forth in "Attachment A: Scope of Work and Deliverables, Compensation and Expense Schedule," dated July 24, 2002, for the independent scientific peer review of a methodology to set a minimum aquifer level. The methodology review**ed** by the Committee is documented in the August 21, 2002 draft report entitled: ***Saltwater Intrusion and the Minimum Aquifer Level in the Southern Water Use Caution Area.***

Seawater intrusion is a problem in coastal aquifers in many parts of the world. The problem is exacerbated where a highly permeable aquifer, such as the Upper Floridan Aquifer, extends off shore beneath the sea floor. Under virgin conditions, before development, fresh groundwater flows outward at the coastline and discharges to the sea off the coast. This outward discharge maintains a sufficiently high hydraulic head within the aquifer at the coastline to maintain the seawater/freshwater interface off shore.

As development of the aquifer occurs groundwater that originally discharged beneath the sea floor is diverted by the pumping to wells. Groundwater levels decline in response to the pumping. With the decline in the hydraulic head the seawater/freshwater interface moves toward the land, and ultimately it moves on shore. The seawater/freshwater interface moves in an attempt to reach a new stable configuration.

This is a general description of groundwater conditions within the Upper Floridan Aquifer near the coast in the Southwest Florida Water Management District (SWFWMD). The seawater/freshwater interface is onshore and moving eastward (landward) within the most permeable portions of the aquifer. A number of investigations that included both data collecting and model analyses were conducted to investigate the position of the interface and its rate of movement.

Fortunately the movement of the interface is slow. The toe of the interface currently moves one to one and a half miles in fifty years, or at a rate of 200 to 300 feet per year. Given the current rate of movement of the interface it would probably take something like 1000 years to reach a new equilibrium position where the interface was no longer moving.

Even where the interface moves into the aquifer the toe is very gently sloping; the slope of the toe is one to two degrees from seaward toward the land. Near the toe of the interface the seawater is actually lying along the bottom of the aquifer. Pumping freshwater can occur in areas where the toe of the interface underlies the well. However, wells that overlie the interface are at risk to seawater contamination. The pumping can cause the underlying interface to be perturbed upward into the well—so-called ***upconing*** of the seawater.

Dynamic Equilibrium

With a given 1) distribution and 2) rate of pumping water levels within the Floridan Aquifer become stable quickly. The water levels stabilize within a matter of months to changes in the pumping. Associated with the stable water level is a rate of seawater intrusion. In other words, for each stable water level within the aquifer there is an associated rate of movement of the sea-water/fresh water interface. In general the lower the water level the faster the interface moves landward.

If one manages the aquifer to maintain the current water level then one also stabilizes the current rate of the seawater intrusion—approximately 100 to 200 feet per year. If the objective is to slow the rate of movement then one needs to raise the water levels (hydraulic head) within the aquifer. If we assume that the distribution of pumping remains distributed approximately as it is currently, then we can raise the water levels only by reducing the pumping. ***If the objective of the water management by SWFMWD is to slow the rate of landward movement of the seawater/freshwater interface it must reduce the pumping. Holding the current water levels within the aquifer will stabilize the rate of movement of the seawater interface at its current rate.***

A MINIMUM WATER LEVEL

Florida Law mandates that minimum water levels be established on priority water bodies—the Upper Floridan Aquifer is considered a priority water body within the District. The subject document addresses the establishment of a minimum water level.

Ten-Year Moving Average

The suggestion is not to select a single water level in time, but rather to average the water levels over a 10-year period. The thinking is that a ten-year period is sufficiently long to average out normal wet and dry periods, but not too long to obscure long-term trends. ***The Peer Review Committee agrees that using a 10-year moving average is a wise choice.***

The period chosen for setting the minimum water level was chosen as 1999 and the preceding 9 years—1990-1998. The subject document shows that this is the highest 10-year average water level within the last several years. The hydrograph of the Sarasota **9** Deep Observation well, Figure 1, indicates that water levels were more or less stable during the decade of the 1990s**.** ***The period 1990 to 1999 seems like a good choice although we recognize that this period represents the highest average water level in recent years.***

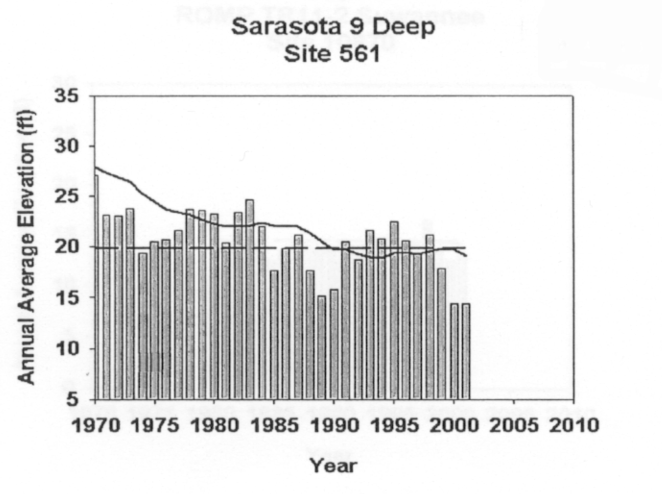

Figure 1. Hydrograph of Sarasota Deep well. The solid black line is the 10-year moving average plotted for the last year averaged. (Figure 21—subject document)

The Area

The question is what area to consider in establishing the minimum water level. The document states:

"With respect to saltwater intrusion, the area of concern for which the minimum aquifer level is being established is the ETB MIA [Eastern Tampa Bay Most Impacted Area]. The ETB MIA is an area of about 708 square miles that encompasses the coastal portions of southern Hillsborough, Manatee, and northern Sarasota Counties." (page 25)

However, a large cone of depression occurs in the potentiometric surface of the Upper Floridan Aquifer at the boundary and to the east of the MIA. Figure 2 (Figure 12 from the subject document) shows the drawdown from predevelopment to 1999; the cone of depression is clear on this figure. Thus, part of a major pumping center apparently occurs landward (east) of the designated ETB MIA. Pumping from this area is reducing groundwater discharge in the coastal area and causing the interface to move farther inland. To control the rate of movement of the interface in the coastal ETB MIA area, it is important to control pumping in the area east of the MIA as well as in the MIA. Pumping throughout SWFWMD has an impact on the potentiometric surface and as a consequence the rate of movement of the interface. We suggest that the District investigate the pumping to the East to determine its impacts on water levels within the MIA; it may be necessary to control this pumping to effectively control water levels within the MIA.

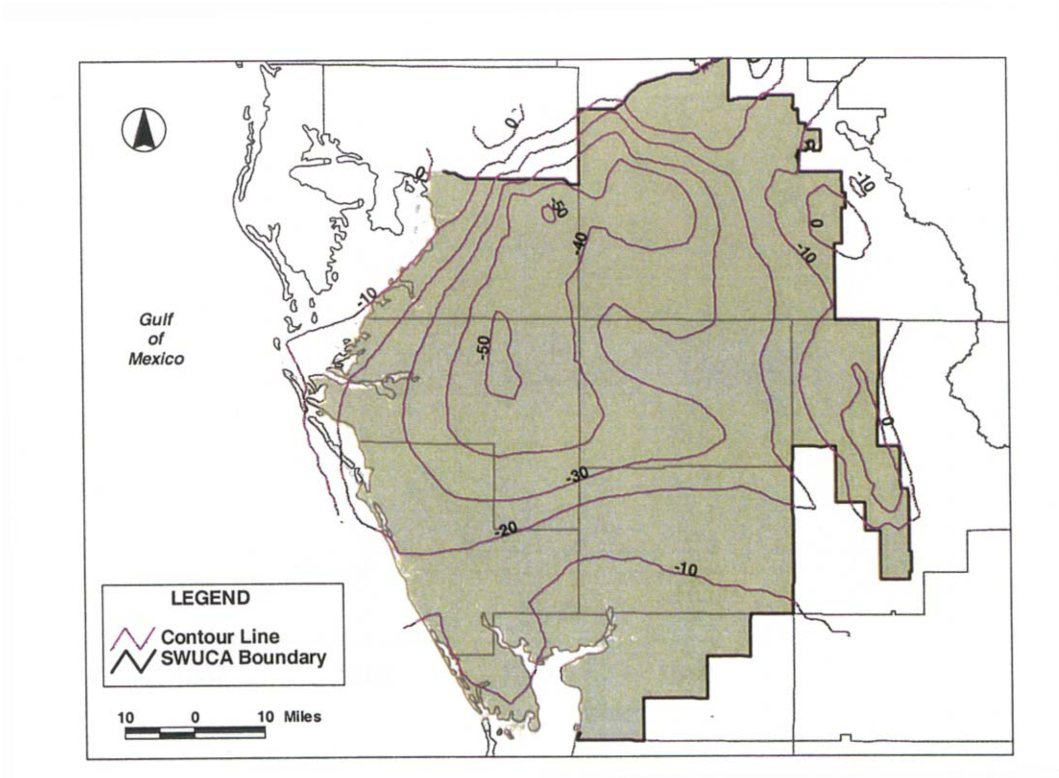

Figure 2. Drawdown from predevelopment to 1999 in UFA. (Figure 12—Subject document).

The Technique

The staff decided to suggest a single "average" water level for the area of concern as the minimum. ***A single value, average water level for the area has the advantage that it does not single out a single well or group of wells where pumping has created a deep cone of depression.*** Both low and high wells are averaged together to determine a single value.

Two procedures were discussed in the subject document (Section 6.3). The two alternative procedures were:

1. Average the water levels in a selected set of ~~16~~ **10** observation wells for the ten-year period;
2. Use the Geographic Information System (GIS) Arc/INFO to create a potentiometric surface for the area of interest and then use its capabilities to compute an average water level.

The report points out that both procedures give comparable results. It is ambiguous in the document which procedure the staff favors. In discussions with them they prefer the Arc/INFO method; this should be made clear in the document. In anticipation of challenges and/or litigation it is important that the procedure used by the District to determine the average water level be described in such a way that the result is reproducible. Other experts using the same data and following the same procedure should get the same result.

The Peer Review Committee agrees that the Arc/INFO procedure, outlined in Section 6.3 of the subject document, will yield a reasonably formulated, average water level for the Upper Floridan/Avon Park aquifer within the Most Impacted Area (MIA). The procedure does not yield a simple average, nor is it easy to give an exact formulation of the spatial weighting embedded in the calculated average; but we do not believe these considerations should preclude using this method. In our opinion, so long as the calculation is carried out consistently, the resulting water level average provides an effective index by which the relative rate of saline water encroachment in the aquifer can be gauged. For these reasons ***we prefer to refer to the average determined by the Arc/INFO procedure as an Index.***

Specifically, we believe that if the index is calculated according to the Arc/INFO protocol, outlined in Section 6.3, for two different time periods, the landward velocity of saline water movement, averaged both over the area normal to the flow and the time period of calculation, will virtually always be greater in the period for which the calculated index is lower. In other words, the total volume of saline water that moves landward in the aquifer within the MIA will be greater during the period for which the calculated index is lower. We assume that the rate of encroachment is visualized as the apparent velocity of a given concentration surface, rather than as the time rate of change of concentration at a given point in the aquifer.

The method of calculation, described in Section 6.3, was applied to the data collected from 16 selected monitoring wells in the decade from 1990 through 1999. The resulting average water-level elevation, 12.8 feet (above mean sea level—msl), is taken as the reference level or index. The panel agrees that this reference level is associated with the average rate of landward saline movement in the MIA during the 1990-1999 decade, and that for any ten-year period for which the index is greater than 12.8 ft-msl, the average rate of saline encroachment will be less than that during the 1990-1999 period. ***The Peer Review Committee thus agrees that the issue paper presents an effective methodology for determining whether the rate of encroachment is greater or less than that prevailing during the 1990's.***

Recommended Further Work to Refine and Clarify the Method

While the committee agrees with the overall concept and procedure as presented in the subject paper, we feel that the District and those who may be impacted by its decisions would be well served if 1) the relationship between the index and the hydrologic factors controlling it, particularly the pumping rate in the SWUCA, were explicitly quantified and discussed, and 2) the relationship between the index and rate of saline encroachment were similarly quantified. This could be done in the issue paper itself, or in a supporting document.

The index can be viewed as an intermediate variable, controlled by pumping and other hydrologic stresses, which in turn controls the rate of saline water encroachment.
The rate of saline encroachment could itself be considered an intermediate term, since it determines the number of wells at risk in the aquifer at any given time (where the "at risk" designation implies that saline water is present within the aquifer beneath the well). In the subject document, a link is established between the pumping rate in the SWUCA and the number of wells at risk after fifty years time. While this presentation is enlightening, it gives no direct information on the intermediate variables—the water level index and the rate of encroachment. However, the policy mandated by the Governing Board is framed in terms of the water level; the water level index is to be the trigger, and the rate of migration is specified as the variable to be controlled.

We believe that an examination of the explicit relationships involving 1) pumping, and 2) the rate of the interface movement is warranted. This would allow everyone involved to visualize what a given change in the index means, both in terms of the hydrologic stresses which caused it, and the change in the encroachment rate which accompanies it. These insights could help the District staff in formulating the best response to a given change in the index, and might help in winning public support for that response. We believe that much of the information required for such an analysis already exists in the results of completed simulations, and if necessary further information could readily be generated through additional simulation.

As we understand the work done to date with the density-dependent flow and transport model (HydroGeoLogic, 2002), predictive simulations have been completed corresponding to pumping from the SWUCA of 400, 600, 800, and 1,000 MGD. In each case the pumping within the transport model domain was scaled as a fraction of the total pumping from the SWUCA. Lateral (fresh water) boundary conditions were taken from the results of parallel simulations using the Southern District groundwater flow model (SWFWMD, 2001), which includes the entire SWUCA. The effects of pumping from areas of the SWUCA outside the density-dependent model domain are thus embedded in the boundary heads of that model. Initial conditions for the predictive runs were taken as those prevailing in December 2000. The results of these simulations were used in the analysis noted above that relates the number of wells at risk after 50 years of pumping at different rates. We recommend that the results be further processed 1) to calculate the water level index associated with each pumping rate, and 2) to determine the rate of movement of the seawater/freshwater interface associated with each value of the index.

Calculating the index would involve retrieval of fresh water heads at nodes corresponding to the monitoring well locations, from those layers corresponding to the open or screened intervals in the observation wells. If there are cases where the screen or open interval extends over more than one model layer, an average of the heads in the represented layers, weighted by the layer transmissivities, should be used. The procedures of Section 6.3 would then be applied to the head values, except that time averaging over a ten-year period would not be required because the simulated levels would generally represent steady-state hydraulic conditions.

Calculation of the rate of seawater encroachment could be carried out, for example, by processing the transport results to develop a three-dimensional isochlor surface at two times during pumping at a given rate. These surfaces could be taken for a concentration of 1000 PPM, or could represent any other concentration considered characteristic of the transition zone. At evenly spaced locations, the horizontal and vertical components of the separation between the two surfaces would be divided by the time interval to obtain estimates of both the horizontal and vertical velocities of seawater encroachment. These velocity components could then be combined to yield the resultant velocity of saline water encroachment at each point. Averaging of these velocities over the cross-sectional area of flow within the MIA would then yield the average rate of migration associated with the calculated water level index. Averaging of the horizontal components of the migration rate over the MIA would also be of interest, as would averaging of the vertical components. The results of this analysis could be presented in a number of ways—for example, a plot of water level index vs. pumping rate, a plot of the average seawater migration rate versus the water level index, or plots of the average horizontal and vertical migration rates versus the water level index.

In carrying out the analysis, the information derived from the predictive simulations could be supplemented with information from the final post-development calibration run. We understand that this calibration represented the period from 1900 to 2000, and incorporated temporal pumping rates based on historical records, and changing landward boundary conditions based on parallel simulations with the Southern District flow model. Again, we believe the dominance of the seaward boundary probably brought simulated water levels to equilibrium rapidly after each change in pumping, and that the results could therefore provide additional data points for linking the water level index to pumping rate, and the rate of encroachment to the index. Particularly for the periods in which pumping was varied at four-month intervals, however, the assumption of hydraulic equilibrium should be verified by checking the simulation results at successive times.

One can imagine a series of new simulations that could be designed and implemented to supplement existing information. For example, it may be of interest to consider the effect of severe and prolonged drought on the rate of saline encroachment. This could be done through a series of simulations in which the general head boundary (GHB) heads on the uppermost layer were reduced to simulate a lower water table, inflows across landward boundaries were reduced, and pumping rates were increased to represent the heavier demands associated with drought.

SUMMMARY AND CONCLUSIONS

The Peer Review Committee found the following:

- ***If the objective of the water management by SWFMWD is to slow the rate of landward movement of the seawater/freshwater interface it must reduce the pumping.***

- ***Holding the current water levels within the aquifer will stabilize the rate of movement of the seawater interface at its current rate.***

- ***The Committee agrees that using a 10-year moving average is a wise choice.*** Ten years is long enough to damp out normal wet and dry years, but not too long as to obscure the long-term trends.

- ***A single value, average water level for the area has the advantage that it does not single out a single well or group of wells where pumping has locally created a deep cone of depression.***

- ***The period 1990 to 1999 seems like a good choice even though we recognize that this period represents the highest average water level in recent years.***

- ***The Peer Review Committee agrees that the Arc/INFO procedure, outlined in Section 6.3 of the subject document, will yield a reasonably formulated average water level figure for the Upper Floridan/Avon Park aquifer within the Most Impacted Area (MIA).***

- ***We prefer to refer to the average determined by the Arc/INFO procedure as an Index (Florida State Law may require it be called a "minimum water level").***

- ***The Peer Review Committee agrees that the issue paper presents an effective methodology for determining whether the rate of encroachment is greater or less than that prevailing during the 1990's.***

- ***We believe further analysis would be beneficial to link explicitly the Index (or the average water-level elevation) to both the rate of pumping and the rate of movement of the interface.***

Finally we would like to compliment the staff on a job well done. The subject document presents a careful analysis of the seawater intrusion problem. It further suggests a thoughtful procedure for establishing a minimum water-level elevation for the Upper Floridan Aquifer within the MIA.

APPENDIX

Notes on the Supporting Documents

As background the Peer Review Committee reviewed in detail a number of supporting documents. Of particular interest was a series of model analyses that date back to the early 1990s—HydroGeoLogic, 1993, 1994a, 1994b, 2002. The earlier model analyses were done in two-dimensions utilizing cross-section oriented along flow lines. Two types of models were used; a sharp interface model and a density dependent model. The 2002 analysis was done with a fully three-dimensional, density dependent model. The model results are not identical, but the results present a coherent picture of the position and movement of the seawater interface. The fact that the results of the several analyses using different methods are coherent gives one confidence in the results.

The staff has utilized the results of the models accompanied by data collection to estimate the number of wells that will be underlain by the seawater interface during the next 50 years at various levels of groundwater pumping. Wells that are underlain by seawater are considered at risk for seawater contamination. It is helpful for management purposes to have an estimate of how might wells might be at risk.

Notes on the Use of Simulation Models

The Peer Review Committee is agreed that a careful peer review of a model analysis involves independently running the actual model. We have not carried out such a full-scale review of the District's three-dimensional, density-dependent flow and transport model (HydroGeoLogic, 2002)—we did not run the HydroGeoLogic (2002) model. However, we did review the report of the latest model analysis. On the basis of the documents we have seen, the model appears to be a well-formulated representation of the hydrogeologic system, and to offer the best approach to predictive calculations available at the present time. As with all simulation, the model is an approximation of reality which can and should be improved and refined continuously in the future; and as with all simulation, the greatest value of the model is not its predictive capability, but the insights and understanding which can be gained in that process of continuous improvement and refinement.

Simulation offers a vehicle for integrating the many complex processes controlling a hydrogeologic system; continuous updating and improvement of a model yields a continuous improvement in understanding of those processes and their interactions. We hope that the District will view the model primarily in this context, i.e., as a dynamic and evolving vehicle for enhancing understanding of the system, rather than as a completed and static predictive tool.

We also recommend that as the transport model is refined and updated, a parallel effort be made to refine and update the sharp interface model (HydroGeoLogic, 1994b). Density dependent flow and transport are inherently complex processes, and their analysis is inherently challenging. The maintenance of two models based upon different approaches would provide increased confidence in calculated results, and increased opportunities to gain greater understanding of the hydrogeologic system. It is our understanding that the source codes of both HydroGeoLogic models are proprietary. If the source codes remain unavailable to the District in the future, consideration should eventually be given to reformulating the models using public domain software of comparable capacity—e.g., SEAWAT (Guo and Langevin, 2002) for coupled flow and transport, or SHARP (Essaid, 1990) for an interface approach. This would ultimately enhance the District's ability to use, modify, and learn from the models.

A Note on the Saline Water Upconing Issue

Saline water contamination of an individual discharging well usually begins through the process of vertical upconing of saline water from beneath the well. The three-dimensional models of the ETB-MIA system that exist today lack the resolution to address this problem on an individual-well basis. This may change eventually as the resolution of those models increases; we believe, however, that some investigation of the vertical coning issue is warranted at the present time.

At least some wells that are considered at risk as suggested by the regional analyses carried out to date may actually have a measure of protection provided by the vertical hydrogeologic separation between the well bottom and the saline water. We recommend that studies based on single-well (r-z plane) simulation or analysis be undertaken to gain insights into the upconing process and its consequences. These studies might address, for example, the degree of protection afforded by a given vertical conductivity and thickness of geologic material, or the effectiveness of such measures as restricting pumping or plugging back the lower sections of a well. Hydraulic parameters typical of the Upper Floridan/Avon Park Aquifer should be used, and well designs (particularly aquifer penetration ratios) typical of the MIA should be employed.

Reilly and Goodman (1985) provide a discussion and literature review of the saline upconing problem. An analytical solution by Motz (1992) can be used to make preliminary estimates of upconing. In the Motz solution the critical pumping rate, relative to upconing of the seawater/freshwater interface, is determined in terms of aquifer properties and the screened (or open-hole) length of a pumped well.

A Note on Field Monitoring

We are not certain how the issue of potential changes in the density of water in the monitoring well columns will be addressed during implementation of the monitoring program. We recommend that fluid conductivity logging of the monitoring wells be carried out at regular, periodic intervals, and that an updated density profile of the water inside the well column be maintained for each well. After each round of water level measurement, an equivalent fresh water head could then be calculated for each well based on the measured water level and the most recent density profile of the well.

We suggest that the water level index always be expressed in terms of equivalent fresh water heads.

Further Editorial Comments

p. 5: "They [Governing Board] further concluded that a minimum aquifer level should be established to achieve the management goal of slowing the rate of movement of the freshwater/ saltwater interface."

The goal of the Governing Board should be accurately stated and consistently applied throughout the report. Generally, "slowing the rate of movement" of the interface relative to the 1990-1999 time period will require *reducing* the pumping rate below the 1990-1999 average pumping rate and maintaining average water levels *above* the minimum index water level based on 1990-1999.

p. 23: "The Governing Board…has determined that it is unacceptable to allow the rate of regional saltwater intrusion to increase beyond the current rates of movement. The methodology to establish a minimum aquifer level to protect against regional saltwater intrusion was thereby developed to achieve the management goal of slowing the rate of saltwater intrusion. The first step in management efforts to slow the rates of movement would be to stabilize the regional water level declines."

The first sentence is not consistent with the second sentence. If the Governing Board's goal is to prevent the rate of movement of the interface from increasing (i.e., the interface will continue to move inland at the same rate) relative to some time period, then the pumping rate that occurred during that time period should be maintained. On the other hand, if the Governing Board's goal is to *reduce* the rate of movement of the interface (i.e., slow the interface), then it will be necessary to reduce the pumping rate.

p. 27: "After examination, four of the wells were eliminated from the data set. Exclusion of a well could occur for one or more reasons."

Two of the wells are already mentioned, i.e., one (ROMP 50 Avon Park well) specifically and another well only generally. This sentence (or two) could be improved by stating specifically the reasons why the four wells were eliminated.

p. 28: "For comparison purposes, the same statistics were calculated using the 10 wells located within the MIA."

Only one method for calculating the average water level should be presented in the document. In anticipation of challenges and/or litigation it is important that the procedure for calculating the average water level be described in such a way that the result is reproducible. Other experts should get the same result using the same data and procedure.

REFERENCES

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Reilly, T.E., and A.S. Goodman, 1985, *Quantitative Analysis of Saltwater-Freshwater Relationships in Groundwater Systems—A Historical Perspective:* Journal of Hydrology, 80, 125-160