NATURAL RESOURCES JOURNAL

Volume 47
Issue 4 *Fall*

Fall 2007

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A few years ago, a colleague of mine presented our well-researched, logically developed paper at an American Water Resources Association (AWRA) conference.[1] Despite her engaging personality and the merits of the paper, her audience expressed considerable displeasure. The problem was that the paper explored a possibility for making use of a little of the huge, unusable volume of ground water in the Albuquerque-Belen Basin, a scheme that is outside the current paradigm, and people were afraid of it. They may have been right, but maybe the right answer isn't as easy to come to as it seems. Sometimes it's good to look beyond the current conventional wisdom.

All hydrologists, and lots of non-hydrologists interested in water issues, know that the amounts of water stored in the ground are enormous. (They also know that in most river-connected basins where surface-water is fully appropriated almost all of the ground water is beyond use. I return to this apparent anomaly later.) In the Middle Rio Grande Basin, one of the more conservative mathematical groundwater models developed by the U.S. Geological Survey and the Office of the New Mexico State Engineer[2] represents a volume of about 460,000,000 acre-feet of ground water in storage—equivalent to 3,000 or 4,000 years worth of water at our present rate of use. A more recent, still more refined model[3] that takes into account a much greater thickness of the aquifer (to more than 9,000 ft) would add much more water to the volume in storage.

The quantity of water in storage in the aquifer beneath the Middle Rio Grande Valley that Bob Grant predicted in 1977,[4] something like 70 percent of the volume of water in Lake Michigan, was not so far wrong. Bob is one of Albuquerque's most respected and most public-spirited veteran geologists, with a long-time interest in water. He estimated the volume of saturated valley fill in the Rio Grande trough in the Albuquerque-Belen Basin, multiplied it by an appropriate value for porosity (the fraction of

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1. J.W. Shomaker, R.L. Swartwout & L.B. Hagan, Using Stored Ground Water Without Depleting a Fully Appropriated Stream (paper presented at American Water Resources Association 2002 Summer Specialty Conference, Keystone, CO).

2. P. Barroll, New Mexico Office of the State Eng'r, Draft Documentation for the Administrative Groundwater Model for the Middle Rio Grande Basin (1999).

3. D.P. McAda & P. Barroll, Simulation of Ground-Water Flow in the Middle Rio Grande Basin Between Cochiti and San Acacia, New Mexico 72 (2002) (U.S. Geological Survey Water-Resources Investigations Report 02-4200).

4. P.R. Grant, Jr., ENERGYtic New Mexico—the Power State (Albuquerque Industrial Development Service, Inc. 2nd ed. 1977).

void volume, filled with water, within a unit volume of the valley-fill sediments), and determined that the valley contained around 2.3 billion acre-feet of ground water. The water was, and is, there. Whether it is a usable resource or not depends on a closer look at the effects of producing it, and on your paradigm.

Basins that have through-flowing rivers in hydraulic connection with the ground water raise the issue of what is a usable groundwater resource and what is not. The Rio Grande trough from Española to the Texas line might contain something like several billion acre-feet. The same theory would apply in the Pecos Basin, but the combined thickness of the aquifers is relatively small and the effects of pumping on the Pecos River are comparatively rapid, so that much less would be gained by trying a scheme to recover the stored ground water. Where there is no river in direct connection with aquifers, as in the Estancia Basin, the San Juan Basin, and much of the rest of New Mexico, the choices are to "mine" the ground water that is there or to import water from somewhere else. Still, as the numbers show, the stored water in river-connected basins is a vast volume, worth some thought.

Why is almost all of that ground water unavailable? One reason, of course, is that the cost of recovering it is too great. The value of stored ground water has its limits, like everything else, and most of it may be in the same category as, for example, the huge amount of gold in the Sandia Mountains that nobody seems to be interested in mining. A rather roughly calculated volume of granite in the Sandias, multiplied by an assumed gold concentration of one part per billion (all granite contains *some* gold) and using the current price of about $920 per Troy ounce, shows that the gold in the Sandias, ignoring altogether any actual minable deposits, would bring about $9 billion—if you could extract it for less than that. But of course you can't.

The example of the Middle Rio Grande shows us another, and perhaps more frustrating, reason that vast amounts of ground water are thought to be unusable. The water rights in the Rio Grande valley allocate the surface water, and that water has been fully appropriated for a long time, perhaps since the advent of the New Mexico water code in 1907, or since the establishment of the Rio Grande Compact in 1938. And it is the surface water rights, in the current paradigm, that control and limit access to the large amount of ground water.

It is simply a fact that pumping of ground water diminishes the flow of the river, either by intercepting groundwater flow that would otherwise discharge to the stream and become streamflow or by directly inducing flow from the stream into the aquifer to fill the cone of depression of the water table caused by pumping. The rate of depletion of the river's flow rises over time, depending on the properties of the aquifer, the distance from the well to the river, and the rates of pumping. Ultimately, the depletion will equal the net pumping rate, that is, the rate of pumping less return flow. The rate-of-depletion curve can be calculated through the use of a mathematical groundwater flow model.

If the amount of net pumping exceeds the flow of the river that is available under existing rights, plus any unappropriated flow, the river will flow less and less until the depletion equals and then exceeds the rights. The rights to water of surface-water users, both in the same basin and downstream, will then be impaired. To put it most simply, net pumping of ground water eventually must be limited to the amount of surface water that can be taken under existing surface-water rights, which is the same as saying that pumping from wells is essentially no different from diverting water from the river except in terms of timing—and that the ground water in storage, however much it may be, is not available for use. An apparent consequence of this is that almost all of the ground water in the valley must stay in place to "hold up" the surface water in the river. But is that really the case?

Another way of looking at the rising graph of streamflow depletion due to pumping from a well is to recognize that, for a while, even a very long while, much more water may come out of storage in the aquifer than is depleted from the river's flow, even if the proportion of the water taken out of storage diminishes over time. If the use that is made of the water leads to a significant return flow, as in the case of municipal water supply, which typically returns to the river through sewers and a wastewater treatment plant about one-half of the water pumped, then the rate of depletion will be negative for a long time. The pumping will actually lead to a net contribution to the river as long as the amount of water returned to the river during a particular period is more than the amount of depletion of river flow owing to the pumping. In the case of the typical municipal system, the pumping from wells would be a net contributor to the river until the rate of river depletion due to pumping rises to 50 percent of the pumping rate.

It is true that if the pump is shut off, and the return flow therefore ceases, the actual depletion of the river's flow is no longer offset by return flow and suddenly jumps alarmingly. So why not plan to make use of water that can be withdrawn from groundwater storage up to the amount such that the return flow will always exceed the calculated depletion rate—and never shut off the pump at all? Clearly, there will come a time when the pump must be operated for no reason other than to continue to supply "return flow," even when there is no water left to be put to any other use, but in the meantime a great deal of formerly stored, and otherwise useless, ground water has been made available. It is necessary only to sell that water at a price sufficient to meet the costs of operation while water is available for sale, plus enough to endow the perpetual pumping that would ensue thereafter.

This was the theme of the paper that led to so much distress at the AWRA conference. The idea was suggested to me some years back by Charles T. DuMars, one of New Mexico's leading water-rights attorneys, and it has intrigued me ever since. The AWRA paper presented such a plan for the Albuquerque-Belen Basin, based on the published results of a sophisticated groundwater modeling study by a consultant to the City of Albuquerque[5] and an equally careful financial analysis by one of my co-authors.[6]

The hypothetical scheme in our AWRA paper contemplated pumping of a constant 100,000 acre-feet of ground water per year (from a new well field), for high-value municipal use with 50-percent return flow. It recognized that streamflow depletion would occur, and therefore also contemplated delivery of a combination of treated wastewater, and pumped ground water sent directly to the river, as needed, to fully offset the depletion. It included the development of a permanent fund sufficient to ensure forever the continued direct pumping to the river to offset depletion, even when no more water is available for use.

In the first year, all of the water would be available for sale. Calculated depletion due to pumping of the hypothetical well field at 100,000 acre-feet per year would be 16,478 acre-feet, and return flow (at 50 percent) would be 50,000 acre-feet, so the river's flow would actually be augmented by 33,522 acre-feet that year. The proportion of the total pumped that would be available for sale would decline over time, and by the fortieth year would have declined to 77,700 acre-feet, and by the one-hundredth year to 30,600 acre-feet. By about the one-hundred-twenty-fifth year, the water available for sale would be small, maybe not worth the trouble, but pumping of 100,000 acre-feet per year would never stop, and the fund to support the future pumping would be fully established.

Analysis of the costs, and of the development of the fund, in our AWRA paper was based on estimates of capital and operation and maintenance (O&M) costs by one of Albuquerque's leading engineering firms and contemplated a range of future interest rates on debt and governing the returns on money invested in the fund. The conclusions were that water not sent directly to the river, that is the "water available for sale," would be priced at $0.38 to $1.22 per 1,000 gallons in 2002 dollars, equivalent to $124 to $398 per acre-foot (that is, per unit volume equivalent to one acre-foot, not per recurring acre-foot as would be represented by a water right). These sales prices are similar to, or less than, the cost of water

5. S.S. Papadopulos & Assocs., Middle Rio Grande Water Supply Study (2000) (consultant's report to U.S. Army Corps of Engineers, Albuquerque District, Contract No. DACW47-99-C-0012, and New Mexico Interstate Stream Commission).

6. Robert L. Swartwout.

from large-scale desalination projects and compare very favorably with the cost of water based on the purchase of Middle Rio Grande water rights—now at $20,000 or more per consumptive-use acre-foot.

In this example case, some 6.8 million acre-feet of ground water is made available for use over 100 years, an average of 68,000 acre-feet per year—a significant amount in an area that now pumps around 150,000 acre-feet of ground water a year. The Rio Grande is "kept whole," in the sense that there is no net depletion of river flow. The groundwater system is near equilibrium after 125 years: very little additional drawdown would occur. And the permanent fund is in place to support the future pumping from wells directly to the river to maintain the cone of depression and prevent the onset of the river depletion that would occur if "return flow" were to stop.

The financial analysis behind the pumping scheme includes a conservative (by today's standards) schedule for replacement of wells and pipelines, repeated into the indefinite future and paid for in perpetuity by interest on the fund that is established during the century or so that water is available for sale. It may seem to us that our heirs will think it strange to be spending money to pump water from wells straight into the Rio Grande, but it may be that they will see the pumping simply as a legacy from their predecessors that allows them to have a flowing river.

It is easy to ask wrenching questions: What will we do when Middle Rio Grande depletions begin to exceed the water available to us under the Rio Grande Compact? It is not always easy to identify all the solutions, and it is even more difficult to set aside paradigms and consider them all on their merits. On its face, our groundwater plan would not increase stream system depletions and might be considered as one of those out-of-the-box solutions to the Compact-imposed limitatons, but the plan drew heavy criticism from people who understand both the technical and policy issues. What were their objections?

First, of course, the plan we described in our AWRA paper would offer a way to use more water at the very time the public is being persuaded, over considerable objection, to use less. It would encourage more water-consuming development in an area already shown to be water short, and to propose and promote it would weaken our efforts to live within our means (that is, to limit ourselves to the surface water nature sends us). The scheme is suspect simply because it might distract us from pursuing the policy the State and the regional water-planning groups have only recently adopted.

It has not been easy for water planners in central New Mexico, and the West in general, to change the paradigm that has guided our water development. Until recently, even water experts have tended to think of ground water stored in the aquifers as a stock (in the economic sense), that is, as a store of goods for use. It is still common to hear people ask "How much do we really have?" and expect an answer in terms of a volume, into which may be divided the annual water requirement to determine how long we can continue to live and prosper here. Everyone knew that pumping of ground water affected surface-water rights, but the solution to that seemingly incidental problem was to retire rights as might be actually required to keep the river whole and thus push the risks into the future.

Since the mid-1990s, and somewhat greater attention to the hydrologic facts, the paradigm has changed radically. The current thinking is that we must live within the renewable supply, which is essentially the same as the surface water that we have the right to divert and use, and that we will treat the stored ground water as a revolving account, none of it, or not much more of it, to be permanently depleted. Ground water might be thought of as a reservoir with the function of smoothing the irregularities of the surface-water supply, but not as a reservoir full of water to be withdrawn and put to use. The hydrologic facts did not change in the mid-1990s and the essentials had been known to the hydrologic community for many years before, but the attention devoted to the facts did change because people began to think through the long-term consequences of following the older paradigm.

An odd feature of this new way of thinking about ground water is that, in basins with no river and very little recharge, like the Estancia Basin, the ground water is still regarded as a stock, but in river-connected basins it is now more likely to be thought of as a revolving account. Ground water in the non-river-connected basins is managed as a finite resource that will one day be gone, but in the river-connected basins, the current thinking is to manage ground water primarily as a way of using the surface water more conveniently. This "convenience" includes, of course, the very important feature of providing a reserve to be called upon in drought. Apart from its (admittedly great) value in this regulating function, stored ground water is not a resource at all.

There is a serious, undesirable physical consequence of withdrawing a large volume of water from groundwater storage, and that is the potential for subsidence of the land surface. The aquifer becomes compacted due to the removal of water from the pore spaces, and as its thickness becomes smaller, the land surface goes down with it. A study by the New Mexico Bureau of Geology[7] gave the prediction that significant subsidence, which would probably lead to some differential change in the land-surface elevation, and thus to damage to foundations, streets, and pipelines, would begin when drawdown of the water table reached about

7. W.C. Haneberg, *Depth-porosity Relationships and Virgin Specific Storage Estimates for the upper Santa Fe Group Aquifer System, Central Albuquerque Basin, New Mexico*, 17 N.M. GEOLOGY 62-71 (1995).

300 feet. The drawdown would be measured from the pre-development position of the water table, and of course a large part of that 300 feet of effect has already occurred under part of Albuquerque. For that reason, the hypothetical well field in the case we developed for our AWRA paper is some distance from the city, in an area where little drawdown has taken place so far. And drawdown in that case was limited to less than 300 feet.

Clearly the 300-feet-of-drawdown constraint would itself remove most of the stored ground water in our basin from consideration, but it would still leave available a project like the one we analyzed, and there would be room for several others like it in the Albuquerque-Belen Basin. The volume of water in the valley fill, even within 300 feet downward from the water table, is likely to be around 90 million acre-feet.

Another point to be raised against the scheme described in our AWRA paper is that the amount of water that would be made available from a single project would inevitably diminish over time. This leads to several questions: Is it wise to allow users to become dependent on a resource that will yield less and less water every year and eventually vanish? This might be even more insidious if, as in the case of our hypothetical example, the amount of water is actually constant at the maximum rate for more than 20 years. Is it useful at all to develop a supply that is available for a while and then begins to dwindle?

Against these objections, one might point out that it has always been customary to exploit natural-resource stocks, other than water, that also follow this pattern. The yield of any single oil field or gas field reflects the same course of development, with roughly constant production, limited by the capacity of the infra-structure in place, for a while, and then a decline. Metallic ores are a similar but less obvious case: economics set the annual production rate, but it can in theory be as great or small as one might desire until the ore is gone. The way we maintain supplies of these natural resources is to move to a new place and exploit a new stock when the current one is depleted, and we can do and do the same with ground water. Many a city in New Mexico has established new well fields as old ones reach their limits.

Mining ground water is much the same as mining any other mineral commodity, but we think of it differently. Perhaps the difference we perceive comes about because we, as members of the public interested in our communities and in a resource that is essential to our lives, and in our roles in water-management and planning, are much closer to water-supply issues than we are to questions of energy or mineral-commodity availability. Another difference between our views related to mining of mineral commodities, and to water, is that most other commodities are less costly to ship, and it matters less how far away the sources are.

The dependency question is an important one. It may not be sound policy to offer water only temporarily, around which permanent growth and investment might occur. But of course, albeit unwittingly, this has been the course of water-supply development in the area until recently, and even with our present good understanding of the availability of water, and the steps being taken to put it on a sustainable footing, it is projected that by some time mid-century the demand will again exceed the renewable supply. A supply that permanently reduces the amount of ground water in storage would not be a good source to depend upon if it were the only one, but as part of a larger coherent plan, it might be.

Another way to frame the dependency question is to ask whether the agricultural development in eastern New Mexico that relies on the stored water of the High Plains aquifer, development which began early in the twentieth century and reached its peak in the mid-1970s, should have been allowed to occur, and whether it should or would be undertaken today, given what we now know. The amount of water withdrawn, perhaps 30 million acre-feet, has supported farm revenues on the order of $11 billion. This line of inquiry leads to the question whether mined ground water should be made available only to short-term uses, as distinguished from uses that are at least tacitly expected to last forever. Municipal supplies are definitely in the latter category.

A scheme for permanently withdrawing a lot of stored ground water for beneficial use, as contemplated in our paper, would require that the public place a great deal of trust in the science and engineering behind it, and in the managers of it. The scheme must be based on a sound understanding of the groundwater system, represented in a comprehensive groundwater flow model. Great improvements in these models have been made in the past few decades, and they can be adjusted, in the process of calibration, so that they will replicate the changes in water levels and various components of the water balance that have occurred over time.

The idea is, that if a model can predict the changes that have already taken place over a fairly long period, it can be trusted to predict future changes. There are always surprises, however, and one distinguished academic has published respected papers on the theme "all models are wrong; how do we know which are useful?" Here again, however, we find that water management in general, even of the renewable supply, depends on predictions and sound modeling. To refuse to withdraw stored ground water because the effects are subject to some uncertainty is not to free water management from dependence on mathematical models. All management must include the ability to refine and adjust models as time goes by.

The financial predictions on which the scheme is based also depend on mathematical models, and these seem likely to be subject to even more uncertainty than hydrologic models. Here, the right approach may be to set the sale price of water by adopting worst-case assumptions as to inflation and interest rates, and also for capital and operating costs, far into the future. Certainly the future price of energy would play an essential part.

Financial projections and pricing of water for sale would be updated frequently.

The managers of the system must also be trusted to keep the scheme in operation, rather than to let it lapse, and thereby bring about the large and long-lasting depletion of the river's flow that would ensue. And in theory, of course, the scheme must continue forever. Both of these factors suggest that only a public agency, perhaps only the state itself, should undertake such a scheme.

One consequence of the scheme for permanent withdrawal of stored ground water in a river-connected basin is that, although a finite amount of water can be produced, sold, and partly consumed, the recurring energy costs continue forever. To undertake the scheme and never "repay" the amount of water taken from the aquifer by allowing inflow from the river to replace it would commit future generations to paying forever for the energy required to operate pumps and the energy and other resources required to provide replacement wells, pumps, and pipelines. (Of course, they will already have the money with which to do it, if the fund has been properly managed.)

Their concern would be related to the "carbon footprint," and other environmental considerations. This aspect of the scheme is different from other categories of natural-resource mining. When we mine oil and gas, coal, or other mineral commodities, once the mining operation has ceased and the proper reclamation of the site has been completed, there is no more demand on other resources.

As mentioned earlier, future generations may have a view of things that is much different from ours. They may find the exchange of money for energy and the depletion of energy resources (which may or may not occur) an acceptable burden because it is the price of maintaining the flow of the river. If renewable energy sources (solar, wind, and so on) are available by that time, there may be little or no depletion of energy-resource reserves. The promise of renewable energy by the end of another 100 or 125 years seems bright. And the future population may thank us for committing them to the ongoing obligation if the water has been used in such a way that it continues to contribute to their prosperity. Their opinion, expressed as "the groundwater scheme made our city what it is today," might be either a favorable comment or a malediction.

Just as a mental exercise, one might try to imagine ways in which the water produced by the scheme could be devoted to support of capital investment in developments that later required much less water.

Of course, an alternative to the continuing energy requirement (given that the *costs* of energy and other costs will always be paid from the income from the permanent fund) is to stop the pumping, and our descendants may choose to do that. If the system has been managed as planned, so that the permanent fund always earns enough to meet all of the costs, there would be no question of expense. To let the river begin to replenish the aquifer seems abhorrent from our point of view because of the reduction in streamflow that would occasion. On the other hand, after a century or so that may be the least of the residents' worries, or they may simply decide they would prefer to use the fund balance for some other purpose.

What if our successors actually need *less* water rather than more, as life in the Middle Rio Grande unfolds after they have committed themselves to the ground-water-from-storage scheme? It is entirely possible that economic changes, or some other influence, having nothing to do with water supply, will lead to a decrease in population. In such a case, they may want to pursue a lower-cost alternative, or decide not to continue the scheme for some other reason, and want to "cancel." Or, what if, having begun to pursue a groundwater-from-storage scheme, our successors think better of it and change their minds for some other reason and want to rely entirely on more conventional water supply?

Almost any decision carries with it the risk that one will later wish he had done something different. We did not examine the consequences of this eventuality, partly because the notion that water demand would cease to rise does not fit our conventional wisdom about the Middle Rio Grande Basin, and partly because the analysis would be so complex. It would be necessary to know when, and therefore where in the cycle of accumulation of money in the fund and expenditure from it, the change in policy would occur.

In this situation, the water to replenish the withdrawn ground water would have to come from somewhere. The City of Albuquerque, and now the Albuquerque-Bernalillo County Water Utility Authority (ABCWUA), is doing something similar by beginning to divert its San Juan-Chama Project (SJCP) water directly into the municipal system and dramatically reducing the amounts that will be pumped from wells. Groundwater levels will come up, and the water to bring that about will come from the surface-water system.

Once the transition from continued reduction of stored ground water to "conjunctive use" is complete, and of course at any time before that, the ABCWUA will be in a position to use the groundwater system as a revolving account to provide supplies during drought. During the transition, however, there will be less water in the river than there was before the changeover begins. This would happen even though the ABCWUA would divert only imported SJCP water (plus the same amount of native Rio Grande water that would return immediately through the wastewater treatment plant).

A simple, hypothetical accounting exercise will show that this is true. If the city used, say, 96,000 acre-feet in a year and returned 50 percent of it as wastewater, the actual loss of water by evaporation and transpiration would be 48,000 acre-feet in that year. If all of the 96,000 acre-feet were drawn from ground water and in that year the accumulated effects of pumping caused streamflow depletion of 10,000 acre-feet, then a net of 38,000 acre-feet (48,000 acre-feet of return flow less the streamflow depletion of 10,000 acre-feet) would be *contributed* to the river. On the other hand, in the first year after groundwater pumping was drastically reduced, the streamflow depletion of 10,000 acre-feet (which now would go toward refilling the depleted groundwater storage) would change relatively little, but all of the loss to evaporation and transpiration, 48,000 acre-feet, would also be of water that has come from the river. The sum of these would amount to streamflow *depletion* of 58,000 acre-feet.

The concept is really much simpler than that, of course: before the transition to "living within our means," all of the loss to evaporation and, on top of that, some water contributed to the stream as treated wastewater came from stored ground water. After the transition, all of the loss to evaporation comes from the river, and any excess over that is simply return flow.

How can, and how should, a decision be made about any plan to permanently withdraw stored ground water, given the range of consequences? Perhaps the question dealt with in this paper, "What shall we do with all of this ground water?," should be "Can we learn to ignore all this ground water?"