Estimating
Groundwater Availability
in Texas

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Introduction

Groundwater availability is simply the amount of groundwater that is available for use from an aquifer. Although easy to define in words, groundwater availability is much more difficult to quantify in practice. There is no set formula or equation for calculating groundwater availability. This is because an estimate of groundwater availability requires the guidance of policy as well as the procedures of science. Science provides the understanding of how an aquifer works and the tools, such as geologic and hydrologic information and numerical groundwater flow models, to help calculate groundwater availability. Policy provides the guidance and defines the bounds that science can use to calculate groundwater availability. Policy involves management goals, environmental issues, and rules and regulations. Although science is required to quantify groundwater availability, policy is the most important factor that influences the final value. Depending on policy, groundwater availability can range from a very large number to zero for the same aquifer.

The purpose of this document is to (1) discuss different methods for estimating groundwater availability, (2) summarize previous estimates of groundwater availability by the Texas Water Development Board (TWDB) and the Regional Water Planning Groups (RWPGs), and (3) suggest one possible approach for estimating groundwater availability in the State’s aquifers.

Sources of Water Available from an Aquifer

When producing water from an aquifer, the water comes from three possible sources: recharge, storage, or cross-formational flow. Recharge is the amount of water that moves into the aquifer, generally from rainfall, melting snow, or rivers. When it rains, some of the rain runs off into streams, some of it evaporates back into the atmosphere, some of it is used by plants, and some of it percolates into the ground, eventually reaching and recharging the aquifer. Conceptually similar to recharging a battery with new power, percolating precipitation recharges an aquifer with new water. In general, the percent of precipitation that eventually recharges the aquifer is small, generally between one and four percent of the total rainfall. However, the volume of recharge can be large when accumulated over a large outcrop, or recharge zone, and/or if the precipitation is large.

Storage is the amount of water stored in the aquifer. When water levels change in an aquifer, that change reflects a change in storage. When water levels rise, there is an increase in storage. When water levels lower, there is a decline in storage. Water levels decline as water is pumped out of a well and removed from storage. There are two types of storage: drainable storage and compressible storage. Drainable storage is the amount of water that can be drained from an aquifer. Compressible storage is the amount of water stored in the aquifer due to the compression of the aquifer and the water itself. Needless to say, drainable storage is much larger than compressible storage.

Cross-formational flow is flow from a bordering geologic formation into the aquifer. This flow may occur naturally or may be induced with pumping. Depending on the aquifer and the surrounding geology, water from cross-formational flow may be of good or poor quality. With pumping, groundwater may flow into an aquifer from a bordering aquifer.

All aquifers have natural discharge, where water moves out of the aquifer. These natural discharges include springs, gaining streams, cross-formational flow out of the aquifer, and evapotranspiration where the aquifer is close enough to the land surface for plants to tap into the water. Water that moves naturally out of the aquifer and discharges to the land surface where it was recharged or a surface-water body is called rejected recharge (Theis, 1940). From the perspective of the aquifer, this water is ‘rejected’ because the aquifer could not take the water into storage.

If there is no pumping, then the natural discharge from an aquifer equals the recharge. When someone drills a well and pumps water from an aquifer, this balance between recharge and discharge is disturbed. Water captured by a pumping well cannot naturally discharge to a spring or stream. Therefore, every well has some effect, however minuscule, on natural discharge from the aquifer. For example, groundwater pumping has caused a number of springs in certain areas around the State to stop flowing (Brune, 1981) and has dried up springs (Dutton and others, 2000) and some streams (Angelo, 1994) in the Ogallala aquifer.

Availability Bookends: From Nothing to Everything

When estimating a parameter such as groundwater availability, it is sometimes useful to define the bounds of possibility for that parameter. For estimating groundwater availability, these bounds are the minimum amount of water available and the maximum amount of water available from an aquifer. The minimum amount of groundwater available from an aquifer is simply zero. This is the extreme case where the goal is to leave the natural system uninfluenced by human hands.

The maximum amount of water available is the amount of water stored in the aquifer plus the amount of water recharging the aquifer. This is the extreme case where the goal is to entirely deplete, or mine, the aquifer of water: something that is essentially impossible to do. Generally, this depletion would be proportioned over a number of years because the removal of water from storage would be a one-time withdrawal. The maximum groundwater availability can be decreased by taking into account a number of factors such as (1) the quality of existing water in the aquifer, (2) the economics of producing water from depth, (3) the feasibility and economics of producing water from thin saturated sections, and (4) the intrusion of poor quality water from bordering geologic formations or saltwater intrusion from the coast.

Having the bounds defined show the range of possibilities for determining groundwater availability. Groundwater availability is somewhere between these two extremes.

Safe Yield

Safe yield is one approach for quantifying groundwater availability. When originally introduced, safe yield was the maximum amount of water that could be produced from an aquifer and still maintain the sustainability of the aquifer (Lee, 1915; Meinzer, 1920, 1923; Williams and Lohman, 1949). In other words, the water resources of an aquifer could be maintained indefinitely if pumping did not exceed the safe yield. Based on concerns of numerous hydrogeologists (e.g. Conkling, 1946 and subsequent comments; Banks, 1953), the definition of safe yield was later amended to include concerns on water quality (such as saltwater intrusion) and environmental damage (such as land subsidence and impacts to stream baseflow) (Fetter, 1980). In other words, an aquifer pumped at or less than the safe yield would be able to be maintained indefinitely and minimize water-quality degradation and some specified environmental damage. Environmental impacts may also include ecological, economical, social, cultural, and political issues (Fetter, 1977) as well as spring flow.

Because of its ambiguity, safe yield is not a popular groundwater resource management concept among scientists (e.g. Thomas, 1951; Muckel, 1955; Thomas, 1955; Kazmann, 1956; Anderson and Berkebile, 1977; Sophocleus, 1997). This is because policy is required to define how much land subsidence, baseflow decline, or spring flow decline is acceptable. Quantifying safe yield requires economists, engineers, engineering geologists, plant and wildlife ecologists, and lawyers (Fetter, 1980). Safe yield is also difficult to determine because it has no unique or constant value depending on the spacing and location of wells and their influence on the aquifer (Domenico and Schwartz, 1990). Safe yield is often incorrectly equated with average annual recharge. Because of environmental impacts to springs and stream baseflow, safe yield is generally less than average annual recharge.

Optimal Yield

Other approaches have been proposed for assessing the availability of water from an aquifer (e.g. ASCE, 1961; Renshaw, 1963; Burt, 1964, 1966, 1967a,b; Chun and others, 1966; Bear and Levin, 1967; Bredehoeft and Young, 1970; Freeze, 1972). An enhancement of safe yield is a concept called 'optimal yield' (Bear and Levin, 1967; Buras, 1966; Burt, 1967b; Domenico and others, 1968; Domenico, 1972). Optimal yield is the determination of a yield using optimization theory considering socio-economic issues (Freeze and Cherry, 1979). The optimal yield of an aquifer is determined by selecting the optimal management approach that best meets socio-economic goals. An optimal yield can lead to depletion or complete conservation of an aquifer, but is usually somewhere between (Freeze and Cherry, 1979). An important distinction between optimal yield and safe yield is that an optimal yield can be safe yield or it can result in depletion of an aquifer. Optimization theory is a mathematical technique for determining the most advantageous approach out of a set of possible alternatives.

Methods Used in Texas

Because Texas has planned for water in the past (TWDB water plans of 1960, 1968, 1984, 1990, 1992, and 1997) and is currently planning under Senate Bill 1 (SB-1), the availability of groundwater has been previously estimated by the TWDB. For the current water plan, RWPGs (fig. 1) were given the option of using previous TWDB estimates of groundwater availability or developing their own estimates.

Methods Used by the Texas Water Development Board

The TWDB has estimated groundwater availability for the aquifers of Texas using a number of different techniques (Muller and Price, 1979). The TWDB defines groundwater availability as the effective recharge plus the amount of water that can be recovered annually from storage over a specified planning period without causing irreversible harm such as land-surface subsidence or water-quality deterioration (Muller and Price, 1979, p. 9). Effective recharge is the amount of water that enters the aquifer that is available for pumping and is generally less than the total recharge which includes all of the water that moves into the aquifer. Note that this definition of groundwater availability is not the same as safe yield because it does not require that the amount of water produced from the aquifer be sustainable. However, ‘irreversible harm’ could also be interpreted to include flow to streams and springs, in which case a sustainable pumpage would be required.

In the Muller and Price (1979) report, the TWDB estimated groundwater availability using four general approaches:

- average recharge,
- recharge with changes in storage,

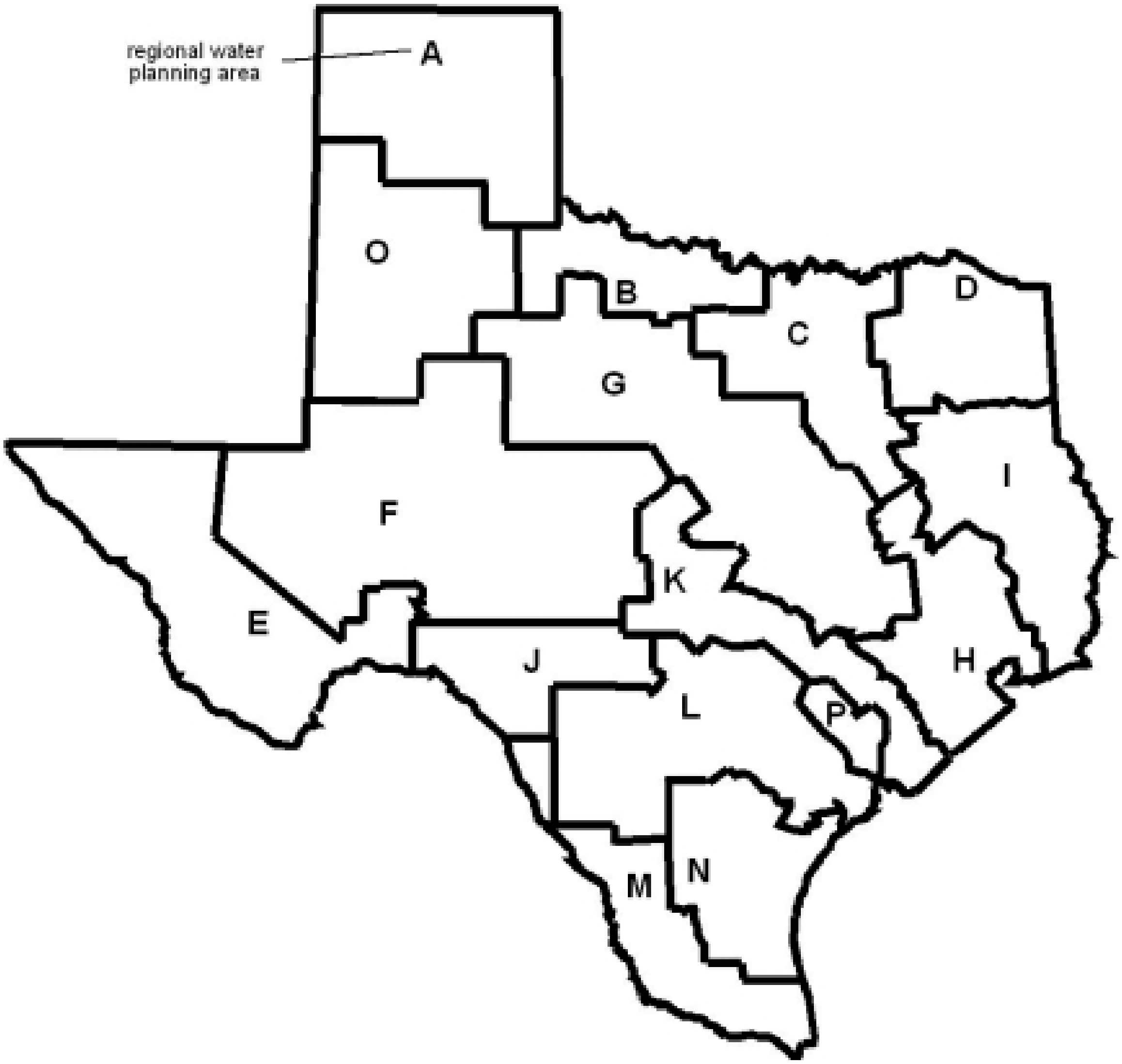

Figure 1. Regional Water Planning Areas in Texas.

- the above two approaches with limitations to prevent water-quality deterioration, land-subsidence, or other undesired effects, and
- systematic depletion.

Different techniques were used to estimate groundwater availability for the average recharge and recharge with changes in storage approaches. Average recharge was estimated using base-flow and spring-flow measurements, low-flow and flow-net analysis (Walton, 1962), the trough method (Peckham and others, 1963; Klemt and others, 1975), comparing pumping and water-level trends (Keech and Dreezen, 1959, p. 44-48; Shamburger, 1967, p. 66-68), or a percentage of the mean annual precipitation. Recharge with changes in storage was estimated using water-budget studies (e.g. Meyer and Gordon, 1972). Results from numerical models for the Ogallala (Knowles and others, 1984), Edwards (Klemt and others, 1979), Carrizo-Wilcox (Klemt and others, 1976; Thorkildsen and others, 1989), and Hueco Bolson (Meyer, 1975, 1976) aquifers were also used.

Methods Used by the Regional Water Planning Groups

The RWPGs estimated groundwater availability using two main approaches: (1) recharge and (2) systematic depletion. The RWPGs used several methods to estimate groundwater availability using the recharge approach:

- Groundwater availability equals the effective annual precipitation on the outcrop, generally between 0.5 to 5 percent of annual precipitation (Regions A, B, C, D, E, G, H, and I).
- Groundwater availability equals the historical pumping if water levels have remained relatively constant (Regions A, E, G, K, M and P).
- Groundwater availability equals the minimum spring flow and groundwater withdrawal during the drought of the 1950s (Regions G and K).
- Groundwater availability is based on computer modeling study with various scenarios (Regions A, D, G, I, K and N).

For systematic depletion, the RWPGs first estimated the drainable storage of the aquifers. Drainable storage was estimated by multiplying the saturated thickness of the aquifer by the specific yield of the aquifer (specific yield describes how much water can be drained from a unit part of the aquifer). The RWPGs then adjusted the drainable storage in several different ways:

- Took 50 percent of drainable storage and divided it equally over a 50-year period (Region A).
- Took 75 percent of drainable storage and divided it equally over a 50-year period (Region F).
- Took 75 percent of drainable storage and divided it equally over a 100-year period (Region F).
- Projected future groundwater storage on the average annual change in the volume of water in storage (net depletion) that occurred between 1985 and 1995 and

reduced the depletion rate by 10 percent each decade to reflect increased conservation and declining well yields (Region O).

Region H accounted for land subsidence, Region N accounted for water quality in their assessments of groundwater availability, and Region L accounted for maintaining spring flow. Many of the RWPGs used TWDB estimates as part or all of their groundwater availability estimates (Regions C, D, E, G, H, I, K, L, M, N and O).

In some cases, the groundwater availability for an aquifer was already defined by an outside entity. In the case of the San Antonio segment of the Edwards aquifer, the 73rd Texas Legislature defined the groundwater availability of the aquifer with SB 1477. This act directs the Edwards Aquifer Authority (EAA) to limit permitted withdrawals to no more that 450,000 acre-feet per year through 2007 and 400,000 acre-ft per year thereafter unless increased by the EAA board of directors based on results of research (EAA, 1998). These numbers were based on previous TWDB water plans (Votteler, 2000). Region L used 340,000 acre-feet per year as the amount of water available from the Edwards aquifer during drought (15 percent less than 400,000 acre-feet per year). In the case of the Gulf Coast aquifer in Harris and Galveston counties, groundwater availability is restricted by a need to prevent land subsidence.

Groundwater Availability Modeling

Numerical groundwater flow models are useful tools for helping to estimate groundwater availability (Chun and others, 1966; Bredehoeft and Young, 1970; Freeze, 1972). A numerical groundwater flow model is a computer model of the aquifer that simulates recharge, surface-water interaction, springs, pumping, and water levels. When designed and used to estimate groundwater availability, we call them groundwater availability models. The TWDB has developed and used models for the Edwards, Hueco Bolson, Gulf Coast, Trinity, Carrizo-Wilcox, and Ogallala aquifers to help estimate groundwater availability.

The TWDB has been working to develop new, and in some cases the first, groundwater availability models for the major aquifers of Texas. Thus far, three models have been completed for the Trinity aquifer in the Hill Country, the northern Ogallala aquifer, and the Barton Springs segment of the Edwards aquifer (Mace and others, 2000; Dutton and others, 2000; Scanlon and others, 2000; respectively). Work continues on nine additional models and four more models are planned (fig. 2). These models have been used as tools by some of the RWPGs to estimate groundwater availability, most successfully for the Ogallala aquifer. Although we call these models groundwater availability models, they cannot, by themselves, be used to assess groundwater availability. Groundwater availability models require the policy guidance of stakeholders such as RWPGs, Groundwater Conservation Districts, and others to determine groundwater availability.

Limitations of the Current Methods and Approaches

The current methods and approaches for assessing groundwater availability have limitations. These limitations are primarily with (1) the technical methods used to assess groundwater availability, (2) the approaches used to include stakeholders in the decision

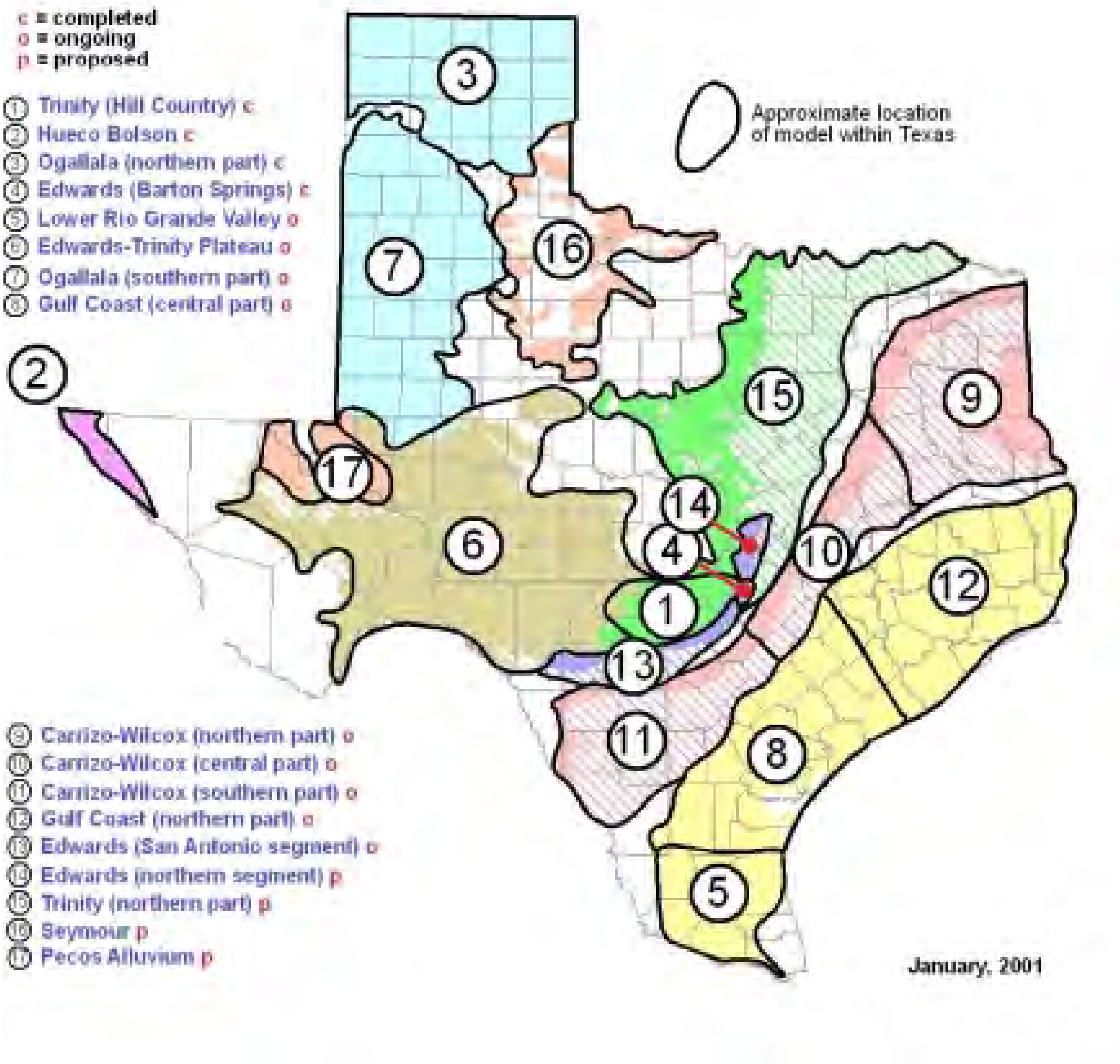

Figure 2. Completed, ongoing, and proposed models of the major aquifers in Texas.

process of how availability was estimated, and (3) disagreement between regions on how to assess availability for the same source of water.

Each of the scientific methods used to estimate groundwater availability has limitations based on the assumptions of the methods and the amount of information for the aquifer. It is outside the scope of this paper to discuss these limitations in detail, but it is important to note that many of the methods (such as average recharge, systematic depletion, current pumping) oversimplify the aquifer and neglect the effects of pumping in an aquifer. These oversimplifications likely result in misleading estimates of groundwater availability. Although models are powerful tools for estimating groundwater availability, they may be misapplied or the results misinterpreted.

During the water planning process, there were inconsistencies in the approaches used for estimating groundwater availability. Many of the TWDB original estimates did not include substantial stakeholder involvement. In some regions, the RWPGs were integrally involved with the process of assessing availability, while in others, RWPGs were minimally involved. Some RWPGs were not aware that they could have an influence on how availability was estimated because consultants were not aware that availability could be defined differently.

Like beauty, availability is in the eye of the beholder. Therefore, different regions have defined groundwater availability differently for the same groundwater source. For example, in the Carrizo-Wilcox aquifer, Region K defined groundwater availability according to recharge, and Region L defined it on potential production from a proposed well field. Different views of availability were also an issue in the Ogallala aquifer between Regions A and O. Different definitions of groundwater availability have caused confusion and heightened suspicions between regions.

Because of the confusion and problems associated with estimating groundwater availability, one recommendation from some of the RWPGs after this first planning cycle was for the TWDB to develop a standard for assessing groundwater availability for the State’s aquifers.

One Possible Approach: Consensus Yield

We propose a new approach, called consensus yield, where the stakeholders for the aquifer are intimately involved with the process of estimating groundwater availability. Note that this is one possible approach that could be used. This approach gets its inspiration from SB 1 water planning where regional water plans are assembled and adopted by stakeholders through consensus building. Consensus yield is similar to optimal yield but with a stronger and more integral involvement of stakeholders throughout the process to identify long-term management goals. As with optimal yield, consensus yield can result in depletion or complete conservation of an aquifer. In developing our approach for defining consensus yield, we assumed the following to be true:

- Groundwater scientists alone cannot estimate groundwater availability.

- A single method or technique for estimating groundwater availability cannot be defined for all aquifers.
- Numerical groundwater availability models are the best tools to use to help estimate groundwater availability.
- An intermediary must be used to facilitate stakeholder discussions and communication between the scientists and stakeholders.

The consensus yield approach has six major steps:

1. Identify coordinator, facilitator, scientists, and engineers
2. Assemble stakeholder group
3. Educate stakeholders
4. Define socio-economic and environmental goals
5. Estimate availability based on socio-economic and environmental goals
6. Stakeholder review of availability (steps 3 through 6 may be repeated as needed)
7. Consensus
8. Periodic review

Each of these steps is briefly described below.

Step 1: Identify coordinator, facilitator, scientists, and engineers

There needs to be a coordinator (or coordinating agency) for the consensus yield process. The coordinator decides whether internal or external facilitators, scientists, and engineers will be used in the process. The coordinator will identify and assemble the stakeholder group.

Step 2: Assemble stakeholder group

A representative stakeholder group needs to be formed to identify long-term management goals. The stakeholder group should consist of people representing the interests of the region which are dependent on the aquifer. These stakeholders include the public, county, municipality, industry, agricultural, environmental, small business, utilities, river authorities, groundwater conservation districts, and others.

Step 3: Educate stakeholders

Before there can be productive discussions of groundwater availability, the stakeholders must be educated. This education includes a basic understanding of how aquifers work, environmental benefits related to groundwater, the different approaches for assessing groundwater availability, and the different scientific methods for estimating availability. The stakeholders will need to have a good understanding of their aquifer and the availability of information on the aquifer. Stakeholders should have a good understanding of the elements of an aquifer that are important for estimating groundwater availability and the strengths, weaknesses, and implications of the different approaches and methods.

Step 4: Define socio-economic and environmental goals

Once the stakeholders are educated, the next step is for them to brainstorm what water-resource issues are important to their region (for example, supplying water to cities, increasing agricultural pumping, maintaining spring flow). After this brainstorming, they will need to prioritize these issues to identify their socio-economic and environmental goals. At this relatively early point in the process, a consensus is not required. Different priorities and alternative socio-economic and environmental goals can be identified and used to estimate different groundwater availabilities. The stakeholders should be encouraged to give the scientists and engineers a number of different scenarios for assessing groundwater availability (for example, safe yield, complete depletion, spring flow maintained at 50 percent of normal, etc.). The scientists and engineers need to be observers during this process to better understand the intent of the different stakeholders.

Step 5: Estimate availability based on socio-economic and environmental goals

Once the socio-economic and environmental goals have been identified, they can be provided to the scientists and engineers to estimate groundwater availability. The scientific techniques used will depend on how the stakeholders have defined socio-economic and environmental goals. For example, the groundwater availability for systematic depletion could be estimated using geology and aquifer properties. A safe yield approach would probably require using a numerical groundwater flow model. It will be important to have these tools ready for estimating groundwater availability. This step may result in several values of groundwater availability if different priorities are generated in the previous step.

Step 6: Stakeholder review of availability numbers (reanalysis if necessary)

After the scientists and engineers have estimated groundwater availability, the stakeholders will meet again to review and discuss the estimates. These discussions may lead to a consensus on one of the approaches or may lead to further refinement of the estimates or to completely new approaches. With these additional comments, the scientists can then refine or re-calculate groundwater availability. These review and recalculation steps can be repeated until there is a consensus among the stakeholders.

Step 7: Consensus

Once there is a consensus, then the methods and numbers can be documented and published. Reports will need to include a list of all participants and discussions of the different concerns identified. Limitations of the scientific approach should be discussed with recommendations for improvement.

Step 8: Periodic review

Because socio-economic and environmental goals and the scientific understanding of the aquifer will change over time, there can be a periodic review of the groundwater availability numbers and approach. A periodic review, perhaps on a five-year time scale, may give stakeholders comfort that their decisions can later be amended to address new concerns that did not exist at the time of the meetings.

How long will it take?

The above process would have to be done over several months to allow time for the scientists to make availability estimates. The education and defining steps (steps 3 and 4) could be done in a single meeting or the education step (step 3) and the defining steps (steps 4) could be done in separate meetings. However, it may be advantageous to minimize the amount of time between the education step and brainstorming and definition steps so that concepts are still clear. Depending on the request from the stakeholders and techniques used, the scientists may need several weeks to estimate availability before having a review meeting. How many times the process will need to go through the estimation and reviews steps (steps 5 and 6) will depend on the stakeholder group. A periodic review should be done on an appropriate time interval, perhaps every five years. An unscheduled review may be needed if there is a sudden change in socio-economic and environmental goals. Flexibility will be key for scheduling a review process. If stakeholders and scientists feel no changes are needed, reviews can be postponed until the need arises.

What if there is no consensus?

A problem that may arise is when the stakeholders cannot reach consensus on an approach or availability for the aquifer. For example, environmental interests may insist on a safe yield approach while agricultural interests may insist on a pumping rate that requires systematic depletion. Rural interests may prefer a lower rate of systematic depletion than municipalities. In these cases, the facilitator may need to carefully negotiate an agreement. If negotiations fail, the coordinator may have to impose a temporary compromise, perhaps somewhere in the middle of the opposing views. Although consensus will not be attained in these cases, the final availability numbers will partially address everyone's concerns.

Consensus is more likely to be achieved if there is a clear incentive for the stakeholders to come to an agreement. A strong incentive will encourage stakeholders to compromise on their socio-economic and environmental goals.

How will the approach be used for different aquifers?

Because aquifers and policy differ for different aquifers, different parts of the aquifer, and different parts of the State, it is not possible to define a specific scientific technique to calculate groundwater availability for the entire State. It may be required to even divide the aquifer into separate parts for this process based on socio-economics, environmental concerns, existing regulations, or hydrogeology.

Groundwater availability does not regulate pumping

Once defined, groundwater availability determined using the consensus yield approach would have to be respected between regions for water planning. However, it is important to note that in Texas, groundwater availability numbers are planning tools and not pumping limits. However, availability numbers could impact pumping limits in aquifers. SB 1 requires that groundwater district management plans be consistent with the regional water plans. Therefore, groundwater conservation districts may have to abide by a consensus yield used by the RWPGs. Ultimately, groundwater pumping is governed by the local rules and regulations promulgated by groundwater conservation districts where they exist and the rule of capture where they don't exist. Therefore, availability determined using the consensus yield concept does not prevent someone from installing a well field that exceeds the consensus yield.

Conclusions

Groundwater availability is the amount of groundwater available for pumping from an aquifer. Quantifying groundwater availability requires the intersection of policy and science: policy to define socio-economic and environmental goals and science to estimate the actual amount of water that can be produced based on socio-economic goals. Groundwater availability can range from nothing to all of the drainable water from an aquifer. In practice, groundwater availability lies somewhere between these two extremes. Safe yield is one method of defining sustainable groundwater availability and requires policy for an adequate definition. Optimal yield can be a safe yield but also allows for groundwater mining depending on socio-economic goals.

A number of different methods and approaches have been used to define groundwater availability for the State's aquifers. However, many of these methods and approaches are limited due to technical restraints, inadequate stakeholder involvement, and competing availability estimates. We propose a possible approach called consensus yield that integrates policy and science throughout the process as one possible approach for estimating groundwater availability in Texas. Consensus yield is essentially optimal yield but with a more integral involvement of stakeholders. A facilitator assembles and educates the appropriate stakeholders, and the stakeholders subsequently identify socio-economic and environmental goals for their area. The scientists and engineers then estimate groundwater availability (preferably using groundwater availability models) using the established socio-economic and environmental goals. The stakeholders then review these numbers and perhaps suggest changes or additional approaches for the scientists to use to adjust availability numbers. This process continues until there is consensus among the stakeholders upon which the availability is approved. Because policy, socio-economic goals, and the scientific understanding of the aquifer change over time, groundwater availability will be periodically reviewed as needed. The end result is groundwater availability estimates for all aquifers in Texas that are flexible over time and have the support of all Texans.

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