GWDSS: A Scientific Platform for Interactive Groundwater Dialog

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ABSTRACT

Conflicts between different groups of users, such as urban development, environmental quality, and agricultural, municipal, and domestic users, often arise when governments seek to plan future aquifer use. To address these issues on a regional basis the Texas State Legislature created 16 groundwater management areas and asked them to develop desired future groundwater conditions. Our research focused on conflict resolution and how to make scientific information meaningful to decision makers. Representative stakeholders were invited to participate in narrative elicitation and analysis to identify commonalities of desired future conditions and allow participation by stakeholder groups. To demonstrate the effects of various management or development decisions on groundwater resources, a decision support system (DSS), using groundwater simulation and geographic information with performance measures was developed, to assess groundwater withdrawal alternatives. Appraisal value, travel distance, and impervious cover data were input for alternatives to describe changes from a base case. Appraisal value assessed development potential, travel distance is an urban sprawl proxy, and impervious cover was used to estimate groundwater recharge. A systems dynamics model links the State of Texas numerical groundwater model with development alternatives. We use GWDSS, a DSS that includes a web-based graphic user interface, flexible system architecture, and application protocols for multi-model simulation, to help stakeholders understand how land-use changes affect land value, sprawl, critical springflows, and well yields through the performance measures. The final outcome preferred by each stakeholder was submitted to a pool of alternatives. GWDSS was designed for rapid development and assessment of alternatives using a system dynamics approach. These assessments provided a basis for comparison which led to a rich dialog e among stakeholders. In the test case, we demonstrate how well placement and impervious cover restrictions can insure minimum springflows to the critical Barton Springs ecosystem and minimize failed wells during major droughts.

1. INTRODUCTION

Conflicts between different groundwater uses, such as urban development, environmental quality, and agricultural, municipal, and domestic users have raised public awareness of groundwater policy in Texas, but consensus on future water use has not commonly been achieved. This research identifies a method of involving stakeholders in a narrative elicitation and analysis to find the commonalities among various stakeholder groups. This process focuses consideration of the preferred metrics needed to evaluate various development scenarios and public policies. The metrics must meet the common goals agreed upon by the stakeholders. This research also developed a decision support system (DSS) that enables water system administrators and stakeholders to assess how well various proposed actions meet agreed-upon metrics. We evaluate these techniques with the Barton Springs (segment of the Edwards) Aquifer of central Texas.

The Barton Springs Aquifer including a contributing and recharge portions is a 917 km^2 karstic aquifer that is part of a larger Edwards (Balcones Fault Zone) Aquifer (Balcones Fault Zone) system (Sharp and Banner, 1997). The aquifer naturally discharges to several springs, principally Barton Springs which has an average discharge of 53 cubic feet per second (cfs) (1.5 m^3sec^{-1}). However, flows vary with drought cycles an average low discharge of 11cfs (0.31 m^3sec^{-1}) was recorded in 1955-56. Since that time, the population of Austin area has increased from 160,000 to over 735,000 (with nearly 1.5 million in the Austin metropolitan region) and approximately 12 cfs (0.34 m^3sec^{-1}) is now pumped from the aquifer. The urbanized area of the City of Austin itself has increased from 100 km^2 to over 600 km^2 in the same time. Barton Springs (Figure 1) is a highly valued recreational asset and hosts 2 salamanders that are federally-listed endangered species. Although the amount of

Figure 1. Barton Springs, Austin, Texas, USA

discharge from Barton Springs necessary for the survival of the endangered species the (Barton Springs salamander and the Austin blind salamander) is uncertain, historical data show that lower flow rates correspond to higher total dissolved solids (TDS) values and lower dissolved oxygen (DO) values. It is unlikely that the salamanders could survive for an extended period of time with no flow. Even under very low-flow conditions, with low DO, their survival is questionable. Projected growth and newly planned developments over the aquifer and its contributing zone (Figure 2) have led to continuing intense conflict between those that wish to develop over the aquifer and in the contributing zone, those that now use Barton Springs Aquifer water, and those wishing to preserve the quality of Barton Springs and protect the endangered species.

The administrative procedures that must reconcile these conflicts are complex. Generally, Texas uses the appropriation doctrine for surface waters and the English (right of capture) doctrine for groundwater. Thus all surface water is state owned with fixed rights that are appropriated by the state, generally on the first in time, first in right basis. Groundwater belongs to the land owner who may pump as much as desired subject to some limitations. This has created a situation in which surface water and groundwater can be considered independent of each other. Because of this and other problems, Texas began to authorize groundwater conservation districts (GCDs), first (in 1951) to manage groundwater in the Texas Panhandle (near Amarillo). These districts now cover much of the state and they have varying degrees of authority. Many of the districts, however, conform to political boundaries and do not reflect the nature of

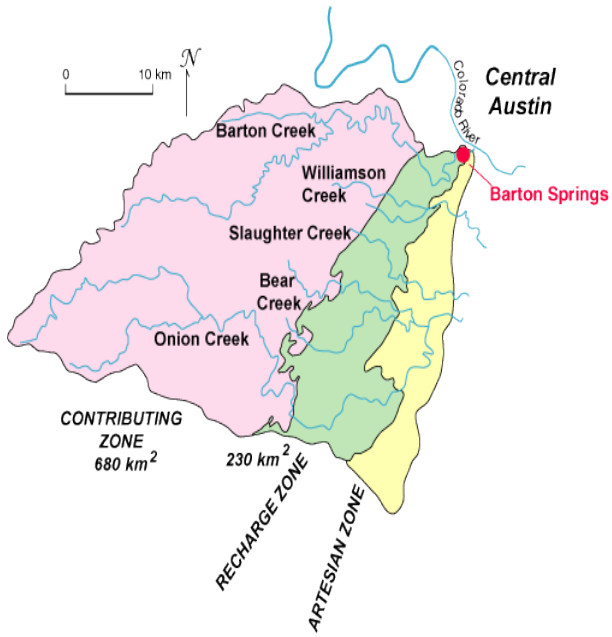


Figure 2. Barton Springs Aquifer showing (right to left) the confined (artesian), recharge, and contributing zone (Budge and Sharp, 2008). The contributing zone consists of watersheds that provide waters to the losing (influent) streams that cross the recharge zone.

the aquifers that they are regulating. To help the GCDs plan for sustainable groundwater management, the Texas Legislature authorized the creation of 16 Groundwater Management Areas (GMAs) that correlate to a greater extent with aquifer distribution to develop desired future conditions (DFCs) of their groundwater resources to exist in 2050 and in the event of a drought of record. Each GMA can define its desired future groundwater conditions, determine what would be their groundwater conditions in 2050, and reanalyze water withdrawals in the event of another drought of record. The standards were quite flexible as the DFCs could specify average piezometric levels, spring flows, or water yields. These could be spatially distributed over the GMA or lumped into a single number. The DFCs are supposed to be reevaluated every 5 years.

This combination of need to define DFCs, the conflicts between stakeholder groups, and the need to make scientific data both accessible and understandable to stakeholders, administrators, water management authorities led to the study. We examined the Barton Springs Aquifer (Sharp and Banner, 1997, 2000; Pierce, 2006) and, to a lesser extent, the situation in Groundwater Management Area #9 (The Texas Hill Country). Below we discuss the narrative elicitation process used to determine stakeholder preferences and, in slightly more detail, the decision support system developed to assist in this process.

2. NARRATIVE ELICITATION AND ANALYSIS

Our research focused on preventing conflict in public policy development and how to make scientific facts meaningful to decision makers. The research had the benefit of access to representative stakeholders. They participated in a narrative elicitation process and in decision making; this allowed stakeholders to express their interest through stories about their lives and allowed decision makers to reflect on how groundwater policies may affect society. Stakeholder interests were captured on film and presented to the stakeholder audience. As a result of the captured moments, each stakeholder had an equal level of participation and no coercion from their peers. The equal participation, clear narratives, and relaxed emotions diminished tensions because stakeholders understood interests and how policy outcomes could affect their lives. These narratives were used to derive performance measures that reflected perceptions, beliefs, and preferences. Models were built with stakeholder input, and a custom interface was developed to interact with policy variables that influence particular areas of concern. Because of the lack of tension and nearly instantaneous modeling, stakeholders were able to engage in dialog on substantive issues rather than get diverted with disagreements over facts uncertainty or positions. Stakeholders reported that the process was cordial, fulfilling, and fast. One stakeholder commented that the process was able to overcome obstacles in one session, which had not been achieved in another stakeholder process of similar context but longer duration.

Stakeholders in the Barton Springs segment represented irrigation, domestic use, municipal demands, economic/development, in stream and spring flows, and recreation. Traditional ranching and farming professions maintain a foothold in this rapidly growing region. Agricultural stakeholders wish to retain a traditional lifestyle earning a living from their land. They believe that this is possible if existing water rights are maintained and development is allowed. If water is not available, their businesses are at risk, and the economy as whole may suffer. Domestic uses (washing, consuming, and irrigating lawns and gardens) have a high priority under Texas law. Homeowners desire clean, safe, and reliable water for their homes. Domestic use is projected to grow by up to 100% in the next 40 years. When the water table is low, homeowners run the risk of burning up pump, drawing brackish water, and requiring the importation of water from other sources under extreme conditions. The bulk of new water demand will be by municipalities or water supply companies that supply subdivisions and new towns. These stakeholders have a high priority and political power and rely on new homes and business for economic development. These users are at risk from overdrafting of limited supplies for neighboring communities. Development interests are reflected in local entrepreneurs are planning and building new subdivisions, retail areas, and industry. Their business livelihood is based on the ability to sell land, develop residential and commercial property, and lease or sell developments. If water is not available, property can lose value; if policies deter development, then developers may lose business. The U.S. Fish and Wildlife Service is concerned with springflows and instream flows. Groundwater discharge to springs and streams has important environmental impact. Federally-listed endangered species cannot be harmed or endangered. Thus aquatic species have first priority to some minimal, but commonly ill-defined level of groundwater discharge. Various environmental groups and the US Fish and Wildlife service are the concerned stakeholders. Finally, Central Texas is known for its rolling hills and natural springs, which provide the venues for its numerous parks and recreation areas. This stakeholder presence is variable, but for the Barton Springs Aquifer, it is considerable. Barton Springs is Austin's highest valued environmental site. If these springs are no longer flowing, recreational usage will be significantly affected.

A DSS should help stakeholders define water pumping policy thresholds through the understanding of pumping effects on water levels, spring flow, and storage as a function of development. Allowing stakeholders to define development scenarios within a context that includes groundwater effects addresses multiple goals: understanding social and environmental impact, clarifying uncertainty of policy, uncovering the sustainability of resources, and realizing the effects of actions regionally. The result was consensus on aquifer yield. We define consensus yield as the acceptable extraction volume from an aquifer or aquifer systems as determined by the inter-related elements of both local and regional hydrologic regimes within the context of the specific preference sets held by affected stakeholders.

Tools and data used to demonstrate the effects of various management or development decisions on groundwater resources were a geographic information system, and two versions of a groundwater model for the aquifer with performance measures to assess groundwater withdrawal alternatives (Pierce et al., 2007). The groundwater models included a detailed numerical model for the aquifer built and approved by the State of Texas for use in groundwater management decisions and a lumped value systems dynamics model that emulated the more detailed model behavior with the addition of appraisal value, travel distance, and impervious cover relationships. Data were input for each alternative to understand differential changes from a base case. Appraisal value assessed development potential, travel distance is an urban sprawl proxy, and impervious cover was used to estimate groundwater recharge (Wiles and Sharp, 2007; Garcia-Fresca, 2007).

3. DECISION SUPPORT SYSTEM

Models are important tools for science and policy, yet the same models are rarely used to address both areas simultaneously. Scientific understanding should be incorporated into policymaking, but the elements that are important to a policy decision may be distinct from those that are critical to a scientific perspective. Enabling interchange between scientific knowledge and policy decisions is a complex challenge. To address the disparity between scientific models and models used within a decision making context, techniques for merging the processes are needed.

We used a web-based software system Groundwater Decision Support System as a computer assisted dispute resolution tool (GWDSS) (Pierce, 2006; Cain et al., 2008). This is a graphic user interface (GUI) that provides a platform to incorporate elements common to an integrated assessment framework for the purpose of science-based decision support. The overriding premise in guiding project development holds that while multiple contexts exist for every complex decision problem, it may not be necessary for distinct models to be used to evaluate problems within both the policy realm and scientific domain. Physical process models that are at the heart of GWDSS are usually built as high-resolution models in space and/or time. In practice, models of different scales that emphasize different processes and/or outputs are needed to address distinct but related questions. Development for GWDSS is focused on creating, calibrating, interrelating, and optimizing the computational models to support policy dialogue. We selected the Barton Springs Aquifer as a test case. The objective of model development was the construction of a systems dynamics (SD) to emulate a spatially explicit numerical model for the test case groundwater system.

The Groundwater Availability Model (GAM) that had already been developed by the Barton Springs Edwards Aquifer Conservation District (BSEACD) (Scanlon et al., 2001, 2003) was used as the template for designing a systems dynamics (SD) model of the same region, but at lower spatial resolution, for rapid analysis purposes. Several interacting sub-process models (i.e., drought detection/land use models) were developed through a participatory modeling process with stakeholders. It is necessary for a DSS to yield compatible results, thus requiring calibration to a common 'base case'. For Barton Springs, we developed a scoping level groundwater model using a lumped parameter SD approach that maintains important spatial relationships within the broader context of socio-economic conditions and matches the general behavior of the MODFLOW model. Pumping and drought restrictions are determined by the BSEACD, which evaluates sustainable yield using the GAM developed with MODFLOW as a science-based planning tool (Smith & Hunt, 2004). The GAM represents the results of an effort to model Texas aquifers with a standardized, technically rigorous process. The resultant models are approved by the TWDB for use as an allocation and planning tool and identified by the Texas Legislature as the mechanism for determining the available yield for communities throughout the state. We define available yield as the volume of water that is considered acceptable for permitted extraction from an aquifer because it is scientifically feasible, within the bounds of effective yield quantification, and acceptable to the community of stakeholders. Effective yield is defined as the implementable and quantifiable volume of water that can be allocated from an aquifer regardless of stakeholder preference. We use the potential effective yields to define the feasible region for guiding dialogue with stakeholders about their preferences relative to aquifer response, the resultant election of a particular management alternative is a consensus yield that incorporates societal preferences within the context of expected groundwater behavior.

The Barton Springs GAM demonstrates a high sensitivity to recharge, limited response to changes in pumping, and two drains that represent drought sensitive springs. The model is constructed on a 120x120 grid with cell sizes of 1000 and 500 feet (300 and 150 m)in the *x* and *y* directions, respectively (Figure 3). Although the model assumes a continuous, porous media to represent a karstic system, the calibration results indicate adequate performance for use in management analyses (Scanlon et. al., 2001), at least for the conditions simulated. Scanlon et al. (2003) also state that discharge from the Barton Springs Aquifer can be simulated adequately using either equivalent porous media models or lumped parameter models.

Lumped parameter models can aid the negotiation process by providing a means for linking disparate systems to provide real-time feedback for scenario and hypothesis testing. Although the lumped parameter model for Scanlon et al. (2003) considered 5 hydraulic conductivity zones, calibration and testing during the early design phases for this project determined that effective replication of the spatially explicit GAM was best achieved using 11 zones, with each lumped-parameter zone corresponding to one of the 11, irregularly shaped, multi-celled zones of hydraulic conductivity within the GAM (Figure 3).

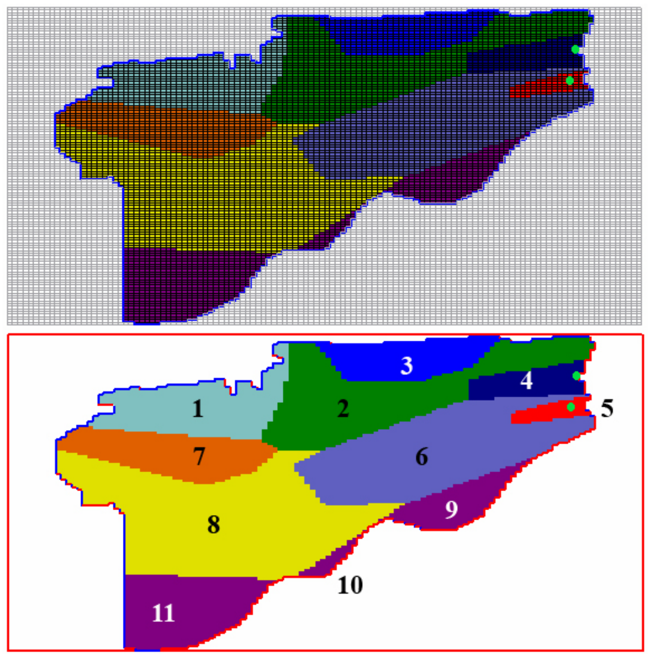


Figure 3: Top figure shows discretization of the GAM, which consists of 7036 active cells. The bottom figure illustrates the 11 zones used in the SD model.

Drought is one of the primary limiting factors in estimating available yield for the Barton Springs segment. The BSEACD designates an extreme drought withdrawal limitation to define a drought-period regulatory cap on pumping for periods when the sustained flow at Barton Springs is at or below 14 cfs (0.40 m^3sec^{-1}) on a 10-day running average basis. The BSEACD determined an allowed sustainable yield of 8.5 cfs (0.24 m^3sec^{-1}) as an aggregate withdrawal rate on an average annual basis with the goal of minimizing impacts on water wells, pumpage, and springflow at natural aquifer outlets, principally Barton Springs.

GWDSS (Cain et al, 2008) has interactive components that include screens for defining simple scenarios with a set of dashboards for land use distribution and density assignments (Figure 4), interactive map panes for adjusting pumping rates, and real-time viewing of results (Figures 5 and 6). Interaction with the application allows stakeholders to understand how land-use changes affect land value, sprawl, critical springflows, and well yields through the performance measures. Output screens display ranked results in both a table and graphical formats to aid comparison of results and provide tools to facilitate dialogue among stakeholders. The DSS showed that pumping in zones 6, 7, and 10 (Fig. 4) had the least effect on flow from Barton Springs. Pumping in zone 4 also had minimal effect on Barton Springs, but could affect a smaller set of springs, Cold Springs. In addition, building setbacks from streams was shown not to be an important factor. Aggressive pumping reduction strategies increase available yield and spring flow rates during drought conditions. Better recharge inputs, both spatial and temporal, and potential water quality variations at low flow rates are two important factors that should be considered in subsequent versions of the DSS.

4. CONCLUSIONS

This study demonstrated that it is useful to identify environmental and critical issues early, maintain a dialogue among affected communities and stakeholders, and develop performance measures that reflect stakeholder issues. Stakeholders reported that the narrative process allowed them to talk about their

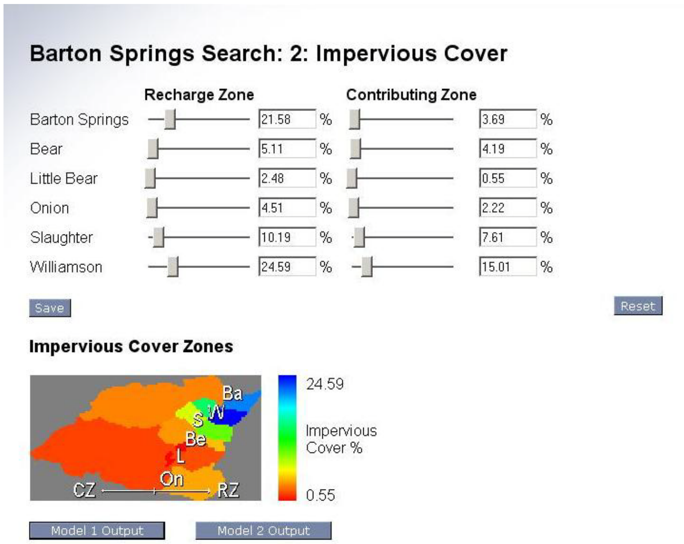


Figure 4: GWDSS land use distribution and density assignment screen for the Barton Spring project.

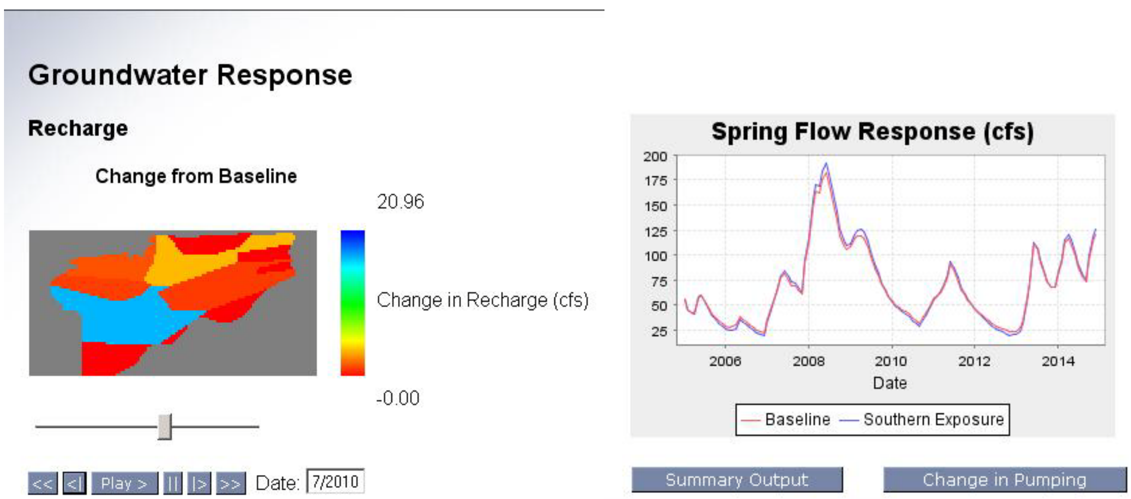
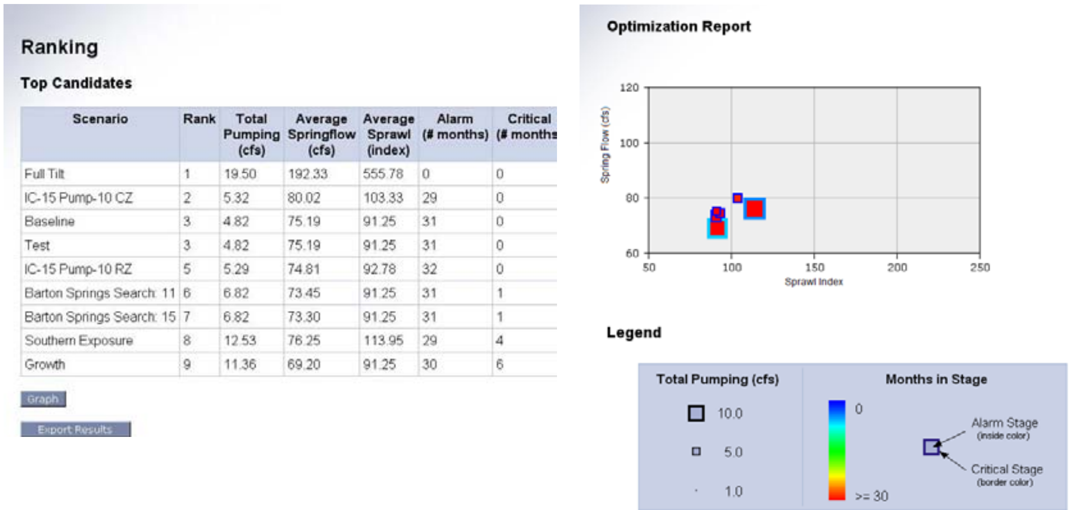


Figure 5: GWDSS interactive map panes for viewing dynamic output.

beliefs and concerns and to be sure that other stakeholders would hear them through the videos. Narrative elicitation using film proved to be a viable media during meeting, and narratives allowed for deeper understanding of stakeholder concerns. The DSS model is well suited for real-time discussions over consensus yield. The detailed model (i.e., the GAM) can be used to determine effective yield for the aquifer system. Combined, the two models can be used to evaluate a comprehensive available yield for the aquifer that is both scientifically credible and sustainable within the context of the community that depends upon the aquifer as a resource. The complexity of this combined scientific, management, and stakeholder process requires the definition of four different yields: available, consensus, effective and sustainable.



Scenario	Rank	Total Pumping (cfs)	Average Springflow (cfs)	Average Sprawl (index)	Alarm (# months)	Critical (# months
Full Tilt	1	19.50	192.33	555.78	0	0
IC-15 Pump-10 CZ	2	5.32	80.02	103.33	29	0
Baseline	3	4.82	75.19	91.25	31	0
Test	3	4.82	75.19	91.25	31	0
IC-15 Pump-10 RZ	5	5.29	74.81	92.78	32	0
Barton Springs Search: 11	6	6.82	73.45	91.25	31	1
Barton Springs Search: 15	7	6.82	73.30	91.25	31	1
Southern Exposure	8	12.53	76.25	113.95	29	4
Growth	9	11.36	69.20	91.25	30	6

Figure 6: GWDSS optimization results view.

Sustainable yield is the volume of water that can be extracted annually from the aquifer that can, in conjunction with other available water resources, sustain a reasonable human population. The project also sought a consensus yield, which is the acceptable extraction volume from an aquifer or aquifer systems as determined by the inter-related elements of the hydrologic regime within the context of the specific preference sets held by affected stakeholders. The effective yield is an implementable and quantifiable volume of water that can be allocated from the aquifer. This is deduced from standard scientific and engineering analysis. The simultaneous consideration of the stakeholder-derived consensus yield with the effective yield provides the available yield - the volume of water that is considered acceptable for permitted extraction from an aquifer that is: scientifically feasible; within the bounds of effective yield quantification; and acceptable to the community of stakeholders.

The GWDSS was developed for use in support of live, rapid dispute prevention/resolution sessions. Model sessions can be used for either community consensus or for setting policy strategies within the feasible ranges of social preference sets. The results represent a first approximation of model parameters that can be refined with time. GWDSS may be used as a platform to test a series of multi-disciplinary hypotheses and method comparisons, within areas of inquiry ranging from hydrogeology, economics, operational research, decision analysis, behavioral psychology, and public affairs. In addition, GWDSS is an aid to the consensus building process by engaging stakeholders in meaningful, science-based dialogue.

We developed a DSS that is an interactive tool for strategic planning and modeling for the Barton Springs/Edwards Aquifer Conservation District, as well as a platform upon which the components for a real-time rapid dispute prevention process can be based. The capabilities of the Barton Springs test case show that this DSS can be used to: 1) evaluate operational rules by the groundwater conservation district (GCD); 2) rank alternative management plans; 3) facilitate consensus building sessions with stakeholder groups; 4) conduct multi-model and method comparisons; and 5) identify general behavior trends or aquifer response to management related stresses.

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