Uncertainty and urban water recharge for managing groundwater availability using decision support

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ABSTRACT

Quantifying groundwater availability depends upon sound methods and the use of integrated models. To determine availability or sustainable yield, the influence of scientific uncertainty from key sources, such as anthropogenic recharge, must be considered. This study evaluates uncertainty in recharge interpretations on the modeled available water balance for an urban case in Texas, USA. Analyses are completed using the Groundwater Decision Support System, which is a research code-base for an integrated modeling. The case study develops spatially and temporally resolved recharge interpretations based on NEXRAD precipitation and detailed land use data. Results demonstrate the implications of scientific uncertainty as it influences recommendations for policy and urban water management decisions that are based on modeled outputs. Geospatial methods account for spatial and temporal components and can be replicated for other systems. These methods are also useful for resolving uncertainty in relation to the influence of urbanization on recharge through land use change.

Key words | decision support, groundwater availability, integrated assessment, sustainable yield, uncertainty, urban recharge

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INTRODUCTION

Calculation of the sustainable yield for a groundwater system requires the quantification of spatial and temporal components. As it relates to groundwater, sustainable yield is defined as the volume of water that can be extracted annually or for a given period from an aquifer or a groundwater basin that can, in conjunction with other available water resources, sustain a reasonable human population indefinitely at an acceptable standard of living and maintain critical natural habitats indefinitely. A key constraint in any estimate of sustainable yield is the relationship between pumping limits and long-term recharge rates. Human-induced changes in parameters, such as recharge, become critical for groundwater management (e.g. Alley *et al.* 1999; Pierce *et al.* 2013). Shifts in recharge conditions and the water balance for urbanizing systems are particularly difficult to quantify due to the heterogeneous nature of spatial conditions and rapid rate of land use change.

A broad and growing literature identifies a wide range of risk factors and complex interactions of variables and flows that represent urban influences on groundwater (see for example Starke *et al.* 2010 for recharge and evaporation; Barron *et al.* 2011 for water quality). The systems include many interdependent components in dynamic settings with a great deal of uncertainty about how the systems are interconnected. Pressures on water resources in urban areas are increasing and integrated systems models of comprehensive urban water budgets and flows are needed (Wolf *et al.* 2006). Integrated models that address urban infrastructure and groundwater models, such as Wolf *et al.* (2006) or Charalambous *et al.* (2012), address the interconnections of urban water infrastructure and present systematic approaches to evaluate possible management strategies. At the same time, integrated models have the potential to improve understanding about urban groundwater management options, and it is critical that embedded uncertainties within those models and their related influences on modeled outputs are assessed.

This paper looks at refining uncertainties in a sustainable yield calculation by addressing weak points in the scientific interpretation of recharge for an urban groundwater case. Quantifying and explicitly defining uncertainty within simulation models are needed to help user confidence in modeled outputs, particularly at the intersection between measured values and the limits of reliable predictions from

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models (Vezzaro et al. 2013). The study focuses specifically on contributions from epistemic uncertainty in relation to recharge calculations for a groundwater management case in central Texas. Epistemic uncertainty can be attributable to incomplete knowledge about a phenomenon versus the inherent uncertainty that cannot be easily reduced, which is frequently represented as stochastic or random behavior in models (Beven & Young 2013).

While a myriad of approaches for addressing uncertainty exist (see for example Bennett et al. 2013), these methods tend to involve complex steps that require subject matter expertise and rely on a series of assumptions or other challenges for practical interpretation of modeled outputs (Vezzaro et al. 2013). This study implements an approach for comparative analysis of uncertainty in a structured way with the goal of improving model performance for use in a decision support system to aid policy and operational yield recommendations for an aquifer. By understanding the nature, or source, of uncertainty in a modeled system, the influence of imperfect knowledge (epistemic uncertainty) related to aquifer properties can be reduced and the resultant recommendations may, therefore, be viewed with greater confidence.

A data-driven approach is implemented to develop four scientifically viable, or equally credible, interpretations of input values for recharge developed for the rapidly urbanizing area of the case study. Modeled responses using the original and 'best fit' recharge interpretations are simulated within a Groundwater Decision Support System (GWDSS). The original recharge interpretation (Recharge 1) was developed by Scanlon et al. (2001, 2003) using average springflow and pumping data to estimate total recharge and then distributing the recharge estimate spatially across the recharge zone according to previous studies (Slade 1985; Barrett & Charbeneau 1997). The approach for calculating a recharge input file was replicated using data for 1999–2009 (Passarello 2011) to create Recharge 1 as a baseline equivalent recharge file for use in comparisons.

A set of three additional approaches for quantifying recharge in the model horizon from 1999 to 2009 incorporated various interpretations of natural and artificial recharge contributions, as well as the addition of spatially distributed precipitation data from NEXRAD and updated land use surveys (summarized in Table 1). The 'best fit' recharge interpretation (Recharge 4) was selected for further use in the GWDSS evaluation. Recharge 4 recalculates natural recharge calculations with updated spatial distribution of stream recharge, NEXRAD precipitation data, and land use surveys for diffuse recharge. The calculation differs from other interpretations in the inclusion of diffuse recharge in cells that are overlain by altered land use, and the resultant model runs using the baseline simulation settings provided the best fit match with actual springflow data for the modeled time period.

Pumping regime solutions are evaluated between the Recharge 1 and 4 (original and 'best fit') interpretations using a non-classical optimization within the GWDSS (Pierce 2006). Results shed light on the influence of scientific interpretations in relation to land use and allocation policies, particularly for sustainable yield recommendations for the Barton Springs segment of the Edwards Aquifer (BSEA). Methodologies and the use of decision support tools are appropriate for advancing knowledge about integrated water resource connections in the context of urbanization, adaptive response, and decision making.

Table 1 | Recharge interpretations evaluated for use in models of the Barton Springs segment of the Edwards Aquifer

Interpretation	Modeled scenario	Description	Total recharge (TR)
Recharge 1	Baseline equivalent[a]	Original interpretation with inputs from losing streams and precipitation	TR calibrated with observed springflow
Recharge 2	Natural sources only[b]	Recalculated natural recharge uses spatial distribution of stream recharge, NEXRAD precipitation data, and land use surveys for diffuse recharge	TR = DR + SR
Recharge 3	Natural + Artificial[c]	Combines Recharge 2 estimate with updated anthropogenic inputs	TR = DR + SR + AR
Recharge 4	Altered Natural + Artificial[d]	Altered diffuse recharge calculation using an infiltration percentage of 6%	TR = DR* + SR + AR

SR, stream loss; DR, diffuse recharge; DR*, altered diffuse recharge; AR, leakage from utility lines and irrigation return flow.
Detail for data and settings used in each recharge interpretation from the following:
[a]Scanlon et al. (2001);
[b]Passarello (2011) and Passarello et al. (2012);
[c]percentages estimated within Wiles (2007) (21% for impervious cover) and Hauwert (2009) (32% for pervious cover);
[d]Barrett & Charbeneau (1997).

BARTON SPRINGS CASE STUDY

This study focuses on the region of the karstic Edwards Aquifer known as the Barton Springs segment, which is within and adjacent to Austin, Texas in the United States (Figure 1). The rapid urbanization of the city of Austin has caused concern about the potential for resulting water quality degradation and impacts to the water availability of the aquifer due to increased impervious cover and intensification of land use.

Hydrologically, the BSEA is generally separated from larger regional systems by no-flow boundaries, providing water to approximately 60,000 residents and with springs that serve as a natural habitat for an endangered species of salamander. Increased population and recent droughts in 1996 and 2009 have focused attention on groundwater availability and sustainability of flow at the springs. In response to the potential compromise of these vulnerable groundwater resources, several numerical groundwater flow models have been developed for BSEA to aid in aquifer management (e.g. Slade *et al.* 1985; Barrett & Charbeneau 1997; Scanlon *et al.* 2001; Smith & Hunt 2004; Painter *et al.* 2007).

The Barton Springs Groundwater Availability Model (BS GAM) developed by Scanlon *et al.* (2001) was the first state approved model for the aquifer and serves as a foundational version for comparison and method development. The BS GAM represents a baseline interpretation of groundwater behavior, the model is readily accessible, and the model can be used to compare the decision relevance of scientific uncertainty. At the same time, the BS GAM has various recognized limitations with a primary source of uncertainty in the understanding of data for the spatial and temporal distribution of recharge (Lindgren *et al.* 2009). For example, the BSEA is characterized by five major streams and two primary discharge points at Barton and Cold Springs (Hunt *et al.* 2007). Models of the system calculate flow at Cold Springs (between 15 and 20%) as a percentage of flow at Barton Springs (usually representing 80% of flow in the system). While Cold Springs is the secondary discharge point located northwest of Barton Springs and included in the BS GAM as a drainage cell, observational data for flow rates at Cold Springs are absent because the discharge point is flooded (Scanlon *et al.* 2001).

The original BS GAM model couples the discharge at Barton Springs with the calculation of effective recharge into the aquifer by capping inputs according to estimated pumping and springflow data (Scanlon *et al.* 2001) and a

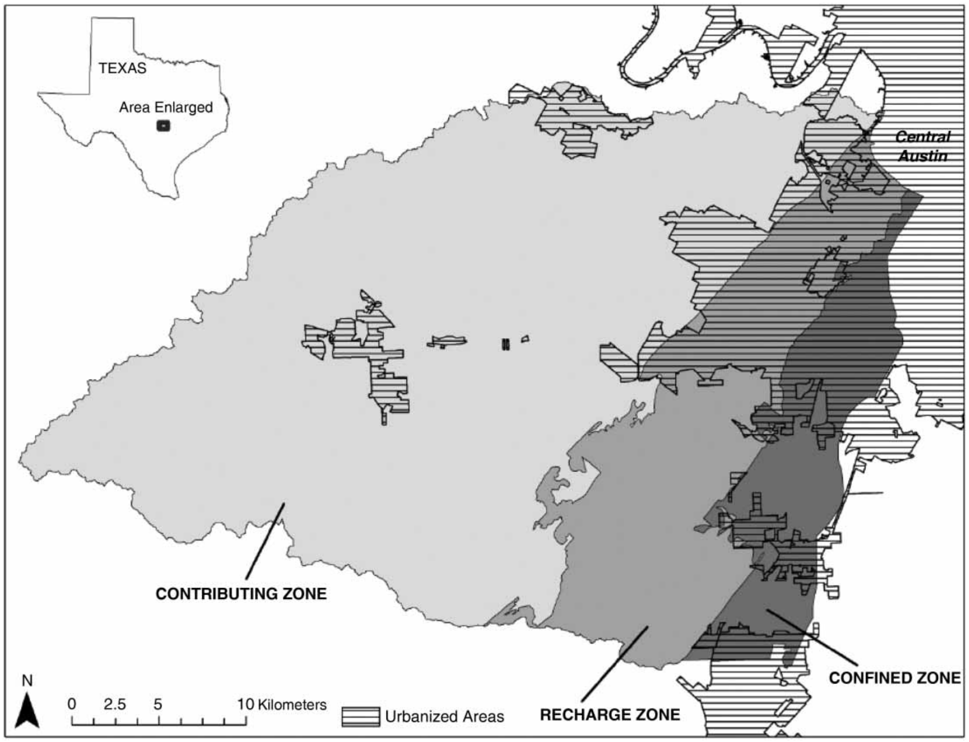

Figure 1 | Location of the Barton Springs segment of the Edwards Aquifer indicating extent of urbanized areas and recharge zone boundaries used in availability models (from Passarello *et al.* 2012).

subsequent model by Smith & Hunt (2004) incorporates the same recharge calculation. Therefore, the resulting BS GAM simulation uses observed springflow at Barton Springs as a primary performance measure while also using the same observed dataset to generate input values for recharge; this result creates a mutually dependent method (i.e. circular logic). One of the goals of the study presented here is the development of methods for calculating recharge for the BS GAM that are reliable and representative of actual conditions.

METHODS

This study revises the scientific interpretation of recharge for the BS GAM and evaluates the importance to decision criteria for assessing sustainable yield and pumping regimes. In particular, recharge input interpretations are decoupled from discharge to increase fidelity of the inputs with observed data and reduce uncertainty propagation through the model. The updated interpretation is used then to evaluate implications for relevant policy recommendations using spatially zoned pumping decisions and springflow response.

RECHARGE INTERPRETATION SCENARIOS

Numerous studies assess the physical and chemical characteristics of natural recharge processes and impacts of urbanization on surface water and groundwater for Austin, Texas (Krothe 2002; Garcia-Fresca & Sharp 2005; Wiles & Sharp 2008; Wiles 2007; Christian *et al.* 2011). Results of previous inquiries have generated a rich interpretation and understanding of natural and human-induced processes that control aquifer recharge. This research combines the scientific knowledge about recharge in the case area with computational tools to assess the significance of urban-induced recharge in relation to policy and management considerations.

The objective of this portion of the study is to reinterpret spatial and temporal distribution of recharge to reflect various interpretations that are derived from more recent scientific study of the region (Barrett & Charbeneau 1997; Wiles 2007; Hauwert 2009). Each of these studies reflects an equally credible interpretation of observed information and data for the Barton Springs segment. Using results of the recharge reinterpretation, a water budget analysis reveals that artificial recharge can constitute as much as 52% of the overall water budget for the Barton Springs segment under dry, or drought-like, conditions (see Figure 2).

All human-induced recharge is important for habitat conservation planning, because contributions maintain flows during critical drought periods for the case aquifer as shown in Figure 2 (Passarello 2011). A set of four recharge interpretations or model scenarios were constructed to test the effects and relevance in the modeled period from 1999 to 2009 as summarized in Table 1. Recharge interpretations differed in the methods for quantifying recharge inputs and distributing these values within the BS GAM.

The interpretation, called Recharge 1, quantified inputs from losing streams and precipitation data. The analyses included estimates of actual infiltration with improved spatial distribution across the recharge zone and input total recharge rate estimates that corresponded with observed measurements of springflow and pumping (Scanlon *et al.* 2001, 2003). The methods reported for determining recharge in the BS GAM model development (e.g. 1989–1998) are described in detail by Scanlon *et al.* (2001). These calculations were replicated to create a baseline equivalent recharge file using average recharge and pumping data for 1999–2009 (Passarello 2011).

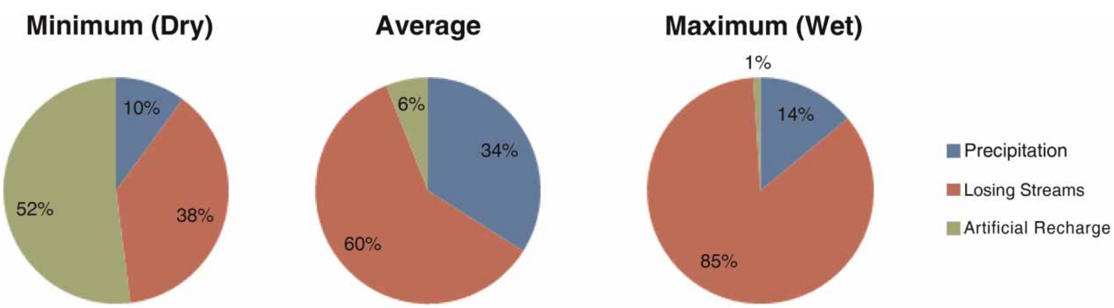

Figure 2 | Comparison of the relative contributions to recharge from artificial and natural sources during dry, average, and wet conditions for the Barton Springs segment of the Edwards Aquifer.

Interpretations of Recharge 2, 3, and 4 incorporate geospatial analysis to decouple recharge quantification from springflow through combinations of (1) integrated assessment of land use change through time, (2) precipitation calculations with temporal and spatial resolution, and (3) incorporation of three key sources of artificial recharge (leakage from water lines, leakage from wastewater lines, and irrigation return flow).

The interpretation, called Recharge 2, quantified and refined components from natural recharge using a combination of spatial analyses and incorporating new scientific interpretations. For example, Recharge 2 uses precipitation data from NEXRAD and updated land use survey information from the City of Austin, which were previously unavailable.

The Recharge 3 and 4 interpretations incorporated artificial recharge, which for the purposes of this study include human-induced recharge from treated water, wastewater, and irrigation return flow (based on infrastructure and treatment datasets from Austin Water Utility). Leakage from water lines, leakage from wastewater lines, and irrigation return flow are used to determine the monthly volumes of recharge for each anthropogenic contributor, but do not have spatial considerations. Consequently, a series of spatial analyses were used to distribute these recharge volumes across the recharge zone (see Figure 1) as modeled in the BS GAM.

In the case of the Recharge 3 interpretation, direct recharge from precipitation was determined using infiltration factors from previous research (Wiles 2007; Hauwert 2009), along with monthly precipitation volumes calculated using NEXRAD and land use datasets. Whereas, Recharge 4 interpretation differed from Recharge 3 only in the diffuse recharge calculations. The results from model scenarios using Recharge 3 suggest that diffuse recharge is overestimated, although the estimates are based on field measurements. However, it is likely that these values are site specific and should be scaled up only with great caution. Consequently, the greatest influence of uncertainty in terms of recharge sources is diffuse recharge due to its significance from a volumetric standpoint and the poor understanding of infiltration percentages.

Therefore, a lower infiltration percentage was applied for Recharge 4 using an infiltration rate of 6% (Barrett & Charbeneau 1997), because this infiltration percentage is based upon sampled data (soil and vegetation types, topography, etc.) and was independent from Barton Springs discharge. Thus, the goal of decoupling recharge calculations from Barton Springs discharge could be achieved. Complete decoupling is ultimately not achieved, because the accuracy of the model scenarios is based on how well they can simulate Barton Springs discharge, but these recharge inputs are not calculated from Barton Springs discharge data as previous methods have done.

Figure 3 shows that the new methods generated good agreement amongst simulated and observed (A) discharge (root mean square error, or RMSE, of 0.5 $m^3 s^{-1}$) and (B) water-level elevations (RMSE of 10.5 m). Additionally, these recharge calculations are decoupled from observed values for Barton Springs discharge, which eliminates the circular logic with the previous methodology. The Recharge 4 interpretation, or Altered Natural + Artificial Recharge scenario, proved to be the most accurate at simulating Barton Springs discharge and water-level elevations for the study period. Consequently, the results of the GWDSS analyses are presented as a comparison between the Recharge 1, Baseline Equivalent, and Recharge 4, Altered Recharge.

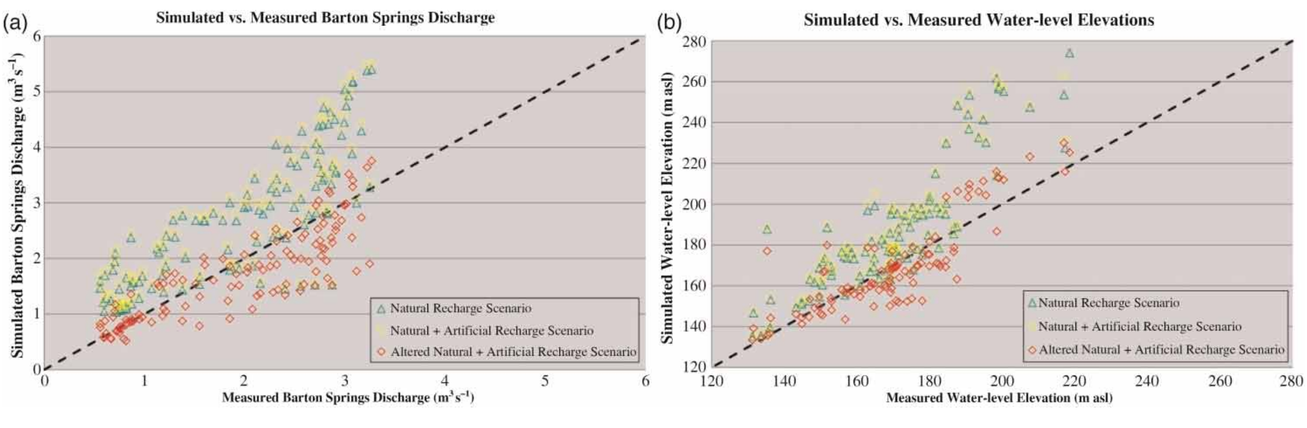

Figure 3 | Plot of simulated versus measured Barton Springs discharge (a) and water-level elevations (b).

GROUNDWATER AVAILABILITY MODELING AND DECISION SUPPORT

Using the improved interpretation of recharge, groundwater management is evaluated by comparing modeled response to various pumping regimes (see Figure 4 for pumping zone map). Estimates of recharge quantities and distributions for Recharge 1 and 4 were input into a GWDSS with the process-based BS GAM embedded.

The GWDSS application used in this study is a hybrid decision support system that links numerical groundwater simulations with non-classical tabu search optimization (Pierce 2006; Pierce *et al.* 2006). A set of candidate solutions was generated using the simulation–optimization features of the GWDSS to evaluate possible recommendations for sustainable yield calculations and determinations for available yield decisions.

The decision problem formulation was created to maximize the available yield for a 10-year modeled period. Available yield is 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 (Pierce *et al.* 2013). In this case, one goal of the region is to assure that extraction does not exceed the sustainable yield while optimizing the effective yield (or pumping regime). The effective yield, or operational pumping allocation, was represented as a set of 11 decision variables in pumping and land use zones that roughly coincide with different hydraulic conductivities in the aquifer. Pumping decision variables change discharge rates or spatial reallocation of pumping. Sustainable yield is quantified as the maximum water availability within the aquifer as a rate of extraction. The objective function is represented as the sum of all pumping throughout the entire modeled period of 10 years in 120 monthly timesteps.

GWDSS was used to generate an initial set of 10,256 candidate solutions with the original scientific interpretation of recharge (Recharge 1) and the accepted BS GAM. Subsequently, the candidate solution set was re-run using the same settings except for the spatially and temporally resolved recharge interpretation (Recharge 4). The updated Recharge 4 interpretation successfully converged to a full solution for 9,353 simulation runs within GWDSS; other runs did not converge.

Results from the GWDSS execution provide a set of high-performing solutions based on a sustainable yield decision problem formulation that was used to allow for maximizing pumping rates within the groundwater system. Comparisons across the datasets and this simple decision problem formulation reflect the frame of this research in terms of identifying robust allocation and management recommendations to delineate sustainable and operational yields for the aquifer.

RESULTS AND DISCUSSION

When modeled outputs are used in a decision support context, the scientific interpretation of parameters and inputs determines the recommendations for management and policy actions. This research demonstrated a reduction in scientific uncertainty in the key input component for a groundwater system. By using an integrated representation of natural and anthropogenic recharge components, input values for the

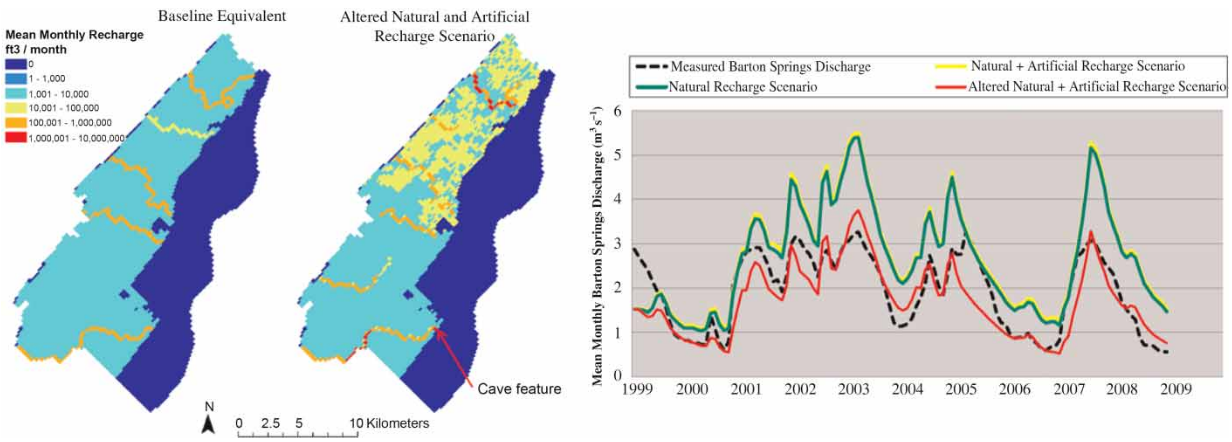

Figure 4 | Comparison of mean monthly recharge distributions between the Baseline (left map) and Altered Natural + Artificial Recharge (right map) interpretations. The Altered Recharge interpretation incorporates urbanized cells that reflect artificial recharge sources (yellow) and conduit recharge features (red), such as caves. Please refer to the online version of this paper to see the figure in colour: http://www.iwaponline.com/wst/toc.htm.

groundwater model reflect actual conditions more closely. Interestingly, results indicate that anthropogenic contributions from water and wastewater lines can be more significant than irrigation return flow in relation to the overall available yield during times of drought. The relative contribution to overall water budget from anthropogenic sources is dependent upon the time of year and consequently the demand for irrigation. It is also important to note that total anthropogenic recharge can be greater than direct recharge from precipitation. Outcomes are relevant for habitat conservation and drought response planning.

Performance measures show that the *a priori* representation of observed data, in this case using the modified recharge interpretation, resulted in improved results. For example, change in storage was calculated by subtracting total discharge (springs + pumping) from total recharge. Results indicate that the Recharge 1 – Baseline and Recharge 2 – Altered Natural + Artificial Recharge scenarios had decreases in storage by approximately -2.8×10^8 and $-1.5\times10^8\,m^3$ (-9.9×10^9 and $-5.3\times10^9\,ft^3$) over the 10-year study period, respectively. The other scenarios observe an increase in storage of approximately 1.7×10^8 and $2.0\times10^8\,m^3$ (6.0×10^9 and $7.1\times10^9\,ft^3$) over the 10-year study period, respectively. In reality, there is probably close to no change in storage, and water-level elevations have not demonstrated long-term declines.

Comparative analysis of modeled response in a decision support system enables evaluation of the necessary level of complexity in scientific interpretations (in this case across recharge). Improved handling of uncertainty can aid the selection of policies for groundwater pumping and management under extreme drought or climate conditions.

Simulated outputs from the GWDSS and a water balance analysis demonstrate that expected groundwater behavior can be matched more closely using the updated scientific interpretations. Results also provide preliminary information for pumping as shown in Figure 5. Optimization results indicate that the revised recharge analysis favors a reduction in the overall sustainable yield for the 10 year model period this aquifer, from an estimated $5.9\times10^7\,m^3$ ($2.1\times10^9\,ft^3$) to a $5.7\times10^7\,m^3$ ($2.0\times10^9\,ft^3$) for the set of candidate solutions that used the modified recharge (Recharge 4). Upon inspection, the GWDSS results demonstrate that pumping on the far east side of the system in

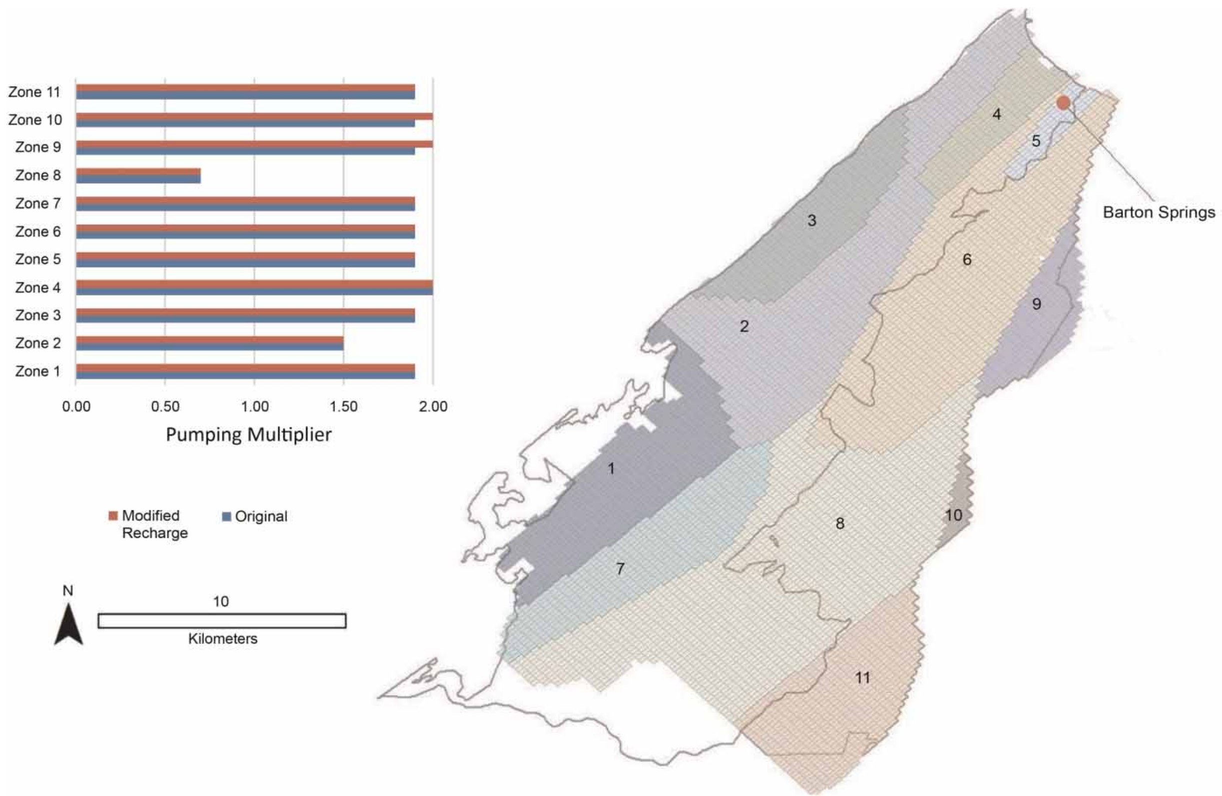

Figure 5 | Pumping zone map for model of the Barton Springs segment of the Edwards Aquifer and comparison of average multiplier settings and pumping intensities for a candidate solution set generated with a Decision Support System.

zones 10 and 9 (see Figure 5) is more productive in the revised recharge scenario than the original estimates, while other zones maintained the equivalent pumping levels. These results have implications for urban water management, because pumping centers are located near dense areas for land use. Therefore, groundwater managers can use the modeled outputs from the GWDSS to guide permitting and extraction policies. At the same time, this aquifer has a recognized bad water line to the east, so that potential saline encroachment could be incurred with increased pumping in those zones. This result demonstrates that further refinement of the optimization constraints is needed to reflect additional vulnerabilities. The results can inform city planners to aid in developing land use intensity and zoning requirements that encourage or incentivize urbanization intensities and population densities in alignment with the relative productivity of zones within an aquifer system.

CONCLUSIONS

Methodologically, this paper presents a comparative analysis between scientific interpretations of key input values for a groundwater system to assess the relevance of scientific uncertainty for decision making based on the modeled outputs. For the case study, recharge estimates were refined spatially and temporally so that model inputs could be successfully decoupled from discharge data. Preliminary results demonstrate that changes in the scientific interpretation influence the resultant yield estimates and recommended pumping intensities in some zones within the aquifer. The method and approach merit further development prior to implementation by policy makers for the case study aquifer. Assessing the decision relevance of scientific uncertainty and implications for urban water management through decision support methods can provide a useful process for identifying more robust groundwater management strategies.

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