

Simulation-optimization approach to assess groundwater availability in Refugio County, TX

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Abstract Sustainable management of groundwater resources is critical for viable development of semi-arid regions. Refugio County, TX, is predominantly a rural community that is in close proximity to two large urban areas of Corpus Christi and San Antonio. Large-scale water supply projects are being planned to export surplus water available in Refugio County to nearby growing cities. Being a coastal county with several sensitive bays and estuaries, these projects have caused concerns with regard to decreases in freshwater inflows to coastal bodies and raised the possibility of saltwater intrusion. A simulation model characterizing groundwater flow in the shallower unconfined and the deeper semi-confined formations of the Gulf coast aquifer was calibrated and evaluated. The model results were used in conjunction with a mathematical programming scheme to estimate maximum available groundwater in the county. Stakeholder concerns were incorporated as constraints, which included prevention of saltwater intrusion in the aquifer, limiting the amount of allowable drawdown in shallow aquifers, as well as maintaining current flow gradients especially near baseflow-dependent streams and rivers. For the conditions assumed in this study, the model results indicate that roughly $4.93 \times 10^7 \text{ m}^3$ of water can be extracted in a typical year. The management model was noted to be very sensitive to the imposed saltwater intrusion constraint.

Keywords MODFLOW · Linear programming · Multi-aquifer system · Coastal aquifers · Sustainability · Texas · USA

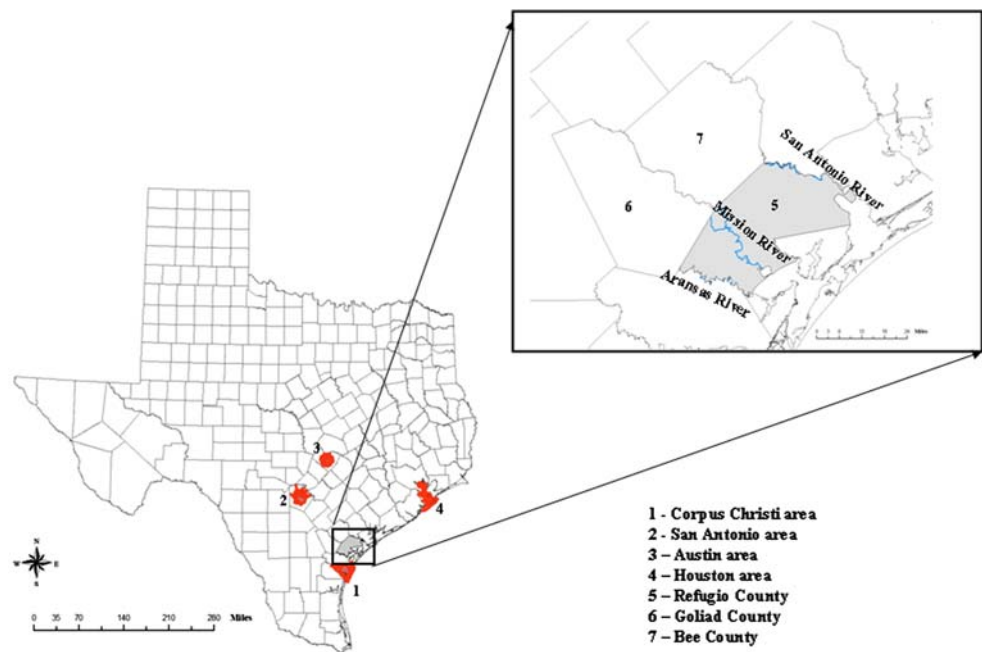
Introduction

Aquifers are a reliable source of water supply and less affected by droughts and other climatic anomalies. As such, groundwater resources are considered very valuable in arid and semi-arid regions that exhibit large-scale climate variability. Groundwater in Texas has traditionally been viewed as a private resource and not subject to regulations. However, in recent years, there has been a greater emphasis on managing the aquifer through the formation of publicly elected groundwater conservation districts (GCDs). GCDs are mandated by law to ascertain the existing amount of usable groundwater within their jurisdiction (Texas Administrative Code Chapter 36§5). Estimating the amount of groundwater requires a thorough understanding of the hydrogeological characteristics within the district. In addition, estimates of groundwater availability also depend upon risk-taking attitudes and perceptions of the various decision makers and stakeholders involved (Mace et al. 2001).

Refugio County is predominantly a rural community in the coastal bend region of South Texas that is in close proximity to the fast-growing urban centers of San Antonio and Corpus Christi (Fig. 1). Although the existing water demands in the county are low and can be easily met with available groundwater, several export-oriented large-scale water supply projects are being planned in this region (GBRA 2005). Being a coastal county with several sensitive bays and estuaries,

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Fig. 1 Schematic of the study area



these proposed water supply projects have raised concerns with regard to decline in freshwater inflows to bays and estuaries and the possibility of saltwater intrusion. In addition, Mission River is a small yet ecologically important river flowing within the county whose flows are largely sustained by groundwater discharges. There is also considerable apprehension among several stakeholders that improper pumping of groundwater could affect baseflows in Mission River and endanger its aquatic ecosystem.

Simulation-optimization schemes provide a useful framework to manage groundwater resources as they effectively couple hydrogeological models with management paradigms (Ahlfeld and Mulligan 2001). As such, this approach has been utilized in several groundwater resources management studies across the world (Shamir et al. 1984; Willis and Finney 1988; Finney et al. 1992; Emch and Yeh 1998; Zhou et al. 2003). Simulation-optimization technique is considered well suited for aquifer management activities in Refugio County, TX, as it can objectively assess available groundwater while incorporating stakeholder concerns as appropriate constraints. Therefore, the goal of this study was to develop a groundwater flow model and use it to formulate an optimization model to estimate the amount of groundwater available in the county.

Hydrogeological setting of the study area

Refugio County, TX, is bounded by Aransas River in the south and San Antonio River in the north (Fig. 1).

The eastern section of the county is bounded by several bays and estuaries in the Gulf of Mexico including Mission Bay, Copano Bay, San Antonio Bay and Hynes Bay. The western parts of the county are bordered by Bee and Goliad counties. The topographic relief within Refugio County is characterized by a relatively flat terrain that ranges from roughly 21.34 m in the west to about a meter above mean sea level near the coast and slopes at roughly 0.38 m/km from west to east. The Fleming formation is of the Miocene series and tertiary age and acts as the bottom confining unit. It is locally referred to as Burkeville formation (Baker 1979). This aquitard is overlain by unconsolidated deposits from Tertiary and Quaternary age and includes Goliad sand formation, Lissie formation and Beaumont formation. Alluvium deposits from the Holocene series can also be found in a few places. The older Goliad sand formation largely outcrops in the adjoining Bee and Goliad Counties and is also visible in the northwestern sections of Refugio County. However, most of the county is covered by Beaumont and Lissie formations which are interbedded deposits of clay and sand (Mason 1963). The stratigraphic structure is presented in Fig. 2 and from a functional standpoint the Gulf Coast aquifer in Refugio County can be roughly divided into two major formations: the unconfined Chicot formation consisting mostly of Beaumont and upper Lissie formation is assumed to extend to about 152.40 m (500 ft) below ground surface; the deeper aquifer consisting of lower Lissie and Goliad formation is also referred to as the Evangeline formation which is known to be in good hydraulic

Fig. 2 Stratigraphic structure of the gulf coast aquifer in Refugio county, TX (after Mason 1963)

System	Series	Geologic unit	Description	Hydrologic unit	Model layer
QUATERNARY	HOLOCENE	Flood-Plain Alluvium	Sand, gravel, silt and clay	BEAUMONT/LISSIE SAND	CHICOT
		Fluvial Terrace Alluvium	Sand, gravel, silt and clay		
	PLEISTOCENE	Beaumont formation	Sand, silt, clay, clayey loam and fine sandy loam		
		Lissie formation	Sand, silt, clay, fine sandy loams		
TERTIARY	PLIOCENE	Goliad sand	Fine to coarse sand and conglomerate, calcareous clay, basal medium to coarse sand stone	LISSIE/GOLIAD SAND	EVANGELINE
	MIOCENE	Fleming formation	Calcareous clay and sand	HURKEVILLE AQUICLUDE	

contact with the upper Chicot layer within the county (Chowdhury et al. 2004) and is modeled as a semi-confining unit.

Groundwater recharge within the administrative boundaries of the Refugio County occurs via direct precipitation. The average annual rainfall in the county is approximately 762 mm (NWS 2003). Roughly 2% of this rainfall was estimated to recharge the aquifer using approaches suggested by Beekman and Xu (2003). Recharge to the deeper Evangeline aquifer within the Refugio County occurs via groundwater inflows from adjoining Bee and Goliad Counties in the west. Hydrograph separation using the USGS HYSEP program (Pettyjohn and Henning 1979) indicated that the major surface water bodies within the county act as gaining streams for most of the year and as such do not significantly recharge the aquifer. However, groundwater discharges sustain the flows in these streams, especially during dry summer months.

Numerical model of the groundwater flow system

Based on the existing hydrogeological conditions within the county, a three-dimensional numerical flow model was set up using the MODFLOW 2000 model (Harbaugh et al. 2000) available within the Groundwater Modeling Software (GMS V4.0, EMS-I Corp., Provo, UT, USA). The San Antonio River was used as the northern boundary and the Aransas River the southern boundary. A general head boundary condition was imposed along the western sections of the

county and a constant head equal to the mean sea level datum was specified along the eastern section of the model domain to simulate the coastal boundary. The cross-section of the aquifer was discretized into two layers with the upper section extending from ground surface to 152.40 m to conceptualize the unconfined Chicot formation. The semi-confined Evangeline formation was assumed to be 182.88 m thick, on average, based on hydrostratigraphic delineations presented by Baker (1979). The entire domain was discretized into 18,605 cells using a cell size of 0.32 km × 0.32 km.

Very little information was available to rigorously identify areal variations in hydrogeological properties. As such, these properties were assumed to be uniform in this preliminary assessment to minimize subjectivity and the associated parametric uncertainty. The effective hydraulic conductivity values for the Chicot and Evangeline formations, the general head conductance, as well as the river bed conductance values for Aransas and San Antonio Rivers, were identified via model calibration. As the aquifer is not significantly stressed, steady-state flow conditions were assumed to exist. Recent simulations with transient models have further corroborated the validity of this assumption (Jones 2005).

Automatic model calibration was carried out using PEST software (Watermark Computing Inc., AU). A total of 25 calibration wells were employed as a trade-off between computational tractability and the ability to obtain a realistic representation of regional hydrogeology. The selection of wells was based on data availability as well as ensuring a uniform distribution

across the county and in both aquifer formations. The evaluation of the model performance was carried out by visual inspection as well as quantitatively checking the predictive capabilities of the model at 10 other observation wells not included in the calibration process.

The relationships between observed heads and model-computed values at calibration wells and in evaluation wells are presented in Figs. 3 and 4, respectively. The root mean square error was less than 3.05 m and the absolute mean error was close to 2.13 m for calibration wells. The *Z*-score is the ratio of the residual standard deviation to the range in heads and is an indicator of model goodness-of-fit. This score was calculated to be 0.11 for calibration wells and values in the range of 0.1–0.15 are considered reasonable for good calibrations (ESI 1996). The root mean square error and the absolute mean error were roughly 2.59 and 2.04 m, respectively, in the evaluation wells used for independent checking of the model. Two-dimensional contour plots of the water table elevation in the Chicot formation and the potentiometric surface of the Evangeline formation are depicted in Fig. 5. The simulated flow direction mimics the topography and is consistent with observed groundwater levels. As general head boundaries can act as an infinite source of water (Anderson and Woessner 1992), the reasonableness of the calibrated general head conductance values was evaluated by identifying three wells along the western section of the boundary in the adjoining Bee and Goliad Counties and computing the groundwater flux using Darcy's law (Pinder et al. 1981). The model-predicted flux across this boundary compared well (within half-an-order of magnitude) to the observed flux and provided another check for model calibration. The values for the calibrated model parameters presented in Table 1 were also noted to be

similar to those obtained from other previous regional-scale modeling efforts (Waterstone 2002), further increasing the confidence in the calibrated model.

A groundwater flow budget was developed using the calibrated model and is presented in Fig. 6. The flow budget indicated that the annual recharge to the county was approximately $7.406 \times 10^6 \text{ m}^3$ per year under unstressed conditions. Most of this recharge occurs due to the movement of water from the adjoining counties. The water budget calculation also suggests that a majority of this water is currently being discharged to coastal bodies. Additional pumping will cause water to be drawn from the adjoining counties and may reduce the available groundwater in these counties especially when newer wells tap into the more prolific formations along the western sections of the Refugio County. Pumping near the coast will reduce the amount of water discharging into the coastal bodies and may also cause a reversal of gradients and lead to further intrusion of seawater inland under extreme stresses. Effective management of the aquifer is therefore necessary to ensure these externalities do not actually occur.

Optimization model for groundwater management

As per the Texas Administrative Code (TAC Chapter 36), the groundwater management within the Refugio GCD must effectively reconcile the competing objectives of identifying groundwater resources available for promoting economic growth while ensuring such activities are not harmful to the environment. Economic growth is assumed to be directly proportional to the amount of groundwater that can be extracted from the aquifer. The major environmental concerns include the possibility of saltwater intrusion across the eastern

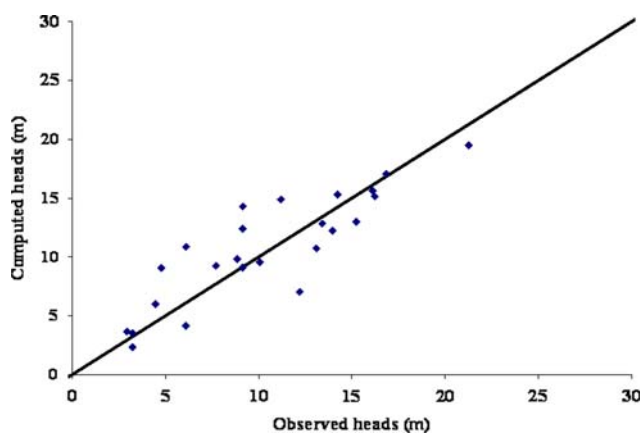


Fig. 3 Observed and predicted heads at calibration wells

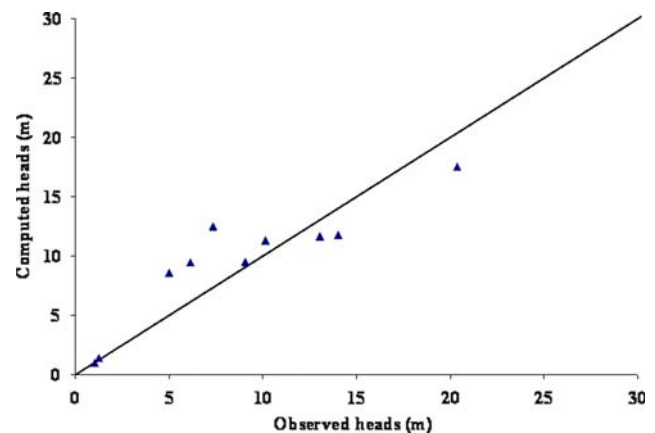


Fig. 4 Observed and predicted heads at evaluation wells

Fig. 5 Predicted groundwater heads in Chicot and Evangeline formations

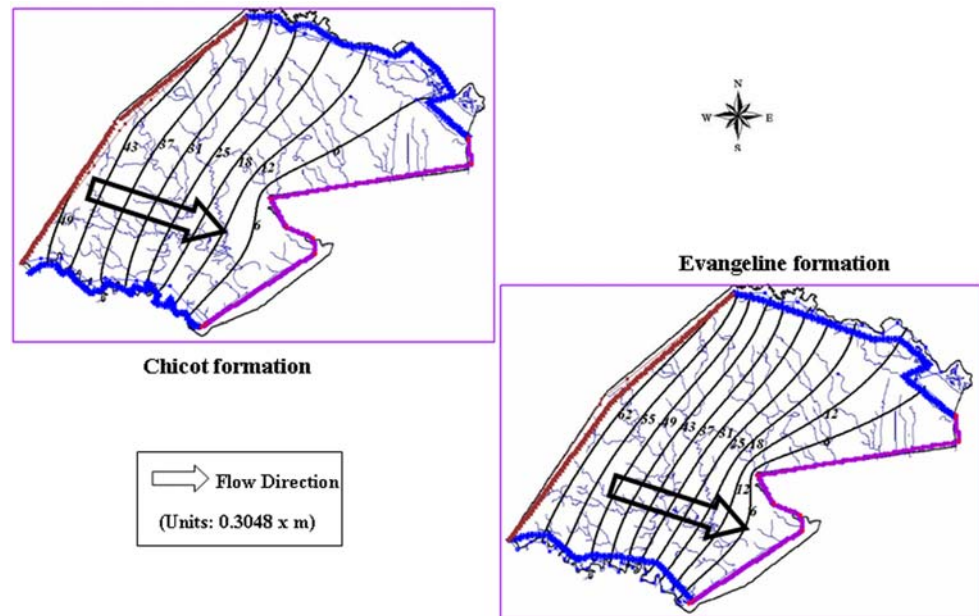


Table 1 Calibrated values for various input parameters

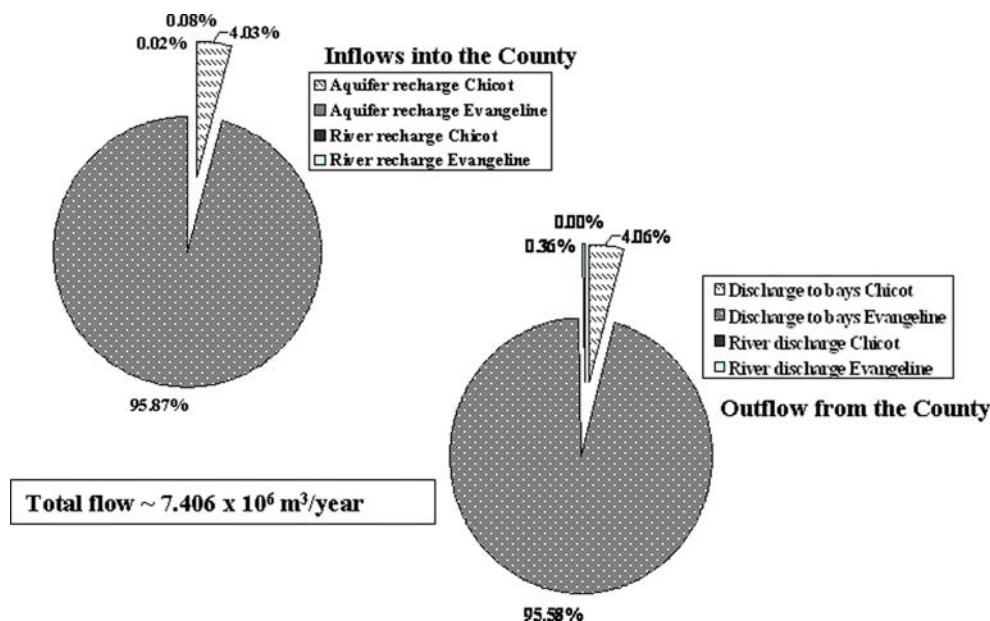
No.	Parameter	Layer	Calibrated value	Unit
1.	General head conductance	Chicot	4.05	(m ² /day)/m
2.	General head conductance	Evangeline	393.80	(m ² /day)/m
3.	Recharge	Chicot	1.52E-05	m/day
4.	Horizontal hydraulic conductivity	Chicot	0.24	m/day
5.	Horizontal hydraulic conductivity	Evangeline	3.05	m/day
6.	Vertical hydraulic conductivity	Chicot	3.05E-05	m/day
7.	Vertical hydraulic conductivity	Evangeline	3.05E-05	m/day
8.	Aransas river head conductance	Chicot	0.68	(m ² /day)/m
9.	Aransas river head conductance	Evangeline	0.22	(m ² /day)/m
10.	San Antonio river head conductance	Chicot	0.01	(m ² /day)/m
11.	San Antonio river head conductance	Evangeline	0.31	(m ² /day)/m

section of the county, reversal of groundwater gradients particularly near streams and creeks and excessive drawdowns, especially in the shallow aquifer, that restrict the use of windmills and limit the ability to withdraw groundwater in remote ranch locations that may not have ready access to power lines.

In light of the above discussion, a management model was developed with the objective of maximizing the amount of water that can be pumped from the two aquifer formations. As Evangeline aquifer is considered to be more prolific than Chicot formation (Mason 1963), a set of 50 management wells (10 in shallower Chicot formation and 40 in the deeper Evangeline formation) were uniformly distributed within the county to simulate future pumping from the aquifer. A set of 10 monitoring wells (M1,..., M10) was set along the coast and the hydraulic heads in these wells were constrained to be greater than the mean sea level to

prevent saltwater intrusion. Four couplet wells (R1–R2, R3–R4, R5–R6, R7–R8) were placed near Aransas, San Antonio and Mission Rivers to ensure the hydraulic gradient near these streams is not altered due to pumping. Similarly, a set of three well couplets (C1–C2, C3–C4, C5–C6) was used to prevent future pumping from altering regional flow gradients. In addition, the drawdown near the vicinity of the pumping well was constrained so as not to exceed a fraction of the initial head. A baseline value of 25% was assumed for this fraction and varied up to 75% in sensitivity runs. A linear response function correlating the drawdown behavior at the monitoring wells to pumping at the management wells was established by sequentially specifying a unit discharge in each management well and running the simulation model to obtain the necessary drawdown. The total drawdown at each well due to simultaneous pumping at all man-

Fig. 6 Groundwater budget for the county depicting various inflows and outflows



agement wells was obtained through the application of superposition principle. The superposition principle and the linear response functions strictly hold true in confined aquifers but can also be applied with little loss of accuracy in unconfined formations when the pumping is not high (Ahlfeld and Mulligan 2001). The linear response functions obtained for unconfined Chicot formation were noted to predict the hydraulic heads with a high degree of accuracy for the levels of pumping considered here (coefficient of determination $r^2 > 0.98$) and as such did not affect the accuracy of the management model. Mathematically, the management model can be represented as follows:

$$\text{Max} : \sum_{i=1}^{i=50} Q_i \tag{1}$$

subject to:

$$H_{MW,j,k} \geq (\text{MSL} - \Delta) \quad \forall j = 1, 2 \text{ and } k = 1, \dots, 10, \tag{2}$$

$$H_{C,i,j} - H_{C,i,k} \geq 0 \quad \forall i = 1, 2 \text{ and } j, k = \{1, 2\}; \{3, 4\}; \{5, 6\}, \tag{3}$$

$$H_{R,i,j} - H_{R,i,k} \geq 0 \quad \forall i = 1, 2 \text{ and } j, k = \{1, 2\}; \{3, 4\}; \{5, 6\}; \{7, 8\}, \tag{4}$$

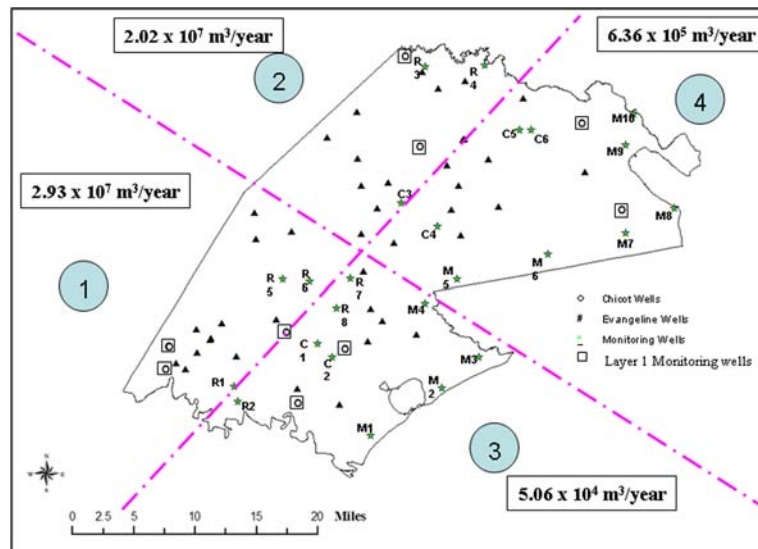
$$H_{L,i,j,0} - H_{L,i,j} \leq 0.25H_{L,i,j,0} \quad \forall i = 1, \dots, 10; j = 1, \dots, 4, \tag{5}$$

$$Q_i \geq Q_{\min,i} \quad \forall i = 1, \dots, 50. \tag{6}$$

Equation 1 represents the objective of maximizing the amount of groundwater that can be safely pumped (Q) from the aquifer. The prevention of saltwater intrusion is captured in Eq. 2, where hydraulic heads (H) monitored at 10 locations along the coast (MW1,..., MW10) in Chicot and Evangeline aquifers ($j = 1, 2$) are assumed to be below specified head ($\text{MSL} - \Delta$), where MSL is the height of the mean sea level from a pre-specified datum (equal to zero when mean sea level is used as the datum) and Δ is the magnitude of the water depth in the coastal monitoring well below the sea level that can be tolerated. The value of Δ was taken to be equal to zero in the baseline case and varied to up to 1.52 m in sensitivity runs to incorporate natural tidal fluctuation of water levels in the Gulf coast.

As noted previously, the groundwater flow in the aquifers is from west to east. One important management objective was to ensure that any future groundwater development should not cause an alteration to this regional flow direction. A set of three well couplets each in Chicot and Evangeline formations ($i = 1, 2$) was selected at different locations (C1, C2, C3, C4, C5, C6) as depicted in Fig. 7 to enforce the constraint that the heads in the western section (i.e., at C1, C3, C5) were greater than the corresponding wells on the eastern side (i.e., at C2, C4, C6) as mathematically stated in Eq. 3. Along the same lines, another management objective was to maintain groundwater flows towards streams to sustain baseflows during dry periods. A set of four well couplets each in Chicot and Evangeline aquifers (R1–R2, R3–R4, R5–R6, R7–R8)

Fig. 7 Location of management and monitoring wells along with the estimates for potential groundwater extractions in different sections of the county



was used for these purposes and the management objective was mathematically stated using Eq. 4.

The pumping in the shallow unconfined aquifer was restricted such that the heads ($H_{L,i,j}$) in the nearby shallow wells were within 75% of the unstressed levels ($H_{L,i,j,o}$). A set of four monitoring wells ($j = 1, \dots, 4$) was utilized with each of the 10 pumping wells that were assigned in the Chicot formation. This constraint is mathematically captured using Eq. 5. Equation 6 implies that the flow rate (Q) in any management well should not be less than a pre-specified flow rate (Q_{min}) specific to that well. A nominal minimum flow rate of 2.27 m³/day was assigned to ensure at least a certain degree of pumping at each well without rendering the linear programming result infeasible.

The necessary response coefficients were generated by carrying out appropriate model runs and the management model was coded in an MS-EXCEL spreadsheet and solved using the WHATSBEST add-in (Lindo Systems Inc. 2005). The management model indicated that 4.93×10^7 m³ of water can be extracted annually without violating any of the specified constraints. The future water demands of the county are projected to remain steady at about 3.33×10^6 m³ per year (TWDB 2002) and can therefore be easily met.

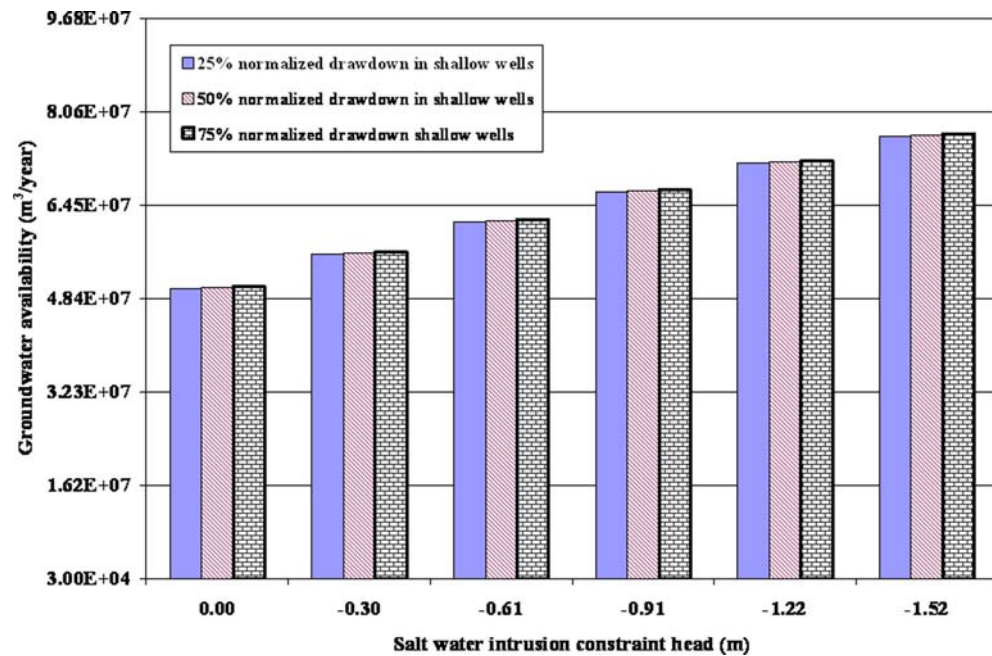
An analysis of the pumping rates optimized by the management model indicates that the deeper wells, in the Evangeline aquifer, near the western sections of the county pumped more than those in the coastal sections (Fig. 7). This result is to be expected as these wells are tapped in the vicinity of the recharge areas and not affected by the stringent saltwater intrusion constraint that was placed along the eastern side. Sensitivity analysis carried out using the management model indicated that the saltwater intrusion constraint

and the drawdown constraint placed in the shallower Chicot formation were the two most limiting factors affecting the optimization process. The results of the sensitivity analysis presented in Fig. 8 indicates that allowing the water levels in the coastal monitoring wells to drop by about 1.52 m below the mean sea level would raise the estimate for the amount of allowable water to about 7.65×10^7 m³/year, a nearly 60% increase from the baseline estimate of 4.93×10^7 m³/year. However, this allowance would render the water near the coast to become more brackish and thereby be of limited utility to meet municipal, irrigation and livestock needs.

Discussion

While the specified constraints were aimed to capture pertinent environmental phenomena, the level of protectiveness provided by them was not completely assessed. By specifying the no saltwater intrusion boundary condition, the management model ensured that the groundwater continued to flow into coastal bays and estuaries. However, the model allows the freshwater discharges to get reduced as long as the reductions do not drop the hydraulic heads near the coastal boundary to below mean sea level. As the water table near the coast is fairly shallow, the reductions allowed by the model are not likely to be substantial. If ecological assessments that quantify habitat freshwater needs are performed, the head constraint at the coastal monitoring wells can be easily modified to ensure sufficient amount of freshwater is discharged to bays and estuaries. Similarly, the head constraints in the monitoring wells near the inland surface water

Fig. 8 Sensitivity of groundwater availability estimates for different saltwater intrusion and drawdown constraints



bodies can be modified to ensure a specific amount of groundwater discharges as baseflows necessary to satisfy in-stream environmental needs.

The modeling effort is confined to a single administrative unit (Refugio County) and does not evaluate the impacts of pumping in adjoining counties. Groundwater inflows from the adjoining Bee and Goliad Counties were noted to be a significant source of groundwater recharge especially for the deeper Evangeline formation. Increased pumping in Refugio County will increase the amount of inflow from these adjoining counties and may cause the water levels in the wells there to drop considerably. While this externality has not been captured in this preliminary study, the management model can be easily expanded to include additional constraints on head drawdown in adjacent counties and the necessary response matrix can be readily constructed if a regional-scale groundwater model is available.

The current modeling effort utilized a steady-state regional groundwater flow model as the basis for development. As such, large-scale groundwater extractions at the management wells were assumed to occur at a continuous rate. This presumption is fairly reasonable for long-term policy planning endeavors as decision makers must work under the assumption that the groundwater users will utilize all of their permitted withdrawals within the allotted time. In addition, groundwater in Refugio County is mainly being targeted to meet urban municipal demands and as such future groundwater extractions are likely to be non-seasonal in nature. The management model should,

however, be coupled to a transient groundwater flow model if seasonal uses do become dominant.

Summary and conclusions

The objective of this study was to develop and illustrate a mathematical framework to assess how much groundwater is available within Refugio County, TX, for various water uses. As a first step, a three-dimensional county-scale mathematical model was developed to represent the groundwater flow characteristics using the USGS MODFLOW model. A variety of evaluative checks were performed to ensure the adequacy of the developed simulation model. This model was then used as the basis to develop a linear programming based management model to estimate how much water can be extracted from the underlying aquifer formations while reconciling the competing objective of environmental protection. The constraints placed on the model addressed several stakeholder concerns and aimed to prevent saltwater intrusion along the coastal boundary, preclude reversal of regional hydraulic gradients and those near streams and limit the extent of drawdown in the vicinity of shallow pumping wells.

The results of the study indicated that for the conditions assumed, roughly $4.93 \times 10^7 \text{ m}^3$ of water could potentially be extracted without violating the specified constraints. Groundwater availability estimates were noted to be most sensitive to the saltwater intrusion constraint. Allowing the reversal of hydraulic gradient along the coast, even by a small amount significantly

increases the amount of available groundwater. This water would, however, not be of high quality and probably would be expensive to treat at present. However, such water may be suitable for certain industries like aquaculture and as such may still be of current economic value. The simulation-optimization scheme provides a practical approach to incorporate the competing objectives of economic growth and environmental protection into a succinct framework and yield objective estimates for groundwater availability in a region and as such is deemed suitable for developing groundwater availability estimates that reflect economic and environmental preferences of stakeholders in the region.

Disclaimer

The mention of any commercial products is for illustrative purposes only and does not constitute an endorsement from the authors.

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