Impacts of sea-level rise and urbanization on groundwater availability and sustainability of coastal communities in semi-arid South Texas

**Venkatesh Uddameri · Sreeram Singaraju ·
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Abstract The sea levels along the semi-arid South Texas coast are noted to have risen by 3–5 mm/year over the last five decades. Data from General Circulation Models (GCMs) indicate that this trend will continue in the 21st century with projected sea level rise in the order of 1.8–5.9 mm/year due to the melting of glaciers and thermal ocean expansion. Furthermore, the temperature in South Texas is projected to increase by as much as 4 °C by the end of the 21st century creating a greater stress on scarce water resources of the region. Increased groundwater use hinterland due to urbanization as well as rising sea levels due to climate change impact the freshwater-saltwater interface in coastal aquifers and threaten the sustainability of coastal communities that primarily rely on groundwater resources. The primary goal of this study was to develop an integrated decision support framework to assist land and water planners in coastal communities to assess the impacts of climate change and urbanization. More specifically, the developed system was used to address whether coastal side (primarily controlled by climate change) or landward side processes (controlled by both climate change and urbanization) had a greater control on the saltwater intrusion phenomenon. The decision support system integrates a sharp-interface model with information from GCMs and observed data and couples them to statistical and information-theoretic uncertainty analysis techniques. The developed decision support system is applied to study saltwater intrusion characteristics at a small coastal community near Corpus Christi, TX. The intrusion characteristics under various plausible climate and urbanization scenarios were evaluated with consideration given to uncertainty and variability of hydrogeologic parameters. The results of the study indicate that low levels of climate change have a greater impact on the freshwater-saltwater interface when the level of urbanization is low. However, the rate of inward intrusion of the saltwater wedge is controlled more so by urbanization effects than climate change. On a local (near coast) scale, the freshwater-saltwater interface was affected by groundwater production locations more so than the volume produced by the community. On a regional-scale, the sea level rise at the coast was noted to have limited impact on saltwater intrusion which was primarily controlled by freshwater influx from the hinterlands towards the coast. These results indicate that coastal communities must work proactively with planners from the up-dip areas to ensure adequate freshwater flows to the coast. Field monitoring of this parameter is clearly warranted. The concordance analysis indicated that input parameter sensitivity did not change across modeled scenarios indicating that future data collection and groundwater monitoring efforts should not be hampered by noted divergences in projected climate and urbanization patterns.

Keywords Sea level rise · Urbanization · Groundwater availability · Climate change impact assessment · Salt water intrusion

Introduction

The coastal semi-arid region of South Texas has several ecologically sensitive bays and estuaries, is home to several endangered species, and is a common stopping ground for migratory birds. The region offers a temperate climate,

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limited urbanization and excellent recreational opportunities, particularly birding, fishing and hunting. As such, the region is undergoing a steady population growth, particularly in the smaller rural communities surrounding major urban centers of the region (Census 2010). Most small and rural communities of the coastal South Texas rely on groundwater resources to meet their domestic, livestock and municipal needs (TWDB 2012). However, improper development of groundwater resources in coastal areas can lead to inward intrusion of saline water and result in the loss of water supply sources. Many urban areas of South Texas are also looking towards using groundwater resources to meet their future water supply needs. Hinterland groundwater use can reduce the amount of groundwater being discharged to coastal bodies and cause further intrusion of saline water (Vappicha and Nagaraja 1976; Mantoglou 2003; Guha and Panday 2012). Fossil fuel production in the area is known to have caused local subsidence which is another factor that enhances the landward intrusion of saline water (Sharp et al. 1991).

In addition to the anthropogenic factors discussed above, the saline water interface in the shallow groundwater systems of South Texas can also be influenced by natural climatic and geomorphological factors. The alluvial, estuarine, and the deeper marine sediments accumulated over the last 150 million years in South Texas are estimated to be compacting due to their own weight at a rate of 0.05 mm/year (Paine 1993). Sea level rises are noted to be caused by the melting of snowcaps and glaciers as well as the thermal expansion of the oceans due to rising temperatures (Church et al. 2007). The overall rate of sediment delivered to the littoral zones has been noted as insufficient to combat the effects of sea level rise and has led to the breaching of barrier islands and loss of coastal habitats in South Texas (Gibeaut and Tremblay 2003). The measured relative sea level rise (i.e., change in the sea level relative to the land) has been significant in South Texas and has occurred at a rate of 4.6 mm/year at Rockport, 3.6 mm/year at Port Mansfield and 3.44 mm/year at South Padre Island over the last 50–60 years.

Global climate change projections using coupled atmosphere ocean general circulation models (AOGCMs) indicate that thermal expansion and glacier melting may be exacerbated due to anthropogenic greenhouse gas emissions in recent times. The global mean sea level (GMSL) is estimated to have increased at a rate of 1.8 mm/year (Douglas 1997). Nicholls and Cazenave (2010) estimate a GMSL rise of 3.3 mm/year during the period between 1992 and 2010. Based on an ensemble of AOGCMs, Church et al. (2007) estimate a GMSL rise of 4.63 mm/year during the period of 1990–2100. This represents an approximately 2.5 times increase in the rate when compared to the 20th century. While sea level changes can vary dramatically in different parts of the world, the projections for sea level rise in South Texas are in the order of 0.18–0.59 m over the 21st century (1.8–5.9 mm/year) from climate change. Accounting for subsidence effects, the total change in relative sea level rise is estimated to range from 0.46 to 0.87 m at Rockport, 0.2–0.67 m at Port Mansfield and 0.34–0.75 m at South Padre Island by the end of the 21st century (Montagna et al. 2007).

From a hydraulic standpoint, relative rise of sea levels will reduce and possibly reverse the groundwater flow gradient causing the saltwater wedge in the aquifer to intrude further inland (Uddameri and Kuchanur 2007). Inundation of littoral zones due to sea level rise will increase the infiltration of the saline water into the aquifer and over a long period will raise the saltwater-freshwater interface in the aquifer. In a similar vein, the reduction in groundwater inflows, say due to economic development inland, can lower the hydraulic heads in the coastal aquifers on the landward side and will also cause the saltwater wedge in the aquifer to move further inland. Climate change and anthropogenic influences also have other impacts on the groundwater flows in the coastal aquifers. The sea level rise due to thermal expansion of water will lower the density of the seawater. By the same token, the melting of glaciers will add freshwater to the oceans and reduce its salinity which also decreases the density. This lowered density will actually depress the saltwater freshwater interface deeper in the aquifer and prevent the inland movement of the saltwater wedge. Using the Ghyben-Herzberg principle, a 0.5 % change in seawater density (from 1.025 to 1.02 g/cc) can lower the static saltwater-freshwater interface by over 25 % (i.e., 12 m (~40 ft) below MSL to 15 m (~50 ft) below MSL per 0.3 m (1 ft) of freshwater head above the mean sea level). On the other hand, increased groundwater temperatures due to atmospheric heating will reduce the freshwater density and elevate the freshwater-saltwater interface causing it to move further inland. Similarly, increased groundwater salinity due to anthropogenic pollution will have an opposing effect on the saltwater-freshwater interface. There is a growing recognition that climate change can have a profound influence on groundwater resources and affect the saltwater-freshwater interface in coastal aquifers (e.g., Werner and Simmons 2009; Guha and Panday 2012; Loaiciga et al. 2012). Given the shallow bathymetry of South Texas bays and estuaries and the gentle slopes of the coastal areas, the impacts of sea level rise can have a significant influence on coastal communities.

In addition to climate change (natural stresses), coastal aquifers also undergo changes due to urbanization.

Urbanization increases the reliance on groundwater resources and decreases the landward hydraulic heads, which, in turn, exacerbate the intrusion of the saltwater-freshwater interface. Urbanization hinterland leads to greater groundwater production in the inland areas and diminishes the amount of groundwater flowing towards the coast. Urbanization can also lead to the deterioration of groundwater quality, the alteration of the salinity of freshwater and affect the location of the freshwater-saltwater interface. As such, urbanization can have very similar impacts on coastal aquifers as climate change. In fact, in the absence of proper planning, urbanization can occur at a fast pace and work in consort with naturally occurring climatic phenomena. Alterations to groundwater availability in the coastal South Texas affect the carrying capacities of rural coastal communities due to diminishing freshwater supplies. Suitable decision support tools are necessary to help water resources planners and managers in the region evaluate these impacts and assess the suitability of adaptation measures. However, unlike climate induced change, the impacts of urbanization within a coastal region are more controllable and the effects can be mitigated through careful land and water resources planning.

Successful adaptation to climate change and proper management of urbanization of coastal regions is possible when planners and decision makers have a sound understanding of potential impacts and the mechanisms controlling them. However, developing such an understanding can be arduous as it is impossible to predict future events with a high degree of certainty. Downscaled data from General Circulation Models (GCMs) are known to exhibit divergent behavior (Hewitson and Crane 2006). In a similar fashion, the nature and extent of urbanization are difficult to predict a priori (Nelson et al. 2009; Bierwagen et al. 2010). Therefore, it is not only important to evaluate a range of scenarios that bracket the likely future events but also explicitly characterize the uncertainty stemming from imprecise knowledge of processes and parameters that affect groundwater availability in coastal regions.

Building on the above discussion, the overall goal of this study is to develop a modeling framework to evaluate the combined impacts of climate change and urbanization on a coastal community in South Texas. The framework developed here integrates a coastal groundwater flow model with scenario planning and sampling based global sensitivity methodologies to understand how saltwater intrusion will affect coastal communities in the future. The utility of the proposed framework is illustrated by applying it to evaluate the impact of sea-level rise and urbanization on groundwater resource availability for a small rural coastal community in South Texas.
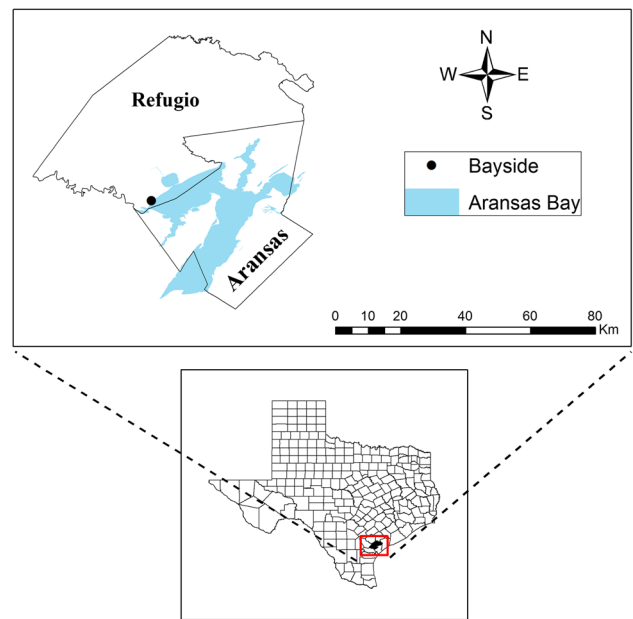

Fig. 1 Map of the study area

Methodology

Mathematical model

The conceptual model of the coastal aquifer system considered is schematically presented in Fig. 1 and represents a section of the upper unconfined portions of the Gulf Coast Aquifer in South Texas near the township of Bayside in Refugio County, TX (Fig. 1). The model assumes the presence of a sharp interface exists between the freshwater (zone 1) and saltwater (zone 2) portions within the aquifer. The location of the interface is modeled using the Ghyben-Herzberg principle. As the study area comprises a small portion of the Gulf Coast aquifer, the aquifer is assumed to be semi-infinite in the X and Y directions and the thickness of the aquifer in the modeled domain is assumed to be approximately constant. The interaction of the modeled domain with the larger regional aquifer is captured using a uniform freshwater influx term, q, expressed in m²/d or (m³/d/m). In other words, the groundwater development in the inland areas surrounding the model domain will cause a reduction in the inward freshwater flow. The areal recharge over the model domain is also assumed to be uniform and expressed as a volumetric flux, N (m/d), and includes the combined effects of return flow to the aquifer as well as direct precipitation. The distance to the mean sea level is assumed to be constant over the simulation time-frame and is denoted by d (m). A set of groundwater extraction wells are assumed to produce uniformly to meet the groundwater supplies in the model domain. The groundwater extraction rates at these wells are assumed to be constant in time but

variable from well to well and are denoted by Q_i (m³/d) where the sub-script, $i = 1,..., M$, and refers to the ith well with a total of M production wells. The locations of these wells are represented using Cartesian coordinates (x_i, y_i). The aquifer within the modeled domain is also assumed to be homogeneous and isotropic with an effective hydraulic conductivity, K (m/d).

Following Strack (1976) the hydraulic head in the aquifer is modeled using a single potential that is defined throughout the aquifer. The steady-state governing groundwater flow equation can be written as (Mantoglou and Papantoniou 2008):

$$K\frac{\partial^2 \varphi}{\partial x^2} + K\frac{\partial^2 \varphi}{\partial y^2} + N - Q^* = 0. \tag{1}$$

Following Strack (1976) and Cheng et al. (2000) the potential, ϕ, can be written as:

$$\varphi = \frac{h_f^2 - (1+\delta)d^2}{2} \quad \forall \text{ zone 1} \quad \text{and}$$
$$\varphi = \frac{(1+\delta)\left(h_f^2 - d^2\right)}{2\delta} \quad \forall \text{ zone 2} \tag{2}$$

Given

$$\delta = \left(\frac{\rho_s - \rho_f}{\rho_f}\right) \tag{3}$$

where, ρ is the density (kg/m³), the subscripts s and f refer to saltwater and freshwater, respectively, and h_f is the hydraulic head of the freshwater measured from the datum (m). The term Q^* in Eq. 1 is the groundwater production rate per unit area (i.e., groundwater withdrawal flux) and has the units of (m/d). Using the superposition principle and the method of image wells, the governing groundwater flow equation can be solved for the potential, ϕ using the techniques presented in Strack (1976) and Mantoglou (2003) to yield the following expression:

$$\varphi(x,y) = \frac{q}{K}x + \frac{N}{K}x\left(L - \frac{x}{2}\right)$$
$$+ \sum_{i=1}^{M} \frac{Q_i}{4\pi K}\ln\left[\frac{(x-x_i)^2 + (y-y_i)^2}{(x+x_i)^2 + (y-y_i)^2}\right] \tag{4}$$

where, L is the length of the modeled aquifer domain where direct recharge is considered. Recharge to the aquifer occurring outside the modeled domain is implicitly included in the freshwater inflow term (q). All other terms in Eq. 4 are described in Table 1. The potential at the toe location or where the saltwater zone ceases to exist is given as:

$$\varphi_t(x_t, y_t) = \frac{(1+\delta)\delta}{2}d^2. \tag{5}$$

The relationship between the mean sea level and the extent of the saltwater-freshwater interface can be seen

from Eq. 5. The locus of the saltwater-freshwater interface in the plan view (XY plane) can be obtained by solving Eqs. 5 and 6 for x_t as a function of y_t. In other words, the locus can be determined by assuming a value of y, equating the RHS of Eq. 5 to the LHS of Eq. 4, and solving for the unknown x. Clearly, Eq. 4 is a nonlinear function of x and has to be solved using numerical root finding techniques (Chapra and Canale 2010).

Equations of state for densities

As discussed previously, climate change can alter freshwater and saltwater densities due to changes in temperature (thermal expansion) as well as salinity changes caused by mixing of freshwater. The following equations of state (EOS) given by Millero and Huang (2009) were used to express the density of freshwater as a function of temperature and that of the seawater as a function of both temperature and salinity. As the bathymetry of the Texas bays are rather shallow, the pressure variation is likely to be insignificant and as such not corrected for in the density calculations.

$$\rho_f(T) = \sum_{i=0}^{5} a_i T^i \tag{6}$$

$$\rho_s(T, S) = \rho_f(T) + \Delta\rho(T, S) \tag{7}$$

where, T is the temperature in °C and S is the salinity in practical salinity units (psu). The coefficients required for calculations are summarized in Millero and Huang (2009) however are not presented here in the interest of brevity. It is important to note that the temperature in the above equations refers to that of the water in the coastal body and not the atmospheric temperature.

Metrics to assess salt-water intrusion

The mathematical model developed above provides a profile of the salt water-freshwater interface. Two metrics were developed to quantify the impacts of salt-water intrusion using this interface as the basis. The first metric quantifies the maximum distance (inland) the salt-water wedge intrudes as measured from the coastline. The second metric calculates the area intruded by the saltwater wedge. Both these metrics are affected by seaward side phenomena (sea level rise, ocean temperature), natural and anthropogenic stresses (net recharge and groundwater production) within the study area, and inland groundwater inflow (controlled by climate change and groundwater production) from the neighboring areas.

Table 1 Model inputs and their range of variability corresponding to different climate-urbanization scenarios

S. no.	Parameter	Unit	Base scenario		Moderate scenario		Severe scenario		Distribution	Category	Remarks
			Minimum value	Maximum value	Minimum value	Maximum value	Minimum value	Maximum value			
1	Sea-level (sl)	m	−0.6096	0.6096	−0.2096	1.0096	0.0904	1.3096	Uniform		
2	Temperature	Celsius	10	36	12	38	14	40	Normal	Climate	
3	Precipitation	cm	50.8	101.6	38.1	114.3	25.4	127	Uniform		
4	Aquifer Inflow	m/day	1.5	7	1.2	5.6	0.75	3.5	Lognormal		Can also be affected by climate change hinterland
5	Recharge	% of precipitation	0.9	1.1	0.75	0.85	0.6	0.7	Uniform	Urban	
6	Population density	People/sq.km	1,036	2,072	3,885	5,180	7,252	8,288	Uniform		
7	Per capita water use	L/capita	757	833	681	757	606	681	Uniform		
8	Number of wells	No Units	4	10	6	10	6	12	Discrete		
9	Hydraulic conductivity	m/day	0.11304	151.411	0.11304	151.411	0.11304	151.411	Lognormal		Remain same across all scenarios
–	Aquifer thickness	m	152.4	152.4	152.4	152.4	152.4	152.4	Constant	Geology	
–	Length	m	800	800	800	800	800	800	Constant		
–	Width	m	1,600	1,600	1,600	1,600	1,600	1,600	Constant		

Scenario development for climate change and urbanization with characterization of hydrogeological uncertainties

A total of nine scenarios were developed to bracket the range of potential climate change and urbanization outcomes. The climate change impacts, namely the sea level rise and temperature, are assumed to be largely uncontrollable on a local spatial scale as they are affected by large-scale meteorological phenomena. On the other hand, urbanization at the local scale and as such the recharge and groundwater production within the study domain is completely controlled by the land and water planning decisions within the study area. Regional land and water planning affects the amount of groundwater that enters the study area. The coastal community may have some influence on this parameter as groundwater availability is ascertained via groundwater joint planning in Texas [Uddameri et al. 2013 (in press)]. However, the extent of influence depends upon whether the community has a groundwater conservation district (GCD) and as such is represented in the planning process as well as the amount of regional cooperation and whether coastal-aquifer fluxes are considered as a desired future condition metric during the joint planning process.

Given the planning nature of the study, three levels of urbanization were considered: (1) the baseline corresponded to current levels of population density and imperviousness; (2) the moderate level of urbanization corresponded to population density and imperviousness of the City of Corpus Christi, TX (12th most populous city in Texas); and (3) the extreme level of urbanization corresponded to population density and imperviousness of the city of San Antonio, TX (7th most populous city in the US and 2nd most populous in Texas). Both of these cities lie within South Texas and as such provided bracketing estimates for plausible future growth in the region. The climate scenarios corresponding to the baseline case indicate current sea level fluctuations around a mean value and observed temperature variability over the last decade. The moderate scenario corresponded to a 0.4 m increase in the mean sea level and 2 °C warming on average. The severe scenario corresponded to 0.7 m increase in the mean sea level and 4 °C warming on average. The average rainfall in all three scenarios was assumed to be constant and set equal to the historical average of 76.2 cm/year (30 in/year). However, the variability of the temperature was progressively changed from ±10 to ±15 °C and ±20 °C in baseline, moderate and severe climate scenarios, respectively.

The mathematical model presented above also requires specification of hydrogeological parameters, namely the hydraulic conductivity and the aquifer thickness both of which are not known with complete certainty due to intrinsic aquifer heterogeneity. In particular, sedimentary coastal deposits in the Gulf Coast Aquifer are comprised of inter-bedded layers of sand, silt and clay and known to exhibit considerable heterogeneity due to their depositional history (Baker 1979; Chowdhury and Turco 2006). Furthermore, the local geology in conjunction with the amount of groundwater pumped (a function of urbanization) will influence the number of wells needed to produce the requisite amount of groundwater. Therefore, it is imperative that the uncertainties associated with geologic parameters be properly accounted for while attempting to characterize the relative impacts of climate change and urbanization in coastal aquifers. Furthermore, uncertainties associated with hydrogeological parameters were characterized using appropriate probability density functions. The parameter ranges for hydrogeological parameters were compiled from previous investigations (Shafer and Baker 1973) in the region and are summarized in Table 1 along with the range of values used for other climate and urbanization parameters. The uncertainties associated with hydrogeological parameters were kept the same across all climate and urbanization scenarios.

Assessing the relative importance of climate, urbanization and geological variability

As seen from the above discussion, it is clear that different model inputs capture the effects of climate, urbanization and geology of the region. Therefore, identification of parameters, which have the greatest influence on the adopted salt-water intrusion metrics, provides one convenient way to ascertain the relative impacts of climate, urbanization and geological variability within the study area. Global sensitivity methods are particularly suited to identify salient model inputs given the wide range of variability associated with the climate, urbanization and geological characteristics of the region (Saltelli et al. 2008). Mattot (2012) summarizes a variety of different global sensitivity analysis approaches that can be coupled with groundwater models. Sampling based sensitivity analysis used Monte Carlo simulations to carryout sensitivity and uncertainty analysis. These sampling based methods are known to be robust (i.e., not suffer from numerical instabilities) and effective, and as such are widely used in groundwater modeling studies (Ballio and Guadagnini 2004; Gurdak et al. 2007; Kucherenko et al. 2009). Helton et al. (2006) present a comprehensive survey of sampling based methods for uncertainty and sensitivity analysis. The entropy measures for patterns (EMP) adopted here provides a convenient measure of association between the input and the output (Press et al. 1992; Helton et al. 2006). Briefly, entropy is an information theoretic concept which indicates

the degree of unpredictability or uncertainty in a random variable. Entropy is also a measure of information content in the variable and denotes the information gained when the entropy (or uncertainty) is removed (van der Lubbe 1997). The entropy approach begins by categorizing the input (x)-output (y) pairs into a set of bins (a two-dimensional grid). If the data is binned into I rows (for inputs) and J columns (over the output range) and N is the total number of Monte Carlo simulations, and $N_{i,j}$ is the number of samples in the grid cell (i, j), then the joint probability can be written as:

$$p_{i,j} = \frac{N_{i,j}}{N}. \tag{8}$$

The marginal probabilities can be obtained by summing up along the rows and columns as:

$$p_i = \frac{N_i}{N} \quad \text{and} \quad p_j = \frac{N_j}{N} \tag{9}$$

where, p_i is the marginal probability of the input and p_j is the marginal probability of the output and is obtained by summing the number of samples in each row (or column) and dividing it by the total number of simulations. Using the above probabilities, the marginal entropy of the input (x) and output (y) can be written as:

$$H(y) = -\sum_{j=1}^{J} p_j \ln(p_j) \quad \text{and} \quad H(x) = -\sum_{i=1}^{I} p_i \ln(p_i). \tag{10}$$

The joint entropy can be written as:

$$H(x,y) = -\sum_{i=1}^{I} \sum_{j=1}^{J} p_{i,j} \ln(p_{i,j}). \tag{11}$$

The conditional entropy of the output y given the input x is calculated as:

$$H(y|x) = -\sum_{i=1}^{I} \sum_{j=1}^{J} p_{i,j} \ln\left(\frac{p_{i,j}}{p_i}\right). \tag{12}$$

The dependency of the output y on the input x is quantified by an entropic measure of association, which is referred to as the uncertainty coefficient:

$$U(y|x) = \frac{H(y) - H(y|x)}{H(y)}. \tag{13}$$

The uncertainty coefficient varies between zero and unity with the null value, indicating no relationship between the input and the output, while a value of one indicates that the knowledge of x completely predicts the output y. Therefore, the uncertainty coefficient (U) can be used to directly rank the inputs according to their importance.

Comparing sensitivity rankings across scenarios

The entropy measures of association can be assessed over different climate-urbanization scenario pairs to evaluate if and how the sensitivity of various model inputs changes under various assumptions of climate and urbanization growth. Parameters that rank high across all scenarios are clearly of the highest importance and every effort must be made to obtain the best possible information about these inputs using field measurements and observations. By the same token, parameters having consistently lower ranks can be labeled as insensitive. Parameters that exhibit variable ranks exhibit highly nonlinear (scenario dependent) relationships to the adopted saltwater intrusion metrics and represent a major source of discontent and disagreement during the decision making process. Therefore, establishing reliable values for these parameters is critical to reaching consensus in collaborative decision making situations.

The Kendall's coefficient of concordance (W) was used here as a measure to ascertain the level of agreement in input parameter sensitivity rankings across different climate-urban scenarios. This technique has been used previously in water resources investigations to compare different multicriteria decision making methods (Hajkowicz and Higgins 2008). If the kth parameter is given a sensitivity rank of $R_{k,s}$ in the sth scenario where there are K objects and S scenarios, then the total rank given to the kth parameter is:

$$R_k = \sum_{s=1}^{S} R_{k,s}. \tag{14}$$

The mean value of the ranks, R_m and the sum of squared deviation S can be defined as:

$$R_m = \frac{1}{2} S(K + 1) \quad \text{and} \quad S = \sum_{l=1}^{K} (R_k - R_m)^2. \tag{15}$$

The Kendall Concordance Coefficient (KCC), W, can be computed as:

$$W = \frac{12S}{S^2(K^3 - K)}. \tag{16}$$

The KCC statistic is close to unity when there is agreement among different scenarios. The above formulas assume there are no ties in ranks. The formulas for correction of ties and tests for significance of the concordance coefficient are discussed in Legendre (2005) and implemented within the IRR package of the R statistical software (Gamer et al. 2012).

Results and discussion

Salinity-temperature relationships

The density of freshwater is largely a function of temperature while that of seawater (bay water) is a function of both salinity and temperature. The salinity of the saltwater in the bay is also affected by changes in temperature. The salinity and temperature data collected in Aransas Bay and presented by the National Estuarine Research Reserve System, Centralized Data Management Office (CDMO 2012) was used to establish the salinity temperature relationship depicted in Fig. 2. The figure depicts the highly nonlinear relationship of salinity with the bay water temperature. At lower and higher ends, the salinity increases with temperature, because the evaporative losses from the bay tend to concentrate the salt which increases the salinity. However, between these two extremes, the salinity either depicts a decreasing trend or no change with temperature. This result arises because the evaporative losses due to increasing temperature are either overwhelmed or counterbalanced by thermal expansion of water in this temperature range. General Circulation Models do not provide data for bay water salinity. The constitutive relationship developed and presented in Fig. 2 provides a convenient way to incorporate the climate change effects on the bay water salinity, which, in-turn, controls the nature and extent of saltwater intrusion in the bay. It is, however, important to remember that the regression relationship established in Fig. 2 is based on the Bay water temperature and the air temperature (typical output from the GCMs). On average, the ratio of the coastal temperature to atmospheric temperature in South Texas was noted to be approximately 0.8–1.05. The lower fraction corresponds to summer months where the bay water is cooler than the land surface while the higher fractions are for winter months when the land surface is cooler than the ocean due to entrapment of latent heat. These correction factors were used to obtain the bay water temperature from downscaled GCMs outputs.

Saltwater intrusion metrics under different climate and urbanization scenarios

A typical long-term saltwater-freshwater interface within the modeled domain is depicted in Fig. 3 for a single Monte Carlo simulation realization. The saltwater-freshwater interface is seen to extend approximately 2 m inland (denoted by line) for the production schedule being used. The inset chart in Fig. 3 also depicts that the location of the production wells within the model domain has an influence on the intrusion characteristics of the saltwater-freshwater interface and is unlikely to be uniform over short spatial
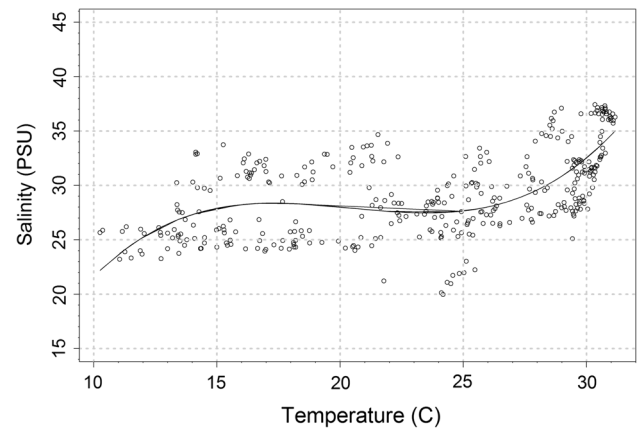

Fig. 2 Salinity-temperature relationship for Aransas Bay, TX (Based on Data from CMDO 2013)
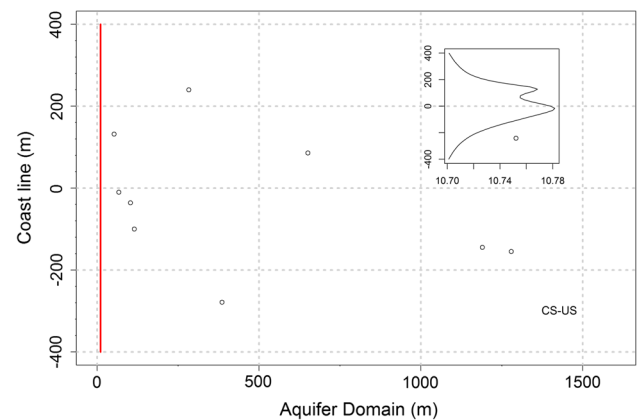

Fig. 3 A typical saltwater-freshwater interface profile obtained using the sharp-interface model

scales due to variability in pumping rates as well as the placement of the wells. Therefore, the maximum toe length of the wedge in conjunction with the total inland area intruded by the saltwater wedge provide a comprehensive set of metrics to evaluate the risks associated with saltwater intruding inland.

The empirical frequency distribution functions for area intruded and the maximum toe length of the intrusion under different climate-urban scenarios are depicted in Figs. 4 and 5, respectively. The results indicate that for the assumed climate change and urbanization scenarios, the extent of saltwater intrusion is likely to be localized near the coast. The affected area is projected to be less than 0.15 % of the total study domain considered. Performing row-wise and column-wise comparisons of various scenarios in Figs. 4 and 5 indicates that overall the impacts of saltwater intrusion increase more rapidly with urbanization than climate change. However, both the intruded area and maximum toe length metrics, on average start out smaller for the urbanization changes but increase more rapidly with
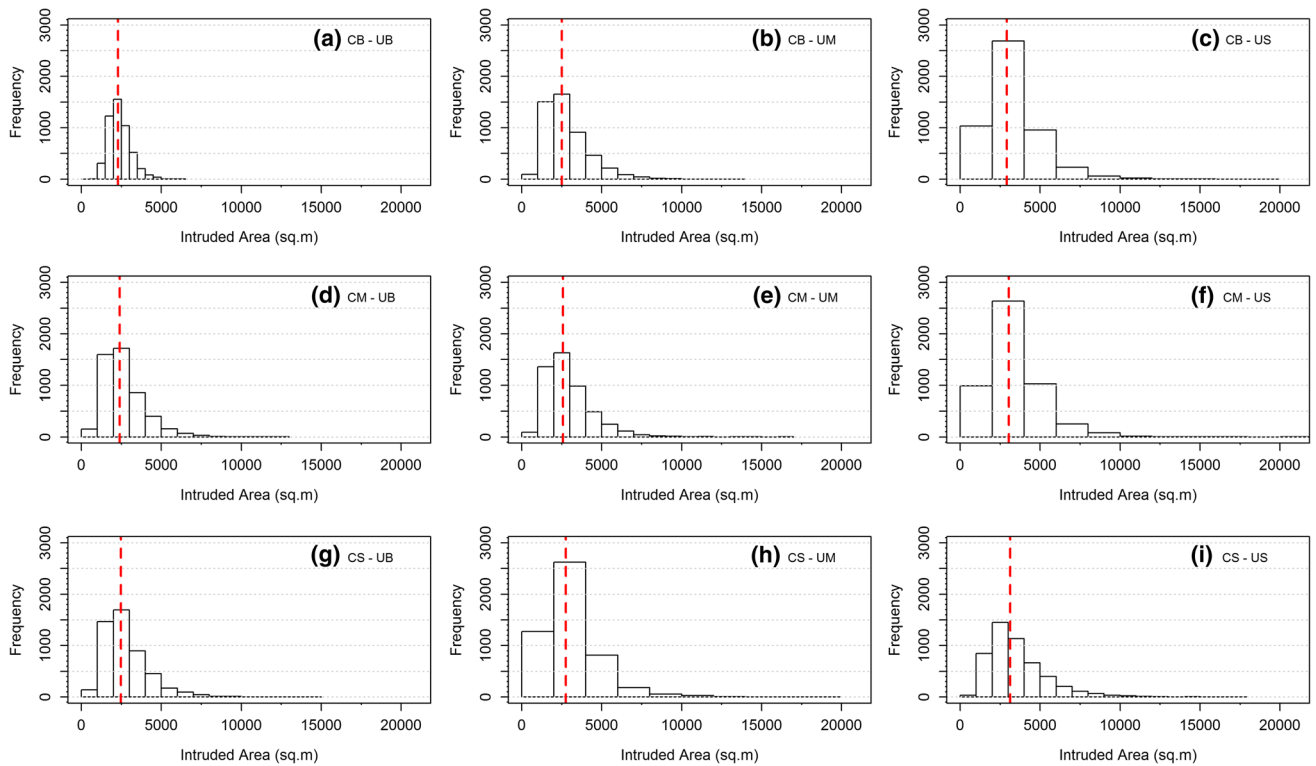
Fig. 4 Empirical frequency distribution for the intruded area (i.e., Areal extent of the saltwater wedge) under various coastal-urbanization scenarios
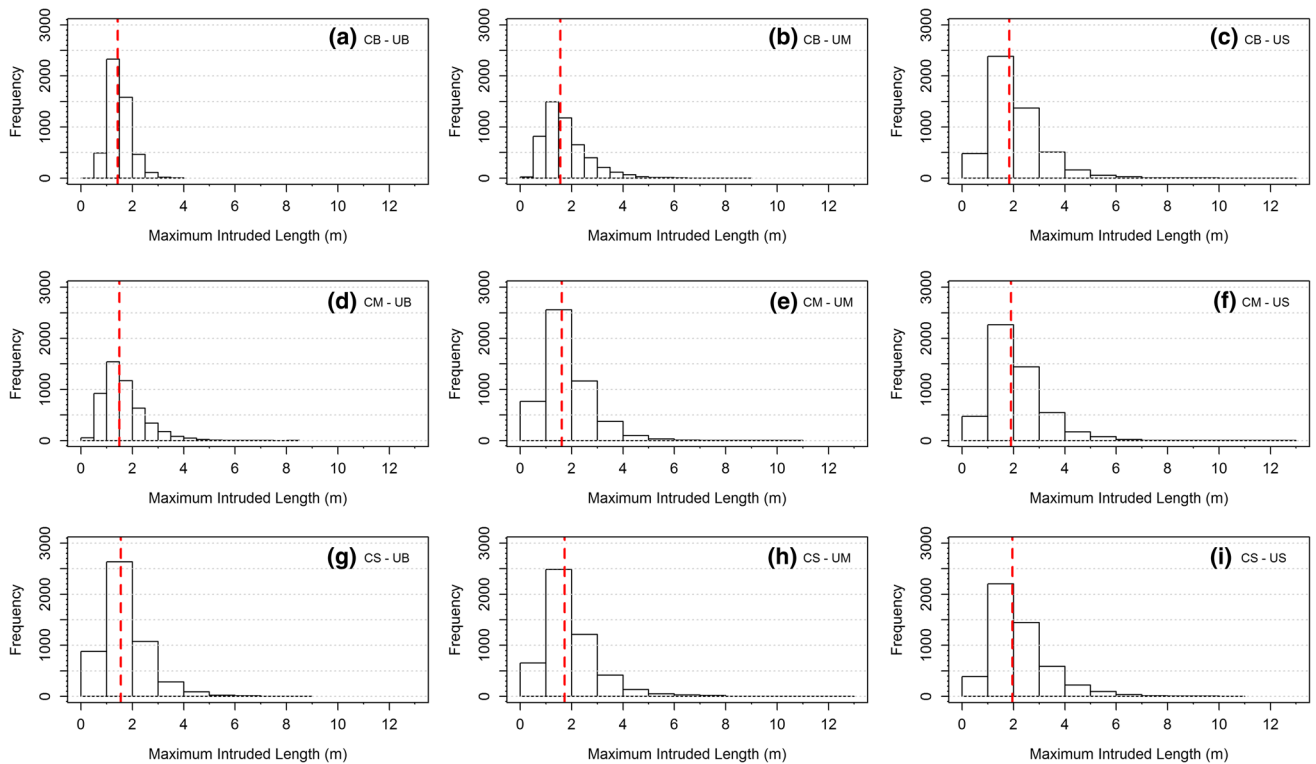

Fig. 5 Empirical frequency distribution for the maximum toe length under various coastal-urbanization scenarios
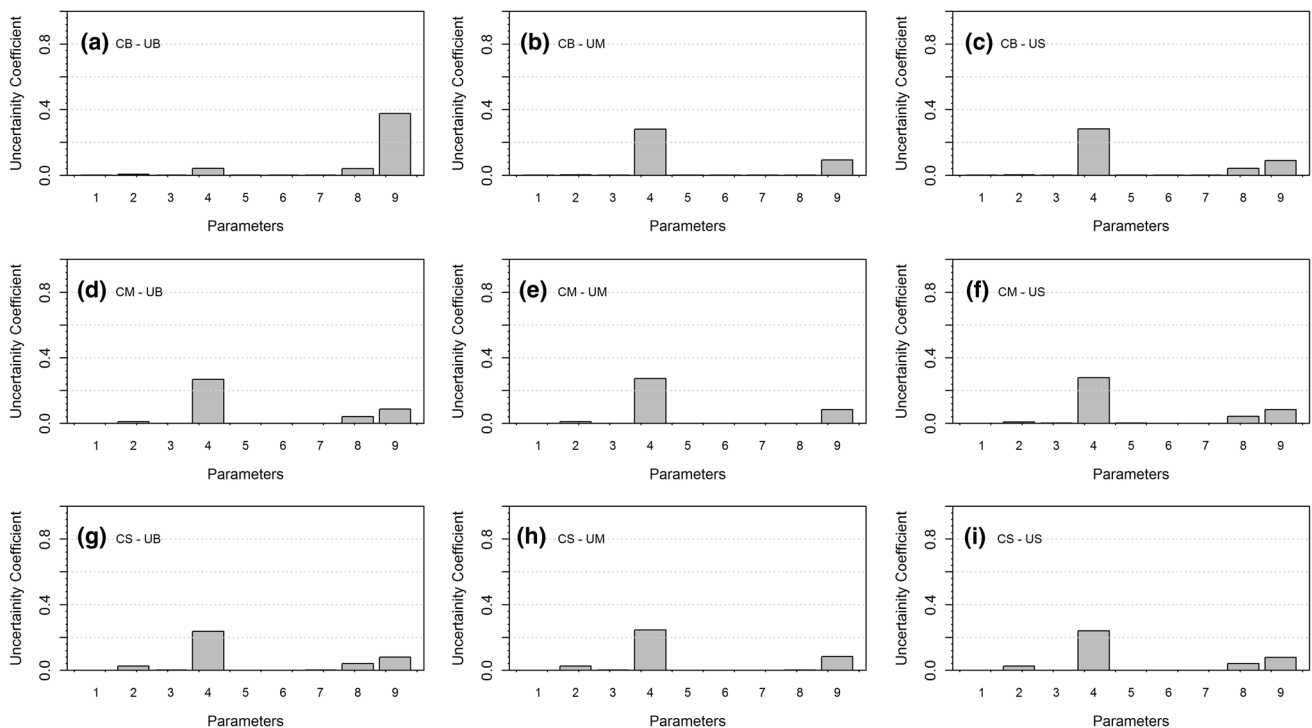
Fig. 6 Uncertainty coefficients of the model inputs measured with respect to the intruded area metric (see Table 1 for the parameter numbers)

moderate to severe degrees of urbanization. This result indicates that smaller changes to climate have a more profound impact on the extent of saltwater intrusion than urbanization; however, over the long run urbanization is likely to control the nature and extent of saltwater intrusion within the study area.

Sensitivity analysis across climate-urbanization scenarios

The results from the Monte Carlo analysis for each climate-urbanization scenario were used to compute entropy metrics and calculate the uncertainty coefficient. The sensitivity coefficients for nine uncertain input parameters identified in Table 1 were calculated for each of the nine scenarios. The numbers in Figs. 6 and 7 correspond to parameter numbers identified in Table 1. It is clear from Figs. 6 and 7 that input parameters exhibit the same level of sensitivity to both the areal extent of intrusion and the depth of the toe metrics. Under current baseline conditions (CB-UB), the uncertainty in characterizing the saltwater-freshwater interface is largely controlled by the variability in the hydraulic conductivity in the study area. However, with increasing climate and urbanization stresses, the groundwater inflow along the landward boundary becomes the most sensitive input. This result indicates that the seaward side influences, namely the sea-level rise, has a lower impact on the saltwater intrusion than the landward

side flows, which can be affected due to the joint effects of hinterland climate change and urbanization. From a practical standpoint, these results also point to the fact that being in down-dip areas, the coastal communities must cooperate with up-dip areas to ensure that the regional groundwater flow gradients continue to be towards the coast and sufficient amounts of water are discharged into the coastal area both for use by the coastal community and for ensuring freshwater inflows to the bay to sustain coastal ecosystems.

The results presented in Figs. 4 and 5 also indicate that with increasing climatic stresses, the sensitivity of saltwater intrusion metrics show a greater sensitivity to temperature. This result is to be expected because the temperature affects several model parameters including the density of the freshwater and the salinity of the bay water, which, in turn, affects the density of the bay water (saltwater). The results also show that the number of pumping wells used to produce water also has an impact on the intrusion of the saltwater wedge, particularly with an increased urbanization stress on the region. This result is to be expected because an increasing urbanization stress places a larger demand on groundwater resources and increased pumping within the area can diminish the capacity of the wells, thereby requiring a greater number of wells to pump the required amount of water.

In addition to identifying critical model parameters, sensitivity analysis is also useful to ascertain inputs that
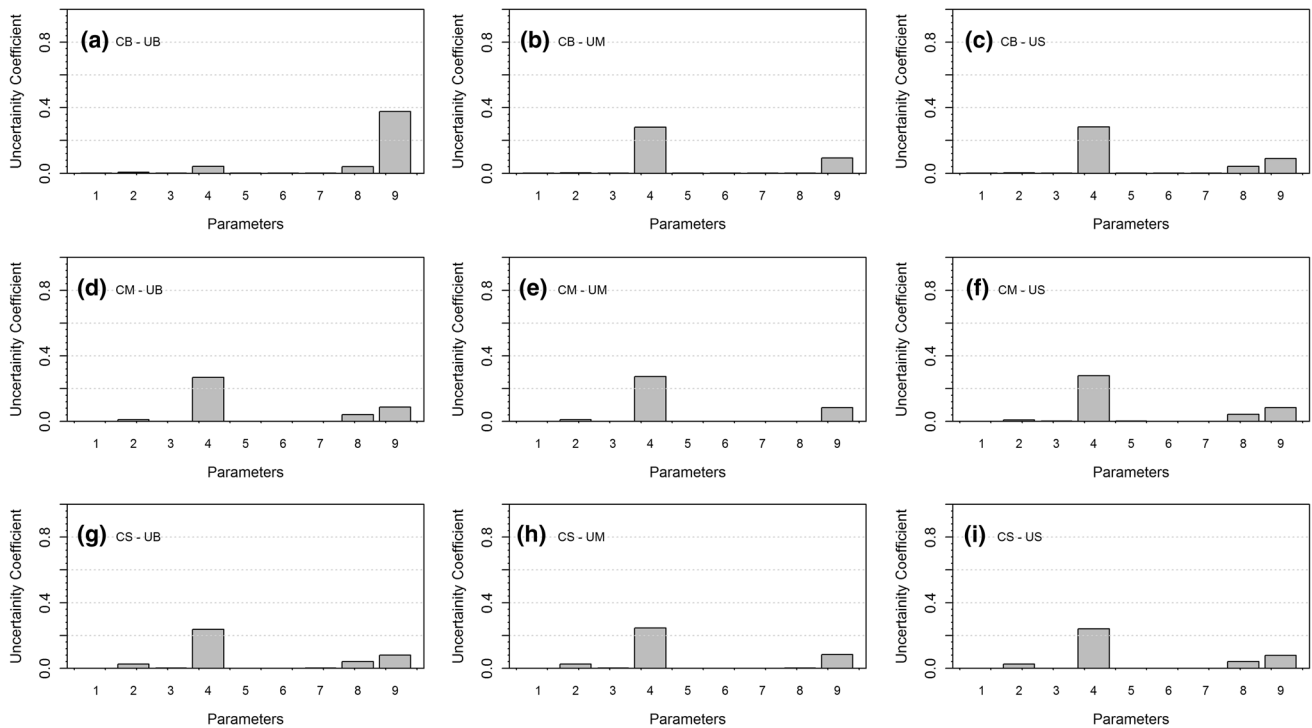
Fig. 7 Uncertainty coefficient of the model inputs measured with respect to maximum toe length metric (see Table 1 for the parameter numbers)

have limited influence on the outputs. Based on the results presented in Figs. 4 and 5, precipitation and recharge fraction have limited influence on the saltwater intrusion into the study area. This result likely stems from the fact that the domain of interest is small and the direct contribution of recharge is extremely small compared to the inflows along the land water boundary. While precipitation effects over the study domain is seen to have limited influence, it is important to recognize that part of the freshwater influx at the landward boundary is due to recharge in the inland areas of the aquifer. The results of the sensitivity analysis also suggest that population density and per capita water demand also have a limited influence on the saltwater intrusion in the study area. This result, in conjunction with the sensitivity of the intrusion metrics to the number of wells, indicates that the nature and extent of the saltwater-freshwater interface is controlled more by where the water is produced than by how much water is being produced. Unfortunately, from a practical standpoint, the result indicates that conservation measures will likely have limited impact on defining the long-term freshwater-saltwater interface in the study area. This result should not be construed to imply that water conservation measures should not be adopted within the region. Clearly, while these measures may have limited impact on the salt water-freshwater interface, they offer advantages, particularly in regulating short-term water use.

Sensitivity concordance among different climate-urbanization scenarios

Assessing the concordance of parametric sensitivity in various climate-urbanization scenarios is useful for both short-term and long-term planning endeavors. The Kendall concordance measures were calculated for eight different scenario combinations and the results are presented in Table 2. The concordance measures, in all cases, are high (typically >0.70) and statistically significant at a 5 % significance level. This result indicates that decision makers can focus on obtaining best possible estimates for the sensitive model inputs identified in Figs. 4 and 5 despite the large uncertainty arising from not knowing future climate or urbanization patterns. The Kendall concordance values for climate scenarios are generally higher than those for the urbanization scenarios. This result reconfirms that changes accompanying urbanization in the study area and the region have a greater impact on defining the saltwater-freshwater interface than the actual sea level rise; therefore, planning for minimizing saltwater intrusion under climate change uncertainty becomes relatively easier if the future urbanization patterns are known with certainty. As water and land are both limited resources for coastal communities in arid and semi-arid regions, it is important that the planning of both these scarce resources be carried out in an integrated manner.

Table 2 Kendall concordance coefficient and significance levels for various climate and urbanization scenarios

S. no.	Description	W-statistic	p value	Remarks
Intruded area				
1	Overall test	0.774	<0.001	Across all 9 climate and urbanization scenarios
2	Climate-base	0.811	0.013	Across 3 urbanization scenarios under baseline climate conditions
3	Climate-moderate	0.785	0.016	Across 3 urbanization scenarios under moderate climate conditions
4	Climate-severe	0.881	0.007	Across 3 urbanization scenarios under severe climate conditions
5	Urban-base	0.911	0.005	Across 3 climate scenarios under baseline urbanization conditions
6	Urban-moderate	0.741	0.023	Across 3 climate scenarios under moderate urbanization conditions
7	Urban-severe	0.904	0.006	Across 3 climate scenarios under severe urbanization conditions
8	Overall test without base scenarios	0.765	<0.001	Across 4 climate and urbanization scenarios excluding the baseline
Maximum toe length				
1	Overall test	0.773	<0.001	Across all 9 climate and urbanization scenarios
2	Climate-base	0.800	0.014	Across 3 urbanization scenarios under baseline climate conditions
3	Climate-moderate	0.807	0.013	Across 3 urbanization scenarios under moderate climate conditions
4	Climate-severe	0.919	0.005	Across 3 urbanization scenarios under severe climate conditions
5	Urban-base	0.881	0.007	Across 3 climate scenarios under baseline urbanization conditions
6	Urban-moderate	0.770	0.018	Across 3 climate scenarios under moderate urbanization conditions
7	Urban-severe	0.896	0.006	Across 3 climate scenarios under severe urbanization conditions
8	Overall test without base scenarios	0.765	<0.001	Across 4 climate and urbanization scenarios excluding the baseline

Summary and conclusions

The primary goal of this study was to develop a decision support system to help regional land and water resources planners in coastal areas of South Texas assess the impacts of climate change and urbanization. The developed system-theoretic framework integrates a sharp-interface coastal aquifer model with data from GCMs and field observations as well as information theoretic uncertainty analysis and statistical evaluation of scenario concordance to assess long-term changes in the freshwater-saltwater interface and help identify salient controls on the saltwater intrusion process. The results of the study indicate that while small shifts in climate are likely to have a relatively higher impact than small-scale urbanization, the rate of inland displacement of the freshwater-saltwater interface is controlled more by urbanization and climate change impacts than the sea level rise. The spatial displacement of the freshwater-saltwater interface is controlled by where (spatial locations) the groundwater is produced more so than how much water is produced. The areal recharge within the study area had limited influence, if any, on the saltwater intrusion. The freshwater influx from hinterlands into the coastal areas has the strongest overall influence on the saltwater-freshwater interface. Freshwater inflow to coastal bays and estuaries are poorly characterized in South Texas. These results suggest that coastal communities must cooperate with water planners and decision makers from the inland areas to ensure adequate groundwater flows to the coastal areas. The concordance of sensitivity measures across various climate-urbanization scenarios indicate that future monitoring and data collection efforts need not be hampered by noted divergences in the results of the general circulation models or plausible alternative urbanization patterns.

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