Uncertainty and Urban Water Recharge for Managing Groundwater Availability: A Case Study and Methods Development for Karst Aquifers

ABSTRACT

Quantifying groundwater availability is dependent upon sound methods and the use of integrated models. To determine availability, or sustainable yield, the influence of scientific uncertainty must be handled appropriately. This work recalculates recharge for one of the Texas Water Development Board's Groundwater Availability Models (GAM) with the goal of evaluating the impact of anthropogenic sources of recharge (leaky utility lines and irrigation return flow), changes in land use and precipitation distribution, as well as the influence of scientific uncertainty on available water balance. Geospatial analysis is used to refine the spatial and temporal components of recharge in an urbanizing aquifer system. Anthropogenic sources of recharge have previously been identified as potential significant contributors to this aquifer system and are thusly emphasized. Methods can be replicated for other systems and results for the test case demonstrate that for peak recharge intervals, irrigation return flow is the most significant anthropogenic contributor. Outcomes are relevant for habitat conservation and drought response planning.

INTRODUCTION

The sustainable yield of a groundwater system requires the quantification of spatial and temporal components. Because sustainable yield looks to quantify the limit of pumping from an aquifer over the long-term (Alley et al. 1999; Sophocleous, 2000) the influence of human-induced change on key parameters, such as recharge, becomes critical for groundwater management. Shifts in the water balance for urbanizing systems are particularly difficult to quantify with precision due to the heterogeneous nature of spatial conditions and rapid rate of change.

We look at reducing uncertainty in a sustainable yield calculation by addressing weak points in the scientific interpretation of recharge. By addressing the nature, or source, of uncertainty as defined in a framework for managing uncertainty (Guillaume et al., 2010), we expect to reduce the influence of imperfect knowledge related to aquifer properties. In particular, we look to decouple the interpretation of recharge for a well studied case in Austin, Texas, USA, such that uncertainty propagation through a model is reduced to the point that relevant policy recommendations can be made. Our case is a well-studied karstic aquifer and numerical Groundwater Availability Model (GAM) for the Barton Springs segment of the Edwards Aquifer (Fig 1).

The Barton Springs segment (BS) is regionally important and has been studied intensively. Previous work has shown that urban land use changes are key drivers in springflow for the aquifer (Garcia-Fresca and Sharp, 2005), urban surfaces are not impervious (Wiles, 2008) , recharge contributions from uplands are on the order of 32% (Hauwert, 2009), and the majority of recharge occurs within stream channels (Slade, 1986 and Barrett and Charbeneau, 1997).

To evaluate the significance of anthropogenic recharge we use the GAM developed by Scanlon et al. (2003) and a Groundwater Decision Support System created by Pierce et al. (2006). The original GAM calculation couples the discharge at Barton Springs with the calculation of effective recharge into the aquifer resulting in a mutually dependent method, or circular logic.

We use geospatial analysis to decouple recharge quantification from springflow using integrated assessment of land use change through time, precipitation calculations with temporal and spatial resolution, and incorporation of three key sources of human-induced recharge from treated water, wastewater, and irrigation.

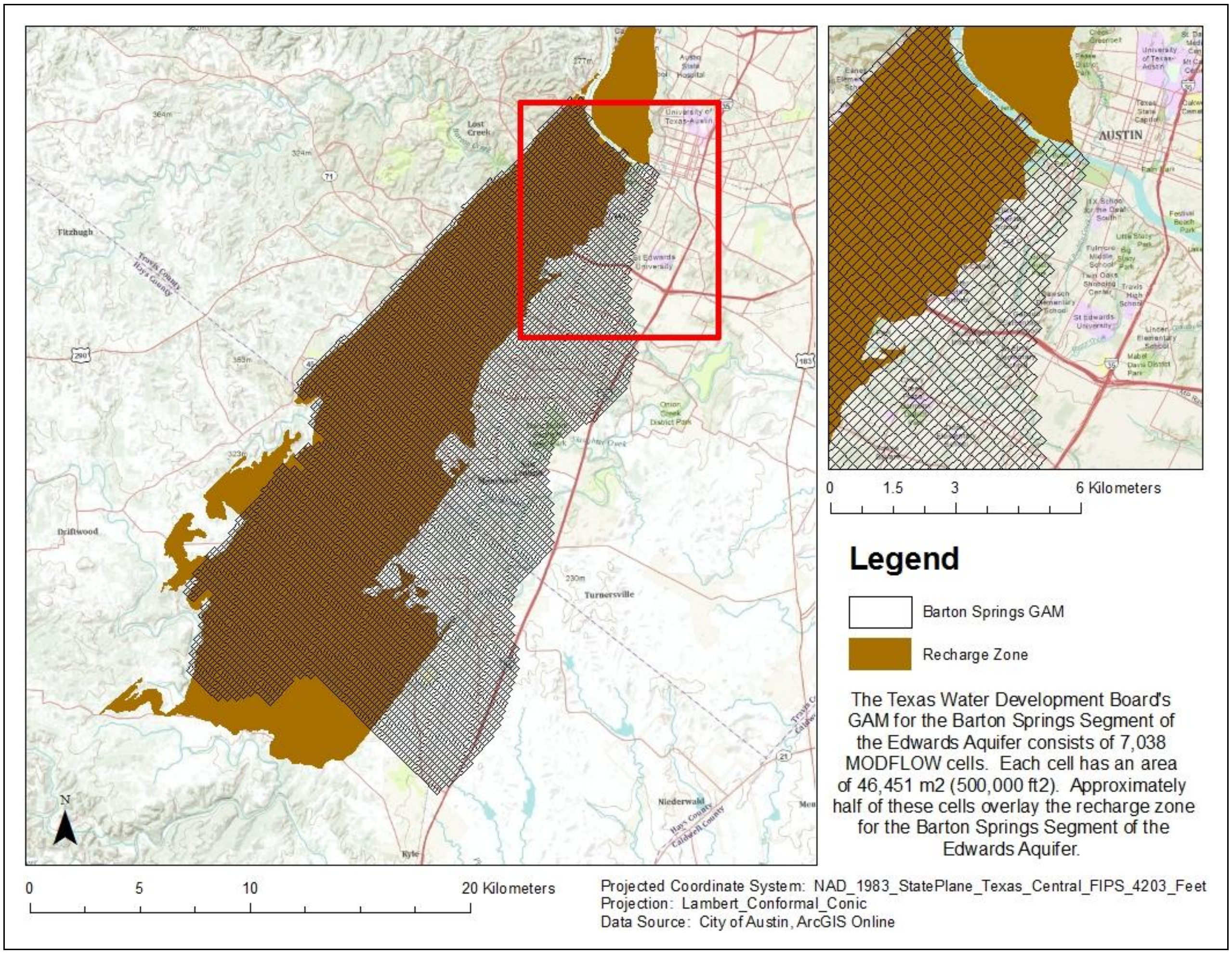


Figure 1. Groundwater Availability Model (GAM) for the Barton Springs segment of the Edwards Aquifer.

METHODS

Sources of recharge for the Barton Springs aquifer are primarily from natural features, such as streams, caves, and direct recharge from precipitation; however, anthropogenic sources such as, leaky water lines, leaky wastewater lines, and irrigation return flows are significant contributors as well. This study focuses on calculations for water lines, wastewater lines, irrigation return flow, and direct recharge from precipitation as a function of land use. The methodology uses a combination of spatial analyses within ArcGIS, new interpretations of aquifer characteristics, and the use of previously unavailable datasets (NEXRAD, City of Austin, Austin Water Utility).

Anthropogenic Recharge

Anthropogenic recharge (R_A) is calculated using the following equations:

$R_A = W_L + W_W + IRF$ **Equation 1**

$W_L = W_D * L_{WL}$ **Equation 2**

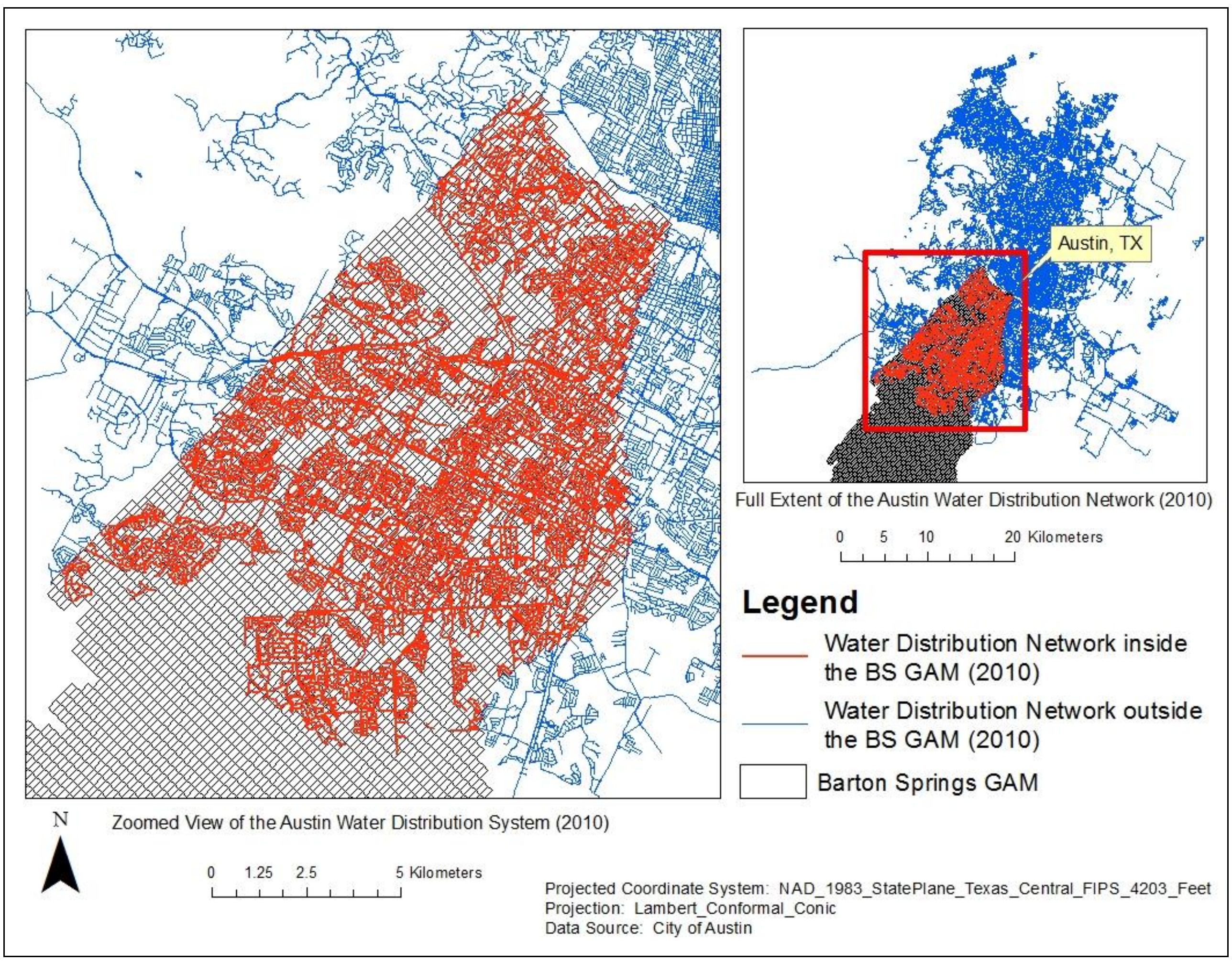
$W_W = [W_T/(1-L_{WW})]*L_{WW}$ **Equation 3**

$IRF = I - PWRi$ **Equation 4**

$I = W_D - W_T$ **Equation 5**

Where W_L, W_W, and IRF are leakage from water lines, leakage from wastewater lines, and irrigation return flow respectively. W_D and W_T are the monthly volumes of water distributed and treated by Austin Water Utility (AWU). L_{WL} and L_{WW} represent the average leakage rates for the water distribution and wastewater networks determined by AWU's water loss studies and Garcia-Fresca and Sharp (2005). Additionally, *I* represents the total irrigation applied to the Austin Water Service Area (WSA) and PWRi is the Plant Water Requirement satisfied by irrigation for the Austin area.

Equations 1 - 5 can be 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 employed to distribute these recharge volumes throughout the BS GAM. For W_L and W_w, ArcGIS shapefiles provided by the City of Austin were utilized to determine the total length of pipe from 1998 - 2010. for each utility network (Fig 2). Leakage volumes were then evenly distributed throughout each utility network to determine a leakage rate for each meter of pipe. Additionally, these shapefiles were then used to calculate the length of each pipe type for each cell of the BS GAM (Fig 2). Lastly, the leakage rates were then applied to each BS GAM cell with known pipe lengths to compute the total recharge from leaky utility lines for each month from 1998 – 2010 (Fig 3).



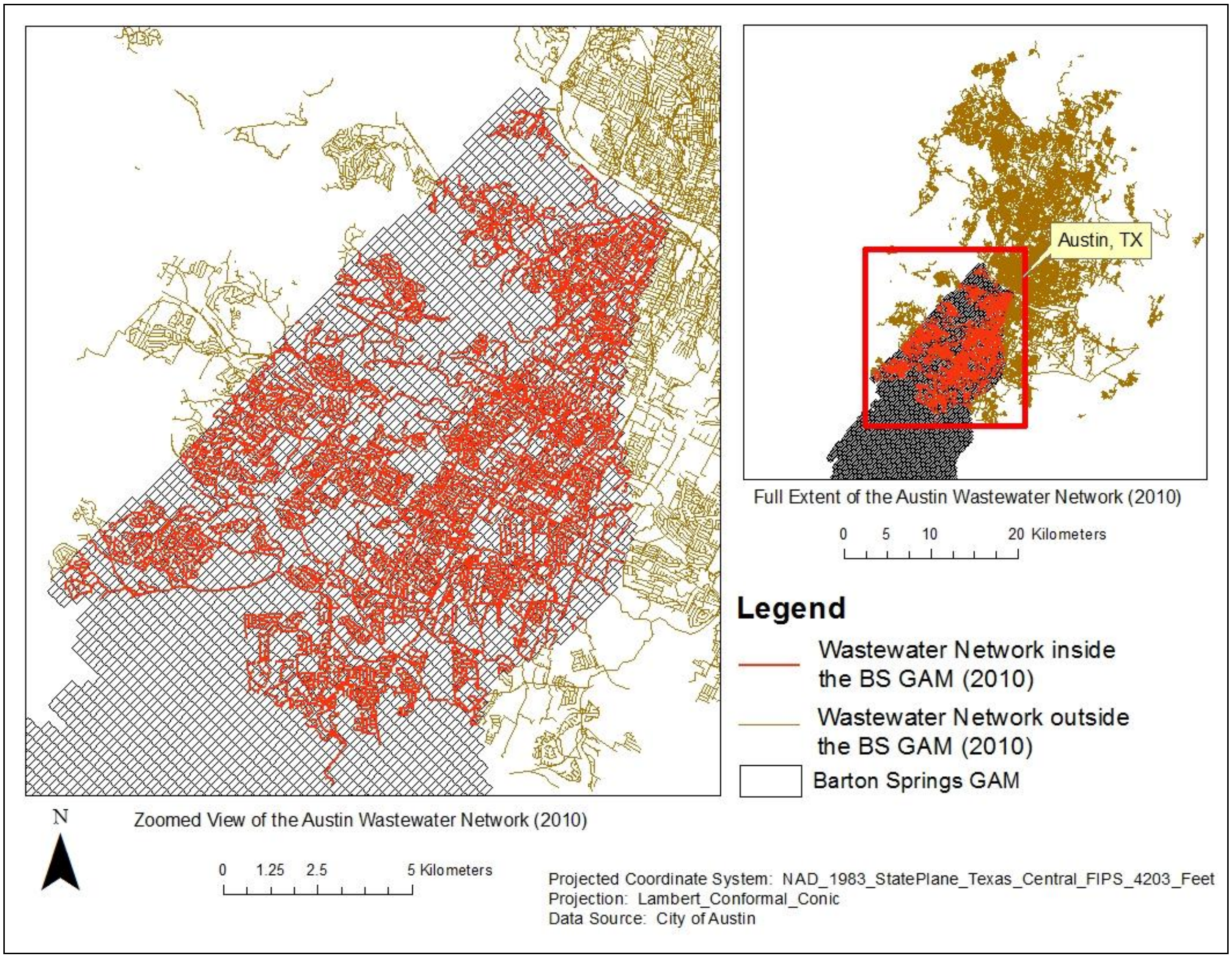
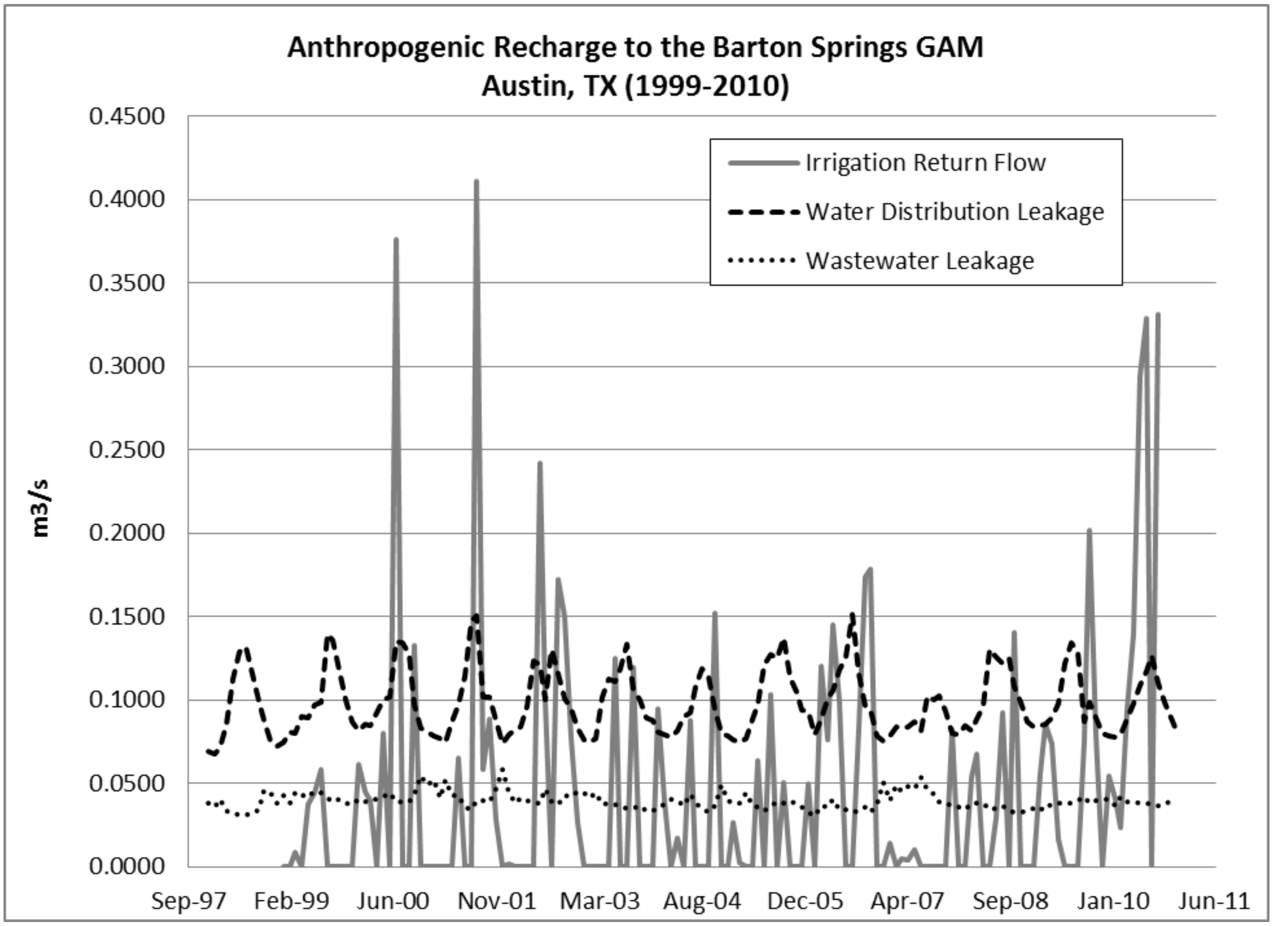
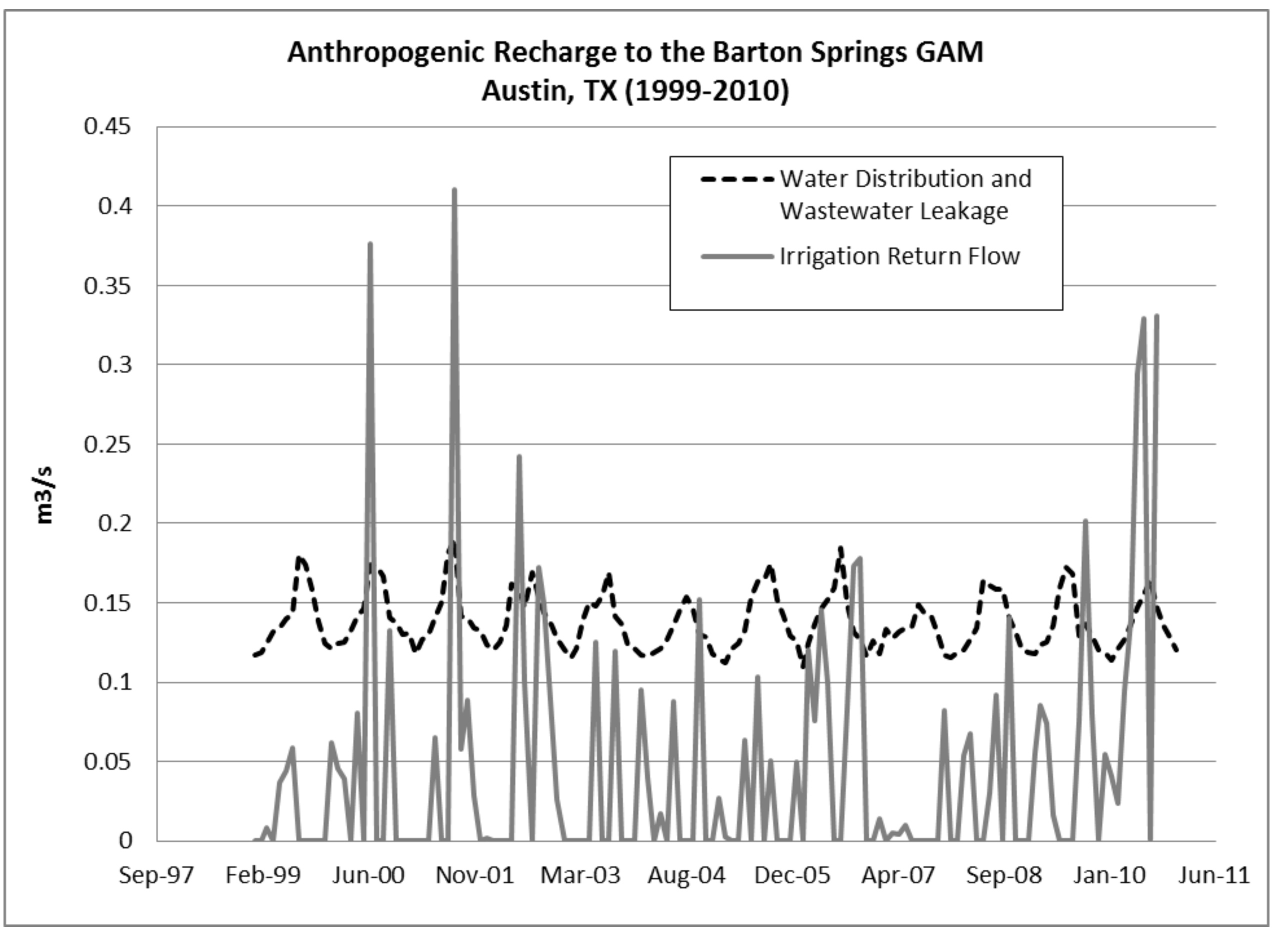


Figure 2. Proportions of the water distribution and wastewater networks that intersect BS GAM for 2010

As seen in Equation 5, irrigation has been designated as the difference between water distributed and wastewater treated. With the data available, it is impossible to determine where this irrigation is being applied; consequently, total irrigation volumes were evenly distributed throughout Austin's WSA. In order to quantify the volume of irrigation return flow to the BS GAM, a shapefile of the WSA was utilized to determine the area of the WSA that intersects each cell of the BS GAM. These areas were then utilized to calculate the volume of irrigation return flow to each cell of the BS GAM from 1999 – 2010 (Fig 3).


Anthropogenic Recharge to the Barton Springs GAM
Austin, TX (1999-2010)
0.4500
0.4000
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
m3/s
Irrigation Return Flow
Water Distribution Leakage
Wastewater Leakage
Sep-97
Feb-99
Jun-00
Nov-01
Mar-03
Aug-04
Dec-05
Apr-07
Sep-08
Jan-10
Jun-11


Anthropogenic Recharge to the Barton Springs GAM
Austin, TX (1999-2010)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
m3/s
Water Distribution and
Wastewater Leakage
Irrigation Return Flow
Sep-97
Feb-99
Jun-00
Nov-01
Mar-03
Aug-04
Dec-05
Apr-07
Sep-08
Jan-10
Jun-11

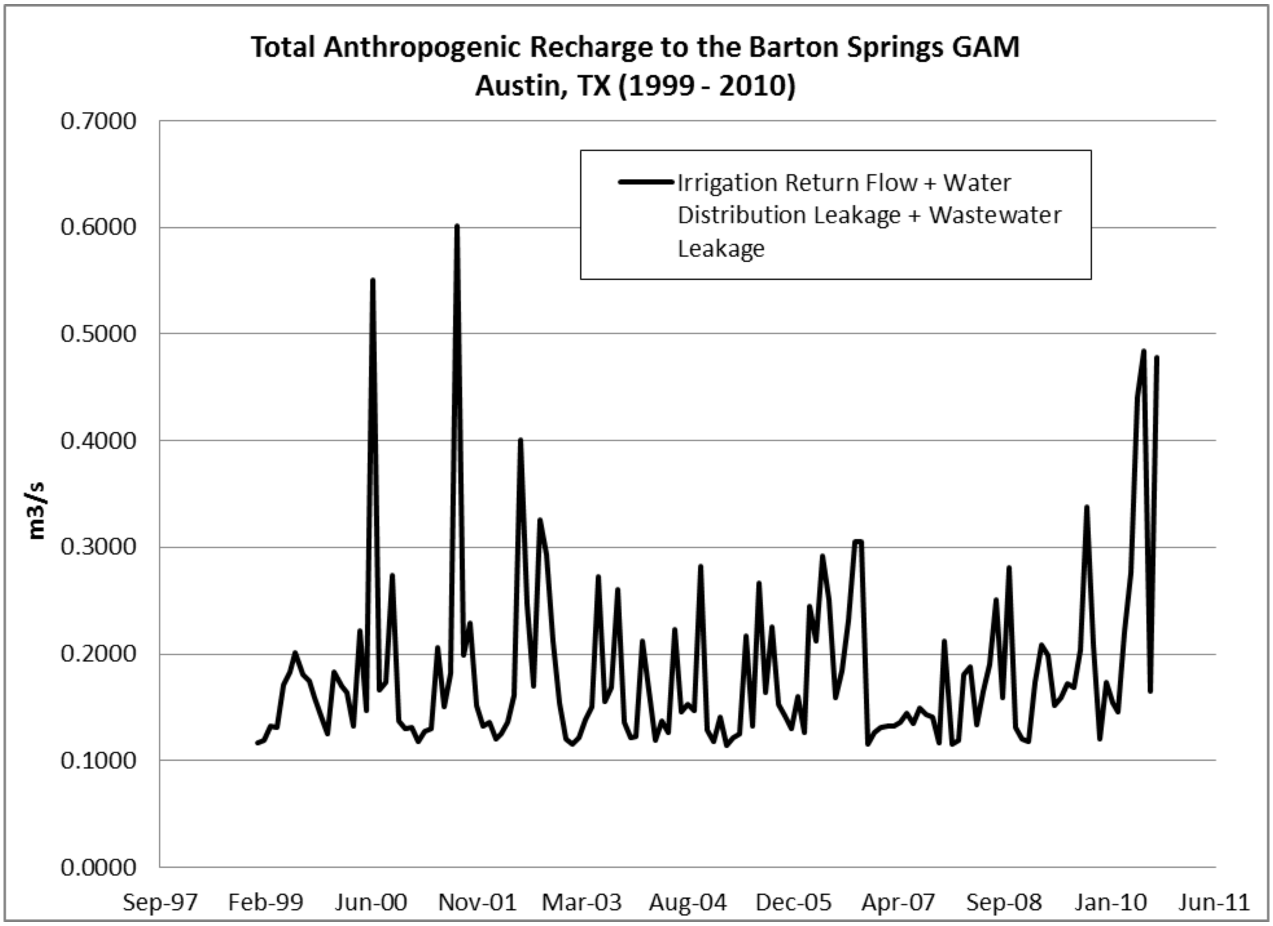


Figure 3. Comparison of various sources of anthropogenic recharge to the BS GAM from 1999 - 2010

Direct Recharge

Direct recharge from precipitation (R_P) was determined using the following equation:

$R_P = (P*0.32*LU_{pervious}) + (P*0.21*LU_{impervious})$ **Equation 6**

Where P represents monthly precipitation, $LU_{pervious}$ is the area of pervious land use, and $LU_{impervious}$ is the area of impervious land use. Based on land use type, infiltration factors of .32 for pervious and .21 for impervious are applied. These infiltration factors are from previous studies of this study site (Wiles, 2007 and Hauwert, XXXX). Monthly precipitation volumes were calculated utilizing NEXRAD and land use data sets. Previously, observations at Camp Mabry, a weather station north of the BS GAM, have been used to characterize precipitation rates and distribution for this area. By employing NEXRAD data, more accurate rates and distribution of precipitation can be determined. Since the NEXRAD shapefiles are point features, they can be used to generate a contour map of precipitation. Utilizing these contour maps and additional spatial analysis tools, the height of precipitation falling on each cell of the BS GAM was determined for each month from 1999 – 2010 (Fig 4). Next, the areas of pervious and impervious land use for each cell of the BS GAM were calculated from City of Austin land use surveys. Each land use type within the surveys (Industrial, Residential, Transportation, etc.) has an average percentage of impervious cover associated with it. Therefore, the area of each land use type was utilized to determine the impervious and pervious cover for each cell of the BS GAM (Fig 5). This was done for years 1990, 1995, 2000, 2003, 2006, and 2008. The areas of impervious and pervious cover determined from these years were applied to years not surveyed. Finally, the height of precipitation and areas of land use can be applied to Equation 6 to calculate the volume of direct recharge for each cell of the BS GAM (Fig 6).

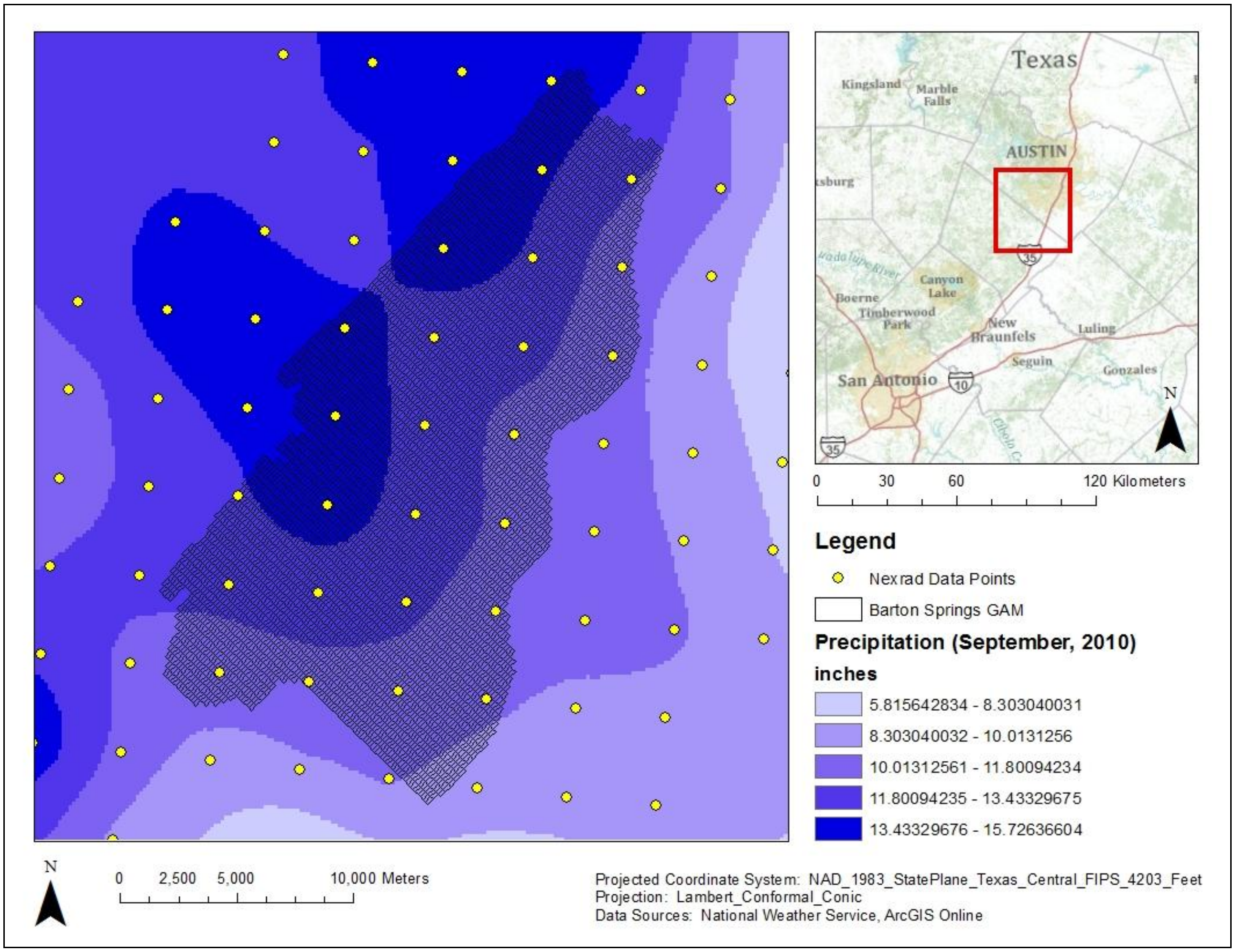


Figure 4. Precipitation distribution over the BS GAM for September, 2010 utilizing NEXRAD data and interpolation techniques within ArcGIS.

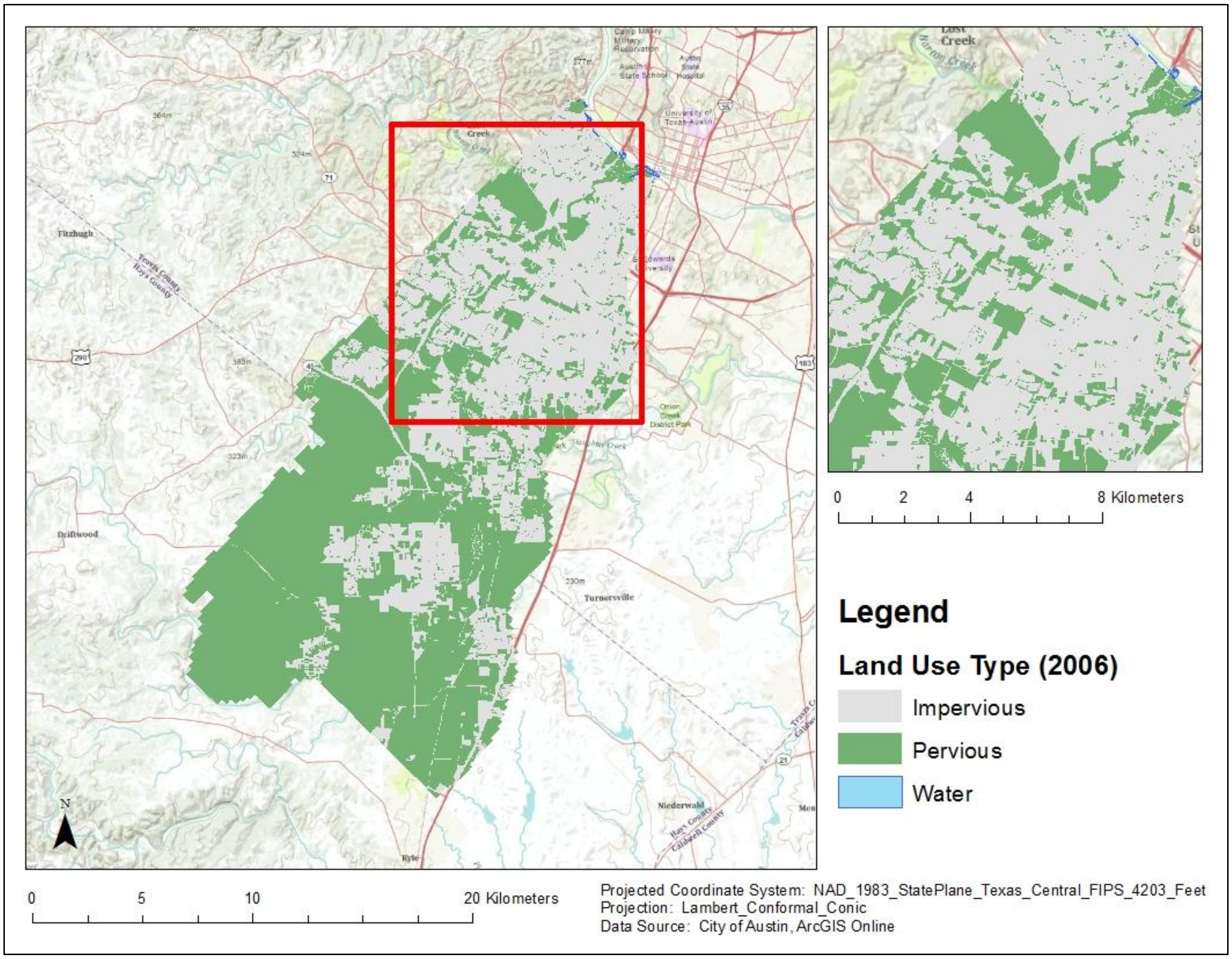


Figure 5. Distribution of impervious and pervious cover over the BS GAM for the year 2006.

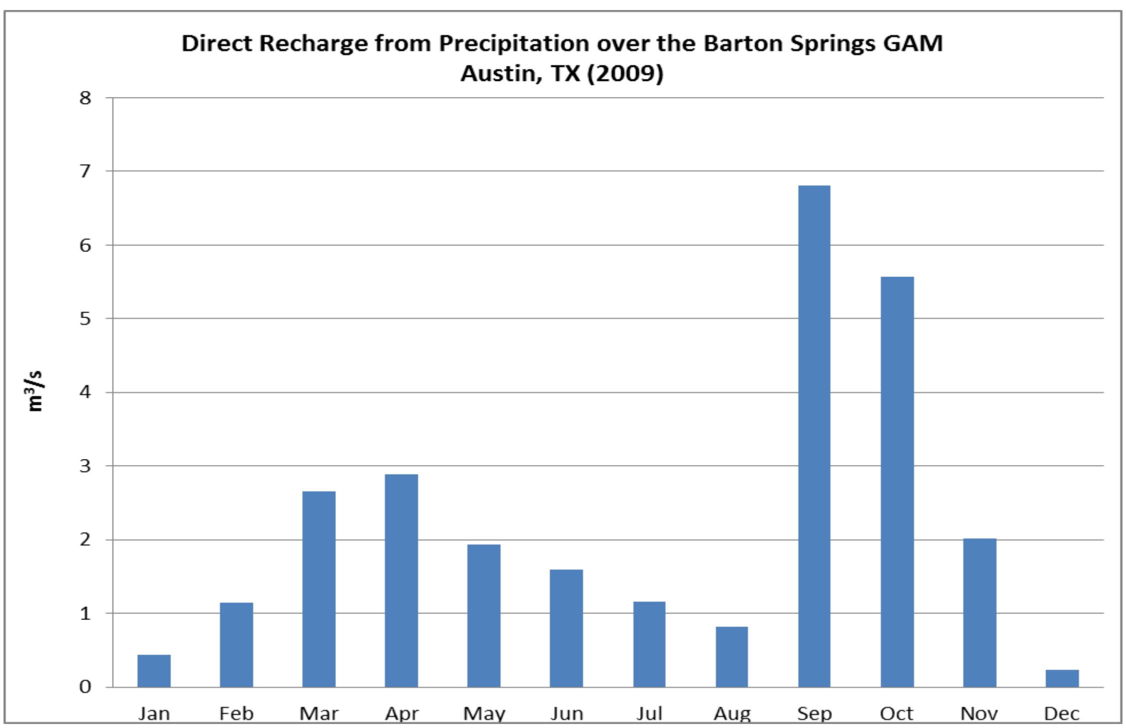


Figure 6. Direct recharge from precipitation over the BS GAM based on NEXRAD data and land use cover distribution for 2009

RESULTS AND DISCUSSION

Analyses show that anthropogenic recharge from leaky water distribution and wastewater pipes, and irrigation return flow are on average 0.100, 0.049, and 0.070 m^3/s respectively. All three recharge sources oscillate between winter and summer months as water demands throughout the year peaks during the summer. These peak recharge intervals coincide with months where lawn irrigation increases; consequently, more water is transmitted through the water distribution network and is therefore available to leak or become irrigation return flow. The range of recharge rates for each source significantly varies. Wastewater leakage has the smallest range of 0.03 - 0.05 m^3/s. Since water for irrigation does not get transported back to treatment plants, an increase in water demand from irrigation does not affect the volume of water that gets treated throughout the year; therefore, there is not an increase in the volume of leakage from the wastewater network from an increase in irrigation demands. Water distribution leakage ranges from 0.06 - 1.51 m^3/s with peaks strongly correlating with summer months. Irrigation return flow has the greatest variance with a range of 0 - 0.41 m^3/s and peaks during the summer months as well. The ranges of these two sources are best explained by the changes in irrigation demand throughout the year. Leakage from water distribution pipes has a more constant rate of recharge since the majority of water distributed is for municipal needs and is independent of the seasons; whereas, irrigation return flow is clearly dependent. It is important to note that during time intervals where water demand for irrigation is high, recharge from irrigation return flow can be twice as large as recharge from both utility networks combined. However, for the majority of the year, recharge from leaky pipes is greater than from irrigation return flow. The average total recharge from anthropogenic sources is 0.20 m^3/s but can range from 0.12 - 0.60 m^3/s.

When analyzing the precipitation data, temporal distribution is most important. On average, the top three wettest months for 1999 – 2010 are June, November, and October. For the year 2009, the average rate of direct recharge was 2.21 m^3/s but ranges from 0.23 - 6.80 m^3/s. In general, direct recharge is greater than anthropogenic sources. For months with large storm events such as September and October of 2009, direct recharge is much greater than anthropogenic recharge; however, for low precipitation months like December and January of 2009 where direct recharge is only 0.23 and 0.44 m^3/s respectively, anthropogenic sources can be greater.

CONCLUSIONS

Results of this research successfully decouple recharge calculations from springflow discharge such that the source of uncertainty is reduced. By using an integrated representation of anthropogenic recharge components, input values for the groundwater model reflect actual conditions more closely. Interestingly, results indicate that anthropogenic contributions from water and wastewater lines can be more or less significant than irrigation return flow for increasing the overall yield quantity for the case study aquifer. This is dependent upon the time of year and consequently the demand for irrigation. All human-induced recharge is important for habitat conservation planning, because contributions maintain flows during critical drought periods for this aquifer.

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