The Evolution of Urban Heat Island and Water Demand

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Abstract

Urban water demand in the arid Southwestern U.S. is influenced by the type, age, and structure of residential and public landscaping. Urban heat island (UHI) coupled with regional climate change have important impacts on urban water demand. Results show that Tucson, Arizona is warming at 0.067 degrees C per year (equivalent to a 1 degree C increase in 15 years). Due to UHI Tucson is warming at 0.040 degrees C per year faster than surrounding nonurban areas (equivalent to a 1 degree C difference in 25 years). The pre-monsoon period (particularly Feb-May) exhibit the most pronounced UHI effects with a high degree of statistical significance. Compared to 1969-1999 results, the rate of urban warming still remains greater than the regional warming trend, but that the rate of UHI urban-nonurban T_{min} divergence has decreased, which is partially attributed to evapotranspiration (ET) from irrigated urban vegetation. This paper attempts to relate 2000 – 2006 residential water use in Tucson to Penman-Monteith potential evapotranspiration (ET_{ref}) derived from weather station data. ET_{ref} exhibits increasing trends for the months of December – May, but declining trends for June – November. The effects of temperature increases on ET_{ref} are offset by decreases in wind speed, possibly related to vegetation-induced changes in surface roughness. Geospatial analysis of normalized difference vegetation index (NDVI) and surface temperature derived from 1984 – 2005 Landsat Thematic Mapper imagery demonstrate the evolution of urban spatial patterns with stable NDVI of mature vegetation in the older urban core contrasted by increasing NDVI in the expanding urban fringes. Spatially disaggregated urban water use is shown to have similar patterns and follow similar temporal trends. The UHI implications of urban landscaping are discussed.

Introduction

Urban heat island (UHI) and climate change-driven warming across the Southwest have implications for water use. Researchers and planners have paid inadequate attention to spatial and temporal patterns in urban warming or the implications of these patterns for urban water demands, particularly for outdoor residential irrigation. This study investigates urban warming and water use in the Tucson, Arizona basin. The research objectives are to a) characterize UHI temporal trends, b) assess impacts on outdoor residential water demand of temperature and reference evapotranspiration (ET) trends, c) measure NDVI temporal trends and spatial patterns, and d) review UHI mitigation potential of irrigated vegetation.

Methodology

Archival Landsat Thematic Mapper (TM) imagery was accessed from the Arizona Regional Image Archive (aria.arizona.edu). Only those images with antecedent precipitation less than 300 mm in the 90-day period preceding the image date as recorded at the Campbell Ave. station (Coop ID 028796) were used for analysis in order to minimize the effects of vegetation greening resulting from natural precipitation (Figure 1).

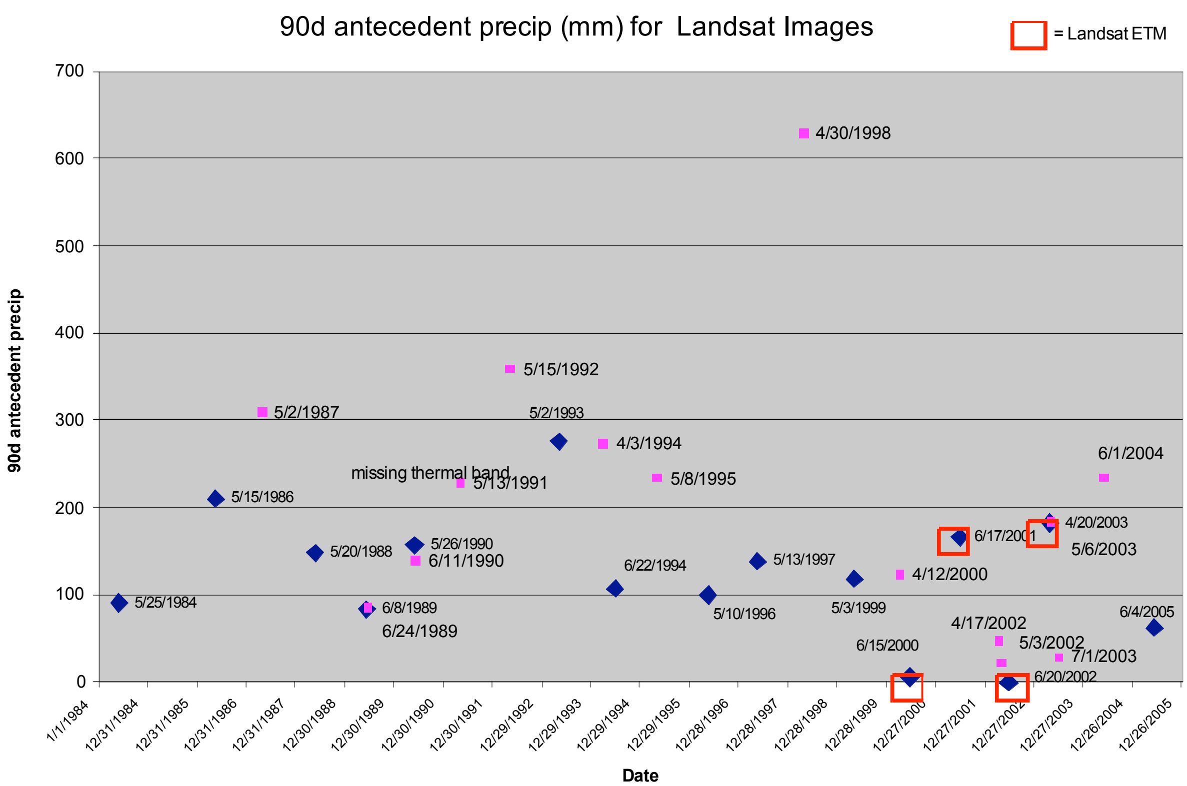

Figure 1. Landsat TM Image Acquisition Dates and 90-day Antecedent Precipitation

TM images were registered and rectified to an orthophoto-derived street map shapefile from Pima Co. Dept. of Transportation resulting in root mean square error RMSE < 15 m (equivalent to half the minimum pixel resolution). The normalized difference vegetation index (NDVI) was calculated from TM imagery using COST-model (Chavez, 1996) atmospherically corrected band 3 (red) and band 4 (near infrared) radiances as follows:

$$NDVI = (B4-B3) / (B4+B3)$$

Surface temperatures were retrieved from TM band 6 (thermal infrared) by converting thermal brightness temperatures into thermodynamic (kinetic) temperatures. We accessed an ASTER image from 5/26/2001, with a processed emissivity layer at 90m. The Landsat NDVI for 6/18/2001 (closest date to the ASTER image) was resampled from 30 m to 90 m, and a per-pixel regression of Landsat NDVI vs. ASTER NDVI yielded $R^2 > 0.98$ indicating reliable NDVI results. Subsequently, we regressed ASTER emissivity vs. Landsat NDVI with $R^2 > 0.36$ and selected the quadratic equation with the best fit in the NDVI range of interest (0.2 ~ 0.7). Finally, kinetic temperature maps were calculated from emissivity and radiant temperatures as:

$$T_{kinetic} = E^{0.25} * T_{radiant}$$

Climatological data were accessed from the National Climatic Data Center (ncdc.noaa.gov) and the Arizona Meteorological Network (AZMET, ag.arizona.edu/azmet). Table 1 lists the meteorological stations used for the urban warming analysis. The analysis period was selected to start from 1/1/1969 in order to allow comparison with, and extend analysis of previous UHI characterization for Tucson by Comrie (2000). Data for 2008 were reviewed but not included, principally due to the fact that Tucson WFO #028815 ceased recording from February 2008. For 1969-2007 and 1984-2005 (the latter corresponding to the period of Landsat record), monthly trend analysis of urban T_{min} and T_{max} were compared to nonurban T_{min} and T_{max}. The urban – nonurban difference in T_{min} provides the rate of warming resulting from UHI processes.

Additional trend analyses were performed on reference evapotranspiration (ET_{ref}) for urban and nonurban stations for the full 1987-2008 time series available from AZMET.

Table 1. Meteorological Stations and Data Analyzed

Station	Urban/ Nonurban	Data Analyzed
Tucson Campbell Ave. #028796	Urban	T_{min}, T_{max}, Precip, ET_{ref}
Tucson WFO #028815	Urban	T_{min}, T_{max}, Precip
Tucson Intl Airport #028820	Urban	*Excluded (due to cold air drainage effects)*
Anvil Ranch #020287	Nonurban	T_{min}, T_{max}, Precip
Cascabel #021330	Nonurban	T_{min}, T_{max}, Precip
Oracle 2SE #026119	Nonurban	T_{min}, T_{max}, Precip
Santa Rita Exp Range #027593	Nonurban	T_{min}, T_{max}, Precip
Safford #027390	Nonurban	T_{min}, T_{max}, Precip, ET_{ref}

Water supply data at township, range, section, and quarter level for 2000-2006 were made available by the public water utility, Tucson Water. Quarter section data of individual months (Jan., Feb., …) and annual total water volumes supplied by Tucson Water were assessed over the 2000-2006 period of record.

Results and Discussion

Quantification of the urban heat island is shown in Tables 2 and 3 (and graphically in Figures 2 and 3), for 1969-2007 and the Landsat period of record 1984-2005, respectively. The 1969-2007 T_{min} results indicate lower warming rates of urban and nonurban stations, and a less marked UHI (their difference) than reported by Comrie (2000). These data analysis indicate that Tucson is warming at 0.067 degrees C per year (equivalent to a 1 degree C increase in 15 years). Due to UHI Tucson is warming at 0.040 degrees C per year faster than surrounding nonurban areas (equivalent to a 1 degree C difference in 25 years). The pre-monsoon period (particularly Feb-May) exhibit the most pronounced UHI effects with a high degree of statistical significance.

The 1984-2005 urban-nonurban differences are lower than for 1969-2007 for the pre-monsoon period of interest (May and June). Further analysis of NDVI imagery and surface temperatures for established urban development areas within Tucson vs. newly developed areas will permit analysis of the degree to which outdoor irrigation depresses urban temperatures. This has significance for adaptation to warming, and also for Tucson's water budget.

While T_{max} is not an indicator of UHI per se, it has an important effect on vegetative water demand. Table 4 shows T_{max} trends for the full 1969-2007 meteorological period of record.

However, the real implications of changing climate for outdoor water demand is expressed in ET_{ref} (and the degree to which irrigation supplies plants with sufficient moisture so that actual ET is close to ET_{ref}). Additional analyses were undertaken of Penman-Monteith reference evapotranspiration (ET_{ref}) trends over time for one of the same urban stations (Campbell Ave. #028796) and for the closest nonurban station (Safford #027390) for which ET_{ref} data were available. These results, presented in Table 5 and Figure 4, are significant because they indicate that the most rapid increases over the time period 1987-2002 occur during the pre-monsoon months of February – April, but with only a modest increase in May and declining trends the remainder of the year. Little difference is discernible between urban and nonurban ET_{ref} over the full 1987-2008 time period, suggesting that minimum temperature as measured by our Landsat TM analysis is only part of the effect on evapotranspiration and thereby on outdoor residential irrigation demand.

Table 2. Annualized 1969-2007 Minimum Temperature Trends (Linear Slope Coefficients of Monthly Mean Minima at Urban and Nonurban Sites, deg C yr^{-1}) and their Differences with Significance

Month	Urban	Nonurban	Difference	Significance $p <$
Jan	0.051	0.010	0.041	0.001
Feb	0.062	-0.001	0.063	0.001
Mar	0.090	0.019	0.071	0.001
Apr	0.099	0.028	0.070	0.001
May	0.109	0.051	0.058	0.001
Jun	0.087	0.045	0.042	0.001
Jul	0.044	0.019	0.025	0.01
Aug	0.053	0.026	0.027	0.001
Sep	0.063	0.024	0.039	0.001
Oct	0.067	0.035	0.032	0.01
Nov	0.070	0.046	0.024	0.05
Dec	0.015	-0.014	0.029	0.01
Annual	0.067	0.027	0.040	0.001

2 urban stations (Campbell Ave #28796, Tucson WFO #28815) & 4 nonurban stations (Anvil Rnch #20287, Cascabel #21330, Oracle 2SE #26119, Santa Rita Exp Rng #27593)

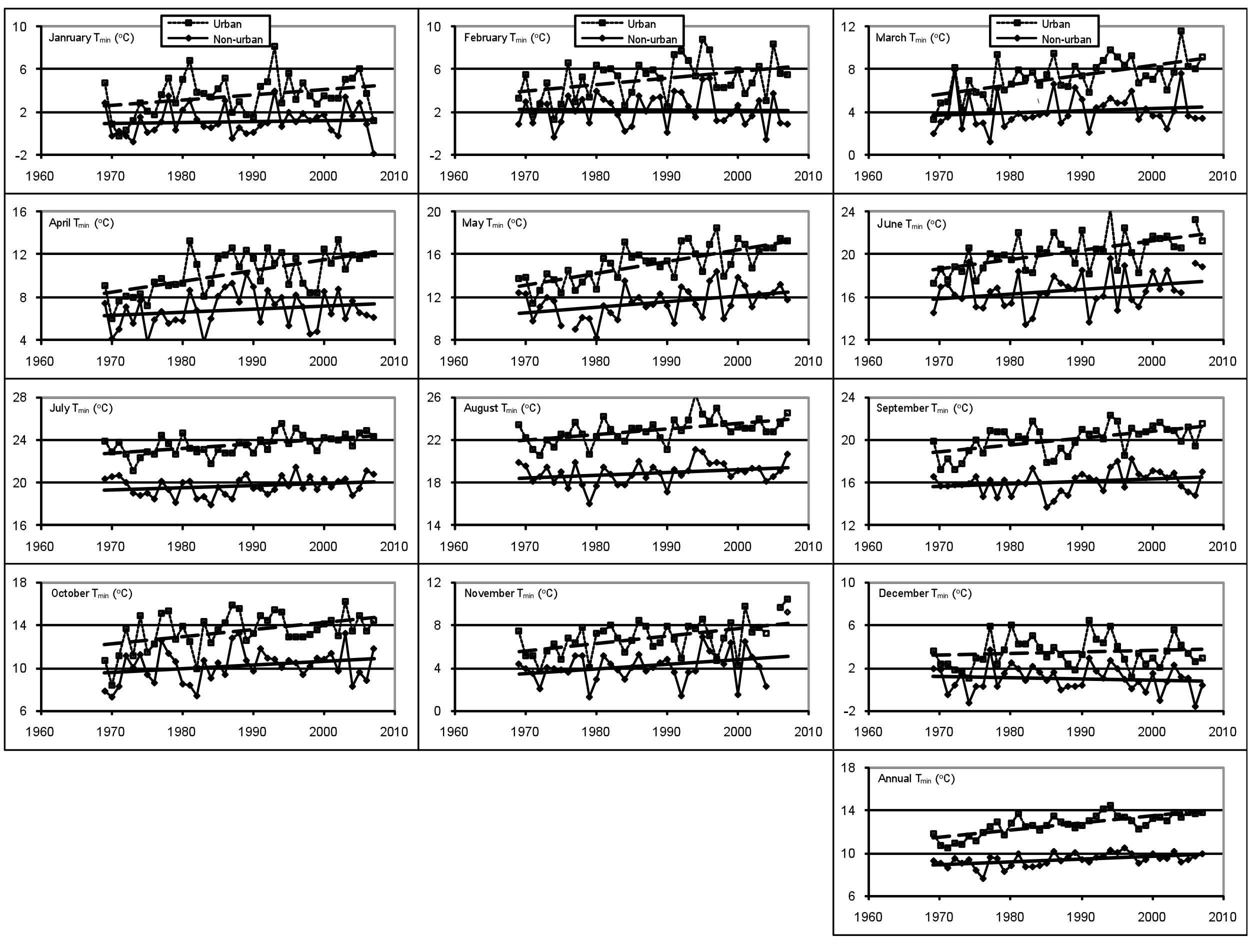

Figure 2. Urban and Nonurban Minimum Temperature (deg C), 1969-2007

Table 3. Annualized 1984-2005 Minimum Temperature Trends (Linear Slope Coefficients of Monthly Mean Minima at Urban and Nonurban Sites, deg C yr^{-1}) and their Differences with Significance

Month	Urban	Nonurban	Difference	Significance $p <$
Jan	0.060	0.058	0.002	
Feb	0.031	-0.003	0.034	
Mar	0.053	0.000	0.053	0.01
Apr	-0.003	-0.081	0.077	0.001
May	0.030	0.024	0.006	
Jun	0.022	0.011	0.011	
Jul	0.074	0.038	0.036	0.05
Aug	0.034	0.015	0.019	
Sep	0.097	0.071	0.026	
Oct	0.009	-0.024	0.034	
Nov	0.034	0.025	0.008	
Dec	-0.001	-0.010	0.009	
Annual	0.036	0.008	0.028	

2 urban stations (Campbell Ave #28796, Tucson WFO #28815) & 4 nonurban stations (Anvil Rnch #20287, Cascabel #21330, Oracle 2SE #26119, Santa Rita Exp Rng #27593)

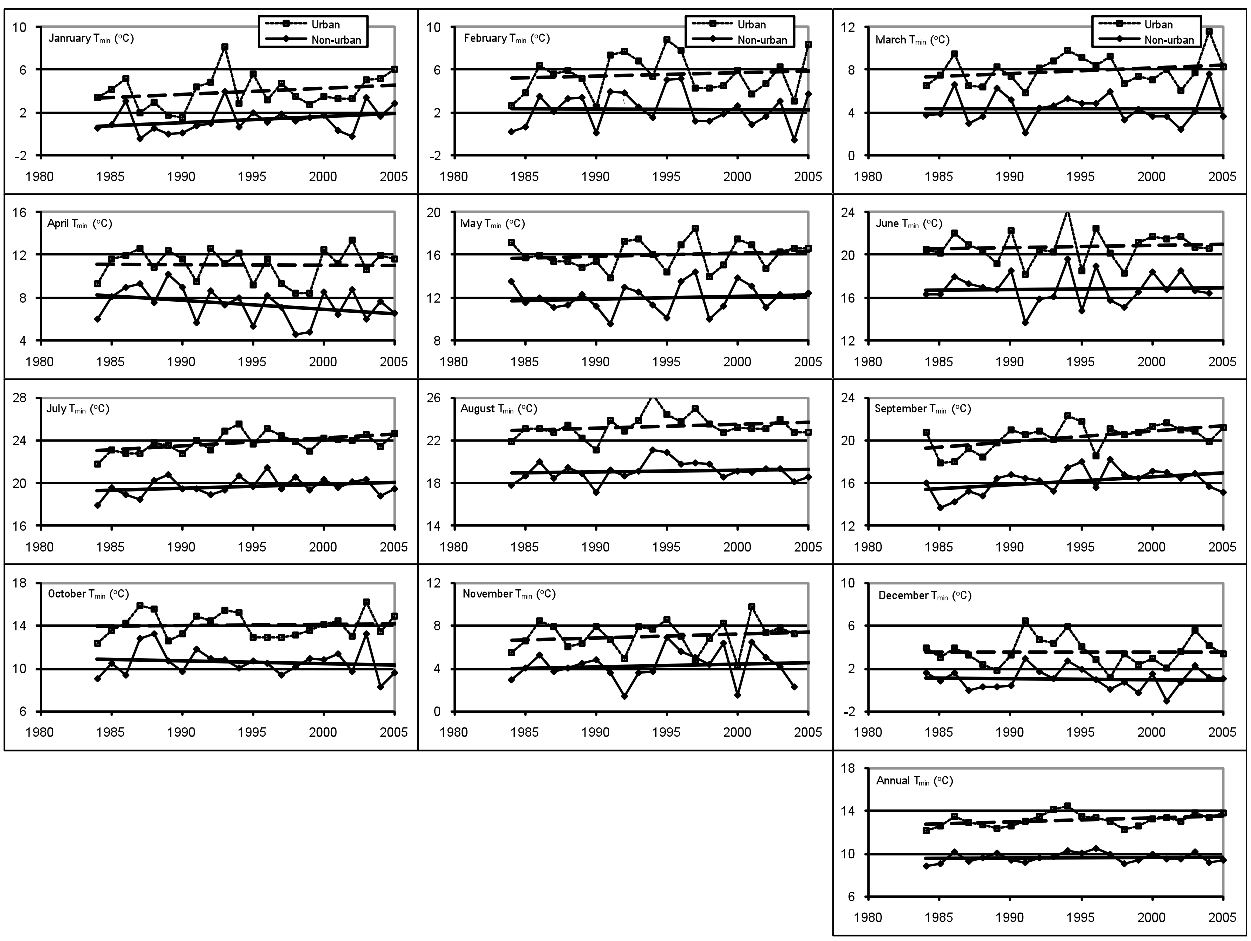

Figure 3. Urban and Nonurban Minimum Temperature (deg C), 1984-2005

Table 4. Annualized 1969-2007 Maximum Temperature Trends (Linear Slope Coefficients of Monthly Mean Maxima at Urban and Nonurban Sites, deg C yr^{-1}) and their Differences with Significance

Month	Urban	Nonurban	Difference	Significance p <
Jan	0.014	-0.007	0.022	0.001
Feb	-0.020	-0.037	0.017	0.01
Mar	0.043	0.017	0.026	0.001
Apr	0.018	-0.001	0.019	0.001
May	0.053	0.051	0.002	
Jun	0.013	-0.001	0.015	0.05
Jul	-0.004	-0.005	0.000	
Aug	-0.021	-0.031	0.010	
Sep	0.015	0.004	0.011	
Oct	0.039	0.022	0.017	0.01
Nov	0.020	-0.009	0.028	0.01
Dec	-0.023	-0.048	0.025	0.001
Annual	0.011	-0.020	0.031	0.05

2 urban stations (Campbell Ave #28796, Tucson WFO #28815) & 4 nonurban stations (Anvil Rnch #20287, Cascabel #21330, Oracle 2SE #26119, Santa Rita Exp Rng #27593)

Table 5. Annualized 1987-2008 Reference Evapotranspiration Trends (Linear Slope Coefficients of Monthly Mean ET at Urban and Nonurban Sites, mm d^{-1} yr^{-1}) and their Differences with Significance

Month	Urban	Significance p <	Nonurban	Significance p <	Difference Urban - Nonurban	Significance p <
Jan	0.023		0.032		-0.008	
Feb	0.017		0.036		-0.020	0.05
Mar	0.036		0.036		0.000	
Apr	0.028		0.029		-0.001	
May	0.021		0.020		0.001	
Jun	-0.033		-0.029		-0.004	
Jul	-0.042	0.05	-0.048		0.006	
Aug	-0.031	0.05	-0.018		-0.012	
Sep	-0.048		-0.035		-0.013	
Oct	-0.016		-0.011		-0.005	
Nov	-0.004		-0.008		0.004	
Dec	0.023		0.022		0.001	
Annual	-0.002		0.002		-0.004	

1 urban station (Campbell Ave #28796) & 1 non-urban station (Safford #27390)

Additional analyses were undertaken to investigate why ET_{ref} trends appear to be time-invariant despite increases in both T_{min} and T_{max}. Time series analyses of relative humidity and radiation resulted in indiscernible trends; however, wind speed demonstrated significant decreasing trends that were also observed at other AZMET stations in the vicinity of Tucson (Table 6 and Figure 5). Whether these trends are related to increased surface roughness from vegetation and other features (e.g., the built environment near urban stations), or the result of synoptic processes remains under investigation.

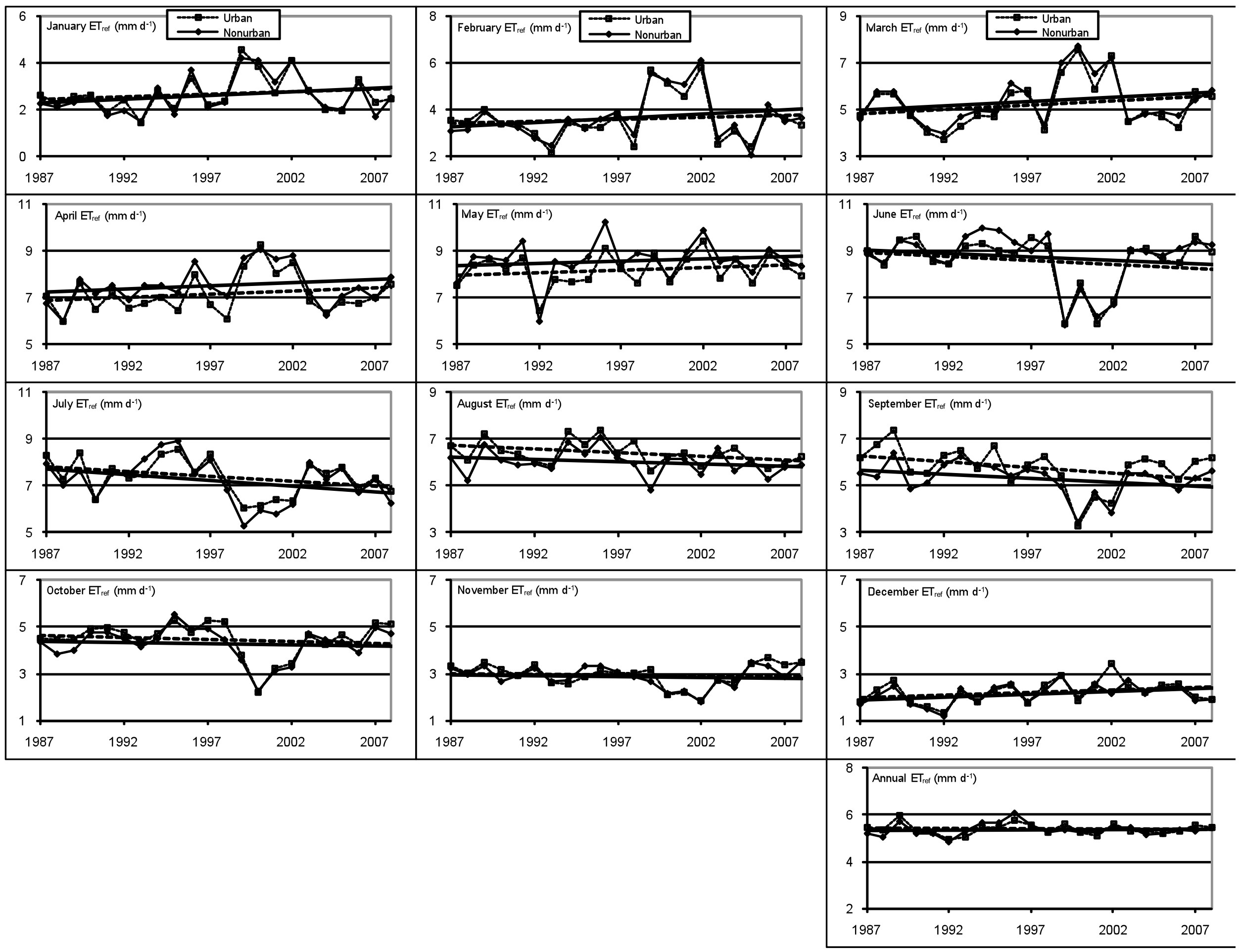

Figure 4. Urban and Nonurban Reference Evapotranspiration (mm/day), 1987-2008

The ET_{ref} results in general lack statistical significance, with the exception of the months of August and September, which show declining trends for urban – nonurban ET_{ref}, and December, which shows a modestly positive difference with increasing urban ET_{ref}. Given these indeterminate ET_{ref} results, the positive trends in T_{min} discussed above and as measured by our Landsat TM analysis would appear to have marginal effect on evapotranspiration and thereby on outdoor residential irrigation demand.

Figure 6 summarizes the results of the water supply data analysis. Outdoor residential use was derived assuming a base indoor requirement of 40 gallons per capita per day, which resulted in an estimated 41% of total supply being used for outdoor irrigation. The balance of 59% indoor use is corroborated by wastewater volumes received at the city's wastewater treatment plants (City of Tucson, 2004). We ran regressions of total annual water supply by section and derived annual outdoor water by section on the following independent variables: year, annual precipitation, and annual ET_{ref}. Additionally we ran regressions of April-May-June (AMJ) water supply by section and derived AMJ outdoor water by section on the following independent variables: year, AMJ precipitation, and AMJ ET_{ref}. As expected, the sections with high NDVI exhibited the most statistically significant results for AMJ total water vs. AMJ ET_{ref}. In general the regression results were weaker for derived outdoor water than for total water supply.

Table 6. Annualized 1987-2008 Wind Speed Trends (Linear Slope Coefficients of Monthly Mean Wind Speed at Urban and Nonurban Sites, mm d^{-1} yr^{-1}) and their Differences with Significance

Month	Tucson (urban)	Signif. p <	Marana (urban)	Signif. p <	Safford (nonurban)	Signif. p <	Bonita (nonurban)	Signif. P <
Jan	-0.023	0.01	-0.024	0.001	-0.021	0.01	-0.013	
Feb	-0.026	0.001	-0.028	0.001	-0.025	0.001	-0.020	0.001
Mar	-0.013	0.01	-0.026	0.001	-0.023	0.01	-0.021	0.001
Apr	-0.009		-0.020	0.01	-0.012		0.000	
May	-0.018	0.001	-0.036	0.001	-0.021	0.01	-0.010	0.05
Jun	-0.006		-0.020	0.01	-0.013	0.05	-0.009	
Jul	-0.011		-0.021	0.05	-0.027	0.001	-0.010	0.05
Aug	-0.026	0.001	-0.018	0.01	-0.035	0.001	-0.016	0.01
Sep	-0.026	0.001	-0.012		-0.028	0.001	0.002	
Oct	-0.012		-0.001		-0.010		0.009	
Nov	-0.023	0.001	-0.010		-0.021	0.05	-0.015	
Dec	-0.021	0.001	-0.014	0.05	-0.019	0.01	-0.022	0.01
Annual	-0.018	0.001	-0.019	0.001	-0.021	0.001	-0.010	0.001

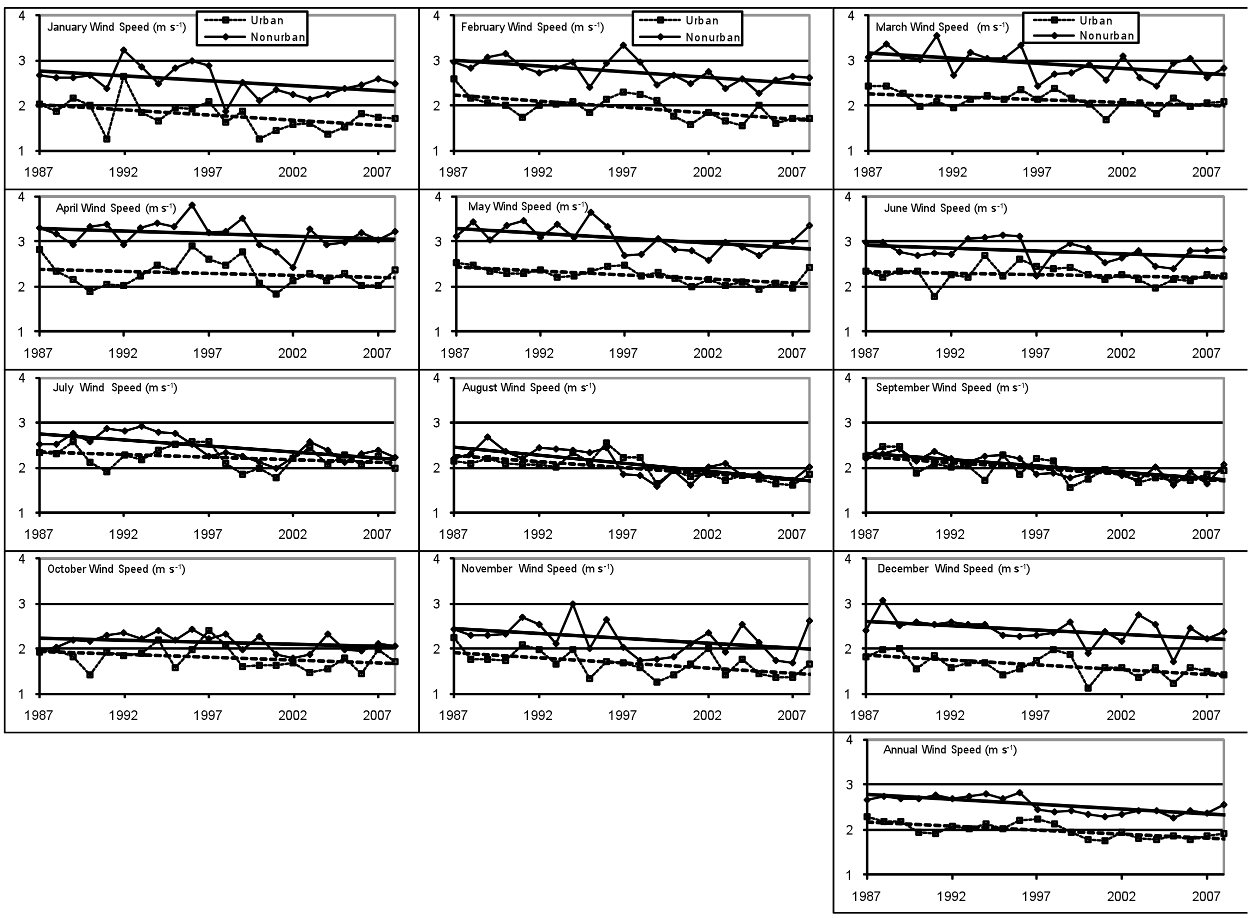

Figure 5. Urban and Nonurban Wind Speed (m/sec), 1987-2008

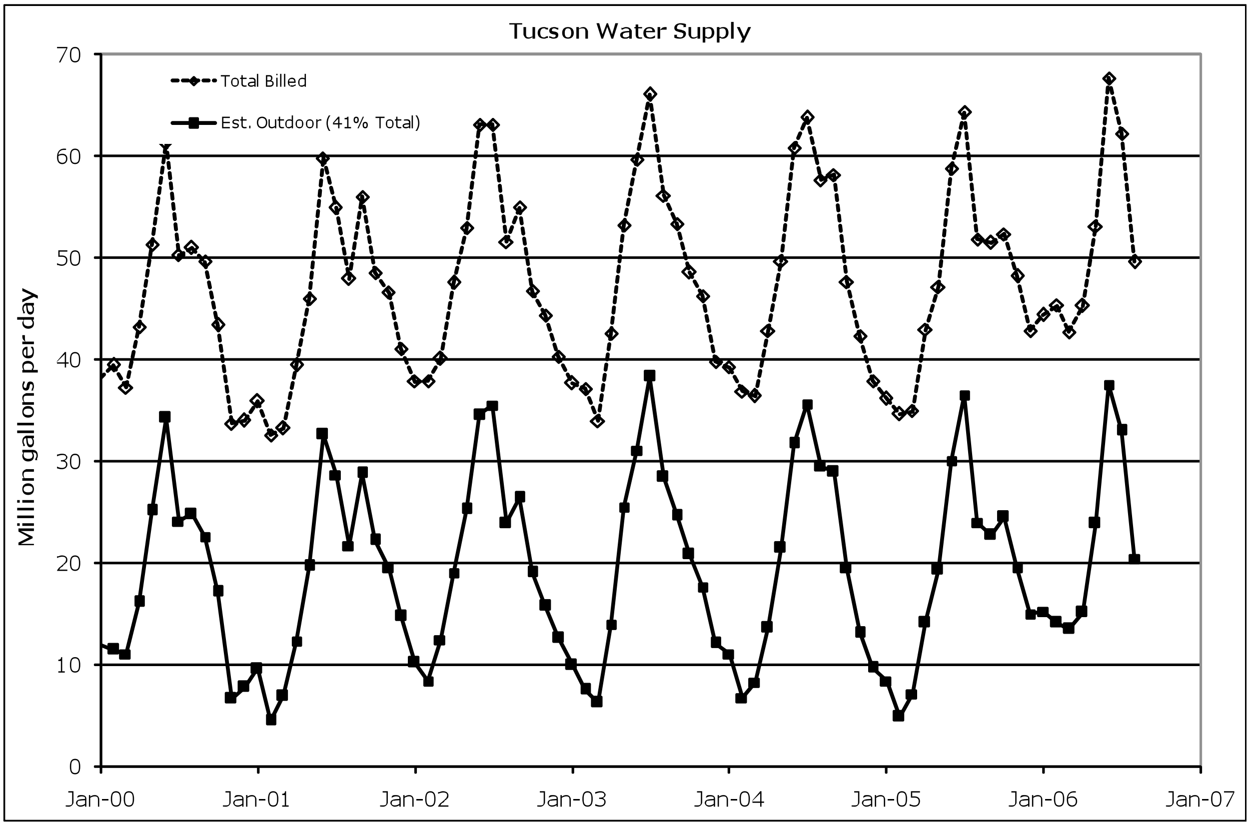

Figure 6. Water Supply and Estimated Outdoor Use

The NDVI time series shown in Figure 7 for central Tucson demonstrates urban growth and the resulting maturation of vegetation principally along the southeast-northwest I-10 corridor and in the Catalina foothills. NDVI values were aggregated at the quarter section level. In order to eliminate high NDVI caused by turf grass irrigated using reclaimed water not included in these water supply data, we eliminated quarter sections with golf courses, public parks, and schools. The remaining sections represented residential and commercial areas of the city, and vegetation trends would respond to natural precipitation and irrigation from the potable supply system for which we had access to data.

The kinetic temperature analysis is illustrative for the spatial patterns observed, particularly the heat sources that dry riverbeds and washes represent (Figure 8). This raises interesting questions about the potential heat mitigation role played by riparian vegetation.

Figures 9 and 10 show times series trends of total water supplied for quarter sections with the greatest rate of increase (Fig. 9) and the greatest rate of decrease in water supplied (Fig. 10). What is particularly notable is that the number of sections with increasing water supply far exceeded the number of sections with decreasing supply.

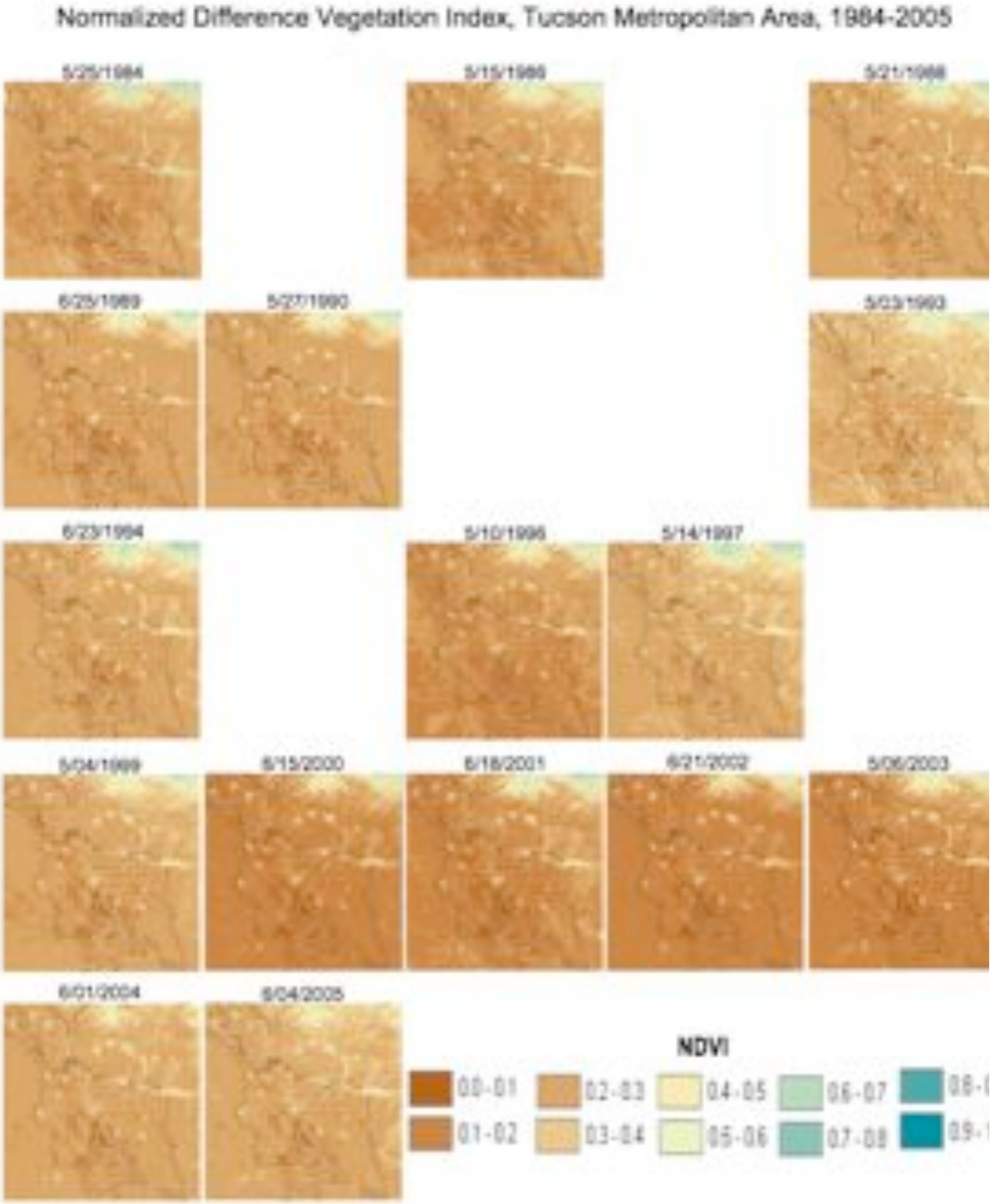

Figure 7. Normalized Difference Vegetation Index, Tucson Metropolitan Area, 1984-2005

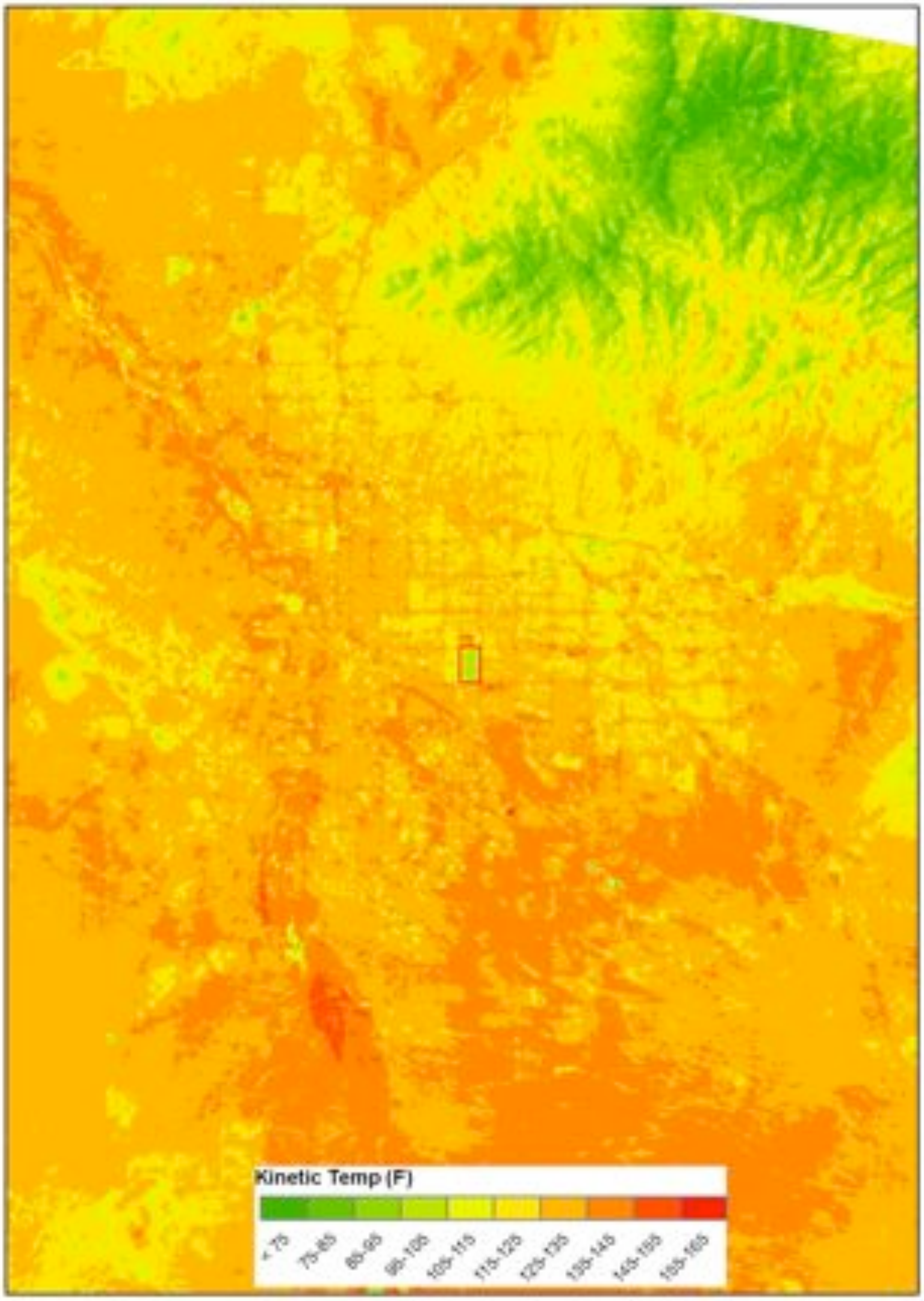

Figure 8. Kinetic Temperature, Tucson Metropolitan Area, 04 June 2005

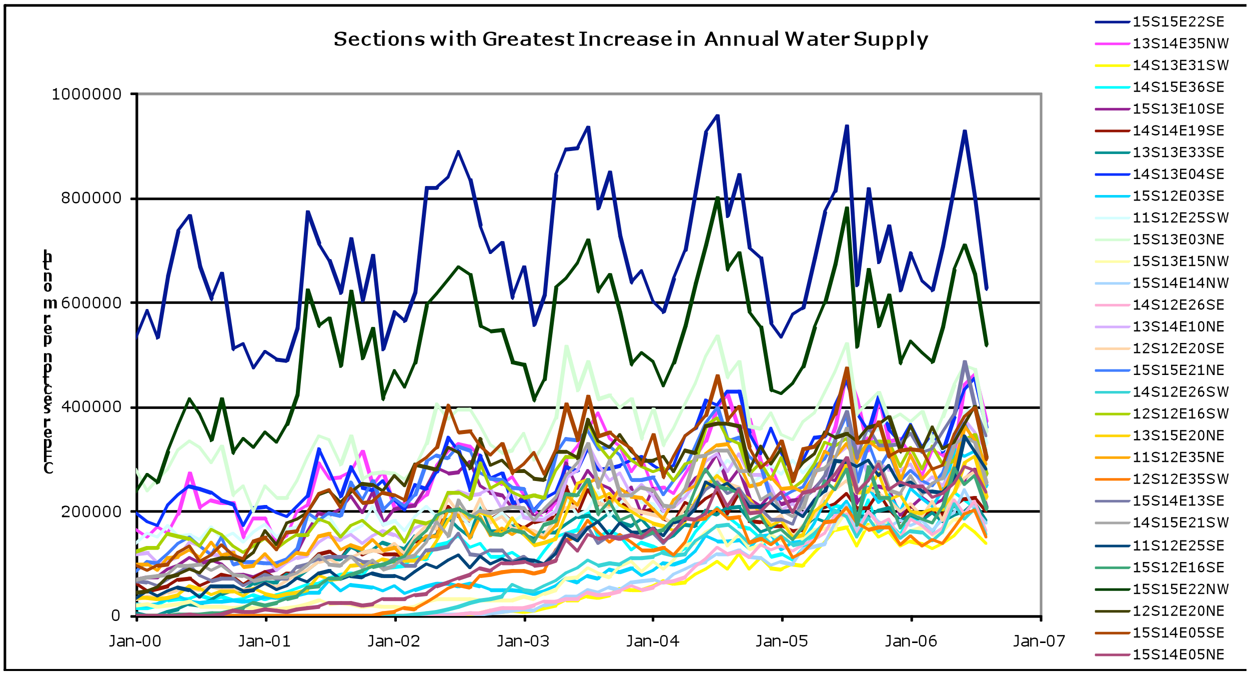

Figure 9.
Total Annual Supply Trends for Quarter Sections with Greatest Rate of Increase in Supply

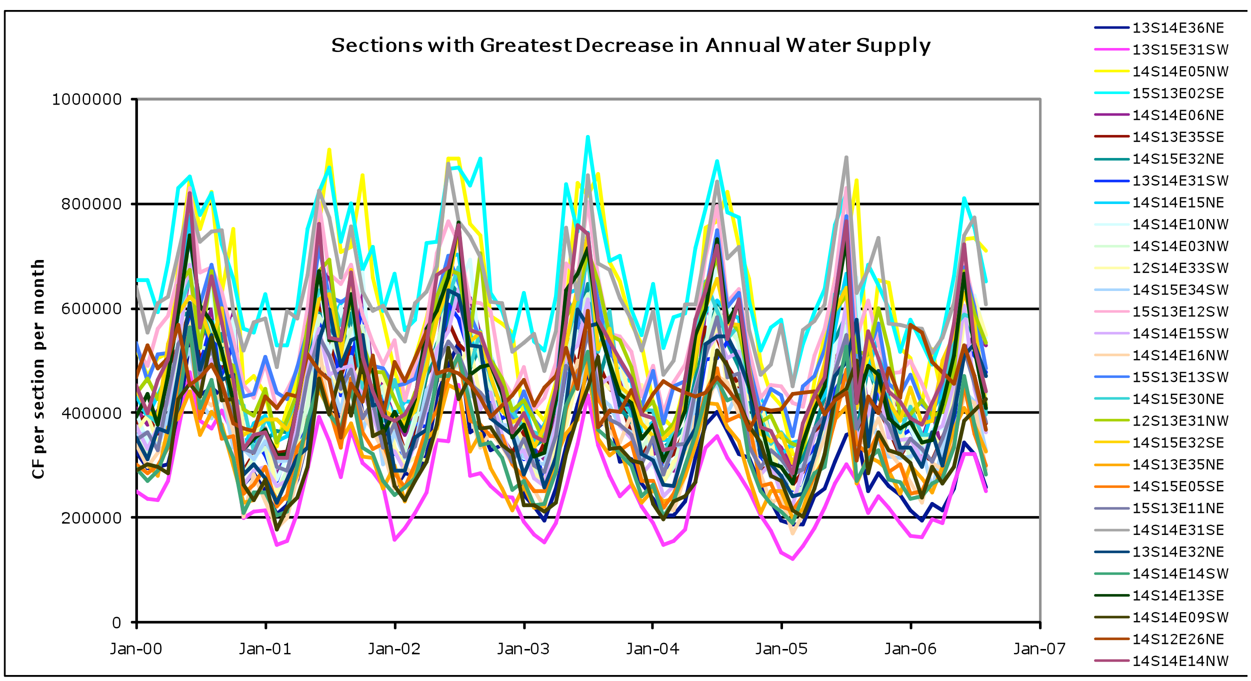

Figure 10.
Total Annual Supply Trends for Quarter Sections with Greatest Rate of Decrease in Supply

Conclusion

Tucson, Arizona is warming at a rate faster than the surrounding nonurban areas, with important implications for vegetation in the built environment. The urban heat island effect is most pronounced in the pre-monsoon months of February – May when outdoor irrigation demand is highest. Warming that occurs earlier in the season, e.g., beginning in February, extends the period of water demand. However, despite warmer minimum and maximum temperatures in the pre-monsoon period, reference evapotranspiration does not demonstrate statistically significant increasing trends for the 19897-2008 period of record. In fact, the only significant trend results for ET_{ref} were monsoon season (July and August) declines, resulting in time-invariant evaporative demand for water. Temperature increases are offset by wind speed decreases at both urban and nonurban stations. Further work is required to explore potential effects that vegetation and the built environment have on wind speeds.

Results of the NDVI analysis indicate a general greening trend over time, particularly for turf grass on golf courses, parks, and schools. Controlling for turf grass, NDVI is higher in the urban core although the most marked increases are for the developing urban fringes. Regression analysis of change in NDVI with change in outdoor water use over time did not yield the expected positive relationship. The water use analysis indicates that less than half of total water supply is used for outdoor purposes.

Residents' choice of vegetation type and amount and timing of irrigation are important determinants of outdoor water demand. Further work is required to realistically reflect water users' practices. Finally, demand forecasting must account for water pricing, perceptions of and responses to scarcity, and policy initiatives promoting (or inhibiting) water conservation.

Acknowledgments

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