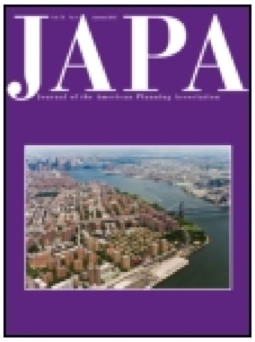

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Using Watered Landscapes to Manipulate Urban Heat Island Effects: How Much Water Will It Take to Cool Phoenix?

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Using Watered Landscapes to Manipulate Urban Heat Island Effects

How Much Water Will It Take to Cool Phoenix?

Patricia Gober, Anthony Brazel, Ray Quay, Soe Myint,
Susanne Grossman-Clarke, Adam Miller, and Steve Rossi

Problem: The prospect that urban heat island (UHI) effects and climate change may increase urban temperatures is a problem for cities that actively promote urban redevelopment and higher densities. One possible UHI mitigation strategy is to plant more trees and other irrigated vegetation to prevent daytime heat storage and facilitate nighttime cooling, but this requires water resources that are limited in a desert city like Phoenix.

Purpose: We investigated the tradeoffs between water use and nighttime cooling inherent in urban form and land use choices.

Methods: We used a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS) model to examine the variation in temperature and evaporation in 10 census tracts in Phoenix's urban core. After validating results with estimates of outdoor water use based on tract-level city water records and satellite imagery, we used the model to simulate the temperature and water use consequences of implementing three different scenarios.

Results and conclusions: We found that increasing irrigated landscaping lowers nighttime temperatures, but this relationship is not linear; the greatest reductions occur in the least vegetated neighborhoods. A ratio of the change in water use to temperature impact reached a threshold beyond which increased outdoor water use did little to ameliorate UHI effects.

Takeaway for practice: There is no one design and landscape plan capable of addressing increasing UHI and climate effects everywhere. Any one strategy will have inconsistent results if applied across all urban landscape features and may lead to an inefficient allocation of scarce water resources.

Keywords: urban heat island (UHI), LUMPS model, scenarios, urban heat island mitigation, water resource planning

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The sustainability of urban areas under financial stress and suffering from global climate change will frame the decisions of urban planners with respect to land, water, and energy use in this century. Evidence is now mounting that human-induced climate change will produce a warmer and drier future for the Southwestern United States and indeed that the shift to new climatic conditions is already underway (Barnett & Pierce, 2008; Barnett et al., 2008; Christensen, Wood, Voisin, Lettenmaier, & Palmer, 2004; Seager et al., 2007).

Although many decision makers may prefer simplicity and known outcomes, the issue of climate change is highly complex and uncertain (Intergovernmental Panel on Climate Change, 2007; Karl, Melillo, & Peterson, 2009). Unfortunately, our understanding of the interactions between climate and urban social and environmental systems is limited. Thus, we are likely to adopt some strategies that have unintended consequences or that fail to achieve desired results. If urban planners are to successfully guide their communities to a long-term sustainable future, they must engage with social and physical scientists to better understand the complexity associated with urban sustainability (Quay, 2009).

This article presents one such engagement exercise focused on the *urban heat island* (UHI) effect (the warming of nighttime temperatures in response to changes in surface characteristics) in Phoenix, AZ. Although the UHI effect is physically distinct from future warming due to climate change, it offers a useful natural experiment for policies and practices designed to ameliorate urban temperatures. In Phoenix, UHI effects have already raised summer nighttime temperatures by as much as 6°C (Brazel, Selover, Vose, & Heisler, 2000), which is comparable to the most pessimistic climate model results for the Southwest (Christensen & Lettenmaier, 2007; Karl et al., 2009).

Urbanization alters the surface properties of regions by increasing heat storage and, hence, temperature over what would occur on undeveloped land. The intensity of the measured UHI depends on land surface characteristics, including the amount of vegetation and impervious surfaces and how effectively surface materials absorb or reflect radiation; *sky view factor* (exposure of surfaces to the cool night sky); and sources of heat in the environment surrounding urban monitoring sites, such as releases from space heating or industrial operations (Oke, 1982). At a parcel level, Stone and Norman (2006) showed that impervious surfaces and lawn cover increase the excess warming due to urban development while a greater proportion of tree canopy reduces it. Guhathakurta and Gober (2009) analyzed interrelationships among the UHI, impervious surfaces, irrigated landscaping, lot size, the presence of pools, and residential water use. They found that impervious surfaces increased UHI intensity, although other land use and land cover characteristics interacted with impervious surfaces and with each other to influence the distribution of nighttime temperatures in Phoenix.

After 50 years of rapid urbanization, the cool nights once characteristic of Phoenix's desert climate are increasingly rare during the hot summer months (Figure 1), and the consequences for human society are well recognized. Higher temperatures increase the potential for heat stress, especially among vulnerable populations (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006); reduce human comfort generally (Baker et al., 2002); raise the costs of cooling buildings during summer months of peak energy use (Golden, Hartz, Brazel, Luber, & Phelan, 2008), exacerbate ozone pollution (Stone, 2005), and increase residential water demand (Guhathakurta & Gober, 2007). The UHI also creates challenges for revitalizing downtowns with dense, mixed-use development to support a pedestrian-oriented lifestyle.

One strategy to mitigate the UHI in Phoenix is to use irrigated landscape treatments. Irrigated surfaces store less heat than buildings, parking lots, streets, and other impervious surfaces, although the effects of trees and turf grass may differ. Stone and Norman's (2006) study of Atlanta found that a tree canopy decreased UHI effects, while grass cover increased it, at least as compared to forested vegetation. Most of the UHI research in Phoenix has not made the distinction between grasses and trees. The key challenge in this desert city is to manage the tradeoff between cooling with irrigated surfaces and securing the water required to maintain them. The scientific and planning question is how to achieve the greatest nighttime cooling while using the least water possible.

In collaboration with the City of Phoenix Water Services Department, we used a simple model of urban heat flux, the Local-Scale Urban Meteorological Parameterization Scheme (LUMPS), to examine the variation in temperature and evaporation in 10 census tracts in the urban core (Grimmond & Oke, 2002; Mitchell, Cleugh, Grimmond, & Xu, 2007). This article reports on our efforts to: (a) validate model results with observational data for Phoenix; (b) describe and explain the interrelationships between temperature and evaporation across the 10 census tracts; and (c) analyze the water use and cooling efficiency of different planning strategies. These planning strategies stressed the use of vegetative surfaces because managing water use was the critical component of the study. The Water Services Department sought a more complete understanding of the water consequences of adding vegetative surfaces to mitigate UHI effects.

Water Use, Urban Climate, and Urban Form

The UHI is typically defined as the temperature difference between a particular urbanized site and a nonurban site (Unger, 2004). These temperature differences are greatest at night when heat stored in urban surfaces during the day is released to the atmosphere (Oke, 1987). There is a growing body of literature showing that the physical form, land cover, and human characteristics of the city influence the intensity and pattern of the UHI. Brazel et al. (2007) found that the amount of increase in summer nighttime minimum temperatures at 37 sites in Phoenix

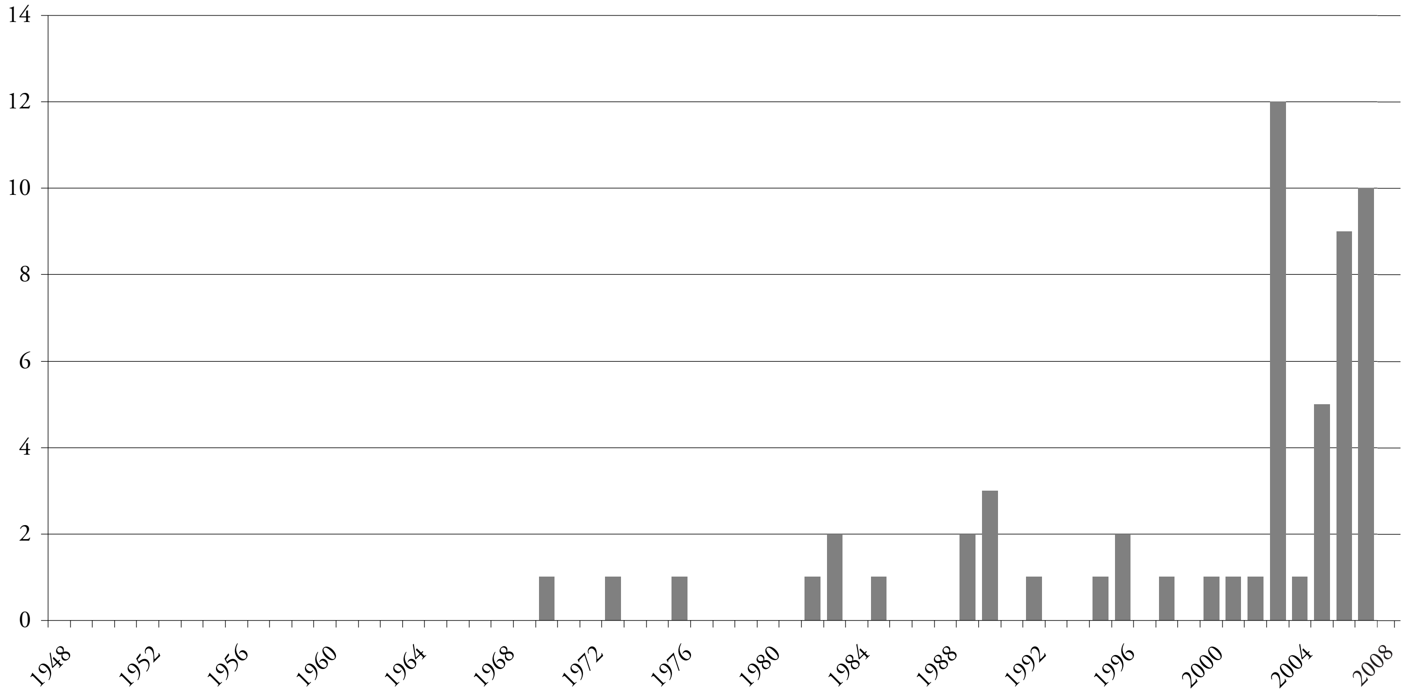

Figure 1. Days per year with minimum temperatures above 32°C, 1948 to 2007.

was best explained by the site's type of development (desert fringe, agricultural fringe, urban infill, or urban core) and recent construction activity within half a kilometer of the site. Jenerette et al. (2007) found a statistically significant link between the density of vegetation and daytime surface temperatures as well as between the density of vegetation and population density and income. They concluded that high-income households and those living at lower densities in Phoenix use irrigated landscapes to lower daytime temperatures and make their immediate surroundings more comfortable. Stone (2005) notes three potential physical planning strategies for urban cooling: increasing surface reflectivity with different paving and roofing materials, increasing tree canopy, and reducing waste heat.

The use of urban water and energy affects how temperature, physical form, and sustainable development interact. Jabareen (2006) examined four types of urban form (compact cities, ecocity, new urbanism, and urban containment) using seven sustainable design concepts (compactness, sustainable transport, density, mixed land uses, social diversity, passive solar design, and greening) and concluded that different types of urban form contribute to different aspects of urban sustainability. Guhathakurta and Gober (2007) empirically examined the relationship between temperature and water use in Phoenix. After controlling for key socioeconomic determinants of residential water use they found that monthly water use in single-family homes increased by 290 gallons for every 0.6°C (1°F) increase in overnight low temperatures.

Climatologists use models of the urban energy balance to explain the process of urban heating, which is driven by shortwave radiation input from the sun. As radiation reaches the surface, some is absorbed and some is reflected. The ratio of reflected radiation to total radiation is called the *albedo* (Sailor, 2006). Cities tend to have lower albedos than their surrounding rural areas, and this is a main cause of urban warming (Oke, 1982). In addition, some of the reflected radiation in cities is absorbed by building walls. Impervious surfaces and lack of vegetation in many urban areas also increases heat storage. Energy balance models simulate the flows of energy at the surface and yield information about changes in temperature and evaporation or water use. Using a modeling approach, Mitchell et al. (2007) estimated the effects of urban design on cooling and evaporation in Canberra, Australia. Adding vegetated roofs without cutting back outdoor watering reduced the maximum temperatures by 0.5° C compared to a typical suburban design. Adding a wetland or grass swale provided little additional cooling because these features accounted for only a small portion of the study's land area. Reducing garden watering by 50% had little additional effect on cooling because the vegetated roofs, along with the remaining outdoor watering, continued to meet the atmosphere's evaporative demand and thus its ability to cool.

Building on the work of Mitchell et al. (2007), we simulated temperature and evaporation conditions in Phoenix in order to identify how best to balance the benefits of holding down nighttime temperatures with the benefits of conserving water. Our study used a set of 10 census tracts chosen by city staff to represent three combinations of land use and landscape: industrial, residential with *mesic* (irrigated) landscaping, and residential with *xeric* (native desert) landscaping.

The Study Area

Metropolitan Phoenix experienced a major growth spurt after World War II, growing from just under one million residents in 1970 to more than four million today. Until recently the city's downtown redevelopment policies were fairly ineffectual (Gober, 2006), but serious efforts to rejuvenate the downtown are now underway including the construction of a light rail system that began operation in December 2008; mixed-use development designed to integrate commercial, recreational, and residential uses; expansion of the downtown campus of Arizona State University; and the creation of a biotechnology research center, an arts district, and a branch of the University of Arizona's medical school.

The intensifying UHI that now characterizes central Phoenix is incompatible with a pedestrian-oriented downtown. Temperatures do not fall below 100°F on a typical summer evening until 8:00 or 9:00 p.m. The city appointed an UHI Task Force in 2005 to recommend mitigation strategies. The city is studying and considering the use of cooler materials for use in pavements, benches, and roofing (City of Phoenix, 2008a) and is also examining using irrigated vegetation, particularly trees, as a mitigation option (City of Phoenix, 2008b).

Methods and Data

Following the work of Mitchell et al. (2007), we used an energy and water balance model to simulate evaporation and temperature under different scenarios for 10 census tracts in and near the urban core of Phoenix. City staff selected these census tracts to be representative of the central areas of Phoenix (Figure 2) using data from the 2000 Census of Population and Housing (U.S. Census Bureau, 2000), parcel data from the Maricopa County Assessor's Office, and the *normalized difference vegetation index* (NDVI; a measure calculated from remotely sensed data which represents green vegetation biomass). They chose four tracts for their industrial character (large buildings,

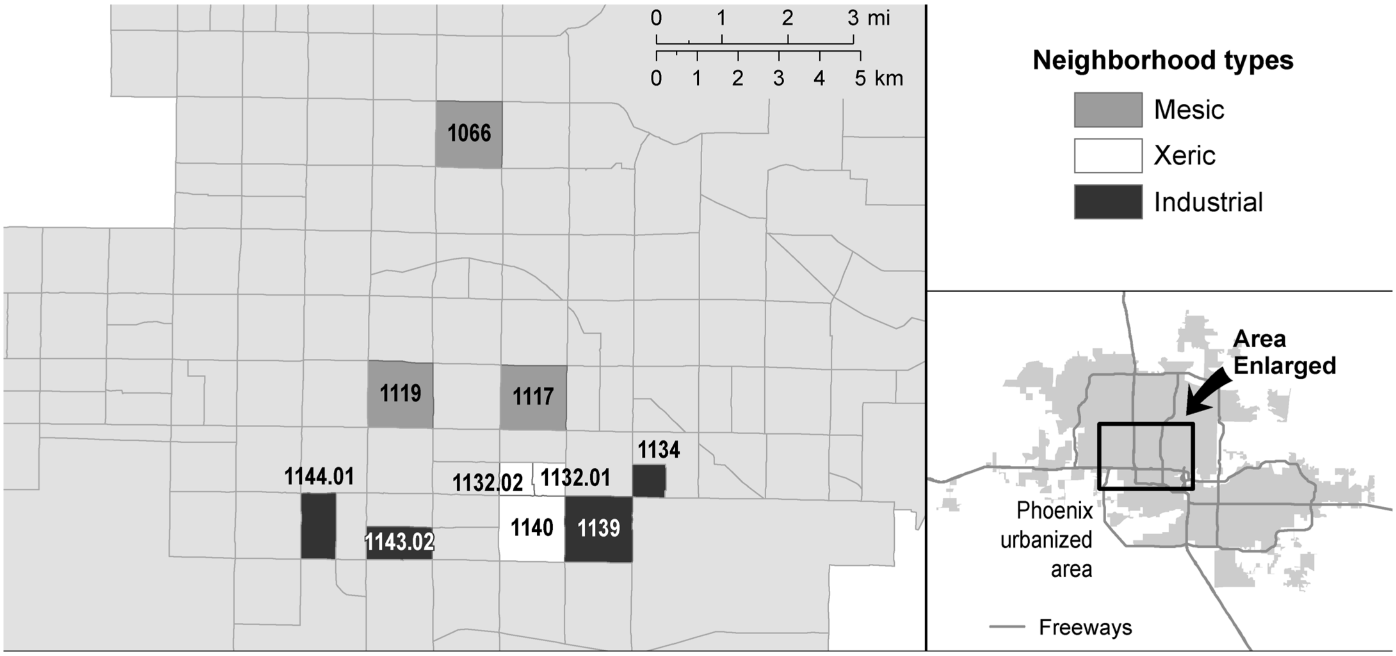

Figure 2. Map of 10 Phoenix census tracts studied.

lots of impervious surfaces, and little vegetation), three for their mesic residential characteristics (a high proportion of irrigated vegetation cover), and three for xeric residential characteristics (little irrigated vegetative cover and more flora native to the desert region).

Following Grimmond and Oke (2002), we used the previously mentioned LUMPS model to partition the flow of *net radiation*, the difference between incoming and outgoing energy carried by short-wave and long-wave radiation, into three parts: the *sensible heat flux* that warms the air directly, the *latent heat flux* that evaporates water, and the change in stored heat. Inputs to the model measure surface cover (the proportion of the surface devoted to trees, grass, water, buildings, soil, and impervious materials other than buildings), *surface roughness* (a measure of building height and density), and standard local weather observations (air temperature, humidity, wind speed, and air pressure). We chose to study the relationship between nighttime temperatures and water use in June because that is typically the hottest, driest month of the year, when UHI effects are most pronounced and city water use is at a maximum.

The LUMPS model has relatively limited data requirements and has proven sophisticated enough to predict hourly temperatures for urban areas as small as a few hundred meters square[1] (Grimmond & Oke, 2000). Grimmond and Oke (2002) describe formulating LUMPS based on prior work (De Bruin & Holtslag, 1982; Hanna & Chang, 1992, 1993; Holtslag & van Ulden, 1983), verifying it with their own extensive observations in a variety of urban areas.

LUMPS aims to estimate and partition the surface energy balance as follows:

$$Q^* = Q_H + Q_E + \Delta Q_S, \quad (1)$$

where Q^* is the net radiation, Q_H is the sensible heat flux (energy used to heat the air), Q_E is the latent heat flux (energy used to evaporate water) and ΔQ_S is the change in heat storage. We are concerned primarily with the right-hand side of equation, tracking hourly changes in air temperature and evaporation at the scale of the census tract. The model assumes no heating from transportation or air conditioning. It also ignores the influence of nearby or upwind land surface characteristics, and will thus be less reliable where there are abrupt changes in land cover from one census tract to another. Grimmond and Oke (2002) acknowledge that LUMPS will be less accurate in locations with abrupt changes in land use, for example, at the urban-rural fringe, in coastal areas, and in areas with complex terrain. Our study of inner-city census tracts in Phoenix should minimize the potential for these abrupt changes in land use and thereby maximize the potential usefulness of the model.

The LUMPS model requires detailed information on surface cover, which we obtained from a May 29, 2007 Quickbird satellite image of central Phoenix at 2.5-meter spatial resolution. The satellite's sensors collect image data in four bands of the electromagnetic spectrum (the blue, green, red, and near-infrared) for every 2.5 square meters of surface. The 10 census tracts included commercial, industrial, and residential urban land uses and undeveloped grassland, unmanaged soil, desert landscape, and open water. We entered into LUMPS the percentage of the land surface in each census tract devoted to each of the following land cover classes: buildings, other impervious surfaces (e.g., roads and parking lots), unmanaged soil, trees and shrubs, grass, swimming pools, and other water bodies (Table 1). Some of these have similar spectral responses (e.g., asphalt roads and parking lots have the same reflectance as asphalt rooftops), which traditional spectral-based image classification techniques cannot reliably distinguish (Green, Cummins, Wright, & Miles, 1993; Kiema & Bahr, 2001; Muller, 1997; Myint, 2003; Myint, Lam, & Tyler, 2002). Hence, we employed an object-oriented image classification approach,[2] which segments image objects and evaluates them at different scales instead of classifying images on a per-pixel basis at a single scale (Desclée, Bogaert, & Defourny, 2006; Navulur, 2007).

In addition to the land surface fractions from the remotely sensed data, the LUMPS model requires hourly meteorological data including solar radiation, temperature, humidity, wind, and pressure. We used hourly conditions for the month of June 2007 from the National Weather Service site at Sky Harbor Airport in central Phoenix. It would be ideal to have accurate meteorological estimates for each of the 10 neighborhoods, but hourly pressure data and cloud cover data are not typically collected at such local monitoring sites. We cross-checked the Sky Harbor temperatures with those from a weather station at one of the local sites and found relatively small differences. While the Sky Harbor site is more open and, therefore, exposed to different wind conditions than the 10 urban neighborhoods, we believe that variations in the key meteorological variables across the 10 neighborhoods are quite small compared to variations in land cover in our data for the neighborhoods.

LUMPS output estimates hourly net radiation flows partitioned into latent heat, sensible heat, and change in stored heat, which we used for two sets of calculations. First, we converted the latent heat flux from hourly energy units of water vapor per square meter to hundreds of cubic

Table 1. Pixels and percentages of surface area devoted to seven categories of land cover in 10 Phoenix census tracts.

	Tract # 1066 Residential (mesic)	Tract # 1117 Residential (mesic)	Tract # 1119 Residential (mesic)	Tract # 1143.02 Industrial	Tract # 1132.01 Residential (xeric)	Tract # 1132.02 Residential (xeric)	Tract # 1140 Residential (xeric)	Tract # 1134 Industrial	Tract # 1139 Industrial	Tract # 1144.01 Industrial
Pixels										
Buildings	104,291	120,390	66,127	43,275	32,835	28,097	121,718	32,570	102,368	84,884
Other impervious surfaces	68,025	92,012	90,232	64,799	23,376	29,573	238,335	37,485	207,077	92,738
Trees and shrubs	130,393	61,986	92,830	3,597	6,468	7,591	23,379	7,053	21,256	6,071
Grass	195,266	170,569	238,161	17,548	27,256	24,849	34,049	24,539	38,914	26,027
Swimming pools	4,191	596	1,336	55	20	25	265	75	58	19
Lakes and ponds	—	6	5,020	—	—	—	3	—	—	—
Unmanaged soil	38,889	95,096	41,532	77,641	45,265	49,923	124,828	36,937	186,182	75,258
Total	541,055	540,655	535,238	206,915	135,220	140,058	542,577	138,659	555,855	284,997
% of tract area										
Buildings	19.3%	22.3%	12.4%	20.9%	24.3%	20.1%	22.4%	23.5%	18.4%	29.8%
Other impervious surfaces	12.6%	17.0%	16.9%	31.3%	17.3%	21.1%	43.9%	27.0%	37.3%	32.5%
Trees and shrubs	24.1%	11.5%	17.3%	1.7%	4.8%	5.4%	4.3%	5.1%	3.8%	2.1%
Grass	36.1%	31.5%	44.5%	8.5%	20.2%	17.7%	6.3%	17.7%	7.0%	9.1%
Swimming pools	0.8%	0.1%	0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%
Lakes and ponds	0.0%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Unmanaged soil	7.2%	17.6%	7.8%	37.5%	33.5%	35.6%	23.0%	26.6%	33.5%	26.4%

feet of water loss for the month, as an indicator of evaporative loss. Second, we estimated the nighttime temperature cooling rates for the 10 neighborhoods from 8:00 p.m. to midnight using an equation modeled after one used by Mitchell et al. (2007) to compute a heating rate.

Model Validation

The usefulness of LUMPS for policy purposes depends on how well its results mimic observable conditions. Although LUMPS was calibrated using field observations from seven North American cities, including Mexico City, Miami, Tucson, Los Angeles, Sacramento, Vancouver, and Chicago (Grimmond & Oke, 2002), we wanted to show that it could simulate actual evaporation and temperature conditions in Phoenix. We used water meter records from the City of Phoenix adjusted for outdoor water use and remotely sensed thermal images to validate model estimates of temperature heating and cooling rates.

We compared hundreds of cubic feet of water loss for the month of June 2007 for each of the 10 census tracts (which we had calculated from LUMPS's latent heat flux estimates, as noted above), to Phoenix's water records. The city estimates that approximately two thirds of municipal water is used outdoors to maintain trees, shrubs, and grass and to compensate for pool evaporation, although this proportion varies quite substantially across the city due primarily to the different water demands of different urban land uses (City of Phoenix, 2005). With the help of staff members from the city's Water Services Department, we adjusted the water records to reflect the types of customers in each census tract. We assumed that: the average indoor use for a single-family unit was 5,515 gallons per month, and that the remainder was for outdoor use; that 10% of restaurant and hotel water use was outdoors; and that 25% of car wash water consumption was outdoors. We estimated outdoor use for commercial, government, and industrial parcels by subtracting winter average use from summer average use. We assumed that all golf course and park water consumption was for outdoor purposes.

After making these assumptions and pairing them with the land use profiles of the studied tracts, we calculated that the share of water used outdoors varied from 88% in one high-status, inner-city residential neighborhood with lush irrigated landscaping, a large golf course, and a large public park to around 40% in tracts containing industrial zones and large concentrations of government buildings. Our decision rules were admittedly somewhat arbitrary, but different land uses are characterized by quite different shares of water devoted to indoor and outdoor uses, and these differences must be considered in any effort to validate LUMPS' water estimates.

The LUMPS evaporation outputs were quite closely correlated with the City of Phoenix's water records for the 10 tracts ($r^2 = 0.89$), indicating that the model produced credible estimates of outdoor water use. The greatest divergence occurred in three tracts that had extraordinarily heterogeneous land use and land cover, including both large industrial buildings surrounded by parking lots and residential subdivisions. The aggregated tract-level percentages of land in different uses did not correspond to actual conditions anywhere in these tracts. In addition, these tracts had low levels of irrigated vegetation, and Grimmond and Oke (2002) also obtained poor model results in such areas. We concluded from this evaluation experiment that LUMPS accurately distinguished high-water-use tracts from low-water-use tracts, but failed to differentiate water use among low-water-use tracts.

We used surface temperatures from satellite data to validate LUMPS temperature outputs. United States Geological Survey's ASTER Level 2 images taken at 8:35 p.m. on June 21, 2007, provide an empirical record of conditions at the surface, which we compared with LUMPS output for the 10 sites. We did not expect that LUMPS air temperature estimates would match the ASTER surface temperatures for each site, but the LUMPS model is largely driven by land cover, which has been shown to influence remotely sensed surface temperatures (e.g., Hartz, Prashad, Hedquist, Golden, & Brazel, 2006; Lougeay, Brazel, & Hubble, 1996), and, as expected, the LUMPS average cooling rates between 8:00 p.m. and midnight (measured in °C per hour) corresponded well ($r^2 = 0.81$) with the ASTER surface temperatures at 8:35 p.m.

Results: Nighttime Cooling and Evaporation

We standardized the LUMPS evaporation estimates for census tracts by areal unit, computing an index of evaporation in hundreds of cubic feet of water per QuickBird image pixel ($2.5m^2$). Figure 3 plots this against hourly cooling rates. Not surprisingly, surfaces that evaporated large amounts of water per day produced the greatest nighttime cooling. More irrigated vegetation produced more evaporation and less stored heat to be released at night. This relationship is nonlinear, however, suggesting that cooling levels off when evaporation rates are high.

We defined an *efficiency ratio* to measure the amount of nighttime cooling achieved for a given evaporation rate, with the latter indicating the amount of water loss. When the efficiency ratio is high, there is rapid cooling (UHI mitigation) relative to the amount of evaporation (water use). Increasing the application of water produces rapid cooling. Efficiency declines as the *wet fraction* (share of the surface area devoted to irrigated vegetation) increases, but not in a linear fashion (Figure 4). A logistic model fits the data better than a linear one, with the flattening slope indicating that adding water is an inefficient strategy for reducing temperatures in densely vegetated neighborhoods.

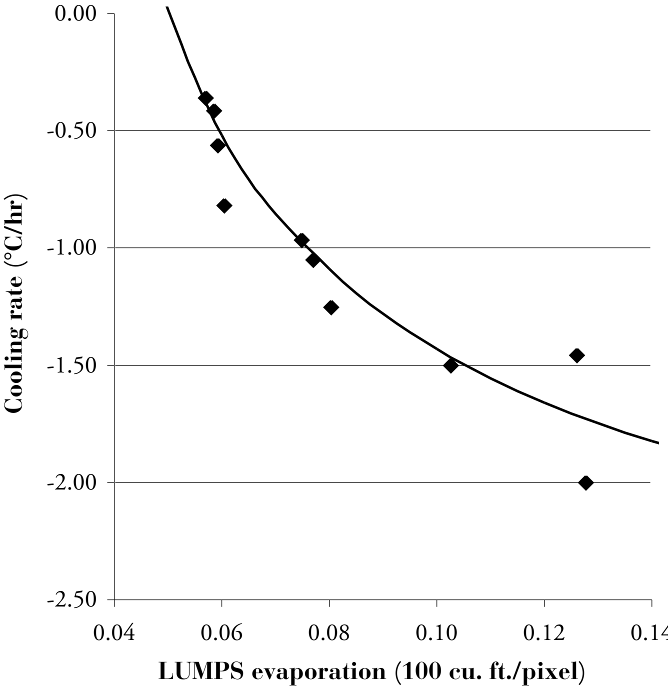

Figure 3. Nonlinear correspondence between rates of nighttime cooling and daily evaporation.

Note:
$R^2 = 0.908$.

Scenarios and Simulation Experiments

We created three urban design scenarios focused primarily on water use and applied them to each of the 10 census tracts using LUMPS (Tables 2–4). Scenario 1 assumed that the city would use vegetation as its primary UHI mitigation strategy. This first scenario replaced 20% of existing surfaces with grasses and trees and shrubs by reducing impervious surfaces and *unmanaged soil* (desert

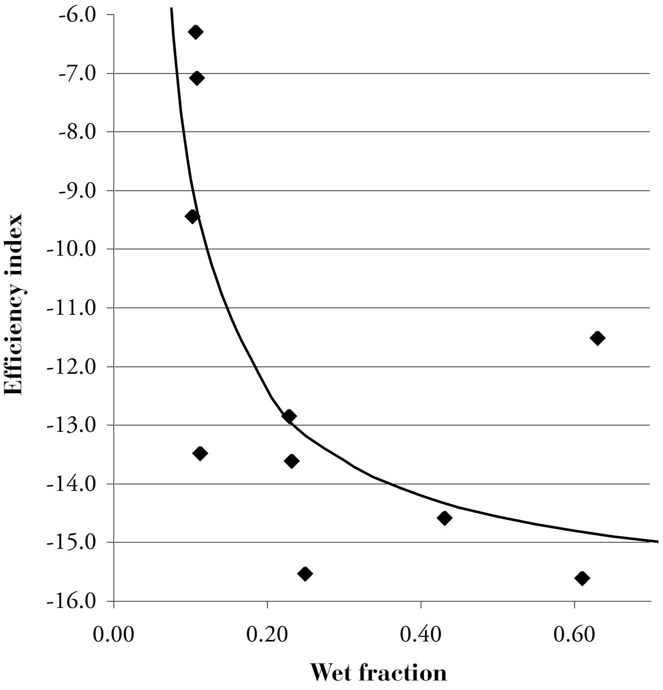

Figure 4. Nonlinear correspondence between declining efficiency index and increasing wet fraction.

Note:
The *efficiency index* is the amount of nighttime cooling per unit of evaporation. The *wet fraction* is the percentage of surface vegetation that is irrigated. $R^2 = 0.534$.

land unaffected by human intervention) by 10% each, and in some extreme cases by reducing the fraction of the land surface covered with buildings. Scenario 2 assumed that the city would ultimately face water shortages from drought or climate change and implement a water conservation plan; in this scenario, we replaced trees and grass (5% each) with unmanaged soil. Scenario 3 simulated a more compact city, increasing surface area covered with buildings by 10% by reducing impervious surfaces by 5% and unmanaged soil by 5%. This allowed us to compare the results of scenarios implementing explicit water policies to a land-based strategy, recognizing that the latter also has implications for water use.

An infinite set of scenarios could be generated from the six land cover categories; we chose these three because they show the impacts of policy levers that are currently under discussion in Phoenix and because they explicitly or implicitly affect the city's water planning. Scenario 1 uses water generously for UHI mitigation, Scenario 2 considers the very real possibility that water conservation will be required to deal with future drought and climate change. Scenario 3 takes account of the implicit relationship between water use and urban densities. High-density residential development would use substantially less water per capita in a city where two thirds of residential water consumption is for outdoor use. Smaller lot sizes and a shift from single- to multi-family residential structures would facilitate continued urban growth with existing water supplies. We aimed to understand what the implications of this strategy were for urban temperatures.

In Scenario 1, the city becomes a true oasis in the desert. The addition of 20% more vegetative cover would produce substantial nighttime cooling compared to the

Table 2. Water use under Scenarios 1, 2, and 3.

	Evaporation rate (hundreds of cubic ft. per 2.5 m^2 per month)	**Change in evaporation rate from base case (hundreds of cubic ft. per 2.5 m^2 per month)**		
Tract	**Base Case**	**Scenario 1**	**Scenario 2**	**Scenario 3**
1066 (mesic)	0.128	0.032	−0.013	−0.003
1117 (mesic)	0.103	0.030	−0.012	−0.002
1119 (mesic)	0.127	0.031	−0.013	−0.003
1134 (industrial)	0.075	0.028	−0.012	−0.002
1139 (industrial)	0.059	0.026	−0.010	−0.001
1140 (xeric)	0.057	0.026	−0.010	−0.001
1132.01 (xeric)	0.081	0.029	−0.012	−0.002
1132.02 (xeric)	0.077	0.029	−0.012	−0.002
1143.02 (industrial)	0.059	0.027	−0.008	−0.001
1144.01 (industrial)	0.061	0.027	−0.008	−0.001

Table 3. Cooling under Scenarios 1, 2, and 3.

	Night cooling (ºC per hr.)[a]	**Change in night cooling from base case (ºC per hr.)**[a]		
	Base Case	**Scenario 1**	**Scenario 2**	**Scenario 3**
1066 (mesic)	1.999	0.406	–0.163	0.358
1117 (mesic)	1.502	0.588	–0.217	0.391
1119 (mesic)	1.457	0.451	–0.188	0.354
1134 (industrial)	0.966	0.722	–0.270	0.430
1139 (industrial)	0.416	0.814	–0.340	0.451
1140 (xeric)	0.360	0.821	–0.329	0.453
1132.01 (xeric)	1.252	0.687	–0.260	0.425
1132.02 (xeric)	1.051	0.712	–0.266	0.430
1143.02 (industrial)	0.561	0.805	–0.386	0.453
1144.01 (industrial)	0.818	0.780	–0.367	0.451

Notes:

a. Average night cooling per hour from 8 p.m. to midnight.

Table 4. Efficiency of cooling obtained through water use under Scenarios 1, 2, and 3.

	Efficiency (cooling per unit evaporation)	**Change in efficiency from base case (cooling per unit evaporation)**		
Tract	**Base Case**	**Scenario 1**	**Scenario 2**	**Scenario 3**
1066 (mesic)	15.617	–0.551	–0.163	2.390
1117 (mesic)	14.583	1.130	–0.217	3.392
1119 (mesic)	11.472	0.607	–0.188	2.476
1134 (industrial)	12.880	3.552	–0.270	5.302
1139 (industrial)	7.051	7.435	–0.340	7.328
1140 (xeric)	6.316	8.017	–0.329	7.584
1132.01 (xeric)	15.457	2.186	–0.260	4.830
1132.02 (xeric)	13.649	3.102	–0.266	5.143
1143.02 (industrial)	9.508	6.465	–0.386	7.231
1144.01 (industrial)	13.410	4.831	–0.367	6.958

Note:

Cooling and evaporation rates for the base case and change under the scenarios reported in Tables 2 and 3.

base case of today's vegetative cover, but would require substantially more water. LUMPS estimates that outdoor water use in June would increase by 103,982 hundred cubic feet or 77.8 million gallons in the 10 tracts. This amounts to a total increase of 32.8%. Adding vegetation would accelerate nighttime cooling over the base case by between 0.41°C and 0.82°C per hour between 8:00 p.m. and midnight, meaning that early evening hours would be noticeably more comfortable. Increases in the cooling rates would be highest in the industrial and xeric tracts where vegetation now is sparse. Mesic neighborhoods would experience smaller gains in cooling from this heavy-water-use strategy because they are above the threshold beyond which adding vegetation yields diminished cooling.

Scenario 2 simulates a major campaign to reduce outdoor water use. Such a campaign might occur in response to an extreme or prolonged drought occasioned by drier and warmer climate conditions in the future. This scenario assumes many vegetative surfaces would be eliminated and transforms Phoenix into more of a desert city. Such changes in land cover would reduce outdoor water use by 40,756 hundred cubic feet (12.8% of the estimated total), but these water savings would exacerbate UHI effects. The rate of cooling would fall by between 0.16°C and 0.39°C per hour. The xeric and industrial tracts would be especially hard hit. More than half of the total water savings would occur in the three mesic tracts, where only relatively minor changes in nighttime cooling would occur. We infer that these tracts have enough irrigated landscaping to meet the atmosphere's evaporative demand, even with reductions in outdoor watering. This finding is consistent with that of Mitchell et al. (2007), who showed that reductions in garden watering up to 50% had minor effects on cooling in their study of suburban development in Canberra.

Scenario 3's more compact city would slightly increase evaporation rates and thus moderately increase nighttime cooling. Total outdoor water use would increase by 2.6% in these 10 tracts, but nighttime cooling rates would improve by between 0.36°C and 0.45°C per hour. In this scenario, heat storage that contributes to the nighttime UHI is reduced because there are fewer flat impervious surfaces and less unmanaged soil. The increased building density causes slightly more turbulent exchange of latent heat by creating a more irregular surface. Results suggest that increasing densities at the city center may not exacerbate UHI effects if the new buildings replace parking lots and undeveloped land as they do in our experiment. It is also significant that our model captured only the lowered water use due to reductions in impervious surfaces. There would be additional water savings from reduced per capita outdoor space and thus lower per capita outdoor water use. We estimate that at a density of one person per acre an individual uses an average of 179,000 gallons of water per year, compared to 91,000 gallons per year at a density of 8 persons per acre, and 33,000 gallons per year at a density of 40 persons per acre.[3]

On the all-important efficiency ratio of cooling to evaporation, the model showed that Scenario 1, the oasis city, increases the efficiency of water use except in one highly vegetated tract, and Scenario 3, the more compact city, also increases water efficiency because it creates substantial cooling without any sizable increase in evaporation or water use. Scenario 2, the desert city model employing water conservation, is the least efficient overall strategy for UHI mitigation. It saves water, but the loss of vegetative surfaces substantially increases surface warming.

These results offer guidance for spatially explicit policies that target different neighborhoods with different policies. Our three simple scenarios indicate that mesic neighborhoods would benefit from strategies that increase building density by decreasing the amount of land area in impervious surfaces and unmanaged soil. This would achieve moderate cooling and slightly reduce evaporation and outdoor water use. The industrial and xeric neighborhoods would benefit from either increasing density or adding more irrigated vegetation, depending of course on local water scarcity conditions.

Discussion and Conclusions

There are always qualifications associated with a study of this sort. In this case, the main limitation is the small sample size of 10. The relationships are strong and statistically significant, but we would have more confidence in the results if there were more cases, especially cases with more intermediate levels of water use and more typical distributions of land cover. For this pilot project, we chose tracts at the extremes to determine how effectively LUMPS could discriminate temperature and evaporation rather than choosing tracts that were representative of land cover in the city. The next step in our research program is to replicate our study for the city as a whole and experiment with land and water policies that apply citywide as well as in specific small areas.

There are other limitations of this work. As noted previously, the LUMPS model ignores anthropogenic sources of warming like waste heat from transportation and air conditioning, does not consider the effects of surrounding areas on the target neighborhoods, and uses meteorological measures from a single weather station rather than accounting for neighborhood-level variations. While these variables could be incorporated into a more sophisticated microscale energy balance model, such a model would be more complex and costly. One of the main reasons for modeling rather than using empirical data is to provide timely information for developing planning strategies for UHI mitigation and climate adaptation. In many cases, decisions will be required soon, before we have complete answers about the tradeoffs between energy and water in rapidly changing urban environments. Our results demonstrate that LUMPS provided credible, if not perfect, estimates of the consequences of different water and UHI mitigation policies, and did so with readily available and inexpensive data sets. Demonstration projects are expensive, so conducting this kind of experiment with simple scenarios before implementing a strategy may save a city money as well as time.

One of our more revealing and important findings is the threshold beyond which more watered plants, shrubs, and grasses produce little additional cooling although they use a lot of water. In areas where water supply is not an issue, this will be of less importance, but in cities where water supplies are stressed, this will be a major consideration. In such areas, a uniform regional approach to UHI mitigation may not be desirable. Rather, efforts to increase vegetative cover should concentrate on neighborhoods with the least vegetation, where substantial gains in cooling can be achieved with minimal additional water use. Increasing density and replacing impervious surfaces is a more practical strategy for highly vegetated neighborhoods.

Scenario 2 (the desert city with strict water conservation) provides insight for regions in which periods of drought will require consumers to reduce water use. Outdoor water uses will be among the first to be targeted for reduction. Albuquerque, NM, for example, has adopted landscaping requirements for new developments that limit the amount of turf that can be installed, and Tucson, AZ, uses a block rate structure that makes it quite expensive to maintain water-intensive gardens and yards (Western Resource Advocates, 2006). In Las Vegas, NV, the Southern Nevada Water Authority (2008) will rebate customers $1.50 per square foot of grass removed and replaced with desert landscaping up to the first 5,000 square feet converted per property per year. The impacts of such policies will not be uniform everywhere, but rather will affect drier, less vegetated neighborhoods the most. And if Jenerette et al.'s (2007) interpretation that high-income people use irrigated landscaping for cooling is correct, these will probably be disadvantaged neighborhoods. Drought response programs should target mesic neighborhoods, where they will have the most impact on reducing water use with the least impact on nighttime temperatures.

We experimented with changing the albedo to 0.7 across all the tracts to simulate the effects of more reflective roofing materials. The result was an average increase in cooling of 0.15°C per hour. This would amount to changing the evening temperatures from 6:00 p.m. to midnight by about 1°C. The effects are greater in xeric and industrial neighborhoods than in the mesic ones. Given that the UHI is between 5°C and 6°C, it appears that more reflective roofing materials would make a difference in reducing surface warming. They alone will not solve the problem, however.

The results for Scenario 3, the compact city, imply that it is not density itself that aggravates the UHI. Adding density has a positive influence on nighttime cooling when buildings replace impervious parking lots and undeveloped land. There is a growing body of literature that pinpoints impervious surfaces for their deleterious effects on urban warming (Guhathakurta & Gober, 2009; Sailor, 2006; Stone & Norman, 2006). The simple correlation between nighttime cooling rates and the percentage of impervious surfaces across our study neighborhoods was −0.71 and between evaporation rates and percentage of impervious surfaces it was −0.88. Stone and Bullen (2006) have shown the relationship between land use regulations and the presence of impervious surfaces. The amount of impervious surface increases with lot size, street frontage, and the frontyard setback. Developments with smaller lots and shorter frontages and setbacks would reduce impervious surfaces by 30% in their study area of Madison, WI. But while land use regulations may help regulate temperatures in new neighborhoods, they are less relevant to established inner city neighborhoods where urban design features are already in place and would be difficult to alter.

A real concern in a place like Phoenix, and indeed for other cities facing the potential for water shortage, is that unmanaged soil as a land cover facilitated daytime warming and retarded nighttime cooling in our study neighborhoods. If we simply move from watered to unwatered landscapes to conserve water in the face of climate change, the result will be increasing urban temperatures. This would cause another critical urban resource tradeoff, between water and energy: How much additional energy will be used to cool warmer neighborhoods? Thus, water conservation programs should be accompanied by aggressive strategies to help existing homes mitigate UHI effects. Sailor (2006) notes the potential for roofing and paving materials to increase reflectivity. Roofing materials such as asphalt tiles, clay tiles, and wood shingles have albedo factors of 0.90, compared to an aluminum roof of 0.25 or a galvanized steel roof of .04. The albedo factors of concrete mixes for pavements can vary from 0.41 to 0.77, with substantial gains to be made by replacing gray cement mixtures with white ones. Additional gains can be had by planting shade trees, developing green roofs, and replacing traditional pavements with pervious pavements.

The results of this article and this discussion point to the enormous complexity of urban resource issues in the face of climate change and other environmental stressors. When we make land decisions in urban areas, we make de facto water and energy decisions. While UHI mitigation strategies have traditionally focused on land use regulation, they should not be seen as independent of other urban resource decisions. The LUMPS model is an approach that allows integrated analysis and decision support. It is a way of seeing the critical interactions between land and water regulations, and of addressing the tradeoffs between temperature amelioration and water use. LUMPS allows us to play out different decisions and view their holistic consequences rather than talk about land use codes independent of water and energy conservation campaigns. Integrated and anticipatory approaches like this will increasingly be needed to tackle the complex and uncertain challenges that climate change will set for urban planning and governance.

Notes

1. "The 'surface' here is the top of a 'box,' the height of which extends from a measurement level above the city down to a depth in the ground where the diurnal conductive heat flux ceases. By 'local scale' we refer to horizontal areas of approximately 102–104 m on a side and to measurement heights in the inertial sublayer above the urban canopy and its roughness sublayer. At this height and scale, we expect the microscale variability of atmospheric effects generated by individual houses and other surfaces to be integrated into a characteristic neighborhood response" (Grimmond & Oke, 2002, p. 792).

2. We used the eCognition Professional 4.0 software to classify objects into land surface categories. eCognition uses a segmentation function (Baatz et al., 2004; Baatz & Schape, 2000) based on shape, compactness, and scale parameters to identify objects in an image, and a nearest neighbor method based on training from known objects to assign objects to land surface classifications (Ivits & Koch, 2002; Myint, Giri, Wang, Zhu, & Gillette, 2008; Myint, May, Cerveny, & Giri, 2008).

3. Our calculations were based on water duties produced by the 2000 Salt River Project in Phoenix, AZ.

References

Baatz, M., Heynen, M., Hofmann, P., Lingenfelder, I., Mimier, M., Schape, A., et al. (2004). *eCognition User Guide 4.0: Object Oriented Image Analysis.* Munich, Germany: Definiens Imaging GmbH.

Baatz, M., & Schape, A. (2000). Multiresolution segmentation: An optimization approach for high quality multi-scale image segmentation. In J. Strobl, T. Blaschke, & G. Griesebner (Eds.), *Proceedings of the Angewandte Geographische Informations-Verarbeitung XII* (pp. 12–23). Karlsruhe, Germany: Wichmann Verlag.

Baker, L. A., Brazel, A. J., Selover, N., Martin, C., McIntyre, N., & Steiner, F. R. (2002). Urbanization and warming of Phoenix (Arizona, USA). *Urban Ecosystems, 6*(3), 183–203.

Barnett, T. P., & Pierce, D.W. (2008. When will Lake Mead go dry? *Water Resources Research, 44*(3), W03201.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., et al. (2008). Human-induced changes in the hydrology of the western United States. *Science, 319*(5866), 1080–1083.

Brazel, A., Gober, P., Lee, S., Grossman-Clarke, S., Zehnder, J., Headquist, B., et al. (2007). Determinants of changes in the regional urban heat island in metropolitan Phoenix (Arizona, USA) between 1990 and 2004. *Climate Research, 33*(2), 171–182.

Brazel, A., Selover, N., Vose, R., & Heisler, G. (2000). The tale of two climates—Baltimore and Phoenix urban LTER sites. *Climate Research, 15,* 123–135.

Christensen, N. S., & Lettenmaier, D. P. (2007). A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. *Hydrology and Earth System Sciences, 11*(4), 1417–1434.

Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., & Palmer, R. N. (2004). The effects of climate change on the hydrology and water resources of the Colorado River Basin. *Climatic Change, 62*(1–3), 337–363.

City of Phoenix. (2005). *Water resources plan, 2005 update.* Phoenix, AZ: Water Services Department.

City of Phoenix. (2008a). *Sustainability.* Retrieved August 3, 2009, from http://www.phoenix.gov/greenphoenix/sustainability/summary/land.html

City of Phoenix. (2008b). Chapter 4—Sustainable development in a desert climate. In *Downtown Phoenix Plan, Adopted July 2, 2008.* Retrieved June 26, 2009, from http://phoenix.gov/urbanformproject/dtplan04.pdf

De Bruin, H. A. R., & Holtslag, A. A. M. (1982). A simple parameterization of the surface fluxes of sensible and latent heat during daytime compared with the Penman-Monteith concept. *Journal of Applied Meteorology, 21*(11), 1610–1621.

Desclée, B., Bogaert, P., & Defourny, P. (2006). Forest change detection by statistical object-based method. *Remote Sensing of Environment, 102*(1–2), 1–11.

Gober, P. (2006). *Metropolitan Phoenix: Place making and community building in the desert.* Philadelphia: University of Pennsylvania Press.

Golden, J. S., Hartz, D., Brazel, A., Luber, G., & Phelan, P. (2008). A biometeorology study of climate and heat-related morbidity in Phoenix from 2001–2006. *International Journal of Biometeorology, 52*(6), 471–480.

Green, D. R., Cummins, R., Wright, R., & Miles, J. (1993). A methodology for acquiring information on vegetation succession from remotely sensed imagery. In R. Haines-Young, D. R. Green, & S. Cousins (Eds.), *Landscape ecology and geographic information systems* (pp. 111–128). London: Taylor and Francis.

Grimmond, C. S. B., & Oke, T. R. (2000). Heat fluxes and stability in North American cities. In American Meteorological Society (Ed.), *Third urban environment symposium* (Paper 4.3). Boston: American Meteorological Society.

Grimmond, C. S. B., & Oke, T. R. (2002). Turbulent heat fluxes in urban areas: Observations and a local-scale urban meteorological parameterization scheme (LUMPS). *Journal of Applied Meteorology, 41*(7), 792–810.

Guhathakurta, S., & Gober, P. (2007). The impact of the Phoenix urban heat island on residential water use. *Journal of the American Planning Association, 73*(3), 317–329.

Guhathakurta, S., & Gober, P. (2009). *Linking urban heat islands to water use in Phoenix: A path analysis.* Unpublished manuscript.

Hanna, S. R., & Chang, J. C. (1992). Boundary layer parameterization for applied dispersion modeling over urban areas. *Boundary-Layer Meteorology, 58*(3), 229–259.

Hanna, S. R., & Chang, J. C. (1993). Hybrid plume dispersion model (HPDM): Improvements and testing at three field sites. *Atmospheric Environment, 27A*(9), 1491–1508.

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science and Medicine, 63*(11), 2847–2863.

Hartz, D. A., Prashad, L., Hedquist, B. C., Golden, J., & Brazel, A. J. (2006). Linking satellite images and hand-held infrared thermography to observed neighborhood climate conditions. *Remote Sensing of the Environment, 104*(2), 190–200.

Holtslag, A. A. M., & van Ulden, A. P. (1983). A simple scheme for daytime estimates of the surface fluxes from routine weather data. *Journal of Climate and Applied Meteorology, 22*(4), 517–529.

Intergovernmental Panel on Climate Change. (2007). *Climate change 2007: The physical science basis.* (Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis,

K. B. Averyt, M. Tignor, & H. L. Miller, Eds.). Cambridge, UK: Cambridge University Press.

Ivits, E., & Koch, B. (2002). Object-oriented remote sensing tools for biodiversity assessment: A European approach. In T. Benes (Ed.), *Geoinformation for European-wide integration: Proceedings of the 22nd EARSeL Symposium* (pp. 465–473). Rotterdam, The Netherlands: Millpress Science.

Jabareen, Y. R. (2006). Sustainable urban forms: Their typologies, models, and concepts. *Journal of Planning Education and Research, 26*(1), 38–52.

Jenerette, G. D., Harlan, S. L., Brazel, A., Jones, N., Larsen, L., & Stefanov, W. L. (2007). Regional relationships between surface temperature, vegetation, and human settlement in a rapidly urbanizing ecosystem. *Landscape Ecology, 22*(3), 353–365.

Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States*. New York: Cambridge University Press.

Kiema, J. B. K., & Bahr, H. P. (2001). Wavelet compression and the automatic classification of urban environments using high resolution multispectral imagery and laser scanning data. *GeoInformatica, 5*(2), 165–179.

Lougeay, R., Brazel, A., & Hubble, M. (1996). Monitoring intraurban temperature patterns and associated land cover in Phoenix, Arizona using Landsat thermal data. *Geocarto International, 11*(4), 79–90.

Mitchell, V. G., Cleugh, H. A., Grimmond, C. S. B., & Xu, J. (2007). Linking urban water balance and energy balance models to analyze urban design options. *Hydrological Processes, 22*(16), 2891–2900.

Muller, E. (1997). Mapping riparian vegetation along rivers: Old concepts and new methods. *Aquatic Botany, 58*(3–4), 411–437.

Myint, S. W. (2003). Fractal approaches in texture analysis and classification of remotely sensed data: Comparisons with spatial autocorrelation techniques and simple descriptive statistics. *International Journal of Remote Sensing, 24*(9), 1925–1947.

Myint, S. W., Giri, C. P., Wang, L., Zhu, Z., & Gillette, S. (2008). Identifying mangrove species and their surrounding land use and land cover classes using an object oriented approach with a lacunarity spatial measure. *GIScience and Remote Sensing, 45*(2), 188–208.

Myint, S. W., Lam, N. S. N., & Tyler, J. (2002). An evaluation of four different wavelet decomposition procedures for spatial feature discrimination within and around urban areas. *Transactions in GIS, 6*(4), 403–429.

Myint, S. W., May, Y., Cerveny, R., & Giri, C. P. (2008). Comparison of remote sensing image processing techniques to identify tornado damage areas from Landsat TM data. *Sensors, 8*(2), 1128–1156.

Navulur, K. (2007). *Multispectral image analysis using the object-oriented paradigm*. Boca Raton, FL: CRC Press.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal Royal Meteorological Society, 108*(455), 1–24.

Oke, T. R. (1987). *Boundary layer climates*. London: Routledge.

Quay, R. (2009). Anticipating adaptation to climate change. *Practicing Planner, 7*(2). Retrieved October 20, 2009, from http://www.planning.org/practicingplanner/2009/sum/specialfeature01.htm

Sailor, D. J. (January 31, 2006). *Mitigation of urban heat islands—Recent progress and future prospects*. Invited presentation at the Sixth Symposium on the Urban Environment, American Meteorological Society, Atlanta. Retrieved June 26, 2009, from http://ams.confex.com/ams/Annual2006/techprogram/paper_105264.htm

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., et al. (2007). Model projections of an imminent transition to a more arid climate in Southwestern North America. *Science, 316*(5828), 1181–1184.

Southern Nevada Water Authority. (2008). *Water smart landscapes rebate*. Retrieved October 15, 2009, from http://www.snwa.com/html/cons_wsl.html

Stone, B. (2005). Urban heat and air pollution: An emerging role for planners in the climate change debate. *Journal of the American Planning Association, 71*(1), 13–25.

Stone. B., & Bullen, J. L. (2006). Urban form and watershed management: How zoning influences residential stormwater volumes. *Environment and Planning B, 33*(1), 21–37.

Stone, B., & Norman, J. M. (2006). Land use planning and surface heat island formation: A parcel-based radiation flux approach. *Atmospheric Environment, 40*(19), 3561–3573.

Unger, J. (2004). Intra-urban relationship between surface geometry and urban heat island: Review and new approach. *Climate Research, 27*(3), 253–264.

U.S. Census Bureau. (2000). *Summary File 1* (SF1). Retrieved January 15, 2008, from http://factfinder.census.gov/

Western Resource Advocates. (2006). *Water in the urban Southwest: An updated analysis of water use in Albuquerque, Las Vegas Valley, and Tucson.* Boulder, CO: Western Resource Advocates.