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IMPLEMENTING LANDSCAPE WATER CONSERVATION IN PUBLIC SCHOOL INSTITUTIONAL SETTINGS: A CASE FOR SITUATIONAL PROBLEM SOLVING[1]

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ABSTRACT: Urban water conservation programs and research generally focus on residential and commercial use while paying less attention to institutional settings. We studied irrigated landscape water conservation at public schools, controlling for type of irrigation system (manual *vs.* automated control) and water conservation interventions (control, directive, prescriptive, and educational). We monitored landscape water use to compare changes among interventions and irrigation systems to measured plant water needs and historical use. Interviews and diaries allowed the study of behavior among custodians managing landscape irrigation. Large irrigation system effects overshadowed impact of the interventions. Schools using automated systems had high landscape water use and substantial capacity for water conservation but actual savings varied among schools. Schools using manual systems were the opposite yet many still managed further reductions in response to interventions. Effectiveness of water conservation interventions depended upon the contexts in which they were applied. Interventions were more effective when they led to situational problem solving that integrated generalized scientific and technical knowledge with experiential knowledge. Our findings suggest ways for school districts to decide where, when, and how to intervene in promoting water conservation but caution school districts investing in automated-irrigation systems, particularly if they will be operated remotely.

(KEY TERMS: water conservation; urban areas; drought; education; landscape irrigation; public institutions; experimental intervention.)

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INTRODUCTION

The United States Intermountain West experienced rapid population growth in recent decades and has become a highly urbanized region (Riebsame and Robb, 1997; Hobbs and Stoops, 2002; Travis, 2007). This region is subject to drought and is considered arid to semiarid, receiving 150-500 mm of water a year. Water supplies are highly variable and irrigation season demands are largely met with water derived from snowmelt runoff and storage reservoirs. Water supplies to meet growing municipal demands are limited and are subject to competing water demands from agriculture, recreational interests, environmental purposes, energy production, and

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Native American tribes. Long-term water shortages are projected in many areas of the United States Intermountain West as a result of the interaction of population growth, climate change, regional development patterns, and social resistance to traditional water supply augmentation approaches (Riebsame *et al.*, 1997; Western Water Policy Review Advisory Commission, 1998; United States Department of the Interior, 2005; Western Governors' Association, 2006, 2008; National Research Council, 2007; Barrera, 2009; Elcock, 2010; House-Peters *et al.*, 2010).

Efficient water use and conservation on urban landscapes are critical for extending existing water supplies and can contribute significant water savings (Vickers, 2001; Utah Division of Water Resources, 2003). Irrigated urban landscapes are largely turfgrass and account for approximately 60-70% of annual municipal water consumption in the Intermountain West (Grisham and Fleming, 1989; DeOreo *et al.*, 1996; Kjelgren *et al.*, 2000). Some of the region's urban landscapes are irrigated in excess of actual turfgrass water need (Kjelgren *et al.*, 2000; St. Hilaire *et al.*, 2008). Excess landscape irrigation is caused by a combination of factors, including poor irrigation system design and maintenance and watering too frequently for too long (Kilgren, 2001; Klien, 2004; Endter-Wada *et al.*, 2008). Many cities are strengthening their landscape water conservation programs by encouraging people to irrigate more effectively and to establish water conserving landscapes (Mee *et al.*, 2002; Western Resource Advocates, 2003; St. Hilaire *et al.*, 2008; Meyer *et al.*, 2009). Most programs focus on single family residential consumption while water conservation in institutional landscape settings, such as public schools and parks, receives less attention.

Public schools can play an important role in municipal water conservation programs, as they typically maintain large irrigated grounds which are highly visible and can be good examples of water conservation for the entire community. However, water conservation on public school irrigated landscapes must be reconciled with user expectations for appearance, playability, safety, and health of school grounds that in many places are considered to be pubic parks (Kennedy and Zube, 1991; Thompson, 2002; Jansson and Persson, 2010). Common water conservation strategies geared to promoting rational choices of individuals that are assumed to prevail in personal (household) and private-sector (business) contexts (e.g., price signals, billing inserts, and limitations on watering) often are not appropriate to institutional water users and may be less effective in those contexts. Research on public service motivation reveals that public sector employees respond to diverse motivations (including obligation, trust, respect for rules, and desire to be of service) and that work performance is determined not only by work-related motivations but also by various environmental or situational constraints (Jurkiewicz *et al.*, 1998; Perry, 2000; Wright, 2001; Frank and Lewis, 2004; Pandey *et al.*, 2008; Perry and Hondeghem, 2008; Gailmard, 2010).

Water conservation through improved irrigation management potentially can reduce irrigation costs and provide school districts with greater budget flexibility while still maintaining the quality of recreational turfgrass areas. In particular, irrigation scheduling based on local evapotranspiration (ET) rates (plant water use) can substantially reduce excess irrigation and maintain turf quality (Kjelgren *et al.*, 2000). Public school landscape managers are often building custodians who may not have irrigation or turfgrass management training or experience, and who face competing demands on their time and flexibility. Water conservation programs aimed at these locations need to be based on a better understanding of the situational factors shaping their water use.

Improving landscape irrigation scheduling and water management has generally been approached as a technological problem related to the design, installation, and maintenance of irrigation systems for distribution uniformity (DU) and appropriate application of water to crops or landscape plants (Bennett and Hazinski, 1993; Irrigation Association, 2005, 2007). Human behavioral research, however, has shown that water consumption is the result of a variety of cognitive processes (e.g., awareness, knowledge, and attitudes), behavioral habits or routines, and situational or structural factors (Bruvold and Smith, 1988; Aitken *et al.*, 1994; Chappells *et al.*, 2001; Gregory and Di Leo, 2003). Endter-Wada *et al.* (2008) found that the most significant factors predicting landscape water use were the type of irrigation system (automated or manual) and the type of water consumption unit (household or business). They provided insights into how irrigation technologies shape the watering practices and habits of their users and how the interface between human behavior and irrigation technology needs to be understood within the situational constraints of various landscape irrigation contexts.

Our research objectives were to evaluate three interventions with elementary school custodians to promote water conservation on school landscapes, and to assess how type of irrigation system may affect a school's ability to conserve water. Interventions were based on findings and practices from several disciplines. Findings from environmental psychology and environmental education suggest people need to be aware, motivated, and informed to adopt more environmentally appropriate behaviors (e.g., Bechtel and Churchman, 2002; Jackson, 2005).

Land grant university extension programs are designed to transfer scientific and technical information to people who can apply it and this research was conducted under its auspices. Insights from literature on "local knowledge" (a.k.a. "traditional knowledge" or "indigenous knowledge") documents the depth of knowledge about places and resources acquired by people through their interactions and observations over time (e.g., Bicker *et al.*, 2004). The research's underlying premise was that landscape water conservation depends upon behavioral motivations and the appropriate application of technical and local knowledge and skills to particular situations that pose various constraints to efficiency. The interdisciplinary research brought together expertise in irrigation technology, plant science, and social science. While this research focused on public school grounds, it has important implications for promoting water use efficiency at other types of institutional landscapes.

METHODS

Experimental Approach

Study Design. This study was conducted with a large school district located in Utah's Salt Lake Valley (elevation 1,370 m) during 1996, 1997, and 1998. Thirty-five elementary schools (60% of the district's elementary schools) are included in this analysis. Each landscape was composed almost entirely of turfgrass, with Kentucky bluegrass (*Poa pratensis* L.) being the primary turf species. Each school's custodian served as the landscape manager, which included the responsibility for landscape irrigation. The study was an unbalanced, two-way factorial design consisting of two levels: (1) type of irrigation system (manual *vs.* automated control) and (2) water conservation interventions with four levels (educational, prescriptive, directive, and plus a control).

The study's experimental design was constrained by a limited number of schools with automated or time clock-controlled irrigation systems. As the primary focus of this study was the water conservation interventions, 10 schools with automated-irrigation systems were randomly assigned to the three conservation interventions, but none were assigned to the control group. Of the 25 schools with manual irrigation systems, 10 were randomly assigned to the control and the remaining 15 randomly assigned to the three conservation intervention groups.

Water Conservation Interventions. Experimental activities aimed at improving landscape irrigation efficiency were combined cumulatively to define the intervention groups (Table 1). As originally designed, experimental activities included: (1) a letter from the school district directing custodians to conserve water, (2) a prescribed site-specific ETo-based irrigation schedule, and (3) an educational water conservation workshop. Experimental activities were implemented each year to accommodate custodial changes. No experimental activities were applied at the set of control schools.

TABLE 1. Experimental Interventions.

	Experimental Activities			
Interventions	Letter About Conserving Water	ETo-Based Watering Schedule	Water Conservation Workshop	Interviews/Water Diaries
[Control Group]				
Directive	X			X
Prescriptive	X	X		X
Educational	X	X	X	X

Note: Cumulatively combined experimental activities defined the interventions for 35 elementary schools in suburban Salt Lake City, with the effects of the interviews and water diaries (data collection activities) recognized as part of the overall experimental design.

Custodians in the directive intervention only received the letter. This intervention was designed to assess the impact of increasing custodians' awareness of the need for water conservation and their motivation to use water more efficiently by having institutional representatives direct them to conserve. The letter instructed custodians to save water any way possible. These letters were written by the senior author, but signed by the school district supervisor and sent from the district's main office. From 1996 to 1998, two letters were sent annually to each school, one at the beginning of the season and another mid-season.

The prescriptive intervention was designed to assess the importance of technical information, in the form of a local ET-based irrigation schedule, and its implementation. In addition to the directive letter, the prescriptive intervention included irrigation schedules, prescribed by a specialist and tailored to the soils and irrigation system characteristics specific to each school location, which indicated when and how long to irrigate. It was assumed these schedules would keep turf green at the most efficient levels of water use. Custodians were asked to follow the schedules to the best of their abilities.

The educational intervention was designed to assess the effectiveness of educating custodians about irrigation scheduling based on ET rates and soil properties. In addition to receiving the directive letter and a specialist-prescribed irrigation schedule, custodians in the educational intervention attended one-day educational workshops conducted in spring 1996 and 1997 by the senior author of this article and university extension faculty. Workshop topics included basic principles of irrigation scheduling, including water holding properties of soil, plant water use, ET, and irrigation system management and operation. They were intended to empower custodians to bring their own site-specific knowledge to bear on applying technical information in the context of their particular schools.

Additional experimental activities resulted from data collection strategies that, by necessity, involved interacting with the custodians. All custodians involved in the study, except those in the control group, were interviewed at the beginning of the study and at the end of each irrigation season, kept diaries of their irrigation practices and observations of their effects, and interacted with the senior author. During the irrigation season, custodians in the educational and prescriptive groups were contacted every two to four weeks, while less frequent contact was made with custodians in the directive intervention. Water meters were read at all schools included in the study to quantify landscape water use. The data collection strategies reinforced awareness about water conservation among custodians as conveyed in the letter sent from the school district, but also encouraged custodians to observe and record the results of changes in their watering activities.

The experimental interventions were based on the assumption that most school landscapes were overwatered and that water could be conserved. We hypothesized that the letter (and diaries) functioned to increase awareness of and motivation for water conservation. Because of the cumulative nature of the experimental activities employed, we anticipated that the educational group would exhibit the greatest water savings, followed by the prescriptive group then the directive group, with the control group showing little effect. We were unsure of the effects that the custodians' knowledge and previous experience would have on water conservation efforts, so survey questions and diaries were designed to better understand these effects.

Irrigation Systems and Scheduling. Manual irrigation systems consisted of underground pipes with surface connection quick-coupler valves to attach large impact sprinkler heads. Custodians irrigating with manual systems would insert a set of sprinkler heads, allow them to run until they could return from other duties, and then relocate the sprinklers. Automated-irrigation systems consisted of underground piping separated into valve zones of up to five irrigation heads wired to a controller clock. Irrigation duration, frequency, and time of day were set by the landscape manager and automatically controlled by the clock. Irrigation application efficiency, to properly schedule irrigation, was measured by placing 36 plastic cups, calibrated to measure precipitation in mm, in a 1-2 m square grid in a representative landscaped area with complete overlap from four adjacent sprinklers. For automated systems, the grid was set out within a representative zone controlled by a single valve. The irrigation system was then run for 20 and 30 min and application rate and DU were calculated (Bowman *et al.*, 2001). Soil samples were collected at each school to obtain approximate turf rooting depth and soil texture to determine water holding capacity, and both variables were used in the irrigation schedules (Westerman, 1990). Total irrigated turf area was measured with a wheel measure.

Monthly irrigation schedules were based on replacing turf water used over a given period as estimated from local historical ET rate and to compensate for system nonuniformity as determined by application efficiency measurements. Turf water need was estimated as the product of ET and a plant-based correction factor divided by DU. ET was calculated using Hargreaves historical max/min air temperature equation (Hargreaves and Allen, 2003) projected on a monthly basis, and then corrected for actual turf water use with the plant factor (Kc) of 70% of ET (Kneebone *et al.*, 1992), then corrected upward for system nonuniformity by dividing by DU.

The scheduling information received by custodians at the educational and prescriptive-intervention schools varied with type of irrigation system according to what best fit their management system. Custodians with manual irrigation systems were told how much water to apply (application rate by irrigation duration) at each irrigation and when to irrigate, or days between irrigations, to replace water depleted by turfgrass within its root zone (product of water holding capacity and rooting depth). Frequency of irrigation was adjusted based on the rate of estimated turf soil water depletion as weather changed over the season and amount of water applied was held constant (Bowman *et al.*, 2001).

Changes to irrigation schedules were somewhat different at the schools with automated-irrigation systems. Altering irrigation run times with time clocks is easier rather than changing irrigation intervals. These schools were given schedules with varying run times based on ET replacement, where irrigation frequency was held constant, ranging from one to three days, based on soil properties (Bowman *et al.*, 2001). Although scheduling differed, both methods achieve nearly identical water use over a season. It was assumed that custodians would deal with rain as part of the overall response to the interventions.

Data Collection

Landscape Water Use. Water meters were read at each school on a monthly basis from April 1st through November 1st of each year. Water billing data were obtained for each school from the water purveyors who supplied the school district for five years prior to the study and for the study period. Water use data from 1995 were not used because of quality control issues. However, omitting 1995 also provided a clear separation between the prestudy and study periods.

Landscape irrigation water at two schools was separately metered, giving a direct measure of landscape water consumption at those locations. The remaining schools each had one water meter where landscape use was mixed with indoor use. Landscape water use was calculated by defining a baseline indoor water use when outdoor irrigation was not needed (December through January) for the years 1991-1994. Landscape water use was then calculated by subtracting baseline use from total water use when a school was in session during the April-October growing season (Kjelgren *et al.*, 2000). To the best of our knowledge, there were no significant changes in school enrollments during the study period and, thus, monthly indoor water use was the same during the school year and between years.

Finally, solar radiation, wind, air temperature, and humidity data were collected daily during 1991-1998 from a university weather station located approximately in the middle the study area. For *post hoc* estimation of turf water use in subsequent data analysis, a Penman Monteith equation was used to calculate ETo that is more biologically accurate by specifically incorporating turfgrass water use characteristics (Allen *et al.*, 1998). Penman-Montheith ETo correlates well with the Hargreaves ET over an extended period (Hargreaves and Allen, 2003).

Custodian Interviews and Water Diaries. Prior to the study, all 25 intervention school custodians were interviewed separately to obtain background information on the custodian, the irrigation system, the watering routine, factors that influence irrigation, and water conservation attitudes. These custodians also were given water diaries to complete daily in 1996 and 1997 and all of them were paid a standard amount in recognition of the time they spent recording information. The diaries included sections on the watering routine, efforts to conserve water, and conditions that inhibited the custodian from saving water. Postseason interviews were conducted each intervention year (1996, 1997, and 1998) and focused on custodians' watering routines, conservation attitudes, the study intervention, and the water diary for that year. No custodians at control schools were interviewed.

Data Analysis

Monthly billing data in volume units were divided by previously measured irrigated landscaped area to calculate depth of water use by month, and then summed for April through October to arrive at total seasonal water use for each school for each year. As landscape irrigation is affected by year-to-year seasonal weather variation (Hoffmann *et al.*, 2006), for each year of 1991-1994 (baseline) and 1996-1998 (study) periods, two turf water need thresholds were calculated for comparison to seasonal landscape water use. As similarly employed in Endter-Wada *et al.* (2008), a ceiling threshold delimiting maximum possible water need was defined as ETo from April to October without subtracting rainfall. Seasonal school water use above this ceiling is not justified biologically or meteorologically, and thus was considered *wasteful* irrigation. A lower floor threshold was defined as ETo from May to September minus effective rainfall, assuming 80% of rainfall was effective (Blaney and Criddle, 1962), which is a reasonable assumption since April and October are usually wet and cool and irrigation is rarely needed. Seasonal water use below this floor was considered *conserving*. Water use between the ceiling and floor thresholds was considered *acceptable*. Implicit in these thresholds is the assumptions of a uniform, exclusively turf landscape and that the correction factor Kc and DU are equivalent at 70% and cancel such that the thresholds are defined solely by ETo and rainfall. These thresholds represent an ecologically based standard of water use appropriateness against which to evaluate intervention groups instead of comparing them to each other.

Water use data initially were analyzed by conventional analysis of variance (ANOVA; using SigmaStat ver. 3.0, Systat Inc, San Jose, California), then subsequently by more detailed comparisons within individual treatments and schools. The initial ANOVA (one-way) analyzed differences in total seasonal (April-October) water use among intervention treatments (combining manual and automated schools) and the control (manual schools only) to determine if there was a bias in water use among schools preintervention and if there was an easily detectable intervention effect. A subsequent ANOVA (two-way excluding manual control schools) analyzed for an easily detectable intervention by irrigation system effect. We further suspected that differences in weather and preintervention water use could potentially confound intervention effects and so normalized by those two factors. Consequently, we ran the two ANOVAs on transformed total seasonal water use data that was normalized by subtracting seasonal floor (minimum) landscape water need thresholds by year. Finally, we further normalized the weather transformed water use data by subtracting preintervention water use then running the two ANOVAs.

We also reasoned that impact of interventions and irrigation system could be affected by the capacity to conserve water applied above the water need thresholds. We assessed this effect by comparing intervention and irrigation system means to water need thresholds to assess capacity to conserve. Average total seasonal landscape water use for each year of each intervention by system combination for 1991-1994 and 1996-1998 was compared to the water need ceiling and floor thresholds to assess whether it was significantly greater than the ceiling threshold or lower than the floor threshold. We used a one-sample, one-tailed Student's *t*-test at $p < 0.05$, and mean yearly values and thresholds were then plotted for each year (Figure 1).

Finally, we reasoned that intervention impact could potentially be detected in capacity to conserve relative to historical use for individual schools with yearly weather differences factored out. For each school, we compared weather-normalized total yearly landscape water use during the intervention period (1996-1998) to the mean preintervention weather-normalized water use to determine if the number of schools able to respond to the interventions varied among the intervention treatments and system types. We used a one-sample, two-tailed Student's *t*-test at $p < 0.05$ to test differences between preintervention and intervention water use. However, for the sake of clarity only total seasonal landscape water use was plotted for each school by intervention and system type (Figure 2). Differences between interventions based on weather-normalized water use that were significantly higher or lower than preintervention are indicated by solid data symbols and asterisks, respectively.

Then, after these statistical procedures were employed and results inspected, further assessment was done by analyzing contextual factors present at each location, which included various situational and behavioral constraints to efficiency. This supplemented the statistically based variable-oriented approach with a case-oriented strategy which is best suited for identifying invariant patterns common to relatively small sets of cases and for revealing how combinations of factors work in context (Ragin, 1987; Honadle, 1999; Brady and Collier, 2004).

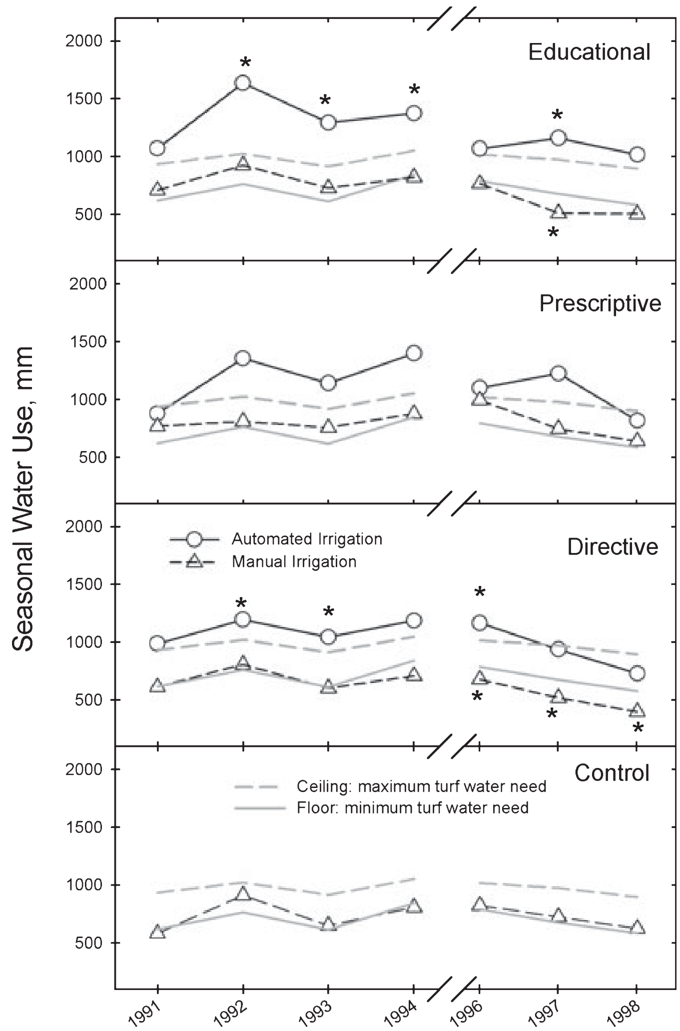

FIGURE 1. Comparison of Intervention Groups by Irrigation System Relative to Thresholds. Total seasonal landscape water use was averaged for elementary schools with automated and manual irrigation systems receiving educational, prescriptive, directive interventions in Salt Lake Valley, Utah for the preintervention (1991-1994) and study/intervention (1996-1998) periods. Dashed gray lines indicate the ceiling/maximum threshold for landscape water needs and solid gray lines indicate the floor/minimum threshold. Asterisks indicate use significantly greater or lower from the nearest threshold line, at $p < 0.05$.

RESULTS

Initial analysis showed that differences between automated and manual irrigation systems overshadowed the impact of the interventions on school water use (Table 2). One-way ANOVA showed no differences among intervention schools during the prestudy period, as the chance of falsely declaring significance ranged from 14 to 31% for the years 1991-1994 prior to intervention. This indicted no inherent biases in water use among schools randomly assigned to the

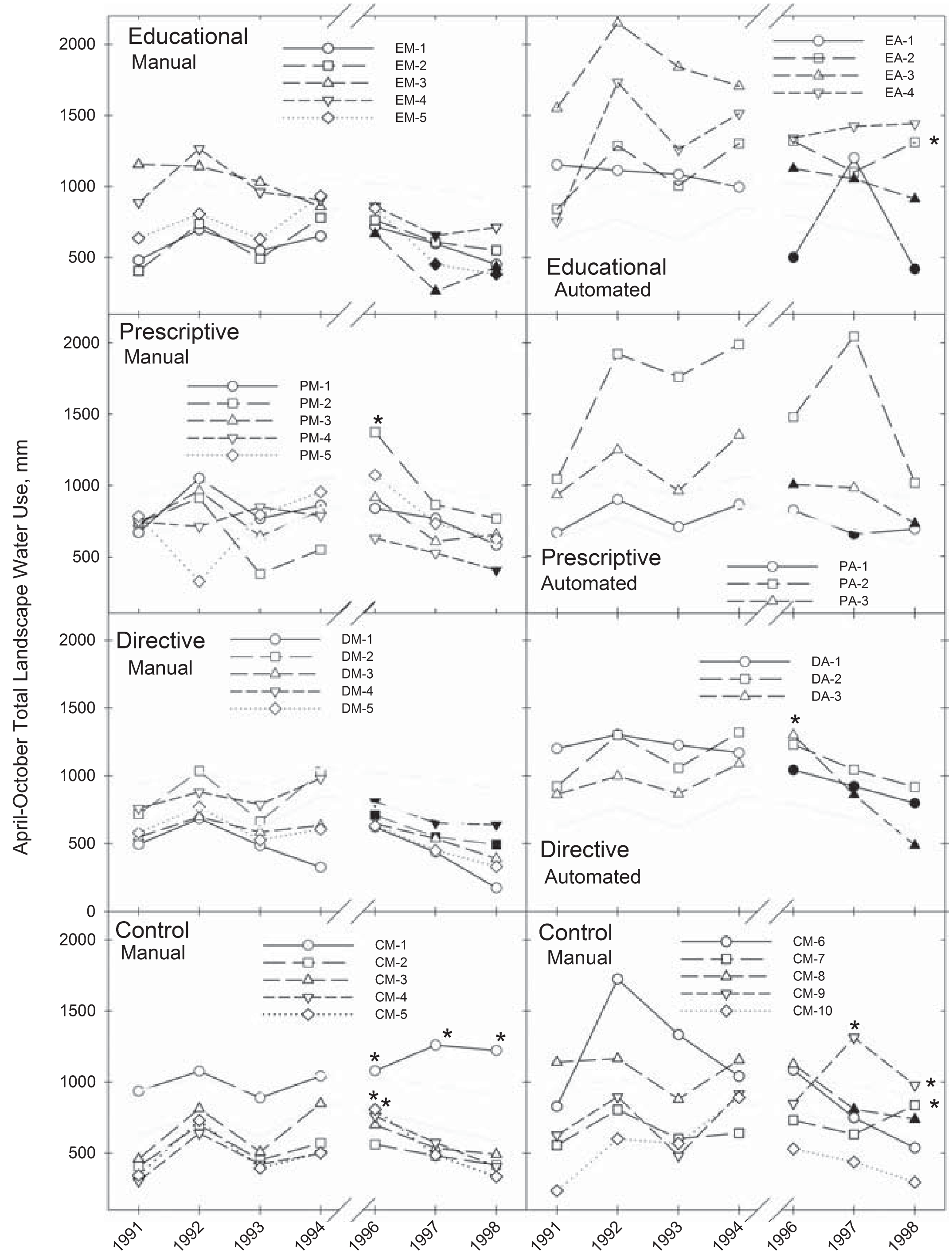

FIGURE 2. Comparison of Individual Schools by Intervention and Irrigation System Relative to Thresholds. Total seasonal landscape water use in relation to floor (solid gray lines) and ceiling (dashed gray lines) thresholds for individual elementary schools receiving educational, prescriptive, and directive interventions, and control schools, in suburban Salt Lake City Utah for the prestudy (1991-1994) and study (1996-1998) periods. Solid data points during the study period 1996-1998 indicate that water use for that school was significantly lower ($p < 0.05$) than that school's prestudy (1991-1994) water use; an asterisk indicates it was significantly higher than prestudy water use. Note that statistical comparisons were performed on weather-normalized total seasonal water use.

different intervention groups. However, this initial analysis also showed no differences in water use among intervention schools during the study period, with a 39-58% chance of falsely declaring significance for the years 1996-1998. This indicated that other factors had greater effect on seasonal water use than

TABLE 2. Effects of Interventions and Irrigation Systems on Landscape Water Use.

	Total Seasonal Landscape Water Use (mm)						
	Prestudy Period				Study Period		
	1991	1992	1993	1994	1996	1997	1998
Interventions							
Educational (n = 9)	873	1,245	983	1,071	904	803	734
Prescriptive (n = 8)	790	961	876	1,014	1,033	897	696
Directive (n = 8)	760	959	775	894	867	681	529
Control (n = 10)	584	915	653	811	827	728	626
p-Value[1]	<0.14	<0.28	<0.21	<0.31	<0.39	<0.58	<0.50
Irrigation system							
Manual (n = 25)	705	849	703	810	827	604	525
Automated (n = 10)	992	1,423	1,177	1,330	1,111	1,116	874
p-Value[1]	<0.005	<0.001	<0.001	<0.001	<0.005	<0.001	<0.002
Climatic data							
May-September ETo[2]	778	836	764	894	851	813	757
May-September rain	193	87	183	58	73	164	214

Notes: Total seasonal (April-October) landscape water use, evapotranspiration rate (ETo) and rainfall in mm for 40 elementary schools in suburban Salt Lake City, compared among landscape water conservation interventions (educational, prescriptive, directive, control) using one-way analysis of variance, and between irrigation system types (manual *vs.* automated but excluding manual control schools) for the prestudy years (1991-1994) and years of the study (1996-1998).
[1]Probability of making a type I error.
[2]ETo = reference evapotranspiration.

did the interventions. Specifically, the effect of irrigation system on total seasonal landscape water use overwhelmed any intervention effects (Table 2).

Two-way ANOVA of intervention by irrigation system (without control schools) showed that schools with automated-irrigation systems had significantly higher water use each year (chance of declaring false significance <1% every year), during both the prestudy and study periods, compared to schools with manual irrigation systems. The schools with automated systems applied 40-85% more water to their landscapes than the schools with manual systems. Weather varied from year-to-year with a pattern of hot-dry years alternating with cool-wet years during the prestudy period, but became progressively cooler and wetter during the intervention study period. However, even after normalizing for weather, and preintervention water use, there was no detectable intervention effect on seasonal landscape water use through one- or two-way ANOVA (data not shown).

However, intervention differences do emerge when exploring how capacity to conserve varied by system type over the entire study period (Figure 1). Seasonal water use of schools with automated systems was consistently above the upper water threshold (ceiling) during the preintervention period, with water applied to these landscapes in the range of 850-1,400 mm (33-55 in.). In the educational intervention, automated schools irrigated significantly more than the ceiling in three of the four prestudy years, and in the directive intervention two of four prestudy years. Despite randomization in assignment to intervention groups, the baseline water use patterns of the automated schools (unknown to us when research was initiated) were not equally distributed. Consequently, some of the intervention groups and individual schools with automated systems that significantly reduced their water use during the study period initially had a greater capacity to conserve than others. Interestingly, in no year was average water use for any of the intervention groups with automated systems significantly lower than the ceiling threshold.

The most striking observation from Figure 1 is that schools with manual irrigation systems in all intervention groups were already irrigating in the conserving or acceptable ranges prior to the study and had minimal capacity to conserve. However, despite existing efficiency, some of them managed to reduce water use further. No manual-system intervention group had average water use exceeding the ceiling threshold in any year, while most were closer to the floor threshold, suggesting they were generally tracking plant water need. Indeed, the directive intervention appeared to encourage custodians with manual systems to water very conservatively, as average water use during the study period (1996-1998) was significantly lower than the floor threshold. Similarly, the average manual educational school water use was reduced from the acceptable range (between floor and ceiling thresholds) prior to the study to at or below the floor threshold during the study, with use significantly lower than the floor threshold in 1997. Interestingly, the prescriptive intervention appears to have been the least effective when applied to manual-system schools, which showed increased average use in the first year of study intervention (1996) before dropping back to use similar to that of the prestudy period (but in all years their average was within the acceptable range).

The ways in which irrigation systems shaped the watering routines of custodians in the context of public school landscapes supports previous research findings that it is convenient to *conserve* water with manually operated systems but convenient to *waste* water with automated-irrigation systems (Endter-Wada *et al.*, 2008:915). The influence of irrigation system type and the effectiveness of interventions designed to change the behaviors associated with that system become more apparent when analyzing the performance of individual schools compared to the ETo-based thresholds and their own historical water use (Figure 2). Complex situations demand more complex and contextualized analysis.

In the contexts of schools with automated-irrigation systems (top three boxes on right-hand side of Figure 2), the interventions appear to have reduced egregious overwatering and eliminated erratic year-to-year variation characteristic of prestudy automated system use (except at EA-1 and PA-2, anomalies discussed below). Each intervention was successful at some automated-system schools, helping custodians reduce use to within an acceptable range. The directive intervention appeared to be most successful, with all three schools trending downward over the study period. The educational intervention yielded mixed results. The prescriptive intervention was effective at two of the three schools with automated systems.

In the contexts of schools with manual irrigation systems (top three boxes on left-hand side of Figure 2), the educational and directive interventions were more successful than the prescriptive intervention, resulting in fairly consistent and sometimes significant reductions in yearly school water use compared to the prestudy period. By comparison, of the ten control schools which all had manual systems, only CM-8 in two of the three study years achieved significant water savings compared to its prestudy usage, whereas five control schools (CM-1, CM-4, CM-5, CM-7, and CM-9) together had eight years of significantly higher water use compared to their prestudy use. The behavior of the manual system control schools strongly suggests that the interventions had some positive effects in the context of schools with manual systems. The generally low water use at all manual-system schools, often below the floor threshold of water need calculated on area-wide ETo, is best explained by the custodians' abilities to further refine watering practices for site-specific conditions and their inabilities to apply enough water during very hot, dry periods due to system and time constraints (which may have resulted in acceptance of lower turf quality).

Further examination of water conservation outcomes in relation to the ETo-based thresholds by intervention and irrigation system type illustrates that the nature of success is not easily characterized (Table 3). Success is clearly relative to a school's initial capacity to conserve and depends not only on the amount of water saved but whether these savings subsequently put that school in the conserving or acceptable ranges of water use. Other indicators of success are whether the reductions were consistent over time (an indication of durability of change), whether high water use variability between years comes closer to tracking the narrower range of ETo variability, and whether use that is already characterized as conserving is further reduced or at least maintained. Of the 13 schools characterized as *successful at reducing water use*, observations in Table 3 show: (1) all had high or medium initial capacity to conserve; (2) 38% received educational intervention, 23% received prescriptive intervention, 31% received directive intervention, 8% were control schools; and (3) 54% were manual schools and 46% were automated schools (six of the ten automated-system schools exhibited this outcome). Of the 10 schools characterized as *successful because they already were and remained conserving*, Table 3 observations show: (1) all had low capacity to conserve; (2) 20% received educational intervention, none received prescriptive intervention, 30% received directive intervention, 50% were control schools; (3) 100% were manual schools; and (4) 70% still managed to consistently reduce water use over the study period (and 30% reduced after an initial increase). Intervention at these schools was probably unwarranted. Of the 12 schools characterized as *not successful at reducing water use*, observations from Table 3 show: (1) all had medium to high initial capacity to conserve; (2) 17% received educational intervention, 42% received prescriptive intervention, 8% received directive intervention, 33% were control schools; and (3) 67% were manual schools and 33% were automated schools (four of the ten automated-system schools exhibited this outcome).

Taken together, these observations suggest that to conserve water on public school institutional landscapes, interventions should be targeted at schools with automated systems and at schools with medium-to-high initial capacity to conserve, and that education or directive interventions are likely to be most effective. The fact that these two approaches were more successful than the prescriptive approach is likely due to the fact that they relied on custodians'

TABLE 3. Characterizing Water Conservation Success.

Characterization of Intervention Response	School	CTC[1]	Intervention[2]	System[3]	Changes in Study Years Relative to Baseline Average[4]		
					Year 1	Year 2	Year 3
Successful at reducing water use (cases have preintervention capacity to conserve)							
Become conserving (at or below floor)	EM-3	H	E	M	↓	↓	↓
	EM-5	M	E	M	-	↓	↓
	PM-4	M	P	M	-	-	↓
	DM-4	M	D	M	↓	↓	↓
	DM-2	M	D	M	↓	↓	↓
Become or remain acceptable (between floor and ceiling)	EM-4	H	E	M	-	↓	-
	PA-3	H	P	A	↓	-	↓
	PA-1	M	P	A	-	↓	-
	DA-1	H	D	A	↓	↓	↓
	CM-8	H	C	M	-	↓	↓
Reduce but remain wasteful (above ceiling)	EA-3	H	E	A	↓	↓	↓
Mixed results (highly variable)	EA-1	H	E	A	↓	-	↓
	DA-3	M	D	A	↑	↓	↓
Successful at remaining conserving (cases have little preintervention capacity to conserve)							
Consistent conservers (at or below floor)	EM-1	L	E	M	-	-	-
	EM-2	L	E	M	-	-	-
	DM-1	L	D	M	-	-	-
	DM-3	L	D	M	-	-	-
	DM-5	L	D	M	-	-	-
	CM-2	L	C	M	-	-	-
	CM-3	L	C	M	-	-	-
	CM-10	L	C	M	-	-	-
	CM-4	L	C	M	↑	-	-
	CM-5	L	C	M	↑	-	-
Not successful at reducing water use (preintervention capacity to conserve)							
Variable with little or no significant water use reductions compared to baseline	PM-1	M	P	M	-	-	-
	PM-3	M	P	M	-	-	-
	PM-5	M	P	M	-	-	-
	CM-6	H	C	M	-	-	-
	CM-7	M	C	M	-	-	↑
Remain wasteful and/or has significant water use increases some years	EA-2	H	E	A	-	-	↑
	EA-4	H	E	A	-	-	-
	PM-2	M	P	M	↑	-	-
	PA-2	H	P	A	-	-	-
	DA-2	H	D	A	-	-	-
	CM-1	H	C	M	↑	↑	↑
	CM-9	M	C	M	-	↑	↑

Note: Description of water conservation intervention outcomes relative to initial capacity to conserve and water use ceiling and floor thresholds for each school, indicating intervention, type of irrigation system, and statistically significant changes.
[1]CTC is "Capacity to Conserve": H = high (above ceiling threshold), M = medium (between ceiling and floor thresholds), and L = low (below floor threshold).
[2]Intervention: E = educational, P = prescriptive, D = directive, C = control.
[3]System: A = automated, M = manual.
[4]Statistically significant change over baseline indicated for ↓ = decrease and ↑ = increase; dash line = no significant change.

site-specific knowledge and experience. Custodians at the educational and directive intervention schools averaged more time working for the school district (12.1 and 13.6 years, respectively) and working at that particular school (7.6 and 6.4 years, respectively) than custodians at the prescriptive-intervention schools (with averages of 9 years working for the district and 5.4 years working at that particular school, after removing the outlier custodian from PA-3, discussed more below). However, an additional element to consider when characterizing the effectiveness of an intervention is custodian satisfaction. In this regard, the educational approach had an advantage over the directive intervention, because custodians in the latter group felt subjected to the mixed messages of "keep the lawn green" but also "save water," as their intervention was not designed to provide the information necessary to help them achieve both objectives simultaneously.

Prescriptive was the least effective intervention overall, but the results are particularly interesting when comparing its application at automated-system schools *vs.* manual-system schools. As this intervention focused on implementing an ETo-based irrigation schedule, it was more successful when applied to automated-system schools that overwatered, particularly when that led to adjustments in the automated-time clock (as we know happened at PA-2 in 1996 and 1998). Looking across all automated-system school cases for all years in Figure 2, water use variability can be seen to track ETo, but often at levels far in excess of plant need. This overwatering was likely the cumulative effect of adjusting the time clock too high in response to observed changes in weather without adequate understanding of plant water need or irrigation system application rates. One of the difficulties in achieving efficiency in landscape watering is the fact that people do not have as clearly understood and interpretable observational cues that trigger appropriate behavioral reactions when it comes to plant water need and irrigation system application rates as in the case of weather. It is relatively easy to observe rain and not water on rainy days. Wilting and brown spots are the main cues of plant water need and irrigation system inefficiency, but these cues reflect extreme stress and often trigger a negative reaction that likely contributes to unintentional overwatering (Klien, 2004). The ETo-based irrigation schedule appeared helpful at addressing these information needs. However, when applied to manual-system schools that were already watering in the conserving or acceptable ranges, it failed. This was because, in most cases, the prescribed schedule based on area-wide ETo indicated that custodians should water more than they were already watering, which was often physically impossible to do. Water use increases at manual-system, prescriptive-intervention schools in 1996 were the result of custodians attempting to implement the irrigation schedules they were given before abandoning them the following year. Several custodians in this group admitted they ignored the irrigation schedules; a few of them were amused in light of contextual constraints that prohibited implementation.

Variability between individual schools in the baseline period and in responding to interventions suggests that other contextual factors besides intervention and irrigation system affected water use patterns. The Spearman Rank Order Correlation Test revealed a significant negative correlation between baseline water use and size of landscaped area of school grounds (−0.349, $p < 0.05$), indicating that higher water use tended to occur at schools with smaller landscaped grounds. Additionally, there was a significant negative correlation between baseline water use and custodians' reports of the severity of problems with water pressure (−0.675, $p < 0.000$), indicating that lower water use tended to occur at schools with poor water pressure. Lower water pressure means more time is needed for watering. Small landscapes and reportedly good water pressure help explain, for instance, the relatively high baseline water use at the automated schools of EA-3 (1.1 ha) and PA-2 (0.9 ha) and at the manual schools of EM-3 (0.7 ha) and DM-2 (0.9 ha), which were the only four schools in the study with <1.2 ha of green landscape (the average landscaped area for all elementary schools was 2.5 ha and ranged from 0.7 to 4.2 ha). Custodians at the large-landscape, manual-system schools of EM-1 (3.4 ha), PM-1 (3.5 ha), and DM-5 (2.8 ha) reported the greatest number of water pressure problems, which may help explain their relatively low baseline water use. Thus, the combined situational factors of automated systems, high water pressure, and small landscapes appear to inhibit the ability of custodians to be water efficient in relation to plant water need, whereas the combined situational factors of manual systems, poor water pressure, and large landscapes appear to inhibit their ability to waste water.

In-depth analysis of other school-specific characteristics that affected custodians' watering routines sheds additional light on patterns and anomalies affecting water use. Data on these characteristics come from face-to-face interviews and water diaries. School-specific physical characteristics included the layout and condition of the irrigation system, malfunctions and maintenance, type of soil, shape of turf areas, slope of school grounds, and microclimates (variation in rain, heat, wind, sun/shady areas). For example, wide swings in water use at EA-1 during the study period are related to major irrigation system breakdowns (rupture of a water main, broken heads on a weekly basis) and the installation of new sod (which required additional watering).

Conditions related to human motivations and behaviors that affected watering routines included workplace and institutional factors such as time schedules, esthetic expectations, and maintenance issues. The school calendar (year round or nine month), competing demands on custodians' time, and when and how school grounds were used affected time schedules for watering. Esthetic expectations included pressures from principals and users of the grounds as well as the visibility of different areas, making some areas subject to greater scrutiny and likely to be watered more. Maintenance factors included vandalism that affected irrigation systems and coordination with the school district that handled repairs and mowed the grass. For example, numerous custodians complained about breakdowns that interrupted their watering routines until district personnel came to fix their systems, whereas most custodians noted watering could not occur before or on days when other district employees came to mow the grass.

Factors related to the custodians' personal backgrounds and public sector work experience also likely influenced watering routines and responses to the interventions. These factors included: previous experience with irrigation system management (67% in education intervention, 25% in prescriptive intervention, and 38% in directive intervention); length of time working for the school district (12.1 years for educational intervention, 9 years for prescriptive intervention after removing the outlier PA-3, and 13.6 years for directive intervention); and length of time working at that particular school (7.6 years for education intervention, 5.4 years for prescriptive intervention after removing outlier PA-3, and 6.4 years for directive intervention). PA-3 was the most successful prescriptive intervention case in terms of bringing formerly wasteful use into the acceptable range. Interestingly, its custodian was a clear outlier in terms of having worked for the school district for 30 years and at that particular school for 29 years (the next highest tenure in the district and at any one school was 17 years). The custodian found the irrigation schedule unhelpful and ignored it, and success at this school apparently resulted from the encouragement to conserve, which motivated the custodian to make various irrigation system adjustments utilizing his long-term experience and knowledge of site conditions. In fact, landscape water use at PA-3 likely would have been significantly lower in all three intervention years and not just two of them (i.e., even more successful) if not for the installation of new sod in September 1997 that the custodian said required more water than normal. In an interview, this custodian observed: "Different sites have different needs and different systems have different needs."

Interaction of various physical and human factors influenced custodians' watering routines in a variety of ways, but the overriding effect was that it constrained the process of allocating and managing custodial work time. Manual systems were more time intensive to operate, requiring an average of 2.4 hours per day of custodial time, whereas automated systems required on average 0.75 of an hour per day of custodial time. Automated systems were more time flexible to operate (they could run at night and avoid people's use of the grounds), enabling water to run over a more varied time span (4-18 hours a day) than at manual schools (7.5-10 hours a day). Thus, custodians at schools with manual systems faced two interconnected operational constraints that were much less problematic for custodians at schools with automated systems: their own working hours and people's use of the school grounds. Custodians at manual-system schools often complained about the difficulties of watering within their work day, and some reported coming in on unpaid time to water. Custodial time constraints were significant considerations as schools also included nonlandscaped areas that needed maintaining, which averaged 1.7 ha for all elementary schools and ranged from 0.7 ha (PA-2) to 2.3 ha (DM-5). Coordinating landscape watering with other custodial duties was particularly difficult at year-round schools that were in session during the summer irrigation season.

Closer inspection of intervention responses in a few specific examples further illustrates how contextual factors affect water use and can provide the keys to increasing water use efficiency. For instance, EA-3 was the biggest success in terms of significantly and consistently reducing water use in the study period compared to its own baseline period. Very high initial capacity to conserve was likely the result of its automated-irrigation system, small landscape, good water pressure, nine-month school calendar, and minimal reported interference in watering routine from school ground use. The custodian had been there for 15 years and reported receiving pressure from the school principal to keep the grounds nice as well as compliments on the grounds from other people, which may have reinforced existing watering routines. The custodian reported he was experienced at irrigating, motivated to conserve, and did not overwater (he was unaware of how high water use actually was). But in answering a list of prestudy interview questions with forced-choice, Likert-scale responses about the degree to which 13 different physical conditions influenced his watering routine, he indicated that only rain, heat, and slopes affected it while other conditions did not (such as seasons, time of day, soil, wind, grass type, etc.). This custodian did not exhibit strong outward enthusiasm or motivation for participating in the study, but he made three significant changes in his watering routine during the study period: he did not start irrigating until late in the spring (he formerly started in April); he was more likely to turn sprinklers off in response to rain; and he reduced irrigation frequency over the course of the season from four times per week to three times per week. He recorded (in the diary) and reported (in interviews) that these changes were made in response to information acquired in the educational workshop on soil water retention and plant water use, to the realization from receiving the water schedule that he was watering too much, and to his experience that the lawn still looked good after he changed his watering routine. The cumulative effect of these various automated-time clock adjustments clearly produced water savings. This school was still above the ceiling threshold in 1998, but the custodian was interested in receiving additional information on how to further reduce water use.

A comparison of PM-3 and PA-2 is particularly instructive as to the interactive role of irrigation systems, custodian landscape management, and site factors. Starting in 1993, these two schools were managed by the same custodian (who was based at PM-3), their irrigation systems had nearly identical water pressure and DU, and both were on nine-month school calendars. However, PM-3 had a manual system, 2.2 ha of landscaped area, and acceptable water use, whereas PA-2 had an automated system, 0.9 ha of landscaped area, and one of the two highest water uses (along with EA-3 discussed above) of all schools in the prestudy period. Both PM-3 and PA-2 were in the prescriptive intervention. The custodian was enthusiastic and tried to save water at both locations in 1996. In referring to PM-3, the manual-system school, he reported on all the time constraints he faced and said, "I need to figure out a faster way of watering…I waste three hours a day on watering." However, at PA-2, he changed the automated-time clock, and this resulted in a large water use reduction (Figure 2). But in 1997, the school district took over irrigation management of PA-2 as it was used for district-wide functions and had an automated-irrigation system (on the assumption it needed minimal custodial services). Little or no adjustment was made in the water schedule throughout the watering season, resulting in a huge water use increase in 1997. The senior author pointed this out to the school district prior to the 1998 irrigation season and changes in the automated-time clock settings resulted in the huge water use decrease in 1998. The results at PA-2 indicate that overwatering can easily be the result of unmonitored automated-irrigation system watering, but also may be easily corrected if the water user is notified about the problem and responds.

CONCLUSIONS

Water conservation programs targeted at large institutional landscapes like public school grounds are likely to produce water savings mainly because of the size of irrigated acreage. However, water savings might best be realized by focusing resources and education primarily on locations that have historically over irrigated. Locations with high capacity to conserve water can be identified through analysis of water billing data and comparison to ETo-based thresholds that categorize landscape water use as conserving, acceptable, or wasteful. Absent the resources to conduct such analyses, conservation interventions would likely be most effective if they are targeted at schools that fit certain profiles (automated-irrigation systems, smaller grounds, high water pressure, and nine-month calendar) and at schools in certain circumstances (in transition from manual to automated-irrigation systems, experiencing custodian turn-over, exhibiting high water use variability between years). Monitoring water use and being strategic about *when* as well as *where* to undertake conservation efforts is important for achieving larger system efficiencies in water use and conservation program administration.

In our study, schools with automated-irrigation systems generally exhibited the greatest capacity to conserve. Experimental conservation interventions at automated schools helped decrease water use, but not always to the point that water use could be considered acceptable as defined by ET-based thresholds, indicating there was additional capacity to conserve. Most school grounds with manually operated irrigation systems were already irrigated in the acceptable or conserving ranges defined by ETo-based thresholds, especially those with large areas that made it logistically impossible to apply too much water. Nevertheless, conservation interventions at these schools often resulted in water savings because they offered custodians encouragement to save water which also saved their time. Making custodians consciously observe, record, and reflect upon their watering practices through use of diaries often assured them that further water use reductions could occur without seriously compromising turfgrass appearance. Stressing the importance of water conservation and providing recommendations on how to achieve it appeared to reinforce and further their already efficient irrigation practices. These findings suggest that care needs to be taken in characterizing different types of water conservation successes so that past and current efforts to save water are appropriately recognized or rewarded and not penalized should they entail tradeoffs (e.g., water conservation *vs.* lush green grass all summer).

Our findings suggest a word of caution for school districts transitioning to automated-irrigation systems, particularly if their intention is to operate these systems remotely, as was the plan of the school district in this study. We found that automated-irrigation systems do not appear to be water-saving devices as much as time-saving devices, confirming previous work (Endter-Wada *et al.*, 2008:915). The case of PA-2 showed how high water use can result if remotely operated automated systems are not carefully monitored. Depending on a school district's objectives and a careful cost-benefit analysis, changing to automated-irrigation systems may or may not be justified financially. School districts could inadvertently end up spending more money if transitioning to automated-irrigation systems results in the application of more water, or if the investment in automated systems is not offset by cost savings on water bills and custodial time. Custodians, however, expressed very strong preferences for automated systems. When asked in the postsurvey what could help them become even more water conserving, almost every custodian at a manual-system school said, "an automated system," indicating they perceive these systems to be water-saving devices. Appropriate training and monitoring needs to accompany transitions from manual to automated-irrigation systems since the watering practices often differ. Manual watering of a particular turf area tends to occur less frequently but often for longer periods of time at each application. Monitoring water use during transitions to automated systems can help ensure that the frequency and duration of irrigation schedules are appropriate.

We found that the effectiveness of water conservation interventions depends upon the contexts in which they are applied. Water use and conservation in public school institutional settings is highly dependent on multiple factors often unrelated to irrigation, plants, or weather. Of the three conservation interventions, the educational and directive ones appear to have been most effective. They relied on custodians' knowledge and experience to achieve conservation while taking into account various constraints at their particular schools, gave custodians decision-making authority, and provided information that empowered custodians to save water while maintaining acceptable landscape conditions. These factors may have increased custodians' motivations in the absence of increased pay or other individualized incentives. Changes in irrigation scheduling, as relied upon in the prescriptive approach, were easier to implement at automated-system schools because of time flexibility in operating the system and minimal custodial time needed for implementation. Changes in irrigation scheduling were harder to implement in manual-school settings because they often entailed modifications of work routines contingent upon other activities. These results imply that water conservation programs need to be designed to fit different contexts and that, in institutional settings, approaches that appeal to a variety of public service motivations are likely to be more successful.

While irrigation systems were a predominant influence on water use, other contextual factors played a role. The variability in specific site conditions meant that custodians continually had to engage in decision-making on how best to meet other people's expectations while working within multiple physical, technical, and human constraints. Many of them reported that landscape irrigation was definitely a challenge, which made their successes all the more meaningful. Through the participation and effort of these custodians, we were able to document that incorporating local, site-specific knowledge in applying more general technical knowledge is one of the keys to successful landscape water conservation. While it is difficult to determine the effect of interactions between custodians and the senior author (while making site visits, reviewing diaries, and conducting interviews for data collection on human behavior), it appeared qualitatively significant enough that we realized it constituted a fourth experimental activity. The senior author was often asked for his advice and feedback. He became keenly aware of situational complexity and sympathetic to the challenges custodians faced. Most probably, these on-going interactions between researcher and custodians led to some situational problem solving that helped to integrate generalized scientific and technical knowledge with contextualized experiential knowledge. We suggest that this integration is a key element of successful landscape water conservation programs.

These findings imply a challenge to re-conceptualize the approach to understanding landscape water use and to conduct research that will further examine and test how best to design landscape water conservation programs. Instead of approaching landscape water conservation primarily as a matter of irrigation system efficiency, behavioral motivation, and technical information transfer, greater consideration should be given to problem-solving approaches that can deal with the contextual complexities in which landscape irrigation occurs and the subtleties of human agency and ingenuity in working within those contexts. Engaging people in the process of deciding upon, implementing, monitoring, and evaluating their own efforts to save water would likely prove useful and effective.

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LITERATURE CITED

Aitken, C.K., T.A. McMahon, A.J. Wearing, and B.L. Finlayson, 1994. Residential Water Use: Predicting and Reducing Consumption. Journal of Applied Social Psychology 24(2): 136-158.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization (FAO) of the United Nations, Rome, Italy.

Barrera, L., 2009. Portraits of Climate Change: The Rocky Mountains. World Watch 22(4):8-16.

Bechtel, R.B. and A. Churchman (Editors), 2002. Handbook of Environmental Psychology. John Wiley, New York.

Bennett, R.E. and M.S. Hazinski, 1993. Water-Efficient Landscape Guidelines. American Water Works Association, Denver, Colorado.

Bicker, A., P. Sillitoe, and J. Pottier (Editors), 2004. Investigating Local Knowledge: New Directions, New Approaches. Ashgate Publishing Ltd., Aldershot, Hamshire, United Kingdom.

Blaney, H.F. and W.D. Criddle, 1962. Determining Consumptive Use and Irrigation Water Requirements. Technical Bulletin 1275, Agricultural Research Service, U.S. Department of Agriculture, Washington, D.C.

Bowman, D.C., B. McCarty, and J. Camberato, 2001. Water Management in Turf. *In:* Best Golf Course Management Practices, L.B. McCarty (Editor), Prentice-Hall, Inc., Upper Saddle River, New Jersey, pp. 261-280.

Brady, H.E. and D. Collier (Editors), 2004. Rethinking Social Inquiry: Diverse Tools, Shared Standards. Rowman and Littlefield Publishers, Inc., Oxford, United Kingdom.

Bruvold, W.J. and B.R. Smith, 1988. Developing and Assessing a Model of Residential Water Conservation. Water Resources Bulletin 24(3):661-669.

Chappells, H., J. Selby, and E. Shove, 2001. Control and Flow: Rethinking the Sociology, Technology and Politics of Water Consumption. *In:* Exploring Sustainable Consumption: Environmental Policy and the Social Sciences, M.J. Cohen and J. Murphy (Editors). Pergamon Press, London, Vol. 1, pp. 157-170.

DeOreo, W.B., J.P. Heaney, and P.W. Mayer, 1996. Flow Trace Analysis to Assess Water Use. Journal of the American Water Works Association 88(1):79-90.

Elcock, D., 2010. Future U.S. Water Consumption: The Role of Energy Production. Journal of the American Water Resources Association 46(3):447-460.

Endter-Wada, J., J. Kurtzman, S.P. Keenan, R.K. Kjelgren, and C.M.U. Neale, 2008. Situational Waste in Landscape Watering: Residential and Business Water Use in an Urban Utah Community. Journal of the American Water Resources Association 44(4):902-920.

Frank, S. and G. Lewis, 2004. Government Employees: Working Hard or Hardly Working? American Review of Public Administration 34(1):36-51.

Gailmard, S., 2010. Politics, Principal-Agent Problems, and Public Service Motivation. International Public Management Journal 13(1):35-45.

Gregory, G.D. and M. Di Leo, 2003. Repeated Behavior and Environmental Psychology: The Role of Personal Involvement and Habit Formation in Explaining Water Consumption. Journal of Applied Social Psychology 33(6):1261-1296.

Grisham, A. and W.M. Fleming, 1989. Long-Term Options for Municipal Water Conservation. Journal of the American Water Works Association 81(3):34-42.

Hargreaves, G.H and R.G. Allen, 2003. History and Evaluation of Hargreaves Evapotranspiration Equation. Journal of Irrigation Drainage Engineering 129(1):53-63.

Hobbs, F. and N. Stoops, 2002. Demographic Trends in the 20th Century. Census 2000 Special Reports, Series CENSR-4. U.S. Census Bureau, Government Printing Office, Washington, D.C. http://www.census.gov/prod/2002pubs/censr-4.pdf, *accessed* February 2010.

Hoffmann, M., A. Worthington, and H. Higgs, 2006. Urban Water Demand With Fixed Volumetric Charging in a Large Municipality: The Case of Brisbane, Australia. Australian Journal of Agricultural & Resource Economics 50(3):347-359.

Honadle, G., 1999. How Context Matters: Linking Environmental Policy to People and Place. Kumarian Press, West Hartford, Connecticut.

House-Peters, L., B. Pratt, and H. Chang, 2010. Effects of Urban Spatial Structure, Sociodemogaphics, and Climate on Residential Water Consumption in Hillsboro, Oregon. Journal of American Water & Resources Association 46(3):461-472.

Irrigation Association, 2005. Turf and Landscape Irrigation Best Management Practices. Water Management Committee of The Irrigation Association, Falls Church, Virginia. http://www.irrigation.org/Resources/Turf_Landscape_BMPs.aspx, *accessed* September 2010.

Irrigation Association, 2007. Landscape Irrigation Auditor Manual. Irrigation Association, Falls Church, Virginia.

Jackson, T., 2005. Motivating Sustainable Consumption: A Review of Evidence on Consumer Behavior and Behavioural Change: A Report to the Sustainable Development Research Network. Centre for Environmental Strategy, University of Surry, United Kingdom.

Jansson, M. and B. Persson, 2010. Playground Planning and Management: An Evaluation of Standard-Influenced Provision Through User Needs. Urban Forestry & Urban Greening 9(1):33-42.

Jurkiewicz, C.L., T.K. Massey, Jr., and R.G. Brown, 1998. Motivation in Public and Private Organizations: A Comparative Study. Public Productivity and Management Review 21(3):230-250.

Kennedy, C.B. and E.H. Zube, 1991. Attitudes Towards Vegetation in a Desert Urban Forest: Creating a Sense of Place. Journal of Arboriculture 17(6):159-165.

Kilgren, D., 2001. Implementing Water Conservation in an Institutional Setting. M.S. Thesis, Utah State University, Logan, Utah.

Kjelgren, R., L. Rupp, and D. Kilgren, 2000. Water Conservation in Urban Landscapes. HortScience 35:1037-1040.

Klien, C., 2004. Understanding Household Landscape Water Conservation. M.S. Thesis, Utah State University, Logan, Utah.

Kneebone, W.R., D.M. Kopec, and C.F. Mancino, 1992. Water Requirements and Irrigation. *In:* Turfgrass, D.V. Waddington, R.N. Carrow and R.C Shearman (Editors). ASA-CSSA-SSSA, Madison, Wisconsin, pp. 441-472.

Mee, W.J., R. Barnes, R. Kjelgren, R. Sutton, T. Cerny, and C. Johnson, 2002. Water Wise: Native Plants for Intermountain Landscapes. Utah State University Press, Logan, Utah.

Meyer, S.E., R.K. Kjelgren, D.G. Morrison, W.A. Varga, and B. Schultz. 2009. Landscaping on the New Frontier: Waterwise Design for the Intermountain West. Utah State University Press, Logan, Utah.

National Research Council, 2007. Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability. Prepared by the Committee on the Scientific Bases of Colorado River Basin Water Management. The National Academies Press, Washington, D.C.

Pandey, S.K., B.E. Wright, and D. Moynihan, 2008. Public Service Motivation and Interpersonal Citizenship Behavior in Public Organizations: Testing a Preliminary Model. International Public Management Journal 11(1):89-108.

Perry, J.L., 2000. Bringing Society In: Toward a Theory of Public-Service Motivation. Journal of Public Administration Research and Theory 10(2):471-488.

Perry, J. and A. Hondeghem (Editors), 2008. Motivation in Public Management: The Call of Public Service. Oxford University Press, Oxford, United Kingdom/New York, New York.

Ragin, C.C., 1987. The Comparative Method: Moving Beyond Qualitative and Quantitative Strategies. University of California Press, Berkeley, California.

Riebsame, W.E. and J.J. Robb (Editors), 1997. Atlas of the New West: Portrait of a Changing Region. Center of the American West, Boulder, Colorado; W.W. Norton & Company, New York.

Riebsame, W.E., J. Wescoat, and P. Morrisette, 1997. Western Land Use Trends and Policy: Implications for Water Resources. Report to the Western Water Policy Review Advisory Commission. National Technical Information Service, Springfield, Virginia. http://repository.unm.edu/dspace/bitstream/1928/2808/1/LANDUSE.pdf, *accessed* February 2010.

St. Hilaire, R., M.S. Arnold, D.C. Wilkerson, D.A. Devitt, B.H. Hurd, B.J. Lesiker, V.I. Lohr, C.A. Martin, G.V. McDonald, R.L. Morris, D.R. Pittenger, D.A. Shaw, and D.F. Zoldoske, 2008. Efficient Water Use in Residential Urban Landscapes. HortScience 43(7):2081-2092.

Thompson, C.W., 2002. Urban Open Space in the 21st Century. Landscape and Urban Planning 60(2):59-72.

Travis, W.R., 2007. New Geographies of the American West: Land Use and the Changing Patterns of Place. Island Press, Washington, D.C.

United States Department of the Interior, 2005. Water 2025: Preventing Crises and Conflict in the West – August 2005 Status Report. http://permanent.access.gpo.gov/lps77383/water2025-08-05.pdf, *accessed* February 2010.

Utah Division of Water Resources, 2003. Utah's M&I Water Conservation Plan: Investing in the Future. Utah Division of Water Resources, Salt Lake City, Utah. http://www.water.utah.gov/M&I/Plan7-14-03.pdf, *accessed* February 2010.

Vickers, A., 2001. Handbook of Water Use and Conservation: Homes, Landscapes, Businesses, Industries, and Farms. Water-Plow Press, Amherst, Massachusetts.

Westerman, R.L. (Editor), 1990. Soil Testing and Plant Analysis (Third Edition). Soil Science Society of America, Madison, Wisconsin.

Western Governors' Association, 2006. Water Needs and Strategies for a Sustainable Future. Prepared by Western Governors' Association (Denver, Colorado) in cooperation with the Western States Water Council (Midvale, Utah). http://www.westgov.org/wga/publicat/Water06.pdf, *accessed* February 2010.

Western Governors' Association, 2008. Water Needs and Strategies for a Sustainable Future: Next Steps. Prepared by Western Governors' Association (Denver, Colorado) in cooperation with the Western States Water Council (Midvale, Utah). http://www.westgov.org/wga/publicat/water08.pdf, *accessed* February 2010.

Western Resource Advocates, 2003. Smart Water: A Comparative Study of Urban Water Use Across the Southwest. Western Resource Advocates, Boulder, Colorado. http://www.westernresourceadvocates.org/water/smartwater.php, *accessed* February 2010.

Western Water Policy Review Advisory Commission, 1998. Water in the West: Challenge for the Next Century. Final Report, Western Water Policy Review Advisory Commission, Washington, D.C.

Wright, B.E., 2001. Public-Sector Work Motivation: A Review of Current Literature and a Revised Conceptual Model. Journal of Public Administration Research and Theory 11(4):559-586.

Quantifying Urban Landscape Water Conservation Potential Using High Resolution Remote Sensing and GIS

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Abstract

Research goals were to analyze patterns of urban landscape water use, assess landscape water conservation potential, and identify locations with capacity to conserve. Methodological contributions involved acquiring airborne multispectral digital images over two urban cities which were processed, classified, and imported into a GIS environment where landscaped areas were extracted and combined with property and water billing data and local evapotranspiration rates to calculate landscape irrigation applications exceeding estimated water needs. Additional analyses were conducted to compare classified aerial images to ground-measured landscaped areas, landscaped areas to total parcel size, water use on residential and commercial properties, and turf areas under trees when they were leafed out and bare. Results verified the accuracy and value of this approach for municipal water management, showed more commercial properties applied water in excess of estimated needs compared to residential ones, and that small percentages of users accounted for most of the excess irrigation.

Introduction

Competition over scarce water supplies has increased in the rapidly urbanizing Western United States. Building new supply structures to meet increasing urban demand is problematic economically, socially, and politically. Alternative solutions are water reallocation from irrigated agriculture, as urban water uses exercise higher-valued market demand (Pimentel *et al.*, 2004; Postel, 2000), and urban water conservation strategies (Carr and Crammond, 1995; Vickers, 2001). Re-allocating water from agricultural to urban uses comes at the cost of lost farmland, compromised national food security, and dislocations in agriculturally-dependent communities (National Research Council, 1992; Postel, 2000). Increasingly, water re-allocation from agricultural to municipal use is being scrutinized on the basis of how much water is actually needed by urban areas and how efficiently urban areas use their existing water supplies. Determining urban water *needs* in relation to urban water *use* (i.e., identifying potential inefficiencies or waste) can reveal potential conservation savings that could help minimize competing demands on agricultural water as well as on a variety of environmental uses.

In urbanizing parts of the arid U.S. West, irrigation of outdoor landscapes consumes most municipal water, accounting for 50 percent or more of total annual urban-municipal potable water use (Kjelgren *et al.*, 2000). Nationally, it is estimated that approximately 30 percent of total annual municipal water consumption in the U.S. is used on urban landscapes (Solley *et al.*, 1998). Unlike indoor water use, outdoor landscape water use has not been rigorously quantified, but potentially conservable water, or capacity to conserve, can be quantified by comparing actual irrigation usage to estimated water needs (Endter-Wada *et al.*, 2008; Kilgren *et al.*, 2010). Estimated water needs can be expressed in depth units, and can be determined from local cool-season reference evapotranspiration rate (ETo). ETo is a function of local air temperature, wind speed, humidity, and incoming solar radiation that drive evaporation, which is modified by a correction factor unique to a given plant type (Allen *et al.*, 1994). Actual landscape water use can be derived from water purveyor billing data measured in volumetric units. However, in order to compare estimated landscape water needs to actual usage, both ETo and water use need to be expressed in common units.

Careful measurements of irrigated landscaped areas and determination of plant types are necessary for this conversion. Compared to large-scale agricultural production, measuring irrigated urban areas is difficult because of the wide range in sizes, shapes, and fragmentation of these areas, as well as diversity in plant material used and the types and functions of various landscapes (residential, commercial, institutional, public). Manual measurement is impractical on a large scale, and the great diversity of plant species used in urban landscapes makes area determination from conventional black and white or color aerial images

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difficult (Kjelgren *et al.*, 2000). Most satellite multispectral images have too low a spatial resolution for this functional use in urban areas.

The purpose of this paper is to present research findings which demonstrate that high-resolution airborne multispectral imagery can be used to determine irrigated landscaped areas and aid in quantifying urban water conservation potential. Images can be taken over a large area with high spatial resolution, and different vegetation types can be classified based on their spectral properties. A geo-rectified and classified aerial image can then be imported into a geographic information system (GIS) environment and integrated with municipal databases to extract irrigated landscaped areas for individual properties or water users. We argue that this methodology could be employed by water agencies to assess potentially conservable water on both an aggregate (e.g., municipal) and an individual (e.g., customer) basis.

Our research is based on a conceptual approach that uses airborne multispectral imagery to obtain irrigated landscape areas that, when combined with local reference evapotranspiration data, can be used to estimate reasonable, area-specific urban vegetative water demand. The estimated water demand is compared to actual landscape water use by parcel, obtained by mining water supplier billing data. This approach is used to determine potentially conservable landscape irrigation water and to identify end users with high capacity to conserve. This methodological approach is a key component in a trajectory of interdisciplinary research designed to investigate site characteristics and human behaviors affecting urban water use (Endter-Wada *et al.*, 2008; Kilgren *et al.*, 2010).

Methods

Study Areas

Research was conducted in two suburb cities of Salt Lake City, Utah and one northern Utah community. The City of Layton, approximately 35 km north of Salt Lake City (population in 2000 of about 58,000) was the initial project study area. Layton was selected for study as it is rapidly urbanizing, and yet retains older areas that may vary in landscaped area and landscape water use characteristics. We focused on a section of the city, approximately 17 km^2 that encompassed newer and older residential areas, as well as commercial-industrial and institutional (CII) areas. All customers in this area relied on municipally-supplied culinary water and did not have access to landscape water from secondary irrigation systems. A second suburb of Salt Lake City, the City of West Jordan, was additionally selected in order to validate the image analysis process and assess if the landscaped area and water use trends observed in Layton might be representative of other urban areas in Utah. West Jordan (population in 2000 of about 68,000), located approximately 15 km southwest of Salt Lake City, is mostly residential but with a fast-growing commercial district and covers an area of 80 km^2. Research conducted in Logan, Utah, approximately 120 km north of Salt Lake City, determined the percentage of turf grass shaded by tree cover. The area of tree canopy in relation to underlying turf area needs to be taken into consideration when estimating the demand for urban irrigation water. Findings from the Logan research were integrated into the calculations of landscape water needs.

Image Acquisition

Multispectral airborne digital images of Layton were taken in August 1998, and repeated for both Layton and West Jordan in August 2000 using an airborne multispectral digital imaging system (Cai and Neale, 1999; Neale and Crowther, 1984). This system consisted of three Kodak Megaplus 4.2i digital cameras using Nikon 20 mm lenses with interference filters forming spectral bands in the green (0.545 to 0.555 μm), red (0.665 to 0.675 μm) and near infrared (NIR) (0.790 to 0.810 μm) wavelengths mounted in a Piper Seneca II aircraft, dedicated to remote sensing research. The cameras were computer controlled using in-house software. The multispectral images were acquired at 1-meter pixel resolution. In the Logan research (quantifying shaded turf areas under trees), images were acquired at 0.5-meter pixel resolution on 20 May 1999, early enough in the growing season that leaf cover from trees and shrubs was minimal. Images were taken again on 16 September 1999, at the end of the growing season when trees and shrubs were at full leaf cover.

Image Processing

The individual images were corrected for lens vignetting effects and geometric radial distortions, using the same calibration techniques from a previous generation of the airborne digital system developed by Neale and Crowther (1994) and described by Sundararaman *et al.* (1997) for airborne multispectral video images. The removal of the lens vignetting effects in the imagery minimizes image-to-image brightness variations, allowing for the mosaicing of overlapping images along flight lines with no perceivable seams.

The spectral images were then registered into 3-band images and rectified individually to digital 7.5-minute orthophotos quads (1:24 000) with 1-meter pixel resolution, using the Universal Transverse Mercator (UTM) projection and a root mean square error for the transformation of less than 1 meter. The rectified images were mosaiced along the flight lines into image strips of six to ten images each. The strips were joined together into large image mosaics covering the entire study area in each research location (Layton, West Jordan, and Logan). The final images were re-projected to the Utah State Plane coordinate system to match the GIS parcel boundary layers provided by the respective cities.

The 3-band image strips along each flight line were calibrated in terms of reflectance through the ratio of outgoing over incoming radiation. Outgoing radiation was obtained using system calibration curves relating image digital numbers with radiance (W/m^2) (Neale and Crowther, 1994). Incoming solar irradiance was measured with an Exotech radiometer with similar spectral bands to the airborne digital cameras, placed at nadir over a leveled barium sulfate standard reflectance panel with known bi-directional reflectance properties (Jackson *et al.*, 1992) located in central locations in each study area. The Exotech radiometer was sampled every minute throughout the image acquisition period using a CS21X data logger synchronized to the GPS time stamp of the airborne system digital images (Chavez *et al.*, 2005; Crosby *et al.*, 1999). Each 3-band image strip was thus calibrated prior to the formation of the final mosaics covering the entire research areas.

Image Classification

Spectral signatures of ground surface classes of interest were extracted and on-site verification through ground measurements and observations were conducted using laminated printed portions of the multispectral mosaics, marked up to indicate the different surface classes visible in the imagery. In agricultural areas adjacent to Layton, signatures from identifiable crop types, evaluated as to stage of growth, were extracted. In the urban areas, the classes trained represented the turf grass, trees, shrubs and other landscape features, physical structures and shadows. Several dozen signatures were extracted visually and iteratively from each mosaic to cover most agricultural and urban surface classes, using the seed property method of the ERDAS Imagine® (version 8.4; Leica Geosystems; Norcross, Georgia) with the appropriate spectral Euclidian distance.

The high spatial resolution of the airborne digital images complicated the signature extraction and classification. Several spectral signatures were needed in the training set to represent a specific surface's illumination or vegetation density variations. For example, darker reflectance values for shaded portions of trees and large shrubs could lead to misclassifications and thus were extracted as a separate class. Class spectral separability, a statistical measure of distance between two signatures, was studied using the Transformed Divergence Index (TDI) method within ERDAS Imagine® (ERDAS, 1999). For the Euclidean distance evaluation, the spectral distance between the mean vectors of each pair of signatures was computed and evaluated for significance.

The transformed divergence has lower and upper bounds of 0 and 2,000, respectively. If the calculated divergence for a signature pair is equal to the upper bound, then the signatures are considered to be totally separable in the spectral band combination being used (in our case, the three bands of the airborne multispectral system). A calculated divergence of zero means that the signatures are inseparable and should be either merged or one of them discarded. For the classification of the Layton mosaic, signatures below a TDI value of 1,500 were discarded while signatures above 1,500, such as those for trees and shrubs, were added to capture the nuances in variability due to bi-directional effects. TDI values above 1,800 were accepted with little confusion and high relative confidence of separability between the signatures.

Images were iteratively classified using the maximum likelihood scheme. Surfaces with spectral reflectance not encompassed within the selected signatures were successively set as "unclassified" in the classification and the signatures corresponding to the unclassified area re-assessed to the individual pixel level and incorporated to the signature set after every iteration. The final classified image was created by forcing the remaining unclassified pixels into the class with the most similar signature. After filtering using a 3×3 majority filter to remove "salt-and-pepper" pixels, the resulting several dozen classes were re-coded into specific basic classes. The recoded classes were "grass," "trees and shrubs," "concrete," "asphalt," "bare soil," "shadow," "water," and "meadow."

An accuracy assessment was conducted on the urban portion of the classified image product. A stratified random sampling scheme in ERDAS Imagine® was used to generate 217 random points on the classified image, proportional to class surface area present. The urban surface class corresponding to each point was verified on 2006 NAIP (National Agricultural Inventory Program) color, digital orthophotography of the same area. Because of the changes that occurred in some portions of the imagery between the date of multispectral image acquisition (1998 and 2000) and the NAIP image acquisition, 60 points of the 210 had to be verified by visual interpretation of the multispectral image itself. A contingency table was built with this information which allowed for calculation of the errors of omission and commission (Congalton, 1991).

GIS Landscape Area Extraction

Residential and commercial (CII, or "commercial-industrial-institutional") GIS layers were obtained from Layton and West Jordan cities. These layers contained parcel boundaries, streets names, parcel tax identification numbers, and other information. The Layton residential layer divided parcels into subdivisions or neighborhood areas, designated by name, while the West Jordan layer did not. The Layton commercial GIS overlays were out of date and thus were not usable. The layers were matched to the projection of the high-resolution multispectral mosaic and its classified rendition. In addition, residential and commercial water billing data were also obtained from Layton for 1996 to 2001, and from West Jordan for 2000 and 2001.

The GIS parcels layer was overlaid on the recoded classified images imported to ArcInfo® (version 8; Esri, Inc.; Redlands, California) in GRID format. Water billing database files were linked to the GIS database for both cities using property tax ID number as the common attribute. Within the Layton study area, the number of GIS parcel boundary records we were able to join to residential water billing records varied by year (initially with 1,000 in 1997, but up to 2,800 by 2001) due to updates and changes in the water billing database. We also randomly selected approximately 2,000 residential parcels in West Jordan from the entire city to match Layton residential numbers for 2000 and 2001. Two hundred and thirty-one CII parcels with landscapes were identified within the Layton study area for analysis, and again a similar number of commercial parcels were randomly selected from West Jordan City.

Remotely sensed landscape area accuracy was assessed by regressing against ground-measured landscape areas. In Layton, 53 residential parcels were randomly selected and a walk-behind measuring wheel was used to physically measure dimensions for calculating total lot size and landscaped area. Contiguous shrub areas were physically measured on the ground separately from turf, and irregularly shaped areas beyond simple rectangles or circles were approximated as rectangles. All Layton CII parcels were similarly hand measured but could not be related to GIS-derived areas for lack of an accurate parcel layer, but in West Jordan we were able to link 73 GIS-derived cases, with up-to-date parcel layers, to hand-measured commercial properties. Water billing data collection frequency varied between cities, and between residential and CII areas. All West Jordan and Layton CII parcels had monthly water billing data, while Layton residential billing data were bi-monthly; all water billing data were in volume (gallon) units. All parcels, except for several institutional landscapes, were served by a single water meter and thus indoor water use and outdoor landscape water consumption volumes were combined and could not be directly separated. Since plant dormancy and low temperatures preclude winter irrigation in Utah, we assumed that average monthly winter (December through February) billed water use was exclusively indoors and further assumed that indoor use is constant year round. We estimated landscape water use by subtracting the derived indoor water use from monthly or bi-monthly billed water use during the potential (April through October) irrigation growing season (Endter-Wada *et al.*, 2008). Non-landscape seasonal outdoor water use, for features such as swimming pools, was assumed to be negligible, and CII users with seasonally variable or unusually high non-landscape water use, such as car washes, were excluded.

Parcel landscape area was extracted from the classified and recoded image within the GIS database. The area of each surface cover was obtained by GIS analysis using the tabulated-areas method to obtain the areas of one theme within the zones of another. Total landscaped area was then calculated as the sum of the three turf class areas (good growth, stressed grass, and sparse cover grass) and the tree and shrub class areas, and the output tables were joined with water billing data through the common identifier of tax

ID. Water volume applied to landscapes was extracted from billing data, as described above, and normalized to depth units by dividing by GIS-derived landscaped areas.

Data Analysis

Descriptive statistics were calculated for the percentage area of good, stressed, and sparse grass, as well as for trees and shrubs. Total landscaped area, total parcel size, and percent landscaped area were also analyzed. GIS-derived landscape areas were regressed against landscape areas obtained from on-site ground measurements for verification. GIS-derived landscaped areas were then regressed on total parcel size (ground-measured for Layton CII; GIS parcel boundaries for the others) to evaluate the potential for estimating landscaped areas from total parcel size for the subsets of residential properties in both cities, but for all CII properties within the study areas.

The frequency distribution of percent turf coverage was determined for CII and residential landscapes in Layton and West Jordan. We also calculated frequency distribution for the fraction of total seasonal water use within 500 mm increments of water consumption for CII and residential parcels in Layton (1998 billing data) and West Jordan (2000 billing data) during the period 01 June 1 through 30 September when data were most complete. This period of water consumption was chosen because the two-month residential billing period for Layton limited the availability of reliable irrigation season data to only two billing periods during the growing season of June/July and August/September. Consequently, we constrained the water billing data for Layton CII, and West Jordan residential and CII, to the same four-month time period in order to compare results.

Capacity to conserve water used on landscapes is the difference between water actually applied and water needed which is based on a reasonable estimate of landscape evapotranspiration. Estimated landscape water need is based on local reference evapotranspiration, or ETo (Allen *et al*., 1998), that integrates radiation, air temperature, humidity, and wind into calculated water loss for a hypothetical uniform cool-season turf grass surface for a fixed set of plant characteristics. ETo generally ranges from 0 to 6 mm/day in northern Utah, when constraints are not imposed by non-uniform urban conditions (Snyder and Eching, 2005). The product of local ETo and an empirical-fractional plant correction factor (Kc; reflecting variable plant characteristics) proportional to plant water needs is the depth of estimated water needs for a regional area defined by the position of the weather station used to calculate local ETo. Empirical Kc values are not seasonally well defined for turf, but an intra-seasonal value of 0.8 is commonly used for cool season turf grass (Kneebone *et al*., 1992). While precise empirical Kc values defined for trees and shrubs require additional research, a value of 0.5 is reasonable (Montague *et al*., 2004; Costello *et al*., 1992).

Our initial approach to quantifying capacity to conserve was a frequency distribution end user applied water depth (per parcel, seasonal water use divided by GIS-derived total landscape area) for Layton and West Jordan residential and CII end users for 1998 and 2000, respectively (image acquisition years). Capacity to conserve was identified in those users applying water above a ceiling threshold of estimated needs, defined by seasonal ETo (years 1998 and 2000 for Layton and West Jordan, respectively) multiplied by 0.8 Kc that assumes a uniform turf grass surface (Endter-Wada *et al*., 2008; Kilgren *et al*., 2010). We constrained seasonal ETo to June through September to match the constrained billing data. We did not subtract rainfall, in order to provide a generous estimate from the user point of view, or include an empirical correction factor for irrigation system non-uniformity because the study did not include on-the-ground irrigation system assessments (Solomon *et al*., 2007).

Here, we calculated capacity to conserve on an aggregate volume basis. Volume of estimated water need was calculated for each end user parcel using the following equation:

$$\mathbf{V}_{\text{water needs}} = \frac{A_{\text{total}} \times ET_0 \times Kc_l}{E_i} \quad (1)$$

where $V_{\text{water needs}}$ is the estimated volume of landscape water needs for given end user, A_{total} is total landscaped area, ET_0 is reference water loss (mm/time period; in this case, the constrained June through September billing periods and data obtained from nearby weather stations in Layton and West Jordan), Kc_l is a composite landscape correction factor that integrates the different Kc values for turf, shaded turf and trees, and shrubs. Finally, E_i is the estimated efficiency of irrigation application where a value of 0.85 was used and chosen to give a more generous estimate of landscape water needs. Kc_l can be further defined such that:

$$Kc_l = \left(\frac{A_{\text{turf}} \times K_{\text{turf}}}{A_{\text{total}}}\right) + \left(\frac{A_{\text{ts}} \times (1 - T_{\text{sh}}) \times K_{\text{ts}}}{A_{\text{total}}}\right) + \left(\frac{A_{\text{ts}} \times T_{\text{sh}} \times K_{\text{turf}}}{A_{\text{total}}}\right) \quad (2)$$

where, A_{turf}, A_{ts}, and A_{total}, are the areas (m^2) of turf grass, trees and shrubs, and total landscape respectively; T_{sh} is the fraction of shaded turf grass under tree canopies; K_{turf} and K_{ts} are the previously defined Kc values for turf and trees/shrubs (0.8 and 0.5, respectively). We assumed a Kc value of 0.8 for turf under trees under the assumption that reduced water loss in shaded turf is compensated by the water loss in overlaying tree canopy. The resulting $V_{\text{water needs}}$ from Equation 1 will vary largely with A_{total}, as Kc_l will vary within the range of 0.5 for an all woody plant landscape to 0.8 for an all-turf grass landscape.

Results and Discussion

Plate 1a shows the location of the Layton study area with the calibrated multispectral mosaic of the research area and the surrounding agricultural fields (Plate 1b). The classified rendition of the image is also shown (Plate 1c) with the property boundary layer used for the extraction of the overlaid landscape vegetation areas. The accuracy assessment of the classified and recoded product is shown in Table 1 including only the urban vegetation classes and bare soil. The overall accuracy was 89 percent, similar to classification accuracy results obtained by Neale *et al*. (2007) for wetland habitats using a similar type of imagery and methodology. Some spectral confusion occurred between the trees and shrubs class and the grass classes, but overall, the results were similar to those obtained by Thomas *et al*. (2003) for an urban setting resulting from the classification of airborne multispectral imagery at the same pixel resolution. The classification accuracy would have been reduced if the impervious surface classes had been included (asphalt, roofs, concrete, etc.) due to the spectral variability of these classes within the urban setting.

Landscaped areas derived from the digital imagery through GIS analysis correlated with those derived from ground truth measurements (Figure 1). For Layton residential parcels over a range of landscaped areas of 200 to 1,200 m^2, the relationship was reasonable ($r^2 = 0.74$), but still somewhat unexpectedly low. Similarly, correlation of GIS-derived commercial landscaped areas to ground

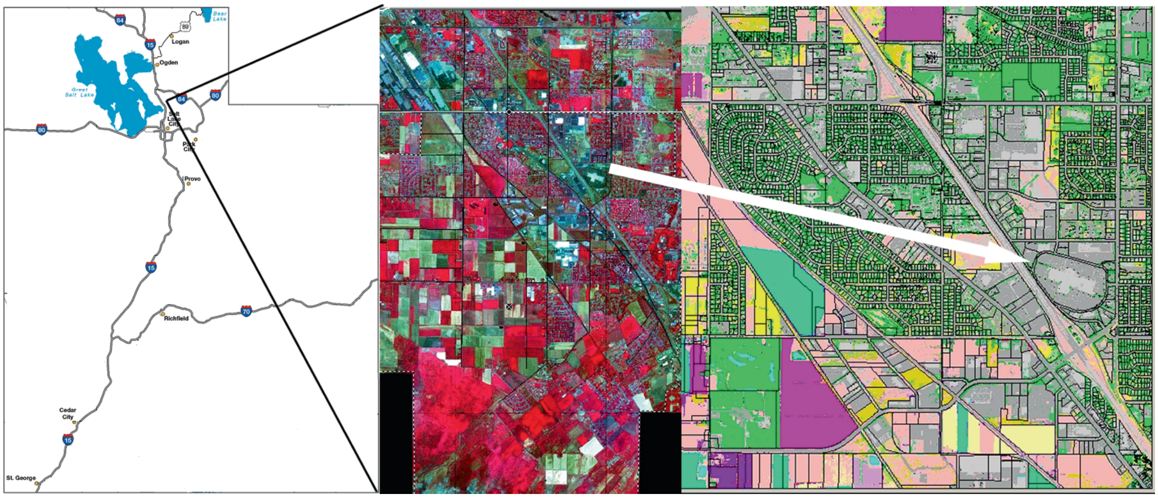

Plate 1. (a) Layton, Utah study area, (b) multispectral image mosaic, and (c) the GIS parcel boundary layer placed over the classified image of the Layton study area.

TABLE 1. ACCURACY ASSESSMENT OF THE CLASSIFIED IMAGE PRODUCT INCLUDING ONLY THE URBAN VEGETATION CLASSES

						Errors of Commission	
Classified Data	Good Grass	Sparse Grass	Stressed Grass	Trees & Shrubs	Bare Soil	Row Total	% Correct
Good Grass	58	4	1	2	0	65	89.2
Sparse Grass	4	22	0	2	0	28	78.6
Stressed Grass	0	1	44	4	3	52	84.6
Trees And Shrubs	0	1	0	27	0	28	96.4
Bare Soil	0	1	0	0	36	37	97.3
Column Total	62	29	45	35	39	**210**	
Errors of Omission							
% Correct	93.5	75.9	97.8	77.1	92.3		**187.0**
Total Error							**89.0**

measurements in the City of West Jordan also showed scatter within the range of smaller landscapes, but the large range of landscaped areas up to 30,000 m^2 yielded a close fit (r^2 =0.96). The scatter at the lower end of the range for the commercial landscapes, as well as the scatter observed for the residential areas, is possibly due to the limits of the 1-meter imagery resolution and uncertainty in the parcel boundary layer. These factors would give greater weight to errors in smaller, fragmented landscapes than would be the case for larger, contiguous landscapes characteristic of large parcels in the Salt Lake City metropolitan region. Possible errors in landscape ground measurements could have also contributed to the scatter, particularly related to the difficulty of measuring irregular shaped landscape areas on the ground. However, given that the residuals in Figure 1a were normally distributed, it appears that errors in remotely sensed and ground measured landscape areas were random. We think these reasonable relationships between ground-measured GIS-derived landscaped areas imparted enough confidence to conduct further analyses using the GIS-derived landscaped areas.

Since parcel size is a key element in municipal construction permitting and property taxation, this information is generally readily available. Landscaped area parameterized as a function of total parcel size can be developed into a model and ultimately a functional tool, when remote sensing is not possible, to estimate irrigated landscape area. We tested the relationship between GIS-derived landscape area and GIS-derived total parcel area (Figure 2) and found a modest-to-good fit for residential Layton and West Jordan (r^2 = 0.48 and 0.91, respectively), but each relationship exhibited unique properties. As parcel size increased, Layton residential landscape areas formed an upper threshold, under which there was substantial scatter. Since this residential study area contained a large percentage of older homes in subdivisions (dating back to 1940), it included more parcels that had been converted to other non-vegetated uses, such as patios, decks, and building additions. In West Jordan, average parcel size was much larger than in Layton, with upper bounds of nearly 5,000 m^2 versus 1,400 m^2. The landscape area to parcel size relationship became weaker above 2,000 m^2, because the randomly selected residential parcels above this range were higher-income custom-built homes with larger landscaped areas that were customized and irregular rather than standardized, as in a subdivision. Future regression analyses conducted in sections of cities and incorporating census and demographic information could better explain outliers and further refine these data into more robust relationships.

Landscaped area and parcel size for CII parcels in Layton and West Jordan were not statistically related in any meaningful way. Isolated large parcels defined the fit and

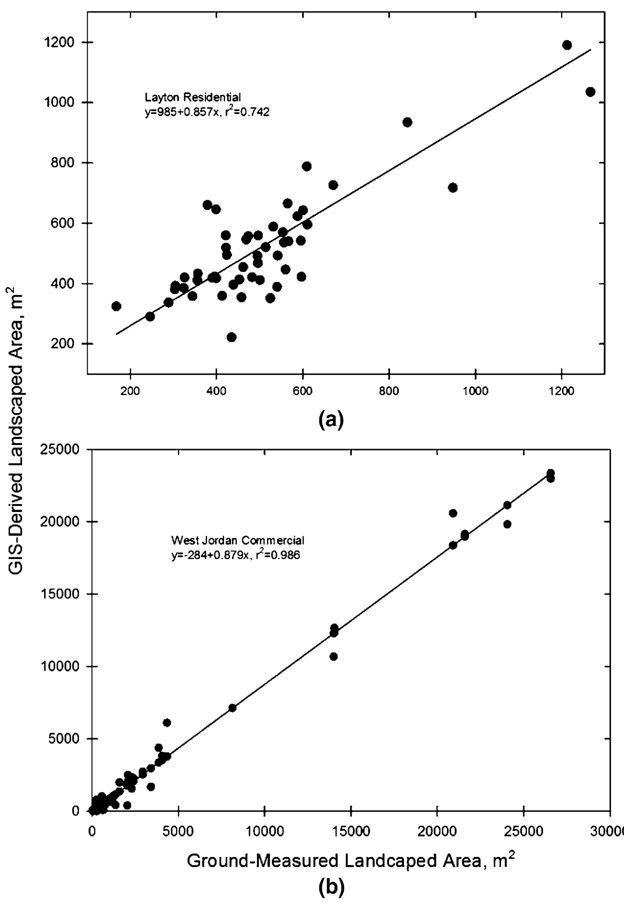

Figure 1. Comparison of GIS-derived landscaped areas to ground measured landscaped areas for (a) residential parcels in Layton, and (b) commercial-industrial-institutional (CII) parcels in West Jordan, Utah.

increased the r^2 values but substantial scatter made the relationships less predicatively useful. The high degree of variability amongst the majority of the CII parcels for both cities suggests that trying to predict landscape area from parcel size would be difficult. Compounding this difficulty would be CII landscape regulations that would vary from municipality to municipality, likely rendering a robust, widely-applicable, predictive model nearly impossible. Thus, the use of high-resolution multispectral imagery to quantify landscaped areas on an individual parcel basis would be an advantage for determining CII irrigated landscaped areas.

The amount of landscaped area in turf varied between the Layton residential and the other three groups (Figure 3). CII landscapes, and West Jordan residential landscapes, all showed somewhat to heavily right hand-skewed frequency distributions in terms of the number of parcels with high turf, and low tree-shrub coverage. West Jordan residential parcels showed a relatively even distribution (12 to 15 percent of the total population for each bin) in the 51 to 90 percent turf coverage range, with a sharp decline in the fraction of water users with turf coverage below 50 percent. West Jordan CII parcels showed a similar percentage of the population having more turf coverage than tree and shrub coverage. Since turf has higher water use and a shallower root zone than trees, quantifying parcels with high turf area is potentially diagnostic and predictive of higher water use.

The skewed distribution of the fraction of parcels with high turf coverage is much sharper for CII parcels in Layton, with about 60 percent of all the parcels falling in the range of 81 to 100 percent turf coverage. This different distribution is due, in part, to a larger number of institutional landscapes within the Layton study area, such as parks and schools that are largely turf grass and used for recreational purposes, and to a larger number of industrial business landscapes where the easiest type of landscape coverage is turf grass that lends itself to uncomplicated irrigation and maintenance. In contrast, the largest fraction of residential parcels in Layton had 41 to 50 percent turf coverage, with a roughly normal distribution on either side. This lower amount of turf grass is due to the many older landscapes in the Layton study area that had mature trees covering more of the landscaped area. An analysis (data not shown) of neighborhood age in Layton showed that about half were older than 20 years at the time of the study. A high proportion of tree cover has water conservation policy implications. Urban trees represent a significant time and financial investment and produce water (as well as energy) savings as they mature and provide shade. Tree water needs during drought should be factored into conservation measures to reduce risk of tree loss, help ensure water user acceptance and compliance, and avoid liability concerns.

Tree cover may include turf growing under the tree canopy, however. The Logan research was conducted on imagery from three residential neighborhoods on the Logan bench and one cemetery selected for analysis because of the diversity and maturity of the trees. After image classification using the same techniques described above, the areas of turf and trees were extracted from the imagery acquired at two different dates in the growing season and shown in Table 2. The average amount of turf under tree canopy weighted according to the size of the section areas analyzed was 34 percent. This overlapping coverage also means that water consumed through evapotranspiration is from a combined turf/tree system and was taken into account in our landscape water need calculations.

Seasonal (01 June through 30 September) water applied to landscapes (year 1998 for Layton; year 2000 for West Jordan) varied the most between residential and CII users in both cities (Figure 4). The largest fraction of residential water users in both Layton (90 percent) and West Jordan (80 percent) used below 1,000 mm/year, showing a sharp left hand distribution. Again, because the residential neighborhood areas in Layton were older, there were fewer automated sprinkler systems and more manual irrigation, which led to lower overall water use (Endter-Wada *et al.*, 2008). In West Jordan, there was a higher percentage of new parcels with automated systems (characteristic of the area), likely leading to higher irrigation application amounts. Average cumulative reference evapotranspiration (Allen *et al.*, 1994) for the Salt Lake City region is approximately 750 mm. Allowing for irrigation non-uniformity that increases water needs (Kjelgren *et al.*, 2000), 1,000 mm of water applied to landscapes can be justified. Thus, the majority of residential water users in Layton and West Jordan appeared to be relatively efficient at irrigating their landscapes. CII parcels exhibited something similar to a bimodal pattern of water use, with only 40 to 45 percent of the total number of parcels using less than 1,000 mm. Both cities had a long tail at the high end of water use for CII parcels where 17 percent of the West Jordan and 7 percent of the Layton CII parcels used in excess of 5,000 mm of water. These potentially excessive water users are most likely businesses with automated systems where water use is not closely monitored; such systems have been shown to contribute to excess irrigation (Endter-Wada *et al.*, 2008; Kilgren *et al.*, 2010).

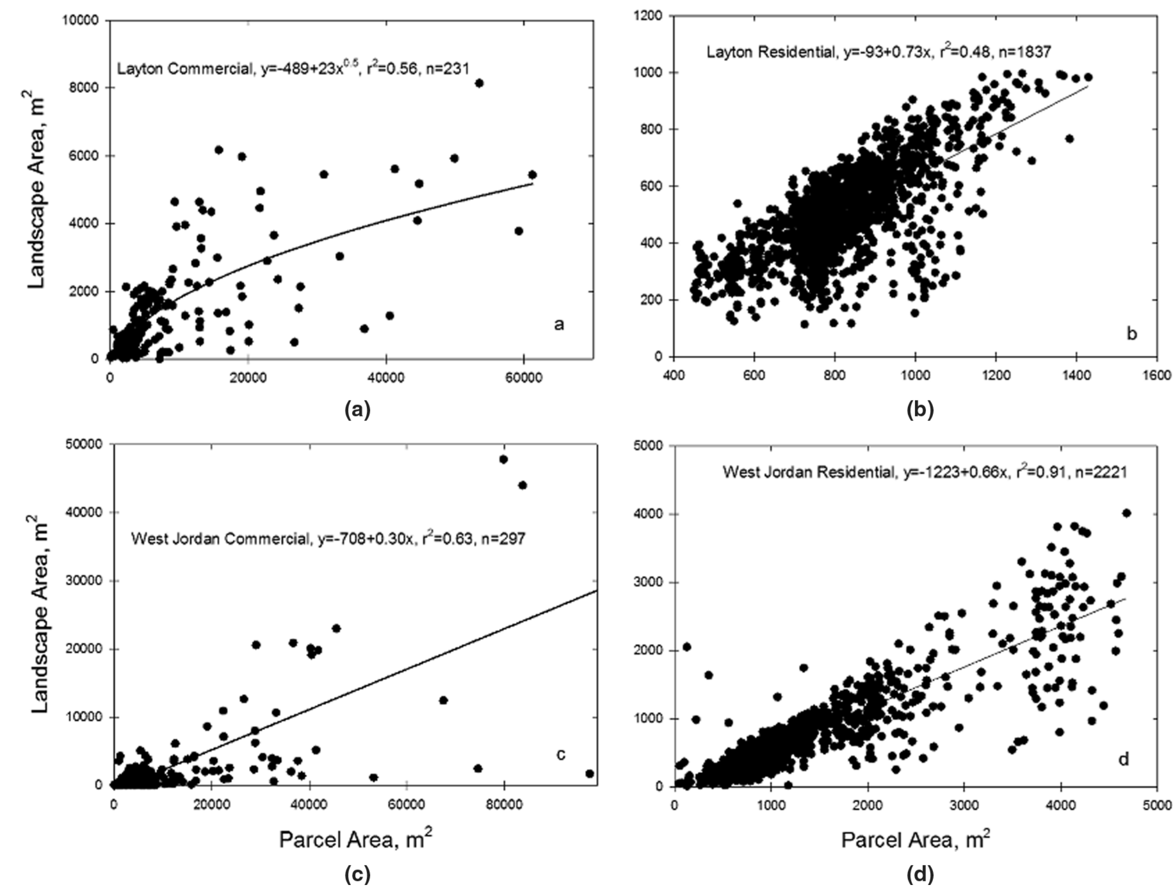

Figure 2. Relationship between GIS-derived landscaped area and total parcel size, in m^2, for residential and commercial-industrial-institutional parcels in (a) and (b) Layton, and (c) and (d) West Jordan, Utah.

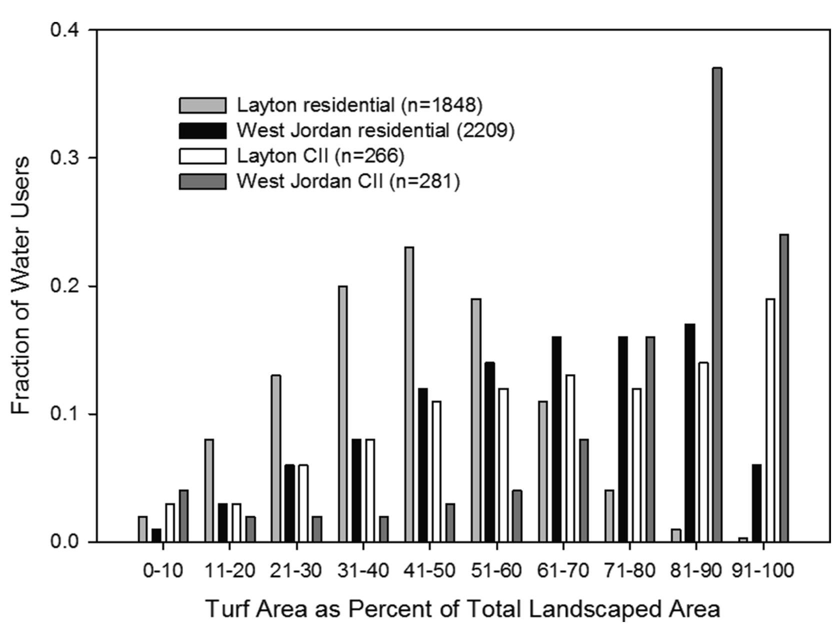

Figure 3. Frequency histogram of the percentage of landscaped area that is covered by turf for commercial-industrial-institutional (CII) and residential water users in Layton and West Jordan, UT.

TABLE 2. TURF AND TREE SURFACE AREAS EXTRACTED FROM MULTISPECTRAL IMAGERY ACQUIRED OVER THE CITY OF LOGAN, UTAH IN EARLY MAY 1999 PRIOR TO FULL TREE LEAF OUT AND IN SEPTEMBER 1999 AFTER FULL LEAF OUT, TO DETERMINE THE PERCENT OF TURF AREA UNDER TREE CANOPY

Image	Turfgrass Area			Tree Area	Size Area	Shaded Grass	
Areas Examined	5-May (m^2)	16-Sept. (m^2)	Difference (m^2)	September (m^2)	Analyzed *Weight*	Actual %	Weighted %
Cemetery	114,365	84,013	30,352	44,394	1	0.68	0.12
Section 1	149,977	132,495	17,482	64,143	1.5	0.27	0.07
Section 2	78,024	61,614	16,410	44,831	1	0.37	0.07
Section 3	162,846	143,097	19,749	98,622	2	0.20	0.07
Average						0.38	0.34

Residential water use in excess of estimated needs in Layton over a five-year period showed substantial variation among years as estimated water needs varied (Table 3). The years 1997 and 2000 were relatively hot and dry, and a higher percentage (68 percent and 66 percent, respectively) of the study population irrigated their landscapes in excess of water needs as estimated from local reference evapotranspiration and landscape areas. Again, the population size varied among years as the water billing data set received from the city varied from year to year in terms of the number of billing records that we were able to link to parcel boundary records. In late 1999, Layton changed to a new water billing system that resulted in more consistent water billing data. In 1998/1999, evapotranspiration was lower and rainfall higher than in 2000 and 2001, thus fewer Layton residential water users irrigated in excess of estimated needs compared to 1997 and 1998 (54 to 59 percent). In 2001, the number of people irrigating their landscapes in excess of estimated needs fell as a result of a state-wide, state-run advertising campaign asking the population of Utah to reduce water consumption due to the third year of below normal winter snow pack. Over all five years, approximately the same percentage of residential water users, 9 to 13 percent, accounted for 50 percent of the excess irrigation in any given year. This result is consistent with the right hand tail of seasonal water use (Figure 4) where a small number of parcels had very high consumption rates.

Conclusions

High-resolution airborne multispectral imagery obtained over urban areas in northern Utah was classified to extract turf grass, trees, and shrub areas resulting in an accuracy of 89 percent of the final recoded product. This imagery analyzed in a GIS environment can be a very useful tool in urban areas for estimating evapotranspiration from landscaped surfaces, identifying high-end landscape water users, and formulating water management and conservation plans by cities. This process provides data on irrigated landscaped areas of thousands of parcels through remote sensing that would otherwise be logistically impossible to obtain with on-the-ground measurements. Remotely sensed landscaped and total parcel area provided the basis for a practical model to predict residential landscaped area from total parcel area.

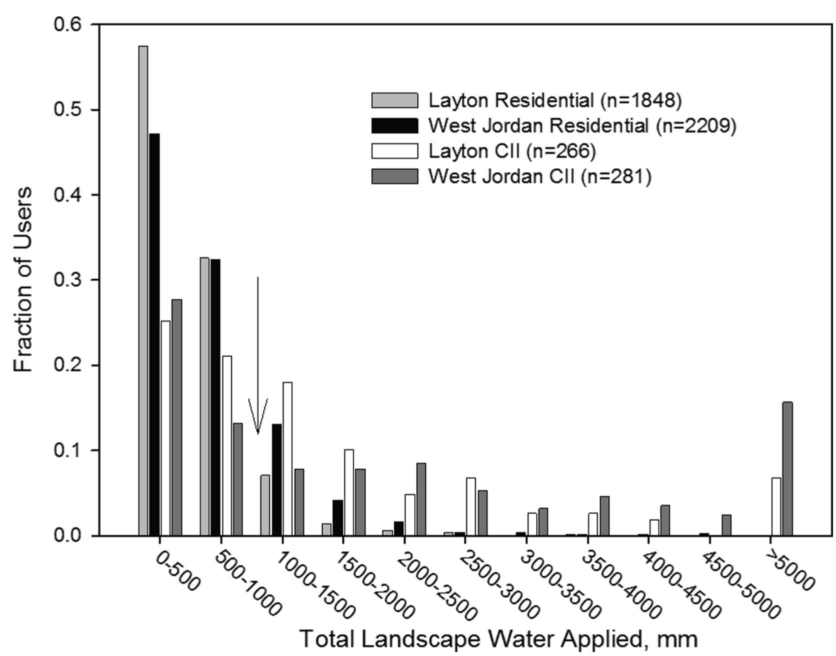

Figure 4. Frequency histogram of landscape irrigation water consumption for the period 01 June through 30 September by commercial-industrial-institutional (CII) and residential water users in Layton (data from year 1998) and West Jordan (data from year 2000), Utah. Arrow indicates approximate cumulative ETo for same time period for both years.

TABLE 3. NUMBER OF PARCELS, LOCAL EVAPOTRANSPIRATION AND RAIN FOR 01 MAY THROUGH 30 SEPTEMBER, PERCENTAGE OF ALL RESIDENTIAL PARCELS CONSUMING WATER FOR LANDSCAPE IRRIGATION ABOVE ESTIMATED NEEDS, PERCENTAGE OF RESIDENTIAL PARCELS ACCOUNTING FOR 50 PERCENT OF THE VOLUME OF LANDSCAPE WATER APPLIED IN EXCESS OF ESTIMATED NEEDS, FOR 1997 TO 2001 FOR LAYTON, UTAH

Year	Total Parcels Examined *Number*	ET (*mm*)	Precipitation (*mm*)	Excess Irrigation (m^3)	% of Parcels Accounting for Excess Irrigation *Total*	*50%*
1997	1,034	678	353	100,167	68	12
1998	1,865	720	408	147,538	59	11
1999	2,149	736	312	131,976	54	10
2000	2,862	887	278	310,520	66	13
2001	2,859	903	209	158,703	37	9

Further work is needed to determine if such a model from this data set would be applicable to residential areas in other cities around the western U.S.

Estimating irrigated landscape area and using water billing data allowed us to determine the actual amount of water applied to CII and residential landscapes. This practical analysis of landscape water consumption showed that all the groups studied, residential and CII in Layton and West Jordan, had a small percentage of users accounting for most of the excess irrigation above estimated landscape needs. Thus, if a city wanted to implement water conservation measures, those individual water users could be identified and targeted in an efficient manner without offering or delivering conservation programs to the majority of users already irrigating their landscapes efficiently. However, more CII than residential parcel owners were applying water in excess of estimated needs, and in vastly greater amounts. Thus they would be the most likely targets for conservation interventions in order to most efficiently achieve the greatest water savings from the smallest percentage of users.

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References

Allen, R.G., M. Smith, L.S. Pereira, and A. Perrier, 1994. An update for the definition of reference evapotranspiration, *ICID Bulletin*, 43:35–92.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998. *FAO Irrigation and Drainage Paper, No. 56, Crop Evapotranspiration (Guidelines for Computing Crop Water Requirements),* Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 300 p.

Cai, B., and C.M.U. Neale, 1999. A method for constructing 3-dimensional models from airborne imagery, *Proceedings of the 17th Biennial Workshop Color Photography and Videography for Resource Assessment*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland.

Carr, K.M., and J.D. Crammond (editors), 1995. *Water Law: Trends, Polices, and Practice,* American Bar Association, Chicago, Illinois.

Chávez, J.L., C.M.U. Neale, L.E. Hipps, J.H. Prueger, and W.P. Kustas, 2005. Comparing aircraft-based remotely sensed energy balance fluxes with eddy covariance tower data using heat flux source area functions, *Journal of Hydrometeorology*, 6(6):923–940.

Congalton, R.G., 1991. A review of assessing the accuracy of classifications of remotely sensed data, *Remote Sensing of Environment*, Vol. 37, pp 35–46.

Costello, L., N. Matheny, and J. Clark, 1992. Estimating crop coefficients for landscape plantings, *University of California Agriculture and Natural Resource Leaflet 21493*.

Endter-Wada, J., J. Kurtzman, S.P. Keenan, R.K. Kjelgren, and C.M.U. Neale, 2008. Situational waste in landscape watering: Residential and business water use in an urban Utah community, *Journal of the American Water Resources Association*, 44(4):902–920.

ERDAS, 1999. *ERDAS Field Guide,* Fifth edition, ERDAS, Inc., Atlanta, Georgia.

Jackson, R.D., T.R. Clarke, and M.S. Moran, 1992. Bidirectional calibration results for 11 Spectralon and 16 Baso4 reference reflectance panels, *Remote Sensing of Environment*, 40(3):231–239.

Kjelgren, R., L. Rupp, and D. Kilgren, 2000. Water conservation in urban landscapes, *HortScience*, (35):1037–1043.

Kilgren, D.C., J. Endter-Wada, R.K. Kjelgren, and P.G. Johnson. 2010. Implementing landscape water conservation in public school institutional settings: A case for situational problem solving, *Journal of the American Water Resources Association* (JAWRA), 46(6):1205–1220.

Kneebone, W.R., D.M. Kopec, and C.F. Mancino, 1992. Water requirements and irrigation, *Turfgrass, Agronomy Monograph No. 32*, ASA-CSSA-SSSA, Madison Wisconsin.

Montague, T., and R. Kjelgren, 2006. Use of thermal dissipation probes to estimate water loss of containerized landscape trees, *Journal of Environmental Horticulture,* (24):95–104.

Montague, T., R. Kjelgren, R. Allen, and D. Wester, 2004. Water loss estimates for five recently transplanted landscape tree species in a semi-arid climate, *Journal of Environmental Horticulture*, 22:189–196.

National Research Council, 1992. *Water Transfers in the West: Efficiency, Equity, and the Environment,* National Academy Press, Washington, D.C., 320 p.

Neale, C.M.U., and B.G. Crowther, 1994. An airborne multispectral video/radiometer remote sensing system: Development and calibration, *Remote Sensing of Environment*, (48):1–25

Neale, C.M.U., D. Wenger, H. Jayanthi, and F. Farag, 2007. Mapping and monitoring wetlands using airborne multispectral Imagery, *Remote Sensing for Environmental Monitoring and Change Detection - Proceedings of Symposium HS3007 at IUGG2007, Perugia*, IAHS Publication 316.

Pimentel, D., B. Berger, D. Filiberto, M. Newton, B. Wolfe, E. Karabinakis, S. Clark, E. Poon, E. Abbett, and S. Nandagopal, 2004. Water resources: Agricultural and environmental issues, *Bioscience*, 54(10):909–918.

Postel, S.L., 2000. Entering an era of water scarcity: The challenges ahead, *Ecological Applications,* 10(4):941–948.

Snyder, R.L., and S.O. Eching, 2005. Microclimate corrections for urban landscape evapotranspiration, *ASCE Conference Proceedings 173*, 544, DOI:10.1061/40792(173)544.

Solley, W.B., R.R. Pierce, and H.A. Perman, 1998. *Estimated Use of Water in the United States in 1995,* U.S.G.S. Circular 1200, U.S. Dept. of the Interior, U.S. Geological Survey, Reston, Virginia, 27 p.

Solomon, K.H., J.A. Kissinger, G.P. Farrens, and J. Borneman, 2007. Performance and water conservation potential of multi-stream, multi-trajectory rotating sprinklers for landscape irrigation, *Applied Engineering in Agriculture* (23):153–163.

Sundararaman, S., and C.M.U. Neale, 1997. Geometric calibration of the USU videography system, *Proceeding of the 16th Biennial Workshop on Videography and Color Photography in Resource Assessment*, 29 April - 01 May, Weslaco, Texas, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland.

Thomas, N., C. Hendrix, and R.G. Congalton, 2003. A comparison of urban mapping methods using high-resolution digital imagery, *Photogrammetric Engineering & Remote Sensing*, 69(9):963–972.

Vickers, A., 2001. *Handbook of Water Use and Conservation: Homes, Landscapes, Industries, Businesses, Farms,* 464p.

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Software for Analyzing Municipal Water Data to Design Water Conservation Strategies

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SOFTWARE FOR ANALYZING
URBAN LANDSCAPE WATER USE
TO TARGET CONSERVATION PROGRAMS

by

Adrian Welsh

A report submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

in

Human Dimensions of Ecosystem Science and Management

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2011

ABSTRACT

Software for Analyzing Municipal Water Data

to Design Water Conservation Strategies

by

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Utah State University, 2011

Co-Major Professors: Dr. Joanna Endter-Wada, Dr. Christopher M.U. Neale
Department: Environment and Society

Planning for drought and growth-induced water scarcity is a challenge confronting municipal water departments. When water shortages occur, demand management policies and programs are often implemented to encourage water conservation. Due to the nature of water resources and municipal water delivery systems, cities are concerned about meeting citizens' water needs. A city can review water billing records to see how much water people use, but how do they know how much water people need? Standards and guidelines have been established for indoor water use (gallons/person/day), but the amount of water needed to irrigate outdoor landscapes is more variable, highly contextualized, and harder to determine. To aid in answering that question, this project developed a custom software application, Landscape Water Use Software, which allows water billing data to be integrated with GIS and other types of municipal databases. Using GIS and remotely sensed images gives the software a strong spatial component for use of parcel, structure, and land cover data. The resulting output shows how actual landscape water use compares with estimated landscape water need, which is then used to determine capacity to conserve outdoor water. The software can display spatial patterns and

analyze factors contributing to water use variation. This project will help cities design landscape water conservation programs that have the greatest potential for water savings.

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Adrian Welsh

CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Background and Rationale

Many municipalities in the Western United States, especially in arid Utah, are subject to various water shortages that are caused by general aridity and periodic drought cycles. Important water sources in the Intermountain West, like the Colorado River, Lake Mead, and Lake Powell, have been at record lows during the past decade. In addition to the low precipitation and water shortages, there has been a decline in the quality of ground water supply, making this source less suitable and available for uses like culinary water. In some areas, salinity concentration is rising as the water supply dwindles. In order to combat recurring shortages of water, management strategies must be employed to meet the demands and burdens of municipal, industrial, agricultural and environmental uses, all of which compete for scarce water resources. Demand management will require effective policies and intervention strategies that can help water agencies allocate and deliver water efficiently and fairly (National Research Council, 2007; Standish-Lee et al., 2006; US Dept. of the Interior, 2005; Western Governors' Association, 2006, 2008; Western Water Policy Review Advisory Commission, 1998).

Promoting water conservation as a demand management strategy has been pursued by many of the region's municipalities (Western Resource Advocates, 2003) and Utah is no exception (Utah Division of Water Resources, 2003). Water conservation programs generally consist of broad public appeals about the need to conserve and dissemination of educational materials on ways to conserve. Programs aimed at helping people at site specific locations to conserve, such as water audits or rebates (for installing water efficient appliances or fixtures), are most often offered on a voluntary basis (Vickers, 2001). However, municipalities undertaking water conservation programs face difficulties in being able to target and tailor water conservation efforts in order to yield the greatest water savings for the costs of providing the programs. Having a greater ability to analyze water billing data and to integrate it with other sources of information that would help to identify sources of water inefficiency would overcome the major barrier to identifying locations with high capacity to conserve (where conservation interventions are likely to produce the greatest water savings) and assessing effectiveness of implemented programs.

Landscape irrigation constitutes approximately 65% of urban water use in the U.S. West and has been identified as the most significant source of potential municipal water savings (Utah Division of Water Resources, 2003; Vickers, 2001). This is especially true in locations where outdoor landscapes consist primarily of unshaded turfgrass (Grisham et al., 1989; DeOreo et al., 1996; Kjelgren et al., 2000) and where irrigation is in excess of actual turfgrass water needs based on local evapotranspiration (ET) rates (St. Hilaire et al., 2008; Kjelgren et al., 2000). Many Americans use more water on their landscapes than is needed to meet plant requirements (Kjelgren et al., 2002; Endter-Wada et al., 2008; Glenn, 2010). Vickers suggests that "the biggest drinking problem in America is not alcohol but lawn watering" (Vickers, 2006:56). Even where conservation initiatives are in place, a growing demand for amenity uses of water such as "water features" (like ponds and fountains) can increase urban water demands. Vickers argues that conservation initiatives have a hard time competing against the "water features" industry and its huge advertising budgets, but encourages water managers and officials to make innovative rules and create proactive water-saving strategies to end landscape irrigation excess (Vickers, 2006). Many cities are strengthening their landscape water conservation programs by encouraging people to irrigate more effectively and to establish low water use landscapes (Western Resource Advocates, 2003; St. Hilaire et al., 2008).

According to Vickers, there are five general strategies that water managers typically use to promote landscape water conservation: (1) limit the number of water days per week or month that people can water; (2) reduce the area that requires irrigation; (3) promote Xeriscape principles; (4) attempt to stop the escalating lawn chemical-watering cycle; (5) promote natural lawns and landscapes that can be irrigated with rainwater only (Vickers, 2006). While these approaches have produced landscape water savings in many communities, they do not work for all locations or suit all customer preferences. More site-specific assessments and recommendations are often needed (Glenn, 2010; Kilgren et al., 2010).

A variety of factors related to site characteristics, irrigation systems, plant material and human behavior affect water use on urban landscapes (Endter-Wada et al., 2008; Glenn, 2010; Kilgren et al., 2010; Klien, 2004; Pataki et al., 2011). One of the difficulties involved in assessing the efficiency of landscape water use and promoting landscape water conservation is the tremendous variability between landscapes in the urban environment. Urban lots vary greatly in terms of geographic features such as size of landscaped area, shape of the landscape, soil characteristics, slope of the terrain, access to various sources of water (groundwater, secondary water), plant material present, and shading, as well as in terms of the irrigation systems and human water use patterns (Glenn, 2010). Approaches that consider this variability and determine the amount of water needed for landscape irrigation at each location can help municipal water providers accurately assess landscape water use in relation to situational site characteristics and plant water needs (Endter-Wada et al., 2008; Farag et al., in press; Glenn, 2010; Kilgren et al., 2010).

Project Objectives

This project builds upon research work conducted at Utah State University focused on individualizing the assessment of landscape water use efficiency. The research has utilized remote sensing, water billing data, and GIS technologies to: 1) determine landscape water use in relation to plant need; 2) establish thresholds and indices for assessing the appropriateness of landscape water use; 3) explain variations in water use patterns in relation to these independent and objective measurements (Endter-Wada et al. 2008; Farag 2003; Farag et al. in press; Glenn, 2010; Kilgren et al., 2010; Kjelgren et al., 2002; Klien, 2004). Much of this research involved intensive analysis of billing data and site characteristics on an individual parcel basis. Through utilizing data that was obtained from surveys and interviews, the research suggested factors contributing to landscape water use inefficiency that are worth exploring on a more systematic basis with a larger sample size.

This project addressed the outstanding need to automate some of the analytic functions pioneered in this USU research by developing computer software designed to help cities utilize this approach prior to water conservation program delivery. Such a tool aids in the analyses municipalities could undertake to utilize their own billing data in connection with other databases to identify locations with the greatest capacity for landscape water conservation. The conceptual approach embedded in the software is grounded in calculating a landscape water budget, and responds to a recent recommendation that more advanced tools for water budget calculation and implementation are needed (Mayer et al., 2008). This software tool utilizes multispectral imaging to characterize different landscape water needs based upon plant type (Farag, 2003) and then compares landscape water need to landscape water use (calculated using water billing data) to produce a landscape water use ratio for each location that is then indexed by ranges of appropriateness of water use (Glenn, 2010). The software tool developed here allows for the visual display and analysis of spatial patterns of these indices on a city-wide basis.

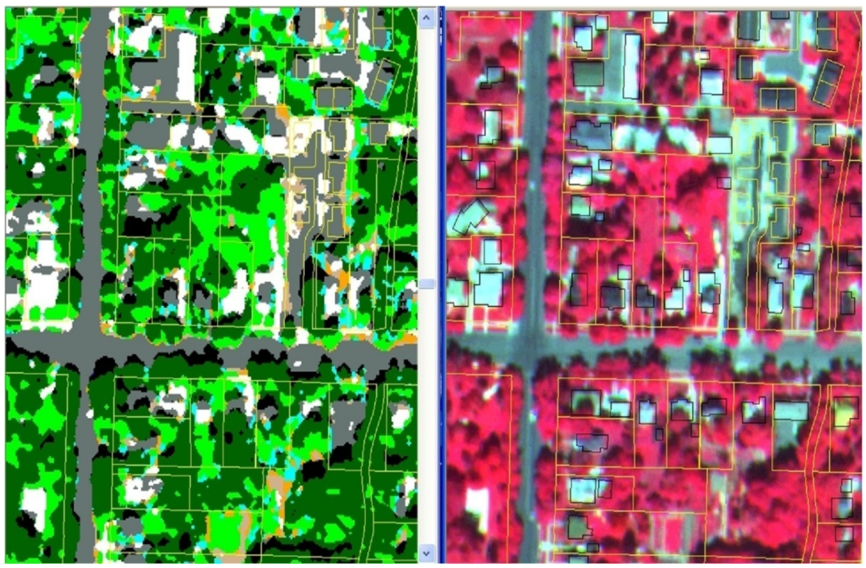
CHAPTER 2

MODEL DEVELOPMENT

This research integrates data from GIS, remote sensors, weather, and municipal water billing into a dynamic software application using Microsoft Visual Studio 2008 and VB.NET programming language. Instead of using an existing software program to conduct the analysis, the Landscape Water Use Software program is a stand-alone application that directly accesses the programs needed to run this application (Microsoft Access; ESRI ArcGIS) without having to open these other programs. This creates an easy-to-use interface that allows the software to run faster and more efficiently than if it was embedded in another application (such as a form built into an MS Access Database or a form built into an ESRI ArcMap Project).

Using Remote Sensing Data to Identify Urban Cover Types

Remotely sensed data was obtained by an over flight using the Utah State University airborne digital system (modified from Neale and Crowther 1994) that acquired imagery processed to produce a calibrated false color composite image (red, green, and near infrared bands) of Logan City, Utah in 2004. The resulting spectral band images were registered into 3-band images with a pixel resolution of 1m and rectified to an ortho-photo map base. The geo-rectified image formed a large mosaic covering the city. The imagery was calibrated for reflectance. The mosaic was classified using a supervised signature extraction and maximum likelihood method. In order to capture variability, 140 surface cover classes were obtained and then recoded into nine specific cover types relevant to the urban environment (*Figure 1*): grass, sparse grass, stressed grass, trees and shrubs, bare soil, concrete and roofs, asphalt and roofs, shadows, and water. The original image processing produced 140 classes that were then combined to yield 9 major classification cover types (*Figure 2*). The file was then prepared to be used in a GIS application.



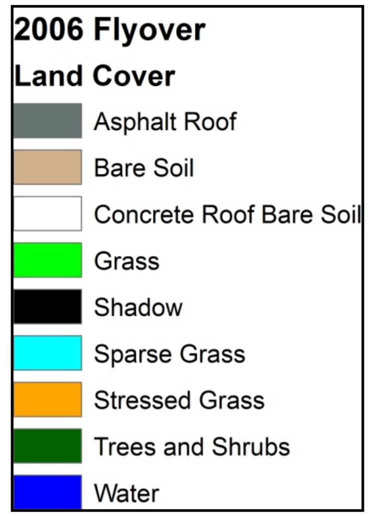


Figure 1. Portion of the 3-band multispectral image (right) and corresponding classified and recoded image (left).

Figure 2. Legend showing the 9 different urban cover classifications.

Linking Landscape Cover Types to City Databases

Raw water billing data, as it is normally maintained in city databases, is not conducive to being directly used with GIS data; it has to be rearranged so the two databases can be joined together. The Landscape Water Use Software converts water billing data that is normally maintained in a columnar format to a linear format (*Figure 3*) through a complex coding scheme utilizing ADO.NET and the Microsoft Access software. This portion of the software package is accessed behind the scenes without the need to be opened. Since billing data is primarily organized to link meter readings to particular customers for billing purposes, the software resolves issues that are problematic from a data analysis viewpoint and takes into account issues such as meter changes, multiple meters, and residential mobility to produce complete and temporally continuous data representing metered water use for each location receiving municipal water.

Rate	LocID	DSPR	Jan	JanR	Feb
RS	2517	33	6	17	6
RS	2517	37	7	18	5
RS	2517	0	0	16	6
RS	8356	38	1	19	0
RS	8356	64	1	18	1
RS	16694	302	0	0	0
RS	15922	37	8	18	5
RS	8299	38	11	19	5
RS	20947	215	0	0	0
RS	18217	34	6	18	5
RS	18217	38	5	19	4
RS	18217	0	0	14	5

Figure 3. Linearized billing data.

The linearized water billing data is joined to the appropriate GIS layers resulting in a master file. Because of how the GIS files relate to one another (by finding common attributes), this process is not as streamlined as one would think. Water billing data has to have a geographic component to be used in analyses of landscape water need. This is accomplished by getting the lot size of each parcel (*Figure 4, Panel 1.2*). However, in the case of Logan City database, the parcel data does not have a direct link to the water billing data (*Figure 4, Panel 1.1*). An intermediate GIS file was used, which in this case was the building footprints. The building footprints join with the parcels by tax ID number (*Figure 4, Panel 2.1*) to create a ParcelBuildings (PB) file. The reclassified image is then tabulated to determine how much of each of the nine land cover types are contained on each parcel. This tabulated table is joined with the ParcelBuildings to create a ParcelBuildingsVeg (PBV) file (*Figure 4, Panel 2.2*). Finally, the water billing data is separated out by each year and is joined up with the ParcelBuildingsVeg (PBV) file (*Figure 4, Panel 2.3*).

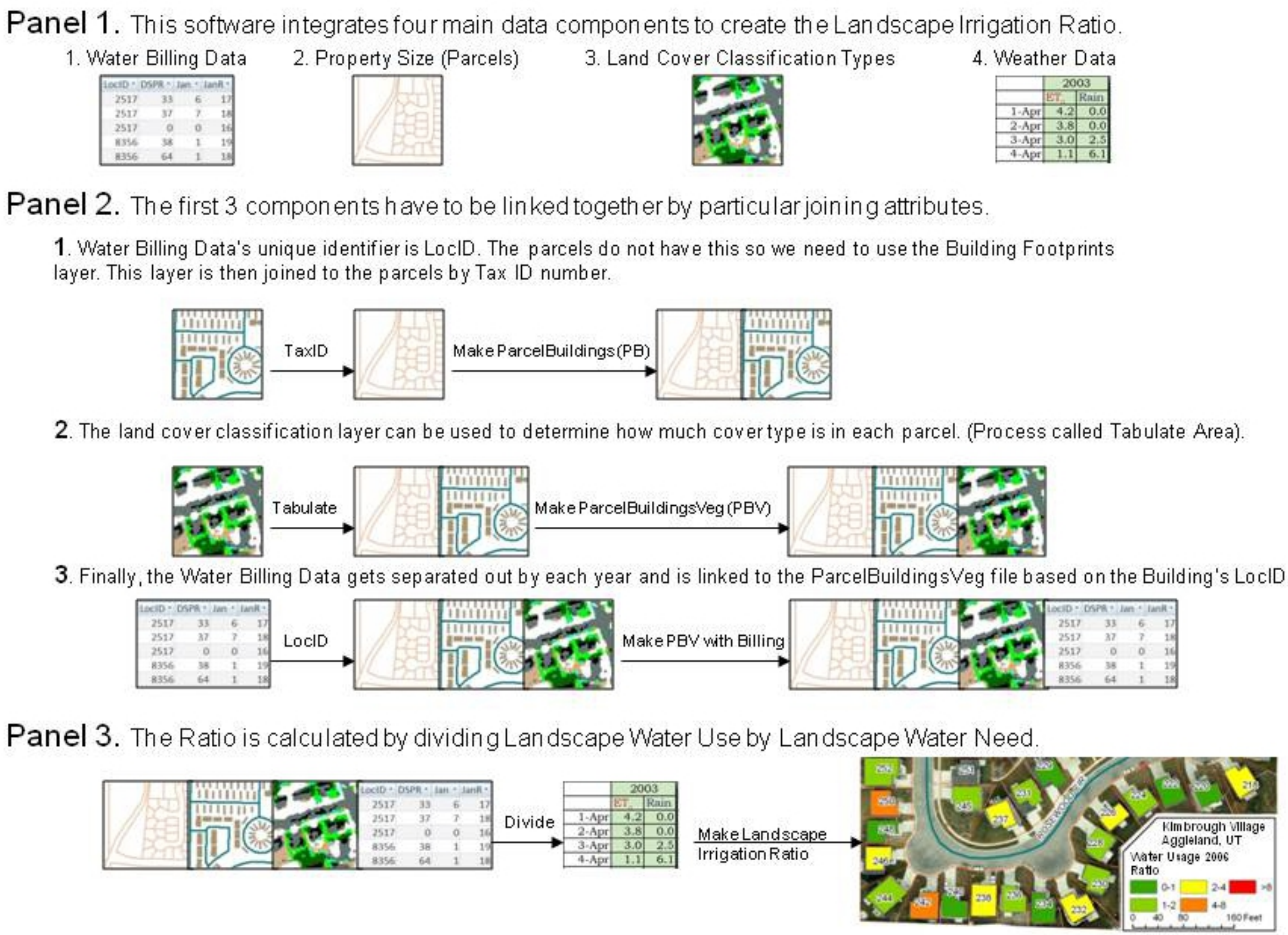
Calculating Landscape Water Use Indices

Using the PBV file, an annual landscape water use ratio is obtained by running a series of calculations on each record of data. This ratio is determined by dividing landscape water use by landscape water need. Landscape water use is a calculation of how much the parcel uses on outdoor water during the irrigation season (assumed to be April 1 through October 31) and landscape water need is determined by knowing the area's reference ET rates, and how much of the parcel area is comprised of differing vegetation types.

Because the GIS files are stored in an ESRI File Geodatabase, the shape area of each parcel is automatically calculated. By knowing parcel area and knowing how much grass (a combination of the three grass categories) and trees/shrubs are on the landscape, we can calculates the percentage of landscape for each parcel, as well as percentage of grass and trees/shrubs. Seasonal daily ET measurements were obtained from a local weather station, and used in determining landscape water need. Using common ET "crop" coefficients for grass (0.8) and trees/shrubs (0.5), we can calculate the adjustment on how much water is needed to satisfy these plants for the duration of the irrigation season. Images used for this project included ones taken with trees at full canopy in September, and similar images when trees had no leaves (taken during spring). Previous research had calculated the average amount of turf under tree canopies at 34% (Farag, 2003). This was accounted for in the irrigation equation.

Calculating outdoor landscape water use is a complicated task using multiple variables and assumptions. The first difficulty is estimating the amounts of total water use that likely comprises indoor and outdoor use. To incorporate this consideration into a large database (i.e. Logan City) where individualized household occupancy data is unavailable, we assumed and calculated indoor water use based upon the U.S. Census average household size for Logan City, Utah of three people and the U.S. average indoor use of 70 gallons per person per day (Vickers, 2001). If water meters are read monthly, more site-specific indoor water use calculations can be made by using billing data for winter months, enabling calculation of a more accurate depiction of actual outdoor water use. If water meter readings are less than monthly and not of consistent intervals across locations (as was the case in Logan City until 2010), then extrapolations have to be made. For Logan City, we assumed the irrigation season lasted from April 1st through October 31st and that no landscape irrigation occurs outside of those dates. When assumed indoor water use is subtracted from total water use between those dates, we get the total seasonal water use for that particular parcel (*Figure 4, Panel 3*).

Figure 4. Conceptual Flow Chart of the Landscape Water Use Software



CHAPTER 3

DISCUSSION

The Landscape Irrigation Ratio is calculated by dividing landscape water use by landscape water need. The result is a number from 0 to roughly 100 (mathematically the high end can be approaching infinity). The purpose of assigning a ratio in this manner is to create easily interpretable data. For example, if the ratio is 1, then the parcel is using the correct amount of water on their landscape to meet the plants' needs. If the ratio is 2.5, then the parcel is using 2.5 times as much water as is needed on their landscape. We have categorized residential properties using several ratio ranges. A ratio of 0 to 1 is efficient; 1 to 2 is acceptable; 2 to 3 is inefficient; and anything over 3 is wasteful. For good visual purposes of displaying the ratios on a map, there were 5 categories to show the best variation: 0 to 1, 1 to 2, 2 to 4, 4 to 8, and greater than 8. The rationale for using a category of greater than 8, when clearly over 3 is wasteful, was to potentially catch any database errors or water leaks that may have occurred.

Once databases have been constructed with landscape water use indices determined on a city-wide, site-specific basis, it is possible for municipal water departments to investigate patterns and trends in water use. By running the Landscape Water Use Software, a water department could identify problematic areas for planning purposes, detect water leaks or other anomalies, and locate high-end water users, which would enable targeting water conservation programs to specific locations. By having an entire city dataset of indices, patterns can be analyzed by looking at clusters, dispersions, and trends both spatially and temporally. Questions related to what might be contributing to high water use, low water use, and high variations in water use can then be investigated. Such analyses can help cities determine, for instance, whether high water use is related to water infrastructure problems (e.g. leaks), neighborhood or site specific geographic conditions (e.g., poor soils, windy areas, high sun exposures, new neighborhoods in the process of establishing landscapes), neighborhood demographics and characteristics, or individual household-level human behaviors.

The factors that most often affect water use in residential areas are location, parcel size, soil type, slope and aspect, type of landscape, residential mobility, and occupants' behaviors. The Landscape Water Use Software can help in determining which factor is causing the high, low, or variable water usage for each parcel. Spatial patterns of similar water usage can be related to the age of the homes, geographic locations, demographics, or whether or not the parcel is owner or renter occupied (*Figure 5.*). Knowing the history of a particular household can help in determining how the water use pattern has changed, possibly between one occupant and another (*Figure 6*). Such information is valuable for helping cities decide not only where but also when and how to take action to increase water use efficiency within their service areas.

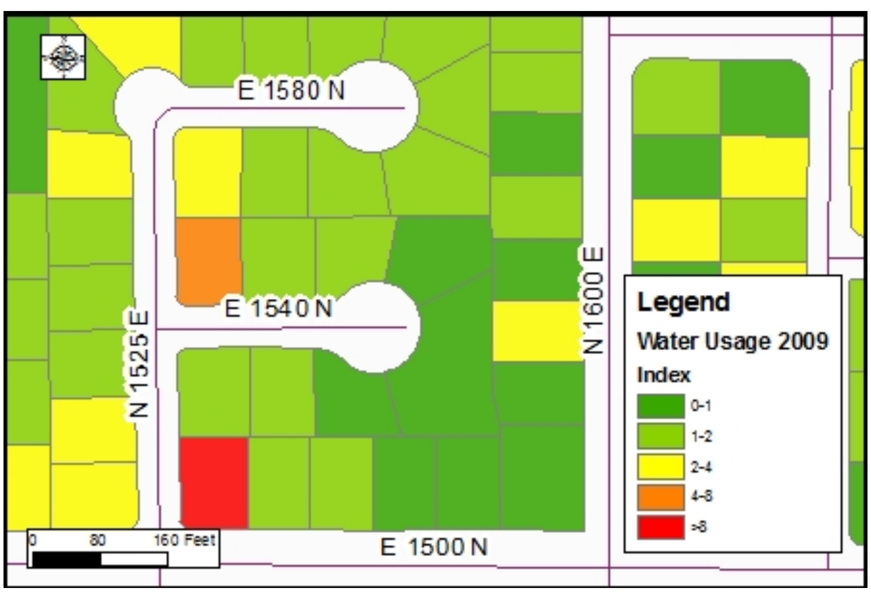


Figure 5. Color coded neighborhood showing the landscape water use ratio in 5 different categories (0-1, 1-2, 2-4, 4-8, >8). This particular neighborhood has a preponderance of lower

landscape water users with the majority having indices less than 2, meaning they applied less than twice as much water as plants were estimated to require.

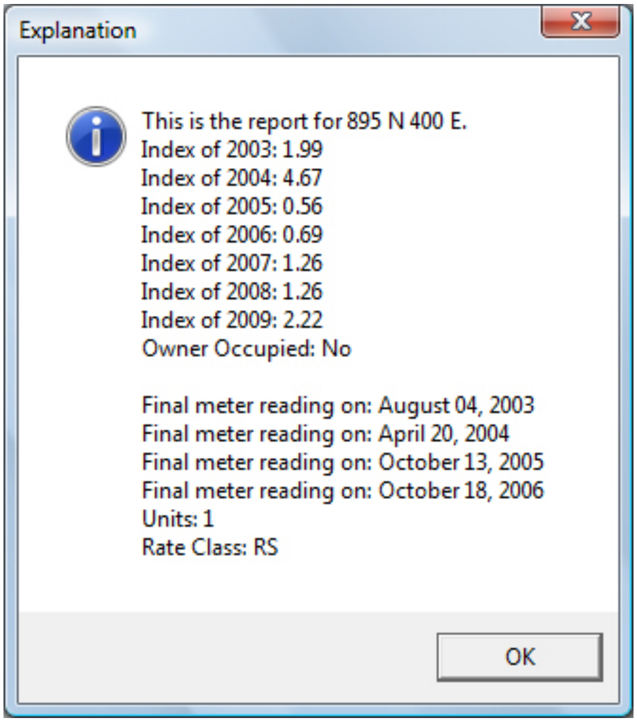


Figure 6. A brief history of one parcel's water usage, showing the ratio (index) for each year as well as when final meter readings took place. A parcel that is not owner occupied will often have multiple final meter readings as well as variable water usage related to its occupancy by different renters.

References

DeOreo, W.B., J.P. Heaney, and P.W. Mayer. 1996. Flow trace analysis to assess water use. *Journal of the American Water Works Association* 88(1):79-90.

Endter-Wada, J., J. Kurtzman, S.P. Keenan, R.K. Kjelgren, and C.M.U. Neale. 2008. Situational Waste in Landscape Watering: Residential and Business Water Use in an Urban Utah Community. *Journal of the American Water Resources Association* 44(4):902-920. DOI: 10.1111/j.1752-1688.2008.00190.x

Farag, F.A., C.M.U. Neale, R. Kjelgren, and J. Endter-Wada. *In press.* Quantifying Potential Urban Landscape Water Conservation Using Remote Sensing. *Photogrammetric Engineering and Remote Sensing Journal.*

Farag, F.A. 2003. *Estimating farm and landscape water use at the rural-urban interface using remote sensing and geographic information systems*. PhD Dissertation, Utah State University. Logan, UT.

Glenn, D.T. 2010. *Residential Landscape water check programs: Exploring a conservation tool*. M.S. Thesis, Utah State University. Logan, UT.

Grisham, A. and W.M. Fleming. 1989. Long-term options for municipal water conservation. Journal of the American Water Works Association 81(3):34-42.

Hilaire, R.S., M.A. Arnold and D.C. Wilkerson, D.A. Devitt, B.H. Hurd, B.J. Lesikar, V.I. Lohr, C.A. Martin, G.V. McDonald, R.L. Morris, D.R. Pittenger, D.A. Shaw, and D.F. Zoldoske. 2008. Efficient Water Use in Residential Urban Landscapes. *HortScience.* 43(7): 2081-2092.

Kilgren, D., J. Endter-Wada, R.K. Kjelgren, and P.G. Johnson. 2010. Implementing Landscape Water Conservation in Public School Institutional Settings: A Case for Situational Problem Solving. *Journal of the American Water Resources Association* 46(6):1205-1120.

Kjelgren, R., F.A. Farag, C. Neale, J. Endter-Wada, and J. Kurtzman. 2002. Quantifying potential urban landscape water conservation through billing data analysis in Layton, Utah. In: *Proceedings, American Water Works Association Sources 2002*: *Reuse, Resources, Conservation*, January 27-31, Las Vegas, NV.

Kjelgren, R., L. Rupp, and D. Kilgren. 2000. Water conservation in urban landscapes. *HortScience* 35:1037-1040.

Klien, C. 2004. *Understanding household landscape water conservation*. MS Thesis. Utah State University, Logan, UT.

Mayer, P., W. DeOreo, T. Chesnutt, and L. Summers. 2008. Water Budgets and Rate Structures: Innovative Management Tools. *Journal of the American Water Works Association* 100(5): 117-131.

National Research Council. 2007. *Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability*. Prepared by the Committee on the Scientific Bases of Colorado River Basin Water Management. Washington, D.C.: The National Academy Press.

Pataki, D.E., C.G. Boone, T.S. Hogue, G.D. Jenerette, J.P. McFadden and S. Pincetl. 2011. Socio-ecohydrology and the urban water challenge. *Ecohydrology* DOI:10.1002/eco.209.

St. Hilaire, R., M.S. Arnold, D.C. Wilkerson, D.A. Devitt, B.H. Hurd, B.J. Lesiker, V.I. Lohr, C.A. Martin, G.V. McDonald, R.L. Morris, D.R. Pittenger, D.A. Shaw, D.F. Zoldoske. 2008. Efficient Water Use in Residential Urban Landscapes. *HortScience* 43(7):2081-2092.

Standish-Lee, P., E. Loboschefsky, and K. Lecina. 2006. "Half Full or Half Empty? Either Way It's Time to Plan." *Journal of American Water Works Association*. 98(6): 76-79.

United States Department of the Interior. 2005. *Water 2025: Preventing Crises and Conflict in the West - August 2005 Report*. Accessed 10/02/08 at: http://www.usbr.gov/water2025/report.html

Utah Division of Water Resources. 2003. *Utah's M & I water conservation plan.* Retrieved from http://www.water.utah.gov

Vickers, A. 2001. *Handbook of Water Use and Conservation: Homes, Landscapes, Businesses, Industries, and Farms.* Amherst, Massachusetts: Water-Plow Press.

Western Resource Advocates. 2003. *Smart Water: A Comparative Study of Urban Water Use Across the Southwest*. Boulder, CO: Western Resource Advocates. Available at: http://www.westernresourceadvocates.org/water/smartwater.php

Western Governors' Association. 2006. *Water Needs and Strategies for a Sustainable Future.* Prepared by Western Governors' Association (Denver, Colorado) in cooperation with the Western States Water Council (Midvale, Utah). Accessed 10/02/08 at: http://www.westgov.org/wga/publicat/Water06.pdf

Western Governors' Association. 2008. *Water Needs and Strategies for a Sustainable Future: Next Steps*. Prepared by Western Governors' Association (Denver, Colorado) in cooperation with the Western States Water Council (Midvale, Utah). Accessed 10/02/08 at: http://www.westgov.org/wga/publicat/water08.pdf

Western Water Policy Review Advisory Commission. 1998. *Water in the West: Challenge for the Next Century*. Final Report, Western Water Policy Review Advisory Commission.

APPENDIX: Landscape Water Use Software

User's Manual
Landscape Water Use Software

System and Software Requirements:

- Microsoft® Windows® Vista or later
- ArcGIS® 10 for Desktop Advanced (formerly known as ArcINFO® license) or later
    - Spatial Analyst® extension
- Microsoft® Access® 2003 or later
- The system requirements stated for the above software will suffice for the Landscape Water Use Software

Data Requirements:

- Water Billing records in a CSV format
- Parcels in GIS file
- Building Footprints in GIS file
- Aerial imagery that has been reclassified:
    - From a raw false color composite image to a supervised classification image
        - This reclassified image must have trees and grass classes
- Weather information in database (dbf or Geodatabase) file

Customization:

This software is currently customized to work with Logan City, Utah. But any other databases that match the style and format of Logan City data would work in this software as well.

Logan City database format:

Any city will have to find a way to join together their water billing data with their GIS data. For Logan City, there are two joining factors: Location ID (LocID) and Parcel Tax ID (TaxID). Each water meter has a LocID and each parcel of land has a TaxID. The factor in-between these two is the Building Footprints GIS file (which displays the LocID AND the TaxID for each building).

In general, the GIS files needed are:

- Parcels
    - With each having a TaxID and indication of single family residential (zoning)
- Building Footprints
    - With each having a TaxID and LocID

The CSV file containing the Water Billing Data must have these headers (in this order):

- Rate Class
- Meter Size

- Meter Number
- Total Consumption
- Read Type
- Month Read
- Day Read
- Year Read
- Estimate Code
- Century
- Units
- Location ID
- Meter Service
- Sequence Number

Weather database format:

The weather database can be stored in a dbf file or a Geodatabase file (either File Geodatabase or Personal Geodatabase). The headers for this file need to be:

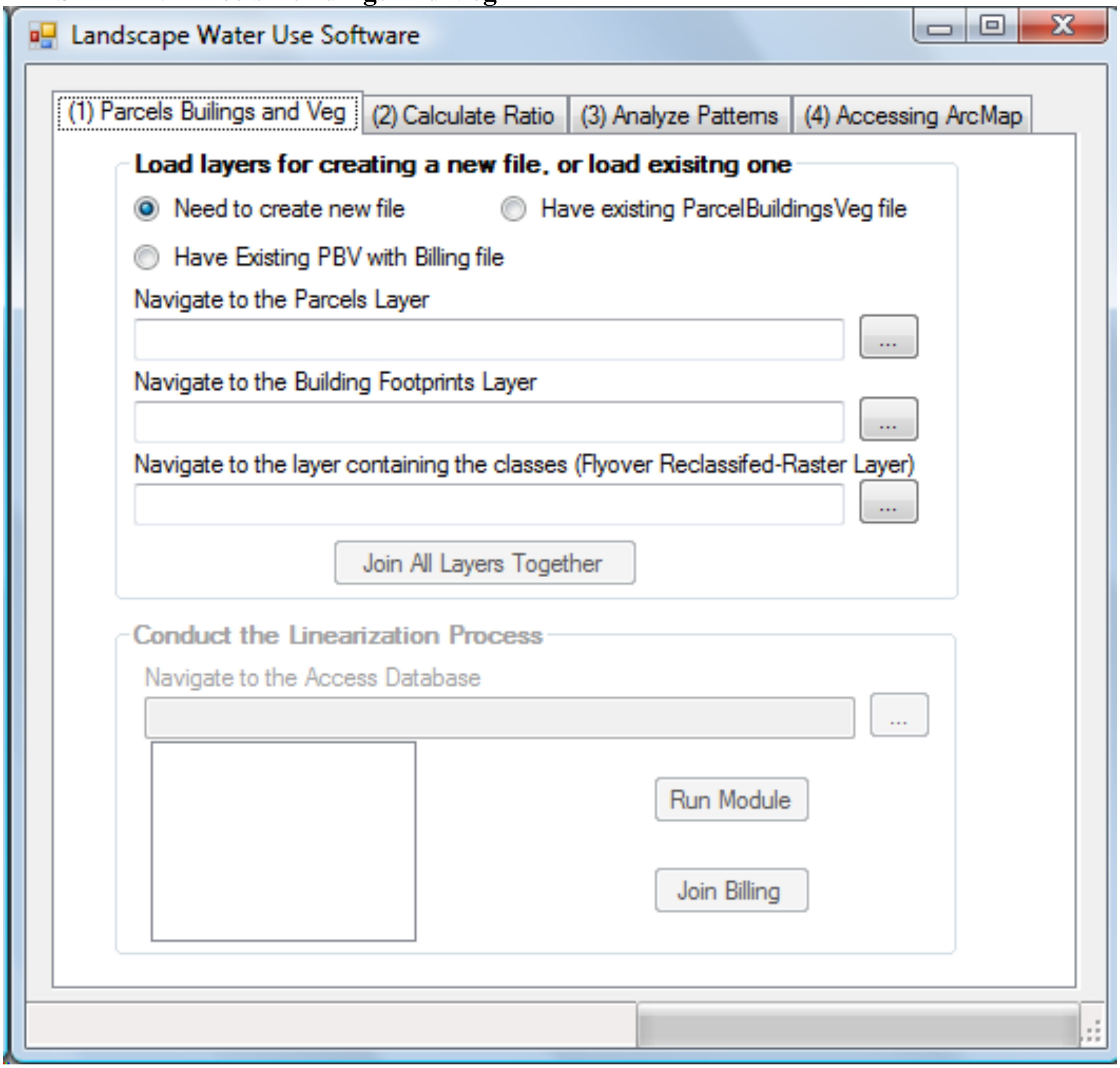
- Day (Date)
- DayJul (Integer)
- ETo + two digit year (Decimal)
- Rain + two digit year (Decimal)
    - Continue with each subsequent year
    - Example for ETo header is ETo02, ETo03, etc.
    - Example for Rain header is Rain02, Rain03, etc

User Interface:

The user interface for the software is divided into 4 tabs:
(1) Parcels Buildings and Veg
(2) Calculate Ratio
(3) Analyze Patterns
(4) Accessing ArcMap

The following explains the functions contained under each tab and the steps a user would go through in operating the software.

FIRST TAB: Parcels Buildings and Veg



The creation and use of the ParcelBuildingVeg (hereafter referred to as PBV) file and linearization of billing data.
In the first tab, the user indicates whether to create a new file or if a former file exists. There are two ways in which the former file can exist: as the PBV file or as the PBV file with the Billing data added.

Creation of new PBV file

Navigate (by clicking on the browse  button) to the Parcels GIS layer, the Building Footprints GIS layer, and the Reclassified aerial flyover image. Once these are loaded, the "Join All Layers Together" button becomes enabled; click on it.

This will join the 3 layers together. Follow the steps (by reading the message boxes that appear) on what to name the joining file and where to save it.

Note: If these layers do not have the appropriate joining attributes, then the join will not occur and an error will happen. See above requirements for appropriate joining attributes.

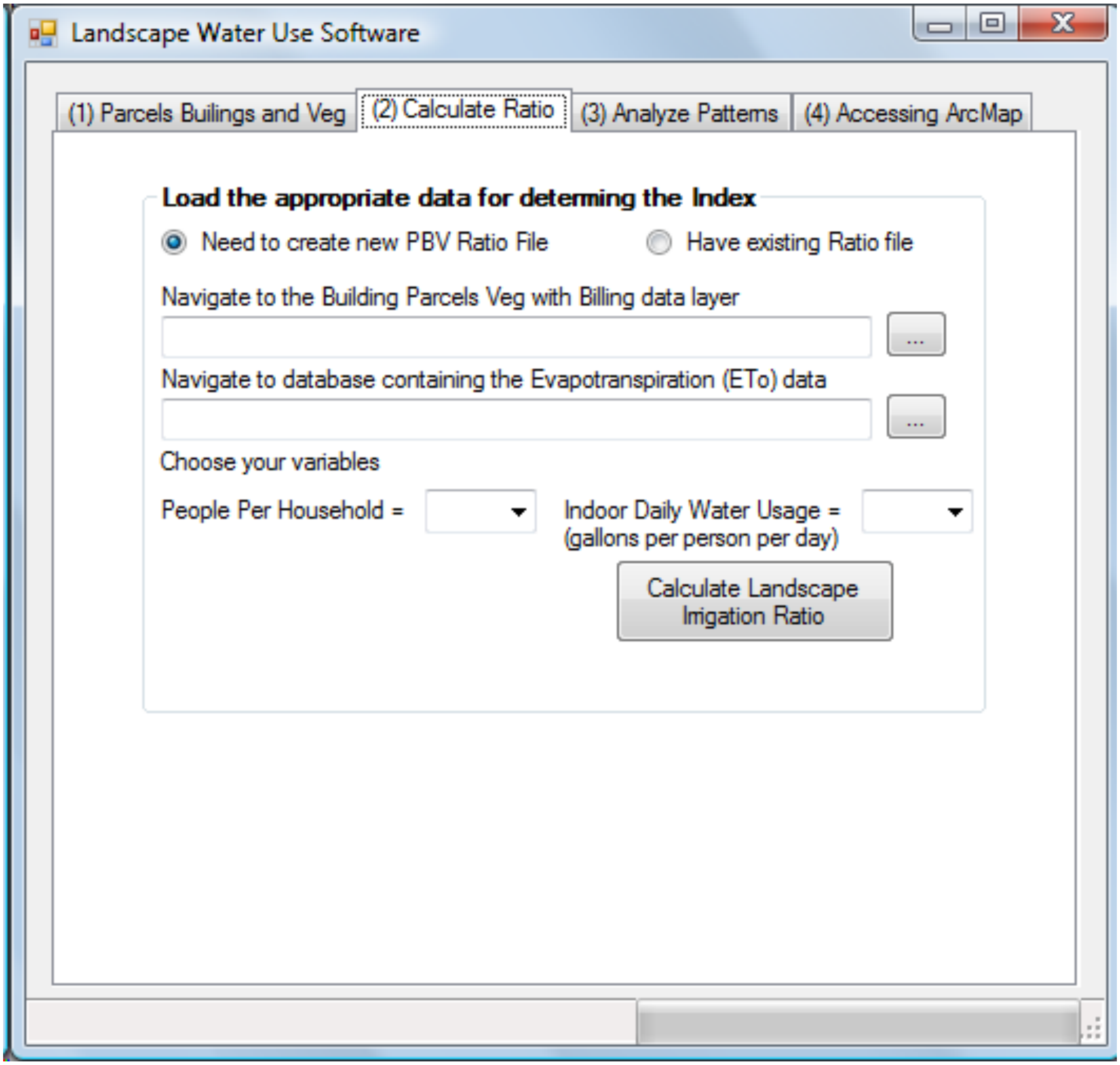
Conduct the Linearization Process

The "Conduct the Linearization Process" group box becomes enabled when the PBV file is created, or if the user chooses to load an existing PBV file. Navigate to the Access Database (by clicking on the browse  button) that will store the water billing data (or that has existing billing data). Click on the "Run Module" button. Depending on the size of the data, this procedure may take some time. Once finished, the listbox on the left will be populated with the years that were in the billing data. Select which years to join to the PBV file and click the "Join Billing" button. Again, follow the steps on what to name it and where to save it. The second tab is activated.

Load Existing PBV with Billing file

If the user has an existing file, navigate to it, and the software will make the second tab active.

SECOND TAB: Calculate Ratio



Calculating the Landscape Irrigation Ratio
The user can choose to create a new file or load an existing file.

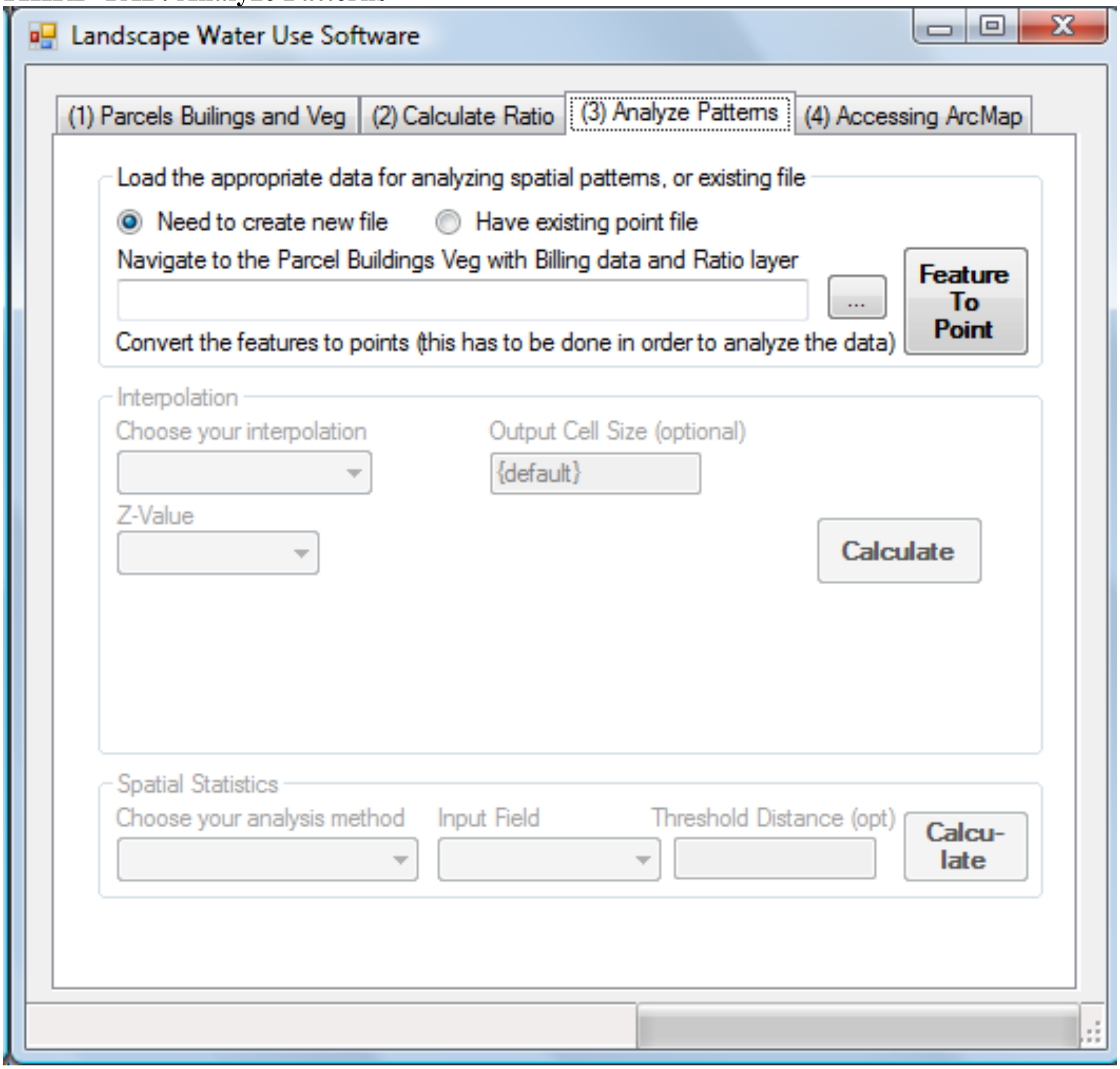
Create new PBV Ratio file
Navigate to the PBV with Billing file and navigate to the Evapotranspiration (weather) database file. Chose the 2 necessary variables (people per household, typical value of 3 and indoor daily water usage, typical value of 70). Click on the "Calculate Landscape Irrigation Ratio" button. Once the process is finished, the third tab is activated.

Note: If the Evapotranspiration (weather) database file is not formatted properly, this Ratio creation process will have errors. Please see the above requirements for a properly formatted database file.

Load existing PBV Ratio file

Navigate to the existing file. The third tab becomes active.

THIRD TAB: Analyze Patterns



Analyzing patterns with Spatial Analyst
This tab is strictly for creating files to potentially show patterns or trends.

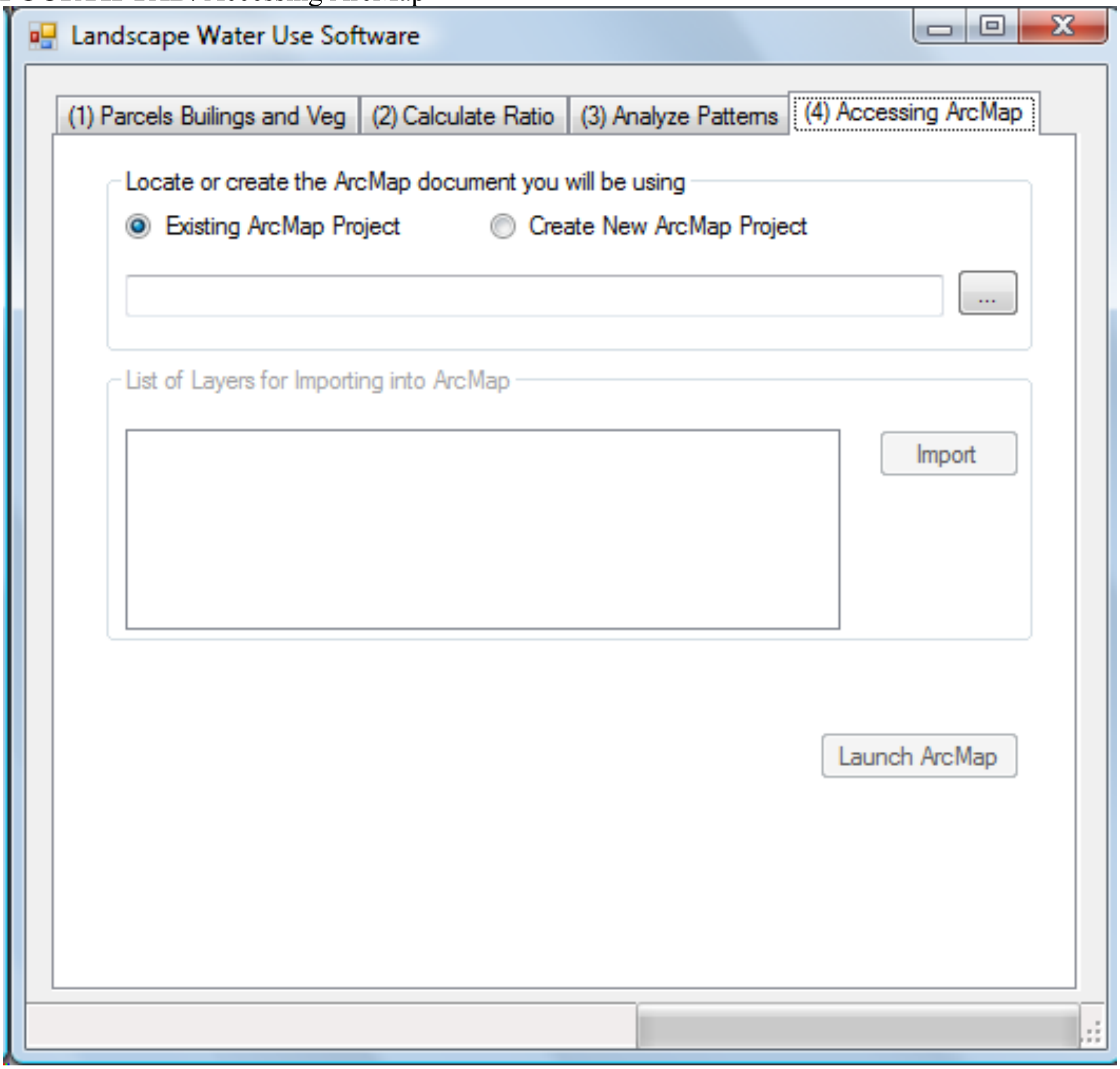
Getting a point file
Either navigate to an existing one or create a new one from the PBV with Billing and Ratio layer. Creating a new point will run the "Feature to Point" Geoprocessing command to create the point file. The next two group boxes are activated once the point file has been loaded or created.

Interpolation
With a point file, the user can choose to make an interpolation to show values in between known points. The different types of interpolation this software can perform are: IDW (Inverse

Distance Weighted), Kriging, Natural Neighbor, and Spline. Once an interpolation method is chosen, the user will be able to input variables with text boxes that will become active.

Spatial Statistics
Also using a point file, the user can perform two types of spatial statistics: Cluster/Outlier with Rendering, and Hot Spot Analysis with Rendering.

FOURTH TAB: Accessing ArcMap



Accessing the ArcMap Application
Once all of the analyses have been completed, the user can input these layers into an existing ArcMap project or create a new one.

Importing Layers

Every GIS layer that is created with this software (on the current instance; meaning if the user closes the software and opens it again, it will be a new instance) will show up in this listbox. The user can select each layer and import it into the ArcMap application that has been instantiated.

Launching ArcMap

Once the user has loaded all the chosen layers into ArcMap, click on the "Launch ArcMap" button to get to the ArcMap application.