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Insights into Efficient Irrigation of Urban Landscapes: Analysis Using Remote Sensing, Parcel Data, Water Use, and Tiered Rates

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Abstract: To understand how landscape irrigation can be better managed, we selected two urban irrigation systems in northern Utah, USA, and performed a statistical analysis of relationships among water use, irrigated area, plant health (based on the Normalized Difference Vegetation Index), and water rate structures across thousands of parcels. Our approach combined remote sensing with 4-band imagery and on-site measurements from water meters. We present five key findings that can lead to more efficient irrigation practices. First, tiered water rates result in less water use when compared to flat water rates for comparable plant health. Second, plant health does not strictly increase with water application but has an optimum point beyond which further watering is not beneficial. Third, many water users irrigate beyond this optimum point, suggesting that there is water conservation potential without loss of aesthetics. Fourth, irrigation is not the only contributor to plant health, and other factors need more attention in research and in water conservation programs. Fifth, smaller irrigated areas correlate with higher water application rates, an observation that may inform future land use decisions. These findings are especially pertinent in responding to the current drought in the western United States.

Keywords: irrigation; tiered water rates; landscape; water use; remote sensing

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1. Introduction

Growing populations, increased temperatures, and drought have emphasized water sustainability questions in the western United States and other water-stressed areas [1–4]. Indoor water use has become more efficient thanks to water conservation programs, building codes, and energy policies implemented over the last few decades [5] and there has been considerable work on both large scale agricultural and urban irrigation [6,7]. However, in arid settings, high irrigation demands for lawns and gardens can account for a substantial portion of the total annual water use, with outdoor uses described as discretionary, conspicuous, and sumptuary [8–13]. Accordingly, reduction of landscape irrigation is an obvious place to improve water efficiency and often the focus of water reduction campaigns and regulations [14,15]. Water managers throughout the work have implemented a range of management strategies with varying success [16,17].

The difficulty in achieving such efficiency, however, is multifaceted and researchers have evaluated several issues that affect water use, including social capital [18], household size [19,20], and various other factors. Cook et al. [21] reviewed over 200 studies in the literature on urban landscapes, including irrigation, and described the links among social drivers and ecological outcomes. Jorgensen, Graymore, and O'Toole [9] studied household water use and found that both interpersonal trust (i.e., whether other people are conserving) and institutional trust affected water use. Llausàs and Saurí [10] reviewed over 400 published studies to develop a theoretical model of outdoor domestic water consumption based on spatial-structural, social-structural, and cultural and psychological factors that interact locally and found the interactions complex.

Landscape irrigation is less regulated than indoor (potable) water use. Potable water is a matter of public health and is, therefore, controlled through plumbing codes and water quality standards. It is also generally metered at the customer endpoint for billing purposes. By contrast, landscape watering often has little or no regulation (or at least enforcement) at the customer level. Irrigation systems providing untreated (secondary) water often do not measure water consumption or charge fees based on the amount of water used. In cases where landscapes are irrigated with potable water, the indoor and outdoor uses are rarely metered separately, and assumptions about household sizes and irrigation seasons are required to separate the two when studying water use and efficiency measures.

Outdoor water use varies by location, over the year, with recent precipitation, with soil conditions, by plant type, by irrigation technique, by parcel size, by price structure, and by customer preference, complicating efforts to offer general guidance on how to encourage efficient irrigation. Overirrigating is a common problem; water is necessary, but too much water can damage plant health, contribute to iron chlorosis (yellowing), and wash away nitrogen [22]. DeOreo, Mayer, Dziegielewski, and Kiefer [5] studied hundreds of residential landscapes and found that about 20% of the users were applying more water than needed.

Non-pricing and pricing solutions that include water use restrictions or incentives for water-saving devices have been studied [23,24]. However, implementing efficient irrigation practices with many individual users and diverse landscapes is challenging [25]. One approach is an educational solution; many water conservation programs and university extension programs seek to communicate optimum watering practices to water users, including proper timing and depth of irrigation as well as fertilizer application [26–30]. Another option is a technical solution; irrigation systems with automated soil moisture sensors may help reduce water use as the systems only irrigate when plants require water, reducing over-irrigation [31–35]. A third approach is a policy solution designed to influence water use [36]; tiered rates—that is, water fees where the unit price for water increases with volume [37]—have been a key ingredient to successful water conservation programs in Tucson [38], Los Angeles [39], Irvine Ranch [40], Charlotte [41], Southwest Florida [42], and elsewhere, because of the price signals associated with excessive consumption.

To advance understanding of how urban landscapes are irrigated, we examine two municipal irrigation systems with thousands of customer parcels, one system with tiered rates and the other without. We use a combination of remote and on-site measurements to correlate plant health with water application rates, irrigated area, and rate structures for the purpose of identifying insights that may lead to more efficient water use. Performing this analysis at the parcel level is important because that is where customers make decisions about landscapes and water use, so differences at this level reflect customer practices. Unlike studies of single fields common in the literature, we characterized these variations over an entire water utility service area. The study is unique in that it captures these variables on a scale relevant to water suppliers and with a resolution relevant to water users.

Our contribution is twofold: first, an effective method of irrigation analysis that may be repeated in other urban areas, and second, a set of data-driven findings with direct implications for water management decisions by both water suppliers and water users. We discuss how the findings can promote practical interventions to make landscape irrigation more sustainable. These contributions are especially timely given recent advances in remote sensing technology, greater availability of water use data, and the need for efficient irrigation in the face of water scarcity.

2. Methods

2.1. Study Areas

The two water systems we studied are in northern Utah, USA (Figure 1). Each water utility, while also providing drinking water, has a separate secondary system for irrigation that has its own meters. Table 1 presents the pertinent characteristics of each study area.

The two systems are geographically close (about 25 km apart) and at similar elevations (about 1370 m), but use different rate structures—one tiered, one flat (Figure 2). The number of irrigation connections, irrigated area, and evapotranspiration are similar, but Study Area B receives approximately 65% more precipitation. However, most of this precipitation occurs during the winter season, while our study uses data only from August.

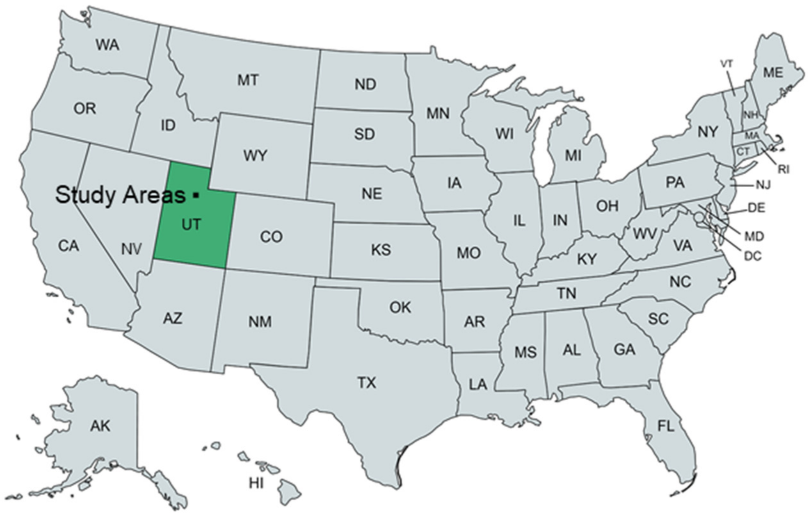

Figure 1. Location of study areas in northern Utah, USA.

Table 1. Water system characteristics.

Characteristic	Study Area A	Study Area B
Irrigation connections	5198	7146
Total irrigated area, ha	244	328
Rate structure (Figure 2)	Tiered	Flat
Annual average precipitation, cm [1]	32.3	53.6
Annual evapotranspiration, cm [1]	135	131

[1] Data from local weather stations in or near the study areas as reported by Hill, et al. [43].

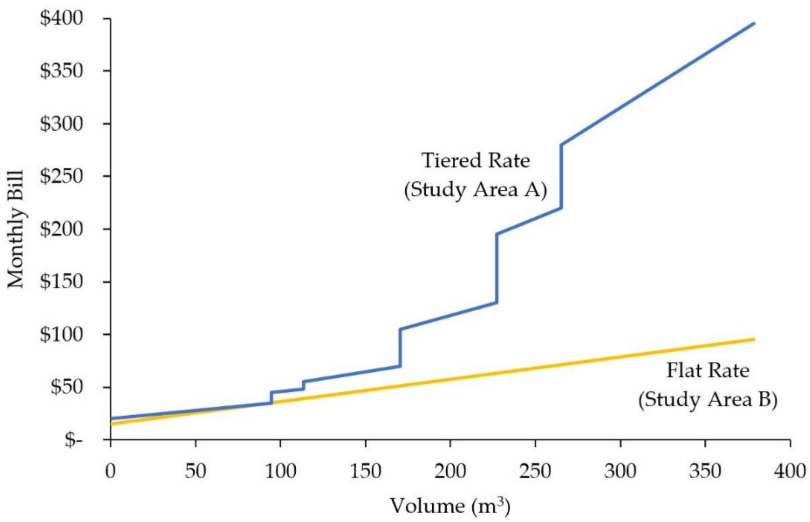

Figure 2. Water rate structures in both study areas.

2.2. Data Sources

We obtained the data for this analysis from both public and private sources. Public sources included 4-band, 1 m imagery from the National Agriculture Imagery Program

(NAIP) collected in the summer of 2016 [44], parcel location and sizes from local county property records, and rate structures from published information on the water systems' websites. Private sources included the secondary water bills provided by the two water systems. Such data are generally available in the United States through existing web services, government agencies, and/or reasonable requests to water utilities, so the procedure we present should be feasible in other U.S. locations. We obtained the parcel records and water use data for August 2016 to match the collection data of the NAIP imagery. While the data came from different sources, all contained spatial information, which we used to associate parcel size, location, aerial imagery, and water use for each parcel in a geographic information system (GIS).

We used NAIP imagery with 1 m spatial resolution rather than satellite data because the 1 m resolution enables meaningful analysis of urban parcels, which are generally smaller. This analysis would not have been possible with data products from Landsat, which, though available more frequently each year, have a 30 m pixel resolution and do not capture sufficient resolution to distinguish urban features like sidewalks, planter beds, grass areas, and buildings.

2.3. Analysis Methods

We used the process outlined in Figure 3 for analysis. We completed most of the GIS analysis and data extraction using ESRI ArcGIS 10. We used the Excel app from Microsoft 365 along with SAS JMP Pro 16.1.0 for graphing and statistical analysis.

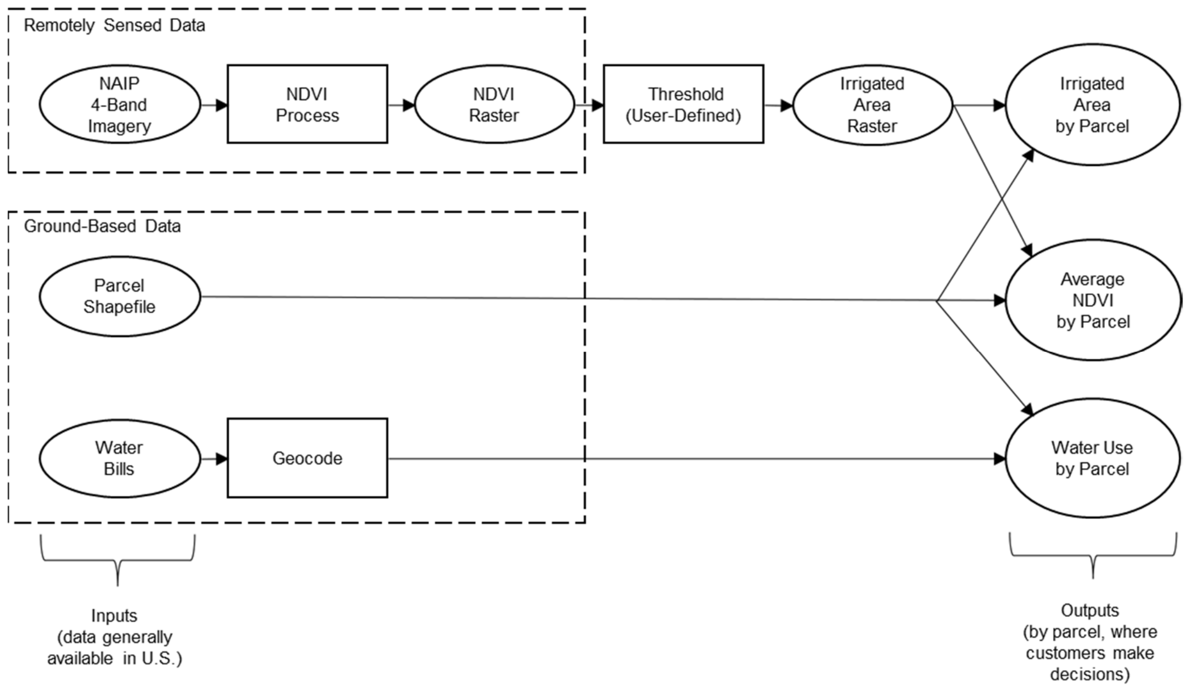

Figure 3. Flowchart showing how imagery, water use, and parcel data were analyzed.

Because of the large spatial scales involved, analysis of extensive landscapes often relies on remote sensing and GIS [45–47]. Using 4-band imagery, plant health can be assessed using the Normalized Difference Vegetation Index (NDVI) [48]. This is a key step in our analysis. NDVI is computed using near-infrared (NIR) and red bands in a multispectral image as:

$$\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} \quad (1)$$

where NDVI ranges from −1 to 1, with higher values associated with healthy plant life and lower values associated with plant stress or lack of vegetation. Because healthy vegetation with more chlorophyll reflects higher levels of light in the NIR and absorbs light in the red band, the NDVI distinguishes between areas of thick, healthy plant life vs. unhealthy and/or sparse plant life and has been used to both monitor plant health and drought conditions [49–51]. Researchers have shown that NDVI is directly related to the photosynthetic capacity and to energy absorption of plant canopies while minimizing changes from other materials in the scene [52].

We processed the NAIP images to produce an NDVI. While NDVI ranges from –1 to 1, to facilitate processing with 8-bit GIS data we scaled the results to range from 0 to 255:

$$\text{Scaled NDVI} = 127.5(\text{NDVI} + 1) = 127.5\left(\frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}} + 1\right) \tag{2}$$

We visually determined an appropriate NDVI threshold in each of the two study areas to separate pixel values representing irrigated and unirrigated areas. We did so by examining imagery of large grass areas that included both green, healthy, presumedly well-watered vegetation and yellow, brown, presumedly underwatered vegetation with bare earth, paved areas, and structures. We visually compared the plant-covered areas in the true-color image to the NDVI image (Figure 4) and adjusted the scaled-NDVI threshold to isolate the pixels we visually identified as irrigated areas. We selected a scaled-NDVI threshold of 150 (NDVI of 0.17) for each study area. The selected threshold values happened to be the same in both study areas, but this is a coincidence likely due to their similar geographic setting as well as the similarity of the imagery in terms of collection dates and reflectivity. This value compares well with the literature; Hashim, et al. [53] set a threshold of 0.19 for the boundary between no- and low-vegetation coverage, which is consistent with our value of 0.17 for non-scaled NDVI. Using these threshold values, we isolated irrigated areas (areas with scaled values greater than the threshold) from other landcover types in the images. This also allowed us to obtain a measure of plant health based on the magnitude of the scaled NDVI value, with higher values indicating healthier vegetation.

Figure 4. An example of determining the NDVI threshold value for irrigated areas. These images are for Study Area B with the true-color image on the left and the NDVI raster overlay on the right. In the NDVI image, yellow, light green, and dark green values indicate increasing levels of healthy vegetation, while no-data areas indicate non-vegetated landcover.

The parcel data consisted of geolocated polygons that defined each parcel's boundaries while the water bills were identified by a street address. We geocoded the billing addresses and joined the water use records to the corresponding parcels to produce a dataset that quantified the irrigation water used for each parcel in August 2016. We overlaid the parcel boundaries on the NDVI raster to compute the irrigated area for each parcel. The parcel irrigated area was smaller than the complete parcel because of structures, driveways, and other non-irrigated areas. In a few cases, the entire parcel was irrigated.

Finally, we computed the average scaled-NDVI of the irrigated parcel area. This produced a parcel-level dataset that included: (a) the amount of water applied, (b) the irrigated area of the parcel, and (c) the plant health in the irrigated area as measured by the scaled-NDVI. See the Supplementary Materials. We used these data to analyze relationships at the parcel level among water application rate (volume of water applied per unit of irrigated area, expressed as a depth), plant health, irrigated area, and rate structures.

3. Results and Discussion

Figure 5 presents statistics on the irrigated area, scaled-NDVI values, and water application rates for our study areas. Figure 6 presents log-scaled values for irrigated area and water application rates, as these data are skewed but have an approximate log-normal distribution. Figure 5 shows that the irrigated area values for both study areas are right skewed, with the majority of the data showing as outliers on the box-whisker plots on a linear scale. Both study areas have a median value of about 900 m^2 for the irrigated areas, with values of 929 m^2 and 845 m^2 for Study Areas A and B, respectively. The 75th and 25th percentiles were also similar with values of 1057 m^2 and 759 m^2 for Study Area A and 1089 m^2 and 695 m^2 for Study Area B, respectively. The scaled-NDVI values for both study areas are similar and are approximately normally distributed with median values of 177 and 163 for Study Areas A and B, respectively. As with the irrigated area, the amount of water applied was heavily right skewed, with the box-and-whisker plots of the linear data essentially only showing outliers. The median values for water application are different, with values of 30 and 38 cm for Study Areas A and B, respectively. Figure 6 shows the log-scaled distributions for parcel area and applied water for Study Area A (top panel) and Study Area B (bottom panel). The data included some abnormally high application rates, which we attribute to leaks, billing errors, undermeasurement of irrigated area, and account starts and stops. Regardless, the plots show that most of the data are relatively close to the median value. While both data sets have outliers with significantly high values, these outliers do not represent a large portion of the data.

As water application rates above 100 cm/month are obvious outliers, for the remainder of the study we restricted our analysis to data with water application rates equal to or below 100 cm/month.

Figure 7 shows the correlation between scaled-NDVI and water application rates. In these plots, the box indicates the 50th percentile (center line) and the 75th and 25th percentiles (ends of the box). The whiskers represent 150% of the interquartile range, while the diamond indicates the 95% confidence interval for the mean, with the center of the diamond being the mean, which can be different from the 50th percentile (skewed data have different 50th percentiles and means). By separating the scaled-NDVI data into water application rate bins, some trends become apparent, even though there is a large spread in the data. These trends have two distinct parts. A visual inspection of the box-plots shows that scaled-NDVI correlates positively with water application rates up to a point: scaled-NDVI increases up to about 20–30 cm/month and afterward declines with increasing water application. This pattern is consistent with that reported by Shedd, et al. [54], who found that increasing water application can result in lower plant health. The optimum water application rate for our data, which we determined by visual inspection, is 20–30 cm/month for August, the month for which we have data. This value is similar to that reported by Hill, Barker and Lewis [43], who reported typical August evapotranspiration requirements to be 20.8 cm and 20.0 cm in Study Areas A and B, respectively, based on long-term records from local weather stations.

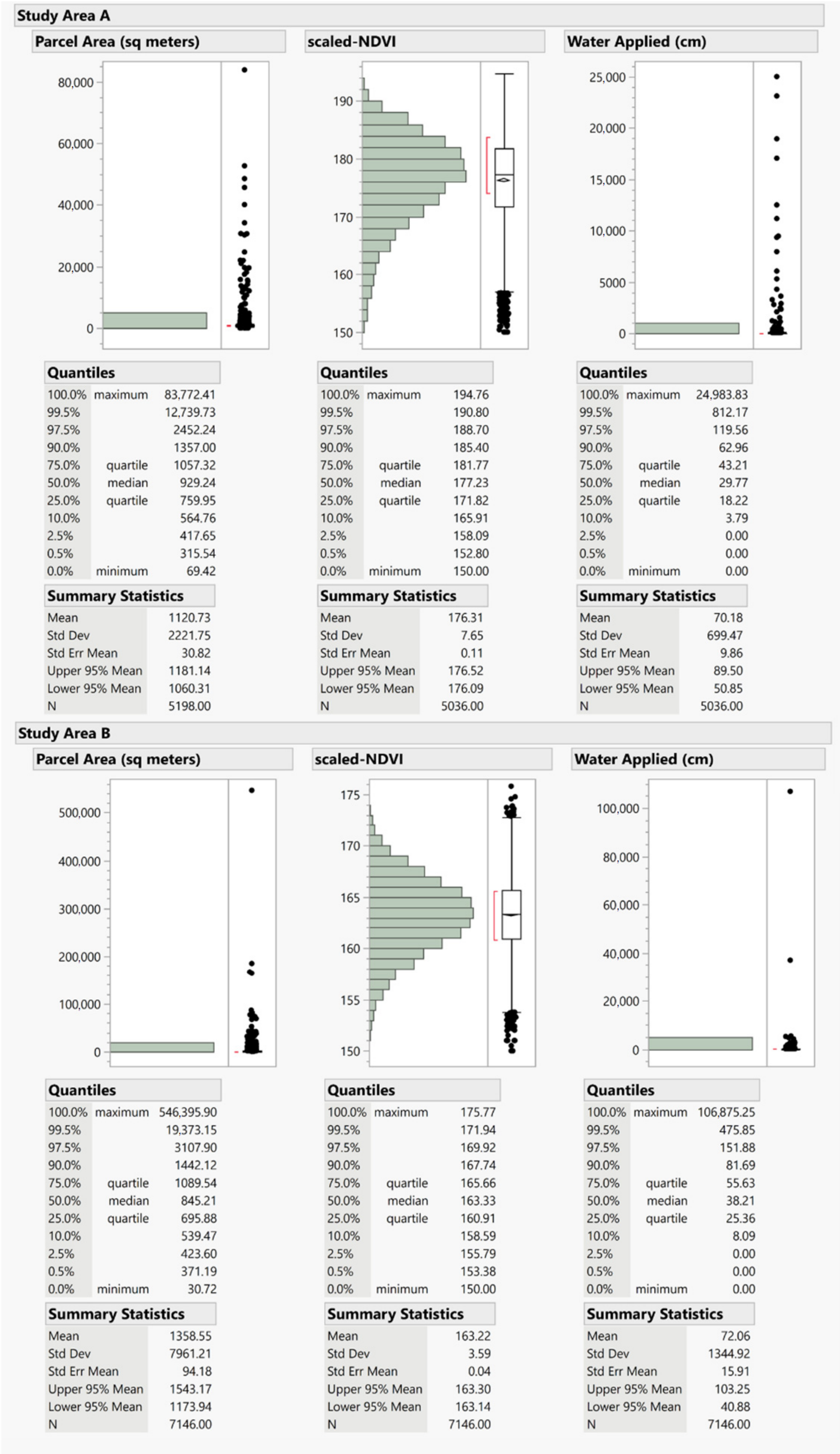

Figure 5. Distribution and summary statistics for irrigated area, average scaled-NDVI, and water application rate for Study Area A (top panel) and Study Area B (bottom panel).

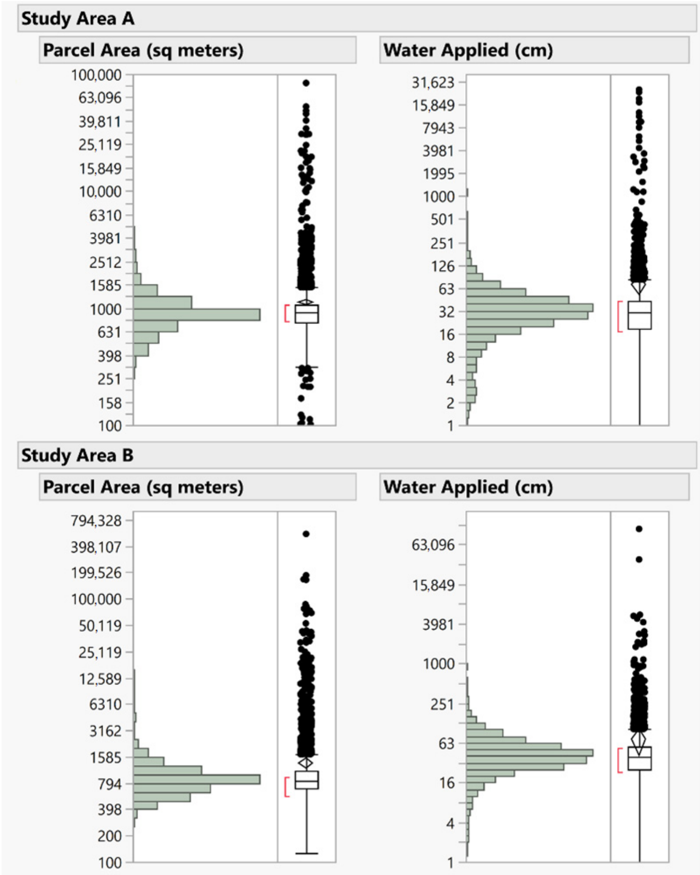

Figure 6. Log-scaled distributions for parcel size and water application rate. These plots show that while the data are significantly right skewed, most of the data appear to follow a log-normal distribution with a relatively small spread.

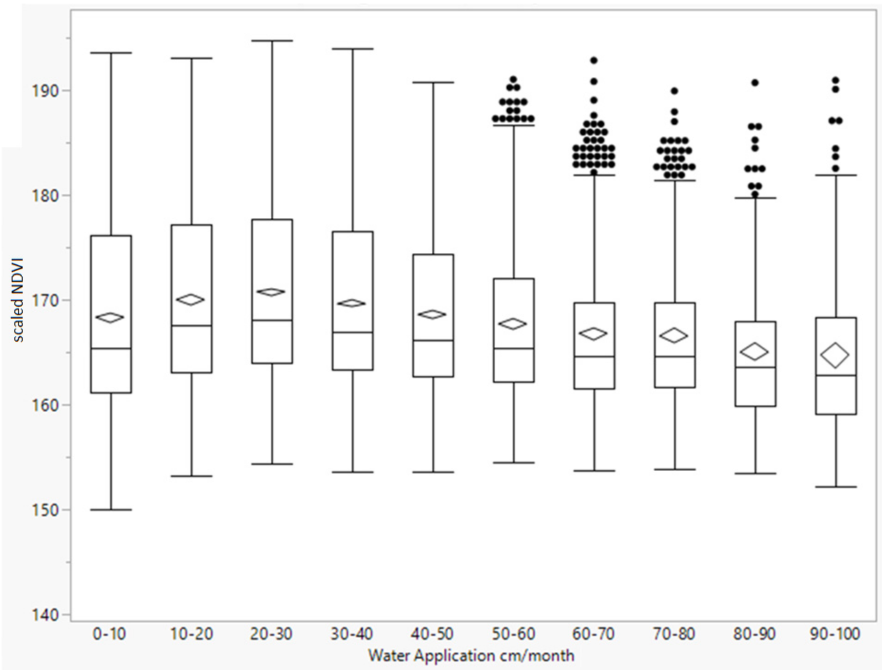

Figure 7. Scaled NDVI vs. water application. The data show a general increase until about 20–30 cm/month, then a decrease with increased water application.

We conclude that our data show that in Study Areas A and B irrigation improves plant health, but only up to a certain point, which is 20–30 cm/month, beyond which further irrigation offers no benefit and results in less healthy vegetation.

In dry areas, there may be a natural impulse that to achieve a greener lawn more water is required, but research and our data show that this impulse is misguided, that additional water, over the optimum, may not improve vegetation and may result in vegetation yellowing. Figure 5 shows that parcels receiving more than 60 cm had lower vegetative health than those that received just 10 cm, below the optimal watering level. While this idea may be well understood among plant scientists, we arrived at it here through an empirical analysis of full-scale water systems in the two studied service areas.

Our analysis of urban water application rates and plant health follows research that excess irrigation can reduce plant health. These results suggests that for a given study area, plant type, and time of year, there is an optimum water application rate that can be determined. This rate would provide the highest plant health without excess watering.

The box-and-whisker plots and histograms in Figure 8 show how water application varies among the customers in the two study areas. Clearly there is a wide range, with most water application rates concentrated in the middle of the distribution with little spread. Figure 7 shows that for our study areas in August, 20–30 cm appears to be the optimum water application rate. Figure 8 shows that a water application rate of 30 cm corresponds to approximately the 50th and 40th percentile for Study Areas A and B, respectively. This means that about 50% and 60% of the parcels applied water above the optimal level in Study Areas A and B respectively. Our finding is similar to that of DeOreo, Mayer, Dziegielewski, and Kiefer [5], who found that about 20% of users overwatered relative to the theoretical requirement, and that a few indulgent users accounted "for the bulk of excess irrigation for the whole group." We found that in our two study areas, many customers irrigate above the optimum point.

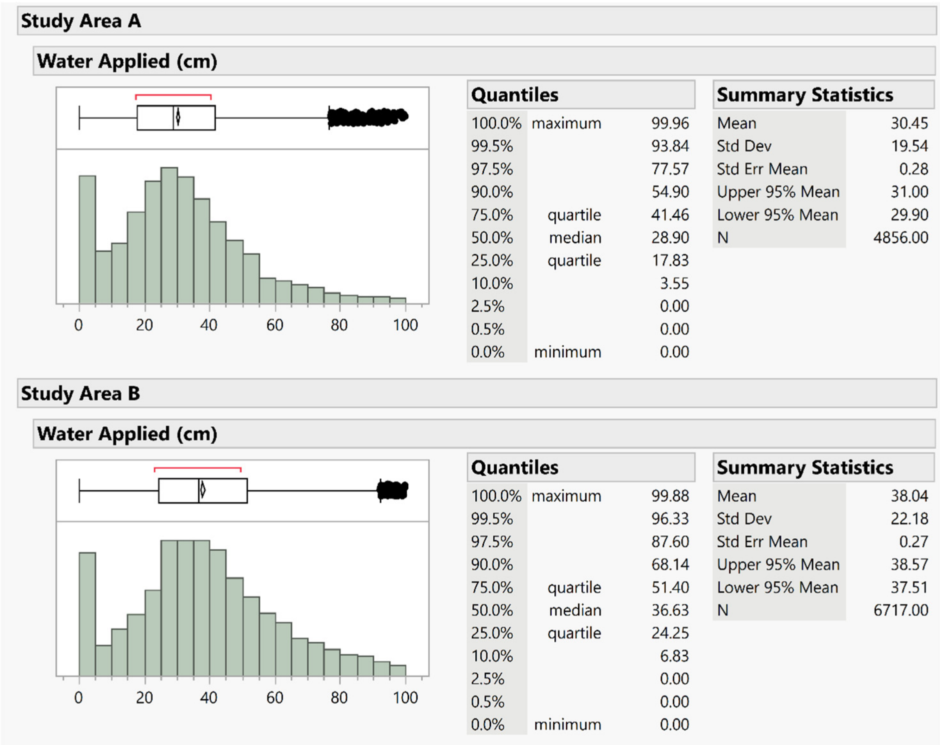

Figure 8. Histogram of water application rates for Study Area A (top) and Study Area B (bottom). These distributions show a clear difference in water application rates with the 50th percentile being 28.9 and 36.6 cm per month for Study Areas A and B, respectively.

Our data showed that even at the same water application rate there is considerable variation in plant health as shown by the spread in the data for each application rate bin in Figure 7. There is considerable overlap in plant health among the various bins, and large spreads in plant health within a single bin. If water application alone were the sole predictor of plant health, we would expect a smaller spread and less overlap than exhibited by our data. This may be caused by a number of factors, such as fertilizers, plant type, soils, land use, and pests. For example, nitrogen, a primary fertilizer component, affects NDVI [55] and there is most likely a range a fertilizer application rates within the study areas.

For comparable scaled-NDVI values, water application rate decreases with increased irrigated area (Figure 9). These data imply that smaller parcels are less efficiently irrigated than larger parcels, perhaps because of small, irregular landscape areas that are not contiguous, where sprinklers overshoot. Another possible explanation is that small parcels are less sensitive to the pricing because of the low water volumes involved. Larger parcels, by contrast, may have an economy of scale and/or greater sensitivity to price because of water volumes required for irrigation.

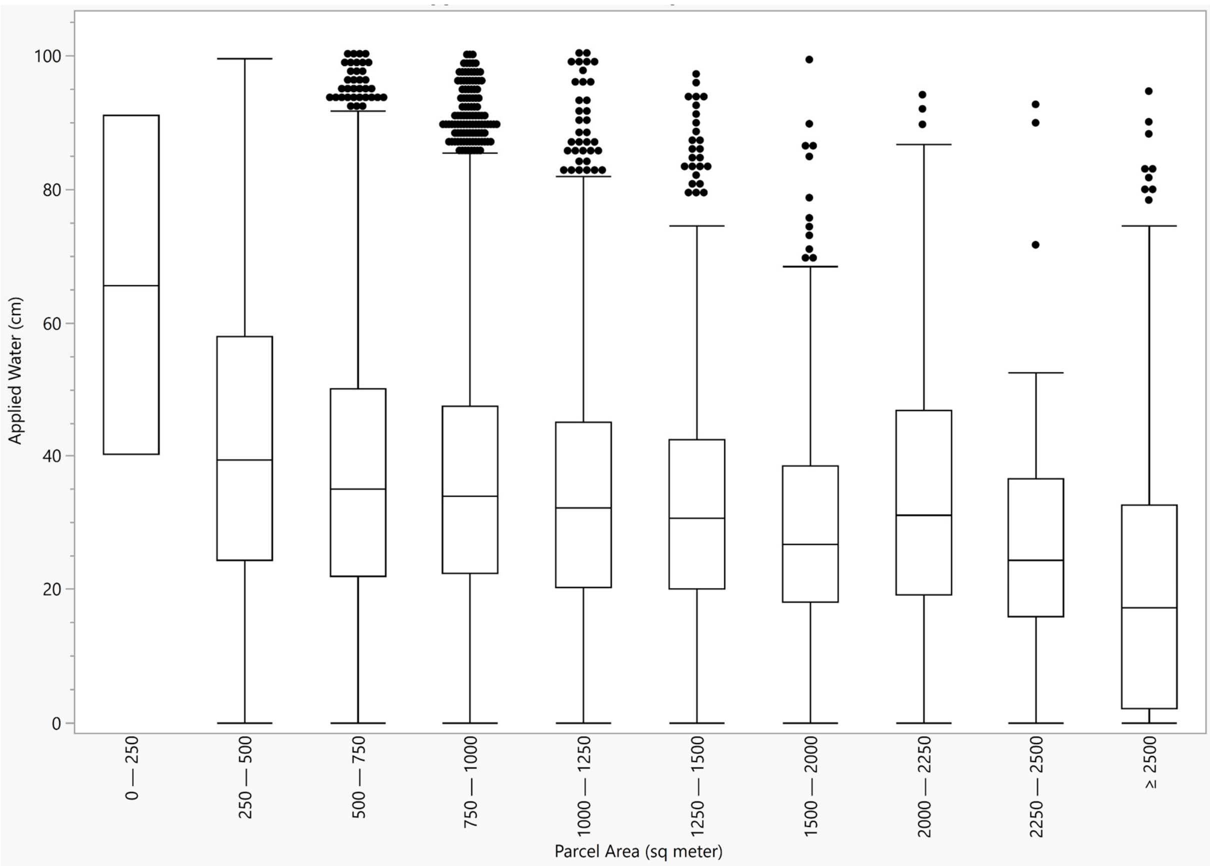

Figure 9. Water application rates by irrigated area. In general, small irrigated areas have higher water application rates than larger ones, though there is significant spread in the data.

While we do not know the cause, our data show that smaller parcels correlate with higher water application rates. This finding should be considered when assessing impacts of new land developments and establishing associated land use policies, especially for high-density developments with many small parcels. While irrigated areas smaller than 250 m^2 were a trivial fraction of the study areas here (less than 1%), this category may be significant in other regions.

We found that for comparable scaled-NDVI values, customers in Study Area A apply less water than customers in Study Area B (Figure 10). In other words, water users in Study Area A achieve similar plant health (i.e., green grass) with less water. This occurs despite the fact that Study Area A receives approximately 40% less precipitation than Study Area B, with values of 32.3 and 53.6 cm/year for Study Areas A and B, respectively (Table 1). By way of example, comparing the median values from Figure 5, irrigated areas in Study Area A took 22% less water but had scaled-NDVIs 9% higher than those in Study Area B.

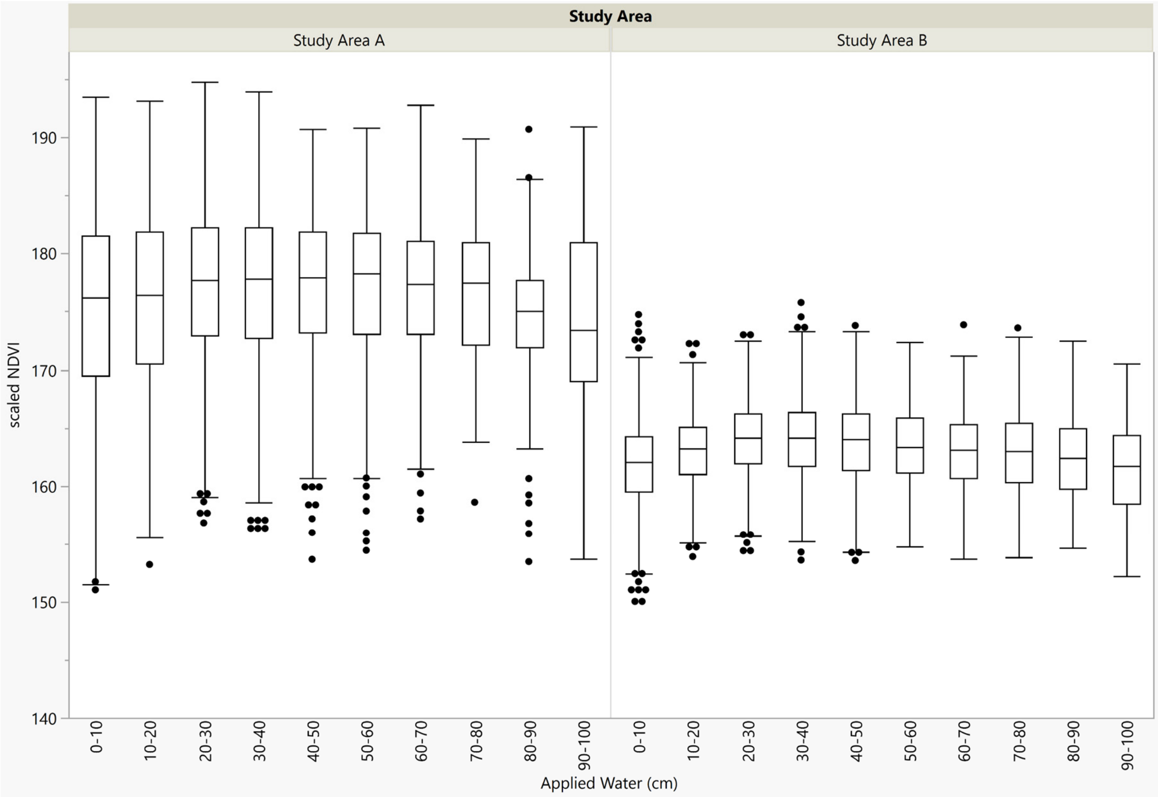

Figure 10. Water application rates for Study Area A (tiered rates, left) compared to Study Area B (flat rates, right). For comparable scaled-NDVI values, water application is significantly lower with tiered rates. Conversely, for comparable water application, scaled-NDVI values are significantly higher with tiered rates.

Both water systems are similar in many ways, but a major difference is their rate structures. We attribute the difference in water use to this difference in rate structures. We acknowledge there could be other influences, such as soil type, fertilizer use, landscape choices, and other factors that we could not measure, but a causative role of tiered rates is well supported by the literature: Customers who are subjected to tiered rates receive a stronger price signal and, therefore, tend to apply less water on their landscapes than customers with flat fees and no price signal to curb excessive use. Our data show that tiered pricing saves water. If the goal is to conserve water, tiered rates—with appropriately aggressive tiers—should be implemented.

4. Conclusions

We examined parcel-scale water application rates by combining remotely sensed irrigated area, a remotely sensed plant health index, and parcel-scale water use records for two similar urban areas. While the study areas were similar, the main difference was their water rate structures.

Our data showed five key conclusions. First, tiered pricing correlates with lower water application rates for comparable plant health relative to flat-rate pricing. Second, plant health does not strictly increase with water application but has an optimum point, with water application rates above this resulting in lower plant health. Third, many water users irrigate above this optimum point, suggesting opportunities to save water without negatively affecting plant health. Fourth, for comparable plant health there is a range of observed water application rates, indicating other factors that deserve attention in water conservation programs. Fifth, for comparable plant health, smaller parcels require higher water application rates than larger parcels.

While we found no other full-scale urban irrigation studies using the same methods as ours, our findings are consistent with certain components in the literature cited earlier, such as the role of tiered rates, the existence of optimum irrigation depths, and the effects of overwatering. Our work further strengthens the case for interventions already recommended by others. Specifically, our results suggest the following recommendations for both water resource/infrastructure managers and water users:

- Determine the optimum location-specific irrigation depth for best plant health.
- Communicate this optimum value to customers and explain why overwatering is both unnecessary and inadvisable.
- Focus landscape and water conservation programs on proper fertilizer application and other non-water factors that will support healthy lawns and gardens.
- Adjust land-use policies to avoid producing small, irregular, and/or disconnected landscaped areas, especially on small individual parcels. Where green space is needed in high-density developments, encourage larger, contiguous landscaped areas.
- Meter outdoor water use and establish tiered water rates with aggressive tiers that will discourage excessive use.

While we cannot provide detailed implementation strategies here, we invite others to do so based on our results, developing effective irrigation management solutions adapted to local circumstances.

The strengths of our method are its use of public data (imagery and parcel records), its ability to cover large urban areas, and its ease of pairing imagery with water use data. It is inherently an empirical method that can be repeated whenever 4-band imagery and water use data are available for the same period. Nonetheless, we acknowledge several limitations in our work. We did not know the exact collection dates of the NAIP imagery to align with water use records (only a summer month in 2016). We did not distinguish between tree canopies and irrigated vegetation, meaning that irrigated parcel area estimates could be incorrect for some parcels. We visually determined the scaled-NDVI threshold value for distinguishing irrigated and non-irrigated areas for each study area, which may have introduced some uncertainty. We had no information about parcel-level fertilizer application or soil types in either study area, though we know these to influence plant health and water use.

Further work may extend this type of analysis to other systems where landscape irrigation is separately metered, or perhaps employ drones to capture high-resolution, multispectral imagery multiple times in a single season or in custom study areas. Another important study would address the roles of fertilizers and soil types in water use at the same scale we studied here. Soil moisture sensors and smart irrigation controllers are among several promising technologies to optimize landscape irrigation, and further work is needed to understand the benefits of these devices across large study areas with thousands of users. Finally, we encourage further study of the effect of tiered rates, in the context of all these variables, as a policy solution for more sustainable water use.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14031427/s1, Table S1: Supplementary Data.

Author Contributions: Conceptualization, K.M.S.; methodology, K.M.S.; validation, R.B.S. and E.D.; resources, R.B.S.; data curation, K.M.S. and E.D.; writing—original draft preparation, R.B.S.; writing—review and editing, K.M.S., E.D., R.B.S. and G.P.W.; visualization, G.P.W. and E.D.; supervision, K.M.S., R.B.S. and G.P.W. All authors have read and agreed to the published version of the manuscript.

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