Pathways to Enhancing Analysis of Irrigation by Remote Sensing (AIRS) in Urban Settings

Annelise M. Capener, Robert B. Sowby * and Gustavious P. Williams

Abstract: In contrast to agricultural settings, irrigation of residential properties in urban settings is typified by small and irregular areas, many untrained water users, limited end-use metering, and differing groundcover. This makes analyzing irrigation patterns to promote efficient water use challenging. We explore the use of remote sensing tools and data sets to help characterize urban irrigation use in the United States. Herein, we review available multispectral imagery datasets and discuss tradeoffs among spatial resolution, collection frequency, and historical availability. We survey options for evapotranspiration data at various spatial and temporal scales that could be paired with the multispectral imagery to estimate irrigation demand. We call the general approach Analysis of Irrigation by Remote Sensing (AIRS). We discuss the potential of drones to capture higher-resolution temporal or spatial data in study areas and/or multiple flights in a single season to provide ground truth or establish patterns. We present data and analysis options that may be suitable depending on specific project objectives. Through a case study scenario, we illustrate some tradeoffs. As a starting point, we recommend public 1 m National Agriculture Imagery Program (NAIP) images for irrigated area estimates and normalized difference vegetation index (NDVI) calculations, combined with open-source OpenET for evapotranspiration, to provide historical snapshots of water use, vegetation quality, and general irrigation efficiency in urban areas. The method is most effective when paired with optional water use data and can provide information with which to design more optimal studies.

Keywords: irrigation; NDVI; urban water use; landscape; sustainability

1. Introduction

Irrigation is the largest consumptive use of water globally and in the United States [1,2]. Research shows that more than 50% of household water use is for irrigation outside of the home [3]. Freshwater resources are limited and must be deliberately managed. While new technologies and practices are helping to optimize agricultural water use, the irrigation of residential, commercial, and institutional properties in urban settings is less well measured, and the characterization of these use patterns presents different sustainability challenges. In contrast to agricultural irrigation, urban irrigation involves much smaller parcels (on the order of 10 ha), irregular areas (around buildings, roads, and landscape features), limited separate end-use metering [3], thousands of untrained water users, and various vegetation conditions. Accordingly, analyzing urban irrigation, identifying areas for conservation, and determining best practices with which to promote sustainable water use is challenging.

In instances of drought, managing water use becomes even more vital. In the western United States, the past few years of exceptional drought and heat have brought irrigation—already a very visible form of water use in most communities—under scrutiny and propelled it to the forefront of local water conservation discussions [4–6].

Preventing overwatering of landscapes is an effective and non-intrusive way to avoid wasting water. Prevention is especially effective if over-users can be identified and encouraged to scale back their watering to the optimum depth, thereby achieving water savings without losing the aesthetic quality of the landscape, as Shurtz et al. [7] proposed.
However, individual water users may find it difficult to determine when their watering habits are excessive, and local water managers may find it difficult to provide effective guidance to thousands of water users whose plant choices, property sizes, soil conditions, and landscape designs vary so much. The identification of overuse is compounded when outdoor water use cannot be measured at the customer level due to water service being provided by a single drinking water system (for indoor and outdoor purposes) or by a dedicated irrigation system that lacks end-use meters. Without regular feedback on water use or plant health, both water users and water managers are ill-equipped to improve irrigation management, particularly in times of drought.

Remote sensing may help overcome some of these difficulties. Remote sensing can cover large areas, capture multiple time periods, enable repeat observations, provide timely measurements, and facilitate automated analyses. These are the general benefits of most remote sensing approaches and are especially appealing when publicly available data can be used. Here, we show that, by using four-band imagery and publicly available evapotranspiration data, we can estimate irrigation volume and plant health without needing on-site measurements. We show that this practical approach can help characterize urban irrigation and fill several data gaps, but there are numerous additional potential applications.

While several studies have used remote sensing for this purpose, more datasets and methods are now available to accelerate their application. However, there is no catalog of the opportunities or discussion of the tradeoffs to guide their use. This paper surveys the available remote sensing data and associated methods that can be used to enhance the analysis of irrigation in urban settings. It outlines pathways for application, serves as the basis for future studies, and recommends specific image data and methods to characterize urban irrigation.

2. Materials and Methods

Irrigation requirements for vegetation on a given parcel can be estimated by the product of irrigated area and evapotranspiration depth, yielding an irrigation volume (Figure 1). Regardless of what specific data are used, we call the general approach Analysis of Irrigation by Remote Sensing (AIRS). Both the irrigated area and the evapotranspiration (ET) depth can be acquired using remote sensing data along with modeling of conditions for a given time and place. Using ET models, the depth of required water can be estimated over a region. The product of the ET water depth and the irrigated area determines the volume required to maintain vegetation wellness on the parcel of land. This is the general approach discussed in this paper.

Irrigated area can be estimated by using the normalized difference vegetation index (NDVI), computed using four-band imagery, to distinguish it from other types of land cover. We discuss the NDVI below. This means that the measurement of irrigated areas can be automated [8]. Because NDVI is a measure of vegetation quality, which, in dry areas, is influenced by irrigation amounts, it can further inform the analysis regarding whether water use is higher or lower than optimal for plant growth. This water volume strictly represents the consumptive water use of evapotranspiration. Because of this, water application efficiency, sources of water loss, and other upstream effects are not included in our water volume calculations.

ET, the other important variable, is specific to plant types, locations, and time of year. Until recently, evapotranspiration data have been sparse, as it is difficult to measure, but new tools are filling the gaps. These tools include land surface models that use remote sensing data and produce gridded time-varying estimates ET [9]. These are discussed in detail later.

Combined, land imagery and ET data can substitute for or enhance on-site measurements of irrigation in urban areas. Where irrigation use is metered, the methods can be verified; then, these validated approaches can be used to encourage more efficient irrigation use for water users as part of water efficiency programs.
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Figure 1. General approach for Analysis of Irrigation by Remote Sensing (AIRS).

3. Results and Discussion

3.1. Multispectral Imagery Data Sources

Many potentially suitable imagery products exist for the United States, including data acquired from satellites, airplanes, and drones. Their suitability for application to urban irrigation analytics depends on their spatial resolution, spectra, collection frequency, and period of record.

3.1.1. Resolution

Spatial resolution (pixel size) is critical in urban settings, where irrigated areas contain features on the order of 1 m, such as strips of grass bordering sidewalks or small planter beds with shrubs. Satellite images with 30 m resolution (e.g., Landsat) or even 10 m resolution (e.g., Sentinel-2) that are otherwise suitable for large, contiguous agricultural lands may not capture urban landscape features with sufficient detail to measure irrigated area or vegetation health. However, they may be suitable for parks, golf courses, and other open spaces found in urban areas. The National Agricultural Imagery Program (NAIP) provides images over the contiguous United States with 1 m resolution or better that, despite their intended use for agriculture, are well suited to the purpose at hand. Commercial imagery can deliver resolution down to 0.15 m and drones down to 0.01 m, but with more cost/effort and less geographic coverage.

3.1.2. Spectra

Computing vegetative indexes, such as NDVI, requires multi-spectral imagery with bands that contain the proper spectra. For example, NDVI requires red, green, blue, and near-infrared (RGBI or RGB-NIR) bands. For the best results, these should be distinct bands without overlap. Most cameras have significant overlap in the spectra collected for the red, green, and blue bands. Specialized multi-spectral cameras for remote sensing generally include more than three bands but also have narrow filters for each band [10]. NDVI is “one of the most widely used indices in the literature for vegetation cover analysis, environmental degradation, and vegetation primary production resilience” [11]. NDVI assists in monitoring “agricultural crops, forest ecosystems, and drought assessments”, as well as urban irrigation, which is the focus of this paper [11].

NDVI is computed using the near-infrared (NIR) and red (R) bands [12,13]:

\[
\text{NDVI} = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}}
\]
NDVI values range between $-1$ and $1$, with values close to 1 indicating dense vegetation and negative values indicating a body of water [11], rock, sand, or snow [1]. An NDVI value near the center of this range (0.2 to 0.5) corresponds to “sparse vegetation such as shrubs and grasslands or senescing crops” [1]. By using threshold values, NDVI (1) can differentiate between vegetated and non-vegetated pixels, thereby providing a measurement of irrigated area, and (2) can quantify the average index of the vegetated pixels, thereby indicating the relative health of vegetation in the vegetated areas.

The NDVI accuracy depends on spatial and spectral resolution. As discussed, spatial resolution is important for defining smaller areas, and it is also important for a single pixel to denote a single land cover type (i.e., vegetated or non-vegetated). While there are subpixel techniques used to estimate the percentage of land cover in one pixel, these approaches are not well suited for characterizing urban irrigation [14]. Spectral resolution also matters. If the spectral data are not calibrated, NDVI values computed from one image may not match those computed from another image. While the multispectral sensors are generally well calibrated, the atmosphere can significantly change these values. Level 2 data products from Landsat and Sentinel-2 are corrected to provide data representing reflectance at the ground surface [13]. Unlike Landsat and Sentinel-2, however, NAIP images are not corrected for reflectance, meaning that only in-scene features can be analyzed, and differences in NDVI over large areas and time periods may not be comparable [5]. The same is generally true of commercial and drone imagery. Calibration panels are often used with multi-spectral cameras mounted on drones. These panels are imaged during the collection flights and are used to correct the drone imagery. However, a recently developed pseudo-invariant near-infrared threshold (PINT) method, where NAIP imagery is compared to Landsat imagery to correct reflectance, may help address this issue [5]. While correction of NAIP imagery is not generally feasible, NDVI is less influenced by non-calibrated images, as it is computed using a band ratio rather than relying on band values.

For analyzing vegetative health associated with urban irrigation, the collection time as related to the growth period must be considered when looking at NDVI. The NDVI follows the seasonal growth pattern of the targeted vegetation, with higher values during the summer months and lower values in the winter [3]. This seasonality is more pronounced with agricultural crops and less pronounced in urban grass because grass exhibits little change in color over the growing season. In general, the NDVI associated with grass is related to water, health, and fertilizer status rather than seasonal changes. Since the NDVI values associated with grass are less sensitive to seasonal changes, in general, the main difference in NDVI is due to over- or under-watering, although fertilizer application rates may also affect the NDVI. To analyze the efficiency of urban irrigation, we used data from the irrigation and growing seasons. Many water users increase irrigation rates as the weather becomes hotter, as ET increases with temperature. Analysis during the growing season can estimate the health of the vegetation and can be used to infer whether the irrigation rates are appropriate, too low, or too high.

3.1.3. Frequency

Remote sensing collection frequency and meter reading frequency determine when we can analyze irrigation conditions, how promptly the analysis can occur, and how often it can be repeated. Landsat has a 16-day revisit time, although there are currently two active satellites providing an 8-day collection schedule. Sentinel-2 has a 5-day revisit time. This means that data from these satellites can provide measurements on the order of weekly to once every two weeks if the images are not occluded by clouds. NAIP, by contrast, is only captured once every two or three years in each state during the summer growing season. Commercial imagery products vary, and drones can provide frequent custom flights if needed.

3.1.4. History

A long historical record is useful for analyzing long-term trends and changes in an area. Landsat data are available from 1984 onward, and this long record combined with
the relatively short revisit time enables valuable longitudinal studies to be conducted. NAIP, too, has a significant record—approximately 20 years—and while infrequent and not reflectance-corrected, it may still be useful for qualitative comparisons because of its high spatial resolution. Imagery from commercial sources or drones do not support longitudinal studies but can be useful because both temporal and spatial resolutions can be specified.

3.1.5. Benefits and Limitations

The various image products have several benefits and limitations, as summarized in Table 1.

Table 1. Imagery options.

<table>
<thead>
<tr>
<th>Imagery</th>
<th>Type</th>
<th>Source</th>
<th>Resolution</th>
<th>Spectra</th>
<th>Frequency</th>
<th>History</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat</td>
<td>Satellite</td>
<td>Public (USGS)</td>
<td>30 m</td>
<td>4 band (RGB-NIR)</td>
<td>8-16 days</td>
<td>1984-present</td>
<td>Long history, frequent readings, large area</td>
<td>Low resolution</td>
</tr>
<tr>
<td>Sentinel-2</td>
<td>Satellite</td>
<td>Public (ESA)</td>
<td>10 m</td>
<td>4 band (RGB-NIR)</td>
<td>5 days</td>
<td>2015-2022</td>
<td>Frequent readings, large area</td>
<td>Medium resolution, difficult access</td>
</tr>
<tr>
<td>NAIP</td>
<td>Aerial</td>
<td>Public (USGS)</td>
<td>0.3–1.0 m</td>
<td>4 band (RGB-NIR)</td>
<td>2–3 years</td>
<td>2003–present</td>
<td>High resolution, large area, no cloud cover</td>
<td>Infrequent collections, historical consistency, reflectance not corrected</td>
</tr>
<tr>
<td>Commercial imagery</td>
<td>Aerial</td>
<td>Private</td>
<td>0.15–1.0 m</td>
<td>Varies</td>
<td>Varies</td>
<td>Varies</td>
<td>High resolution, custom study areas, advanced spectra</td>
<td>Licensing, historical consistency (various providers)</td>
</tr>
<tr>
<td>Drones</td>
<td>Aerial</td>
<td>Private</td>
<td>&gt;0.01 m</td>
<td>Varies</td>
<td>As needed</td>
<td>N/A</td>
<td>High resolution, custom study areas, multiple flights, custom instrumentation and spectra</td>
<td>Expensive equipment or contracts, special software, much data, historical consistency, small study areas</td>
</tr>
</tbody>
</table>

Landsat has a long history, large geographic coverage, and frequent readings (16 days, with approximate 8-day resolution since Landsat 8 in the 1990s). However, the 30 m spatial resolution of Landsat images is generally too coarse for irrigation analysis in many urban settings, although, as discussed above, it may be useful in parks, golf courses, and other large, contiguous open spaces. The dataset is publicly accessible and will likely continue for several years. The USGS provides a calibrated Landsat Level 2 surface reflectance product, which means that the NDVI or other indexes computed using Landsat data can be compared in both time and space. A limitation, however, of the use of Landsat imagery is the inconsistency of capturing images with low cloud cover [15,16]. Nezry et al. [17] calculated the probability of acquiring an image with less than 70% cloud cover during a given year using Landsat MSS, Landsat TM, or SPOT-HRV imagery to be 26%. This inconsistency is a significant challenge for these imagery sources.

Sentinel-2 has finer resolution (10 m) and more frequent readings (5 days) than Landsat but a shorter history. Its images may be appropriate for irrigation analysis in urban settings with the understanding that they may not capture some details, but with the benefit that more timely analysis is possible. Downloading Sentinel-2 data has also become more difficult since the USGS stopped providing downloads. However, downloads can still be made through the European Space Agency (ESA) and Google Earth Engine (GEE) [18].

We determined that NAIP is the best option for publicly available, high-resolution (0.3–1.0 m) four-band imagery suitable for municipal irrigation analysis. It also has a fairly long record and is likely to continue. Unfortunately, it is only available every two or three years, precluding timely analysis, and is not reflectance-corrected, limiting historical and geographic comparisons. In addition, data are not always collected during the same time in the growing season, making historical analysis difficult. However, because it is aerial imagery and not satellite imagery, images will not be altered by cloud cover. This allows for the collection of unobscured images.

A benefit of using Landsat, Sentinel-2, and NAIP imagery is that Google Earth Engine can be used to analyze their geospatial data. GEE is free for non-commercial use and non-profit projects, like academia, news media, indigenous governments, and government
research [19]. GEE centralizes the source of spatial imagery and allows users to analyze the data collected within that image.

Commercial imagery can deliver very high-resolution data, often down to 0.15 m, but is limited by smaller geographic areas, data subscriptions, historical consistency, and the general variability among the several private vendors.

Aerial drones are ideal for special investigations requiring high-resolution imagery (down to 0.01 m), custom flights, multiple flights, and/or particular spectra or instruments. Both fixed-wing and multi-rotor aircraft have successfully captured sufficient imagery for the type of analysis discussed here. Fixed-wing aircraft can cover larger areas, fly faster, and run longer [20], while multi-rotor aircraft are more affordable, more customizable, and easier to operate. Investments for equipment, software, training, and licensing is required if one desires to develop in-house drone capacity; funding is required if one needs to contract such services to outside vendors. Another requirement for processing aerial drone images is storage capacity and processing power, as even images taken of a small geographical area can be space-intensive. This is a limitation of using drone-collected imagery, as it is not feasible to collect high-resolution images of large areas.

A disadvantage of remote sensing modeling is the unpredictability of capturing quality data at the scheduled passing of the satellite. With the gaps between satellites capturing data as well as cloud cover, it is difficult to collect consistent high-quality data samples [21,22]. This is important to remember when searching for data on specific dates. A method to assist with this problem involves using data from several different satellites to find the data needed for the desired time period. This is not a fix-all solution, however, as not all satellites may capture the desired imagery resolution and spectra.

Although satellites and drones appear to be competitors in terms of the products they provide, it is beneficial to use them together. In remote sensing, it is important for ground-truth to validate that the satellite images are accurate. Ground truthing consists of gathering reference data of what is currently on the Earth’s surface and comparing them to previously collected images. Drone images can be used to ground-truth previously collected satellite and aerial images as an alternative to traditional field-based ground truthing, which is cost- and labor-intensive and often inaccurate [23]. Instead of using drones over a large area as the primary source of data collection, previously collected satellite or aerial images can be used as the primary source, while drone imagery can be used to ground-truth over a small area.

3.2. Evapotranspiration Data Sources

Remote sensing imagery becomes effective in estimating irrigation demand when it is paired with evapotranspiration data. Evapotranspiration (ET) data can address a variety of problems, including ecosystem conservation, monitoring of protected areas, and water consumption assessment. Regarding water consumption assessment, the ET from crops can track the depletion of groundwater resources for water-scarce regions [24]. As with remote sensing imagery, there is unpredictability in capturing quality evapotranspiration data due to overpass schedules and cloud cover.

For our application, we will use ET data to calculate the volume of water needed to irrigate the area. ET data is collected by satellites and processed using models which improve accuracy by correcting issues in the data. Some of these satellites include Landsat and Sentinel-2 satellites as mentioned above. Two more satellites that are used for ET data collection are the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS).

MODIS is an instrument aboard the Terra (EOS AM-1) and Aqua (EOS PM-1) satellites. With their respective rotation patterns, they view Earth’s surface every 1 to 2 days and acquire 36 spectral bands [25,26]. The project was initiated by NASA and EOS to estimate global terrestrial evaporation from Earth’s land surface with the intent of measuring the effects of changes in climate, land use, and ecosystem disturbances on regional water resources [27]. MODIS has undergone several version updates since its launch in December.
1999. As of October 2022, MODIS version 6 has been decommissioned and replaced by VIIRS, which provides similar data to MODIS but with a higher spatial resolution (350 m and 750 m versus 500 m and 1000 m) [28].

In preparation for the retirement of MODIS, VIIRS was developed by Raytheon as a part of the Joint Polar Satellite Systems in October 2011. The system was developed for NASA and the National Oceanic and Atmospheric Administration (NOAA) and provides full global coverage twice daily [26].

The following models take ET data from MODIS, VIIRS, and other satellites and improve the accuracy of the data. Table 2 summarizes their benefits and limitations.

Table 2. Evapotranspiration data options.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Data Sources</th>
<th>Available Dates</th>
<th>Resolution</th>
<th>Frequency</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLDAS</td>
<td>NASA</td>
<td>1948–present</td>
<td>1000 m</td>
<td>48 days</td>
<td>Long history</td>
<td>Low resolution</td>
</tr>
<tr>
<td>CFS</td>
<td>NOAA</td>
<td>April 2011–present</td>
<td>56,000 m</td>
<td>Hourly</td>
<td>High frequency</td>
<td>Limited historical data; low resolution</td>
</tr>
<tr>
<td>SSEBop</td>
<td>NASA</td>
<td>January 2003–present</td>
<td>~1000 m</td>
<td>1 time/month</td>
<td>Visually interpretable</td>
<td>Low frequency; no quantitative data</td>
</tr>
<tr>
<td>OpenET</td>
<td>USGS</td>
<td>2016–present</td>
<td>30 m</td>
<td>1 time/day</td>
<td>User-friendly, multiple sources, high resolution</td>
<td>Limited historical data</td>
</tr>
<tr>
<td>GloDET</td>
<td>NASA, NOAA</td>
<td>2013–January 2021</td>
<td>375 m</td>
<td>2 times/day</td>
<td>User-friendly</td>
<td>Limited historical data; no current data</td>
</tr>
</tbody>
</table>

3.2.1. GLDAS

The Global Land Data Assimilation System (GLDAS) was created by NASA with the goal of generating “optimal fields of land surface states and fluxes” using land surface models and data-gathering techniques [9]. The results are given within 48 h of observation, allowing for almost real-time tracking of data from 1948 to the present. The vegetation dataset is globally representative and has a spatial resolution of 1 km. Along with ET data, GLDAS provides data on snow cover and water equivalent, soil moisture, surface temperature, and leaf area index [29].

3.2.2. CFS

The Climate Forecast System (CFS) was created by NOAA and is a global model that forecasts Earth’s climate. It produces hourly data with 56 km resolution, as modeled by re-forecasts of previous weather events from 1979 to 2011. CFS has been providing forecasts from April 2011 to the present [30].

3.2.3. SSEBop

The Operational Simplified Surface Energy Balance (SSEBop) uses Landsat and MODIS data to provide a model with evapotranspiration estimates [12,13]. It is an image service created by USGS, derived from MODIS data to provide daily, monthly, 8-day, yearly, and seasonal images from January 2003 to the present with a 0.01 degree (about 1 km) spatial resolution. Its purpose is for the overall demonstration of landscape changes between dry and rainy seasons. The service helps users to see an overview of vegetation changes and download data at their timesteps of choice [24].

3.2.4. OpenET

Similar to SSEBop, OpenET uses data from multiple satellites to calculate a single estimated ET value based on several models. There are currently six models that OpenET uses, including EEMETRIC, SSEBop, SIMS, PT-LPL, DisALEXI, and geeSEBAL, with most of them being based on the surface energy balance (SEB) approach. The SEB approach uses satellite measurement to account for the energy used to transform the liquid in plants and soil into released atmospheric vapor. The spatial resolution of these data is 30 m, as provided by Landsat. It provides data from 2016 to the present, including daily, weekly,
and monthly estimates, with plans to include more historical data in the near future [31]. The models and data have limitations during times of consistent and dense cloud cover and when analyzing areas with complex topography [32]. Some models also have “systematic low bias for smaller agricultural areas in very arid regions”, which is a problem that OpenET plans to address in the coming months [33]. OpenET’s goal is to provide consistent and easily accessible data to assist in the development of water budgets, groundwater management programs, water trading programs, and irrigation practices [31]. The interface of OpenET is easy to use and provides quantitative data.

3.2.5. GloDET

Global Daily Evapo-Transpiration (GloDET) is similar to OpenET in that it is a portal to view and download daily ET spatial datasets. It was created by the University of Nebraska and uses one of the six models used by OpenET, the Atmosphere–Land Exchange Inverse (ALEXI) model. With data provided by MODIS/VIIRS, it produces data with a 375 m resolution from 2013 to January 2021. Its purpose is to provide information on daily crop water use in inches or millimeters per day [21,22].

3.2.6. Local Models

Some jurisdictions maintain their own ET datasets. Idaho has Mapping EvapoTranspiration using high Resolution and Internalized Calibration (METRIC), and Utah has GridET [34,35]. By using customized models, it is easier to retrieve data and add other applications suited to the region. For example, the California Simulation of Evapotranspiration of Applied Water (Cal-SIMETAW) uses ET and precipitation information to generate potential water-balance irrigation schedules [36]. This system also accounts for weather forecasts and their impacts on water demand.

3.3. Municipal Water Use Data Sources

Managing urban irrigation is most effective when all customer end-uses are metered. Despite the advantages of the remote approaches described above (namely, automation, scalability, and consistency), when water volume is the variable in question, on-site measurements are still the most accurate.

Some municipal water suppliers serve irrigation in separate systems from drinking water, thereby removing the need for assumptions about indoor/outdoor partitioning and seasonality that are necessary when both uses are combined. When such systems are fully metered on the customer side, it is possible—and desirable—to analyze the water use in concert with the remote sensing approaches described above. The process requires matching up water bills, parcels, irrigated area, and NDVI to provide a complete portrait of water use, landscape size, and vegetation quality on each customer’s property. When irrigation end-use data are available at the customer level, connections between water use and lot size, customer segments, user behavior, climate, and location are easier to find and explain, and implications for water management become much more apparent and useful. Shurtz et al. [7] did just this in two Utah communities and found very practical insights that have since been shared with water managers and landscape professionals.

Data availability for this type of analysis depends entirely on the local water supplier because there is not yet a national database of urban water uses [37]. Communities with fully or partially metered irrigation systems have much to gain from embracing remote sensing methods, even using the publicly available sources. We encourage state regulators to inventory public water suppliers that have such metered irrigation systems, and we encourage those suppliers to follow the path of Shurtz et al. [7] and explore irrigation performance by matching water bills with four-band imagery in their own service areas. Even if a particular water supplier does not have the required metering capabilities, a neighboring one might, and a joint or regional study could benefit everyone involved.
3.4. Case Study

It is important that one uses the combination of ET and spatial data that best addresses the task at hand. In this case study, we calculated the volume of water necessary to maintain plant health according to a few of the ET and spatial data options listed above. We analyzed the same area, as recorded from Landsat and NAIP images taken three days apart (9 and 11 September 2018), as shown in Figure 2. No filters or enhancements were used on the images. We estimated the irrigated area by deciding which NDVI value was the boundary between irrigated and non-irrigated areas (Figure 3) and then multiplying the number of pixels by the area of each pixel. We then multiplied the irrigated area by the actual ET water depth, as found by OpenET for that area. Because the ET value is representative of the entire study area, individual vegetation types within the study area were not identified. The water needed to meet the needs of the study area, therefore, is assumed to be uniform across the irrigation areas.

Figure 2. Images of Cedar Hills, Utah. (a) NAIP from 11 September 2018 and (b) its corresponding NDVI. (c) Landsat from 9 September 2018 and (d) its corresponding NDVI.

Figure 3. Difference in NDVI thresholds for distinguishing between irrigated and non-irrigated areas. (a) NDVI derived from NAIP (Figure 2a); threshold: 0.37. (b) NDVI derived from Landsat (Figure 2c); threshold: 0.29. Both panels overlay a NAIP aerial image.
The two approaches produced different results (Table 3). The Landsat approach identified about three times as much irrigated area as the finer NAIP approach. Because the images were taken just three days apart and NAIP has a much higher resolution, we can rely on the NAIP estimate of the area. The difference in date led to a difference in ET of about 33%. Together, the Landsat image and ET data for 9 September 2018 suggest a water volume of 911 m³, while the NAIP image and ET data recorded two days later suggest just 173 m³.

Table 3. Calculated values from NAIP and Landsat images.

<table>
<thead>
<tr>
<th>Calculated Values</th>
<th>NAIP</th>
<th>Landsat</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI Vegetated Area Threshold</td>
<td>0.37</td>
<td>0.29</td>
</tr>
<tr>
<td>Number of Pixels</td>
<td>209,842</td>
<td>332</td>
</tr>
<tr>
<td>Irrigation Area (m²)</td>
<td>75,543</td>
<td>298,800</td>
</tr>
<tr>
<td>Average NDVI for Irrigated Area</td>
<td>0.28</td>
<td>0.31</td>
</tr>
<tr>
<td>Water Depth from OpenET (m)</td>
<td>0.002286</td>
<td>0.003048</td>
</tr>
<tr>
<td>Water Volume (m³)</td>
<td>173</td>
<td>911</td>
</tr>
</tbody>
</table>

When analyzing coarse images, the largest source of uncertainty and error is the choice of NDVI threshold for irrigated and non-irrigated areas. Figure 4 compares the Landsat-derived NDVI with thresholds of 0.28 and 0.30. Several trees were excluded at 0.28 that were included at 0.30, but 0.30 also picked up considerable infrastructure. Choosing a threshold, therefore, (1) influences the resulting irrigated area and (2) is a source of bias. To prevent inaccuracy and reduce subjectivity, we caution against using coarse imagery for such applications. Similar errors have been found by other studies using Landsat imagery; because of its large pixel size, using Landsat images overestimates the irrigated area [15].

![Figure 4. NDVI threshold comparison. NDVI derived from Landsat (overlaying NAIP aerial image) with (a) threshold of 0.28 and (b) a threshold value of 0.30. Pixels added between 0.28 and 0.30 are shown in orange in (b). The selected threshold value influences the irrigated area calculation and should be based on finer imagery where possible.](image)

4. Conclusions

Urban irrigation suffers from several measurement and management gaps that hinder sustainable water use. With the wide range of imagery and evapotranspiration data now available via remote sensing, there are many options and combinations of methods to enhance urban irrigation analytics. This paper catalogued the options and discussed the tradeoffs.

The choice of spatial imagery will depend on the needs of the project. For analyzing small geographical areas (on the scale of individual properties), we recommend drones, which can achieve high-resolution images (>0.01 m), custom study areas, multiple flights,
and custom spectra; the tradeoff is expense and effort. For analyzing large geographic areas in high resolution on a specific future date, we recommend commercial imagery (i.e., from a low-flying airplane) that would provide images without cloud cover on the date and at the time of choice; this would require planning and funding. For analyzing large geographical areas with limited funding, we recommend NAIP, which provides biannual or triannual historic snapshots at 0.3–1.0 m resolution. For analyzing historical time series, we recommend Landsat because its data collection process began earlier than that of the others; however, its resolution is much lower and may not be suitable for small, irrigated areas.

Regarding ET data, as with spatial imagery, the best source of information depends on the needs of the project. In the absence of specific project constraints, we recommend using OpenET, which is user-friendly and provides ET calculations for the six major ET models, as well as an ensemble model of its own.

For analyzing recent water use and vegetative health snapshots on a limited budget, we recommend using NAIP for spatial imagery, OpenET for evapotranspiration data, and municipal water metering data to determine water use, vegetation quality, and general irrigation efficiency in urban areas.

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