Landscape and Urban Planning 214 (2021) 104178

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Building to conserve: Quantifying the outdoor water savings of residential redevelopment in Denver, Colorado

Kyle Blount [a,*], Reza Abdi [b], Chelsea L. Panos [b], Newsha K. Ajami [c], Terri S. Hogue [b,*]

[a] Hydrologic Science and Engineering, Colorado School of Mines, Golden, CO 80401, USA
[b] Civil and Environmental Engineering, Colorado School of Mines, Golden, CO 80401, USA
[c] Woods Institute for the Environment, Stanford University, Stanford, CA, 94305, USA

HIGHLIGHTS

- A novel framework for evaluating redevelopment and water demand is presented.
- Mean single-family irrigation rates exceeded multi-family rates by 46% in 2018.
- Modeled redevelopment of single-family parcels reduced residential outdoor demand.
- Infill may help offset climate change-driven increases in urban water demand.
- Combining land and water use in urban planning can yield significant water savings.

ARTICLE INFO

Keywords:
Outdoor water use
Urban redevelopment
Urban irrigation
Infill development
Land use planning
Denver, Colorado

ABSTRACT

Outdoor water use represents up to half of total urban water demand in many semi-arid and arid cities and presents a climate adaptation challenge in urban centers. As indoor efficiency and reuse improves, outdoor use amounts to an increasingly large portion of consumptive urban water demand. Infill development, or the redevelopment of single-family properties to more dense multi-family and mixed-use developments, is a growing trend in urban planning; however, the influences of infill on outdoor water demand are poorly understood. The current work utilizes a remote sensing-based methodology to calculate parcel-scale irrigation rates in Denver, Colorado and applies a novel resampling methodology to model the impacts of redevelopment on outdoor water use. Results for 2018 showed irrigation rates varied by almost 250 mm between park and commercial land uses, and mean single-family irrigation rates of 224 mm exceeded multi-family rates by 70 mm. In the Berkeley neighborhood, modeled redevelopment of 1,347 single-family parcels (39.5%) resulted in a 102,000 m^3 (83 acre-feet, or 30.2%) reduction in outdoor use. Citywide analyses indicate reductions of 141,000 m^3 (114 acre-feet, or 0.76%) of residential outdoor use per one percent increase in redeveloped single-family parcels. These savings are equivalent to new annual supply for 181 four-person households and may provide significant contributions towards climate adaptation. Results highlight the importance of the continued integration of land use and water supply for demand management within the urban planning process.

1. Introduction

Outdoor water use represents a significant portion of urban water demand, especially in semi-arid and arid climates. Across the continental United States, irrigated turfgrasses are the largest cultivated crop, occupying approximately two percent of land area and three times more land than the next largest single crop (Harrington, 2016; Milesi et al., 2005). In the western U.S., outdoor use to irrigate turfgrasses and other urban vegetation makes up 40–70% of total water use (Hogue & Pincetl, 2015), and evapotranspiration (ET) from irrigated turfgrass occurs at rates near potential ET indicating that these surfaces are well-watered (Litvak, Manago, Hogue, & Pataki, 2017). In Los Angeles, unshaded turfgrass irrigation frequently exceeds recommended irrigation rates by 40%, which corresponds to a 114 L (30 gallons) per day excess for a

* Corresponding authors.
E-mail addresses: wkblount@mymail.mines.edu (K. Blount), rabdi@mines.edu (R. Abdi), cpanos@mines.edu (C.L. Panos), newsha@stanford.edu (N.K. Ajami), thogue@mines.edu (T.S. Hogue).

https://doi.org/10.1016/j.landurbplan.2021.104178
Received 29 August 2020; Received in revised form 20 April 2021; Accepted 14 June 2021
Available online 5 July 2021

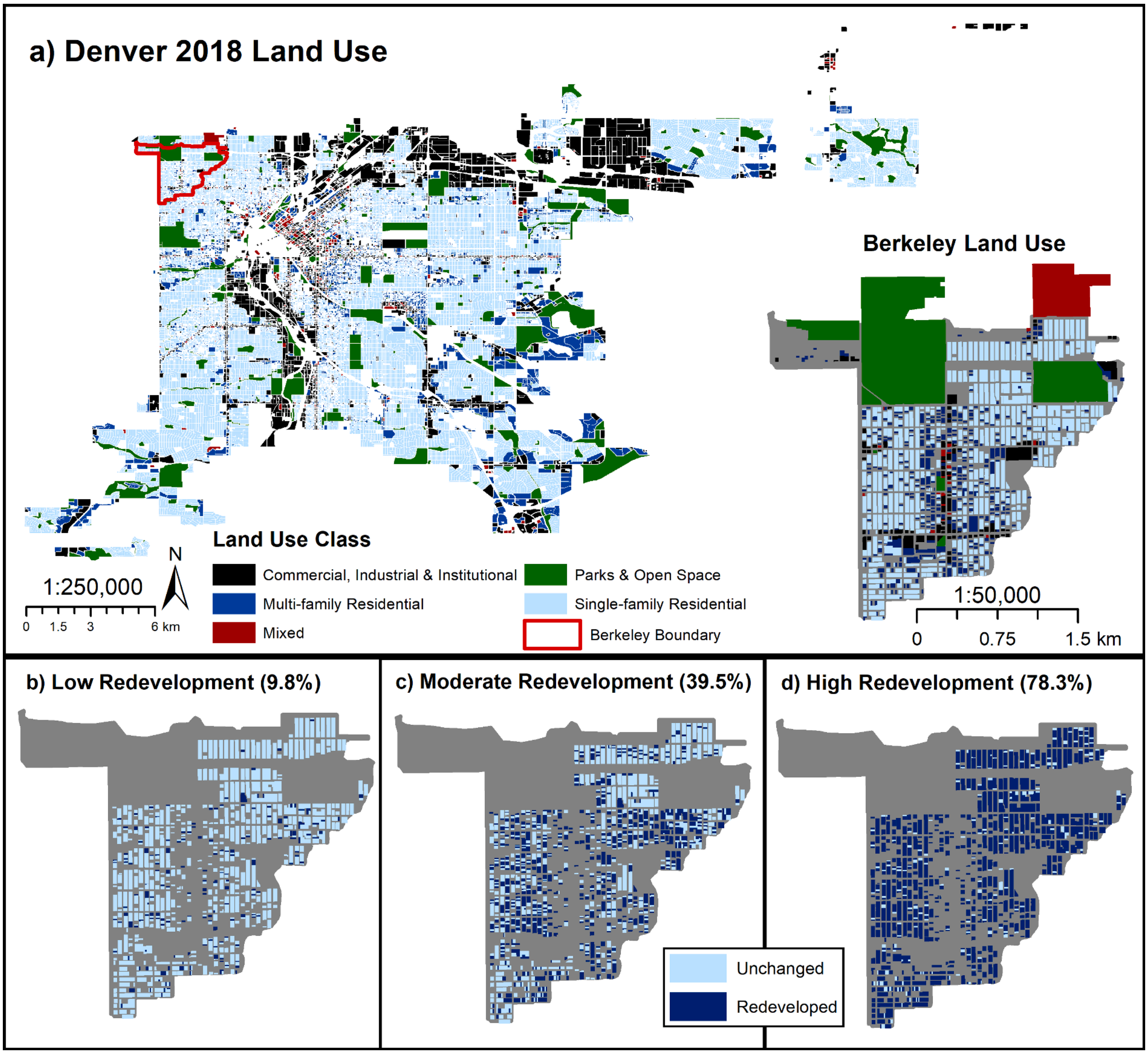

Fig. 1. Parcel-level land use classification and Berkeley redevelopment scenarios. Panel a) shows citywide existing land use in 2018, the extent of the Berkeley neighborhood sewershed within Denver, and the distribution of land use classes in the Berkeley neighborhood. Panels b), c), and d) show the scenarios for low, moderate, and high redevelopment in the Berkeley neighborhood, respectively. These scenarios correspond to 9.8%, 39.5%, and 78.3% of SFR parcels being redeveloped into the MFR land use.

typical residential lawn, or 56,800 m^3 (15 million gallons) citywide (Litvak & Pataki, 2016). However, turfgrass shading by trees can reduce water use by up to 50% (Shashua-Bar, Pearlmutter, & Erell, 2009). Residential land uses, including single-family residential (SFR) and multi-family residential (MFR), comprise significant portions of outdoor demand (Denver Water, 2019a; U.S. EPA, 2013). In Denver, Colorado, outdoor water use represented 40% of total annual demand in 2010 (Colorado Water Conservation Board, 2016), and SFR irrigation represents approximately 23.5% of total demand (Denver Water, 2019b).

Outdoor use presents a significant climate adaptation challenge for cities in water scarce regions and an increasingly important target of water conservation efforts. Anthropogenic climate change is projected to influence both water supplies and outdoor water demand, especially in semi-arid and arid cities (Blount, Wolfand, Bell, Ajami, & Hogue, 2021; Gober, Quay, & Larson, 2016; Lukas, Barsugli, Doeksen, Rangwala, & Wolter, 2014). Increasing temperatures and altered precipitation patterns are projected to reduce the reliability of water supplies and potentially decrease total supplies in the western U.S. Simultaneously, Pickard, Nash, Baynes, & Mehaffey (2017) predict increasing water demand across urban centers in the U.S., including more than a 50% increase in demand in several counties surrounding Denver by 2060. Increased temperatures are also projected to drive increases in demand for outdoor water use in existing developments (Blount et al., 2021; Breyer, Chang, & Parandvash, 2012), without considering new demand from current and future development in these urban regions. While significant improvements have been made toward indoor efficiency in the urban water sector (DeOreo, Mayer, Dziegielewski, & Kiefer, 2016), the consumptive nature of outdoor use and its relationship to climate change make it a growing challenge for water resource managers (Gober et al., 2016). Similarly, many cities are increasing their wastewater reuse as a source of new supply, which reduces consumptive indoor demand and increases the portion of consumptive demand represented by outdoor use (Blount et al., 2021; Landers, 2019).

To promote water conservation, development policy and urban planning efforts are focusing on achieving water conservation through land use planning globally (Bates, 2012; Blanchard, 2018; Mitchell, 2005). In the context of the study site, Colorado's State Water Plan (Colorado Water Conservation Board, 2016) sets the goal that 75% of Coloradans will live in communities that have integrated saving measures into land use planning by 2025. While the State Water Plan identifies outdoor use as a significant source of conservation potential, specific guidance for land use planning is lacking; instead, the plan focuses on removing legal and financial barriers, implementing more efficient technologies, and implementing low water use, or xeric, landscaping practices (Gilliom, 2020). Similarly, guidance documents focus on institutional and legal barriers to integrating land use and water planning but do not provide quantitative summaries of the benefits of increased density (Blanchard, 2018). Despite a growing focus on combining landscape and water planning and removing institutional barriers, little progress has been made toward wide-scale integration. For example, a review of Australian case studies highlights that only 15% of land and water planning documents consider both land use and water together (Serrao-Neumann, Renouf, Kenway, & Choy, 2017).

While these efforts lay out important steps for the implementation of outdoor conservation efforts, they provide little guidance for specific development policies to achieve this end. Land use planning and development policy focused on the types and location of development may provide important paths and specific recommendations for reducing outdoor demand beyond promoting low-water-use landscapes. Redevelopment, or infill development, provides an opportunity to reduce urban sprawl as vacant or underutilized parcels are developed, increasing urban density and providing economic revitalization (McConnell & Wiley, 2010). The terms redevelopment, infill development, and infill are often used to describe the same phenomenon, and this study uses these terms interchangeably. These urban transitions are frequently characterized by the transition of SFR residential properties with large irrigated lawn areas to MFR residential properties with increased impervious area and decreased lawn area (Panos, Hogue, Gilliom, & McCray, 2018). Reductions of lawn area associated with infill are likely accompanied by decreases to outdoor water demand (Gilliom, 2020), and large-scale implementation of infill projects may provide an opportunity to achieve demand reduction for large urban water systems.

Several studies have shown that density and urban form can influence water use patterns. Sanchez, Smith, Terando, Sun, & Meentemeyer (2018) show that spatial patterns of development better account for variations in total water use than socio-economic, environmental, and climatic factors in North and South Carolina. They find that more densely clumped infill and higher density developments in simple, aggregated forms may provide for growth patterns that maximize the efficiency of water use. In Salt Lake City, Utah, Stoker and Rothfeder (2014) observe higher total annual water use within commercial land uses than in residential land use classes and suggest the use of form-based zoning codes to promote water conservation in new developments. In Portland, Oregon, over 93% of total water use can be explained by land use building area, and the authors note that growing calls for integrated land use and water planning have yet to result in significant examination of urban form and development patterns on water consumption (Shandas & Parandvash, 2010). Polebitski, Palmer, & Waddell (2011) used an urban simulation model to predict changes to SFR variables in Seattle, Washington, and evaluate their effects on total water demand with previously identified multiple regressions for the Puget Sound Region. They show that MFR properties have less outdoor use and exhibit lower seasonality than SFR properties and project that changes in building characteristics and urban density will decrease total and summer water use. Polebitski et al. (2011) note the contribution of outdoor use as a driver of SFR water demand despite Seattle having some of the lowest outdoor water use rates in the United States. Previous studies have also identified relationships between outdoor water use and socio-demographic variables and the influence of drought restrictions (Mini, Hogue, & Pincetl, 2014, 2015; Quesnel & Ajami, 2019).

Redevelopment provides opportunities to reduce outdoor demand and improve the resilience of urban water systems. However, there is a paucity of literature that explicitly examines the influences of land use or redevelopment on outdoor water demand. This study aims to quantify the relationship between urban development and outdoor water use to better inform the integration of land use and water planning for improved water conservation. Remote sensing-derived parcel-scale irrigation data are evaluated for 2018 in Denver, Colorado to answer the following research questions: (1) *To what degree does outdoor water use vary between land use types?* and (2) *What are the cumulative effects of increased residential density due to redevelopment of single-family residences on outdoor water use?*

2. Study site

2.1. Denver and the Berkeley neighborhood

The City and County of Denver, Colorado (Fig. 1a) covers 401.4 km^2 and was home to an estimated population of 716,492 in 2018 (U.S. Census Bureau, 2019). The city has an annual population growth rate of 1.6% since 2010 (Murray, 2019). From 2010 to 2018, the population served by Denver Water grew by 181,000, the total annual treated water consumption varied between 227 and 273 million m^3 (60,000 and 72,000 million gallons), and daily per capita water use decreased by approximately 0.11 m^3 (30 gallons) (Denver Water, 2019a). Denver has a cold, semi-arid (steppe) climate (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), with a mean annual temperature of 10.3 °C, a mean annual precipitation of 363 mm (National Weather Service, 2018), and an annual potential ET of 1.28 m (Abatzoglou, Dobrowski, Parks, & Hegewisch, 2018). Average annual snowfall of 1.45 m occurs between October 18–April 28 (National Weather Service, n.d.), and irrigation typically occurs from May through October (Denver Parks & Recreation, 2016). Significantly increasing temperatures, projected alterations to snowmelt timing and peak runoff, and decreasing snowpack are threatening reductions in surface water availability (Lukas et al., 2014), and more frequent water shortages a (Brown, Mahat, & Ramirez, 2019).

The Berkeley neighborhood is located in northwest Denver and occupies 4.8 km^2. It is home to approximately 11,000 people and comprised of 53% impervious area as of 2014 (Panos et al., 2018). Berkeley contains 30.7% single-family, 17.8% parks and open space, 7.9% multi-family, 3.9% commercial, industrial, and institutional, and 0.3% mixed land uses by area in 2018. In the last decade, extensive infill development has begun within the neighborhood (Cherry et al., 2019), making this an ideal location for a case study on the effects of redevelopment at the local scale.

2.2. Redevelopment scenarios

This study builds upon previous work by Cherry et al. (2019) and Panos et al. (2018) that evaluate infill in the Berkeley neighborhood to assess redevelopment scenarios. Cherry et al. (2019) estimated redevelopment probabilities for all parcels in the Berkeley neighborhood based on a linear regression of changes in building area coverage and a logistic regression of parcel characteristics including total value, year built, percent difference between current and maximum building cover, and parcel use classification. Panos et al. (2018) applied these probabilities to evaluate redevelopment scenarios and their impacts on runoff and stormwater management in the Berkeley neighborhood.

Using these same probability thresholds of 0.3, 0.2, and 0.1 from Panos et al. (2018), the current work evaluates three redevelopment scenarios – low, moderate, and high, respectively (Fig. 1b, c, d) – to assess the impact of infill on water use. Because the scope of the current work considers infill development of residential properties and because redevelopment of SFR parcels comprises a majority of redevelopment in the Berkeley neighborhood (81–82% in all three scenarios), only SFR parcels are projected to redevelop in each scenario. The low, moderate, and high scenarios correspond to 9.8%, 39.5%, and 78.3% of SFR parcels redeveloped, respectively. These values provide a wide range of redevelopment possibilities to evaluate potential impacts on outdoor water use. Citywide redevelopment scenarios use the same percentages of SFR conversion as the Berkeley scenarios.

Table 1
Summary of Denver parcel-level characteristics and data by land use type.

Land Use	Parcels (n)	Post-cleaning parcels (n)	Mean Area (m^2)	Median Area (m^2)	Impervious Cover (%)	Mean 2018 Irrigation (mm)
CII	8013	7430	4816	1379	75.4	26.0
MFR	29,453	14,843	843	163	54.5	153.7
MIX	727	517	3374	895	62.8	66.7
PKO	794	696	35,631	7380	10.4	270.9
SFR	133,475	125,500	605	579	37.2	223.9

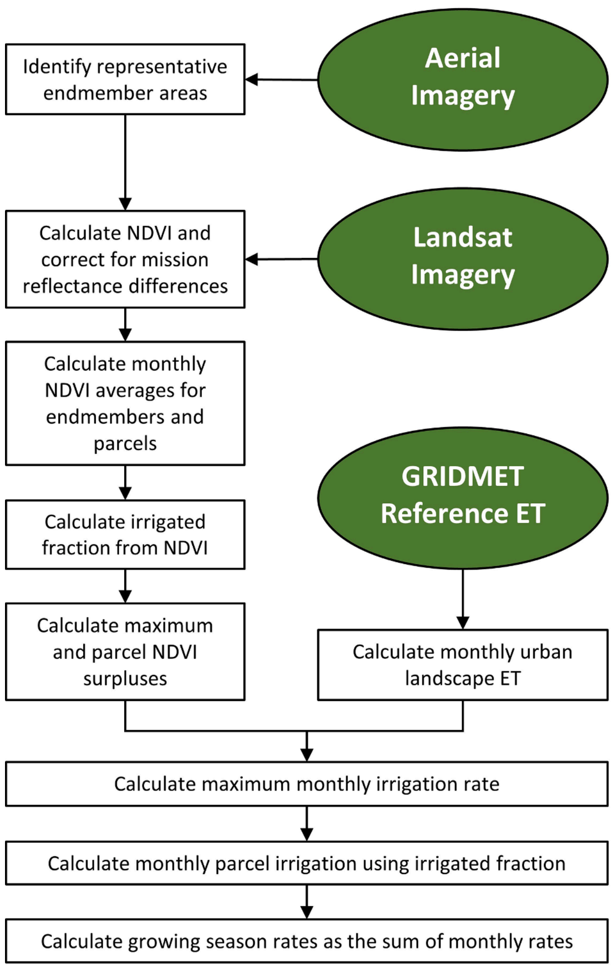

Fig. 2. Flowchart of the remote sensing-based methodology for calculating parcel irrigation rates
adapted from Blount et al. (2021).

3. Data

3.1. Existing land use in 2018

Parcel-level data were obtained as a shapefile from the Denver Open Data Catalog for 2018 (City and County of Denver, 2019). These data are classified into 16 land uses. Because this study focuses on residential redevelopment, these data were reclassified into five groups (Table 1). These classes are (original classes in parentheses): Commercial, Industrial, and Institutional (CII; Commercial/Retail, Industrial, and Office), Mixed (MIX; Mixed-use), Multi-family residential (MFR; Multi-unit residential and two-unit residential), Single-family residential (SFR; Single-unit residential), and Parks and Open Space (PKO; Parks/Open space). The Agriculture, Entertainment/Cultural, Parking, Public/Quasi-Public, ROW/Road, Transportation/Communication/Utilities, Other/Unknown, and Vacant classes were excluded.

Because the 30 m pixels of Landsat imagery used to calculate parcel-level irrigation rates often overlap more than one parcel, a buffer was applied to reduce the effects of mixed-land use pixels on final irrigation calculations. Landsat pixels were used to calculate irrigation rates for a parcel if the centroid of the pixel, 15 m from each edge of the pixel, fell within that parcel. For each land use class, a 15 m buffer was created around parcels of all other classes, and those parcels which intersect the buffer, or were within 15 m of a parcel of differing land use, were removed. The application of a buffer ensures that pixels containing mixed-land uses were excluded from calculations of irrigation rates and that spectral contributions to the calculation of parcel-level irrigation values were obtained from Landsat pixels comprised entirely of the same land use class.

3.2. Landsat data

Landsat 8 (OLI) Tier 1 Surface Reflectance data were processed in Google Earth Engine to obtain 30 m resolution Normalized Difference Vegetation Index (NDVI) data for irrigated, non-irrigated, and impervious endmembers in the Denver metropolitan region and each parcel for the 2018 growing season (Gorelick et al., 2017; Vermote, Justice, Claverie, & Franch, 2016). NDVI is a measure of the "greenness" of the land surface and is calculated from the near infrared and red reflectance of the scene. NDVI is related to vegetative parameters, providing information of vegetation health, abundance, leaf area, biomass, and productivity (Hunt, 1994). Landsat 8 has a 16-day return period, and each image from May 1, 2018 – October 31, 2018 was masked for clouds, shadows, water, and missing data before calculating NDVI values. NDVI values were used to calculate irrigation rates for 2018 (Section 4.1).

3.3. Tax Assessor's property characteristics

To characterize differences between parcels within the same land use class and account for built environment variables, the Real Property Residential Characteristics data were obtained from the City and County of Denver Assessment Division (2020). For SFR and MFR properties, the following property characteristics were joined to irrigation rates for each parcel: number of buildings, property class, impervious area, number of stories, basement area, number of bedrooms, year built, year remodeled, number of units, total value, and land value. The land area from the property characteristics data was replaced by the land area calculated from the parcel shapefile, which was determined to provide a more accurate representation of parcel area.

3.4. Land cover data

Impervious land cover data were used to characterize the built environment of each parcel. Percent Developed Impervious data were obtained from the National Land Cover Database (NLCD) for 2016 (L. Yang et al., 2018). Area-weighted averages of percent imperviousness were calculated for each parcel and joined to irrigation and property characteristics data.

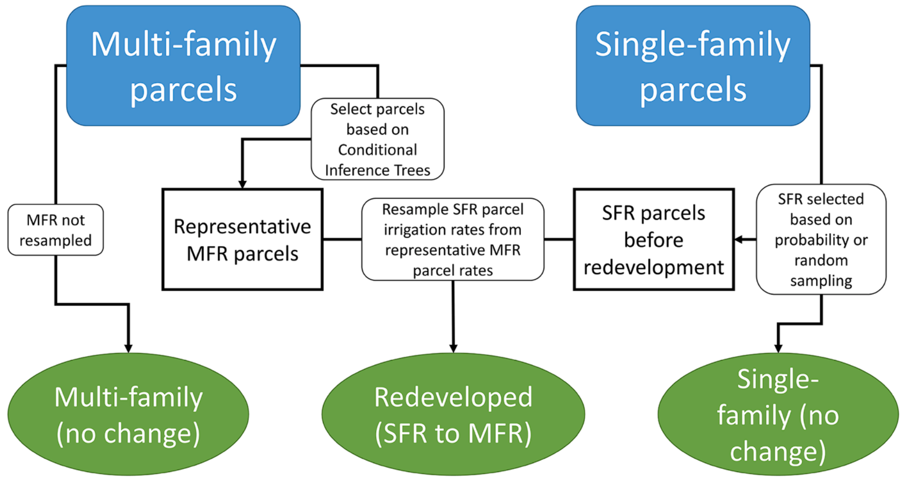

Fig. 3. Flowchart for the resampling methodology. Input data are shown in blue squares, and outputs are shown in green ovals. Processes are shown in white squares with rounded edges, and intermediate data are shown in white squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Methods

4.1. Calculating irrigation rates

Irrigation rates for each parcel were calculated based on the approach of Johnson & Belitz (2012) as adapted in previous work (Blount et al., 2021) (Fig. 2). Prior studies show that these remote sensing-based evaluations provide good estimates of outdoor water use in semi-arid cities. The original model development utilized water billing data to show good correlation between the model NDVI surplus and increased water delivery at the neighborhood scale ($R^2 = 0.94$) and has been shown to improve estimates of outdoor water use over traditional billing-based methods in semi-arid regions where irrigation may occur year-round (Johnson & Belitz, 2012; Mini et al., 2014). The current formulation of the model provided good agreement between modeled and observed irrigation at Denver Parks and Recreation golf courses from 2013 to 2017 (RMSE = 31.14 mm/year; PBIAS = -0.05%) (Blount et al., 2021).

Inputs to the model include endmembers – or representative areas of a single, known land cover type that provide a measure of characteristic NDVI for each surface through time – for irrigated, non-irrigated, and impervious surfaces delineated from aerial imagery (Blount et al., 2021), as well as Landsat imagery to calculate NDVI and daily GRIDMET grass reference ET (Abatzoglou, 2013). After delineating endmembers, NDVI values were calculated for each endmember class and every parcel from the buffered subset of each land use class for each Landsat image available during the growing season (May-October). In months with more than one Landsat image, NDVI values were averaged into a single monthly value. Next, the irrigated fraction of each parcel was calculated based on the NDVI of that parcel and the NDVI of the irrigated and impervious endmembers. Maximum NDVI surplus for each month, which represents the increased greenness of irrigated vegetation over non-irrigated vegetation, was multiplied by each parcel's irrigated fraction to calculate the NDVI surplus of each parcel, or the increase in greenness of the parcel over non-irrigated vegetation due to irrigation within the parcel.

Monthly urban landscape reference ET, which is similar to a crop reference ET for urban areas, was calculated as the product of monthly GRIDMET grass reference ET and a landscape coefficient, previously calibrated as 0.46 (Blount et al., 2021). Maximum monthly irrigation rate, or the amount of irrigation used on a fully irrigated surface, was calculated as a function of NDVI surplus and urban landscape ET. Finally, monthly parcel irrigation rates were calculated as the product of parcel irrigated fraction and maximum monthly irrigation rate before being summed to obtain a growing season total irrigation rate.

To evaluate differences between land use class irrigation rates, a two-sample Kolmogorov-Smirnov test (K-S test; Smirnov, 1939) was used for each combination of land use classes. The K-S test is a non-parametric evaluation of two distributions that evaluates the null hypothesis that the two samples are derived from the same continuous distribution.

4.2. Data cleaning

After irrigation rates were calculated and parcel characteristics and land cover data were joined for all parcels, data cleaning was employed to remove negative irrigation values and parcels with incomplete data. Negative rates occur when the NDVI of a parcel is less than the NDVI of non-irrigated surfaces, typically when a parcel is comprised primarily of impervious surfaces. In such cases, little to no irrigation was hypothesized to occur on highly impervious parcels. Therefore, negative irrigation rates were set to zero. The records for parcels that were missing any value were removed to obtain the final set of irrigation rates for analysis. Final data sets were deemed to be sufficiently large sample sizes to be representative of each land use class (Table 1).

4.3. Conditional inference trees

Conditional inference trees (CI trees) were used to identify subsets of the SFR and MFR land use classes that are representative of redeveloping or redeveloped parcels, respectively. CI trees use a recursive method to partition a response variable, such as irrigation rate, into groups based upon predictor variables, such as parcel characteristics (Hothorn, Hornik, van de Wiel, & Zeileis, 2006; Hothorn, Hornik, & Zeileis, 2006). The method is a three-step process: (1) test for global independence of variables and if independent, select the predictor variable with the strongest relationship with the response variable, (2) test for significant differences in populations of the response variable, and (3) implement a binary split based upon the predictor variable if significant differences in populations are identified. The method iterates through these three steps until there are no more independent variables or no more significant differences in populations. The CI tree methodology was implemented in R using the 'party' package (Hothorn, Hornik, Strobl, & Zeileis, 2020). Results of the CI tree outputs are shown in Appendix A and were used to inform resampling for all redevelopment scenarios using a subset of MFR

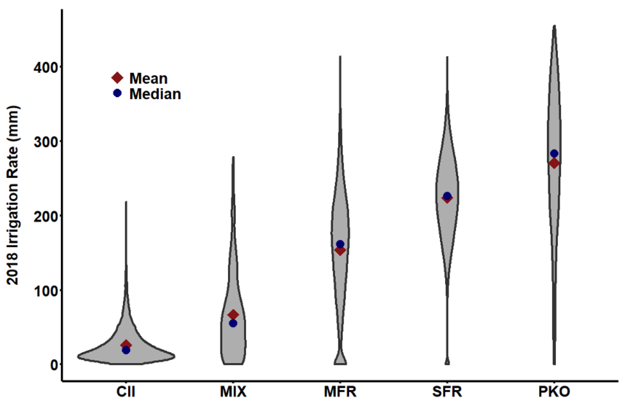

Fig. 4. Violin plots of 2018 irrigation rates for Denver parcels are shown by land use class. Violin plots show the range of calculated irrigation rates for each class with a rotated kernel density plot that shows the probability density of values along the y-axis. Mean irrigation rates for each class are shown with red diamonds, and median land use class values are shown with blue circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

parcels determined to be most representative of post-redevelopment irrigation rates.

4.4. Resampling methodologies for redevelopment scenarios

Simulation of residential infill was conducted by selecting SFR parcels for redevelopment and resampling their irrigation rates from representative MFR parcels (Fig. 3). The novel method begins with pre-redevelopment MFR and SFR parcels with irrigation rates and total irrigation volume calculated from the irrigation rate and land area of each parcel. Because only redevelopment of SFR parcels into MFR parcels is simulated, MFR parcels are not resampled for the redeveloped irrigation rates. SFR parcels are split into two groups, one that remains unchanged as SFR parcels that are not redeveloped and one that is selected to be resampled, based on redevelopment probability in Berkeley or random sampling for citywide analyses. To identify MFR parcels that are characteristic of redeveloped properties, the results of the CI tree analysis were used to select a representative subset of MFR parcels. Based on these results, MFR parcels that were remodeled after 2007 were selected as representative (Appendix A). Finally, irrigation rates from the representative MFR parcels were randomly sampled to replace the SFR parcels before redevelopment, and total irrigation rates were calculated for each redevelopment scenario using the redeveloped parcel irrigation rates.

The resampling method was implemented in the same manner for both the Berkeley neighborhood case study and the citywide analysis with two exceptions. First, for the Berkeley neighborhood, only MFR parcels from within the neighborhood were used. Second, redevelopment probability values were used to select SFR parcels for redevelopment in the Berkeley neighborhood; for the citywide analysis, SFR parcels for redevelopment were randomly selected from the pre-redevelopment SFR parcel distribution as a percent of the total number of parcels.

The analysis was repeated for 10,000 iterations for each redevelopment scenario. Each iteration contained a unique subset of randomly sampled MFR values used to represent redeveloped parcels ('Representative MFR Parcels' in Fig. 3). Berkeley scenarios maintain the same parcels redeveloped in each iteration of a scenario based upon redevelopment probability, while Denver-wide scenarios contained a randomly sampled and unique subset of the SFR parcels selected for redevelopment in each iteration. At both scales, these values ('SFR parcels before redevelopment' in Fig. 3) were replaced by the representative MFR values to form the redeveloped (SFR to MFR) group. These iterations resulted in a distribution of predicted post-redevelopment irrigation volumes for each scenario. In the Berkeley neighborhood, three scenarios were evaluated for redevelopment. For the Denver-wide analysis, ten scenarios representing 10% to 100% of SFR parcels redeveloped in 10% increments were assessed in addition to the low, moderate, and high scenarios.

5. Results and discussion

5.1. Irrigation rates by land use

Denver residential parcels, MFR and SFR, are smaller than CII, MIX, and PKO parcels on average (Table 1). Therefore, almost 95% of parcels analyzed in Denver are classified as residential, but these parcels only cover 62% of the corresponding land area. After data cleaning, 86% of all parcels were retained for analysis, ranging from a minimum of just over 50% for MFR to a maximum of 94% for SFR. All land use classes exhibit right-skewed distributions of land area, indicating that all land uses contain large parcels as outliers with respect to size (Table 1). Land use classes with larger parcel mean area are more highly skewed; therefore, this effect is largest for PKO parcels and smallest for SFR parcels. Parcel impervious cover varies greatly by land use, ranging from 10.4% for PKO to 75.4% for CII.

Mean irrigation rates in 2018 for the five land use classes varied by almost 250 mm (Table 1; Fig. 4). PKO parcels were irrigated at the highest rate (averaging 271 mm and ranging between 150 and 450 mm) in 2018, while CII parcels (averaging 26 mm) received the least outdoor water use. Both SFR and MFR parcels exhibited similar ranges of irrigation rates from approximately 0 mm to 400 mm. However, SFR parcels had higher mean irrigation rates than MFR by an average of approximately 70 mm, and almost all SFR parcels were irrigated with at least 125 mm of water, whereas over a quarter of MFR parcels were irrigated at a rate of less than 125 mm. Both residential classes exhibited an increase in density at irrigation rates of 0 mm relative to other land use classes. A large portion of both CII and MIX parcels had irrigation rates below 100 mm for 2018 (approximately 98% and 80%, respectively), and CII parcels exhibited their highest density between 0 and 40 mm. K-S tests demonstrated that each of the five land use irrigation distributions was unique from each of the other four distributions ($p < 0.001$).

High outdoor water use rates for PKO parcels are likely explained by the high percentages of irrigated area, especially turfgrasses, typically found in public parks; although, many smaller parks contain higher impervious land cover, including parking lots, sidewalks, and tennis and basketball courts, relative to their total size. Though irrigation rates below 150 mm represented only 10% of all PKO parcels, these lower values are likely due to contributions of smaller parks and open space parks, which typically receive little to no irrigation. Similarly, many SFR and MFR parcels contain large irrigated turfgrass areas and have higher irrigation rates. The increase in density of low irrigation rates for residential classes is hypothesized to be caused by the inclusion of vacant lots and multi-family properties that utilize all or almost all of the lot area for the building, representative of typical infill development. CII and MIX parcels both typically utilize larger portions of the parcel for the built environment. CII parcels include strip malls, manufacturing, and retail stores, all of which typically include little irrigated area. Similarly, MIX parcels often aim to utilize the entire area of a parcel for commercial activity and residential development. However, outliers may include office parks (CII) or developments that include public or private green space (MIX) with higher irrigation rates.

5.2. Berkeley neighborhood case study

Redevelopment scenarios utilizing probabilities from Panos et al. (2018) showed that the conversion of SFR to MFR properties results in

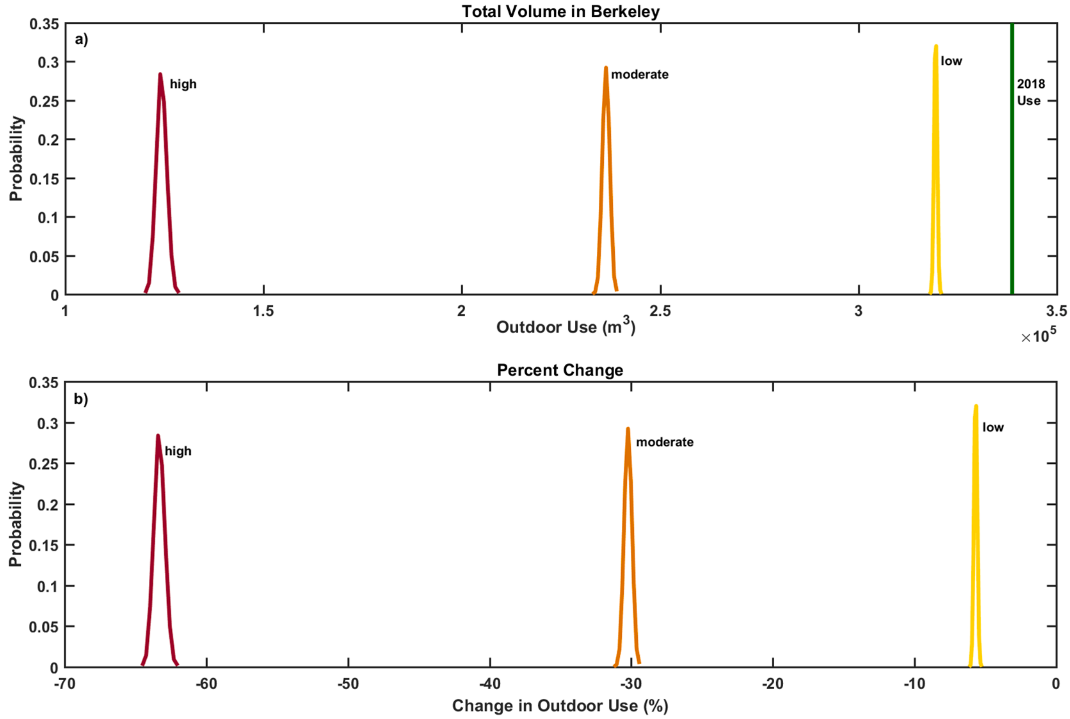

Fig. 5. Probability density functions of the 10,000 resampling solution sets for each of the three redevelopment scenarios in the Berkeley neighborhood. High, moderate, and low redevelopment scenarios are shown in red, orange, and yellow, respectively, and are labeled. (a) Total outdoor water use (m^3) for each of the three redevelopment scenarios and total calculated 2018 outdoor use (the baseline scenario shown with the green vertical line). (b) Percent change in residential outdoor water use relative to 2018 baseline (pre-redevelopment) scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary statistics for the solution sets of outdoor water use volume in the high, moderate, and low redevelopment scenarios for both the Berkeley neighborhood case study and Denver citywide analysis.

	Total Residential Outdoor Use Volume (m^3)									
Redevelopment scenario	Berkeley mean	median	std. dev.	max	min	City-wide mean	median	std. dev.	max	min
Pre-redevelopment	3.39E+05					1.86E+07				
Low	3.19E+05	3.19E+05	3.79E+02	3.21E+05	3.18E+05	1.72E+07	1.72E+07	9.05E+03	1.73E+07	1.72E+07
Moderate	2.36E+05	2.36E+05	8.87E+02	2.39E+05	2.33E+05	1.30E+07	1.30E+07	1.55E+04	1.31E+07	1.30E+07
High	1.24E+05	1.24E+05	1.29E+03	1.29E+05	1.20E+05	7.58E+06	7.58E+06	1.44E+04	7.64E+06	7.52E+06
	Absolute Change in Residential Outdoor Use Volume (m^3)									
Redevelopment Scenario	Berkeley mean	median	std. dev.	max	min	City-wide mean	median	std. dev.	max	min
Low	−1.93E + 04	−1.93E + 04	3.79E + 02	−1.76E + 04	−2.10E + 04	−1.38E + 06	−1.38E + 06	9.05E + 03	−1.34E + 06	−1.41E + 06
Moderate	−1.02E + 05	−1.02E + 05	8.87E + 02	−9.93E + 04	−1.06E + 05	−5.55E + 06	−5.55E + 06	1.55E + 02	−5.49E + 06	−5.61E + 06
High	−2.14E + 05	−2.14E + 05	1.29E + 03	−2.10E + 05	−2.19E + 05	−1.10E + 07	−1.10E + 07	1.44E + 04	−1.10E + 07	−1.11E + 07
	Percent Change in Residential Outdoor Use (%)									
Redevelopment Scenario	Berkeley mean	median	std. dev.	max	min	City-wide mean	median	std. dev.	max	min
Low	−5.69	−5.69	0.11	−5.20	−6.20	−7.41	−7.41	0.05	−7.21	−7.60
Moderate	−30.23	−30.23	0.26	−29.32	−31.33	−29.85	−29.85	0.08	−29.52	−30.14
High	−63.31	−63.32	0.38	−61.87	−64.66	−59.25	−59.25	0.08	−58.94	−59.56

cumulative decreases in outdoor water use (Fig. 5). All analyses, including total volume, absolute change in volume, and percent change in outdoor use, are reported for total residential outdoor use. Total residential outdoor use is the sum of MFR and SFR outdoor use, and percent changes are relative to this volume, not to SFR outdoor use, total outdoor use, or total indoor and outdoor use. The calculated total volume of residential outdoor use for 2018 was 339,000 m^3 (274 acre-feet) and decreased on average by 5.69% in the low redevelopment scenario

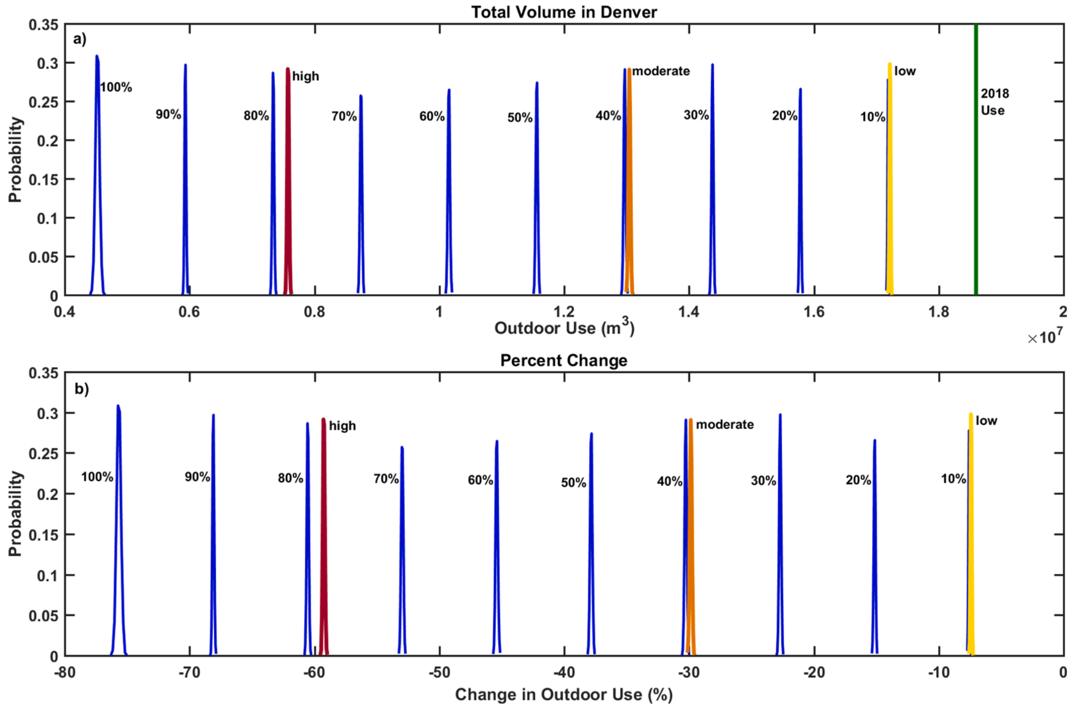

Fig. 6. Probability density functions of the 10,000 resampling solution sets for each of the Denver-wide redevelopment scenarios. High, moderate, and low redevelopment scenarios are shown in red, orange, and yellow, respectively, and scenarios for increments of 10% SFR redevelopment are shown in blue. (a) Total outdoor water use (m^3) for each of the scenarios are shown with the total calculated 2018 outdoor use (the baseline scenario) shown by the green vertical line. (b) Percent change in residential outdoor water use relative to 2018 baseline (pre-redevelopment) scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(9.8% of SFR parcels redeveloped), 30.23% in the moderate redevelopment scenario (39.5% of SFR parcels redeveloped), and 63.31% in the high redevelopment scenario (78.3% of SFR parcels redeveloped) (Table 2). These decreases corresponded to a mean outdoor water use of 319,000 m^3 (259 acre-feet), 236,000 m^3 (191 acre-feet), and 124,000 m^3 (101 acre-feet), respectively. Therefore, increasing cumulative redevelopment is related to decreasing cumulative water use in the Berkeley neighborhood.

The probability distribution of solutions widened as the percentage of SFR parcels redeveloped increased (Fig. 5; standard deviation in Table 2). Because resampling is based on the probability of redevelopment for each parcel, a parcel that was selected for redevelopment in the low scenario was redeveloped in all 10,000 solutions for that scenario as well as each of the 10,000 solutions for both the moderate and high redevelopment scenarios. Therefore, an increasing number of parcels that are redeveloped or resampled from the MFR distribution leads to greater uncertainty within the solution sets. However, K-S tests showed that each of the three solution sets for the redevelopment scenarios were significantly different from the other two sets ($p < 0.001$).

Redevelopment, and specifically the conversion of SFR to MFR properties, provides an opportunity to promote significant water conservation. Even in the low redevelopment scenario where less than 10% of eligible SFR parcels are redeveloped, which accounted for 335 SFR parcels being redeveloped in 2018, appreciable water savings were achieved. The low redevelopment scenario resulted in a decrease in irrigation of almost 20,000 m^3 (16 acre-feet) in a neighborhood that represents 1.2% of total land area in the city of Denver. These savings increased to a maximum of 214,000 m^3 (173 acre-feet) in the high redevelopment scenario. Importantly, these savings only account for irrigation trends within the Berkeley neighborhood. Because infill development increases urban density, it is theorized to reduce sprawl (McConnell & Wiley, 2010), reducing new low-density development. Therefore, it is likely that redevelopment not only reduces outdoor use within the Berkeley neighborhood but also prevents new outdoor demand in low-density SFR development.

5.3. Denver-wide redevelopment

To evaluate large-scale redevelopment on system-wide demand, the redevelopment scenarios were applied to all SFR parcels within the City and County of Denver. These results displayed similar patterns at the city-scale to those seen in in the Berkeley neighborhood (Fig. 6; Table 2). Increasing redevelopment across Denver was associated with reduced outdoor water use. The calculated volume of outdoor use for 2018 is 18,600,000 m^3 (15,079 acre-feet) and decreased on average by 7.41% in the low redevelopment scenario (9.8% of SFR parcels redeveloped), 29.85% in the moderate redevelopment scenario (39.5% of SFR parcels redeveloped), and 59.25% in the high redevelopment scenario (78.3% of SFR parcels redeveloped) (Table 2). These decreases corresponded to mean irrigation volumes of 17,200,000 m^3 (13,944 acre-feet), 13,000,000 m^3 (10,539 acre-feet), and 7,580,000 m^3 (6,145 acre-feet), respectively. Using Denver Water's daily per capita use of 534 L (141 gallons) in 2018 (Denver Water, 2019a), modeled redevelopment reduced demand by the equivalent of reducing the population served by approximately 36,000 (low), 192,000 (moderate), and 402,000 (high) people. The theoretical minimum outdoor use for 2018, representing 100% redevelopment of SFR parcels to MFR land use, reduced total volume by 75.7% to 4,530,000 m^3 (3,672 acre-feet).

Unlike results for the Berkeley neighborhood (Fig. 5), redevelopment scenarios did not display any trends in the width of the solution set probability function (Fig. 6) or standard deviation (Table 2) as the percent of SFR parcels redeveloped increases. Because the SFR parcels for redevelopment in the citywide analysis were randomly sampled, the specific parcels selected for redevelopment varied within solution sets and between redevelopment scenarios. Because both the SFR parcels redeveloped and the MFR parcels selected to represent the redeveloped irrigation rates varied, the range of values within solution sets is not tied to the percentage of parcels redeveloped. This also accounts for the

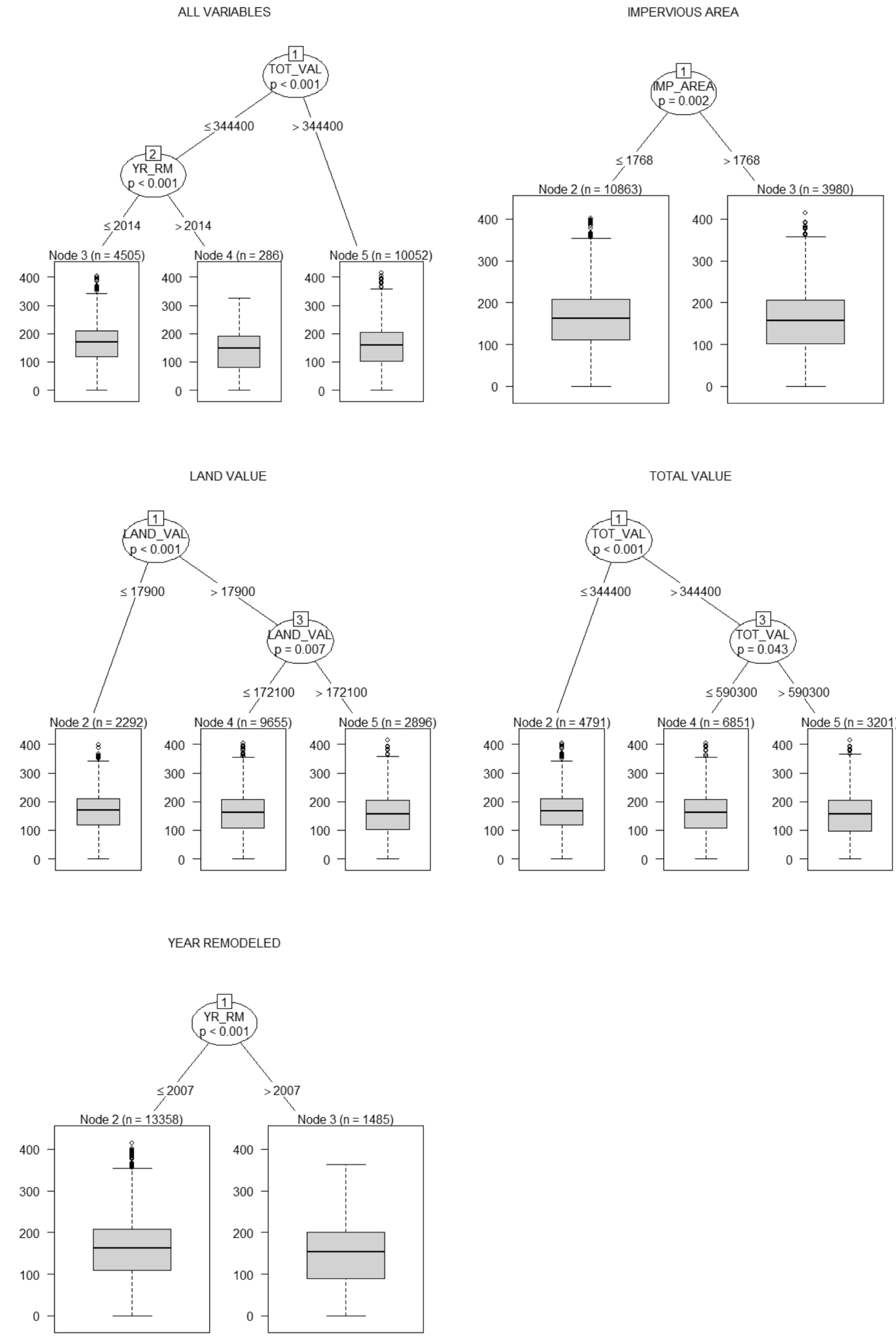

Fig. A1. Conditional inference tree outputs for MFR properties related to significant differences in distributions of irrigation rates. Circle nodes show the significant variable and p-value, branches show the selection criteria value for the significant variable, and end nodes show boxplots of irrigation rates for unique subsets of MFR irrigation rates.

random variance in the maximum probability values between solution sets for the 13 scenarios (Fig. 6). As in the Berkeley neighborhood scenarios, K-S tests showed that all scenario distributions are derived from unique distributions ($p < 0.001$); this includes the low and 10% redevelopment scenarios that differed by only 0.2% of SFR parcels redeveloped.

Although redevelopment may be accompanied by significant variance in parcel-level total water demand, the Conditional Inference Tree analyses were unable to distinguish significant differences in MFR outdoor water use based on density. Therefore, no density metrics were considered when resampling the MFR parcels, and resampling occurred from the full distribution of parcels remodeled during or after 2007. Similarly, these results reflect only outdoor, and not total, water use, which limits insights into how household size and improvements in indoor efficiency typically associated with residential density may affect total residential water demand.

Both total outdoor use and percent change in outdoor use exhibited a linear relationship with the percent of SFR parcels redeveloped (see Appendix B). These models showed that a reduction of 141,000 m^3 (114 acre-feet or 0.76%) was achieved per one percent of SFR parcels redeveloped. Using Denver Water's 2018 average annual per capita use of 194.8 m^3 (141 gallons/person/day; Denver Water, 2019a), the redevelopment of each percent of SFR parcels to MFR use translates into water savings equal to supply for 724 individuals (181 four-person

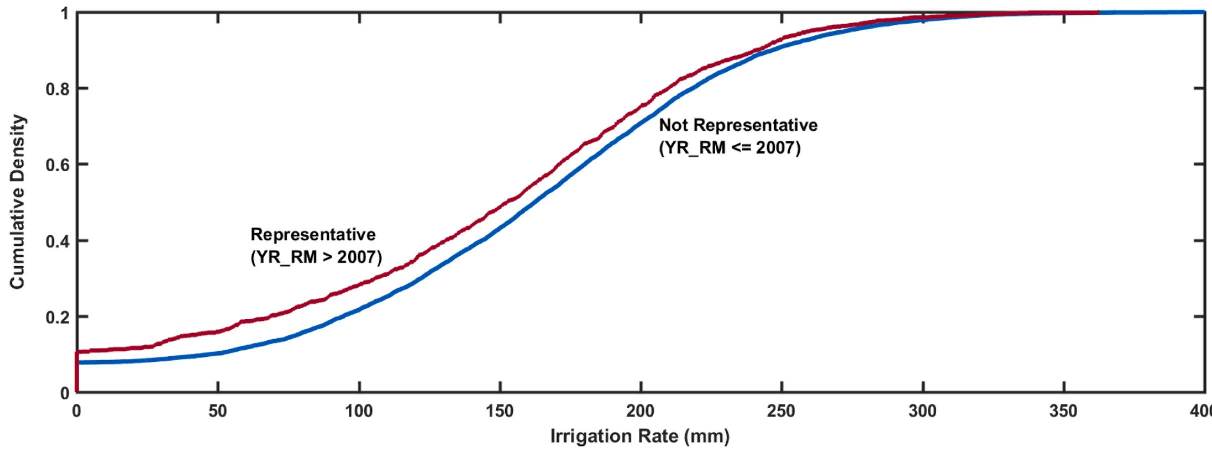

Fig. A2. Cumulative density plot of representative MFR parcels (used for resampling) and non-representative MFR parcels (not used for resampling) based on CI tree analysis.

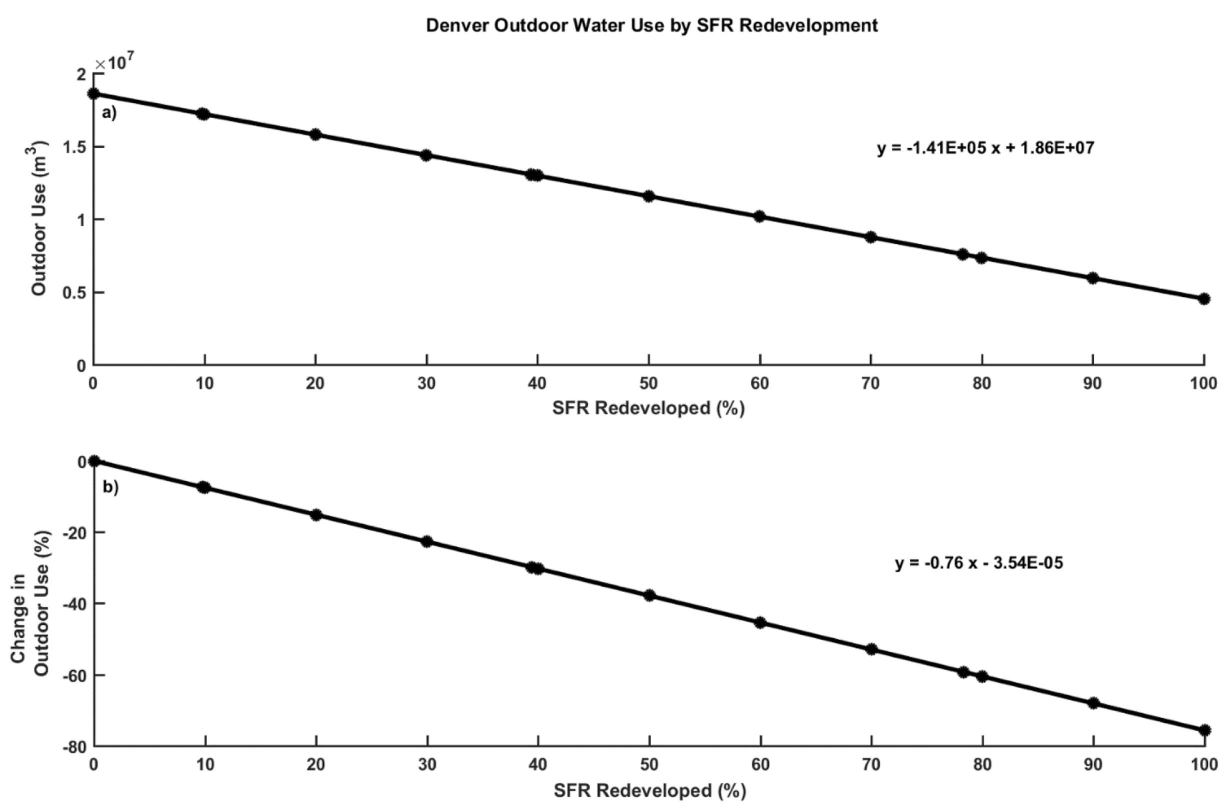

Fig. B1. Changes in (a) total residential outdoor water use and (b) percent change in residential outdoor water use per percent of single-family parcels redeveloped for the Denver citywide analysis.

households) per year. However, these linear models are produced with static distributions of SFR and MFR irrigation rates and do not account for changing biophysical and hydroclimatic conditions of redeveloping cities. Because increased density will likely increase temperatures and vapor pressure deficits, remaining vegetation may require increased water use as cities redevelop and become warmer (Vahmani & Jones, 2017). Conversely, updated irrigation systems in redeveloped properties might provide improved efficiency and reduce water loss. These alterations to water-heat-vegetation interactions likely yield non-linear relationships between redevelopment and outdoor water use as well as diminishing returns with respect to water savings.

The results presented here may represent conservative estimates of savings in Denver. In 2018, Denver Water delivered 121,000,000 m^3 (98,096 acre-feet) of treated water to city of Denver (Denver Water, 2019a). This study calculated that 18,600,000 m^3 (15,079 acre-feet), or 15.4% of potable water deliveries, were used for residential outdoor irrigation. Denver Water reports that 40.0% of potable water was delivered to residential customers (Denver Water, 2019a), and 50% of SFR use is outdoors (Denver Water, 2019b). Based on these estimates, approximately 20.0% of total water delivery, or 24,200,000 m^3 (19,619 acre-feet), would be used for residential irrigation in Denver. Differences in these estimates may be due to variations of development patterns. Development within Denver, less than half of the Denver Water service area, is more dense than surrounding suburban development. The Denver Water service area averages 31.3% impervious land cover, but the city of Denver is 36.7% impervious, and the remainder of the Denver

Water service area is 27.1% impervious (L. Yang et al., 2018). These differences also likely correspond to smaller residential properties, both SFR and MFR, with less irrigated area and lower outdoor water use rates. Similarly, MFR properties likely use less than 50% of their water outdoors, especially in the dense urban core of Denver. Given these considerations, the results show reasonable agreement with Denver Water-based estimates of outdoor water use. However, they may represent slightly conservative estimates and provide a reasonable minimum baseline for the water savings potential of SFR redevelopment.

As in the Berkeley case study, these estimates also only accounted for reductions in outdoor use on existing developed parcels, not for the potential abatement of new outdoor demand driven by more water-intense suburban development along the urban fringe. While these reductions in potential future demand may not be achieved within the boundaries of the city of Denver, they do prevent increases in demand for water systems, like Denver Water, that serve large metropolitan areas. Denver Water predicts that demand will increase by 5.4% per 1℃ increase in temperature, due largely to outdoor use (Denver Water, 2019c). Based on these results, redevelopment of 48.8% of SFR parcels into MFR residences would sufficiently reduce outdoor water use to offset climate-induced increases in total system-wide demand, both indoor and outdoor, associated with a 1℃ increase in temperature. Although increased density on residential parcels likely increases indoor use within the study area, more dense residential development – along with continued improvements to indoor efficiencies and increased water reuse – ensures that population-driven increases in outdoor, consumptive demand are minimized or negated.

Although documentation of historic infill or projections of future redevelopment are limited, extensive redevelopment and infill-favorable policies have been implemented within Denver since the late 1990s. In 1997, the Denver Regional Council of Governments released *Metro Vision*, its vision and guidance document for regional development through 2035 (DRCOG, 2011). This plan implemented new urban growth boundaries in the region and called for increased infill development within existing urban boundaries. Impervious cover increased two percent in Denver between 2017 and 2019 alone, and significant infill development has contributed to large increases in imperviousness locally (e.g., a 22% increase in the Cory-Merrill neighborhood between 2004 and 2016) and created highly impervious neighborhoods (e.g., eight neighborhoods had at least 65% impervious surfaces in 2016) (Anderson, 2017, 2019). This growth has garnered significant public attention, and at least one blog has been developed to highlight and promote infill projects within Denver (denverinfill.com). Although redevelopment of half of SFR properties may be unlikely, significant infill continues to occur within Denver, and these results indicate that this growth will reduce outdoor water use and may provide a substantial contribution to climate adaptation strategies for urban water systems.

5.4. Multi-benefit planning considerations

While these results demonstrate that more dense urban development provides an opportunity to reduce system-level water demand, we do not intend to advocate for universal redevelopment of SFR parcels or the complete removal of urban green spaces. Rather, we seek to quantify the expected changes to outdoor demand associated with redevelopment, providing support for the integration of land use and water planning and giving context for the consideration of water demand in urban planning.

Planning-level decisions in cities should be made while considering the multi-benefit nature of urban green spaces, using irrigation demand as one of many factors. Increased impervious area may be associated with increased stormwater runoff and flooding (Panos et al., 2018) and higher infrastructure cost, so redevelopment decisions must be made while considering stormwater management strategies. Many emerging stormwater management approaches involve the use of green stormwater infrastructure (Bell et al., 2019; Yang & Wang, 2017). Despite reducing flooding and mitigating thermal stress, vegetated green stormwater infrastructure may require irrigation for maintenance and contribute to outdoor water demand in semi-arid regions (Yang & Wang, 2017). Likewise, increased density may influence urban heat islands, intensifying daily maximum temperatures (Gober et al., 2010; Li et al., 2011), which may further increase irrigation demand in remaining green spaces (Blount et al., 2021; Vahmani & Jones, 2017). Similarly, increased densities may i) drive increased total water demand at the parcel level by increasing the number and altering the size of households on a given property while reducing per capita water use through improved indoor efficiency and ii) improve the efficiency of outdoor use in smaller remaining vegetated areas through newer, more efficient irrigation systems.

Finally, decisions to remove green spaces, including both public and private green space, should be made while balancing considerations of their efficacy with ancillary benefits and equity. Both MFR and SFR properties can vary widely in their water use, and reductions in water use can be achieved while maintaining SFR properties by promoting smaller, more efficient houses, reducing irrigated area, and promoting the use of xeric vegetation and rainwater harvesting (Quesnel, Agrawal, & Ajami, 2020; Gilliom, 2020; Keystone Policy Center, 2018). Therefore, development policy should focus on promoting water efficient development, for both indoor and outdoor use, across MFR and SFR properties. Ancillary benefits include enhanced air and water quality, improved physical and mental health, and social and cultural support (Keeler et al., 2019). One planning approach may be to alter the balance between public and private green spaces, as public spaces and pools can serve as a proxy for similar private amenities, reducing residential water demand but maintaining ancillary benefits while meeting increased demand for green space associated with reduced private access (Halper, Dall'erba, Bark, Scott, & Yool, 2015). Further, redevelopment may drive gentrification, reduce access to affordable housing, and exacerbate inequities related to access to green space (Immergluck & Balan, 2018; Pearsall & Eller, 2020; Wolch, Byrne, & Newell, 2014). Redevelopment policy should not overlook affordability and equity in the decision-making process. Both biophysical and social considerations further demonstrate the need for the integration of land use and water planning and the opportunities to reimagine cities as sustainable systems through the design of green spaces that achieve multiple physical and social benefits for surrounding communities.

6. Conclusions

This study was motivated by the increasing importance of outdoor demand in urban water systems and the growing focus on water conservation through land use planning. To quantify the relationship between urban development and outdoor water use, we applied a remote sensing-based method to calculate urban irrigation at an innovative parcel-level scale and used a novel resampling method to model the impacts of redevelopment on system-level demand. Our results demonstrate the significant relationships between urban planning, land use, and outdoor water demand, which represents the largest necessarily consumptive end use of water in semi-arid urban water systems. These results elicit two major conclusions, outlined below.

First, *outdoor water use varies greatly between land use types in Denver*. Mean irrigation rates varied by approximately 250 mm in 2018, with parks receiving the highest irrigation rates, and commercial and mixed-use properties receiving the lowest outdoor water use. Residential land uses were irrigated at rates between these other land uses, but single-family parcels received over 70 mm (46%) more irrigation than multi-family properties in 2018 and likely do not provide the social and community benefits associated with parks. These irrigation rates exhibited an inverse relationship with percent impervious land cover, and land cover differences as well as the inclusion of vacant properties likely account for the wide ranges of irrigation rates within land use classes.

Second, *residential infill development as represented by the conversion of single-family to multi-family properties provides significant opportunities to reduce outdoor water demand.* Results showed that redevelopment reduced outdoor water use in Denver by 141,000 m^3 (114 acre-feet, or 0.76% of residential outdoor use) per one percent increase in redeveloped single-family parcels. This translates to new supply for 141 four-person households per percent of single-family properties redeveloped. Calculations of outdoor use savings may provide conservative estimates and do not account for reductions in use associated with the abatement of new urban sprawl. Integrating land use and water planning in cities can provide significant contributions to climate adaptation and demand management, but this integration should also include considerations such as stormwater management, interactions with urban heat islands, social and cultural benefits of green space, and equitable housing.

This study presents an easily adapted methodology for estimating outdoor water use in semi-arid and arid regions and a novel framework for evaluating the cumulative impacts of redevelopment on outdoor irrigation. Denver-specific results highlight that infill development of residential urban land uses provides an impactful opportunity to integrate urban planning with water demand planning, create water-efficient landscapes, and reduce system-wide demand on urban water systems. Similar analyses can be used to evaluate the impacts of urban planning and redevelopment policy on water demand to inform targeted policy goals, including climate adaptation. However, such decisions should include considerations of biophysical tradeoffs, the benefits of green space, and equity. Planning and policy decisions must also consider indoor use efficiency and total water demand of various development patterns as well as the capacity of system infrastructure to meet increased demand in more dense developments. Future work should incorporate measures of indoor water use associated with redevelopment to evaluate tradeoffs between more dense development, reductions in sprawl, changes in water demand (both indoor and outdoor), and urban heat islands. Similarly, additional work should identify policy-relevant guidance for the development of efficient, multi-purpose green spaces in cities. These lines of inquiry will continue to advance our understandings of the complex interactions between urban form and water demand and help to inform water-efficient urban development policy.

CRediT authorship contribution statement

Kyle Blount: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing - original draft, Visualization. **Reza Abdi:** Methodology, Software, Writing - review & editing. **Chelsea L. Panos:** Methodology, Software, Writing - review & editing. **Newsha K. Ajami:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition. **Terri S. Hogue:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Acknowledgements

The authors would like to thank the anonymous reviewers for their insightful comments that helped improve the context and clarity of this manuscript. This work was primarily supported by the National Science Foundation-funded Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure (ReNUWIt) (NSF EEC-1028968) and a grant from the Colorado Higher Education Competitive Research Authority (CHECRA). Additional support was provided under Assistance Agreement No. R836174 awarded by the U.S. Environmental Protection Agency to the Colorado School of Mines, the Nature Conservancy, and the University of California-Berkeley. The authors declare no conflicts of interest. Data are available upon reasonable request from the corresponding authors (Kyle Blount, wkblount@mymail.mines.edu; Terri Hogue, thogue@mines.edu).

Appendix A: Conditional Inference Trees

Conditional inference trees were built between irrigation rates and all variables, individual variables, and groupings of significant variables for both MFR and SFR properties. The role of the conditional inference tree analysis is to identify subsets of MFR and SFR irrigation distributions that are characteristic of either SFR parcels that redevelop or MFR parcels after redevelopment. For MFR parcels, year remodeled (YR_RM), total value (TOT_VAL), land value (LAND_VAL), and impervious area (IMP_AREA) are the only significant variables ($p<0.05$, Fig. A1). No significant variables for SFR irrigation rates were observed.

While results are shown for significance at $p<0.05$, only results with $p<0.01$ were considered for the selection of representative samples to reduce the changes of Type I errors and increase confidence in differences between representative and non-representative parcels. Because total value, land value, and impervious area are characteristics of MFR parcels post-redevelopment that we cannot predict, they were excluded from consideration. Therefore, MFR properties remodeled after 2007 were selected as the representative subsample of future MFR properties created by infill development. A K-S test confirms that differences in the pre- and post-2007 period are statistically different distributions ($p<0.001$) (Fig. A2). Representative MFR parcels selected for redevelopment analysis exhibit lower irrigation rates than non-representative parcels, and more representative than non-representative parcels exhibit no irrigation.

The importance of the split in representative and non-representative redevelopment around the year 2007 likely corresponds to the result of zoning policy and implementation of infill properties. The City of Denver's Comprehensive Plan, which set the vision for development within the city from 2000 to 2020, notes the increased interest in urban living and more dense development along with recent zoning code changes that promote multi-family and mixed-use developments (Denver Comprehensive Plan, 2000). Similarly, Denver's Comprehensive Plan for 2040 notes the significant increase in infill from 2010 to 2020 and the intent to promote further mixed-use development (Comprehensive Plan 2040, 2020). The separation of representative parcels, therefore, likely represents the point at which changes in zoning codes result in real-world changes to development patterns.

Appendix B: Linear models of Water Use and Redevelopment

Linear models were created to identify the influence of the percent of SFR residential parcels in Denver that were redeveloped on the city-wide total residential outdoor use and percent change in residential outdoor use (Fig. B1). Results show that outdoor use is decreased by 141,000 m^3 (114 acre-feet) per percent of SFR parcels redeveloped. This corresponds to a 0.76% reduction in residential outdoor use per percent of parcels redeveloped.

References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., & Hegewisch, K. C. (2018). Terraclimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958–2015. *Sci. Data, 5*(170191). https://doi.org/10.1038/sdata.2017.191.

Abatzoglou, J. T. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *Int. J. Climatol., 33*(1), 121–131. https://doi.org/10.1002/joc.v33.110.1002/joc.3413.

Anderson, S. (2017). Green Infrastructure & Climate Change: Denver Public Works Presentation. Retrieved from https://www.denvergov.org/content/dam/denvergov/Portals/Denveright/documents/Blueprint/Meeting_Archive/3_Green_Infrastructure_SarahAnderson.pdf.

Anderson, S. (2019). *City & County of Denver Green Infrastructure Program Separated Storm System.* Denver Public Works Presentation. https://www.epa.gov/sites/production/files/2019-06/documents/sea_gig_presentation_190515_reduced.pdf.

Bates, S. (2012). Bridging the Governance Gap: Emerging Strategies to Integrate Water and Land Use Planning. Nat. Res. J. 52:1 Retrieved from http://www.jstor.org/stable/24889598.

Bell, C. D., Spahr, K., Grubert, E., Stokes-Draut, J., Gallo, E., McCray, J. E., & Hogue, T. S. (2019). Decision making on the gray-green stormwater infrastructure continuum.

J. Sustain. Water Built Environ., 5(1), 04018016. https://doi.org/10.1061/JSWBAY.0000871.
Blanchard, J.C.N. (2018). Integrating Water Efficiency Into Land Use Planning In The Interior West: A Guidbook For Local Planners. Retrieved from https://westernresourceadvocates.org/publications/integrating-water-efficiency-into-land-use-planning/.
Blount, K., Wolfand, J. M., Bell, C. D., Ajami, N. K., & Hogue, T. S. (2021). Satellites to sprinklers: assessing the role of climate and land cover change on patterns of urban outdoor water use. *Water Resour. Res., 57*(1). https://doi.org/10.1029/2020WR027587.
Breyer, B., Chang, H., & Parandvash, G. H. (2012). Land-use, temperature, and single-family residential water use patterns in Portland, Oregon and Phoenix Arizona. *Appl. Geogr., 35*(1–2), 142–151. https://doi.org/10.1016/j.apgeog.2012.06.012.
Brown, T. C., Mahat, V., & Ramirez, J. A. (2019). Adaptation to future water shortages in the United States caused by population growth and climate change. *Earth's Future, 7* (3), 219–234. https://doi.org/10.1029/2018EF001091.
Cherry, L., Mollendor, D., Eisenstein, B., Hogue, T., Peterman, K., & McCray, J. (2019). Predicting parcel-scale redevelopment using linear and logistic regression-The Berkeley neighborhood Denver, Colorado case study. *Sustainability (Switzerland), 11* (7), 1882. https://doi.org/10.3390/su11071882.
City and County of Denver (2019). Existing Landuse 2018. Retrieved January 6, 2020, from https://www.denvergov.org/opendata/dataset/city-and-county-of-denver-existing-landuse-2018.
City and County of Denver Assessment Division. (2020). Real Property Residential Characteristics (Version 1.0.1709) [Comma Separated Values]. Retrieved March 26, 2020, from https://www.denvergov.org/opendata/dataset/city-and-county-of-denver-real-property-residential-characteristics.
Colorado Water Conservation Board (2016). Colorado Conservation and Reuse Water Plan Section 6. Retrieved from https://www.colorado.gov/pacific/cowaterplan/plan.
Comprehensive Plan 2040. (2020). Retrieved from https://www.denvergov.org/content/dam/denvergov/Portals/Denveright/documents/comp-plan/Denver_Comprehensive_Plan_2040_city_council_draft.pdf.
Denver Comprehensive Plan. (2000). Retrieved from https://www.denvergov.org/content/dam/denvergov/Portals/646/documents/planning/comprehensiveplan2000/CompPlan2000.pdf.
Denver Parks and Recreation (2016). Water Management Plan. Retrieved from https://www.denvergov.org/content/denvergov/en/denver-parks-and-recreation/trees-natural-resources/water-conservation.html.
Denver Water (2019a). 2018 Comprehensive Annual Report. Retrieved from https://www.denverwater.org/about-us/investor-relations/financial-information/annual-reports.
Denver Water (2019b). Key Facts. Retrieved September 25, 2019 from https://denverwater.org/about-us/how-we-operate/key-facts.
Denver Water (2019c). Adaptation Planning. Retrieved from. https://www.denvergov.org/content/denvergov/en/denver-parks-and-recreation/trees-natural-resources/water-conservation.html.
DRCOG. (2011). Metro Vision 2035 Plan. Retrieved from https://www3.drcog.org/documents/archive/MV2035draftplanbrochure2.pdf.
DeOreo, W., Mayer, P., Dziegielewski, B., & Kiefer, J. (2016). Residential End Uses of Water, Version 2/ Water Research Foundation. Retrieved from https://www.circleofblue.org/wp-content/uploads/2016/04/WRF_REU2016.pdf.
Gilliom, R. L. (2020). Practical viability of rainwater harvesting for outdoor use: water quality, water law, and climate change [Doctoral dissertation]. Retrieved from https://hdl.handle.net/11124/174163.
Gober, P., Brazel, A., Quay, R., Myint, S., Grossman-Clarke, S., Miller, A., & Rossi, S. (2010). Using watered landscapes to manipulate urban heat island effects: how much water will it take to cool phoenix? *J. Am. Plan. Assoc., 76*(1), 109–121. https://doi.org/10.1080/01944360903433113.
Gober, P., Quay, R., & Larson, K. L. (2016). Outdoor water use as an adaptation problem: insights from North American cities. *Water Resour. Manage., 30*(3), 899–912. https://doi.org/10.1007/s11269-015-1205-6.
Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google earth engine: planetary-scale geospatial analysis for everyone. *Remote Sens. Environ., 202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031.
Halper, E. B., Dall'erba, S., Bark, R. H., Scott, C. A., & Yool, S. R. (2015). Effects of irrigated parks on outdoor residential water use in a semi-arid city. *Landscape Urban Plann., 134*, 210–220. https://doi.org/10.1016/j.landurbplan.2014.09.005.
Harrington, R. (2016). Grass takes up 2% of the land in the continental U.S. Retrieved January 28, 2020 from https://www.businessinsider.com/americas-biggest-crop-is-grass-2016-2.
Hogue, T. S., & Pincetl, S. (2015). Are you watering your lawn? *Science, 348*(6241), 1319–1320. https://doi.org/10.1126/science.aaa6909.
Hothorn, T., Hornik, K., Strobl, C., & Zeileis, A. (2020). "party": A Laboratory for Recursive Partytioning (version 1.3-4) [R package]. Retrieved from https://cran.r-project.org/web/packages/party/party.pdf.
Hothorn, T., Hornik, K., van de Wiel, M. A., & Zeileis, A. (2006). A Lego System for Conditional Inference. *The American Statistician, 60*(3), 257–263. https://doi.org/10.1198/000313006X118430.
Hothorn, T., Hornik, K., & Zeileis, A. (2006). Unbiased recursive partitioning: a conditional inference framework. *J. Comput. Graph. Stat., 15*(3), 651–674. https://doi.org/10.1198/106186006X133933.
Hunt, E. R., Jr. (1994). Relationship between woody biomass and PAR conversion efficiency for estimating net primary production from NDVI. *Int. J. Remote Sens., 15* (8), 1725–1729. https://doi.org/10.1080/01431169408954203.
Immergluck, D., & Balan, T. (2018). Sustainable for whom? Green urban development, environmental gentrification, and the Atlanta Beltline. *Urban Geogr., 39*(4), 546–562. https://doi.org/10.1080/02723638.2017.1360041.
Johnson, T. D., & Belitz, K. (2012). A remote sensing approach for estimating the location and rate of urban irrigation in semi-arid climates. *J. Hydrol., 414–415*, 86–98. https://doi.org/10.1016/j.jhydrol.2011.10.016.
Keeler, B. L., Hamel, P., McPhearson, T., Hamann, M. H., Donahue, M. L., Meza Prado, K. A., … Wood, S. A. (2019). Social-ecological and technological factors moderate the value of urban nature. *Nat. Sustain., 2*(1), 29–38. https://doi.org/10.1038/s41893-018-0202-1.
Keystone Policy Center (2018). Colorado Water and Growth Dialogue, Final Report. Retrieved from http://www.keystone.org/wp-content/uploads/2018/10/CO-Water-and-Growth-Dialogue-Final-Report_September-2018.pdf.
Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorol. Z., 15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130.
Landers, J. (2019). Reuse ramps up. *Civil Eng. Magaz., 89*(10), 44–53. https://doi.org/10.1061/ciegag.0001430.
Li, J., Song, C., Cao, L.u., Zhu, F., Meng, X., & Wu, J. (2011). Impacts of landscape structure on surface urban heat islands: a case study of Shanghai China. *Remote Sens. Environ., 115*(12), 3249–3263.
Litvak, E., Manago, K. F., Hogue, T. S., & Pataki, D. E. (2017). Evapotranspiration of urban landscapes in Los Angeles, California at the municipal scale. *J. Am. Water Resour. Assoc., 53*, 4236–4252. https://doi.org/10.1002/2016WR020254.
Litvak, E., & Pataki, D. E. (2016). Evapotranspiration of urban lawns in a semi-arid environment: an in situ evaluation of microclimatic conditions and watering recommendations. *J. Arid Environ., 134*, 87–96. https://doi.org/10.1016/j.jaridenv.2016.06.016.
Lukas, J., Barsugli, J., Doeksen, N., Rangwala, I., & Wolter, K. (2014). Climate Change in Colorado. *University of Colorado Boulder*, 1–108. https://wwa.colorado.edu/climate/co2014report/.
Milesi, C., Running, S. W., Elvidge, C. D., Dietz, J. B., Tuttle, B. T., & Nemani, R. R. (2005). Mapping and modeling the biogeochemical cycling of turf grasses in the United States. *Environ. Manage., 36*(3), 426–438. https://doi.org/10.1007/s00267-004-0316-2.
Mini, C., Hogue, T. S., & Pincetl, S. (2014). Estimation of residential outdoor water use in Los Angeles, California. *Landscape Urban Plann., 127*, 124–135. https://doi.org/10.1016/j.landurbplan.2014.04.007.
Mini, C., Hogue, T. S., & Pincetl, S. (2015). The effectiveness of water conservation measures on summer residential water use in Los Angeles, California. *Resour. Conserv. Recycl., 94*, 136–145. https://doi.org/10.1016/j.resconrec.2014.10.005.
Mitchell, B. (2005). Integrated water resource management, institutional arrangements, and land-use planning. *Environ. Plann. A Econ. Space, 37*(8), 1335–1352. https://doi.org/10.1068/a37224.
McConnell, V. & Wiley, K. (2010). Infill Development: Perspectives and Evidence from Economics and Planning. Resources for the Future. Retrieved from https://pdfs.semanticscholar.org/935e/10836c0d206e00b72d5570aa5c6e796180f1.pdf.
Murray, J. (2019, April 18). Denver's population has grown by nearly 20 percent since 2010 - and it's picking up again. The Denver Post. Retrieved from https://www.denverpost.com/2019/04/18/denver-population-growth-census/.
National Weather Service. (n.d.). Denver Area Snow Statistics. Retrieved October 12, 2019, from https://www.weather.gov/bou/snowstat.
National Weather Service (2018). Denver's 2018 Annual Climate Summary. Retrieved October 12, 2019 from https://www.weather.gov/bou/Denver_2018_climate_summary.
Panos, C. L., Hogue, T. S., Gilliom, R. L., & McCray, J. E. (2018). High-resolution modeling of infill development impact on urban stormwater dynamics high-resolution modeling of infill development impact on stormwater dynamics in Denver, Colorado. *J. Sustain. Water Built Environ., 4*(4), 1–14. https://doi.org/10.1061/JSWBAY.0000863.
Pearsall, H., & Eller, J. K. (2020). Locating the green space paradox: A study of gentrification and public green space accessibility in Philadelphia, Pennsylvania. *Landscape and Urban Planning, 195*. https://doi.org/10.1016/j.landurbplan.2019.103708.
Pickard, B. R., Nash, M., Baynes, J., & Mehaffey, M. (2017). Planning for community resilience to future United States domestic water demand. *Landscape Urban Plann., 158*, 75–86. https://doi.org/10.1016/j.landurbplan.2016.07.014.
Polebitski, A. S., Palmer, R. N., & Waddell, P. (2011). Evaluating water demands under climate change and transitions in the urban environment. *J. Water Resour. Plann. Manage., 137*(3), 249–257. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000112.
Quesnel, K. J., Agrawal, S., & Ajami, N. K. (2020). Diverse paradigms of residential development inform water use and drought-related conservation behavior. *Environmental Research Letters, 15*(12). https://doi.org/10.1088/1748-9326/abb7ae.
Quesnel, K. J., & Ajami, N. K. (2019). Large landscape urban irrigation: a data-driven approach to evaluate conservation behavior. *Water Resources Research, 55*, 1. https://doi.org/10.1029/2018WR023549.
Sanchez, G. M., Smith, J. W., Terando, A., Sun, G., & Meentemeyer, R. K. (2018). Spatial patterns of development drive water use. *Water Resour. Res., 54*(3), 1633–1649. https://doi.org/10.1002/wrcr.v54.310.1002/2017WR021730.
Serrao-Neumann, S., Renouf, M., Kenway, S. J., & Low Choy, D. (2017). Connecting land-use and water planning: Prospects for an urban water metabolism approach. *Cities, 60*, 13–27. https://doi.org/10.1016/j.cities.2016.07.003.
Shandas, V., & Parandvash, G. H. (2010). Integrating urban form and demographics in water-demand management: an empirical case study of Portland, Oregon. *Environ. Plann. B Plann. Design, 37*(1), 112–128. https://doi.org/10.1068/b35036.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2009). The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape Urban Plann., 92*(3–4), 179–186. https://doi.org/10.1016/j.landurbplan.2009.04.005.

Smirnov, N. V. (1939). Estimate of deviation between empirical distribution functions in two independent samples. *Bull. Moscow Univ., 2*(2), 3–16.

Stoker, P., & Rothfeder, R. (2014). Drivers of urban water use. *Sustain. Cities Soc., 12*, 1–8. https://doi.org/10.1016/j.scs.2014.03.002.

U.S. EPA. (2013). Reduce Your Outdoor Water Use. Retrieved May 11, 2020, from https://19january2017snapshot.epa.gov/www3/watersense/docs/factsheet_outdoor_water_use_508.pdf.

U.S. Census Bureau (2019). Quick Facts: Denver City and County, Colorado. Retrieved October 12, 2019 from https://www.census.gov/quickfacts/fact/table/denvercitycolorado,denvercountycolorado/PST045218.

Vahmani, P., & Jones, A. D. (2017). Water conservation benefits of urban heat mitigation. *Nature Commun., 8*(1). https://doi.org/10.1038/s41467-017-01346-1.

Vermote, E., Justice, C., Claverie, M., & Franch, B. (2016). Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product Remote Sens. *Environ, 185*. https://doi.org/10.1016/j.rse.2016.04.008.

Wolch, J. R., Byrne, J., & Newell, J. P. (2014). Urban green space, public health, and environmental justice: the challenge of making cities "just green enough". *Landscape Urban Plann., 125*, 234–244. https://doi.org/10.1016/j.landurbplan.2014.01.017.

Yang, J., & Wang, Z. H. (2017). Planning for a sustainable desert city: the potential water buffering capacity of urban green infrastructure. *Landscape Urban Plann., 167*(July), 339–347. https://doi.org/10.1016/j.landurbplan.2017.07.014.

Yang, L., Jin, S., Danielson, P., Homer, C., Gass, L., Bender, S. M., … Xian, G. (2018). A new generation of the United States National Land Cover Database: Requirements, research priorities, design, and implementation strategies. *ISPRS J. Photogramm. Remote Sens., 146*, 108–123. https://doi.org/10.1016/j.isprsjprs.2018.09.006.