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Effects of urban residential landscape composition on surface runoff generation

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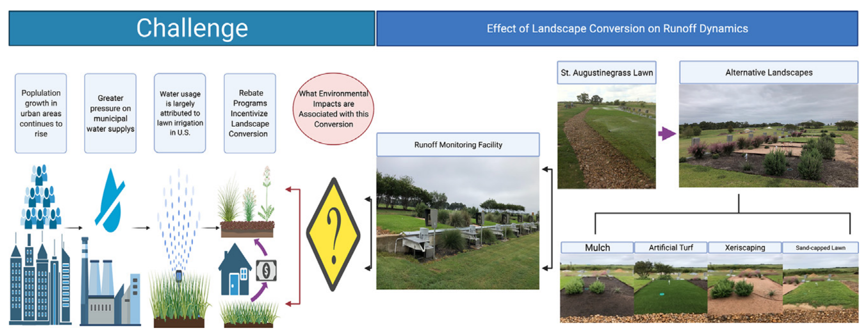
HIGHLIGHTS

- Pressure to save water has caused a shift from lawns to water-efficient landscapes.
- Runoff volumes were affected by landscape, rainfall, and age of the landscape.
- Grass lawns showed greater runoff control than artificial turf and xeriscaping.
- Sand-capped lawn further enhanced control of runoff.

GRAPHICAL ABSTRACT



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ABSTRACT

Lawns have long been a primary feature of residential landscapes in the United States. However, as population growth in urban areas continues to rise, water conservation is becoming a key priority for many municipalities. In recent years, some municipalities have begun to offer rebate programs which incentivize removal of turfgrass areas and conversion to alternative 'water-efficient' landscapes, with the goal of reducing outdoor water use. The environmental impacts and changes to ecosystem services associated with such landscape alterations are not well understood. Therefore, a 2-year continuous research project was conducted at the Urban Landscape Runoff Research Facility at Texas A&M University to evaluate rainfall capture and runoff volumes associated with several commonly used residential landscape types (including, St. Augustine grass Lawn, Xeriscaping, Mulch, Artificial Turf, and Sand-capped Lawn) and to characterize the flow dynamics of surface runoff in relation to rainfall intensity for each landscape. The results demonstrate that runoff dynamics differ between landscapes, but also change over time as the newly converted landscapes become established. Following the initial months of establishment, the effects of landscape type on runoff volumes were significant, with Artificial Turf and Xeriscaping generating greater runoff volumes than Mulch and St. Augustine grass Lawns for most runoff events, which is partially due to the low infiltration rate of such landscapes. Overall, Artificial Turf and Xeriscaping showed the greatest cumulative runoff volumes (>400 L m^{-2}), whereas Water Efficient- Mulch, Sand-capped Lawn and St. Augustine grass Lawn had a significantly lower cumulative runoff volumes, ranging from 180 to 290 L m^{-2}. Information from this research should be useful to municipalities, water purveyors, and homeowner associations as they weigh the long-term hydrological impacts of lawn removal and landscape conversion programs.

1. Introduction

In modern western countries, such as the United States (U.S.), turfgrass lawns have long played an important role in urban landscapes, originally adopted from English pre-romantic gardening (Jackson,

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1985). Turfgrasses in a traditional European-style garden are generally an element of the entire garden, planted along with other ornamental plants, such as flowers and trees (Jenkins, 1994). The use of turfgrass lawns within the American landscape has increased tremendously since the mid-20th century, primarily through the expansion of the monoculture of lawn (Robbins and Birkenholtz, 2003). While turfgrass lawns are a smaller component of the European garden, they have become a major component of residential landscapes in the U.S. (Jenkins, 1994). U.S. turfgrass acreage has been estimated to be 163,800 km^2, which is three times larger than any irrigated crop (Milesi et al., 2005). As rapid population growth continues in urban areas, water conservation has become a key priority for many municipalities. According to the World Health Organization (WHO), more than 50% of the world's population now lives in urban towns and cities, up from 34% in 1960. This trend towards greater urbanization is expected to continue at a rate of 1.63% per year between 2020 and 2025, and 1.44% per year between 2025 and 2030 (WHO, 2020).

If the amount of irrigated urban green space continues to grow as urbanization continues, it will place increasing strains on water supplies. More than 50% of domestic water usage is allocated to residential landscape irrigation in many areas of the world, including parts of the U.S. (Mayer et al., 1999; Degen, 2007; Haley et al., 2007). In Texas alone, Cabrera et al. (2013) estimated the combined sum of water use by golf courses and landscapes to be 46.6% of total water use within the urban/municipal water sector and 12.6% of the total annual demand by all activities during 2010, making urban irrigation the state's third largest water user behind agricultural irrigation and other urban uses. Of this total, the authors estimated annual water use on landscapes to range from 1.898 million to 4.021 million acre-feet, with golf course water use estimated at 0.364 million acre-feet.

While homeowners have traditionally installed and appreciated landscapes comprised predominantly of turfgrass; in recent years some municipalities have begun to offer rebate programs incentivizing removal of turfgrass areas and conversion to alternative landscapes thought to be more water-efficient (Addink, 2005; Zhang and Khachatryan, 2018; Chesnutt, 2019; Pincetl et al., 2019). For example, the 'cash for grass' rebate program developed by North Martin Water District, CA offered residential customers rebates of up to $50 per 100 ft^2 (9.3 m^2) of lawn to remove irrigated grass from the landscape and replace it with approved, low water-use plants (Chesnutt, 2019). As a component of these programs, homeowners are often required to adopt specific landscape designs and planting materials, presumably those with good adaptation to the region. Typical restrictions of these rebate programs include no turf-to-turf conversion, use of smart irrigation installation, and less than 50% overall grassed area within the final landscape (Wilkinson et al., 2013; Zhang and Khachatryan, 2018).

One of the most popular water-efficient landscapes in the southwestern U.S. is xeriscaping, which involves installation of native plants requiring little to no water to supplement precipitation (Mustafa et al., 2010). Studies to estimate the overall water savings from water-efficient landscape conversions have been conducted in recent years. For example, Chesnutt (2019) evaluated changes in water consumption of landscape owners who participated in landscape conversion programs and reported water savings of 2897 L m^{-2} to 3317 L m^{-2} for the first and tenth year following conversion, respectively. Wade et al. (2010) estimated at least $60 per year could be saved on water and sewage costs following conversion of 93 m^2 irrigated to non-irrigated landscape. While water-efficient landscape conversions offer potential to reduce outdoor water use, long-term environmental impacts and ecosystem services associated with these landscape changes following lawn removal are not well understood and are often overlooked. Natural grass lawns provide many benefits both to the environment and to humans, such as temperature mitigation, carbon sequestration, noise reduction, air pollution control, and glare reduction (Beard and Green, 1994; Bolund and Hunhammar, 1999; Monteiro, 2017).

Surface runoff is an important component of the hydrological system of urban areas, and to which stormwater and irrigation water contributes. The effects of urbanization and associated land cover alteration on surface runoff have been widely documented, with more frequent and greater hydrological issues such as stream channel erosion and flooding occurring in recent years, especially for coastal areas (Holman-Dodds et al., 2003; Olivera and DeFee, 2007; Woltemade, 2010). However, most studies of this type have primarily evaluated surface runoff effects occurring from land disturbance, for example, comparing native landscapes to developed areas (Arnold and Gibbons, 1996; Holman-Dodds et al., 2003; Olivera and DeFee, 2007; Guzha et al., 2018; Wang and Stephenson, 2018; Lacher et al., 2019; Gao et al., 2020). Few studies have sought to directly compare ecosystem services between different types of residential landscapes.

To better understand the hydrological impact from landscape conversion, information on rainfall capture and surface runoff dynamics of different urban landscapes is needed. The hypothesis of this study was that runoff generation and patterns should be different for different urban landscapes. Therefore, the objectives of this study were to evaluate the total rainfall capture and runoff volumes generated during natural rainfall events from several commonly used residential landscape types and to characterize the flow dynamics and peak flow of surface runoff in relation to rainfall intensity for each landscape.

2. Material and methods

2.1. Study site

This study was conducted at the Urban Landscape Runoff Facility located at the Texas A&M University Soil and Crop Sciences Field Research Laboratory, College Station, TX from August 2018 to August 2020. The facility comprises 24 individually irrigated 4.1 m × 8.2 m research plots originally established in 2012 with 'Raleigh' St. Augustine grass atop a Boonville fine sandy loam soil (fine, smectitic, thermic, chromic vertic Albaqualf). All plots were constructed to a final slope of 3.7 ± 0.5%, which was intended to preserve the existing native soil profile and slope of the site with minimal disturbance. Each plot was equipped with its own irrigation control and runoff collection system. Runoff was intercepted at the base of each plot by a gutter drain which flowed into a 23 cm H-shaped flume which was equipped with an ISCO bubbler flow meter (ISCO 4230, Teledyne Isco, Lincoln NE) and auto-sampler (ISCO 6712, Teledyne Isco, Lincoln NE). For a complete description of the facility, refer to Wherley et al., 2014. The setup allowed for full documentation of the runoff dynamics including flow patterns and runoff water volumes from irrigation and rainfall events.

2.2. Experimental design

To initiate this study, renovation of some of the grass plots to various types of assumably more water-efficient landscape plots was completed during August 2018, according to a design and native plant selection recommended by a professional landscape architect in the region (personal communication). Due to limitations on number of available plots for use in the research, the study was conducted as an unbalanced randomized complete block design. As there was a difference in the depth of native soil across the study site (25 to 41 cm), which could have an effect on runoff, plots with similar depth were grouped into blocks. Four replications were included for St. Augustine grass Lawn, Mulch, and Xeriscaping, while three replications were included for Sand-Capped Lawn and Artificial Turf, respectively (Fig. 1). Following were the details of five landscape treatments used in the study (Fig. 2):

1) St. Augustine grass Lawn (control): The originally established six-year-old 'Raleigh' St. Augustine grass (*Stenotaphrum secundatum* (Walt.) Kuntze) established from sod atop of native fine sandy-loam soil in 2012.

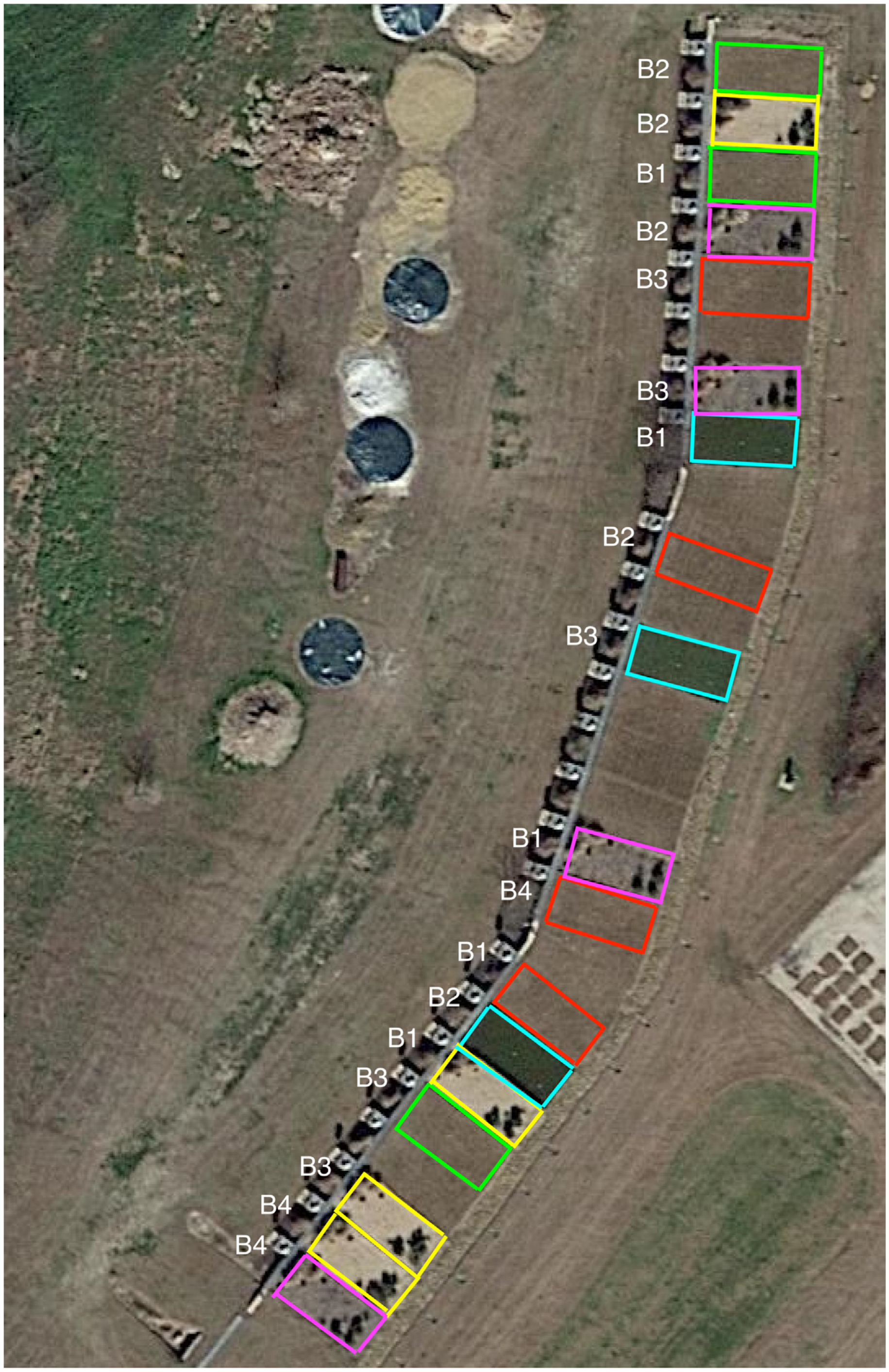

Fig. 1. Google satellite map of the Urban Landscape Runoff Facility located at the Soil and Crop Sciences Field Research Laboratory, at Texas A&M University, College Station, TX. The map was captured during winter. All Lawn plots show brown color due to dormancy. Green frames indicate Sand-capped Lawn. Red frames indicate St. Augustine grass Lawn. Blue frames indicate Artificial Turf. Yellow frames indicate Xeriscaping. Purple frames indicate Mulch. Few grassed plots were not included in this study. Blocks (B) were created based on the depth of topsoil and were highlighted with number (B1 (depth: 37–41 cm), B2 (depth: 34–36 cm), B3 (depth: 31–33 cm), and B4(depth: 25–30 cm)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2) Xeriscaping: Original St. Augustine grass sod and soil were stripped off to a depth of 7.5 cm using a sod cutter and removed. Locally adapted native plants including red yucca (*Hesperaloe parviflora*), Texas sage (*Leucophyllum frutescens*), muhly grass (*Muhlenbergia capillaris*), and dwarf yaupon holly (*Ilex vomitoria*) were then established into two 8.5 m^2 planting beds per plot. Prior to planting, each planting bed was first created by backfilling with 5 cm of the originally excavated soil. After planting, each bed was then covered with a 2.5 cm layer of compacted decomposed granite. The two planting beds occupied 50% of total plot area, which was chosen based on published minimal planted area requirements for several rebate programs (Austin Water, n.d. website; Valley Water, 2020 website). The remaining 50% of the excavated plot was covered with a 7.5 cm deep layer of compacted decomposed granite. When the landscape renovation was completed, no topsoil was visible, and a uniform decomposed granite layer covered the entire plot.
3) Mulch: Original St. Augustine grass sod and soil were stripped off to a depth of 2.5 cm (1 pass at 2.5 cm depth) using a sod cutter and

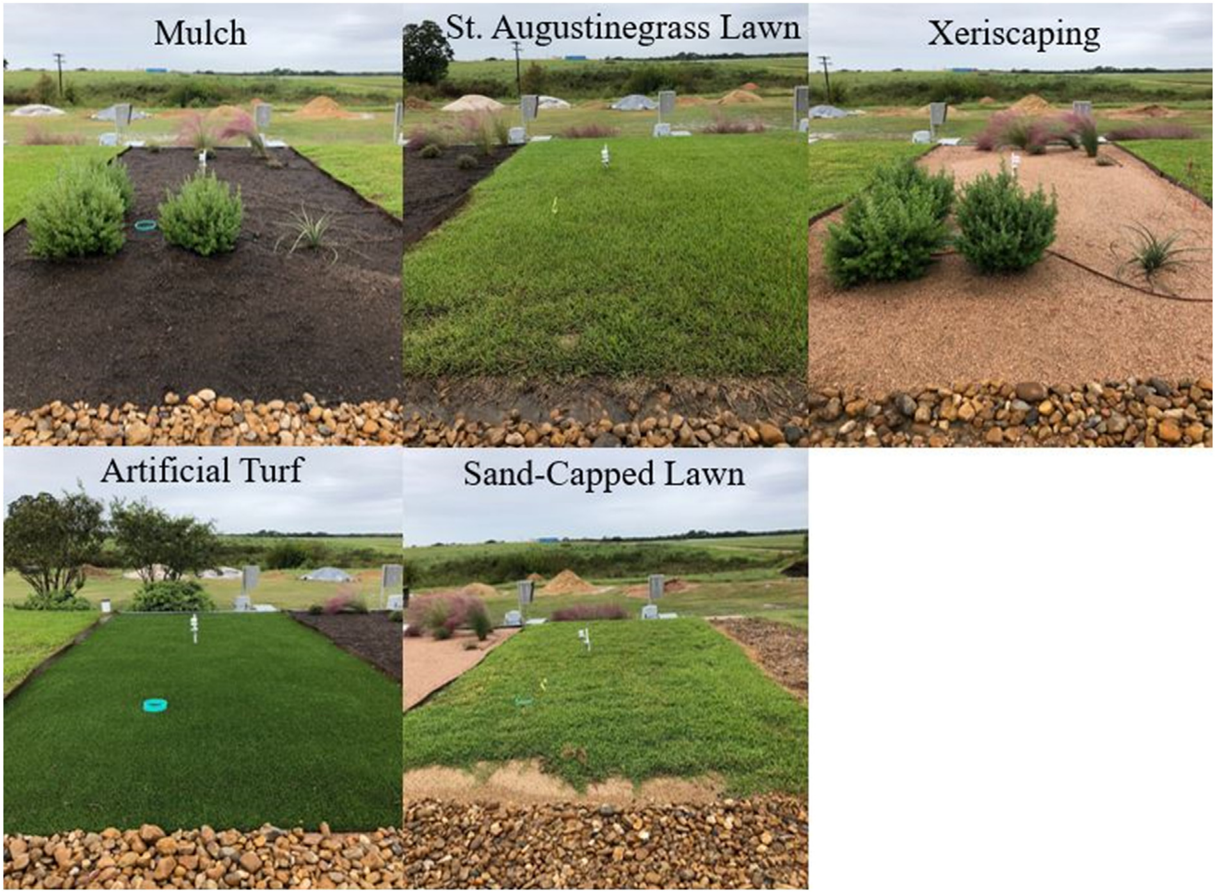

Fig. 2. Turfgrass Lawn and alternative 'water-efficient' landscape treatments tested at the Urban Landscape Runoff Facility at Texas A&M University. Photograph Credit Baoxin Chang August 2018.

removed. The same aforementioned arrangement of native species of water-efficient plants from the Xeriscaping treatment was used. After planting, a 5 cm layer of shredded hardwood mulch (New Earth Compost, San Antonio, TX) was uniformly spread over the entire plot.

4) Artificial Turf: Original St. Augustine grass sod and soil were stripped off to a depth of 7.5 cm using a sod cutter and removed. A 5 cm layer of compacted decomposed granite was uniformly applied to the entire plot. Premium II (EPS Turf, Ewing Landscape Materials, Phoenix, AZ) synthetic turf was then installed atop of compacted decomposed granite base. Green-dyed grit silica sand infill (Ewing Landscape Materials, Phoenix, AZ) was then incorporated into the base of the artificial turf at a rate of 9.76 kg m^{-2}.
5) Sand-Capped Lawn: Original St. Augustine grass sod and soil were stripped off to a depth of 2.5 cm using a sod cutter and removed. A 10 cm deep layer of medium-coarse concrete sand (Knife River Corp. Bryan, TX) was then placed overtop the native fine-sandy loam soil. Particle size analysis of the sand indicated the following mass fractions: 19.5% >2 mm, 7.4% within 1to 2 mm, 14.1% within 0.5 to 1 mm, 36.2% within 0.25 to 0.5 mm, 15.3% within 0.15 to 0.25 mm, and 4.5% <0.15 mm. Washed Raleigh St. Augustine grass sod was then laid atop of the 10 cm sand-cap layer. Due to the limited amount (2.5 cm) of excavation and added depth of sand (10 cm), Sand-Capped Lawn plots were transitioned from 10 cm to a 2.5 cm capping depth across the final 1 m down-slope edge to tie into the surface of the concrete retaining wall containing the drain to collect runoff.

To maintain continuity with non-renovated St. Augustine grass plots, care was taken to ensure that all renovated landscapes were constructed to preserve their original 3.7% slope. An 8.2 m long × 30 cm wide × 2.5 cm deep native soil berm was also created between each plot in order to prevent lateral surface runoff flows between adjacent plots. An 8.2 m long × 10 cm deep strip of plastic edging (Terrace Board, Master Mark Paynesville, MN) was also installed down the center of the berms in order to further prevent lateral surface flow of water as well as contamination of plant or construction materials between plots. Beneath these berms, an 8.2 m long × 45 cm deep × 0.25 mm thick polyethylene liner was also installed in order to prevent lateral subsurface flow between adjacent plots.

2.3. Irrigation of landscape treatments

Artificial Turf treatments received no supplemental irrigation during the study period. The Xeriscaping and mulch landscape treatments were drip-irrigated to supply plants 1.6 L of water per week (0.8 L twice weekly) from May through October, according to a recommended rate of 0.23 L per day (Smith, 2003). During the initial two weeks of establishment, the Sand-Capped Lawn treatment was irrigated twice daily at 3 mm per event. This was reduced to one daily irrigation at 6 mm during weeks 3 and 4 of establishment. After this, both the St. Augustine grass Lawn and Sand-Capped Lawn treatments were overhead irrigated twice weekly at the warm-season turf coefficient of 60% of historical (30-year) reference evapotranspiration (60% × ETo) for the City of College Station, based on data from the Texas ET network (Texaset.tamu.edu). These bi-weekly irrigation events were further split into two start times scheduled two hours apart to minimize runoff. Adjustments to irrigation run times were not accounted for when scheduling irrigation, with the experiment mimicking a "set-it and-forget-it" practice common among urban lawn landscapes in the region. Irrigation applications rarely generated any detectable runoff from plots.

2.4. Fertilization

Artificial Turf Treatments were not fertilized during the study period. St. Augustine grass Lawn and Sand-Capped plots were fertilized at a rate of 4.9 g m^{-2} of N on 27 August 2018 using a 21–7–14 N–P_2O_5–K_2O granular fertilizer (American Plant Food Corp., Millican, TX). On 23 April, 10 July, 27 August 2019 and on 23 April 2020, St. Augustine grass Lawn and Sand-Capped plots were fertilized at a rate of 4.9 g m^{-2} of N using a 32-0-10 N-P_2O_5-K_2O granular fertilizer (Scotts Southern Turf Builder, Scotts Miracle-Gro, Marysville, OH). For Water-Efficient Xeriscaping and Mulch plots, 24-8-16 N-P_2O_5-K_2O liquid fertilizer (Miracle-Gro All Purpose Plant Food, Scotts-Miracle-Gro, Marysville, OH) was applied to planted bed areas on 29 October 2018 and on 23 April 2020.

2.5. Rainfall

Rainfall intensity (mm 2 min^{-1}) occurring during a runoff event was measured and recorded using an onsite tipping-bucket rain gauge (Isco 647, Teledyne Isco, Lincoln, NE) at a two-minute temporal resolution. Total rainfall depth (mm) during a runoff event obtained from rain gauge data were corroborated with precipitation data from an on-site weather station located near the west end of the runoff facility registered with Texas ET Network (texaset.tamu.edu), under station name of TAMU Turf Lab.

2.6. Runoff dynamics- flow and volumes

Runoff dynamics were evaluated for all naturally occurring rainfall events during the study. Flow rates (L s^{-1}) as well as total runoff volumes (L m^{-2}) from each landscape treatment were measured to determine the influence of landscape type on runoff characteristics. Flow rates (L s^{-1}) for each plot were recorded on two-minute intervals (120 s) using ISCO 4230 bubbler flow meters (Teledyne Isco, Lincoln, NE). The flow meter uses the bubbler method of level measurement, and has built-in standard level-to-flow conversions, which automatically converts the level reading (depth) into a properly scaled flow rate (the setting selected for this study was L s^{-1}) according to the primary measuring device. The primary measuring device used for this study was a 23 cm H-type flume. The measurement range of flow meter was 3 mm to 3.1 m, with the maximum level of 23 cm set for this study. More detail regarding the level-to-flow conversions for the instrumentation used can be found in Walkowiak, 2006. Total runoff volumes (L m^{-2}) were then determined by duration of the event (equation: Volume (L m^{-2}) = ($\sum$ (Flow rate (L s^{-2}) × 120 (s))) ÷ plot size (m^2)). Total runoff volume data were analyzed for all rain events.

To better characterize the response of each landscape to precipitation, hydrographs were created by plotting runoff flow rate against precipitation rate during two representative runoff events occurring on 10 October 2018 and 6 June 2019.

2.7. Data analyses

For the effect of landscape on runoff volume analysis, all data were analyzed as a single continuous experiment over two years (September 2018 to August 2020) using a three-factor (Date, Block, and Landscape) mixed-effects model for a repeated measures analysis of variance (ANOVA) (SAS 9.4, SAS Institute, Cary, North Carolina). The equation of the model is:

$$\gamma = \mu + Landscape\ (L) + Date\ (D) + Block\ (B) + L * D + Error(\epsilon)$$

Where γ is the response variable (runoff volume), μ is the overall mean, Landscape and Date are fixed factors, Block is random factor, and ϵ is the error term.

Where significant main effects (Date and Landscape) or interactions were detected, treatment means were compared using Fisher's LSD at $P = 0.05$. Where Date × Landscape interaction was significant, runoff volumes have been presented separately by landscape for each date. There is no intrinsic interest in the block, thus block won't be discussed in this paper.

Peak flow rates (L s^{-1}) of landscapes were compared at three rainfall levels, including 0 to 25 mm (Low to Moderate), 25 to 50 mm (High), and > 50 mm (Very High). These levels were modified from the classification by Li et al., 2015. Data from all runoff events for all replicated plots were included in this analysis, with using a three factor mixed-effects ANOVA to determine the effect of landscape and rainfall level on peak flow rate. The equation of the model is:

$$\gamma = \mu + Landscape\ (L) + Rain\ Level\ (RL) + Block\ (B) + L * RL + Error(\epsilon)$$

where γ is the response variable (peak flow rate), μ is the overall mean, Rain Level and Landscape are fixed factors, Block is a random factor, and ϵ is the error term. Fisher's LSD at P = 0.05 were used for Post hoc analysis.

To predict each landscape's capacity for absorbing rainfall prior to generating surface runoff, the relationships between rainfall amount (mm) and runoff volume (L m^{-2}) were investigated. Several regression models were executed using SAS 9.4 (SAS Institute, Cary, NC), including both nonlinear (using Proc NLIN) and linear models (Proc REG). Quadratic regression was determined to provide the best fit of data based on R^2 and $P \leq 0.05$. Data for all rainfall and runoff events were included in this analysis with the exception of the initial runoff event, which was highly variable and not consistent with subsequent runoff data, likely due to plot settling following construction. The minimal amount of rainfall required for each system to generate runoff was then calculated according to the regression equation while setting runoff volume to zero.

3. Results

3.1. Runoff events and rainfall

During the two-year study period (September 2018 – August 2020), there were 34 runoff events from naturally occurring rainfall. Repeated measures analysis of variance showed a significant ($P < 0.05$) landscape × date interaction for runoff volumes (ANOVA results not shown). Therefore, the effect of landscape on runoff volume was evaluated separately for each date. In general, the magnitude of runoff volume closely related to the rainfall depth, and runoff was usually detected only for rainfall events exceeding ~10 mm (Fig. 3).

During the initial months of establishment (13 Sept. 2018 to 3 Jan. 2019), the effect of landscape type on runoff volume was significant for most events, but there was not a consistent trend with regard to treatment differences (Fig. 3). Also, several high runoff volume events were detected during this period (13 Sept., 17 Oct. 8, and 28 Dec. 2018, and 3 Jan. 2019) due to heavy rainfall. A 226 mm (226 L m^{-2}) rainfall event was detected on 17 Oct. 2018, which generated more than 160 L m^{-2} of runoff water from Artificial Turf, Xeriscaping, Mulch, and St. Augustine grass Lawn, and generated 133 L m^{-2} from Sand-Capped Lawn treatments.

Beginning 23 Jan. 2019, the effects of landscape on runoff volumes became more pronounced, with Artificial Turf and Xeriscaping treatments generating significantly greater runoff volumes compared to other landscapes during most runoff events. In comparison, Mulch and Sand-Capped Lawn treatments yielded the least runoff, around 50% less than that of Artificial Turf and Xeriscaping treatments for most events. The effects of St. Augustine grass lawn on runoff volumes were more complicated than other landscapes. As such, St. Augustine grass Lawn showed similar runoff volumes compared to Artificial Turf and Xeriscaping on several dates including 25 April 2019, 6 June 2019, 31 May 2019 and 28 July 2020. On other dates during the growing season

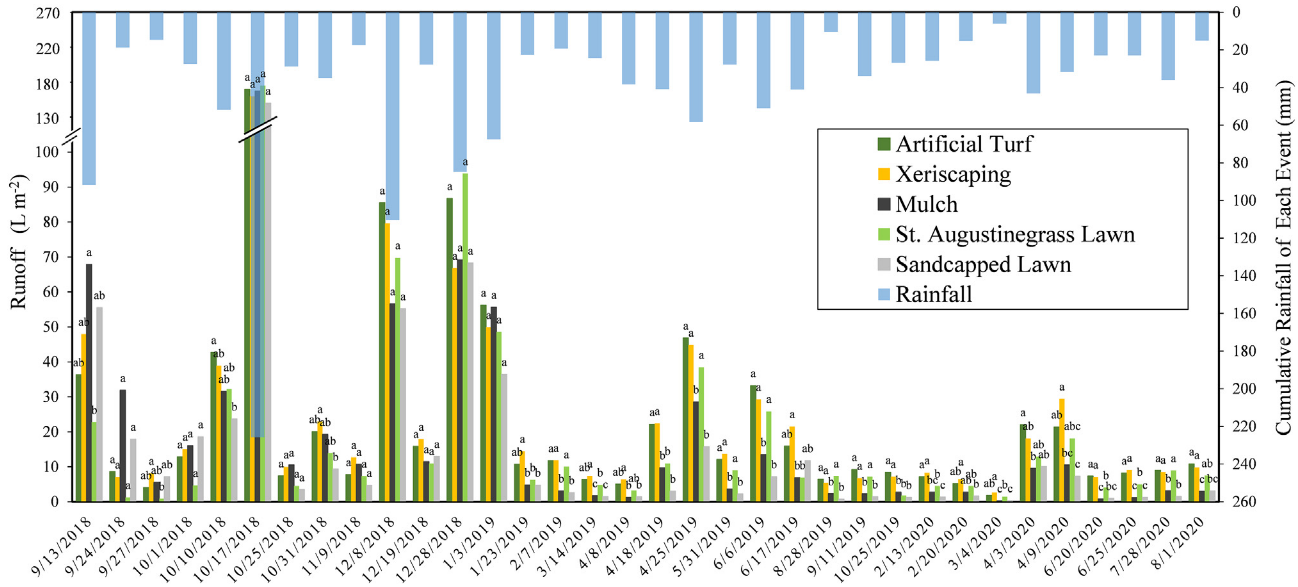

Fig. 3. Cumulative rainfall (mm) of each runoff event and total runoff (L s^{-1}) of all landscapes for each runoff event during the study period. Different lower-case letters signify a significant difference within each runoff event based on Fisher's LSD. A broken y axis was used to fit the 10/17/2018 event in the figure.

(April to October), St. Augustine grass Lawn showed much lower runoff relative to Artificial Turf and Xeriscaping, as observed on 18 April 2019, 17 June 2019, and 25 Oct. 2019.

In terms of cumulative runoff volumes for each landscape across the study period (Fig. 4), Artificial Turf and Xeriscaping showed the greatest cumulative runoff volume (>400 L m^{-2}), whereas Mulch, Sand-capped Lawn and St. Augustine grass Lawn had a significantly lower level of cumulative runoff volume, ranging from 180 to 290 L m^{-2}.

3.2. Runoff dynamics

To characterize the influence of landscape treatments on temporal runoff dynamics, hydrographs integrating rainfall intensity and flow rate over time are presented for two representative runoff events (10 Oct. 2018 and 6 June 2019) (Figs. 5 and 6). On 10 Oct. 2018, a 52 mm rainfall event occurred (Fig. 5). From this event, flow rate (y-axis) is plotted along with precipitation (z-axis), with runoff event timing (x-axis) divided into two phases, 'active rainfall' (1 pm to 5 pm) and 'sporadic rainfall' (5 pm to 9 am). For the decomposed granite-based

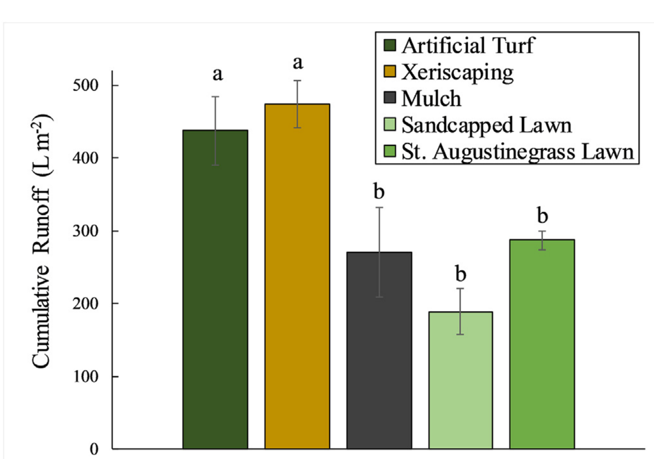

Fig. 4. Cumulative runoff derived from rainfall for landscapes including Artificial Turf, Xeriscaping, Mulch, Sandcapped Lawn, and St. Augustine grass Lawn, during the study period (September 2018 to August 2020). Different lower-case letters signify a significant difference based on Fisher's LSD. Bars represent standard error.

Artificial Turf and Xeriscaping treatments, runoff flow rate mirrored the temporal pattern of precipitation during rainfall, with peak flow rate coinciding with peak precipitation. In comparison, Mulch, Sand-Capped Lawn, and St. Augustine grass Lawn treatments exhibited improved rainfall capture early on, and did not release appreciable runoff until later in the rainfall event (Fig. 5). Among all landscapes, Xeriscaping, Artificial Turf and St. Augustine grass Lawn treatments exhibited somewhat larger peak runoff flows (1 to 1.6 L s^{-1}) compared to Sand-Capped Lawn and Mulch (0.4 and 0.3 L s^{-1}, respectively). During the 12 to 15 h following the rainfall event, the runoff flows from Artificial Turf, Mulch, Xeriscaping, and Sand-Capped Lawn treatments were 5 to 10 times higher than for St. Augustine grass (Fig. 5). As such, the runoff flow rates during the hours post rainfall were 0.001 to 0.002, 0.003 to 0.005, 0.007 to 0.01, 0.01 to 0.017, and 0.015 to 0.025 L s^{-1} for St. Augustine grass Lawn, Xeriscaping, Artificial Turf, Sand-Capped Lawn, and Mulch, respectively. Thus, it can be seen that over the 12–15 h after rainfall, runoff continued to occur from all newly constructed landscapes, which contributed in part to their overall runoff volumes.

Runoff dynamics for the landscape treatments for the 6 June 2019 rainfall event was for a similar precipitation event (51 mm), but after the plots had been established for almost one-year (Fig. 6). These data indicate a change in the hydrological response of landscapes to rainfall when comparing to 10 Oct. 2018 event, as there was no "long-tail" after rainfall runoff for the 6 June 2019 event. All treatments generated runoff during this precipitation event, with the highest flow rates detected for Artificial Turf (peak of 0.25 L s^{-1}) and Xeriscaping (peak of 0.27 L s^{-1}), followed by St. Augustine grass Lawn (peak of 0.19 L s^{-1}). The lowest peak flow rate was associated with Sand-Capped Lawn (0.10 L s^{-1}) and Mulch (0.12 L s^{-1}). Where other treatments showed moderate increases in runoff flow occurring around 7:00 a.m., only minor increases in flow were seen at this time for these two landscapes (Fig. 6).

3.3. Peak flow

The peak flow of all landscapes increased with increasing rainfall level (mm), and a significant interaction between rainfall level and landscape was detected for peak flow rates (Fig. 7). As such, when rainfall was less than 50 mm, the highest peak flow rates were detected for xeriscaping, which showed peak flows of 0.3 L s^{-1} for low to moderate rainfall (0–25 mm) events and peak flows of 0.4 L s^{-1} for high rainfall

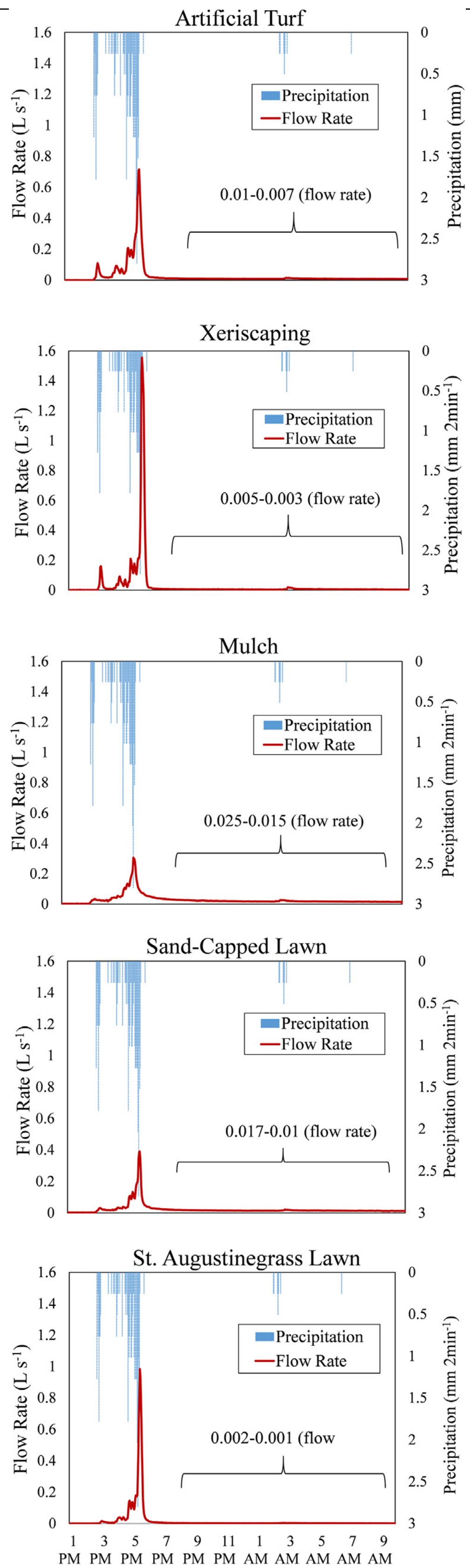

Fig. 5. Runoff flow rates (L s^{-1}) occurring from each landscape during 10 Oct., 2018 rain event. Active rainfall was during the daytime of 1 pm to 6 pm, with scattered rainfall lasted till 7 am of next day. Flow rate and precipitation were measured on 2-min intervals. Red solid line indicates flow rate and blue bar indicates precipitation rate (mm 2 min^{-1}). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

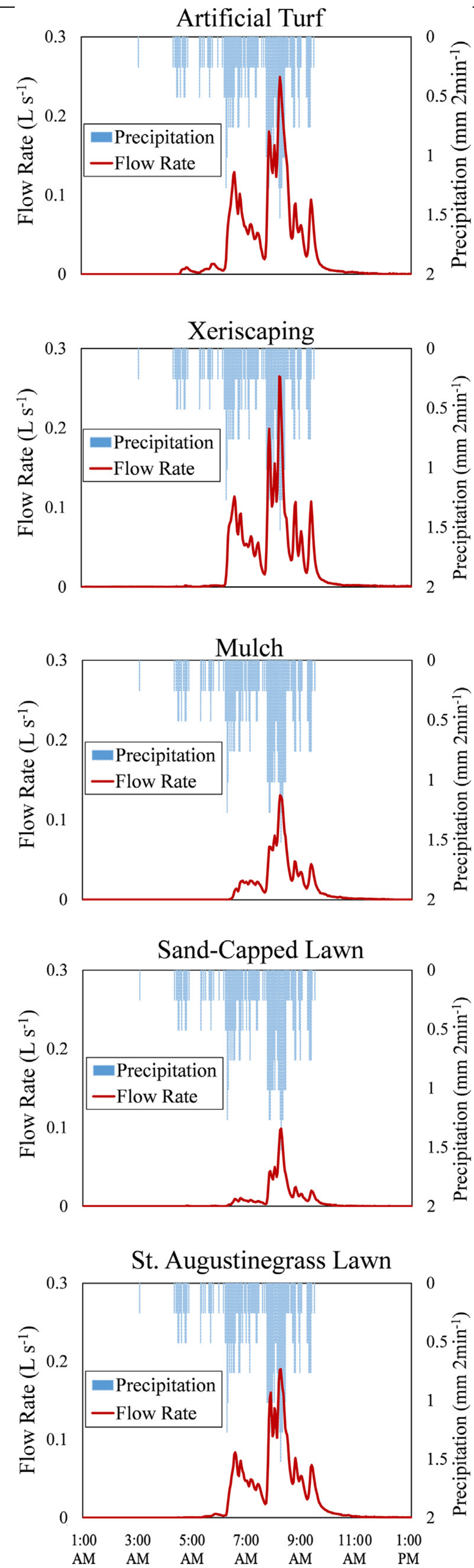

Fig. 6. Runoff flow rates (L s^{-1}) occurring from each landscape during 6 June 2019 rain event. Flow rate and precipitation were measured on 2-min intervals. Actively rainfall was during the daytime of 3 am to 11 am. Red solid line indicates flow rate and blue bar indicates precipitation rate (mm 2 min^{-1}). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

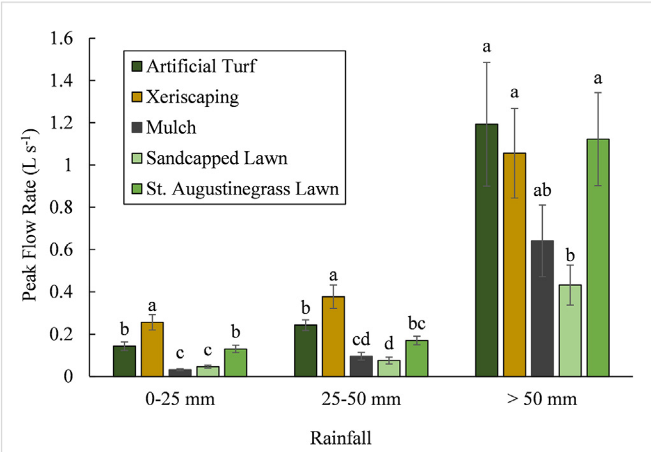

Fig. 7. Peak flow rate (L s^{-1}) of 5 urban residential landscapes under 3 rainfall levels. 0–25 mm, 25–50 mm, and >50 mm, represents rain level of low to moderate, high, and very high, respectively. Data were pooled across all events that falls into each category. Different lower-case letters signify a significant difference based on Fisher's LSD at each rainfall level. Bars represent standard error.

(25–50 mm) events. Artificial turf and St. Augustine grass lawn maintained intermediate peak flow rates, ranging from 0.1 to 0.2 L s^{-1}. The lowest peak flow rates were observed for mulch and sand-capped lawn plots, which were less than 0.1 L s^{-1} under rainfall levels of 0–50 mm. The only significant differences between treatments with regard to peak flow rates were found when comparing Sand-capped Lawn (0.4 L s^{-1}) to Artificial Turf (1.2 L s^{-1}), St. Augustine grass Lawn (1.1 L s^{-1}), and Xeriscaping (1.1 L s^{-1}) treatments at rainfall levels exceeding 50 mm.

3.4. Rainfall capture by landscapes

Quadratic regression of runoff volumes and total rainfall was performed to determine the minimal amount of rainfall required to generate runoff from each landscape (Fig. 8). The calculated R^2 for the regression for Artificial Turf, Xeriscaping, Mulch, St. Augustine grass treatments were all somewhat higher ($R^2 > 0.86$) than Sand-Capped Lawn ($R^2 = 0.77$). Diagnostic analyses including residuals plots and Q-Q plot, etc. (data not shown) indicated that the model assumptions were met for Artificial Turf, Xeriscaping, Mulch, St. Augustine grass. While violation of heteroskedasticity was detected for Sand-Capped Lawn, the actual gradient of the tread line was still unbiased, and thus the same model was used for Sand-capped Lawn. The greater variability in Sand-Capped Lawn treatment was likely the result of greater runoff volumes as a fraction of rainfall during the initial fall season, when plots were irrigated frequently and belowground organic matter had not yet accumulated in plots. Results of quadratic regression analysis indicated Sand-Capped Lawn showed the highest capacity for rainfall capture, with runoff not occurring until rainfall exceeded 22.2 mm (Fig. 8). This was followed by Mulch (18.5 mm rainfall required), St. Augustine grass Lawn (15.7 mm rainfall required), Artificial Turf (13.5 mm rainfall required), and Xeriscaping (10.2 mm rainfall required).

4. Discussion

Competition for potable water supplies has increased dramatically as society has become more urbanized in recent decades. In addition to improved irrigation technologies and day-of-the week irrigation restrictions, landscape conversion rebate programs have been one way a growing number of municipalities have attempted to achieve reductions in outdoor water usage (Austin Water, n.d. website; Valley Water, 2020 website; Chesnutt, 2019; Pincetl et al., 2019). Altered patterns of stormflow concomitant with urbanization and its associated land disturbance increase humankind's vulnerability to natural hazards such as floods and hurricanes (Hur et al., 2008; DeBusk and Wynn, 2011; Burns et al., 2012; Walsh et al., 2012). Water losses derived from surface runoff from landscapes are often accompanied by fertilizers, insecticides, herbicides, and pet waste (Revitt et al., 2002; Smith et al., 2007; Jiang et al., 2012; Yang and Lusk, 2018). Previous studies investigating the impact of landscape disturbance on the surface runoff have been conducted on a broader scale, with few directly comparing runoff dynamics among specific landscape types (Holman-Dodds et al., 2003; Olivera and DeFee, 2007; Woltemade, 2010; Sjöman and Gill, 2014). Specific, in depth information is needed to guide municipalities, policy makers, and landscape architects to make better decisions regarding landscape conversions and their impacts on entire urban ecosystem.

4.1. Runoff events and dynamics

In this study, runoff dynamics differed both between landscapes, but also changed over time as the landscape conversion became established, which may have been due to alteration of physical properties of newly constructed landscape materials (mulch and decomposed granite) over time through due to settling, compaction, and soil aggregation. This is partially supported by the observation that during the initial months of the study, a considerable amount of suspended solids was measured in runoff from Xeriscaping, and to some extent, Mulch treatments (Chang, 2020). Loss of this relatively fine fraction over time may also have altered rainfall capture and water-holding and release dynamics. For example, the newly applied mulch showed the highest runoff volumes during the first two rainfall events, but thereafter showed the least runoff of all treatments. It appears that this may have been due in part to the influence of physical properties of the mulch on water-holding capacity and release after rain events. Early on, during the fifth rainfall event of the study, mulch appeared to release water over a considerably longer period time after rainfall compared to other landscapes, with the post-rainfall flow rate nearly 10 times higher than other landscape treatments (Fig. 5), and this likely contributed to the higher total volume of runoff from mulch during the early stage of the study (Fig. 3). Later on in the study, however, this extended runoff duration was not seen for the Mulch treatment. We suspect that greater settling and aggregation of mulch over time may have contributed to enhanced water holding capacity, which in turn, reduced duration and extent of runoff losses.

Relatively higher runoff volumes were also observed for Sand-Capped Lawn in the early months of this study (Fig. 3). We speculate this was primarily due to the frequent irrigation inputs that were required to establish the washed sod on the sand root zone during the initial month, and resultant impacts on higher soil moisture content. Furthermore, sand-capped lawn treatments would have gradually accumulated greater amounts of organic matter in the upper sand-cap layer over the first full season, which would likely have improved water holding capacity and contributed to runoff reductions over time.

Beginning spring 2019, after plots were established and settled in, and through the end of the study, Sand-Capped Lawn and Mulch generally had significantly lower runoff volumes than all other landscapes. The native soil-based St. Augustine grass Lawn maintained moderately low runoff volumes, while Xeriscaping and Artificial Turf each showed the highest runoff volumes (Fig. 3). It should be noted that, in addition to factors such as particle size density and infiltration rates of the basing material (decomposed granite, mulch, sand, or soil) used, antecedent soil moisture is another important consideration affecting runoff amounts. For example, on 28 July 2020, St. Augustine grass had just been irrigated prior to a 36 mm rainfall, which led to similarly high runoff volumes between St. Augustine grass, Artificial Turf, and Xeriscaping (the latter two of which received drip or no irrigation). Overall, rainfall immediately followed irrigation only three times during the study period. In addition, actively growing warm-season turfgrasses can

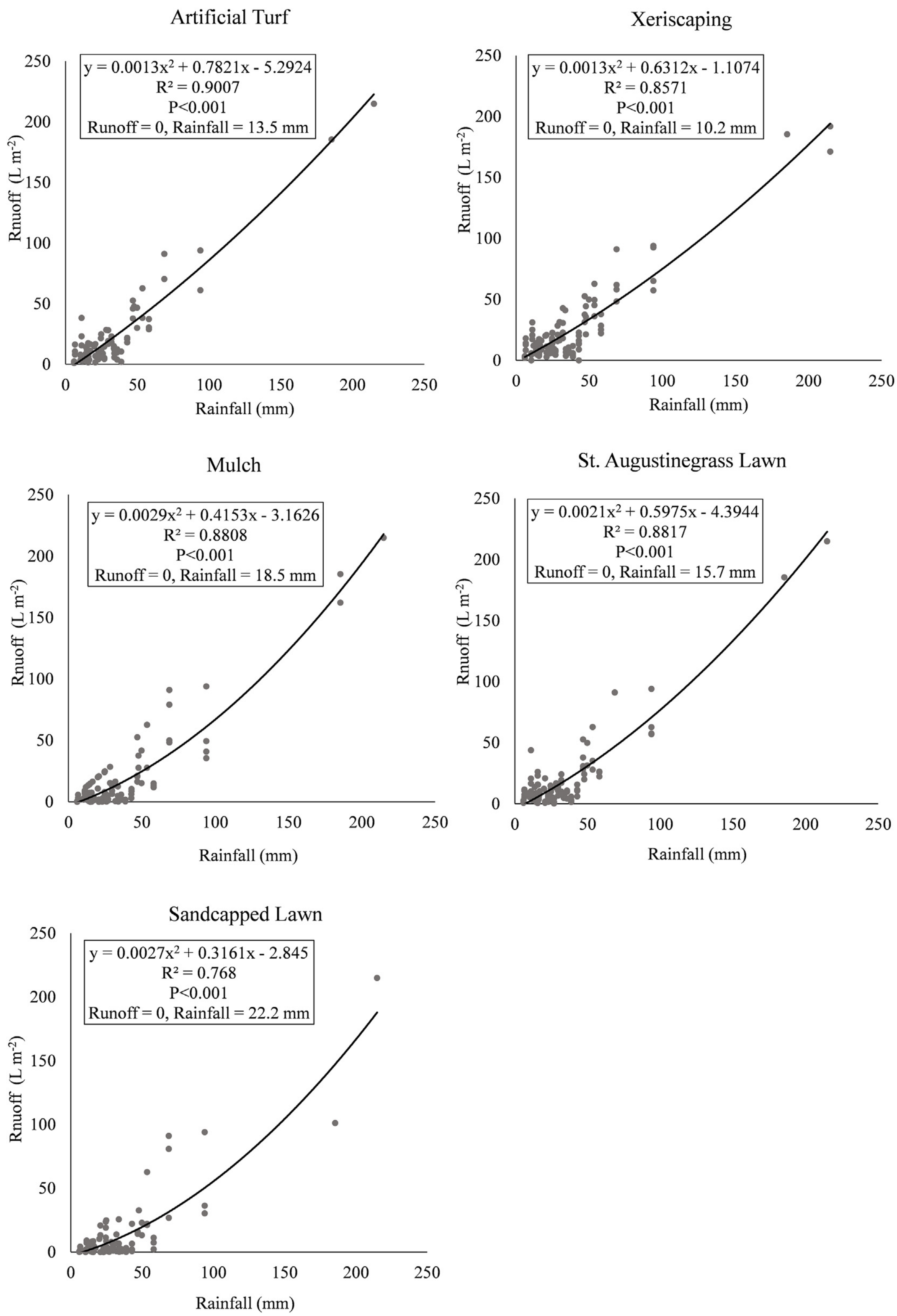

Fig. 8. Quadratic regression of rainfall (mm) and runoff (L m^{-2}) for each landscape during the study period (September 2018 to August 2020). The least amount of rainfall that is required for each system to generate runoff was calculated according to the regression equation with setting runoff volume to 0.

consume more than 3 cm of water weekly during the growing season which can results in significant changes in soil moisture content from day to day during the growing season (Kim and Beard, 1988). Soil moisture depletion due to grass evapotranspiration during the active growing period (summer-fall) likely contributed to observed runoff differences when comparing St. Augustine grass lawn to Xeriscaping and Artificial Turf plots. Similarly, Fontanier et al. (2017) previously demonstrated that deficit irrigation of St. Augustine grass lawn turf reduced summer and early autumn runoff volumes, which highlights the important of antecedent moisture conditions on runoff generation.

The landscape base materials used in this study (decomposed granite, mulch, coarse sand, and native soil) clearly played a role in water infiltration and capture as well as runoff dynamics, however, infiltration rates were not directly measured in this study. While we are not aware of any studies of this exact nature, related studies have been conducted comparing runoff among different urban surfaces including fully pervious, relatively pervious, and impervious soil surfaces (Boyd et al., 1993; Holman-Dodds et al., 2003; Shafique et al., 2018). Runoff as a fraction of precipitation is lower on high-infiltration capacity soils and higher on low-infiltration capacity soils (Holman-Dodds et al., 2003). However very few studies have been conducted to directly compared the infiltration rates of different landscape types, and conflicting results exist in terms of determination of the effects of turfgrass on soil infiltration rate. Turfgrasses have been shown to have a positive impact on reducing runoff compared to other surfaces, and this primarily results from the high shoot density and presence of thatch in turfgrasses (Beard and Green, 1994; Easton and Petrovic, 2004; Liang et al., 2017). Woltemade (2010) determined the impacts of residential soil disturbance on soil infiltration rates and storm water runoff and found that soil infiltration rates differed considerably between residential lawns and agricultural areas, with lawns having measured saturated infiltration rates of 2.8 cm per hour compared to 10.2 cm per hour for agricultural areas.

4.2. Peak flow and rainfall intensity

Another interesting observation was that effect of landscape type on runoff mitigation was insignificant when rainfall exceeded 60 mm, and this was the case for four events during the study (17 Oct. 2018, 8 Dec. 2018, 28 Dec. 2018, and 3 Jan. 2019 (Fig. 3). This finding appeared to be largely driven by the high rainfall intensity during these events, rather than overall amount alone. This can be seen in the peak flow results (Fig. 7). As such, when rainfall amount exceeded 50 mm, differences in the peak flows between landscapes were less apparent. These observations suggest that the effects of landscape composition on runoff volumes are less significant with greater rainfall intensities. Similarly, a previous study that investigated the effect of rainfall intensity, grass type, and vegetation coverage on stormwater runoff of urban green spaces confirmed that rainfall intensity had the highest influence among all factors on surface runoff (Yang et al., 2013).

4.3. Rainfall capture by landscapes

Relative runoff or runoff coefficients, calculated as a percentage of rainfall and lag time between the center of precipitation volume and center of runoff volume have been widely used to characterize the ability of a landscapes to capture rainfall (Paul and Meyer, 2001; Moreno-de Las Heras et al., 2009; Loperfido et al., 2014; Zhang et al., 2015; Liu et al., 2018). For example, Zhang et al. (2015) generated runoff coefficients for various land cover types, and determined the coefficient for residential grass to be 0.23 to 0.34 (i.e. 23–34% of incoming precipitation is runoff). Liu et al. (2018) showed relative runoff of 0.25 to 0.75 for landscapes with vegetation cover of 50%, and noted this number could be decreased to 0 to 0.5 when vegetation cover approached 100%. In this study, a different approach was used to characterize the ability of a landscapes to capture rainfall. Based on the results, rainfall capture by Sand-Capped Lawn and Mulch landscapes was nearly double that of Xeriscaping and Artificial Turf. However, there was a limitation of the current model due to the lack of data on antecedent soil moisture, which has been well documented to influence runoff volumes (Wei et al., 2007; Zhang et al., 2011; Schoener and Stone, 2019). Thus, future studies should also consider soil moisture data for more fully characterizing the complexity of factors influencing runoff.

4.4. Implications

To our knowledge, this is one of the first studies aimed at investigating hydrological impacts of urban residential landscapes on a small scale using a replicated treatment design. One challenge with this type of research is there is no universal landscape type for all urban areas. Our treatments were designed based on our site's climate, locally adapted plants, commonly used basing materials, and recommendations from a local professional architect. Based on the results of this study, it appears that while requiring more water, lawns also offer enhanced rainfall capture/runoff control compared to xeriscaping and artificial turf systems. Although sand-capping is a relatively recent practice in construction and renovation of golf course and sports fields (Dyer et al., 2020), it has not been widely adopted in urban landscapes. Our research suggests that sand-capping may offer improved rainfall capture and runoff mitigation compared to traditional lawn established atop native, clay or loam soils. Also, it may be challenging to extrapolate our findings to landscape situations in other climates, as differences in rainfall, soils, and temperature may have produced somewhat different results. Also, the desired ecosystem services provided by a given landscape may differ based on societal preferences, desired function, and available resources for maintaining such landscapes.

5. Conclusion

The results of our study demonstrate the importance of landscape composition on runoff dynamics and volumes. Generally, landscapes with greater compaction and/or based with materials containing finer particles, such as xeriscaping and artificial turf, would have higher potential of runoff generation. In this study, traditional lawns and sand-capped lawns showed superior runoff control, especially during the growing season. In the future, similar studies should be conducted under different climates in order to provide region-specific recommendations. The environmental impacts of landscape conversions are not limited to runoff, so future studies should also consider dynamics including energy balance, water quality, and air pollution. In addition, the total impact of landscape construction and associated materials on the environment should be considered. Collectively, the information gained from this research could benefit municipalities, water purveyors, and homeowner associations as they weigh the long-term benefits and consequences of lawn removal and landscape conversion programs.

CRediT authorship contribution statement

Baoxin Chang: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Benjamin Wherley:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jacqueline A. Aitkenhead-Peterson:** Methodology, Resources, Writing – review & editing, Funding acquisition, Supervision. **Kevin J. McInnes:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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