

A Study of Soil Infiltration Rates in Diverse Urban Park Settings in Tucson, Arizona: Implications for Urban Planning and Stormwater Management

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Abstract

Urban parks play a crucial role in addressing environmental challenges, including stormwater runoff. However, their effectiveness varies significantly due to factors such as soil type. This study evaluates soil infiltration rates across various soil types in selected urban parks in Tucson, AZ. Twelve urban parks (Augie Acuna, Brandi Fenton, Catalina, Gene Reid, John F. Kennedy, La Madera, McCormick, Mirasol, Ormsby, Santa Rita, Santa Rosa, and Tahoe) were selected using stratified random sampling. *In-situ* soil infiltration rates were measured using a single-ring infiltrometer with a diameter of 4.5 inches and a height of 6.5 inches. Soil infiltration rates across the parks ranged from approximately 0.69 mm/s to 1.56 mm/s. La Madera Park, characterized by sandy loam soil, exhibited the highest infiltration rate at 1.56 mm/s, whereas Mirasol Park, featuring silty clay and sandy soil, recorded the lowest rate at 0.69 mm/s. The data underwent statistical analysis using ANOVA packages in JMP, and treatment means were separated using Tukey's test. Findings emphasize the significant diversity in infiltration capacities of urban park soils, primarily influenced by soil textural properties. This information provides essential, site-specific insights for enhancing urban planning, developing targeted stormwater management strategies, optimizing irrigation practices, and directing park maintenance efforts. The author recommends that urban planning initiatives incorporate soil infiltration data into park design and stormwater management.

Keywords

Infiltration Rates, Urban Parks, Soil Infiltration, Stormwater Management

1. Introduction

Infiltration rate, defined as the rate at which water enters the soil, is a fundamental parameter in flood management [1]. It influences soil moisture, groundwater recharge, and surface runoff, thereby playing a significant role in stormwater management [2]. Soils with high infiltration rates absorb larger volumes of rainwater, which helps reduce both the frequency and intensity of local flooding, lessens stormwater runoff volumes that burden urban drainage systems, and enhances groundwater recharge [3]. Understanding soil infiltration is essential for effective flood management, sustainable water resource management, and maintaining overall environmental health, particularly in flood-prone areas [4].

Urbanization typically disrupts natural hydrological processes by significantly increasing impervious surfaces (e.g., roads, buildings, parking lots [5]. This alteration often results in increased surface runoff volumes and peak flows, reduced groundwater recharge, and consequently heightened flood risks, alongside degraded water quality [6]. Urban parks, as essential components of green infrastructure, play a crucial role in mitigating these adverse effects by providing permeable surfaces that promote water infiltration, decrease runoff, and enhance water quality. However, their effectiveness in delivering these vital ecosystem services varies significantly based on several interconnected factors, particularly the soil's infiltration characteristics [7] [8].

Vegetation cover, land use, park maintenance, and site layout all significantly affect the rate of water absorbed by the soil, which greatly influences groundwater recharge, flood control, and ecosystem health [9]. For example, trees significantly enhance the soil's capacity to absorb water. Tree roots improve porosity and boost infiltration rates. Plant canopies also intercept rainfall, slowing down raindrops and lessening their impact on the soil surface [10]. Land use directly influences water infiltration. In natural settings, such as forests and grasslands, most rainfall seeps into the soil, supporting consistent streamflow and maintaining good water quality [11]. The design and layout of cities greatly influence stormwater management. Impervious surfaces significantly disrupt the water cycle. They reduce water penetration into the ground [12]. Park maintenance practices can greatly affect soil infiltration rates. Regular maintenance can improve infiltration, while a lack of maintenance may cause rates to decline [13]. Although these are essential factors, the focus of the current study is to investigate the effect of soil on infiltration.

The infiltration rate in any given landscape, including urban parks, results from a complex interplay of factors [14]. These factors include soil texture (the relative proportions of sand, silt, and clay), soil structure (the arrangement of soil particles), organic matter content, antecedent soil moisture, and the degree of soil compaction [15]. Soil compaction, often caused by intensive recreational use, foot traffic, or construction and maintenance activities, can impact infiltration capacity, even in otherwise permeable soils. Additionally, vegetation cover and type significantly influence infiltration by maintaining soil structure, protecting the soil sur-

face from raindrop impact, and creating macropores through their root systems [16]. In arid or semi-arid regions, such as Tucson, Arizona, characterized by low average annual precipitation that typically arrives in intense, short-duration storm events, effective management of soil infiltration is particularly crucial [17]. These areas face challenges related to water scarcity as well as risks of flash flooding. Tucson's geological landscape features a diverse range of soil types; some regions have sandy or loamy soils that naturally exhibit higher infiltration rates, while others consist predominantly of clayey soils, which have inherently lower infiltration capacities [17].

Optimizing the infiltration potential of urban green spaces in these climates is vital for water conservation, reducing flood risk, and enhancing urban resilience to climate variability. While the importance of soil infiltration in urban ecosystems, especially in arid-region green spaces, is acknowledged, there has been a notable lack of comprehensive site-specific studies investigating these rates across various urban parks in Tucson. The current study aims to fill the knowledge gap. By examining the infiltration rates and capacities of different soil types found in selected urban parks in Tucson, AZ, this research provides valuable, evidence-based insights that will enhance urban park management, inform targeted storm-water management strategies, and guide park maintenance practices in Tucson and other arid cities.

2. Materials and Methods

2.1. Study Area

The study was conducted in Tucson, Pima County, Arizona, the state's second-largest city [18]. Tucson spans approximately 226.71 square miles and has an estimated population of 547,239 [18]. The city is located in the Sonoran Desert, known for its arid climate, low annual precipitation, and high summer temperatures [19]. July and August typically see the most rainfall, primarily as a result of intense monsoon thunderstorms [19]. Summer temperatures, especially in June and July, often exceed 37.8°C (100°F) [20]. January generally records the lowest temperatures [20]. The natural vegetation is dominated by Sonoran Desert flora, including various species of cacti, particularly the saguaro.

The area where Tucson sits in a broad valley on an alluvial filled down-drop basin and range graben (20) Arizona. The basin is surrounded by five mountains namely Tucson, Sieritta, Santa Rita, Rincon, and Santa Catalina mountains.

2.2. Park Selection and Sampling Strategy

Twelve urban parks were selected for this study: Augie Acuna, Brandi Fenton, Catalina, Gene Reid, John F. Kennedy, La Madera, McCormick, Mirasol, Ormsby, Santa Rita, Santa Rosa, and Tahoe. Stratified random sampling was employed for park selection. This method aimed to choose samples that accurately represent the population. It involved dividing the parent population into two mutually exclusive geospatial strata (Central Tucson and South Tucson) and then randomly selecting

parks from each stratum [21]. This method enhances sampling efficiency. It minimizes sample selection bias by categorizing different types of parks and narrowing the differences between them, while also reducing the overall sample size. Stratified sampling further reduces variability in measurements within each stratum, leading to smaller bounds on estimation errors [21]. The method was chosen because North, East, and West Tucson are bordered by mountain ranges that create a barrier around the city. As a result, rainwater from precipitation flows into the basin, occasionally causing flash flooding since these events primarily occur within the basin. This study focused on strategies to mitigate flash flooding in the area. *In-situ* soil infiltration rates were measured using a single-ring infiltrometer with a diameter of 4.5 inches and a height of 6.5 inches.

2.3. Soil Characterization

At each sampling point, soil samples were collected in triplicate and labeled accordingly. Subsequently, all the soil samples were submitted to the soil science lab at the University of Arizona for analysis of soil composition, texture, and classification.

2.4. Infiltration Rate Measurement

Soil infiltration rates were measured in situ using a single ring infiltrometer (Geopack, ZMFP38) manufactured by Turf-Tec International with a diameter of 4.5 inches and a height of 6.5 inches. The beveled end of the infiltrometer cylinder was carefully inserted into the soil surface to a depth of about 1.5 inches, ensuring that it remained level and perpendicular to the surface. A fall unit (the depth of water infiltration to be timed) of 0.787402 inches was selected for all measurements, following the instructions (Figure 1).



Figure 1. The double ring infiltrometer. Source: Fieldwork. Infiltrometer cylinder filled with water, showing initial fill level.

The cylinder was initially filled with water to a mark of 3.93701 inches. A timer was started at the same time the water began to infiltrate. The time T , in seconds, taken for the water level to drop by the selected fall unit (0.787402), was recorded for each trial (Figure 2).



Figure 2. The double ring infiltrometer. Source: Fieldwork. Infiltrometer showing ongoing infiltration measurement.

After each trial, the cylinder was refilled to the initial 3.93701 inches mark, and the time taken for the water level to drop by the defined unit was noted. This process continued until the time required for the water to infiltrate the fall unit stabilized across three consecutive readings. The average time step length for each park was calculated and recorded. The experiment was not done across seasons because Tucson has an arid weather pattern in very minimal variation from one season to another, therefore, since soil infiltration is mostly dependent on soil properties, it was not considered that seasonal variations will not have a significant impact on infiltration rates.

2.5. Data Calculation and Analysis

The infiltration rate (IR) for each stabilized trial was calculated using the following formula:

$$IR \text{ (mm/s)} = \frac{\text{Depth of water infiltrated (D, in mm)}}{\text{Time taken for infiltration (T) in seconds}}$$

where D = 20 mm or 0.787402. The data collected was subjected to statistical analysis using ANOVA models in JMP, and treatment means were separated using Tukey's test.

3. Results

Soil infiltration rates measured across the twelve urban parks sampled in Tucson are shown in **Table 1**. The rates varied significantly, ranging from a low of 0.69 mm/s to a high of 1.56 mm/s. This notable variation was strongly influenced by the soil type identified at each park location, with statistically significant differences observed among the soil types.

Table 1. Soil type and mean infiltration rates in sampled urban parks in Tucson, AZ.

Park	Soil Type	Infiltration Rate (mm/s)	Tukey Group
Augie Acuna	Silty Clay	0.70	b
Brandi Fenton	Sandy clay + trace of gravel	0.86	b

Continued

Catalina	Sandy clay + trace of gravel	0.83	b
Gene Reid	Sandy clay + trace of gravel	0.84	b
John F. Kennedy	Silty clay	0.71	b
La Madera	Sandy loam	1.56	a
McCormick	Silty clay + traces of gravel	0.88	b
Mirasol	Silty clay + sand	0.69	b
Ormsby	Silty clay + trace of sand	0.78	b
Santa Rita	Silty clay	0.73	b
Santa Rosa	Silty clay + trace of sand	0.76	b
Tahoe	Silty sand	1.47	a

4. Discussion

The findings of this study show significant variability in soil infiltration rates across various urban parks in Tucson, Arizona, ranging from approximately 0.69 mm/s to 1.56 mm/s. This broad range highlights the considerable influence of soil type on infiltration capacity, even within managed urban green spaces. The differences are significant in arid or semi-arid regions, such as Tucson, where effective water resource management and stormwater mitigation are vital due to limited water supplies and the potential for intense rainfall events.

Parks with higher infiltration rates, such as La Madera Park (sandy loam) and Tahoe Park (silty sand), are significantly more effective at absorbing rainfall. This capacity enables better local stormwater runoff mitigation, potentially reducing the risk of localized urban flooding and alleviating the burden on municipal stormwater systems. Moreover, enhanced infiltration in these parks can contribute more meaningfully to groundwater recharge, a vital ecosystem service, particularly in water-scarce regions. For instance, a high-intensity, short-duration Tucson thunderstorm delivering 25 mm of rain in 30 minutes (an intensity of 50 mm/hr) would be largely or entirely infiltrated by the soils in La Madera or Tahoe parks, assuming no surface sealing or extreme antecedent moisture.

Conversely, parks with lower infiltration rates, such as Mirasol Park (silty clay + 0.69 mm/s), Augie Acuna Park (silty clay, 0.70 mm/s), and John F. Kennedy Park (silty clay), are more likely to produce surface runoff during heavy rainfall events. Even the 50 mm/hr storm intensity in the previous example would exceed the infiltration capacity of these soils, leading to ponding or runoff. These areas may require specific landscape design considerations or additional stormwater management strategies to enhance their ability to manage water and mitigate potential flood risks. Such strategies might include constructing rain gardens or bioswales in or near these parks, utilizing permeable surfaces and pavements in nearby pathways or parking areas, or applying targeted soil amendments to im-

prove soil structure and porosity. The results strongly emphasize the need to incorporate soil-specific considerations into urban planning and the management of urban green infrastructure. A quantitative understanding of the infiltration characteristics of park soils enables urban planners, landscape architects, and park managers to make more informed decisions regarding irrigation scheduling (avoiding over-irrigation and runoff in low-infiltration areas), vegetation selection (choosing plants suited to soil moisture conditions and those that can enhance infiltration), and the implementation of best management practices (BMPs) aimed at maintaining or improving soil health and hydrological function. For instance, in parks with compacted soils or those dominated by clay, such as Mirasol or Augie Acuna, practices like core aeration, deep soil mixing, or incorporating organic matter (e.g., compost) could be beneficial for enhancing soil structure and, consequently, infiltration rates. Research has shown that organic matter amendments can significantly improve the hydraulic properties of clayey soils [22].

While soil texture emerged as a primary determinant, other factors likely contribute to variability in infiltration. Soil compaction from foot traffic, sports activities, or the use of maintenance vehicles can significantly reduce infiltration rates, regardless of texture [23]. Although not quantitatively measured in this study, observations in heavily used areas of parks suggest that compaction may lead to lower rates in certain zones. Vegetation type and density also play a role; well-established turf or native vegetation with extensive root systems can enhance infiltration compared to bare soil or sparsely vegetated areas [24].

5. Conclusions

This study effectively characterized and quantified soil infiltration rates across twelve urban parks in Tucson, AZ, revealing significant variations directly linked to soil textural properties. Sandy loam and silty sand soils exhibited the highest infiltration capacities, while silty clay and sandy clay soils recorded substantially lower rates (Table 1). These findings have critical implications for urban planning, stormwater management, park design, and maintenance strategies in Tucson and other cities confronting similar arid environmental conditions and water management challenges. Understanding these site-specific soil hydraulic properties is essential for designing resilient urban landscapes that can effectively manage stormwater, promote groundwater recharge, and contribute to sustainable water resource management in water-limited environments. This research provides an empirical basis for developing evidence-based approaches to optimize the hydrological performance of urban parks, thereby fostering more sustainable and resilient urban ecosystems that can adapt to changing climatic conditions.

This information provides essential, site-specific insights for enhancing urban planning and developing targeted stormwater management strategies, optimizing irrigation practices, and improving park maintenance to enhance soil health and hydrological function in Tucson and similar arid or semi-arid urban landscapes.

6. Recommendations

Based on the findings of this study, the authors recommend the following in Tucson and similar arid or semi-arid urban areas:

1) Integrate Soil Data into Planning and Design: Utilize soil infiltration data as a key input in the design and master planning of new urban parks, as well as the retrofitting of existing ones. Prioritize designs that protect and enhance infiltration in high-potential areas and incorporate engineered solutions (e.g., rain gardens, bioswales) in with low infiltration.

2) Implement Soil-Specific Management Practices: Develop and implement park maintenance plans tailored to specific soil conditions. For parks with low-infiltration soils (e.g., Mirasol, Augie Acuna):

- Minimize soil compaction through designated pathways, restricted vehicle access, and periodic aeration or soil amendment with organic matter
- Select drought-tolerant vegetation adapted to heavier soils and potentially periodic wetness if surface ponding occurs.

By adopting these recommendations, cities like Tucson can more effectively leverage their urban green spaces to manage stormwater, conserve water, and build more resilient and sustainable urban environments.

7. Further Research

- Conduct more detailed studies incorporating quantitative analysis of soil properties (particle size distribution, organic matter content, bulk density) alongside infiltration measurements.
- Investigate the long-term effects of various vegetation types (e.g., turfgrass vs. native xeric landscaping) and soil amendment practices (e.g., compost application, biochar) on infiltration rates in the soils of Tucson's urban parks.
- Monitor infiltration rates seasonally to understand temporal dynamics.
- Expand the study to a broader range of urban green spaces and land use to develop a comprehensive hydrological map for the city.
- Evaluate the cost-effectiveness of different soil improvement techniques in enhancing infiltration and reducing stormwater management costs.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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