

Designing “Complete Green Streets” for Multiple Benefits: Improving Equity, Increasing Safety, and Reducing Flooding Across the Multimodal Transportation Network

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1.0 INTRODUCTION

Transportation systems have historically been designed to move the greatest number of vehicles as efficiently as possible across a city from point to point. However, streets also represent roughly 70–90% of cities’ public open spaces (NACTO, 2020). In addition to being conduits, streets act as an important amateur on which an array of public services can be built. Streets can be designed to provide multiple benefits across multiple modes of transit for aggregate network impact.

The U.S. Department of Transportation defines the term Complete Streets as streets that enable “safe use and support mobility for all users (USDOT, 2020).” Green Infrastructure (GI) is defined by the Environmental Protection Agency as “reducing and treating stormwater at its source while delivering environmental, social, and economic benefits (EPA, 2020).” This paper integrates these two recognized concepts to design a “Complete Green Street” that reduced flooding for increased safety and equitable access while providing an array of community assets. Led through an University of Arizona upper-level design studio that was sponsored by the City of Tucson, the partnership used spatial mapping, quantitative analysis, hydrological modeling, and design inquiry to create a six-mile bicycle boulevard that is slated to be constructed from the northern to southern city limits, passing through the largest municipal park.

This paper starts with a review of recent complete street, flood modeling, and GI literature. Then, research methods are outlined. Results are discussed for a set of four Complete Green Street prototypes: crowned streets, inverted crowned streets, curbed streets, and naked streets. Each of these four Complete Green Street prototypes were designed with a set of corresponding GI kit-of-parts based on the greatest flood reductions modeled for each condition. Based on the hydrological modeling performance results for these prototypical designs across the 6-mile bicycle boulevard, this research concluded that the greatest potential impacts for flood reduction were in locations with the largest existing right-of-way and moderate flooding levels. This paper argues that by

working across disciplines and departments, new typologies for place-specific, multi-benefit street designs can be created and implemented. Complete Green Street design can expand multimodal accessibility and safety through flood reduction and increased community assets.

2.0 BACKGROUND AND LITERATURE REVIEW

2.1 Complete Streets

Complete Streets are streets designed to ensure safe and assessable use across multiple modes and user types. By 2018 nearly 1,500 Complete Streets policies had been adopted across the U.S. (Riveron 2018). Complete Streets have been found to improve community health, increase safety, and advance economic development (Dodds 2017). However, comprehensive reviews of these policies find a consistent deferral to idealistic goals without recognizing the need to negotiate the trade-offs between the many users and modes prioritized in Complete Streets (Gregg and Hess 2019). Further, there is an existing literature gap in the integration of flood mitigation in Complete Street design toward the accomplishment of the fundamental goals of safety and access. This research addresses this gap through the conceptualization of Complete Green Streets designed with GI.

2.2 Transportation Systems, Flooding Analysis, and Hydrological Modeling

Climate change is increasingly stressing the natural system’s ability to manage flood events, especially as they impact urban transportation systems. Recent literature focuses on the transportation system vulnerability to flooding with the need to evaluate network-wide impacts as well as prioritizing mitigation strategies. GI is a multiscalar concept that applies to a continuum of features from the site to landscape to ecoregion scales (Marcucci and Jordan, 2013). Unlike grey infrastructure systems that are often large and centralized, GI can be designed at different spatial scales and implemented in decentralized arrangements (Suppakittpaisarn et al., 2017; Zhang et al., 2019). Due to complex upstream and downstream interactions, “sustainable urban stormwater management must be planned and implemented at the watershed scale (Roy et al., 2008).” Network connectivity is a central concept in both GI and transportation planning. The network needs to function efficiently at multiple scales from region to city to

BICYCLE BOULEVARD FLOODING

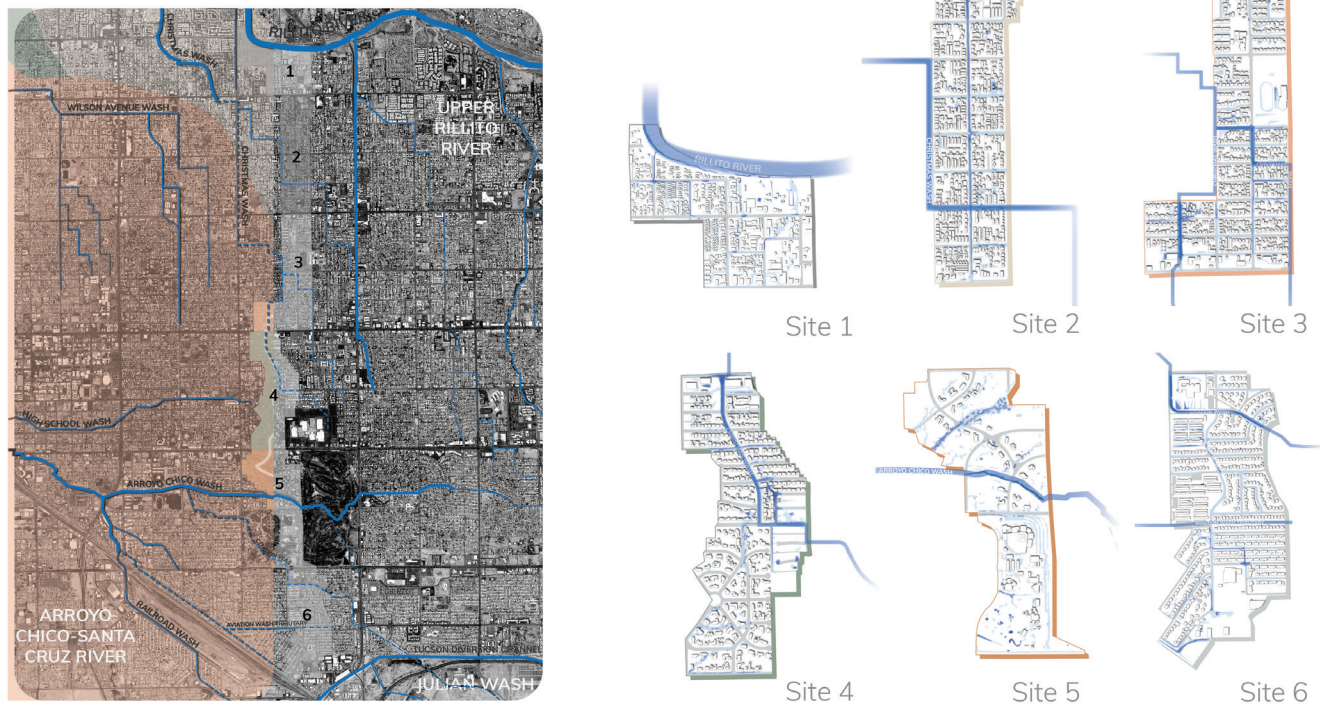


Figure 1. Map of bicycle boulevard and research-design area (Credit: ARCH 451a studio, 2020).

neighborhood to street. This project designed a continuous bicycle boulevard to across the span of a city, traversing six neighborhoods, with details designed at the street scale.

2.3 GI Design, Benefits, and Challenges

There are a host of large, medium, and small scale GI design elements that have been proven to mitigate urban flooding. These elements include basins (Belizario et al., 2016), bioswales (Lucas et al., 2015), bioretention (Lucke and Nichols, 2015), and constructed wetlands (Li et al., 2016). In transportation system flood mitigation, GI is usually installed in the adjacent right-of-way of the street and therefore predominantly uses the smaller GI elements. In transportation projects in Tucson, Arizona, the list of potential GI elements is narrowed to median bioretention, chicane or bump out bioretention, linear street-side bioretention, traffic circle or roundabout bioretention, intersection bump out bioretention, park or open space bioretention, and porous pavement (American Rivers, 2020)

Where gray infrastructure tends to be designed to perform a single function, GI serves multiple purposes and provides a range of services from engineering, environmental, to human benefit (Ely and Pitman, 2014). Literature on the functions and benefits of GI frames effects from the global to local scales. Studies have investigated the benefits of GI for hydrological regulation for water quality, increased rainwater retention, reduced flood damage, improved pedestrian connectivity and safety, and improved transportation accessibility. GI has been

proven to positively impact the urban transportation system by reducing flooding, expanding accessibility, and providing safety through traffic calming and pedestrian and bicycle protection. Additionally, GI has many documented environmental benefits or ecosystem services including: erosion control, improved water quality, groundwater recharge, mitigating effects of urban heat island, reduced energy demands for cooling, and enhanced aesthetics and access to green space (Zhang et al., 2019).

There are challenges associated with the design, planning, implementation, and maintenance of GI over the long-term, which include the development of place-based design standards, regulatory frameworks and policies, continuous funding, socio-economic disparities, and the adoption of innovation (Zuniga-Teran et al., 2019). Additionally, many green infrastructure installations are not properly maintained (Roman et al. 2017) and their actual performance, particularly in the long-term, is unknown (Bell 2018 et al. 2016, Feng and Burian et al. 2016).

3.0 METHODS

3.1 Research Area

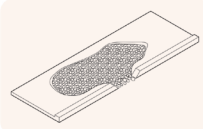
This research designed a 6-mile bicycle boulevard across Tucson, Arizona. Tucson experiences annual events of severe flooding and has recently adopted a Complete Streets policy and a Green Stormwater Infrastructure fee. Located in the

KIT OF PARTS

GREEN INFRASTRUCTURE - BASINS

Curbed Street

Crowned Street



B Roadside Basin

Why use it?

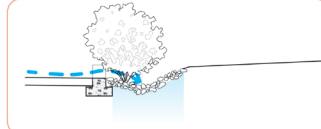
- Reduce road flooding
- Improve stormwater quality
- Increase vegetation and reduce demand for potable water

Co-Benefits?

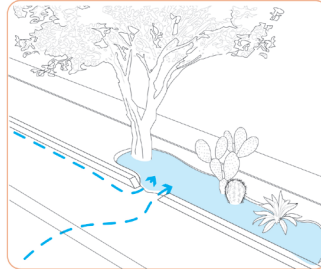
- Provides shade canopy for pedestrians and cyclists
- Reduce heat islands
- Improve wildlife habitat

Considerations + Maintenance

- Cleaned after major rain events
- Checked for damages or obstructions to inlets
- Avoid areas with poor drainage conditions, such as bedrock
- Basins may serve as water destinations for water catchment structures



Section of Basin With Curb Cut



Possible Application - Water Catchment from Pavement



D Basin - Bump-Out (Neck-down)

Why use it?

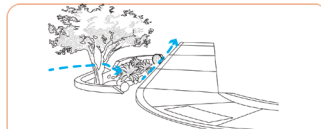
- Reduce Flooding on roadway
- Slow down vehicular traffic
- Protect bicycle lane

Co-Benefits?

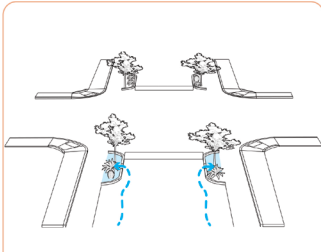
- Improve accessibility and pedestrian safety
- Provide shade canopy

Considerations + Maintenance

- Cleaned after major rain events
- Checked for damages or obstructions to inlets
- Avoid areas with poor drainage conditions, such as bedrock
- Must use vertical reflectors to maintain vehicle visibility



Inlets and Outlets



Possible Application - Bump-Outs at Intersection

Inverted Crowned Street



C Traffic Circle Basin

Why use it?

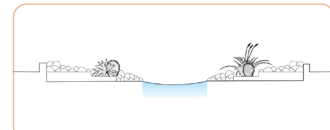
- Traffic calming
- Reduce flooding
- Decrease the demand for potable water at vegetation intersection

Co-Benefits

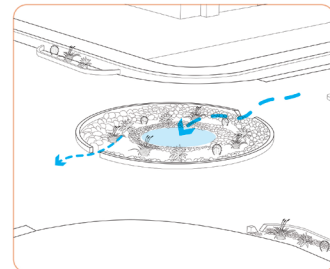
- Reduce vehicle speeds
- Pedestrian safety
- Serve as way-finding markers

Considerations + Maintenance

- Cleaned after major rain events
- Inlets and outlets should resist incursions from bikes and cars
- Low planting required
- Conditions, such as bedrock
- Vehicle reflectors/vertical reflectors required



Center Water Collection



Possible Application - Traffic Circle at Intersection



E Basin - Median

Why use it?

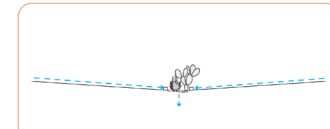
- Reduce flooding in roadway
- Utilize runoff from inverted road conditions

Co-Benefits

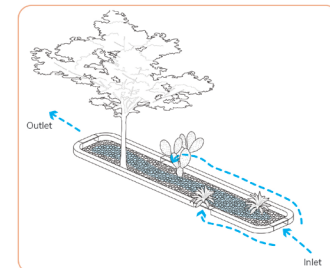
- Narrows road conditions for slower speeds
- Improve aesthetic of roadway
- Mitigates heat islands

Considerations + Maintenance

- Cleaned after major rain events
- Checked for damages or obstructions to inlets
- Avoid areas with poor drainage conditions, such as bedrock
- Must use vertical reflectors to maintain vehicle visibility
- Inlets and outlets should resist incursion from vehicles and cyclists

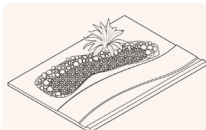


Section of Inverted Crown with Basin



Possible Application - Center Median

Naked Street



A Basin - General

Why use it?

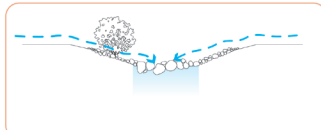
- Reduce Flooding
- Improve stormwater quality
- Reduces demand for potable water

Co-Benefits

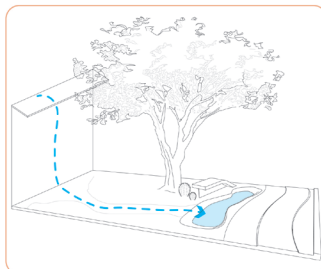
- Improve ground cover
- Provide shade canopy
- Improve wildlife habitat

Considerations + Maintenance

- Cleaned after major rain events
- Checked for damages or obstructions to inlets
- Avoid areas with poor drainage conditions, such as bedrock
- Basins may serve as water destinations for water catchment and GI practices, like rain gardens



Section of Basin



Possible Application - Property Run-off Mitigation

KIT OF PARTS

VEGETATION



A Mesquite



B Palo Verde



C Desert Ash



D Red Yucca



E Cape Aloe



F Agave

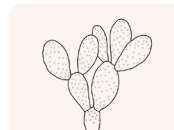
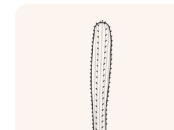


Figure 2. Kit-of-parts for street typologies (Credit: ARCH 451a studio, 2020).

Sonoran Desert, Tucson is subject to fluctuations in daily volumes and seasonal patterns of rainfall. Tucson has a light (roughly December through February) and heavy (roughly July through September) rainy season joined by intense stretches of heat and dryness.

Tucson has a unique stormwater management history. The majority of the urban center of Tucson does not currently have storm water piping. Streets were designed to carry the heavy rain flows that occur during the winter and monsoon seasons to washes throughout the city. Over time, the city grew and greatly shifted its majority pervious land cover to impervious. Tucson has the highest yearly extreme storm count across Western US Metropolitan Statistical Areas (Bakkensen and Johnson, 2017). These urban water extremes affect citizens directly and disproportionately. Tucson averages \$9.5 million in property losses each year from flooding in the city center where stormwater infrastructure was historically not installed, predominately in lower income areas (Bakkensen and Johnson, 2017).

To address these issues, the County and City have worked over the last decade to collaboratively develop policies to address current flooding issues and retrofit Tucson with a network of GI. The City of Tucson established a Green Streets policy in 2013 which requires that the department of transportation design new upgraded streets that convey stormwater into GI features. Additionally, a goal of covering streets with a 25% tree canopy is stated. In 2019, the City passed a Complete Streets policy with the goal of ensuring safety and accessibility to the transportation network to a diversity of citizens. In spring 2020, the Tucson City Commissioners adopted a new GSI fee, previously absent from community water bills. In contrast to the two existing fees for potable water and sewer, this third fee funds the planning and construction of a decentralized GI system throughout the city. The goal of using GI in Tucson is to reduce areas of localized flooding and improve co-benefits such as increased shade, reduced heat island effect, and decreased nonpoint source pollution throughout the city. These three recent policies support the implementation of efficient and connected transportation and stormwater networks, like the funded bicycle boulevard which is the focus of this research.

3.2 Public-Academic Partnership

This paper examines this Tucson case study where a public-academic partnership was formed between neighborhood associations, Tucson Department of Transportation planners, County Flood Control District hydrologists, and the University of Arizona (UA). Led through an UA upper-level design studio, the partnership used spatial mapping, quantitative analysis, hydrological modeling, and design inquiry to create a six-mile bicycle boulevard that is slated to be constructed from the northern to southern city limits, passing through the largest municipal park. The City of Tucson sponsored the research

studio course. The project designed the bicycle boulevard with context-specific GI to provide localized and network benefits including flood reduction, shaded pedestrian and bicycle protected paths, increased safety measures and traffic calming, and neighborhood place-specific social areas. Then, extrapolating from this boulevard design, a set of prototypical interventions were categorized across a variety of conditions to retrofit the City's multimodal transportation system into a network of "Complete Green Streets".

3.3 Hydrologic and Hydraulic Modeling of the Street Network

As a part of this public-academic partnership, Pima County Flood Control completed hydrological modeling across the 6 mile bicycle boulevard design (FIGURE 1). This modeling was completed with Flo-2D, a fluid dynamics software that combines hydrology and hydraulics to model flooding conditions. Student were provided with three iterative flood analyses to inform their designs: a baseline case for their site, flow reduction and storage capacities for their mid-term design, and flow reduction and storage capacities for their final design.

4.0 APPLICATIONS AND RESULTS

Four main street typologies occurred throughout the six-mile bicycle boulevard (Figure 1): Crowned, Inverted Crowned, Curbed, and Naked (Figure 2). Along the bicycle boulevard, the street scape moved through six different neighborhoods and transformed from normal crowned streets with curbs to inverted crowned streets for flood conveyance to naked and narrow streets. Each of these street conditions has a compatible set of 'Complete Green Street' kit-of-parts (Figure 2) to optimize accessibility and flood mitigation performance. This section defines these street typologies, describes typical characteristics, and outlines the kit-of-parts that supports community accessibility and flood reduction.

4.1 Crowned Streets

Crowned streets (Figure 3) are the most common urban street profile where the centerline of the street is graded as the highest point. Water flows to the sides of the streets. This street design condition efficiently moves water away from car travel; however, it can lead to greater flooding in bicycle lanes and pedestrian pathways if not properly designed.

Kit-of-part strategies for crowned streets include the 'bump out basin' and 'roadside basin' (Figure 2). The complete green street kit-of-parts for this street condition are designed to reduce flooding on the sides of the streets to increase bicycle and pedestrian accessibility. Further, this water is directed to the passive irrigation of street trees and vegetation that provide shade to bicyclists and pedestrians, contribute to overall heat island reduction, and enhance neighborhood aesthetics. Figure 3 shows a crowned street at one of the major intersections of the bicycle boulevard. Bicycles are uniquely placed in the middle of the road at this intersection so that both

Crowned and Curbed Street Example

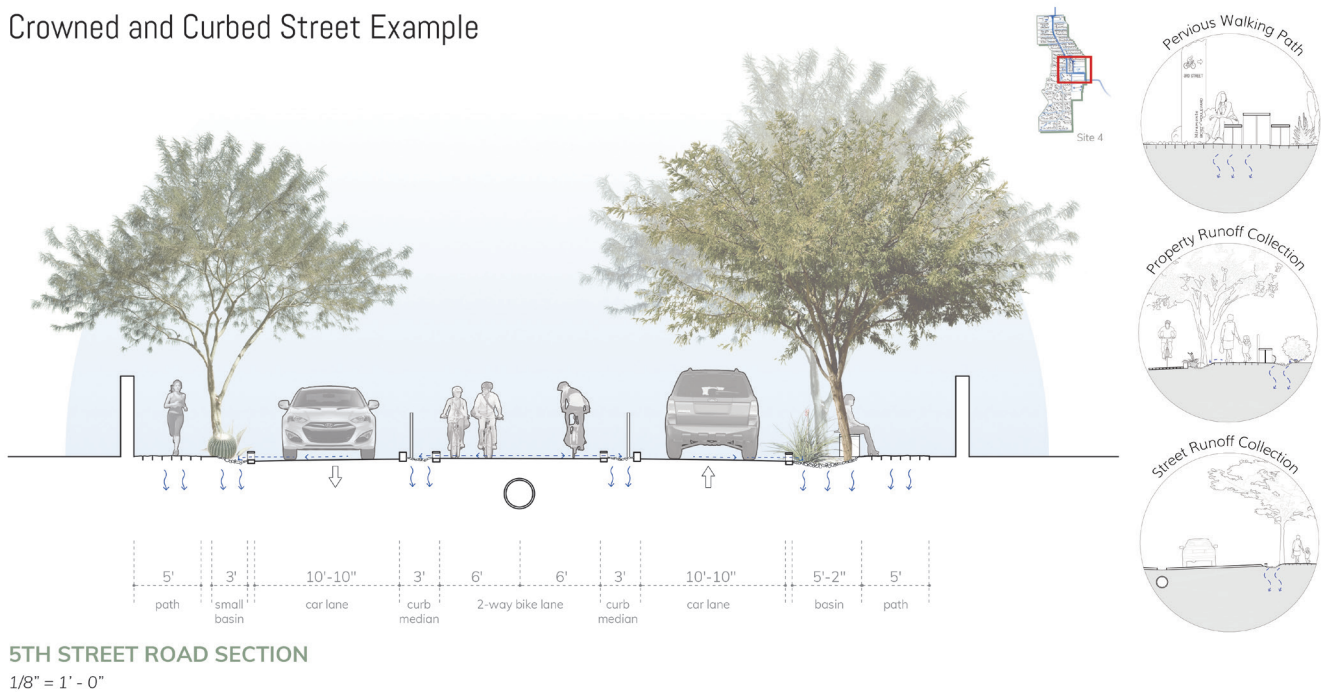


Figure 3. Crowned and curbed street example section (Credit: Mary Henderson and Hannah McCormick, 2020).

directions of travel can uniformly cross the road with one signal. Curb cuts are made at regular intervals to allow water to flow from the street to the roadside basins. Pedestrians are both shaded and protected from cars on the far limits of the street right-of-way. Walking paths are further made of compacted pervious material to allow for the further infiltration of water.

Crowned streets with sufficient right-of-way area for widespread GI implementation can successfully reduce flooding conditions and provide additional assets like shaded walkways and social spaces. The hydrologic modeling of the bicycle boulevard implementation of crowned street kit-of-parts showed flood reduction across this street typology.

4.2 Inverted Crowned Streets

Inverted crowned streets (Figure 4) channel water to the center of the road. Unlike crowned streets, these streets reduce water in the right-of-way and areas typically occupied by bicyclists and pedestrians. These streets are only common in cities that used their streets as surface stormwater channels and do not have underground stormwater piping. Tucson was historically designed for a selection of designated streets (usually ones that followed the natural washes and drainage conditions in the landscape) to be inverted crowned to channel water from the city center to peripheral rivers and washes

The Complete Green Street kit-of-parts for this street condition are designed to reduce flooding in the middle of the street and use this water to increase vegetation. Kit-of-part strategies for inverted crowned streets include the 'traffic circle

basin' and 'median basin' (Figure 2). Also, a 'bump-out basin' can be paired with these kit-of-parts to reduce corner flows. Traffic calming for pedestrians and bicyclists is encouraged with traffic circles and medians. These kit-of-parts are often incompatible with large street trees as their placement in the center of the street can reduce visibility and adversely affect safety. Figure 3 shows an example implementation on the bicycle boulevard that uses median basins with native trees in the right-of-way shoulder to provide shade to pedestrians and bicyclists.

Inverted crowned streets often have the most severe flooding in an urban area because they were designated to convey water. With increased development and impervious areas surrounding these streets, flooding greatens. In cases where flooding is still within a moderate range, the hydrologic modeling of the bicycle boulevard showed significant flood mitigation with kit-of-part implementation throughout inverted crowned streets. Where flooding had reached severe conditions, the GI implementation had little impact on these extremes. In these severe cases, underground piping or large adjoining basins capable of taking substantial amount of water offline is needed.

4.3 Curbed (High Traffic) Streets

Curbed streets were common place across the 6-mile bicycle boulevard, particularly in high traffic areas. The only exceptions were in an industrial area and historic residential landscapes. Curbs are implemented in urban areas to protect the long term life of the street and to provide a barrier between the street

Inverted Crowned and Curbed Street Example

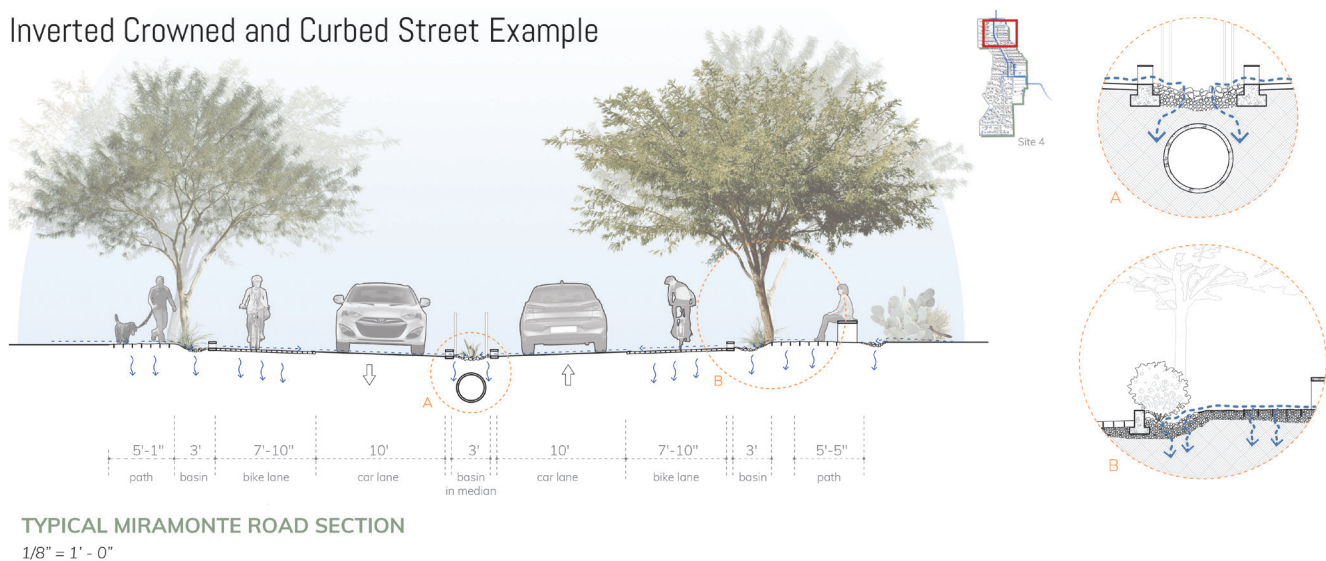


Figure 4. Inverted crowned and curbed street example section (Credit: Mary Henderson and Hannah McCormick, 2020).

and the shoulder where pedestrians walk. Additionally, curbs are often designed to channel water into inlets for underground storm sewers. In central Tucson where there are no storm sewers, curbs hinder the movement of water into GI, such as roadside basins. Curb cuts are important features to implement along with GI.

All of the kit-of-parts outlined in Figure 2 can be successfully used with curbed streets with the regular implementation of curb-cuts. These cuts are depicted in each kit-of-part. On the bicycle boulevard, streets have low enough speeds that curb cuts can be left open to the sky. However, on very high-traffic streets, curb-cuts are covered with a metal plate so that the curb edge is kept continuous and fast moving traffic does not catch a wheel in these cuts and cause an accident.

4.4 Naked (Low Traffic) Streets

Naked streets along the bicycle boulevard occurred in two low-traffic areas: narrow residential streets with historic native vegetation and streets in industrial areas. These naked or curbless streets have the advantage of freely flowing water to the road-side vegetation without having a curb obstruction. In Tucson, many historic neighborhoods have naked streets as their roads were sited within the landscape, rather than the landscape being graded and adapted to a regular plan. Thus, most naked streets in Tucson are also meandering and narrow to traverse these natural landscape conditions. As such, common issues such as blind corners and limited width for multimodal travel occur.

A series of 'general basins' can be designed along these streets for pockets of absorption. This kit-of-part strategy is seen in Figure 2 and Figure 5. If desired by the neighborhood, sidewalks and separated bicycle lanes can be implemented to better protect pedestrians and bicyclists from blind spots in these narrow street conditions. These native landscape and low-traffic neighborhood conditions with narrow streets often have large city-owned right-of-way areas on the shoulders. Small social spaces for neighborhood gatherings or rest places for pedestrians and bicyclists can also be developed in this typology. Generally, flooding issues are minimal for this typology given the large landscape areas, small relative impervious street areas, and the uninhibited flow of water.

5.0 CONCLUSION

This paper argues that by working across disciplines and departments, new typologies for place-specific, multi-benefit street designs can be created and implemented. Complete Green Street design prototypes were developed for four street types: crowned streets, inverted crowned streets, curbed streets, and naked streets. Based on the hydrological and modeling of the prototypical designs, this research concluded that the greatest potential impacts for flood reduction in the city were in locations with the largest existing right-of-way and moderate flooding levels. A set of kit-of-parts is provided for these four street typologies. As the City of Tucson goes forward with bicycle boulevard retrofits to existing streets, these typologies and kit-of-parts can provide the design framework for Complete Green Streets across the urban area.

Naked Street Example

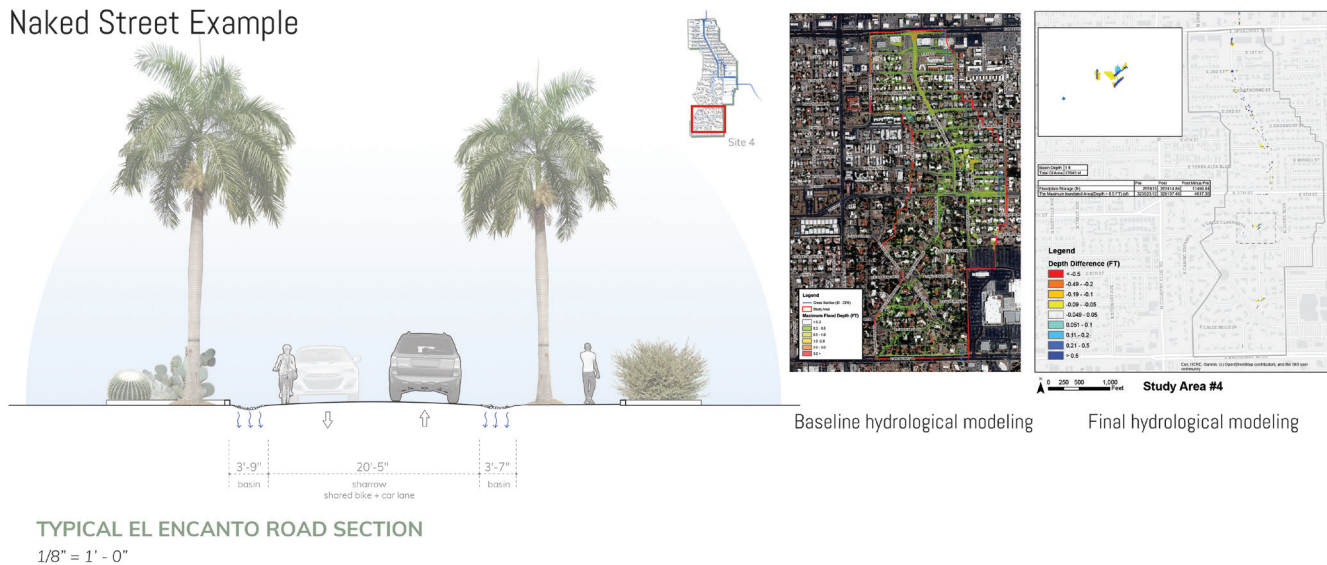


Figure 5. Naked street example section (Credit: Mary Henderson and Hannah McCormick, 2020).

This paper presents a replicable model for architectural academia to join with local communities and government staffs to provide practical solutions to urban transportation and water challenges through a Complete Green Streets design approach. Because of this successful partnership, student interns are working for the City to develop the designs into construction-ready documents. A book entitled “Tucson Adaptive Streets: Designing for mobility, water, and community” with the four street prototypes and corresponding kit-of-parts was provided to the City and County as an outcome to this research.

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