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Urban Transportation System Flood Vulnerability Assessment with Special Reference to Low Income and Minority Neighborhoods

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by

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16. Abstract
A flood vulnerability assessment of the City of Tucson, Arizona's transportation systems was conducted with special reference to low-income and minority neighborhoods. Short-term flooding from extreme storm events pose a serious challenge to transportation system reliability and emergency response in cities across the United States. This problem, which is anticipated to grow over the next century due to climate change, is often hardest on vulnerable populations, including low-income and minority neighborhoods. Our work aimed to advance national research methods for assessing multi-modal transportation degradation due to flooding. We identified priority locations for Tucson to make transportation improvement investments for the purpose of mitigating urban transportation system flooding. This included increasing equitable accessibility to the multi-modal transportation network across three modes: vehicular, bicycle, and public transportation via pedestrian access to bus stops. As a case study, our proposal has national flood hazard transportation vulnerability and equity implications. The project had three stages. In Stage 1 we estimated flood conditions based on a 5-year, 1-hour storm event with FLO-2D and a digital elevation model (DEM) constructed using LiDAR data. In Stage 2 we analyzed neighborhood transportation vulnerability based on overall transportation system performance and use across the three transportation networks. In Stage 3, we performed thirty (the top ten sites for the three modes of transportation) green infrastructure (GI) scenario analyses to determine the impact that GI implementations could have on the multimodal system. Of the thirty areas studied, 93% were part of census tracts with median household incomes below the Tucson average. We found that GI implementation performs most effectively to increase multi-modal access when implemented in moderate flooding conditions. In extreme cases, comprehensive, neighborhood-scale GI implementation did not result in creating greater accessibility during flood events. Rather than municipalities selecting areas for GI implementation that have the highest volumes of flooding or citizen complaints, GI implementation funds may be invested in moderate flooded area for greatest improvement of multimodal access. Future research will assess impact across time durations (rather than simple peak event calculations) and work to optimize GI implementation across multiple benefits for multiple modes of transportation (rather than individual modes). We plan to communicate our findings broadly. This research is a **proof of concept** for a larger, long-term project to advance national research methods to reduce the impact of chronic flooding on the multi-modal transportation network. Additional funding from NITC and other sources is currently being targeted.

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DISCLAIMER

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EXECUTIVE SUMMARY

A flood vulnerability assessment of the City of Tucson, Arizona's multi-modal transportation system was conducted with special reference to low-income and minority neighborhoods. Short-term flooding from extreme storm events pose a serious challenge to transportation system reliability and emergency response in cities across the United States. This problem, which is anticipated to grow over the next century due to climate change, is often hardest on vulnerable populations, including low-income and minority neighborhoods. Our work aimed to advance national research methods for assessing multi-modal transportation degradation due to flooding. We identified priority locations for Tucson to make transportation improvement investments for the purpose of mitigating urban transportation system flooding. This included increasing equitable accessibility to the multi-modal transportation network across three modes: vehicular, bicycle, and public transportation via pedestrian access to bus stops. As a case study, our proposal has national flood hazard transportation vulnerability and equity implications.

The project had three stages. In **Stage 1** we estimated flood conditions based on a 5-year, 1-hour storm event with FLO-2D and a digital elevation model (DEM) constructed using LiDAR data. This hydrological analysis was performed at the city-scale and a 20-foot grid resolution. In **Stage 2** we analyzed neighborhood transportation vulnerability based on overall transportation system performance and use across the three transportation networks. Data from the most recent 10-years of vehicular counts, bicycle counts, and bus stop ridership were used to identify the top ten priority locations for flood mitigation based on usage of each of the three modes. In **Stage 3**, we preformed thirty green infrastructure (GI) scenario analyses in these selected Stage 2 priority locations to determine the impact of neighborhood-scale GI implementations in the right-of-way. Of the thirty areas studied, 93% were part of census tracts with median household incomes below the Tucson average. The hydrological analysis was performed at a neighborhood-scale for these sites and at a 5-foot grid resolution. Adequate access to the transportation network during the modelled event was defined as peak flood depths below an accessibility threshold for each of the three modes (for vehicles = 1 foot, for bicycles = 0.25 feet of pedal height, and for pedestrians = 0.25 feet).

This report starts with an outline of the project background. Then the three stage methodology is described. Results across the thirty modelled scenarios are discussed. Preliminary conclusions complete the report. Across the thirty scenarios, we found that comprehensive neighborhood-scale GI implementation in the right-of-way is most effective at increasing multi-modal access when implemented in moderate flooding conditions. In extreme flooding cases, comprehensive GI implementation in the right-of-way did not result in greater accessibility during flood events. Rather than municipalities selecting areas for GI implementation that have the highest volumes of flooding or

citizen complaints, GI implementation funds may be invested in moderate flooded area for greatest improvement of multimodal access. Future research will assess impact across time durations (rather than simple peak event calculations) and work to optimize GI implementation across multiple benefits for multiple modes of transportation (rather than individual modes). We plan to communicate our findings broadly, starting with summer presentations to City and County leadership and staff. This research is a proof of concept for a larger, long-term project to advance national research methods to reduce the impact of chronic flooding on the multi-modal transportation network, particularly using strategic GI implementation.

1.0 PROJECT BACKGROUND

Short-term flooding from extreme storm events pose a serious challenge to transportation system reliability and emergency response in cities across the United States. This problem, which is anticipated to grow over the next century due to climate change, is often hardest on vulnerable populations, including low-income and minority neighborhoods. The Special Report on Climate Change by the Transportation Research Board states, "Potentially, the greatest impact of climate change for North America's transportation systems will be flooding (National Research Council, 2008)." In 2016 alone, the United States suffered estimated property damages of $15 billion dollars and 83 deaths from flash floods – comprising over half of all damages caused by natural disasters in the United States and the highest death rate. Over 80% of deaths from extreme storms are transportation related. The fourth National Climate Assessment warns of increases in the intensity and duration of precipitation events in the coming decades, leading to a greater severity and frequency of flash floods in portions of the United States (Wuebbles et al., 2017). This concern is exacerbated by a national trend in deteriorating stormwater infrastructure and increased urbanization with densification of impervious land cover. In coastal cities with accelerated development, surge events overwhelm infrastructure that was not expanded with changes in land cover. In older cities with combined sewer systems, floods result in outflows of raw sewage into ecological zones. In sprawling cities with extreme seasonal storms, a historic failure to invest in infrastructure during periods of growth causes significant, annual property damage. The damages will worsen with the projected increases in extreme precipitation if innovations are not made. However, municipalities also face resource constraints. Under limited budgets governments increasingly are asked to monitor, prevent, and respond to the impacts of climate change.

Green Infrastructure (GI) is a growing urban trend where stormwater is managed by expanding pervious areas of natural vegetation throughout a city. The Environmental Protection Agency defines GI as "an approach to water management that protects, restores, or mimics the natural water cycle and one which is effective, economical, and enhances community safety and quality of life (EPA 2020)." This project aimed to assess the impact of Green Infrastructure (GI) installations on the multi-modal transportation system (vehicle, bicycle, and pedestrian access to bus stops) to support a systematic prioritization of these GI projects in the right-of-way toward increased transportation network accessibility and expanded equity.

1.1 RESEARCH AREA

The City of Tucson sits within the United States Southwest where studies have projected a more arid climate and higher risk of water shortages over the coming century (Ault et. al, 2016). While water resources become scarce, population in the region has grown considerably in the past decades and the growth is expected to continue. In Arizona, the population is anticipated to increase by 25% between the years 2012 and 2030.

Located in the Sonoran Desert, Tucson experiences climate extremes with multiyear drought, seasonal dryness, and the annual North American Monsoon season. 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. The City of Tucson, Arizona is well suited for the research given its socioeconomic and climate extremes, which present flooding and equity challenges. Tucson has a population of approximately 527,586 residents (US Census Bureau, 2016). In 2018, the poverty rate of the Tucson MSA was 17.8%, which was the second poorest among the twelve Western US MSAs. Residents are socially and economically diverse. Wide gaps are found in income and educational attainment. The research area for the first stages is the City of Tucson, which covers 22 washes along the Santa Cruz and Rillito Rivers. In the final stage of analysis, priority locations at a neighborhood scale were identified throughout the City for GI implementation and finer resolution modelling.

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. This currently results in annual flooding in parts of the city leading to chronic property damage and loss in transportation accessibility. Tucson has the highest yearly extreme storm count across Western US Metropolitan Statistical Areas (MSAs) (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 are working to collaboratively develop and optimize a network of sites that will address current flooding issues and retrofit Tucson with a new, softer, greener infrastructure. 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. GI has been shown to be more cost effective than grey stormwater infrastructure (Jaffe 2011) and have multiple benefits beyond flood reduction (Tzoulas et al., 2007). These three recent policies support the implementation of efficient and connected transportation and stormwater networks. However, criteria for the selection of projects for the GSI fee investments are not yet clear. This research project sought to produce a set of criteria to prioritize implementations for maximum impact across multiple scales and modes.

The research area for Stage 1 and 2 is the City of Tucson, which covers 22 washes along Santa Cruz River and Rillito River. This research area is illustrated in Figure 1.1 within the red lines. In Stage 3, priority locations at a neighborhood-scale were identified for closer modeling throughout this broader research area.

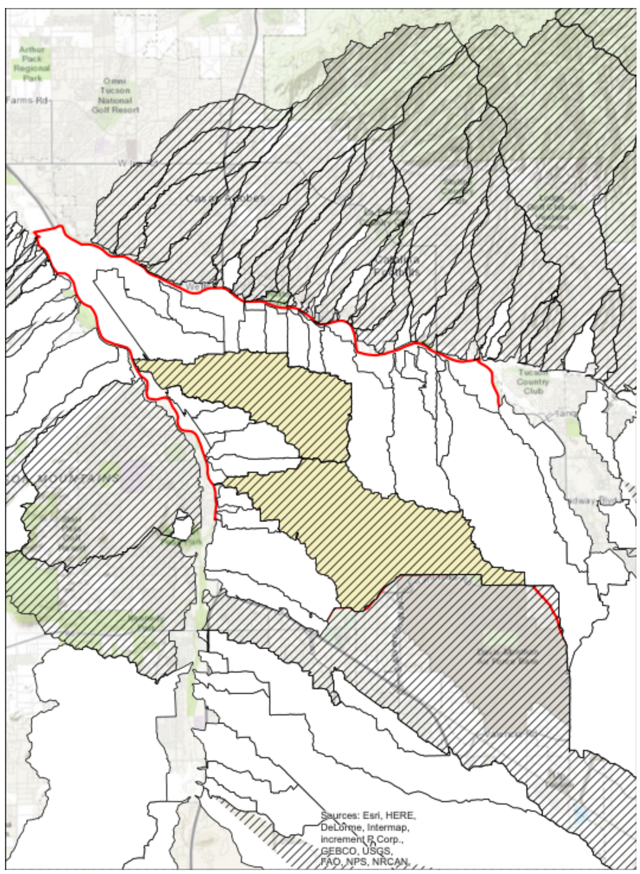


Figure 1.1 Research Area

1.2 DATA RESOURCES

Data for the analyses undertaken during Stage 1, 2, and 3 were provided by various governmental agencies including Tucson Department of Transportation, Pima County Geographic Information System, Arizona Department of Transportation, Pima Association of Governments (the regional transportation authority), and U.S. Geological Survey. Table 1.1 provides a summary of these data sources, types, and a description of their use in our research.

Table 1.1: Data Sources

Data Name	Source	Data Type	Description
2018 Land-Use-Land-Cover Image	PIMA GIS	Raster	The land cover data generated by remote sensing classification based on 2015 orthoimagery. The land cover type includes water, trees/shrubs, irrigated land, desert, barren/ bedrock, impervious, structures, and road. The land cover data were used to generate the manning's n and infiltration data input in Flo-2D.
DEM	USGS	Raster	DEM data provide terrain input in Flo-2D with a resolution of 2 feet.
Road Segments	TDOT	Shapefile	The major roads in Tucson where traffic flow were collected, which were used to select and evaluate the flood mitigating effects of GI on transportation.
Street	PIMA GIS	Shapefile	All the streets in Tucson including major and minor roads, which were assumed as all the walkable streets for the pedestrian. The data were used to select prior locations in the pedestrian scenario.
Bicycle Route	PIMA GIS	Shapefile	Bicycle route in the city of Tucson, which were used to select prior locations and evaluate the flood mitigating effects of GI in bicycle flow scenario.
Intersection	PIMA GIS	Shapefile	The intersection points of street network where bicycle flow were collected with orientations.
Bus Stop	PIMA GIS	Shapefile	The point of bus stops where ridership were collected.
Parcel Region	PIMA GIS	Shapefile	The polygons of parcel region.
Daily Traffic by Road Segment	PAG; ADOT	Excel	Hourly traffic ranging from 1998 to 2017. The latest record of traffic of each road segments were selected to calculate the daily traffic. ADOT data were used as supplement where PAG data were not available.

Daily Bicycle Flow by Intersection	TDOT	Excel	Daily bicycle flow at intersections with four orientations ranging from 2013 to 2018.
Bus Stop Ridership	TDOT	Excel	Daily ridership at bus stops with people on&off.

1.3 SUMMARY STATISTICS

The data resources were cleaned and organized for use in this project. Table 1.2 and Figure 1.2 display the basic information and distribution used in Stage 2 to estimate transportation system vulnerability based on peak flood depth during a 5-year, 1-hour rain event. Stage 3 used the top ten areas of vulnerability of the three scenarios – vehicular traffic, bicycle flow, and ridership at bus stops. The road segments with highest traffic are interstate highways, which were excluded from candidate research locations. The intersections with bicycle flow are shown as orange points and mainly concentrated around campus. Bus stops are concentrated along Alvernon Way and the Ronstadt Center.

Table 1.2 Summary Statistic of the three transportation networks

	Traffic	**Bicycle Flow**	**Bus Stop**
Count:	980	236	1119
Minimum:	87	1	0
Maximum:	163606	818	2860
Sum:	20578273	15585	124531
Mean:	20998.24	66.04	111.29
Standard Deviation:	19884.52	114.64	210.98

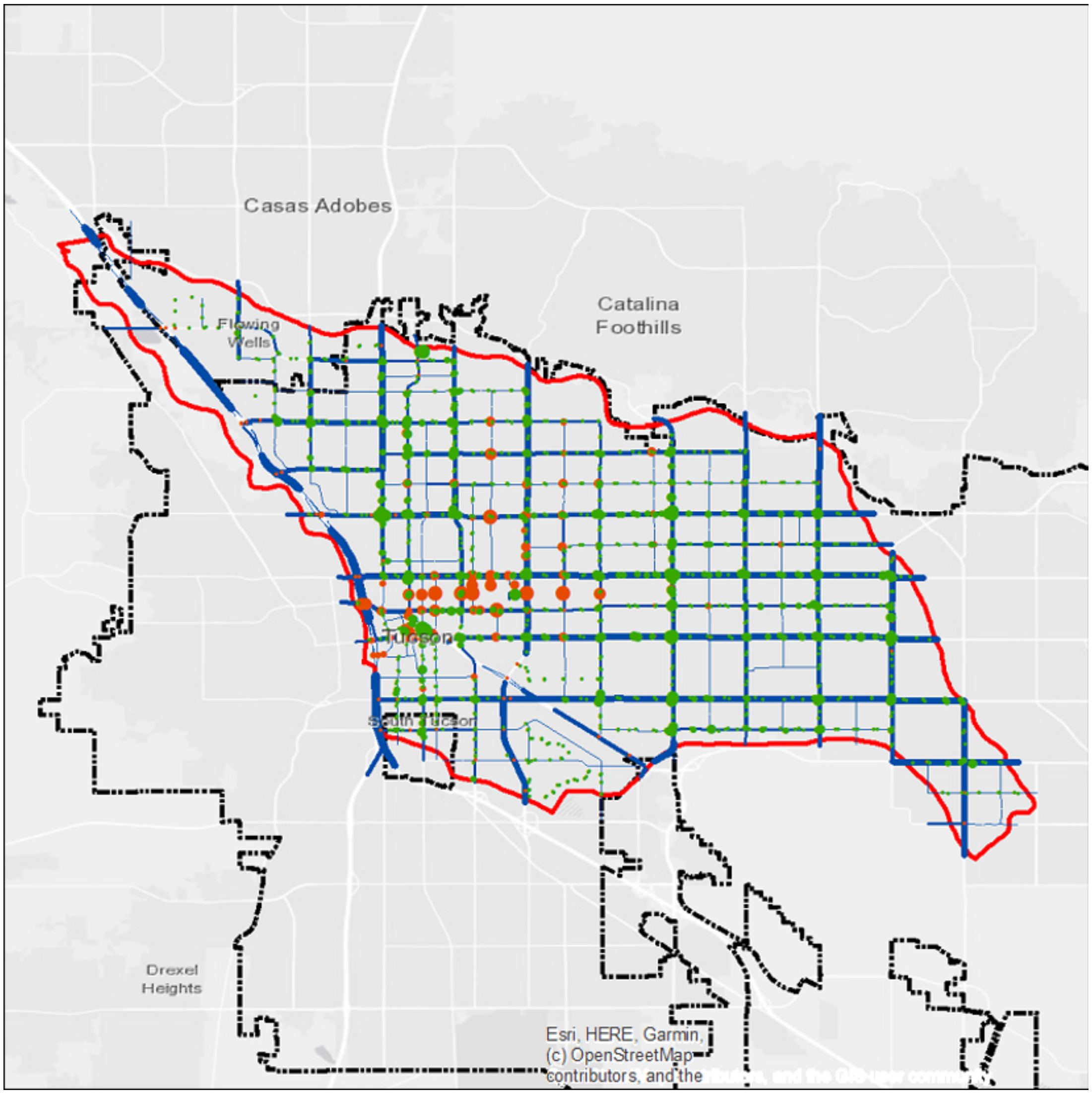


Figure 1.2 Distribution of three data type

2.0 METHODS

This project used a multiscalar and multimodal framework to predict impacts of GSI implementation on accessibility to the multimodal transportation system. This section outlines the novel modeling approach comprised of four stages (Figure 2.1).

- Stage 1, Regional Flood Assessment: Regional flood conditions were estimated based on a 1-hour, 5-year rain event at a 20-foot resolution across the City's transportation system using digital elevation model (DEM) data. This first stage established the baseline for later stages of analysis.

- Stage 2, Multimodal Transportation Network Vulnerability Assessment: Vehicular traffic counts, bicycle counts, and bus stop ridership data were used to identify the top accessed locations across the transportation system. These locations were then catalogued by the flooding modelled in Stage 1 to identify the top ten research areas. Thirty total research locations were selected – ten for each of the three modes of transportation.

- Stage 3, Integrated Hydrological-Transportation Simulations: Comprehensive GI installations were implemented at the neighborhood basin scale for all thirty research locations. GI roadside basins were implemented at 9-inch depths in all available right-of-way and modelled at a finer scale, 5-foot grid resolution, for a 1-hour, 5-year event to obtain detail flooding conditions in these locations.

- Stage 4, Impact Assessment: Impact assessments were completed across the three modes of transit and two scales of analysis resulting in five key design performance priorities.

Data for the analyses undertaken during Stage 1, 2, and 3 were provided by various governmental agencies including Tucson Department of Transportation (TDOT), Pima County Geographic Information System (GIS), Arizona Department of Transportation (ADOT), Pima Association of Governments (PAG, the regional transportation authority), and U.S. Geological Survey (USGS). To complete the hydrological modeling used in Stage 1, 2, and 3, digital elevation model data from USGS provided terrain input in Flo-2D, a common hydrological modeling program. County GIS also provided land cover data generated by remote sensing classification based on 2015 orthoimagery. The land cover types include water, trees/shrubs, irrigated land, desert, barren/ bedrock, impervious, structures, and road. The land cover data were used to generate the manning coefficients and infiltration data input for Flo-2D. Hydraulic structures from County records and major transit infrastructures (such as bridges and underpasses) from City and County records were incorporated in the all stages of the modelling work.

For transportation network analyses in Stage 2 and 3, shape files of the street network, bicycle routes, and bus stop locations were acquired from Pima County GIS. For vehicle traffic by road segment, hourly traffic ranging from 2006 to 2017 was used. The latest record of traffic of each road segments were selected to calculate the daily traffic. ADOT data were used for state owned property as supplement when PAG data were not available. For bicycle counts data, daily bicycle flow at sampled intersections from

2013 to 2018 with four orientations was used. Daily ridership at bus stops of on and off counts from 2008 were used for pedestrian access to the public bus system.

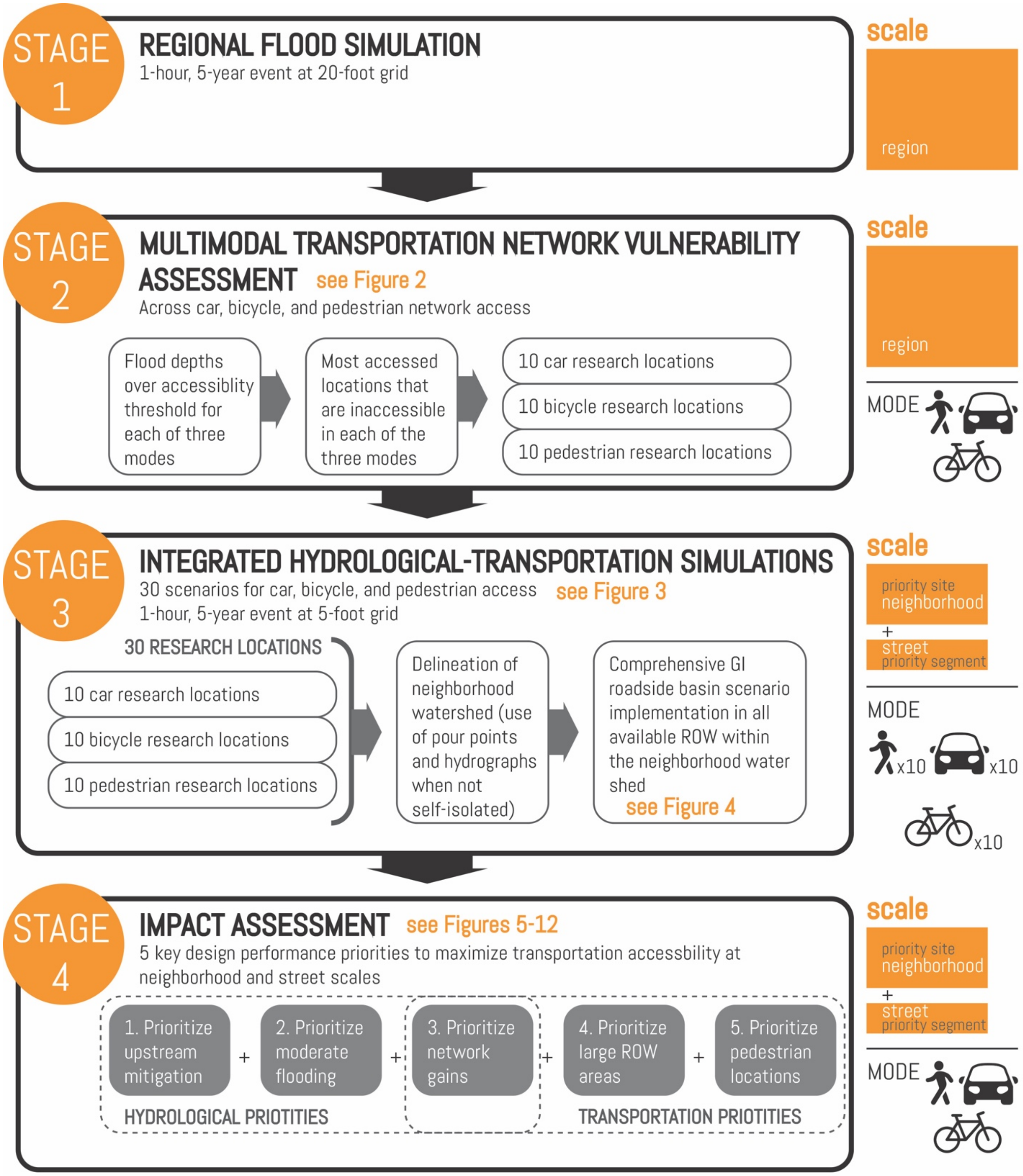


Figure 2.1 The project completed four research stages

2.1 STAGE 1: REGIONAL FLOOD ASSESSMENT

The objective of the first stage was to complete a comprehensive regional flood assessment to identify the locations of highest peak flooding levels across the transportation network. These results were used as inputs for the research area scenario selection for Stage 2 and 3. This regional flood assessment was conducted at the County specified design criteria of a 1-hour, 5-year event at a 20-foot resolution. FLO-2D, a common hydrologic and hydraulic modeling software for high-resolution urban flooding simulation, was used to complete the analysis. The inputs for the model included elevation (from digital elevation model), infiltration and roughness (generated from land cover data from County LiDAR and orthophoto), hydraulic structures (from County Flood Control records), and major transit infrastructure such as bridges and underpasses (from City and County records). When there was a bridge and an underpass, the results for the underpass where given priority in FLO-2D output results. When there was a bridge and a non-road feature, the bridge was given priority in FLO-2D output results. The detailed values for infiltration and roughness are in Appendix A.

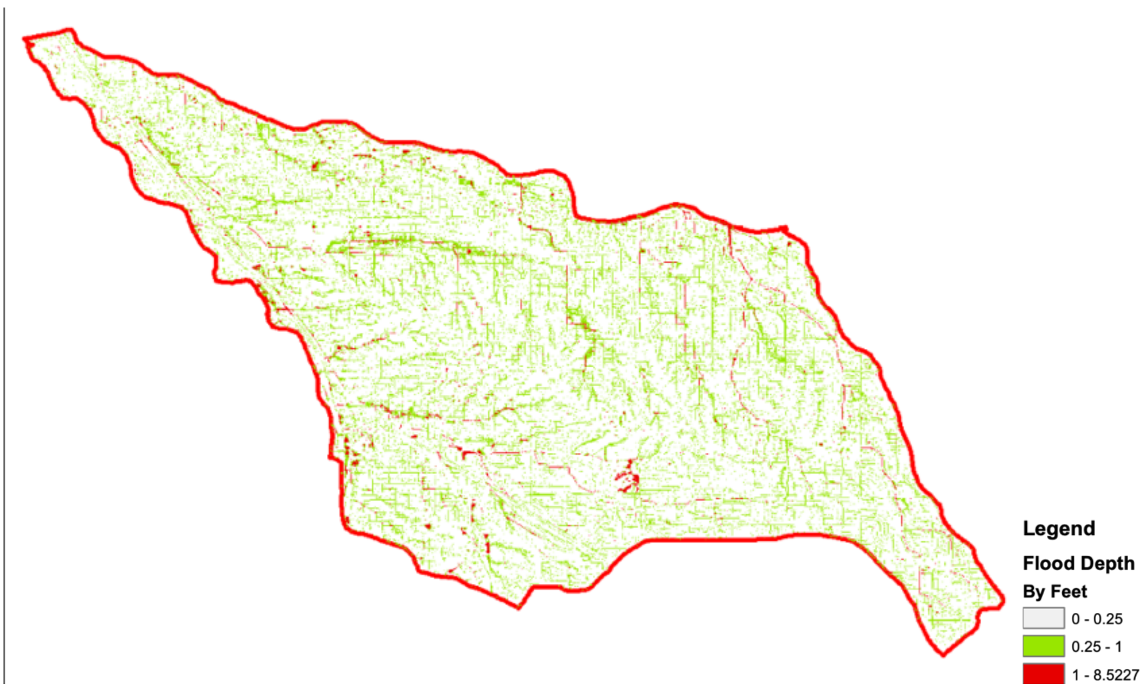


Figure 2.2 Overall water depth From Stage 1

2.2 STAGE 2: MULTIMODAL NETWORK TRANSPORTATION VULNERABILITY ASSESSMENT

The objective of Stage 2 was to select the thirty priority research locations by completing a multimodal network vulnerability assessment. These thirty locations were comprised of ten locations for each of three modes of transportation: car, bicycle, and pedestrian access to bus stops. The modeling results from Stage 1 were overlaid with data for vehicular traffic counts and flow, bicycle counts and flow, and ridership at bus stop (on and off) to complete the vulnerability assessment. Figure 2.2 displays the results from Stage 2, the top ten most accessed locations identified for each of the three modes of transportation. The main process of selecting a research location is shown in the flow chart in Figure 2.4.

To complete the vulnerability assessment, thresholds of access during rain events were set for each of the three modes. For cars, a flood depth of above 1-foot was set as the threshold of inaccessibility in the modeled 1-hour rainfall event with a 5-year return period. For bicycles and pedestrians, flood depths above 0.25 feet were the threshold of inaccessibility.

There were several specific flooding cases for each mode of transportation that were excluded in the vulnerability assessment. First, for cars, a threshold of less than 20 feet (approximately a car length) was specified as the criterion for exclusion. The other three criteria applied to exclude a road segment as a potential research location were: the road segment was an interstate highway; the road segment was outside the boundary of the research area; and the road segment was an underpass. In the ten bicycle scenarios, segments that were flooded less than five feet (approximately a bicycle length) were excluded. The top ten intersections with highest bicycle flow that connected with the flooded segments were selected and considered as research locations. In the ten pedestrian scenarios, all the streets that intersected with impassable areas were considered as flooded segments, and thus the bus stops connected to the flooded segments were assumed to be inaccessible to the pedestrian.

For cars, the ten flooded road segments with the highest traffic are shown as blue lines in Figure 2.3, labeled by the name of the street. The top ten points are shown as red points in Figure 2.3, labeled with the total bicycle flow to four orientations. The majority of these research areas are concentrated around the University of Arizona campus. The top ten stops with highest ridership were chosen as research locations in this scenario, shown as green points and labeled with the total ridership) in Figure 2.3.

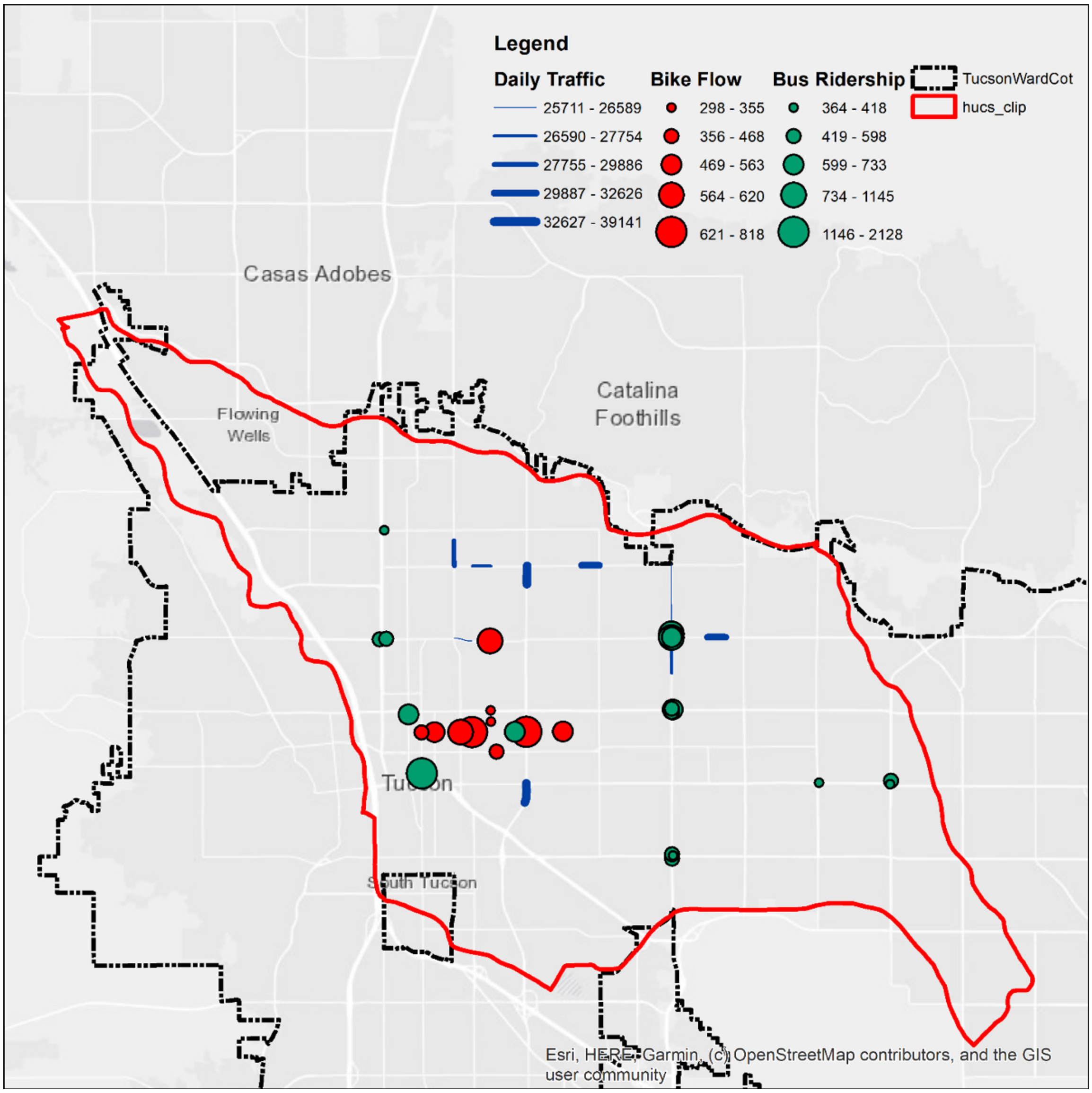


Figure 2.3 Priority segments for thirty scenarios

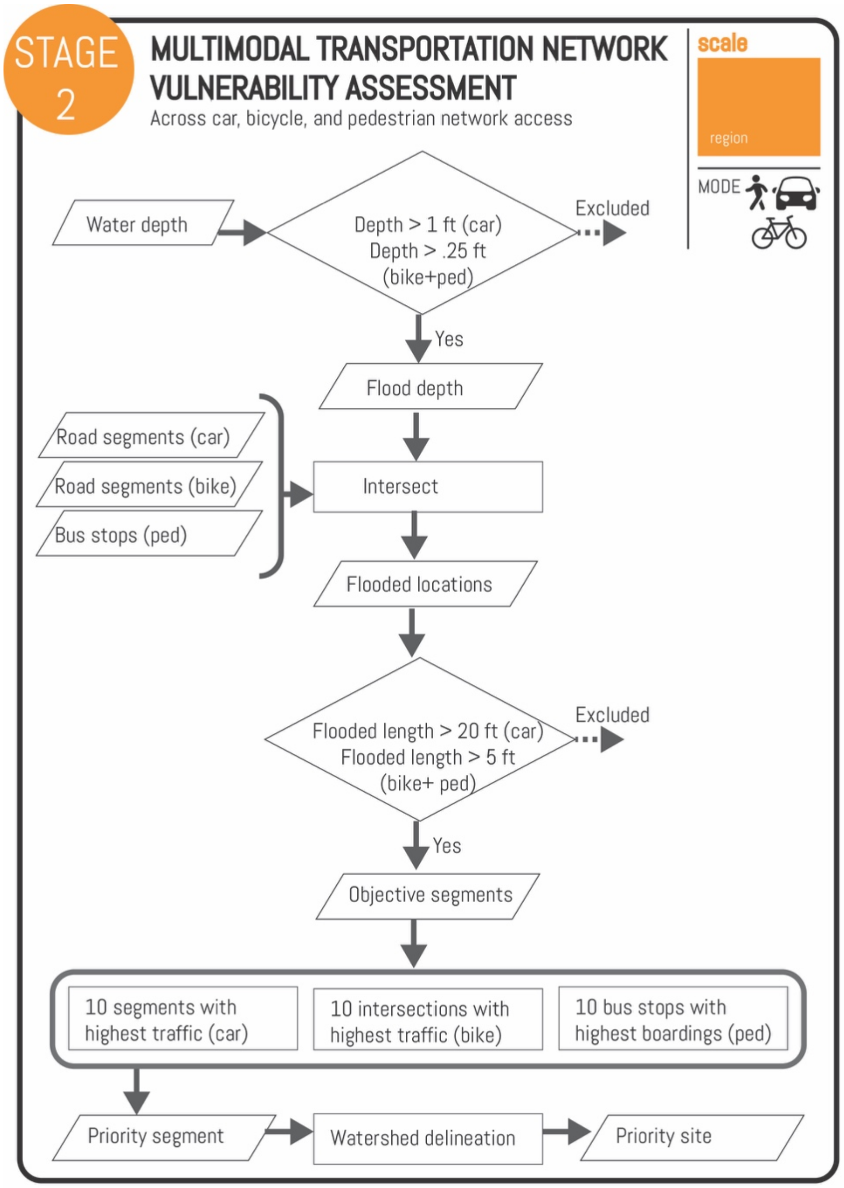


Figure 2.4 Flow chart of priority segments and sites selection

2.2.1 Research Areas and Low Income Neighborhood Statistics

In 2017, the average Tucson median household income (MHI) was $51,425. The average poverty rate was 24%. Tables 1.3, 1.4, and 1.5 summarize the MHI and poverty rates for the thirty research areas. Overall, 93% of the 30 research priority areas were in areas with MHIs averages below the Tucson average, with vehicles at 100%, bicycles at 90% and pedestrians bus stops at 90%. The poverty rates held similar comparisons.

Table 2.1 Vehicle network research priority sites socioeconomic statistics

Priority Site #	Count of Block Group Intersected	Min MHI	Max MHI	Ave MHI	Min Ratio Poverty	Max Ratio Poverty	Ave Ratio Poverty	Poverty Pop
1	13	$24,583	$79,884	$43,313	6%	54%	28%	4,143
2	6	$13,274	$67,000	$35,753	3%	40%	23%	1,423
3	12	$21,513	$57,564	$32,664	6%	38%	27%	3,908
4	12	$12,330	$43,656	$32,781	18%	56%	32%	4,260
5	8	$15,196	$49,938	$31,733	2%	47%	31%	3,226
6	9	$23,300	$53,068	$36,160	6%	54%	34%	3,974
7	12	$16,481	$57,564	$32,048	14%	57%	33%	4,470
8	9	$16,481	$57,564	$33,030	14%	57%	31%	3,016
9	14	$16,481	$57,564	$30,845	14%	57%	33%	5,191
10	11	$14,600	$39,345	$27,245	7%	75%	32%	4,268

Table 2.2 Bicycle network research priority sites socioeconomic statistics

Priority Site #	Count of Block Group Intersected	Min MHI	Max MHI	Ave MHI	Min Ratio Poverty	Max Ratio Poverty	Ave Ratio Poverty	Poverty Pop
1	6	$0	$48,047	$21,521	0%	65%	30%	920
2	8	$0	$74,167	$43,171	0%	65%	21%	1,282
3	8	$0	$48,047	$22,432	0%	65%	32%	1,692
4	4	$13,750	$50,968	$32,435	26%	69%	43%	2,500
5	7	$0	$48,047	$20,283	7%	65%	39%	1,830
6	2	$71,181	$74,167	$72,674	8%	8%	8%	140
7	10	$0	$74,167	$38,424	0%	68%	28%	2,040
8	7	$0	$48,047	$20,283	7%	65%	39%	1,830
9	4	$0	$48,047	$19,351	7%	65%	36%	456
10	6	$0	$48,047	$17,074	7%	73%	53%	2,127

Table 2.3 Pedestrian bus stop network research priority sites socioeconomic statistics

Priority Site #	Count of Block Group Intersected	Min MHI	Max MHI	Ave MHI	Min Ratio Poverty	Max Ratio Poverty	Ave Ratio Poverty	Poverty Pop
1	5	$14,245	$47,841	$33,223	22%	54%	32%	1,433
2	11	$16,481	$38,333	$27,431	17%	57%	33%	3,861
3	8	$0	$48,047	$20,450	7%	65%	40%	2,156
4	9	$16,481	$102,955	$52,081	3%	57%	26%	2,828

5	8	$0	$74,167	$43,171	0%	65%	21%	1,282
6	8	$10,604	$29,515	$17,957	7%	76%	50%	4,067
7	12	$16,004	$85,833	$32,849	0%	58%	30%	4,528
8	7	$19,375	$63,906	$48,807	0%	30%	13%	1,072
9	10	$15,777	$70,000	$43,182	0%	66%	28%	3,380
10	5	$13,946	$49,938	$23,953	2%	66%	45%	4,006

2.3 STAGE 3: INTEGRATED HYDROLOGIC-TRANSPORTATION SIMULATIONS FOR THIRTY GI SCENARIOS

2.3.1 Research Area Delineation

Stage 3 completed integrated transportation and hydrological simulations for the thirty research area scenarios identified from the Stage 1 and 2 results. The aim of the third stage was to evaluate the change in transportation network accessibility during a 1-hour, 5-year event after comprehensive neighborhood-scale GI implementation. To finalize each of the defined research priority areas for the GI implementation in Stage 3, several hydrological factors were taken into consideration. First, the point(s) where water flows out of the research priority area, or pour point(s), were selected and used to delineate the watershed that covered the research area. This process was completed using ArcGIS Hydrology Analysis, with the assumption that water only flows in one direction, which is from higher elevation to lower elevation. Second, there were two cases where an isolated hydrological area was not able to be delineated and the use of hydrographs were required. In one case, when the delineated watershed from the pour points was too large to be considered as a research area (no more than 1 square mile), a hydrograph was set along a 1-mile buffer from the potential research area in the 20-foot model to account for the water flow outside of the 1-mile buffer. The second case was when the delineated watershed was not self-contained and had water flows that went across the delineated sub-watershed and contributed to the flooding condition. This process was completed using FLO-2D, which assumes that water flows in eight directions.

2.3.2 GI Implementation

In each of the thirty scenarios, GI was implemented in all available right-of-way throughout the neighborhood-scale, hydrologically defined research area. Figure 2.5 shows typical sections for these roadside basin GI implementations following design standards from Pima County and the National Association of City Transportation Officials (NACTO). As the analysis was performed at a neighborhood scale with a 5-foot grid, design features smaller that the grid size (such as inlets and outlets) were not incorporated into the design standards. Areas of road land cover, parcel region, and washes were erased from the research area to pursue the potential GI areas using GIS techniques. GI roadside basins were implemented at a depth of 9 inches. Such implementation would require inlets and outlets (such as curb cuts, culverts, or scuppers), armoring these openings with rock of concrete, and removing substrate to reduce curbside elevation of the right-of-way by 9 inches (the maximum allowed by County code). County code stipulates a 9 inch maximum depth to control the levels and duration of standing water in the GSI to minimize mosquito propagation.

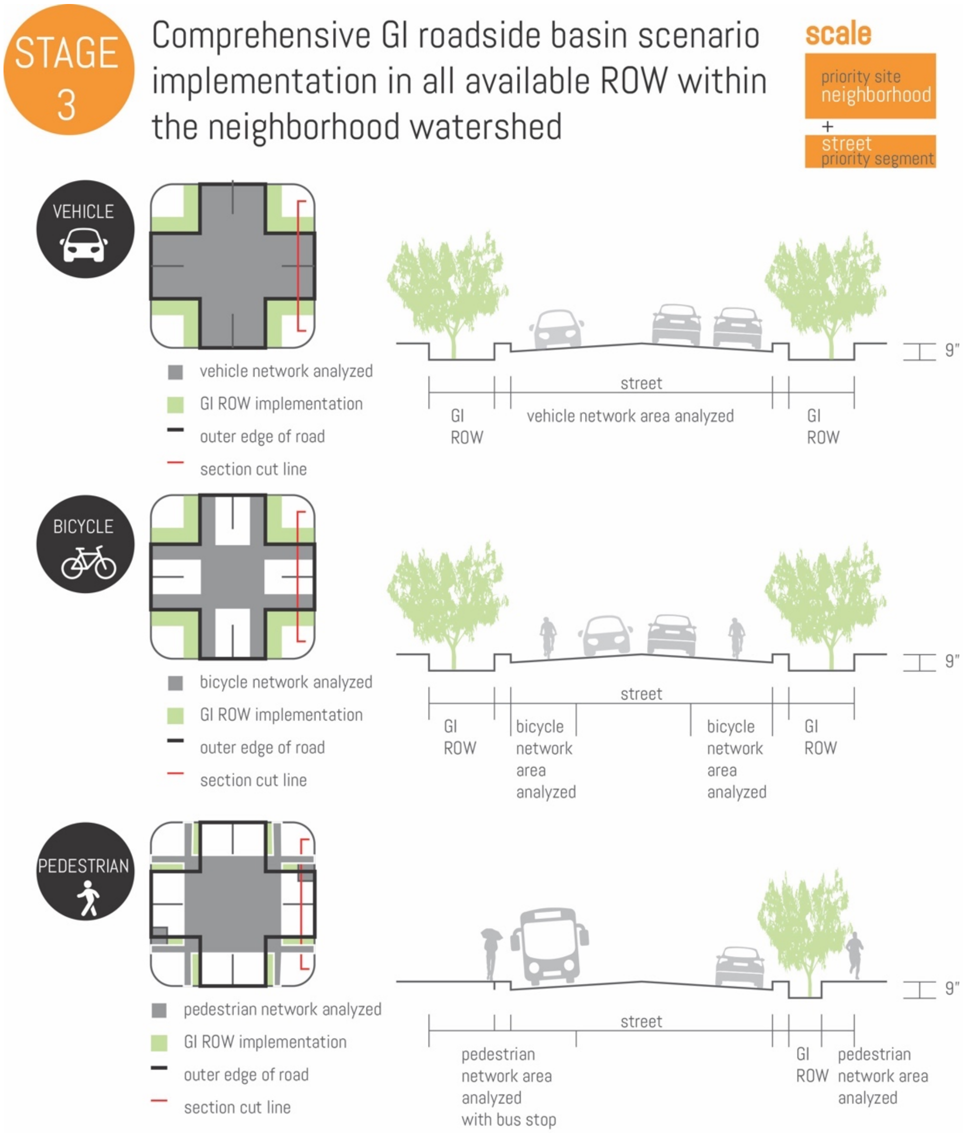
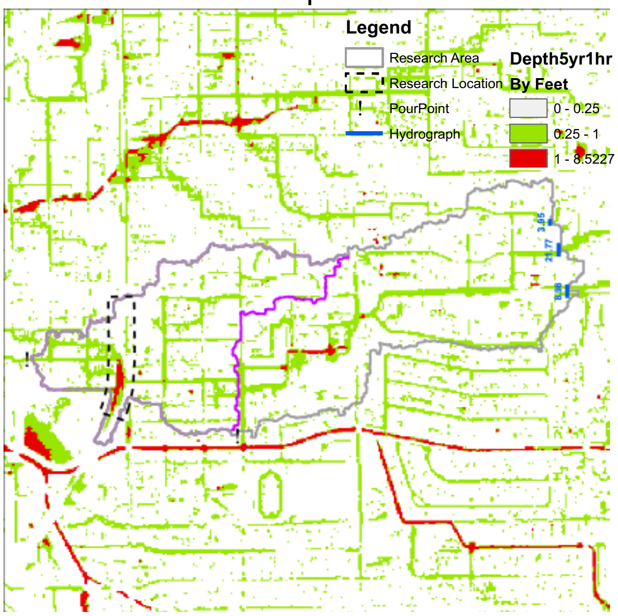


Figure 2.5 Typical roadside basin Gi implementation for each mode of transportation

An example for each of the transportation systems (vehicle, bicycle, and pedestrian access to bus stops) are shown below. Figures 2.6 and 2.7 display the flooding condition from the 1-hour, 5-year event from Stage 1. The flooded road segment is boxed by the black dash line, which is one of the research locations from the process 2.1 (#2 in the traffic scenario). In this example, two pour points were selected and delineated two sub-watersheds, which is divided by the purple line. With the flooding condition, we can see the water flows from the left sub-watershed across the purple line and contributed to the flooding condition of the research location. Thus, the left sub-watershed is also included in the research area for research location #2. The hydrograph shown as blue line were set along the 1 mile buffer from the research location #2 to catch up the flows.



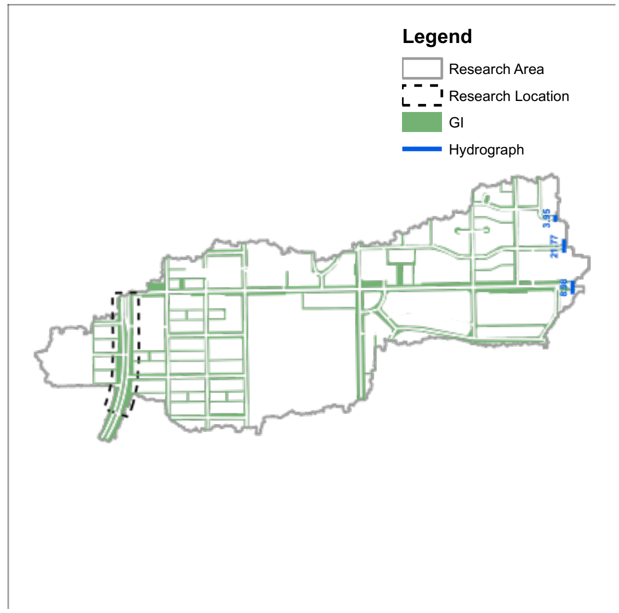
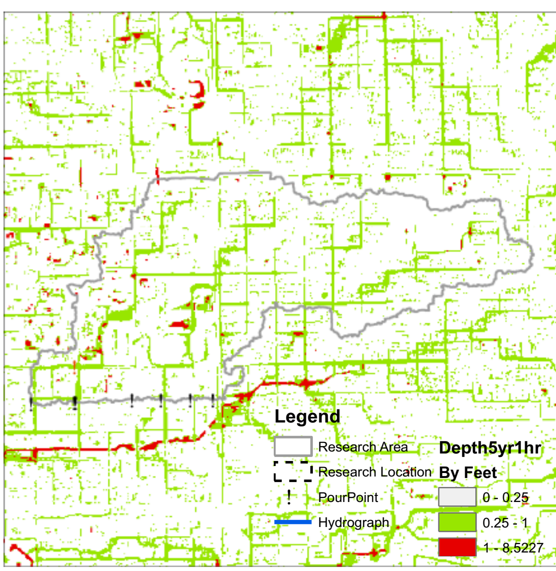


Figure 2.6 Traffic scenario #2 – Priority site and segment (left)

Figure 2.7 GI implementation across the priority site(right)

Figures 2.8 and 2.9 show the research area and GI implementation for the research location #7 in the bicycle scenario. In this case, the research area delineated by the several pour points is self-contained, and GI were set on the upstream to the research location within 1 mile distance.



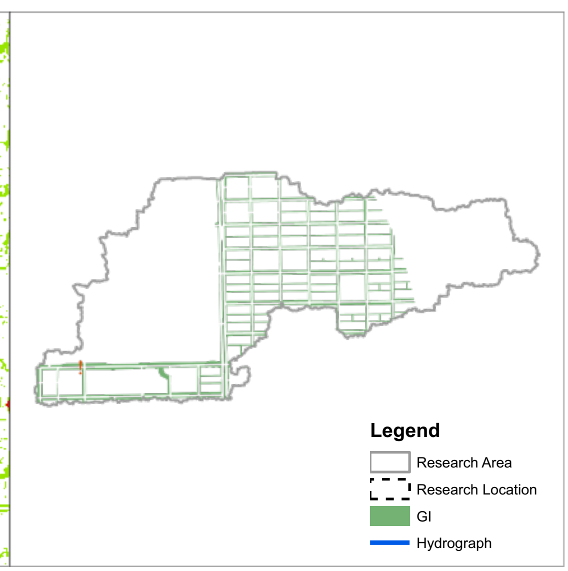
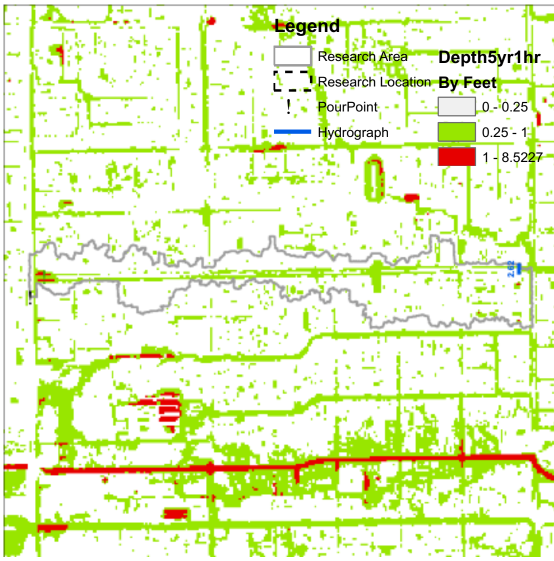


Figure 2.8 Bicycle scenario #7 - Priority site and segment (left)

Figure 2.9 GI implementation across the priority site (right)

Figures 2.10 and 2.11 shows the example of research location #10 in the pedestrian scenario. In this example, the sub-watershed delineated by the pour point is not self-contained and has water flows outside of the boundary.



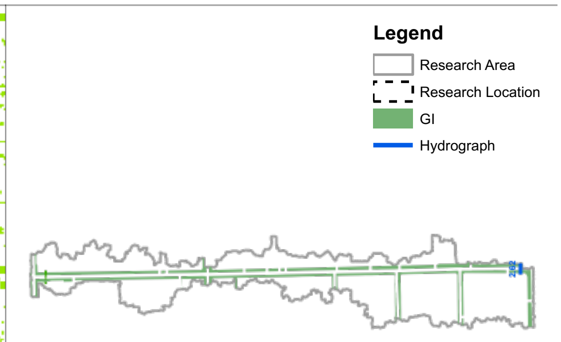


Figure 2.10 Pedestrian Scenario #10 - Priority site and segment (left)

Figure 2.11 GI implementation across the priority site (right)

2.4 STAGE 4: IMPACT ASSESSMENT WITH RESULTING DESIGN PRIORITIES

The final stage of the research method analyzed the modeling results for impact on access to the three transportation networks at the neighborhood and street scale. Based on these results, five key GI design performance priorities were identified to maximize the accessibility of the multimodal transportation through GI implementation. Flood manager, transportation planners, and urban designers can employ these design priorities in future GI projects toward maximum accessibility to the multimodal network.

2.5 TECHNICAL REVIEW COMMITTEE

Due to the multi-discipline and multi-sector character of the work, a technical review committee for the research and design scenarios was codified. Below are the members:

- Robin Raine, Interim Director, Tucson Department of Transportation (TDOT)
- Eric Shepp, Deputy Director, Pima County Regional Flood Control District (PCRFCD)
- Jacob Prietto, Hydrologic Modeler, Pima County Regional Flood Control District (PCRFCD)
- James MacAdam, Superintendent, City of Tucson Water Department

This committee of City and County staff experts provided critical feedback on practical aspects of the hydrological modelling across typical Tucson urban conditions as well as technical feedback while formulating the GI installation scenarios for the right-of-way.

3.0 RESULTS: THIRTY PRIORITY SITES AND SEGMENTS

This section provides results for the thirty GI scenarios implemented in Stage 3 (ten priority sites and segments for each of bicycle, vehicle, and pedestrian bus stop access) and their implications for the Stage 4 impact assessment. Results are structured by the three transportation networks studied. Each set of results reports both the neighborhood-scale (priority site) and street-scale (priority segment) impacts from the GI installation on the hydrological and transportation systems.

3.1 VEHICULAR TRAFFIC: TEN CAR PRIORITY SITES AND SEGMENTS

Figure 3.1 illustrates how the mitigating effects of GI were evaluated. Two areas of analysis are represented. The first is the selected priority segment in the red dashed line box identified during Stage 1 and 2 (see Part 2.2 Research Location Selection). The second is all the gray area identified in Stage 2 and 3, which is the neighborhood-scale priority site area. Table 3.1 to Table 3.4 summarize and compare the mitigating effects of the GI implementation for the ten car priority sites and segments listed in descending order of traffic volume. Roads with flooding at or over one-foot were considered impassable; roads with flooding under one-foot were deemed accessible. GI was implemented in all available right-of-ways throughout the priority site (see Figure 2.5 section).

Table 3.1 Basic information for each research site

Priority Site #	Total Area of Delineated Sub-basin (SQFT)	%Area of ROW for GI application	%Impervious
1	27,493,825	11.96%	51.26%
2	9,679,250	15.37%	67.86%
3	19,934,375	8.99%	46.36%
4	20,591,700	9.17%	50.27%
5	27,583,775	10.05%	51.28%
6	22,447,300	8.55%	37.90%
7	18,930,500	11.64%	48.43%
8	24,816,875	11.27%	48.73%
9	19728925	10.22%	48.01%
10	1868525	15.10%	60.96%

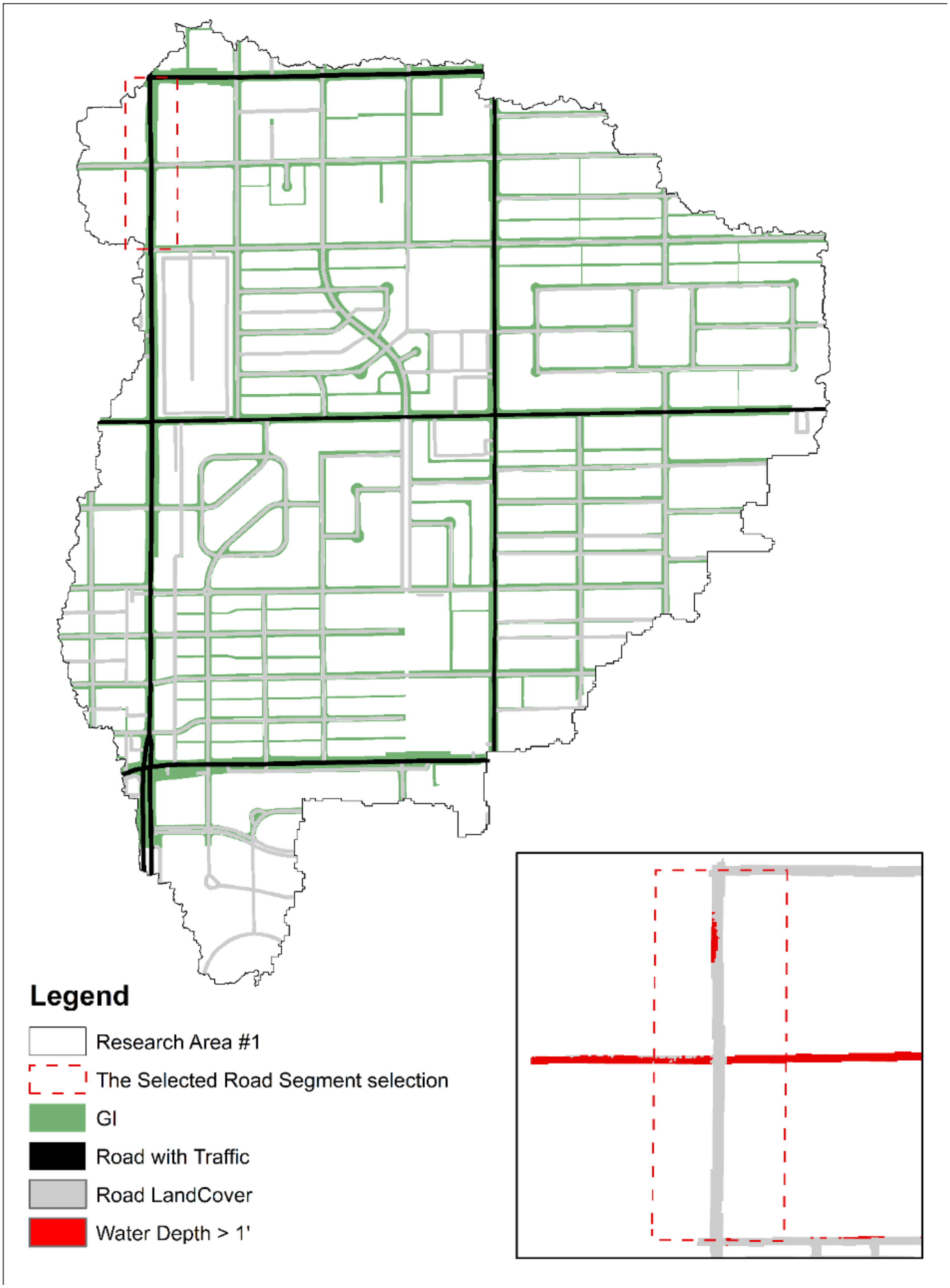


Figure 3.1 Results evaluation

Table 3.2 Comparison between priority segments before and after GI

Priority Site #	Area of Prior Road Segment (SQFT)	Daily Traffic (Cars/ Day)	%Area > 1' (Pre)	%Area > 1' (Post)	Lanes Passable (Pre)	Lanes Passable (Post)	Mitigated Area (SQFT)
1	47,975	39,141	5.37%	8.18%	3	2	-1,350
2	93,975	35,729	19.77%	8.43%	1	4	10,650
3	46,850	31,358	1.39%	0.00%	2	5	650
4	65,775	29,886	5.51%	3.19%	0	1	1,525
5	48,475	27,754	3.20%	2.68%	1	2	250
6	47,125	26,589	13.69%	2.23%	4	4	5,400
7	47,725	26,589	44.05%	5.87%	3	4	18,225
8	47,075	26,589	33.56%	1.22%	1	4	15,225
9	47,075	26,589	41.90%	24.06%	0	0	8,400
10	45,750	25,711	10.33%	10.05%	0	0	125

Table 3.3 Comparison between priority segments with traffic information before and after GI implementation

Priority Site #	Total Area of Roads with Traffic Information (SQFT)	%Area > 1' (Pre)	%Area > 1' (Post)	Mitigated Area (SQFT)
1	765,625	0.59%	0.52%	550
2	337,850	5.50%	2.35%	10,650
3	445,650	21.97%	0.15%	97,250
4	507,125	17.19%	7.60%	48,600
5	727,725	13.90%	5.73%	59,425
6	460,625	1.80%	0.33%	6,800
7	589,700	3.09%	0.34%	16,207
8	863,675	4.49%	0.33%	35,950
9	599,250	15.54%	2.80%	76,325
10	121,775	3.88%	3.78%	125

Table 3.4 Comparison between all the priority sites before and after GI implementation

Research Location #	Total Area of All Road (SQFT)	%Area > 1' (Existing)	%Area > 1' (GI)	Mitigated Area (SQFT)
1	3,825,725	2.09%	1.01%	41,175
2	1,224,950	1.85%	0.81%	12,775
3	1,977,550	6.14%	0.12%	119,000
4	2,504,500	9.39%	6.58%	70,400
5	3,921,000	6.54%	3.63%	114,100
6	1,846,600	0.45%	0.09%	6,775
7	2,066,675	3.09%	0.34%	56,800
8	2,824,275	2.82%	0.78%	57,525
9	2,310,350	4.49%	0.96%	81,500
10	370,350	1.30%	1.26%	125

3.2 BICYCLE FLOWS: TEN BICYCLE PRIORITY SITES AND SEGMENTS

Bicycle flow data was collected at street intersections for all flow directions (i.e. typically following the orientations of NE, SE, NW, SW direction of travel). Figure 3.2 presents an example analysis of a bicycle priority site and segment with the identified intersection. Intersections are included in the bicycle network by linking the outer points of all bicycle network points and including the intersection for protected left turns. Water depth at or over 3 inches (0.25 feet) was considered as flooded and impassable, and water depth less than 3 inches (0.25 feet) was considered as passable. The bicycle area of travel was assumed to have a width of ten feet when a shared road condition and a width of five feet when a designated lane condition (see Figure 2.5 section). Tables 3.5-3.10 present results across the ten bicycle priority sites and segments and the relative impacts of comprehensive GI implementation.

Table 3.5 Basic information of each research site

Priority Site #	Total Area of Delineated Sub-basin (SQFT)	%Area of GI	%Impervious
1	6,696,900	3.50%	71.15%
2	12,939,975	8.85%	56.30%
3	8,897,225	7.16%	71.45%
4	5,058,000	13.23%	50.15%
5	8,509,200	13.48%	68.99%
6	3,191,575	12.55%	34.03%
7	15,964,375	9.12%	56.30%
8	10,910,675	14.42%	65.93%
9	2,389,050	3.59%	77.61%

10	7,323,525	5.40%	70.57%

Figure 3.2 Water depth comparison for bicycle scenario #7 before (left) and after (right) GI.

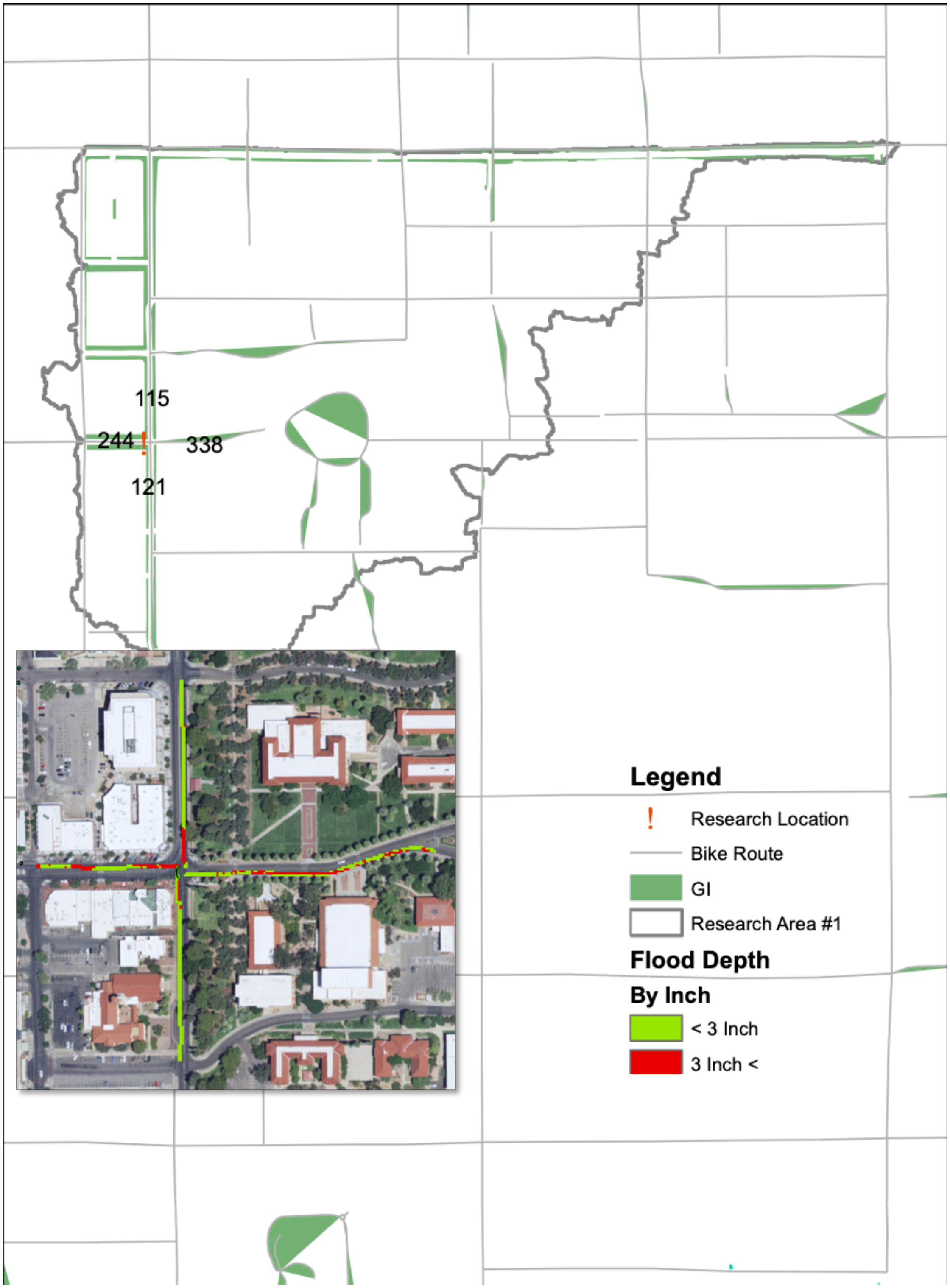


Table 3.6 Comparison among priority segments to the east before and after GI implementation

Priority Site #	Bike Flow to East (Count/ Day)	Area of Bike Lane (SQFT)	%Area > 3" (Pre)	%Area > 3" (Post)	Mitigated Area (SQFT)	Bike Route Type
1	338	6,250	36.40%	36.40%	0	Residential Streets
2	349	4,025	86.34%	16.15%	2825	Bike Blvd/Shared Lane Markings
3	310	4,525	86.74%	3.87%	3750	Bike Blvd/Shared Lane Markings
4	19	2,675	8.41%	11.21%	-75	Bike Route with Striped Shoulder
5	187	4,625	100.00%	10.81%	4125	Bike Blvd/Shared Lane Markings
6	241	4,300	100.00%	20.93%	3400	Bike Blvd/Shared Lane Markings
7	5	8,675	46.40%	4.32%	3650	<Null>
8	162	2,225	0.00%	0.00%	0	Bike Blvd/Shared Lane Markings
9	113	8,975	98.33%	98.33%	0	Residential Streets
10	12	8,050	14.60%	0.00%	1175	Bike Route with Striped Shoulder

Table 3.7 Comparison among priority segments to the north before and after GI implementation

Priority Site #	Bike Flow to North (Count/ Day)	Area of Bike Lane (SQFT)	%Area > 3" (Pre)	%Area > 3" (Post)	Mitigated Area (SQFT)	BikeRouteType
1	115	4,625	75.14%	18.92%	2600	Bike Route with Striped Shoulder
2	14	2,325	100.00%	89.25%	250	Bike Route with Striped Shoulder
3	6	4,575	16.39%	8.74%	350	<Null>
4	225	3,425	100.00%	100.00%	0	Bike Route with Striped Shoulder
5	101	4,500	16.67%	7.78%	400	Bike Blvd/Shared Lane Markings
6	9	1,800	11.11%	12.50%	-25	Bike Route with Striped Shoulder
7	234	8,325	14.11%	15.32%	-100	Residential Streets
8	39	4,500	19.44%	7.78%	525	Shared Lane Markings
9	51	3,600	31.25%	31.25%	0	Residential Streets
10	133	4,350	7.47%	3.45%	175	Bike Route with Striped Shoulder

Table 3.8 Comparison among priority segments to the south before and after GI implementation

Priority Site #	Bike Flow to South (Count/ Day)	Area of Bike Lane (SQFT)	%Area > 3" (Pre)	%Area > 3" (Post)	Mitigated Area (SQFT)	BikeRouteType
1	121	4,600	47.83%	6.52%	1,900	Residential Streets
2	14	4,625	96.22%	54.59%	1,925	Bike Route with Striped Shoulder
3	22	4,500	1.11%	0.00%	50	<Null>
4	335	3,475	100.00%	100.00%	0	Bike Route with Striped Shoulder
5	51	4,575	100.00%	8.20%	4,200	Shared Lane Markings
6	19	4,375	97.71%	15.43%	3,600	Bike Route with Striped Shoulder
7	215	4,425	100.00%	19.21%	3,575	Bike Route with Striped Shoulder
8	39	4,575	1.09%	0.00%	50	Shared Lane Markings
9	124	2,225	14.61%	14.61%	0	Residential Streets
10	143	3,550	47.89%	47.89%	0	Bike Route with Striped Shoulder

Table 3.9 Comparison among priority segments to the west before and after GI implementation

Priority Site #	Bike Flow to West (Count/ Day)	Area of Bike Lane (SQFT)	%Area > 3" (Pre)	%Area > 3" (Post)	Mitigated Area (SQFT)	BikeRouteType
1	244	3,475	91.37%	46.76%	1,550	Bike Blvd/Shared Lane Markings
2	345	12,375	72.12%	69.70%	300	Bike Route with Striped Shoulder
3	282	4,425	1.13%	2.26%	-50	Bike Blvd/Shared Lane Markings
4	18	4,050	29.01%	11.73%	700	Bike Route with Striped Shoulder
5	224	2,175	100.00%	35.63%	1,400	Bike Blvd/Shared Lane Markings
6	258	3,825	19.61%	15.03%	175	Bike Blvd/Shared Lane Markings
7	14	4,125	33.94%	1.21%	1,350	<Null>
8	163	2,075	2.41%	0.00%	50	Bike Blvd/Shared Lane Markings
9	67	3,175	100.00%	100.00%	0	Bike Route with Striped Shoulder
10	10	3,975	94.34%	11.95%	3,275	Bike Route with Striped Shoulder

Table 3.10 Comparison between all the priority sites before and after GI implementation

Priority Site #	Total Area of All Road (SQFT)	%Area > 3" (Pre)	%Area > 3" (Post)	Mitigated Area (SQFT)
1	954,175	45.16%	36.72%	80,600
2	1,670,125	40.38%	22.40%	300,275
3	1,224,475	44.56%	29.27%	187,225
4	1,091,150	35.05%	20.78%	155,675
5	1,342,950	39.81%	16.80%	308,950
6	340,625	36.75%	16.26%	69,800
7	1,782,325	43.65%	24.97%	333,025
8	1,658,250	37.96%	14.33%	391,850
9	382,975	35.13%	31.46%	14,025
10	1,222,775	35.05%	23.47%	141,525

3.3 PEDESTRIAN ACCESS TO BUS STOPS: TEN PEDESTRIAN PRIORITY SITES AND SEGMENTS

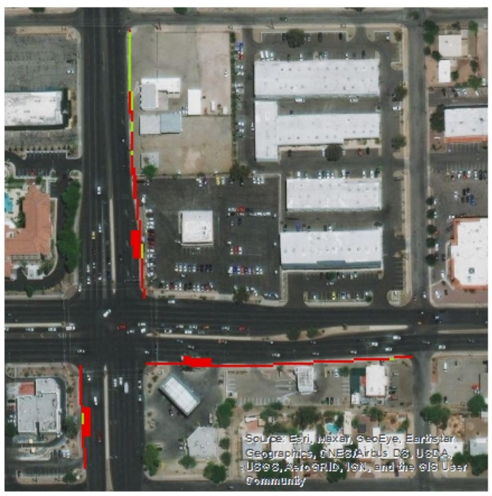
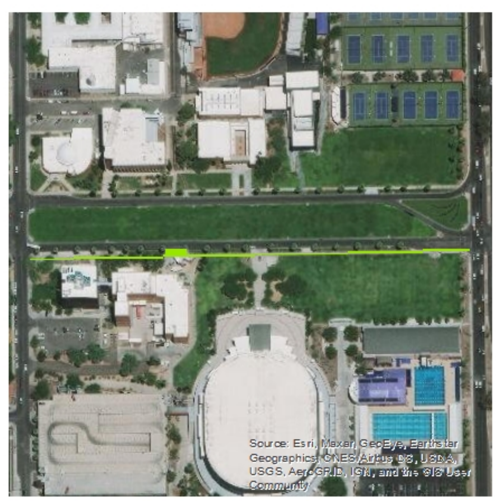
Pedestrian bus stop access included a 70 by 20 foot box around the bus stop and a pedestrian path on each side of the street throughout the priority site street network. Intersections are included in the pedestrian network by connecting the outer points of sidewalks and including the whole intersection. Figure 2.5 presents an example of how pedestrian network sites and segments with access to bus stops were analyzed. GI was implemented in the first five feet of the right-of-way while the next five feet were reserved for pedestrian access (see Figure 2.5 section). Water depths at or over three inches (0.25 feet) were considered inaccessible; water depths under three inches (0.25 feet) were considered accessible. Tables 3.11-3.16 report results of the ten pedestrian priority sites and segments.

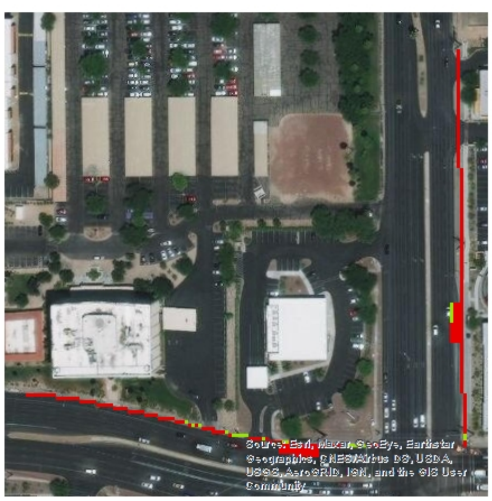
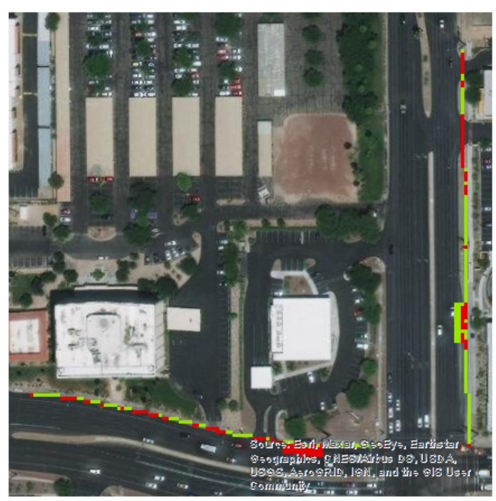
Table 3.11 Comparison between all the priority sites before and after GI implementation

Priority Site #	Total Area of Delineated Sub-basin (SQFT)	%Area of GI	%Impervious
1	10,418,150	13.02%	69.98%
2	15,824,425	9.38%	54.07%
3	11,189,350	13.02%	64.07%
4	13,788,000	9.97%	51.60%
5	12,939,975	10.39%	52.42%
6	11,413,800	15.26%	65.35%
7	25,185,625	10.27%	52.46%
8	12,758,525	12.66%	71.03%
9	25,002,475	10.52%	65.14%
10	2,556,850	13.22%	64.37%

Table 3.12 Results from pedestrian access to bus stops

Priority Site #	Pre	Post
1		
2		

3	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
4	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
5	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

6	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
7	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
8	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community	Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

9

10

Table 3.13 Comparison between all the priority segments before and after GI

Priority Site #	Stop Id	Ridership (Count/ Day)	Evaluated Area (SQFT)	%Area > 3" (Pre)	%Area > 3" (Post)	Mitigated Area (SQFT)
1	42	2128	3250	37.69%	39.23%	-50
2	107	1145	7200	13.19%	13.54%	-25
	121	955	3075	1.63%	1.63%	0
	124	733	2425	22.68%	8.25%	350
	15679	733	3700	70.27%	69.59%	25
3	11167	696	3675	12.24%	10.20%	75
4	46	646	3750	98.67%	92.00%	250
	11610	598	2000	93.75%	93.75%	0
	10981	520	3750	79.33%	76.67%	100

5	100	645	7000	0.00%	0.00%	0
6	184	585	3600	97.92%	77.08%	750
	187	551	2800	85.71%	72.32%	375
7	136	572	3475	66.91%	16.55%	1750
	139	553	2275	97.80%	9.89%	2000
	71	364	4150	100.00%	100.00%	0
8	81	492	3875	94.84%	34.19%	2350
	86	391	3550	86.62%	55.63%	1100
9	13501	418	3675	92.52%	44.22%	1775
10	342	413	2800	87.50%	84.82%	75

Table 3.14 Comparison between all the priority sites before and after GI

Priority Site #	Total Area of All Road (SQFT)	%Area > 3" (Existing)	%Area > 3" (GI)	Mitigated Area (SQFT)
1	686000	35.59%	21.33%	97850
2	980050	36.09%	29.53%	64275
3	1033225	41.43%	28.74%	131125
4	962975	29.57%	23.07%	62625
5	881300	31.24%	25.45%	51000
6	812875	31.37%	22.72%	70350
7	1307550	34.15%	25.09%	118425
8	816150	29.20%	20.00%	75150
9	1481750	31.19%	21.11%	149450
10	145525	41.64%	25.53%	23450

3.4 LIMITATIONS

There are several limitations to this modelling work of transportation and hydrological conditions that have been noted during the processing of results. The Stage 1 results (at 20 foot resolution) used as a baseline assessment for the entire City had results that varied from the Stage 3 model results (at the finer 5 foot resolution). In order to systematically model the hydrology of the whole city to identify the priority locations, this 20 foot grid was a computation limitation of the Flo-2D hydrological model. Additionally, some GI implementations in heavily flooded areas had a spill-over effect to surrounding areas. Although the County mandated nine inch GI depth maximum was followed and GI implementations were successful at concentrating the flood water to an area outside of the road condition, with our coarse implementation strategy, there was sometimes an increase in flooding to GI-adjacent areas. Traffic scenario #1 and pedestrian scenario #8 are examples of this spill-over effect.

4.0 PRELIMINARY CONCLUSIONS

This section provides preliminary conclusions based on initial observations during the processing of the results and highlights areas for future work. Five key design principles and effects such as time duration and co-benefits are discussed. Presentations via zoom are scheduled this summer with staff from Pima County Regional Flood Control District, Tucson Department of Transportation and Mobility, and Tucson Water to obtain further feedback on implication, limitations, and future directions of the study. This summer, in addition to external presentations of the work to the City and County, an academic publication of the results is being written.

4.1 MAXIMIZING GI INVESTMENT TO IMPROVE MULTIMODAL MOBILITY AND ACCESSIBILITY: 5 KEY DESIGN PRINCIPLES

This section outlines five key principles to improve GI design performance that emerged during the Stage 4 Impact Assessment. These five principles can be used by transportation planners and engineers, hydrologists, flood managers, and urban designers when approaching and evaluating GI project sites and investments to maximize the impact on increased multimodal accessibility. The five principles are: (1) prioritize upstream mitigation, (2) prioritize moderate flooding areas, (3) prioritize network gains, (4) prioritize sites with large right-of-way areas, and (5) prioritize locations with high pedestrian travel demands.

4.1.1 Principle 1: Prioritize Upstream Mitigation

Across the thirty scenarios, the priority segments with the greatest improved transportation access were in areas that had substantial upstream mitigation. This result suggests that GI should not only be implemented directly adjacent to priority transit locations, but also (and sometimes more importantly) implemented upstream of the priority segment. Although citizen flood complaints and maintenance concerns may center directly where flood waters accumulate most acutely, it is important to examine upstream opportunities for GI that can in aggregate address the specific area of concern and concerns throughout the watershed. GI depends on the accrual of many small scale implementations to have a lasting impact (as compared to a large multi-foot deep basin that is a single, large scale feature).

4.1.2 Principle 2: Prioritize Moderate Flooding

Across the thirty scenarios, the greatest impact on improved transportation access were in areas that received moderate flooding, in comparison to areas of extreme flooding. Overall, none of the 30 priority segments were completely mitigated from flooding. For cars, several locations do become passable across several lanes of travel. These locations experienced more moderate flooding. Similarly, no bicycle access path was completely mitigated of flooding. There did not appear to be a significant difference between shared road conditions and bicycle lane cases. Again, GI implementation had the largest impact when applied in moderate flooding conditions. The same results were seen for pedestrian access to bus stops.

Often municipalities and transportation agencies are motivated to place GI installations in rights-of-way adjacent to areas where there are the greatest flooding concerns and highest volume of citizen complaints. Our research suggests that volume of citizen complaint or depth of flooding may not be the best criterion to identify GI implementation locations for maximum impact. Rather, areas of moderate flooding with accessibility concerns showed the greatest impact from comprehensive GI implementations at a neighborhood-scale. To address areas of extreme flooding, larger implementations (such as underground stormwater piping or large basins) would need to be implemented in concert with the GI investments. Thus, for the GI installation to visibly show an impact on reducing flooding and increasing accessibility to the multimodal network, moderate flooded sites are the best candidates unless the municipality has additional funding to implement larger scale flood control measures. Future research will clarify these exact investment trade-offs and evaluate flood magnitude and GI effectiveness. This Small Starts grant successfully provided the research team with an initial understanding of the issues at play, so that future research can pinpoint the exact dynamics.

4.1.3 Principle 3: Prioritize Network Gains

When selecting project sites for GI implementation, it is critical to consider the network gains that can be accomplished by concentrating the GI implementation within an area. By addressing the flooding issue in one street or sidewalk segment, other downstream flooding concerns may be helped as well. When evaluating and designing GI projects, the larger hydrological and transportation networks connected to that project area should be considered as part of the potential design strategy and outcomes.

4.1.4 Principle 4: Prioritize Large Right-of-Way Areas

Across the thirty sites and segments, the largest impacts often occurred when there was a substantial amount of right-of-way available for implementation. When selecting and prioritizing projects for GI implementation, the area (and corresponding volume) of the available right-of-way for implementation is critical to long term performance and impact. Taken into consideration with the other four principles outlined, the availability of right-of-way can make a large impact on total flood reduction success.

4.1.5 Principle 5: Prioritize Pedestrian Travel Locations

The greatest impacts of GI on accessibility were in the pedestrian access to bus stop cases. The width of these designated areas to mitigate were smaller in the pedestrian cases compared to bicycle and vehicle cases. Acting as a buffer between road and pedestrian walking areas, the GI implementations most successfully supported greater access. However, consistent with the other two modes, GI did little to mitigate impact in high volume flooding cases. Further work is needed to complete the full analysis of the results and development of conclusions.

4.2 OPTIMIZING CO-BENEFITS

The co-benefits of GI are an important considerations in GI site selection for a transportation network. For example, shading from trees in GI installations can transform an exposed walking or bicycle path into one that is more accessible during times of day for vulnerable populations that may have issues in extreme heat. As the majority of sites were mitigated but still did not meet base accessibility thresholds, co-optimizing site selection with other factors could provide useful additional criteria for site selection, particularly in the case of pedestrian access. As this Small Starts grant aimed to consider equity, it is important to note that these co-benefits are neighborhood-scale and focused on modes of transportation more widely used by lower socio-economic statuses.

4.3 MODELLING TIME DURATION

Time duration of flooding events is a critical dynamic. This Small Starts grant, as a preliminary study, evaluated accessibility with peak flooding criteria at a single time. Despite many sites not meeting accessibility thresholds after GI implementation, it is possible with more nuanced modelling of flood reduction over time some sites/segments would become fully accessible within short time durations. This pre and post-peak flood reduction would make a large impact on mobility despite the single peak outcome observed in this preliminary study. Future research will investigate how long these peak events occur and how quickly GI installations facilitate a return to accessibility of the multimodal transportation network.

4.4 FUTURE WORK

The research team will disseminate this research in several venues this summer and into next year. First, summer presentations via zoom are scheduled with staff from Pima County Regional Flood Control District, Tucson Department of Transportation and Mobility, and Tucson Water to obtain further feedback. An academic article is currently being written to disseminate this work and results to a broader audience. Additionally, the team plans to submit to the Transportation Research Board conference to communicate with an audience of academics and practitioners. The research team has secured additional future cost-share commitments from Tucson Department of Transportation and Mobility and Pima County Regional Flood Control District to apply for new funding to continue this work. The team is currently completing a submission for a NITC General Grant to fund further analysis and the creation of a decision support tool for the City and County to optimize across a Complete ‘Green’ Streets framework. The team also aims to apply to other grant opportunities through the National Science Foundation.

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APPENDIX A

A-1 ROUGHNESS

Land Cover	Manning's n
Water	0.01
Roads	0.02
Structures	0.024
Desert/Grassland/Scrub	0.04
Tree/Shrubs	0.055
Irrigated Land	0.06
Impervious	0.026
Barren/Bedrock	0.065

A-2 INFILTRATION

	Soil Group			
Land Cover	A	B	C	D
Water	100	100	100	100
Trees/Shrubs	83	83	88	91
Irrigated Land	83	79	86	90
Desert/Grassland/Scrub	81	83	86	89
Barren/Bedrock	95	95	95	95
Impervious	99	99	99	99
Structures	99	99	99	99
Roads	99	99	99	99

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Urban Transportation System Flood Vulnerability Assessment with Special Reference to Low Income and Minority Neighborhoods

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