Appendices

1. Stakeholder Presentations
2. Literature Review
3. GIS Analysis Figures & Tables
4. Survey for Criteria Ranking
5. LID Features and Treatment Train Details
6. Surface Water Model Report
7. Urban Heat Assessment
8. Air Quality Assessment
9. Surface Water Quality Assessment
10. Decision Support Tool Memo

Appendix 1. Stakeholder Presentations

RECLAMATION
Managing Water in the West

Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development/Green Stormwater Infrastructure

U.S. Department of the Interior
Bureau of Reclamation

Stakeholder Meeting
March 12, 2019

1

LID Study
Presentation Outline

- Introductions
- LID/GSI Definitions
  - Examples
    Benefits
- Study Details
- Objectives
- Tasks
- Schedule
- Why LID/GSI
- More Examples

RECLAMATION

2

LID Study
LID/GSI Definitions

Low Impact Development:
"Systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat
(https://19january2017snapshot.epa.gov/nps/urban-runoff low impact-development_.htm)

Green Stormwater Infrastructure:
"Involves the use of landscape features to store, infiltrate, and evaporate stormwater. This reduces the amount of water draining into sewers and helps reduce the discharge of pollutants into area water bodies.
https://www.epa.gov/sites/product on/f es/2015-08/documents/fs_green_infrastructure.pdf

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LID Study
Green versus Grey Infrastructure

Green Stormwater Infrastructure (GSI) design is based on features similar to those found in nature to manage storm flows.

Grey Infrastructure (GI) consists of engineered projects to manage storm flows including pipes, pumps, ditches, and detention ponds. (Soil Science Society of America https://www.soils.org/discover-soils/soils-in-the-city/green-infrastructure/important-terms/grey-infrastructure.)

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4

LID Study - LID/GSI Examples

Street median curb cut and bioswale

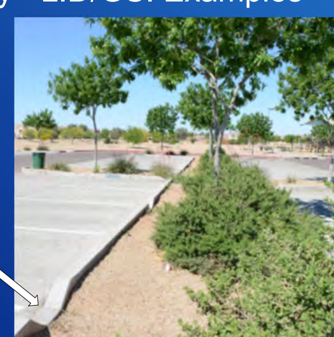
FCDMC *Durango Campus*

RECLAMATION

5

LID Study - LID/GSI Examples

Parking lot curb cuts



City of Phoenix

RECLAMATION

6

LID Study - LID/GSI Examples
Bioswale

FCDMC *Durango Campus*

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7

LID Study - Benefits

- ✓ Water Conservation ↑
- ✓ Water Infiltration ↑
- ✓ Stormwater Runoff ↓
- ✓ Local Flooding ↓
- ✓ Water Quality ↑
- ✓ Urban Heat Island ↓
- ✓ Air Quality ↑

City of Phoenix
36th St. & Rosemont
Primera Iglesias

RECLAMATION

8

LID Study
Bureau of Reclamation Mission

Manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

RECLAMATION

9

LID Study
Bureau of Reclamation
Water Development

Congressional Authority

- Reclamation Act of 1902 authorized BOR to conduct Appraisal Studies, Special Studies and Technical Investigations.
- Feasibility Studies require expressed Congressional authorization.

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LID Study
Reclamation's Principles & Guidelines

Water Resources Planning Act of 1965, as amended.

- **Completeness** a plan that includes all the necessary parts and actions to produce the desired results.
- **Effectiveness** a plan that meets the objectives within the constraints.
- **Efficiency** a plan that minimizes cost and is cost effective.
- **Acceptability** an acceptable plan to all decision makers and compatible with laws and policies.

Evaluate economic and social impacts of alternatives.

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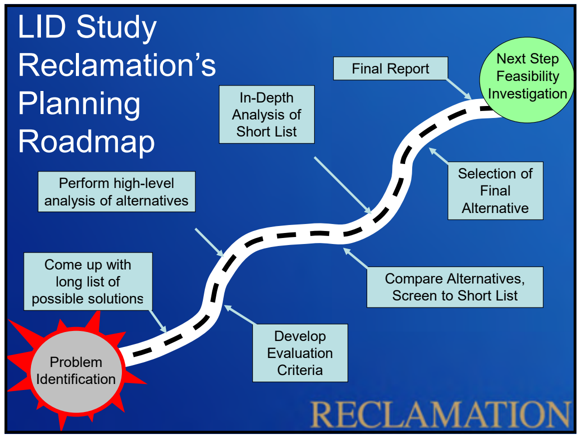
LID Study
Reclamation's Planning Roadmap



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12

LID Study
Study Details

- **Study Title:** *Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development/Green Stormwater Infrastructure*
- **Partners:**

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LID Study - Study Details

- **Special Study**
  - utilize existing data
  - GIS spatial analysis
  - surface water model
- **Duration: 3-years**
  - start May 2018
- **Cost-share:** 50% non-federal and 50% federal
- **Budget:** $404,100
  - $224,100 non-federal cost share
  - $180,000 federal cost share

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LID Study
Study Details - Partner Participation

Partner Agency / Organization	Participation
The Nature Conservancy	Co-Study Manager participatory process, data compilation and review, write summary reports, organize and attend meetings, GIS spatial analysis
Bureau of Reclamation	Co-Study Manager participatory process, provide assistance with data compilation and review, summary reports, meeting organization, GIS spatial analysis, and surface water flow modeling
City of Phoenix	Attend meetings, provide and vet data, review work products and reports
Flood Control District of Maricopa County	Attend meetings, provide and vet data, review work products and reports, support flow modeling as applicable
Maricopa County Air Quality Department	Attend meetings, provide and vet data, review work products and reports

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LID Study
Study Details – Auxiliary Staffing

Reclamation Denver Technical Services Center for modeling

TNC Contractor to assist with data compilation, modeling support, and framework for future use

COP Contractor to supplement work on all Study tasks

ASU Knowledge Exchange for Resilience Fellowship for literature review and shepherding prioritization methodology

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LID Study - Objectives

Identify areas with:
- Favorable conditions for LID
- Potential for improving:
  - Water conservation
  - Flood risk
  - Air and water quality
  - Urban heat

Determine:
- Repeatable approaches to optimize stakeholder-identified benefits: water conservation, infiltration, urban heat, and air and water quality.

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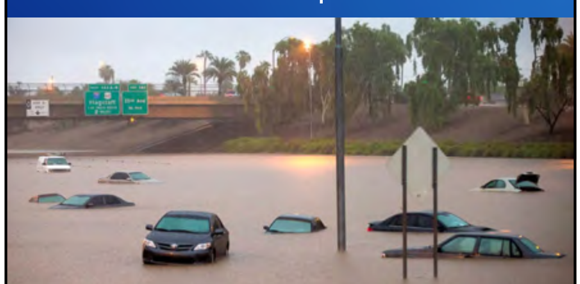
LID Study
Phoenix Flood September 2014



Michael Chow/The Arizona Republic/AP Photo

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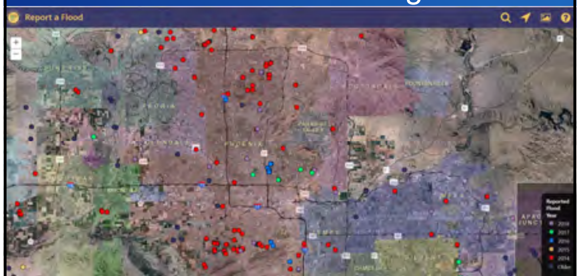
LID Study
Localized Flooding



FCDMC, 2018

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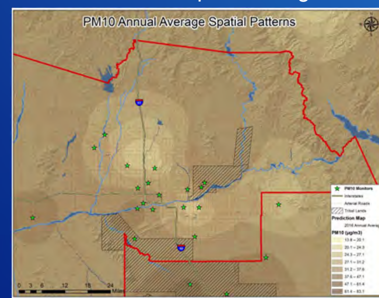
LID Study
Air Quality: Annual Particulate Matter <10 microns (PM_{10})
Phoenix Metropolitan Region



MCAQD, 2018

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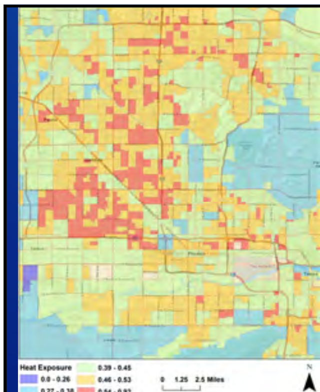

Urban Resilience to Extremes Sustainability Research Network 2018

LID Study
Urban Heat

Heat Exposure temperature plus population density.

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LID Study
Phase I Tasks

Phase I

1. Develop Problem Statement
2. Conduct literature review
3. Identify LID features
4. Conduct GIS catchment suitability analysis
5. Summary Report for Phase I

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LID Study
Problem Statement

The identified need is to prioritize the implementation of Low Impact Development (LID) / Green Stormwater Infrastructure (GSI) to produce multiple, quantifiable benefits.

The objectives are:

1) identify areas to maximize GSI benefits, including increased stormwater infiltration, flood hazard mitigation, and water conservation; reduced urban heat island impacts, and improved air and water quality; and
2) provide the tools to make long-term decisions regarding placement of GSI through the development of a repeatable prioritization method.

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LID Study
Literature Review

Identify types of LID features and effectiveness with:

- slowing storm flows
- increasing water availability via conservation and infiltration
- and improving urban heat, water and air quality

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LID Study – Literature Review Assessing Effectiveness

Hydrological Performance	Stormflow peak reductions, infiltration, water availability for irrigation/irrigation offsets.
Urban Heat	radiant and air temperature surface temperature
Air Quality	PM2.5 PM10 Ozone CO
Water quality	Metals (Lead, copper, zinc) e. Coli sediment transport reduction

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LID Study - LID Features

- Permeable Pavement
- Curb openings
- Sediment traps
- Stormwater harvesting basins
- Vegetated or rock swales
- Bioretention systems
- Curb extensions
- Bioretention planter
- Domed overflow structure
- Grade Control Structures
- Tree pits

PCSWMM
https://www.pcswmm.com/

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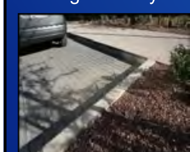
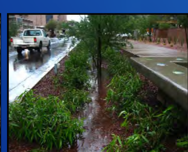
LID Study – LID Features

Permeable Pavers right-of-way



Vegetative Swales Rain Garden



Curb Cuts

City of Phoenix   Taylor Mall ASU
Walter Cronkite School of Journalism and Mass Communication

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LID Study - LID Features

Pervious concrete at Phoenix Manzanita Park Parking Lot

Curb Core for Street Run-off

Vegetative Swale
Primera Iglesia, Phoenix

City of Phoenix

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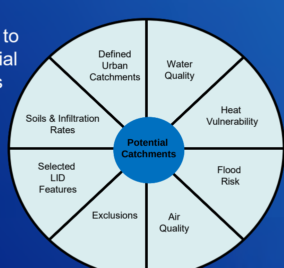
LID Study
GIS Catchment Suitability Analysis

Criteria used to select potential catchments



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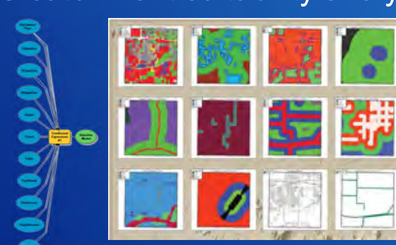
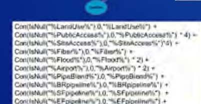
LID Study
GIS catchment suitability analysis





Example - GIS Technical Process Map

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LID Study
GIS Catchment Suitability Analysis


City of Phoenix

GIS Spatial Analysis:
Identify suitable COP stormwater catchments with most potential to improve:

- storm flow management
- infiltration
- urban heat conditions
- water and air quality

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LID Study
GIS Catchment Suitability Analysis

Urban Catchment Definition

An area of land from which all rainwater drains, overland or through pipes and drainage networks, toward a body of water.

Also known as an urban basin, urban watershed, drainage area, or stormwater drainage system.


City of Phoenix

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LID Study – Phase II Tasks

<u>Phase II</u>

1. Model selected catchments using Stormwater Management Model PC SWMM:
   a. Compile and collect site specific data for selected catchments.
   b. Develop model to evaluate a variety of LID features and scenarios
   c. Identify scenarios with optimal improvements to manage stormwater quantity and quality.
2. Prepare final report

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LID Study
PCSWMM – Personal Computer Stormwater Management Model

PCSWWM:
- used for master planning
- provides quick analysis of multiple LID's and treatment areas
- compares hydrologic and water quality benefits of LID scenarios
- scenario comparison tools


PCSWMM; https://www.pcswmm.com/

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LID Study
Compile and Collect Site Specific Data

Data required for model simulations:
- Stormwater system (storm drains, mains, and outfalls)
- Precipitation
- Soil infiltration
- Pollutant loading at outfall
- Land use
- Vegetation density and model add-ons

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LID Study
Develop Model and Identify Scenarios

- Develop LID feature arrangement scenarios.
- Compare types, sizes, and number of LID features.
- Utilize flexible scenario analyses to compare LID arrangements to optimize benefits.
- Assess tradeoffs between scenarios.
- Adjust scenarios according to analysis.
- Select scenario with optimum results.

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LID Study
Final Report

Reclamation and the Conservancy will prepare a final report summarizing Study accomplishments in collaboration with partners.

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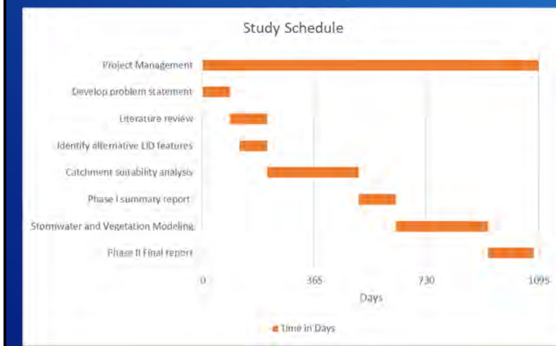
LID Study



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LID Study
Why LID/GSI

- Arizona Department of Water Resources reports that up to 70% of residential water use is outdoors. (https://new.azwater.gov/conservation/landscaping)
- Residential outdoor water (except SRP irrigation areas) primarily consists of water treated to primary drinking water standards.
- Right Water   Right Use
- "green infrastructure is perhaps even more relevant in arid and semi arid climates" (www.epa.gov/ow/eparecovery)

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LID Study – Why LID/GSI
Water Balance Pre and Post Urban

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LID/GSI More Examples

FCDMC   *Durango Campus*

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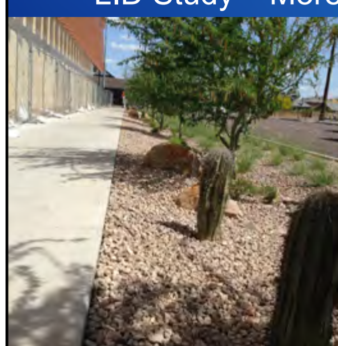
LID Study – More Examples



Bioretention system

7th St. & Filmore

City of Phoenix

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LID Study – More Examples

Pervious pavement
Taylor Mall

City of Phoenix

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LID Study – More Examples

Pervious pavement
Central Station

City of Phoenix

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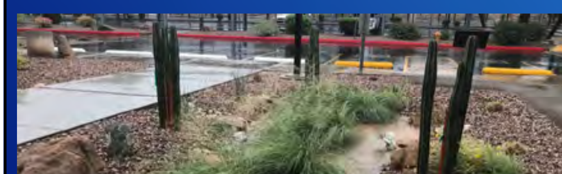
LID Study – More Examples

Greater Phoenix Green Infrastructure & LID Handbook
January 2019
https://sustainability.asu.edu/sustainable cities/resources/lid handbook/



FCDMC *Durango Campus*

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LID Study - Future Use of Study Tools

- A shared vision for investment and implementation of green infrastructure
- Assess effectiveness of hybrid approaches to stormwater management
- Combine siloed resources towards shared goals and outcomes

The Nature Conservancy

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Reclamation's WaterSMART Program

https://www.usbr.gov/watersmart/

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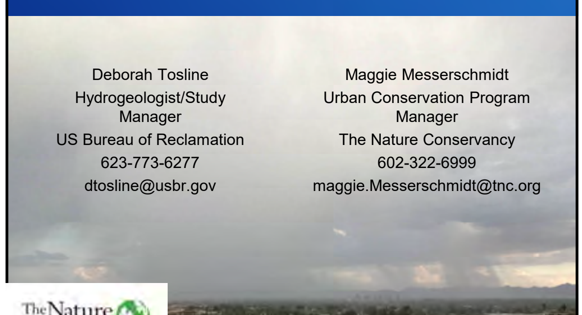
LID Study - Contacts



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Maggie Messerschmidt
Urban Conservation Program Manager
The Nature Conservancy
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maggie.Messerschmidt@tnc.org

The Nature Conservancy Arizona

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BUREAU OF RECLAMATION

The Nature Conservancy Arizona

Identifying Key Areas In The City Of Phoenix For Infiltration And Retention Using Low Impact Development

Stakeholder Webinar
July 30, 2020

1

LID Floodplain Restoration
Survey

- At end of presentation
- Rank the importance of these issues for Phoenix
  - Heat
  - Flooding
  - Stormwater Quality
  - Air Quality

2

LID Floodplain Restoration
Speakers

- Deborah Tosline, Co-Manager of Study, Registered Geologist in Arizona and Hydrologist with the U.S. Bureau of Reclamation.
- Anna Bettis, Co-Manager of Study, Certified Project Management Professional and Healthy Cities Program Manager for The Nature Conservancy in Arizona.
- Dr. Sara Meerow, Assistant Professor, School of Geographical Sciences and Urban Planning, Arizona State University.
- Dr. Lisa McCauley, Spatial Analyst with the Arizona Chapter of The Nature Conservancy.

3

LID Floodplain Restoration
Presentation Outline

1. Study background
2. Updates
   a) Literature review
   b) Geographic information system (GIS) analysis
3. Next steps
4. Q&A

4

LID Floodplain Restoration

- **Duration:** May 2018 May 2021
- **Partners:**

The Nature Conservancy Arizona
Flood Control District of Maricopa County
Maricopa County Air Quality Department
City of Phoenix

5

LID Floodplain Restoration
Tasks

- Develop Problem Statement
- Conduct literature search and analysis
- Develop Geographic Information System (GIS) analysis
- Develop and run stormwater model using PCSWMM
- Evaluate and interpret model results
- Prepare planning report

6

LID Floodplain Restoration

Problem statement

The identified need is to prioritize the implementation of Green Stormwater Infrastructure (GSI) to produce multiple, quantifiable benefits. The objectives are:

1) identify areas to maximize GSI benefits, including increased stormwater infiltration and flood hazard mitigation, reduced urban heat island impacts, and improved air and stormwater quality; and
2) model multiple GSI scenarios to determine which lead to the greatest improvement in the GSI benefits listed in the first objective; and
3) provide the tools to make long-term decisions regarding placement of GSI through the development of a repeatable prioritization method.

7

LID Floodplain Restoration

Study Purpose and Plan

Identify areas with:
- Favorable conditions for theoretical use of low impact development
- Potential for high ecological and social benefit

STEP 1 **Catchment suitability analysis**

STEP 2 **Collaboratively develop criteria**

STEP 3 **Modeling**

8

LID Floodplain Restoration

LID Features

- Used to manage and treat precipitation naturally in urban areas, rather than using conventional stormwater management practices
- Mimic natural processes to infiltrate stormwater into the soil as close to its source as possible

Photo credit: TNC/Mark Ska ny

Photo credit: C ty of Phoenix Tay or Ma

9

LID Floodplain Restoration

Benefits

- ✓Stormwater runoff ⬇
- ✓Urban heat island ⬇
- ✓Local flooding ⬇
- ✓Infiltration ⬆
- ✓Air quality ⬆
- ✓Stormwater quality ⬆
- ✓Biking/Walking Environment ⬆
- ✓Trees and vegetation ⬆

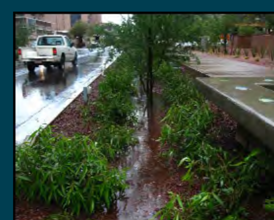

Photo credit: C ty of Phoenix Taylor Mall

10

LID Floodplain Restoration

Maximizing four benefits of LID:

1. Flood hazard mitigation and increased stormwater infiltration
2. Reduced urban heat island impacts
3. Improved air quality
4. Improved stormwater quality

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LID Floodplain Restoration

Phoenix flood September 2014

Michael Chow/The Arizona Republic/AP Photo

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LID Floodplain Restoration
Trees and Urban Heat

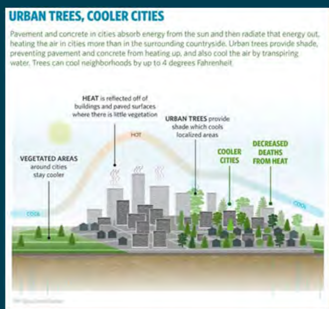


Photo credit: TNC/Mark Ska ny

- Water from LID installations supports native vegetation
- LID features with trees reduce urban heat

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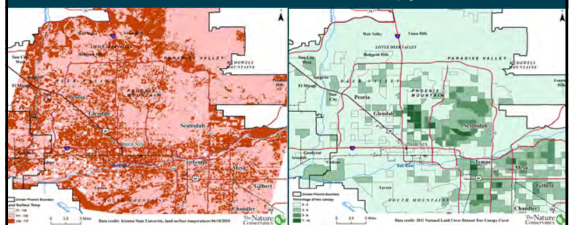
LID Floodplain Restoration
Phoenix Metro Area

Heat | Tree Canopy Cover



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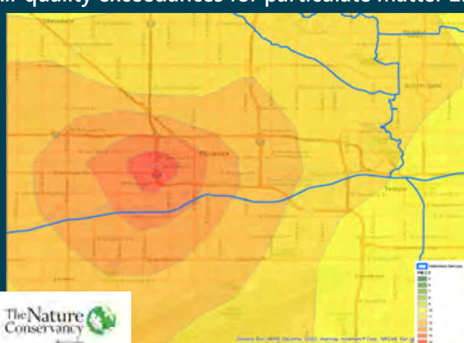
LID Floodplain Restoration
Air quality exceedances for particulate matter 2.5



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LID Floodplain Restoration
Trees and Air Quality


Photo credit: TNC/Mark Ska ny

- LID features with trees improve air quality

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LID Floodplain Restoration
Stormwater Quality

- LID features improve stormwater quality


Photo credit: TNC/Ivan Martinez

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LID Floodplain Restoration

Overview of Literature Review

Reviewed 219 studies identified by:
-searching Scopus & Web of Science citation databases
-the project team

Of 219 studies, 28 assessed hydrologic, stormwater quality, heat mitigation, or air quality benefits of LID in arid or semi-arid urban environments

Categorized them by benefit category, indicator, feature type (e.g. bioswale, permeable pavement), measurement approach, and location

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LID Floodplain Restoration

Literature Review Results

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LID Floodplain Restoration

Literature Review Results

Data available at:
https://tinyurl.com/GSIperformance

Benefit crite	Benefit indi	Feature studied code	Specific fea	Parameter	Measureme	Min	Min units	Max	Max units
air quality	PM10	trees	trees	annual pollutant	modeled			1474	kg
air quality	PM2.5	trees	trees	annual pollutant	modeled			43	kg
air quality	Ozone	trees	trees	annual pollutant	modeled			1885	kg
air quality	CO	trees	trees	annual pollutan	modeled			10	kg
air quality	other	trees	trees	annual pollutant	modeled			964	kg
air quality	other	trees	trees	annual pollutant	modeled			125	kg
air quality	PM10	trees	trees	PM10 removed	modeled	~110	Metric tons		Metric tons
air quality	PM2.5	trees	trees	PM2.5 removed	modeled	~1	Metric tons		Metric tons
air quality	Ozone	trees	trees	ozone removed	modeled	~95	Metric tons		Metric tons
air quality	CO	trees	trees	carbon monoxid	modeled	~15	Metric tons		Metric tons
air quality	other	trees	trees	nitrogen dioxide	modeled	~35	Metric tons		Metric tons
air quality	other	trees	trees	sulfur dioxide re	modeled	~10	Metric tons		Metric tons
air quality	PM10	trees	trees	PM10 removed	modeled				
hydrologic perfo	infiltration	bioretention basin/planter	bioretention bas	runoff reduction	modeled	2.25	%	5.37	%
hydrologic perfo	infiltration	infiltration trench	infiltration trenc	rain intensity sy	modeled	2.5	mm/h	14.58	mm/h
hydrologic perfo	other	bioretention basin/planter	bioretention bas	average capture	modeled	92.6	%	98.4	%
hydrologic perfo	other	bioretention basin/planter	bioretention bas	average capture	modeled	94.2	%	99.8	%
hydrologic perfo	peak flow	bioretention basin/planter	bioretention bas	peak flow reduc	field experiment	50	%	95	%
hydrologic perfo	peak flow	bioretention basin/planter	bioretention bas	peak flow reduc	field experiment	59	%	93	%
hydrologic perfo	peak flow	permeable pavement	permeable pave	change in runof	modeled				
hydrologic perfo	peak flow	other	rain barrel or cis	change in runof	modeled				
hydrologic perfo	peak flow	bioretention basin/planter	bioretention bas	change in runof	modeled				
hydrologic perfo	peak flow	other	retention basin a	change in runof	modeled				
hydrologic perfo	peak flow	other	retention basin a	change in runof	modeled				
hydrologic perfo	peak flow	other	permeable pave	change in runof	modeled				
hydrologic perfo	peak flow	other	combination of (	change in runof	modeled				
hydrologic perfo	peak flow	permeable pavement	permeable pave	chang in peak n	modeled				
hydrologic perfo	peak flow	other	rain barrel or cis	chang in peak n	modeled				
hydrologic perfo	peak flow	bioretention basin/planter	bioretention bas	chang in peak n	modeled				

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LID Floodplain Restoration

Literature Review Results

Review supported all 4 co-benefits of LID

10 studies show different types of LID are helpful for managing stormwater (reducing total runoff and peak flows)

11 heat studies consistently show a cooling effect, especially of shade trees

7 stormwater quality studies found no negative impacts and suggest LID can remove pollutants

3 studies on air quality, all suggest trees beneficial

More LID performance studies needed for arid cities, especially field measurements/experiment

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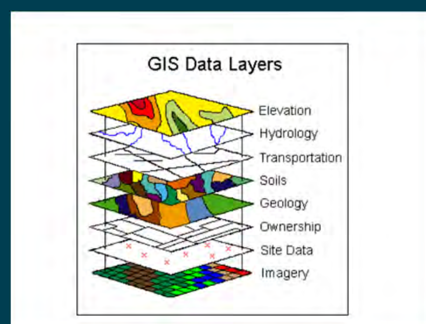
What is GIS?



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LID Floodplain Restoration

Overview of GIS Process

1. Goal - Choose catchment with highest values for each criterion from problem statement:
   - Flooding
   - Stormwater Quality
   - Air Quality
   - Heat
2. Determine GIS datasets for each criterion
3. Score each catchment based on criterion
4. Choose final catchment based on score and professional judgement

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Catchments – City of Phoenix

Range: 0.59 8,300 acres

Avg: 873 acres

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LID Floodplain Restoration

GIS Datasets

- Flooding
  - Curve Runoff Values – USDA, MAG Land Use, 2016
  - Flooding Points   City of Phoenix
- Stormwater quality
  - Industrial Land Use – MAG, 2016
  - Average Daily Traffic Density   City of Phoenix
- Air quality
  - PM10 – Maricopa County Air Quality, 2016
  - Ozone – Maricopa County Air Quality, 2016
- Heat
  - Average Median Land Surface Temperature – ASU, 2018

The Nature Conservancy

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LID Floodplain Restoration

Catchment Score Methods

1. Summarize catchments for each GIS dataset
2. Normalize across catchments - Score
   - Lowest catchment   0
   - Highest catchment = 1
3. Weight multiple datasets
4. Determine score for each criteria and each catchment
5. Weight each criteria using survey
6. Determine overall score for each catchment

The Nature Conservancy

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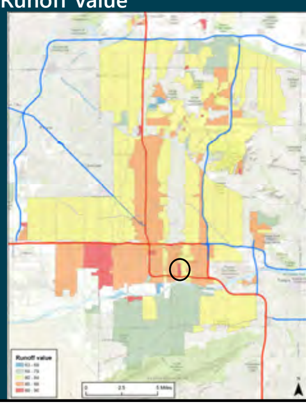
Flooding – Runoff Value



USDA/NRCS. 1986. Urban hydrology for smal watersheds. / MAG Land Use 2016

The Nature Conservancy

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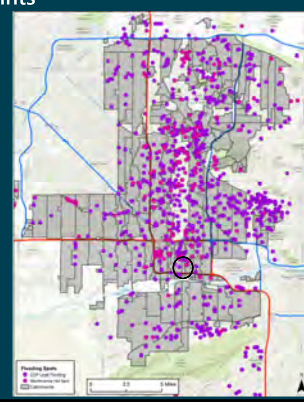
Flooding points



City of Phoenix

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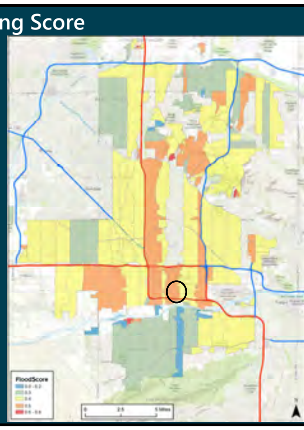
Final Flooding Score



Runoff Score*0.5 + Flood Score *0 5

The Nature Conservancy

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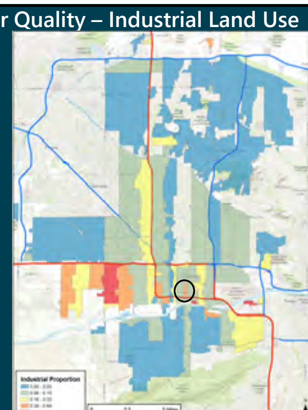
Stormwater Quality – Industrial Land Use



MAG Land Use 2016

The Nature Conservancy

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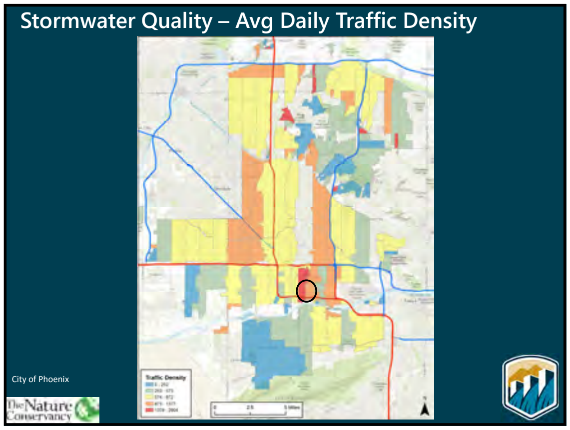

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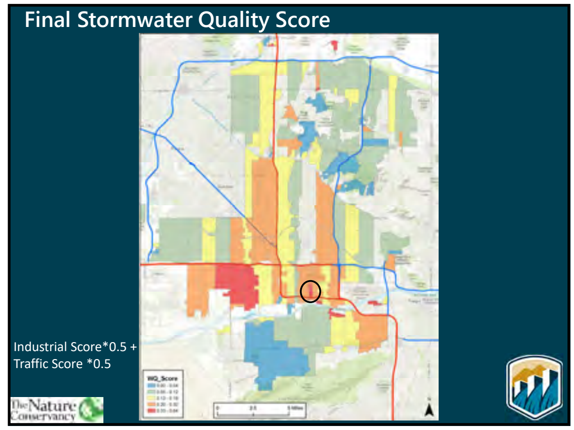

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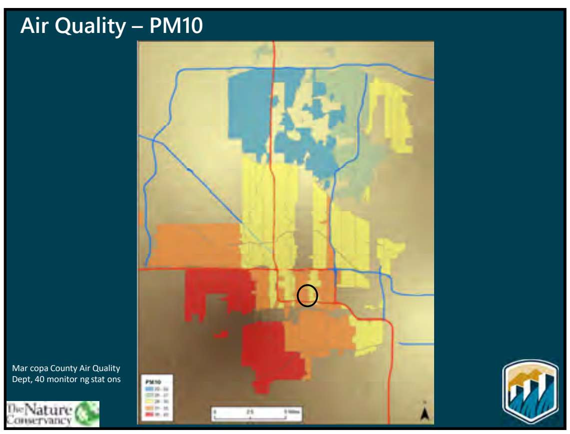

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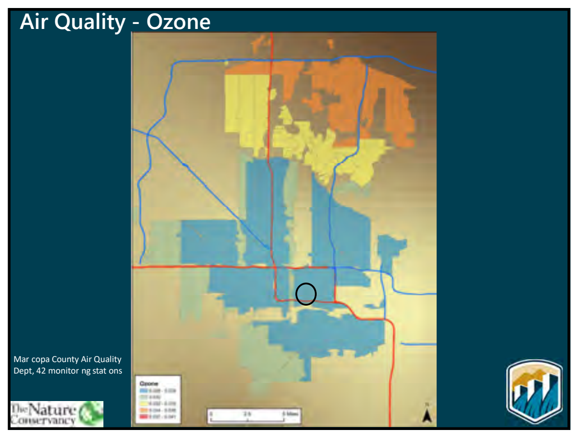

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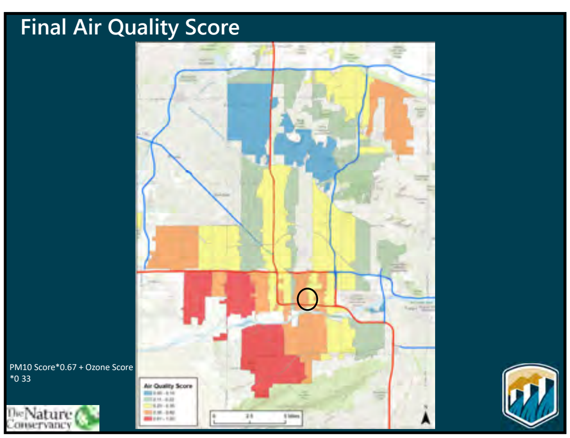

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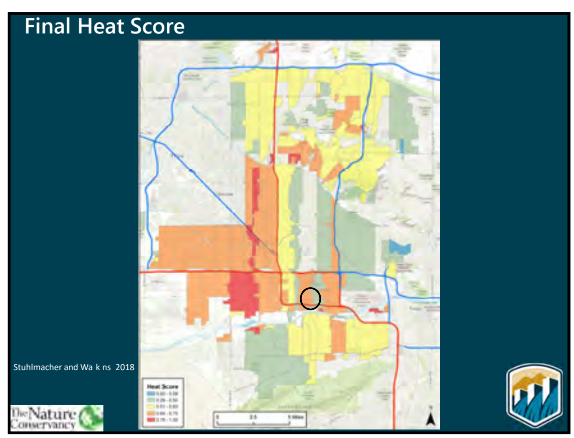

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LID Floodplain Restoration

Study Team Survey

- 3 question online survey
  - Rating – Flooding, Stormwater Quality, Heat, Air Quality
  - Ranking
  - Pair-wise comparison
- 11 participants – BOR, TNC, City of Phoenix, Air Quality, Flood Control
- Aggregated results

ASU, Dr. Sara Meerow

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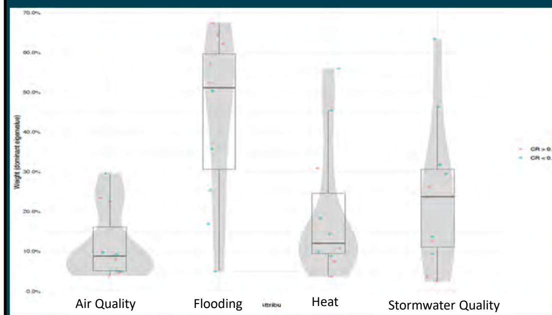
Study Team Survey



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Study Team criteria weights

Criterion	Approved weight
Flooding	0.38
Heat	0.28
Stormwater quality	0.22
Air quality	0.12

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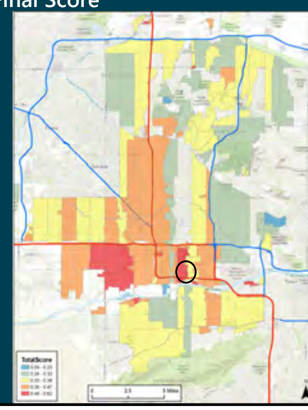
Results – Final Score



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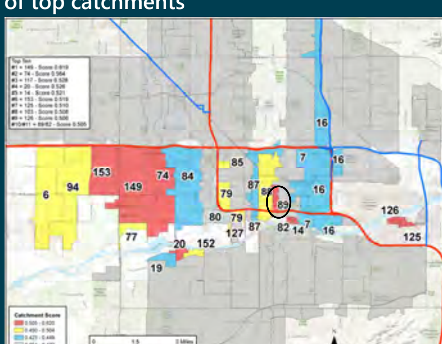
Map of top catchments



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LID Floodplain Restoration

Additional considerations

- Catchment size and Land Use
- Environmental Justice screening
- Superfund/Water Quality Assurance Revolving Fund (WQARF)/Landfills
- Infiltration

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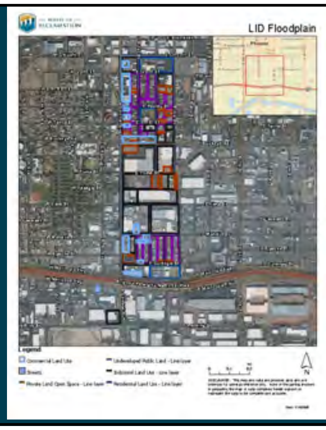
Land Use



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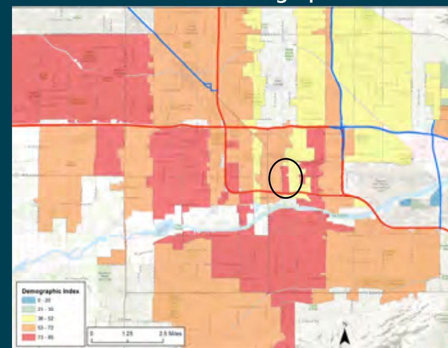
Environmental Justice – Demographic Index



(% minority population + % low income population) / 2

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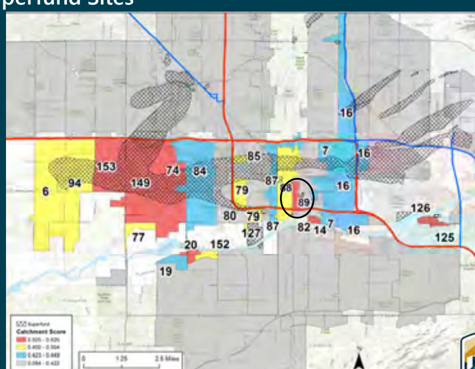
Superfund Sites



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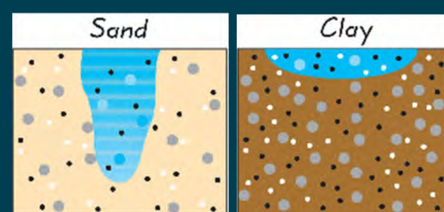
LID Floodplain Restoration

Infiltration



Modified New Mexico State University image:
http://wuc.ose.state.nm.us/irrcalc/SettingSoilTypes.html

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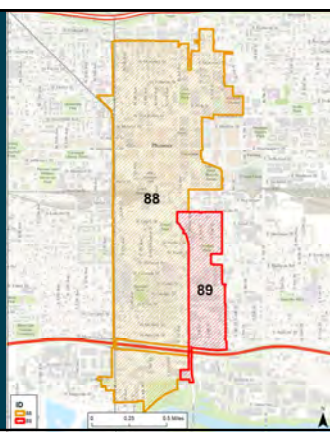
Selected:
Catchment 89

Backup:
Catchment 88



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LID Floodplain Restoration

Next steps

- PCSWMM (Personal Computer Stormwater Management Model) modeling
- Develop modeling criteria
- Build model
- Develop model scenarios
- Run model
- Finalize model

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LID Floodplain Restoration
Next steps

- Assess and interpret model results of theoretical LID treatments
  - Stormwater flow reduction
  - Stormwater Infiltration
  - Stormwater quality
- Identify relative benefits of LID treatments on urban heat and air quality
  - Stormwater infiltration supports trees
  - Tree canopy has been shown to reduce urban heat and improve air quality

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LID Floodplain Restoration
Survey

- www.menti.com - 83 08 98
- or select link in chat
- Everyone fill out survey
- Rank the importance of these issues for Phoenix
  - Heat
  - Flooding
  - Stormwater Quality
  - Air Quality

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LID Floodplain Restoration

Questions?

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Study Co-Managers:
Deborah Tosline, Bureau of Reclamation
Dtosline@usbr.gov
Anna Bettis, The Nature Conservancy in Arizona
Anna.bettis@tnc.org

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— BUREAU OF — RECLAMATION

The Nature Conservancy Arizona

Identifying Key Areas In The City Of Phoenix For Infiltration And Retention Using Low Impact Development

Final Stakeholder Webinar
June 2, 2021

1

Speakers

- Deborah Tosline, Co-Manager of Study, Registered Geologist in Arizona, Hydrologist and Certified Project Management Professional with the U.S. Bureau of Reclamation
- Anna Bettis, Co-Manager of Study, Certified Project Management Professional and Healthy Cities Program Manager for The Nature Conservancy in Arizona.
- Lindsay Bearup, Civil Engineer (Hydrologic), Water Resources Engineering and Management, U.S. Bureau of Reclamation
- Aaron Poresky, Principal Engineer, Geosyntec Consultants
- Sara Meerow, PhD, Assistant Professor, School of Geographical Sciences and Urban Planning, Arizona State University

LID Floodplain Restoration Stakeholder Meeting June 2, 2021

2

Presentation Outline

1. Study Background
2. Overview Phase I Results
3. Phase II Results
4. Final Report
5. Study Limitations / Recommendations
6. Q&A

LID Floodplain Restoration Stakeholder Meeting June 2, 2021

3

Study Background

- **Duration:** May 2018 July 2021
- **Partners:**

The Nature Conservancy Arizona — BUREAU OF — RECLAMATION
Flood Control District of Maricopa County City of Phoenix Maricopa County AIR QUALITY DEPARTMENT

- **Non-signatory Partner:** ASU Arizona State University

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4

Study Tasks

Phase I

- Develop Problem Statement
- Conduct literature search and analysis
- Develop Geographic Information System (GIS) analysis
- Two Stakeholder Presentations https://tnc.box.com/s/8qxbfgrv5gcduhuskfa9zb9w6tm2bobo

Phase II

- Develop and run stormwater model using PCSWMM
- Evaluate and interpret model results
- Stormwater Quality Assessment
- Air Quality and Urban Heat Assessment
- Final Stakeholder Presentation
- Final Report

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Problem Statement

The identified need is to prioritize the implementation of Green Stormwater Infrastructure (GSI) to produce multiple, quantifiable benefits. The objectives are:

1) identify areas to maximize GSI benefits, including
   - **increased stormwater infiltration and flood hazard mitigation**
   - **reduced urban heat island impacts**
   - **and improved air and stormwater quality**; and
2) model multiple GSI scenarios to determine which lead to the greatest improvement in the GSI benefits listed in the first objective; and
3) provide the tools to make long-term decisions regarding placement of GSI through the development of a repeatable prioritization method.

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LID Features

- Used to manage and treat precipitation naturally in urban areas to augment conventional stormwater management practices
- Mimic natural processes to infiltrate stormwater into the soil as close to its source as possible

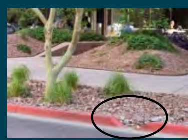
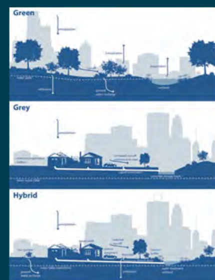


Photo cred t TNC/Mark Skalny



Dep ertr & McPhearson (2017)


Photo cred t City of Phoen x Tay o Ma

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Benefits

- ✓Stormwater runoff ⬇
- ✓Urban heat island ⬇
- ✓Local flooding ⬇
- ✓Infiltration ⬆
- ✓Air quality ⬆
- ✓Stormwater quality ⬆
- ✓Biking/Walking Environment ⬆
- ✓Trees and vegetation ⬆


Photo cred t City of Phoen x Tay or Mal

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Literature Review

Systematic literature review generally supported all 4 co-benefits of LID

Performance data not available for all LID feature types

More LID performance studies needed for arid cities, especially field measurements/experiment

Data available at: https://doi.org/10.7910/DVN/KOF8R4

Published article: Meerow, Natarajan, & Krantz (2021) Green infrastructure performance in arid and semi-arid urban environments, *Urban Water Journal*, 18:4, 275-285 https://doi.org/10.1080/1573062X.2021.1877741

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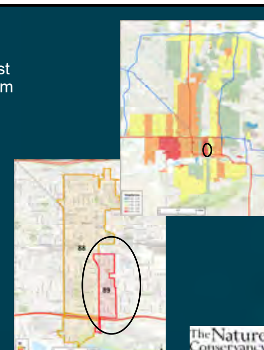
GIS Analysis

Goal: Choose catchment with highest values for each criterion from problem statement:

- Flooding
- Stormwater Quality
- Air Quality
- Heat

Each Catchment in city was ranked. Catchment 89 was chosen



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Phase II Tasks

Assess and interpret model results of theoretical LID treatments

- Stormwater flow reduction
- Stormwater Infiltration

Stormwater quality

Identify relative benefits of LID treatments on urban heat and air quality

- Stormwater infiltration supports trees
- Tree canopy has been shown to reduce urban heat and improve air quality

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Surface Water Model

Setup

PCSWMM 2020

Personal Computer Storm Water Management Model built on the EPA SWMM5 engine for stormwater runoff and routing.

- Subcatchments
- Storm Sewer: Hypothetical
- Soils: NRCS SSURGO
- Digital Elevation Model (DEM): Flood Control District
- Land cover: City of Phoenix

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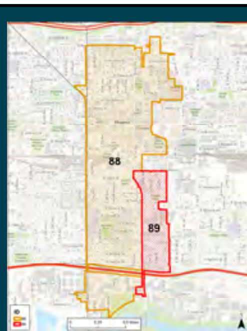
Surface Water Model
Setup – Continuous Precipitation

- Flood Control District's Jackson St. @ 7th Ave. Gauge
- 29 Year Continuous Precipitation from 2/1/1991 through 1/31/2020
- Provides a variety of storms and ambient conditions



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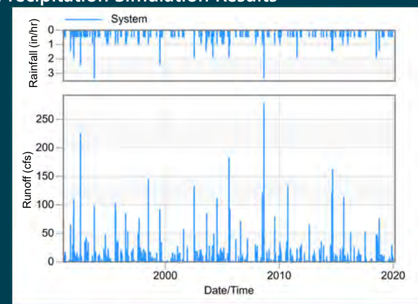
Surface Water Model
Continuous Precipitation Simulation Results



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Surface Water Model
LID Scenarios

- **Participation Rates** 25%, 50% and 100%
  - Baseline model represents no-LID scenario - used for comparison
  - 10% similar to model error, not selected
  - 25% rate selected to assess low participation rate that may show results
  - 50% rate could represent an optimistic actual rate
  - 100% rate or maximum was selected to assess stormwater volume reduction in a fully treated retrofit
- **LID Features**
  - Based on Greater Phoenix Green Infrastructure LID Handbook
- **LID scenarios were identified for each land use**

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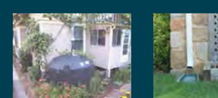
Surface Water Model
LID Features


Rain Gardens / Chicanes


Infiltration Trenches


Bioretention Cells


Linear Basins


Rooftop Capture or Disconnection (cisterns/rain barrels)


Permeable Pavers

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Photo Cred ts: TNC EPA SWMM Manua 2016

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Surface Water Model
Theoretical LID Residential Scenarios

KEY
- Rain garden / Chicanes
- Rain Barrels
- Disconnected Downspout

The information offered herein represents the opinion of the LID F oodplain study author(s). It does not represent and should not be construed to represent the City of Phoen x determination or policy.

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Surface Water Model
Theoretical LID Public Scenarios

KEY
- Bio Retent on
- Rain garden / Chicanes
- Permeab e pavement
- Rain Barrels/ Cisterns
- Disconnected Downspout

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Surface Water Model
Theoretical LID Commercial Scenarios

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Surface Water Model
Theoretical LID Industrial Scenarios

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Surface Water Model
Theoretical LID Scenario Summary

Feature	Residential (#, sq. ft)			Public (#, sq. ft)			Commercial (#, sq. ft)			Industrial (#, sq. ft)		
	25%	50%	100%	25%	50%	100%	25%	50%	100%	25%	50%	100%
	25500	50250	96750	6826	14204	27929	27147	49936	99779	110222	166725	314279
Cisterns / Rain Barrels	34	67	129	3	6	11	6	14	27	4	8	15
Rain Gardens	68	134	258	23	40	77	37	62	110	105	200	387
Linear Basins	34	67	129	12	22	42	-	-	-	-	-	-
Chicanes	27	27	27	12	12	12	-	-	-	-	-	-
Infiltration Trenches	-	-	-	-	-	-	4	12	28	28	58	121
Bioretention	-	-	-	18	33	63	14	17	26	33	57	107
Pervious Pavement Area	-	-	-	4672	9344	18688	11683	23366	46733	21094	42187	84374

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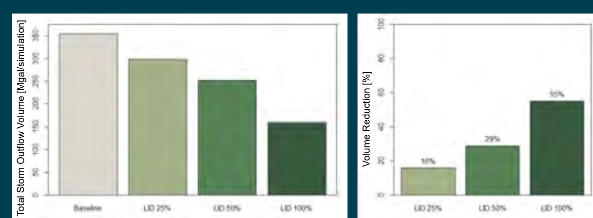
Surface Water Model
Results - Change in Total Outflow Volume



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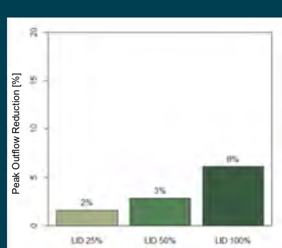
Surface Water Model
Results – Change in Peak Outflows



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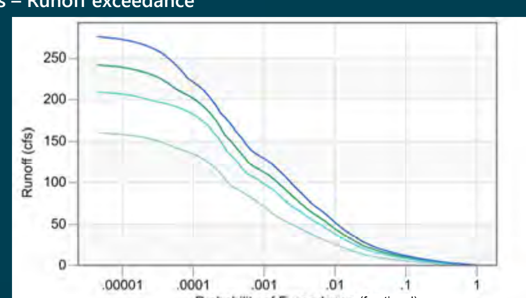
Surface Water Model
Results – Runoff exceedance



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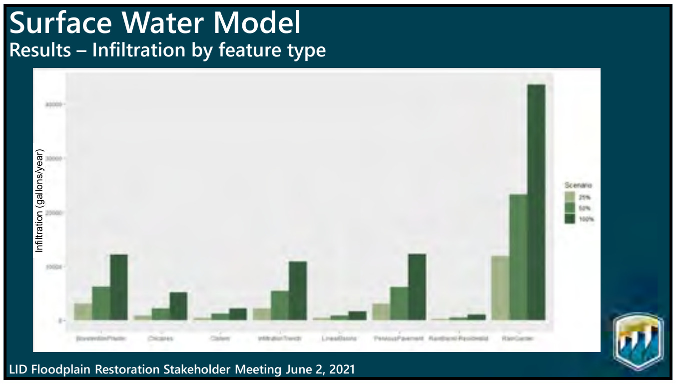

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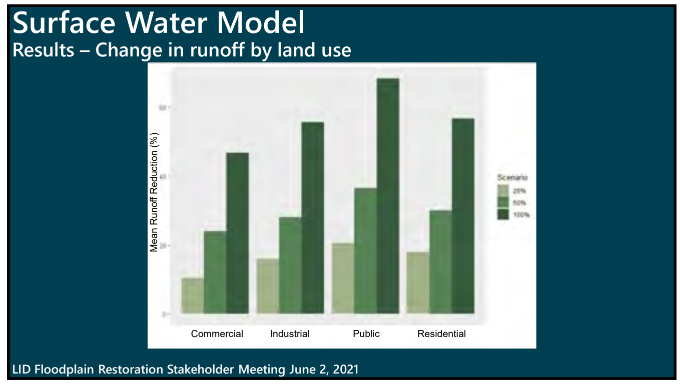

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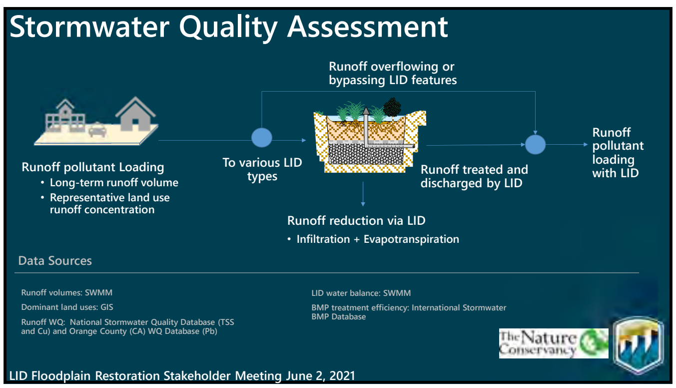

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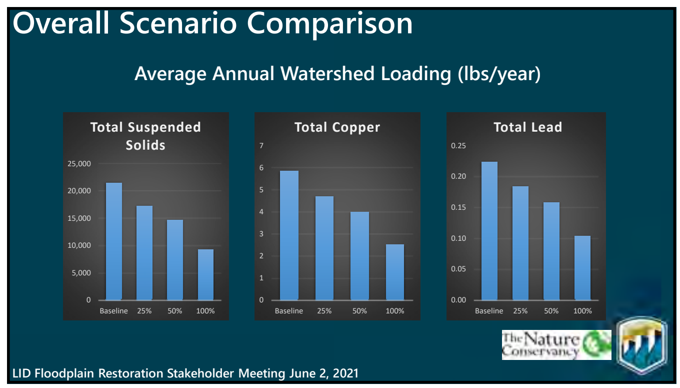

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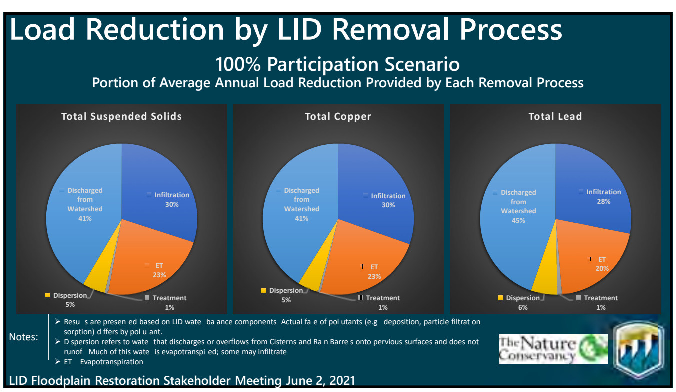

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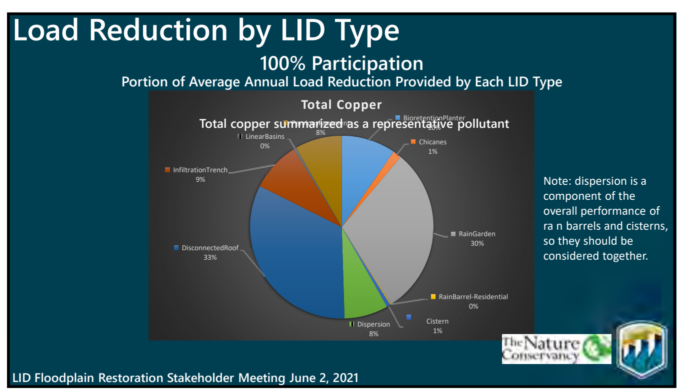

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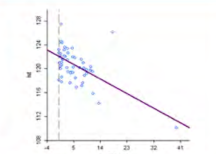
Urban Heat Assessment: Methods

Teresa Garcia's Masters of Urban and Environmental Planning (MUEP) applied project

1. Literature review
2. Spatial & statistical analysis of relationship between land cover, land use, & land surface temperature (LST)
    - Use statistical (regression) model between % impervious & LST and % vegetated & LST to predict how LID scenarios would reduce LST



#obs	R^2	const a	std-err a	t-stat a	p-value a	slope b	std-err b	t-stat b	p-value b
56	0.338	122.043	0.404	301.726	0	-0.271	0.052	-5.253	0.000
0	0	0	0	0	0	0	0	0	0
56	0.338	122.043	0.404	301.726	0	-0.271	0.052	-5.253	0.000

Relat onship between subcatchment percent vegetated & LST: GeoDa linear regress on plot

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Urban Heat Assessment: Results

- Vegetated and pervious areas have lower LST
    - e.g. across city trees average LST =113 F, grass=111 F, roads=119 F
- LID scenarios are predicted to reduce LST
- In 100% participation scenario, if areas converted from impervious to pervious are vegetated, model would suggest that LST would be reduced as much as 4 F in some areas

LID scenario	Average predicted subcatchment LST reduction based on change in imperviouseness	Average predicted subcatchment reduction assum ng new pervious areas vegetated
25% partic pation	0.15°F	0.69°F
50% participation	0.19 F	0.85 F
100% participation	0.26 F	1.18 F

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Urban Heat Assessment: Limitations

- Relies on simplistic statistical modeling
- LST ≠ air temperature
- Estimates likely conservative because only assumes change in vegetation/imperviousness for the area converted from impervious to pervious in surface water modeling
    - e.g. residential lots where rain gardens would be added to gravel not included, but would expect vegetated areas to be cooler

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Air Quality Assessment: Methods

Corey Ferguson's MUEP applied project

1. Literature review
2. i-Tree Eco Model
3. Field data for baseline model from sample land use plots
4. Used stormwater capture volumes from surface water modeling to determine new tree inputs for three participation scenarios
5. Desert Fern/Feather bush (*Lysiloma watsonii*) was selected as the "model" tree

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Air Quality Assessment: Results

- Model shows LID could support vegetation that removes pollution and provides health benefits
- Air quality benefits modest
- i-Tree Eco reports also outline relationships between specific tree species and air pollution removal rates as well as net benefits across land use and species type

Total Catchment			
Land Use	25%	50%	100%
Residential	162	288	461
Public	38	75	129
Commercial	83	150	248
Industrial	297	537	898
Total New Trees	580	1050	1736
Sample Plot			
Land Use	25%	50%	100%
Residential	9	16	26
Public	11	22	38
Commercial	17	31	52
Industrial	109	197	329
Total New Trees	147	267	445

Scenario	# of trees	Pollution removal
Baseline	569	363.9 pounds/year ($739/year)
25% participation	1,144	408.4 pounds/year ($889/year)
50% participation	1612	440.6 pounds/year ($1010/year)
100% participation	2304	483.5 pounds/year ($1190/year)

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Air Quality Assessment: Limitations

- Baseline vegetation information difficult to collect
- Dependent on accuracy of i-Tree model
- Estimates of trees supported in LID scenarios
- Only modeled Desert Fern, more diversity in species selection should be modeled and used to maximize benefits
- Need to investigate opportunities and tradeoffs for green roofs/living walls and grasses within the Phoenix area
- Explore connections between health benefits reported by i-Tree Eco and place-based population health characteristics

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Final Report

- Report available in late August
- Contact Deborah Tosline at Reclamation to request a copy

LID Floodplain Restoration Stakeholder Meeting June 2, 2021

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Study Limitations and Recommendations

Limitations
- Limited modeling investigations of LID features in urban arid and semi-arid lands
- Limited references on effects of LID features in urban arid and semi-arid lands
- Modeling required simplifying assumptions including one small catchment
- Limited empirically derived information in Phoenix metro area including:
  - Effect veness and benefits of LID in Phoenix metro area
  - Urban heat
  - Air quality
  - Stormwater qual ty

Recommendations
- Study builds on the work of others
- Further analyses may be completed using Study model results
  - Stormwater and peak flow reduct ons for a var ety of storms
  - Reduct ons based on feature and storm type
  - Analyze Urban Heat and Air Quality based on varying infiltrat on from a variety of storms
  - Further LID analyses

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Appendix 2. Literature Review

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Green infrastructure performance in arid and semi-arid urban environments
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REVIEW ARTICLE

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Green infrastructure performance in arid and semi-arid urban environments

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ABSTRACT

Urbanization can negatively afect residents' health and wellbeing. Green stormwater infrastructure (GSI) is increasingly advocated as a win-win strategy for addressing multiple urban problems. Literature quantifying GSI benefits is growing, but it is unclear how it performs in arid and semi-arid cities. This study, co-designed with practitioner partners in Phoenix, Arizona, evaluates the current state of knowledge on GSI performance with respect to hydrologic, water quality, urban heat, and air quality benefits. Our systematic literature review confrms a lack of research quantifying GSI performance in arid and semi-arid cities. Our fndings, which we summarize in the paper and present in a searchable, online database, suggest that GSI is benefcial in mitigating runof, urban heat, and air pollution in the surrounding area to some degree. Results for water quality are more mixed. This points to the need for more GSI monitoring and research, especially of air and water quality benefits.

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KEYWORDS
Green infrastructure; arid climates; stormwater; urban heat; air quality; water quality

1. Introduction

Cities are increasingly investing in green infrastructure – a term often used interchangeably with low impact development (LID) – as a strategy for addressing mounting fooding and water quality problems while providing other resilience co-benefits such as improved air quality and mitigation of the urban heat island efect (Norton et al. 2015; Tzoulas et al. 2007). The concept of LID was frst developed in Maryland as a new approach to managing excess runoff from increased impervious surfaces caused by urban development, one that sought to mimic pre-development hydrology (Dietz 2007). In recent years, the U.S. Environmental Protection Agency (EPA) has promoted green infrastructure for stormwater management (Fletcher et al. 2015). Their defnition of green infrastructure is very similar to LID:

> A cost-efective, resilient approach to managing wet weather impacts that provides many community benefits. While single-purpose gray stormwater infrastructure—conventional piped drainage and water treatment systems—is designed to move urban stormwater away from the built environment, green infrastructure reduces and treats stormwater at its source while delivering environmental, social, and economic benefits. (EPA 2017)

The term green infrastructure is also used by other organizations and scholars to refer broadly to networks of vegetation (Benedict and McMahon 2002). Thus, to be more explicit about the types of green infrastructure features we are considering (and in keeping with other recent studies such as Hopkins, Grimm, and York (2018) and Mcphillips and Matsler (2019)), we use the term green stormwater infrastructure (GSI). As the widely used EPA defnition demonstrates, when governments and organizations make the case for a 'green' rather than traditional 'grey' stormwater management approach, they often do so on the basis of GSI's multiple benefits, or ecosystem services. Yet in practice, GSI planning and evaluation often focus on one or a few functions, primarily related to stormwater (Finewood, Matsler, and Zivkovich 2019). Other commonly cited services (e.g. mitigation of the urban heat island efect or improved air quality) are largely ignored (Heckert and Rosan 2018; Meerow 2020).

Where studies have looked at GSI performance, they tend to focus on U.S. cities with abundant rainfall like Detroit or Philadelphia; fewer studies have looked at how GSI performs in arid and semi-arid environments (Jiang, Yuan, and Piza 2015). We defne these locations as those classifed as 'dry' in the prominent Köppen–Geiger global climate classifcation, or in other words, where precipitation is less than potential evapotranspiration (Kottek et al. 2006) – and cities that receive less than 500 mm of rainfall annually. Arid cities like Phoenix, Arizona, are interested in implementing GSI (Middel, Chhetri, and Quay 2015), but recognize that they face a unique set of challenges because of their climate, and therefore GSI models and metrics from other regions may have limited applicability.

To address this gap, and to help inform green infrastructure planning in cities like Phoenix, we systematically review the literature on GSI in arid and semi-arid urban environments to assess the current state of knowledge and create an online, searchable, and flterable database of studies that quantify GSI performance in relation to stormwater management, water and air quality benefits, and impacts on urban heat. This database synthesizes the current state of knowledge for researchers and decision makers, and it could be updated as new performance data become available.

2. Methodology

All aspects of the literature review methodology were co-designed by researchers and a team of Phoenix-based green

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infrastructure experts from the Phoenix municipal government, The Nature Conservancy, The U.S. Bureau of Reclamation, the Maricopa County Flood Control District, and the Maricopa County Air Quality Department. These partners designed the study to fill a gap in both research and practice by establishing the current state of knowledge on green infrastructure performance in arid and semi-arid environments. The literature review itself, however, was conducted and written entirely by the author team. The practitioner partners were interested in having the results to inform their modeling and the development of scenarios for green infrastructure development in Phoenix. While there are many potential benefits of GSI, this review focuses on the four services deemed most critical to Phoenix by the full project team: hydrologic performance, water quality, urban heat, and air quality. Hydrologic performance and water quality were chosen because of the project focus on LID as a new stormwater management strategy. Heat and air pollution are both major concerns for the region, with Phoenix being one of the hottest and most rapidly warming cities in the United States, and both these risks are inequitably distributed across the city's population (Jenerette et al. 2011; Pope, Wu, and Boone 2016). While these benefits were chosen by the Phoenix-based team, they are likely to be important in many other arid and semi-arid cities.

Table 1. Definitions of GI features included in review.

Bioretention basins and planters	Systems that collect and filter stormwater through a variety of media, including vegetation, mulch, rocks, and sand.
Curb openings	Cuts in the pavement that direct stormwater runoff from paved areas to green infrastructure that can absorb the water or channel it elsewhere.
Domed overflow structures	These work like buried water silos for storing and discharging stormwater runoff; the dome is usually accessible from ground level.
Grade control structures	A structure built across a drainage way to protect against erosion.
Infiltration trenches	Linear indentation that collects stormwater and allow it to seep into the ground quickly; they typically are filled with natural materials such as grass or stone.
(Non-tree) vegetation	All planted vegetation aside from trees and vegetation planted as part of another intervention, such as a grade control structure.
Permeable pavement	Pavers or concrete that allows water to drain through it.
Sediment traps	Systems that collect sediment and other debris from runoff, often used with other features.
Stormwater harvesting basins	Stormwater harvesting basins, or rain gardens, are often landscaped and set at a lower grade than surrounding non-permeable surface, they usually include subsurface storage.
Trees and tree pits	Trees that are planted in pits that are surrounded by non-permeable surface, such as the typical street tree.
Vegetated or rock swales	Open channels lined with vegetation and/or rock in order to slow the flow of runoff.
Other	Any feature that does not fit into one of the other categories.

2.1 Defining green infrastructure feature types and performance parameters

The Phoenix project focused on LID, which we define as installation of GSI – interventions that utilize or imitate nature and its processes – to lessen negative environmental impacts from the human-built environment. To synthesize the literature on GSI performance, we had to define it and the specific feature types on which we would focus. The project team identified a list of 11 green infrastructure interventions or features (Table 1) – bioretention basins and planters, curb openings, domed overflow structures, grade control structures, infiltration trenches, non-tree vegetation, permeable pavement, sediment traps, stormwater harvesting basins, trees and tree pits, and vegetated or rock swales – deemed relevant to Phoenix because of their inclusion in a recent Greater Phoenix Green Infrastructure Handbook (Dibble Engineering, & Logan Simpson 2018) as well as prominent literature on LID and its effects (Ahiablame, Engel, and Chaubey 2012; Coffman 2000; Dibble Engineering & Logan Simpson Design Inc. 2018; Dietz 2007; Eckart, McPhee, and Bolisetti 2017; Curtis 2005; Pyke et al. 2011; Zahmatkesh et al. 2015). We used a 12th 'other' category to capture interventions that we encountered that were not on the list.

Although the modern practices of GSI originally were developed for stormwater management (Coffman 2000; Environmental Protection Agency (EPA) 2000), researchers quickly discovered that it also was helpful for addressing a variety of other environmental issues, including air quality (Abhijith et al. 2017; Pugh et al. 2012) and urban heat (Norton et al. 2015; Saaroni et al. 2018; Ziter et al. 2019; Zölch et al. 2016). For our study we examined four categories of benefits from GSI on which the Phoenix project team was focused, namely hydrologic performance, water quality, urban heat and air quality. From these we generated a list of 16 indicators (Figure 1), based on the same literature from which we drew our list of features as well as the practical knowledge of the project team.

Within hydrologic performance we focused on rates of infiltration/runoff reduction, peak flow, irrigation offsets, and water retention/recharge. For water quality, we looked for GSI impacts on levels of E. coli, metals, pesticides, nitrogen, phosphorus, sediment transport and total suspended solids. Within urban heat we were interested in the impact on air temperature, radiant temperature and surface temperature. Within air quality we focused especially on the impact on $PM_{2.5}$ (particulate matter that has a diameter of 2.5 micrometers or less), PM_{10} (particulate matter that has a diameter of 10 micrometers or less), ozone, and carbon dioxide. We added an additional subcategory of 'other' for each benefit category in order to capture measurements that fell outside of the other 16 subcategories.

2.2 Literature review

The literature was primarily identified by the researchers using two major online citation databases: Scopus and Web of Science. The practitioner partners also added relevant literature that they knew of (see the online dataset (Meerow, Natarajan, and Krantz 2020) for a list of literature and sources). The project team identified the following search terms for the citation databases with the goal of capturing different terminology used for green stormwater infrastructure (c.f. Fletcher et al. 2015): 'green infrastructure,' 'low impact development,' 'water sensitive design,' 'water sensitive urban design,' 'sustainable urban drainage,' 'nature-based solution,' 'best management practice,' 'stormwater control measure,' 'sponge city,' 'stormwater quality improvement device,' 'integrated

Benefit	Indicator	Permeable Pavement	Stormwater Harvesting Basin	Vegetation/ Rock Swale	Bioretention basin/ planter	Infiltration Trench	Trees	Vegetation	Green infrastructure (general or multiple)	Other
Hydrologic Performance	Peak Flow Reduction	1			2				1	1
	Infiltration/Runoff Reduction	1			4	2	1		2	3
	Water Retention/ Recharge								1	
	Irrigation Offset									
	Other								2	2
Water Quality	Metals		1	1	1					1
	E. Coli									
	Pesticides									
	Sediment Transport Reduction/TSS				1				1	
	Nitrogen				1				1	1
	Phosporus				1				1	3
	Other	1			1				1	1
Urban Heat	Air/ Radiant Temperature						5	1		
	Surface Temperature	1					2	1		
	Other						3	1		1
Air Quality	$PM_{2.5}$						2			
	PM_{10}						3			
	Ozone						2			
	Carbon Monoxide						2			
	Other						2			

Figure 1. Summary of number of studies by benefit and GSI type. Note: darker shading indicates more studies identified through the literature review, the number of studies is listed in each shaded cell.

urban water management,' or 'source control' and 'arid.' On 24 February 2019, Scopus returned 176 results and Web of Science returned 93 results, with some overlap between the two results. The project team also identified about 30 relevant studies or reports, many of which were specific to Arizona. The final dataset included 219 unique studies for review, which represented a combination of academic journal articles and reports.

There clearly are limitations to our approach, and we do not claim that we have captured all relevant studies on GSI in arid or semi-arid environments that exist. While we primarily used the two large citation databases in an effort to be systematic in our review, we acknowledge that some types of research are missing from these sources, particularly books and non-academic reports (Archambault and Lariviere 2010), which may have relevant content on GSI performance. We included other studies identified by the project team in part to address this limitation, but the team's knowledge is admittedly incomplete and likely somewhat biased towards Phoenix, Arizona and the United States more broadly. In particular, if nonacademic reports from other arid locations exist, they are likely missing from our review. Our search included many different terms for GSI, but there may be others that we have missed, resulting in relevant studies being excluded. Moreover, while we searched the title, abstract, and keywords of articles in the database using an inclusive list of search terms, it is possible that we missed some studies with relevant content in other parts of the paper. Finally, because we reviewed hundreds of papers, it is possible that some performance data were overlooked.

The project team co-developed a codebook for analyzing the studies and a spreadsheet for entering the coded performance values. The researchers then did the reviewing and coding. We first coded several of the same papers and compared resulting spreadsheets to make sure they were consistent, and then independently reviewed the remaining papers. After an initial read, 191 of the studies were eliminated because they did not actually provide empirical data on GSI performance, did not assess any of the four benefits on which we were focused, did not study relevant GSI types (for example, studies on agricultural best management practices), were not in English, did not focus on arid or semi-arid urban environments as indicated by the Köppen–Geiger climate classification (type B) of the location and the city's annual rainfall (less than 250 mm for arid and between 250 and 500 mm for semi-arid), or in a few cases they could not be accessed. Ultimately, 28 studies were included in our analysis: 25 academic journal articles, two papers from conference proceedings, and one government report.

From these 28 studies, we coded the performance values and categorized them by benefit category, indicator, green infrastructure feature type, measurement approach, and location (codebook is provided in the online dataset (Meerow, Natarajan, and Krantz 2020)). Once the coding was complete, we sorted and synthesized the data based on these different codes. Wherever possible, we convert performance values into comparable units (e.g. percent improvement). All of these categorizations are available in the online spreadsheet.

3. Results

The 28 analyzed studies produced a total of 118 performance values (for different feature types, measurements, etc.; for full list see the online dataset (Meerow, Natarajan, and Krantz 2020)). Twelve of the studies and 31% (37) of the performance values focused on hydrologic performance (HP). Seven studies and more than a third of the performance values (46) related to water quality (WQ). Ten studies and more than 18% (22) of the performance values were identified for urban heat (UH) and three studies, or 11% of the performance values, were for air quality (AQ). In terms of the GSI features studied, trees were the most common (29 performance values), followed by bioretention basins/planters, trees (20), green infrastructure (general or multiple types of features: 15 performance values), vegetated or rock swales (11), stormwater harvesting basins (5), generic vegetation (4), permeable pavement (4), and infiltration trenches (2). More than 20% of the values were for features classified as 'other,' such as green roofs or rain barrels. Studies used different methods to determine performance. Modeling was the most common approach (13), whereas 11 studies relied on field measurements or experiments.

Figure 1 shows the number of individual studies reviewed by benefit category, indicator, and feature type. It highlights the need for more consistent performance data, as no cell has more than 5 studies (with that being the impact of trees on air or radiant temperature). Many cells are blank, indicating research gaps. Figure 2 also summarizes the findings by benefit category indicator and feature type, but instead of the number of studies it shows whether our review suggests the GSI type is at least somewhat effective, whether the data was inconclusive (i.e. showed mixed performance), or whether we found no data. Again, the lack of data is quite striking.

		Permeable Pavement	Stormwater Harvesting Basin	Vegetation / Rock Swale	Bio-retention basin / planter	Infiltration Trench	Trees	Vegetation	Green infra-structure (general or multiple)
Hydrologic performance	Peak Flow Reduction	Effective	No data	No data	Effective	No data	No data	No data	Effective
	Infiltration / Runoff Reduction	Effective	No data	No data	Effective	Effective	Effective	No data	Effective
	Water Retention / Recharge	No data	No data	No data	No data	No data	No data	No data	Effective
	Irrigation Offset	No data	No data	No data	No data	No data	No data	No data	No data
Water Quality	Metals	No data	Effective	Effective	Inconclusive	No data	No data	No data	No data
	E. Coli	No data	No data	No data	No data	No data	No data	No data	No data
	Pesticides	No data	No data	No data	No data	No data	No data	No data	No data
	Sediment Transport or TSS	No data	No data	No data	Inconclusive	No data	No data	No data	Effective
	Nitrogen	No data	No data	No data	Inconclusive	No data	No data	No data	Effective
	Phosphorus	No data	No data	No data	Inconclusive	No data	No data	No data	Effective
Urban heat	Air / Radiant Temperature	No data	No data	No data	No data	No data	Effective	Effective	No data
	Surface Temperature	Effective	No data	No data	No data	No data	Effective	Effective	No data
Air quality	$PM_{2.5}$	No data	No data	No data	No data	No data	Effective	No data	No data
	PM_{10}	No data	No data	No data	No data	No data	Effective	No data	No data
	Ozone	No data	No data	No data	No data	No data	Effective	No data	No data
	Carbon Monoxide	No data	No data	No data	No data	No data	Effective	No data	No data

Figure 2. Summary of performance findings by benefit and GSI type. Note: 'Effective' means performance values in reviewed studies all showed a benefit, 'inconclusive' means some performance values showed a benefit, others did not, and 'no data' means no performance values were found.

3.1 Hydrologic performance

Twelve studies were identified that examined hydrologic performance of GSI in arid and semi-arid environments, all of which reported that GSI features mitigate runoff, although they varied widely in terms of how much. Only one of the studies reported the results of field experiments and the rest relied on modeling. By far the most common model used was the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM). Hydrologic performance studies examined bioretention basins/planters, stormwater harvesting basins, infiltration trenches, cisterns/rain barrels, permeable pavement, and combinations of these features.

The parameters and design storms used to assess hydrologic performance differed, however the most commonly used was percent of runoff flow reduction (((input-output)/input) *100). This is also how Jiang, Yuan, and Piza (2015) assessed effectiveness in their previous review paper of GSI in the arid and semi-arid U.S. The studies we reviewed varied widely in terms of level of inflow used (e.g. the intensity and duration of the rainfall event(s) and size of the drainage area), and the time period examined (e.g. a single event versus annual flows), making direct comparisons difficult. No doubt in part because of these differences, reported runoff flow reduction rates range from 1% to 99%. Another commonly examined parameter was the reduction in peak flows.

The only field study we identified (Li et al. 2014) assessed the performance of a bioretention cell with and without an internal water storage layer in Bryan, Texas. They calculated a peak flow reduction of 50–64% and 59–82%, respectively. Their data also showed an average runoff flow reduction of 76% and 80%, respectively.

Guertin et al. (2015) used a GIS-based Kinematic Runoff and Erosion (KINEROS2) watershed modeling tool to assess the performance of permeable pavement, bioretention basins, and a combination of the two in Tucson, Arizona. While the systems performed better than the baseline, they did not achieve predevelopment levels. According to the model, the retention basin would decrease peak flows by 2.03% from post-development without GSI (a 4.96% increase compared to pre-development peak flows). Overall runoff flow would be reduced by 5.54% compared to post-development without GSI and 1.45% compared to pre-development. For the permeable pavement, they determined that it would lead to a reduction of 1.42% from post-development without GSI (or increase peak flows 5.64% compared to pre-development) and reduce total runoff flows 1.55% from the no GSI post-development scenario (2.72% increase from pre-development).

Feng, Burian, and Pomeroy (2016) applied the SWMM model to a small catchment in Salt Lake City, Utah, using data for multiple years close to annual averages, and found that a combination of bioretention basins and green roofs would reduce average annual surface runoff between 35–45% compared with the current baseline. In another study, Houdeshel, Pomeroy, and Hultine (2012) used SWMM modeling to determine that bioretention basins in Phoenix and Salt Lake City ranging from 4% to 11% of the drainage area would capture 92.6–99.8% of the annual average runoff. More generally, Nehrke and Roesner (2004) used SWMM modeling to examine the effectiveness of detention basins in Fort Collins, Colorado, and found that they would reduce peak flows from predevelopment scenarios for 90% of storm events.

A number of studies used SWMM modeling to estimate the share of annual runoff that could be captured by rain barrels of various sizes in arid and semi-arid cities, with results ranging from 2.5% to 17%. Walsh and colleagues (Walsh, Pomeroy, and Burian 2014) found different sized cistern and rainwater systems capture between 2.5 and 12.4% of runoff over many years in San Diego, California. Summerville and Sultana (2019) used the SWMM model to test rain barrel and storage tank rainwater harvesting systems on residential lots in nearby Los Angeles County, California. They found similar results for small cisterns, concluding that single rain barrels could capture around 7% of all the average annual residential runoff, however they suggested a larger storage tank (equivalent to 55 rain barrels) could capture 85%. Steffen et al. (2013) calculated that depending on the size (190–1890 liters), rain barrels or cisterns implemented across neighborhoods in Phoenix and Salt Lake City could capture 10–17% of average annual runoff.

While seemingly not as popular as the SWMM model, two of the reviewed studies used the U.S. EPA's GIS-based 'System for Urban Stormwater Treatment and Analysis IntegratioN' (SUSTAIN) model. Sun, Tong, and Yang, (2016) used the model to analyze the effectiveness of detention and infiltration basins in the Las Vegas Valley, Nevada. They compared the percentage of total flow reduction for the period between July 1 and September 30 under 'current' conditions (using 2006 and 2011 NOAA climate data) and using 2050 climate models. They found that three existing detention basins would reduce 2011 total watershed flows by 9% and 2050 projected flows by 8%, adding two more detention basins would bring that 2050 flood reduction rate to 13%, whereas two additional infiltration trenches would bring it to 46%. An EPA (2018) report based on SUSTAIN modeling included a Maricopa County, Arizona, case study and compared scenarios where a detention/infiltration basin was used and one where permeable pavement, a cistern, bioretention, and a stormwater harvesting basin were included, both under current conditions and based on 2050 climate models. They found that they could capture more than 90% of all annual site runoff under current and future scenarios.

Lizárraga-Mendiola et al. (2017) developed a design for a bioretention cell and infiltration trench in Central Mexico and then estimated that the two interventions would be able to capture between 2.25% and 5.37% of total runoff volume, depending on the precipitation scenario. Finally, Kim and Coseo (2018) used the 'i-Tree Eco' model and local sampling in Phoenix to estimate how much runoff was avoided because of the nearly 517,000 trees in the city's public and private parks. They estimated 52,791 m^3/year, or roughly 0.10 m^3/year per tree.

3.2 Water quality

Our analysis identified seven relevant GSI performance studies with a focus on water quality conducted in Arizona, California, Nevada, Utah, and Texas in the United States, as well as Australia. Six were based on sampling or field data and one was a modeling study. Interventions included bioretention basins, bioswales, permeable pavement, constructed wetlands, and rainwater harvesting tanks. Some of the studies covered multiple interventions. Overall, the results suggest that GSI can improve water quality by reducing TSS, metals such as copper, zinc, and lead, nitrogen, and phosphorus, although removal efficiencies appear to vary considerably.

A study by Li et al. (2014), which was also discussed in the previous section on hydrologic performance, calculated pollutant removal efficiencies for bioretention cells with and without internal water storage in Bryan, Texas, based on water samples. They found that the removal efficiencies for the bioretention cell without water storage for TSS was low to moderate (25–-65%), whereas with water storage efficiencies were higher (over 88%). Another previously discussed study by the EPA (2018) applied the SUSTAIN model to quantify the benefits of a combination of permeable pavement, a cistern, bioretention, and a stormwater harvesting basin in Maricopa County under current conditions and based on 2050 climate models. The GSI was modeled to reduce annual average sediment load by more than 99%.

Li et al. concluded that the removal efficiencies for metals were better than for TSS, although variable. The bioretention without water storage showed removal efficiencies of −14% (an increase) to 100% for copper, −103% to 100% for zinc, and −99% to 100% for lead, although the average of all values was only negative for lead. The retention with water storage performed better, with removal efficiencies of 16% to 93% for copper, −171 to 99% for zinc, and −198% to 87% for lead. All the average values were positive. Further support for the efficacy of GSI in removing metals comes from a study by Evans et al. (2019) that examined metal concentrations in soils along the length of a three catchment bioswale in Claremont, California. They found a significant reduction along the flow path for zinc, lead, cobalt, copper, and manganese. They provided the regression coefficients for the metal concentration versus latitude (as a proxy for distance along the bioswale).

When it comes to total nitrogen removal, Li et al. (2014) found their bioretention systems without water storage showed mixed performance, with measurements varying widely from −1872% to 100% (an average increase in total nitrogen), while the system with storage showed a 34% to 100% total nitrogen removal efficiency. More promising results for nitrogen removal were generated by the EPA (2018) study, in which both the scenario with a detention/infiltration basin and the one with permeable pavement, a cistern, bioretention, and a stormwater harvesting basin showed more than a 95% reduction in total nitrogen.

Similar to the findings for nitrogen, Li et al. (2014) showed mixed total phosphorus removal efficiencies for bioretention systems with and without water storage layers, with the former varying from −49% to 60% and the latter 20% to 72%. Two other studies showed more promising results for phosphorus removal. Lodhi and Acharya (2014) measured the phosphorus in detention basin sediment samples before and after rain events in Nevada, finding some significantly higher phosphorus concentrations after it rained (150 μg/g on average), leading them to conclude that the basins were effective in capturing phosphorus, although they did not provide measurements of removal efficiency since they did not measure levels in the runoff. The EPA (2018) modeled scenarios showed high total phosphorus reduction efficiencies (over 90%) for current and future climate scenarios in Maricopa County.

One study in our analysis focused on constructed wetlands in San Diego (Taylor et al. 2001). This research found that the intervention could reduce copper concentrations by 27% to 99%; reduce diesel and oil concentrations by 6% to 92%; reduce fecal coliform concentrations by 70% to 100%; reduce lead concentrations by 0% to 99%; reduce nitrogen concentrations up to 64% or increase it up to 200%; reduce phosphorous concentrations by 5% to 29%; and reduce zinc concentrations by 33% to 93%.

Kazemi, Golzarian, & Myers' (2018) experimental study of permeable pavement and a bioretention basin in Adelaide, Australia, focused primarily on water quality measures that would impact the resulting effluent's usefulness for irrigation, including electrical conductivity, total dissolved solids, turbidity, dissolved oxygen, and pH. They found that the permeable pavement slightly increased water turbidity, but the bioretention system increased it much more. While the permeable pavement increased water pH, the bioretention basin was able to reduce it. They found that salinity effects differed depending on the initial salinity of the water. In other words, GSI could increase salinity if the runoff had low salinity, but decrease it if initial levels were high.

An older study (Nightingales 1987) measured water quality below five retention basins in Fresno, California, over three years to see whether accumulated pollutants (copper, iron, arsenic, nickel, and lead) in the basins contaminated the groundwater. The study found no evidence of contamination, with concentrations similar to those estimated for the influent.

3.3 Urban heat

Our analysis yielded 10 studies that examine the relationship between green stormwater infrastructure and urban heat in arid and semi-arid urban environments. The geographic areas covered by these 10 studies included Addis Ababa, Ethiopia; Be'er Sheva and its surrounding Negev Desert, Israel; Cairo, Egypt; and U.S. cities including Salt Lake City, Utah, San Diego, Sacramento, San Jose, and Los Angeles, California, Denver, Colorado, and Phoenix, Arizona. Four of the studies were based on field measurements or experiments and the remainder were modeling studies. All but one of the reviewed studies researched the cooling effects of plants, including trees, lawns, or xeriscaping, while the last study looked at pervious concrete. There appears to be a lack of studies that specifically examine the urban heat benefits of common GSI features such as bioretention basins in arid and semi-arid environments.

The identified studies all confirm the oasis effect – that vegetation reduced temperatures in the surrounding area – especially from larger shade trees. Shade trees perform particularly well vis-à-vis other vegetation like grass as an urban heat mitigation strategy when water use is taken into account. For arid environments, where water is limited, there may be a real tradeoff between vegetation benefits and irrigation requirements (Shashua-Bar, Pearlmutter, and Erell 2011).

Similar to the other performance areas, the indicators used in the studies vary greatly, making direct comparisons difficult. Measures used in the reviewed studies include land surface temperature, air temperature at different heights, mean radiant temperature, physiological equivalent temperature (PET), and cooling efficiency. These are assessed at different spatial and temporal scales. Studies also show that the relationships between measures are not always consistent (Shiflett et al. 2017).

Shiflett et al. (2017) assessed the relationship between vegetation and air temperature and land surface temperature through field measurements at different scales in Los Angeles. At all scales they found that increased vegetation had a cooling effect. In particular, taller trees with a closed canopy (blocking sunlight) showed the greatest air temperature difference (mean of 4 at 0.1 meter height) compared with bare soil. The difference was most pronounced around midday (mean of 6.9) and lowest in the late afternoon (2). Plots with shorter trees and grass were only consistently cooler than bare soil in the middle of the day (an average of 4.6 cooler for short trees and 4.1 for grass). At a regional scale, the study also identified an inverse relationship between land surface temperatures and a normalized difference of vegetation index (NDVI), and a positive relationship between air and land surface temperature, with the latter being more correlated at night. They also found that in the more arid areas, vegetation was associated with cooler afternoon air temperatures, whereas in other climates vegetation seemed to have more of an effect on nighttime air temperatures.

Feyisa, Dons, and Meilby (2014) combined field measurements and satellite data to assess the cooling benefit of park vegetation in Addis Ababa. They found that the cooling benefit provided by trees varied significantly by species, but overall they calculated an air temperature drop of 0.2 for every percent increase in overall tree canopy cover. They found other park characteristics (size, shape, and vegetation) impacted cooling. Parks with larger areas and more tree canopy cover had a more intense cooling effect, which extended further beyond the park's borders. More irregularly shaped parts (as opposed to round) cooled a larger area but with less intensity.

A study of Phoenix by Zhao, Sailor, and Wentz (2018) used ENVI-met modeling to determine the human thermal comfort benefit of different arrangements of one or two trees in a neighborhood, concluding that optimal placement (e.g. a single tree in the center of the front yard) could reduce PET by 1 to 1.5 . Fahmy et al. (2018) also used ENVI-met modeling to estimate the air and radiant temperature effects of a combination of trees and green roofs under different future climate scenarios in a residential community in Cairo. They found that the added vegetation could reduce mean radiant temperatures at night by 1.85 under current climate conditions and as much as 3.31 under projected 2080 climate conditions. Air temperature reductions were found to be lower in future climate scenarios, with the vegetation providing an estimated 1.16–2.51 cooling benefit in the current climate but only 0.06–0.85 for the 2080 scenario.

One study that modeled tree benefits in 27 American cities including arid and semi-arid San Diego, Phoenix, Los Angeles, San Jose, Sacramento, and Denver (Kroeger et al. 2018), estimated that on average, if trees were planted in all possible locations across the cities, maximum daily summer air temperatures would decrease by 1.7 . However, they only provide city-specific values for urban heat in relation to population-weighted fiscal return on investment.

Shashua-Bar, Pearlmutter, and Erell (2011) presented the results of a field experiment conducted in Israel to compare the thermal comfort benefits and water-use efficiency of different vegetated elements including shade trees, grass, and a combination of the two. When compared with a bare, unshaded landscape, they found that grass with a mesh shade provided the largest cooling benefit (2.47 kilowatt hours (kWh)), followed by shade trees with grass (2.42 kWh), grass without shade (1.75 kWh), and trees with bare ground (1.50 kWh). However, when water use was considered, the trees with bare ground had a much higher cooling efficiency of 2.72%, as opposed to 1.11% for trees with grass, 1.02% for mesh shaded grass, and 0.53% for unshaded grass.

Two of the studies specifically evaluated the role of xeriscaping on urban heat, both focusing on Phoenix. Yang and Wang (2017) conducted a large-scale Weather Research and Forecasting (WRF) modeling study of the Phoenix metro region, comparing a scenario where all greenspaces are xeriscaped and one where all greenspaces and rooftops are planted with irrigated grass, along with a control scenario (a mix of cropland and native vegetation). They found that, overall, the greened scenario cooled air temperatures by 1.2 compared with the control, while the xeriscaping scenario actually increased air temperatures by 0.92 . Chow and Brazel (2012) used ENVI-met modeling to study how xeriscaping impacts air temperatures. Similar to Yang and Wang (2017), they also found that when compared with mesic vegetation, xeriscaping increased air temperatures and thermal discomfort. However, they found that xeric shade trees cooled surrounding areas as much as 1.5 to 2.4 at night, whereas Yang and Wang acknowledge that they did not include shade trees in their model.

Lastly, a study of pervious concrete (Flower et al. 2010) was based on observations collected from a test site in Salt Lake City. It found that the surface temperature of pervious concrete in the sun was equal to that of traditional concrete in the shade, and was on average about 10 cooler than traditional asphalt in the sun.

It should be noted that several of the studies point out that cooling benefits of vegetation work differently in arid climates. For example, Zhao, Sailor, and Wentz (2018) and Shashua-Bar, Pearlmutter, and Erell (2011) point out that desert cities may be so hot that evapotranspiration from vegetation has less effect on perceived thermal comfort than shading and radiant exchange.

3.4 Air quality

More research on air quality benefits of GSI in arid and semi-arid environments is clearly needed. In fact, we could only identify three studies that quantified air quality benefits in arid and semi-arid urban environments, all of which focused on trees and relied on modeling to estimate impacts. While the data is limited, all three studies do suggest that planting trees helps mitigate air pollution. The three studies assessed impacts on particulate matter with a diameter of 10 micrometers or less (PM_{10}), and two also quantified particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$), ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2).

Two of the studies relied on the i-Tree Eco model to estimate air quality benefits of trees. Kim and Coseo (2018) used the i-Tree Eco model and local sampling in Phoenix to estimate how much trees in urban public and private parks contribute to removal of air pollutants. They estimated that the city's 516,534 trees removed 272 metric tons of air pollutants annually (PM_{10} by 110 metric tons, $PM_{2.5}$ by 1 metric ton, O_3 by 95 metric tons, CO by 15 metric tons, NO_2 by 35 metric tons, and SO_2 by 10 metric tons), which they estimated to be worth 1.16 USD million annually. Jayasooriya, Ng, Muthukumaran, and Perera's (2017) study of Melbourne, Australia examined GSI scenarios for an industrial area with trees, green roofs, and green walls. They found trees to be the most effective at removing air pollution, and estimated that increasing the tree density from 10 trees per hectare to 80 trees per hectare would annually remove 1474 kg of PM_{10} (a 555% increase compared with the baseline), 43 kg of $PM_{2.5}$ (514% increase), 1885 kg O_3 (666% increase), 10 kg of CO (11% increase), 964 kg of NO_2 (1318% increase), and 125 kg of SO_2 (468% increase).

The third study, by Kroeger et al. (2018), which was also discussed in relation to urban heat, used modeling to evaluate the PM_{10} mitigation potential of tree planting in 27 U.S. cities. They concluded that, on average, every US. dollar spent on expanding the urban forest reduces PM_{10} concentrations 0.34 $\mu g \cdot m^{-3}$ for a single person. Phoenix showed the highest return on investment.

4. Conclusion

One of the most important takeaways from our review of the literature on hydrologic, water quality, urban heat, and air quality benefits of green stormwater infrastructure in arid and semi-arid urban environments is that more empirical research is urgently needed. While initial literature searches produced hundreds of publications, in the end we identified relevant performance findings in just 28 studies. Less than half of those were based on field measurements or experiments; most were modeling studies (e.g. EPA SWMM). Research suggests that the lack of robust data on GSI performance can be a barrier for municipalities wanting to adopt a green, rather than grey, approach to stormwater management (Matsler 2019), and we would expect this to be even more problematic for arid and semi-arid cities. Indeed, this was one of the motivations for the broader Phoenix-based project for which this review was developed. The project aims to assess the multiple potential co-benefits of hypothetical green stormwater infrastructure scenarios. Therefore, as municipalities actually implement GSI projects, it is important that different feature types be monitored over time and that these data are reported.

Even if there were more field studies, our review demonstrates that it still might be difficult to draw conclusions about performance for several reasons. First, there is no consensus on what feature parameters, climatic scenarios, or performance metrics to focus on in GSI research, making it extremely difficult to compare performance across studies (Figure 1). This is not a new problem – indeed, more than 20 years ago, Murphy and Lokey (1999, 6) wrote that 'BMP efficiencies are reported in the engineering science literature using a bewildering variety of units, measurements and conventions that prevent direct comparison.' Our review shows that not much has changed since then. It would be very helpful, for example, if there was a standardized typology and terminology for GSI (e.g. the difference between a bioretention basin and a stormwater harvesting basin) or a particular design storm used across modeling studies. Similarly, there are many ways of measuring urban heat benefits (such as air temperature at different heights, surface temperature, and mean radiant temperature, among others), making it impossible to compare across studies and provide a single range of values for how much vegetation cools surrounding areas. Second, performance can vary considerably over time, even for the same GSI installation. In one of the few field studies we reviewed (Li et al. 2014), successive measurements for hydrologic and water quality performance varied even for the same bioretention cell. There are many factors that can impact these results, and it is difficult to control for them. This points to a third challenge, namely that many contextual factors impact GSI performance, and it probably would be difficult to incorporate all of them into a model to predict how a new GSI feature would perform. Future research should identify or install comparable GSI features in different arid and semi-arid cities and monitor their performance using the same approach over an extended period.

While it is clear that many uncertainties remain with respect to GSI performance in arid and semi-arid environments, this review generally confirms the multifunctionality, or multiple benefits, of GSI. There seems to be strong evidence, at least according to models, that various types of GSI are helpful in mitigating stormwater (reducing total runoff flows and peak flows). GSI also does not seem to have negative impacts on water quality, and may even help to remove pollutants. While we found a lack of research on the cooling benefits of GSI features like bioretention or rainwater harvesting basins in arid and semi-arid environments, vegetation – particularly trees that provide shade – show a consistent cooling effect on surrounding areas, whether looking at surface or air temperatures, and across spatial and temporal scales. One study even suggests that non-vegetated pervious concrete is cooler than traditional asphalt (Flower et al. 2010). However, like vegetation, pervious concrete also can lead to higher nighttime surface temperatures, depending upon the gravel base's capacity for thermal storage. While only a few studies assess air quality benefits, and then only through models with many built-in assumptions, they all suggest a measurable benefit. More research would be valuable for understanding all four benefits we reviewed, but air quality stands out as a major opportunity for future investigation.

Scholars have emphasized the practical importance of GSI's multifunctionality and the multiple co-benefits it provides (Hansen et al. 2019). As one study we reviewed concludes, 'cost-effectiveness comparisons between trees and grey alternatives along any single objective such as PM or heat mitigation are inherently biased against trees because they ignore the multi-benefit nature of trees' (Kroeger et al. 2018, 236). If stormwater mitigation is the primary goal of GSI, perhaps factoring in air quality or urban heat co-benefits (even if they are not perfectly quantified) can make up for some degree of hydrologic performance uncertainty. Overall, our review supports arguments that GSI can provide multiple ecosystem services to arid and semi-arid urban environments, although more empirical studies quantifying these benefits across cities and GSI feature types in comparable ways are needed. Our codebook and resulting searchable, online spreadsheet with GSI performance data provides a useful baseline of the current state of knowledge, but we see potential for this to serve as a living document, with new performance studies being added as they are published or identified. These data quantifying multiple benefits of GSI could help cities make a stronger case for implementing a green, rather than traditional grey infrastructure approach. Indeed, this study was co-developed by a team of practitioners in the City of Phoenix, who plan to use the results to inform its GSI planning. The team had hoped to be able to use the results of this literature review directly to establish a range of evidence-based, geographically relevant performance values for hydrologic performance, water quality, urban heat, and air quality benefits against which to evaluate different potential GSI scenarios. This review showed just how difficult that is, and the team decided that setting precise quantitative targets might be unrealistic. With the growing popularity of GSI, it seems likely that other practitioners in arid and semi-arid cities are looking for this kind of information. Consequently, researchers have an opportunity to contribute to practice through multifunctional assessments of GSI performance.

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The authors have no conflict of interest.

Data Availability Statement

A spreadsheet with three sheets containing: (1) the coded performance values from reviewed studies; (2) the codebook; (3) the full literature list is available online:

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Appendix 3. GIS Analysis Figures and Tables

Appendix 3: Tables and Figures

Table 1. Used in flooding criteria to calculate runoff value for each catchment

MAG Land Use Category	Crosswalked land use value from Table 2-2 USDA (1986)	Hydric Soil Group A	B	C	D
Active Open Space	Open space - fair condition	49	69	79	84
Agriculture	Straight Row Crop	72	81	88	91
Airport	Commercial and business	89	92	94	95
Cemetery	Open space - good condition (grass cover >75%)	39	61	74	80
Commercial High	Commercial and business	89	92	94	95
Commercial Low	Commercial and business	89	92	94	95
Developing Employment Generating	Newly graded areas	77	86	91	94
Developing Residential	Newly graded areas	77	86	91	94
Educational	Commercial and business	89	92	94	95
Golf Course	Open space - good condition (grass cover >75%)	39	61	74	80
Industrial	Industrial	81	88	91	93
Medical/Nursing Home	Commercial and business	89	92	94	95
Mixed Use	natural desert	63	77	85	88
Multi Family - Apartment/Condo	Residential 1/8 acres or less	77	85	90	92
Office	Commercial	89	92	94	95
Landfill/Proving Grounds/Sand and Gravel/etc.	Artificial desert landscaping	96	96	96	96
Passive/Restricted Open Space/Undevelopable	Artificial desert landscaping	96	96	96	96
Public Land	Open space - fair condition	49	69	79	84
Public/Special Event/Military	Open space - fair condition	49	69	79	84
Religious/Institutional	Commercial and business	89	92	94	95
Single Family High Density - Greater than 4 du/ac	Residential 1/4 acre	61	75	83	87
Single Family Low Density - Less than 1 du/ac	Residential 1 acre	51	68	79	84
Single Family Medium Density - 1 to 4 du/ac	Residential 1/2 acre	54	70	80	85
Tourist Accomodations - Motel/Hotel/Resort	Commercial and business	89	92	94	95
Transportation	Streets and roads - paved	98	98	98	98
Vacant	Natural desert	63	77	85	88
Vacant State Trust	Natural desert	63	77	85	88
Water	Water	0	0	0	0

Table 2. The top 30 catchments and their criteria score, EJ index, and total score. The colors of the lines correspond to the polygon colors in Figure 13.

ID	OUTFALLID	Water Quality Score	Air Quality Score	Heat Score	Flood Score	EJ Index	Total Score	Rank
149	SR001	0.52	0.68	0.95	0.42	63.60	0.619	1
74	SR002	0.44	0.67	0.85	0.39	80.88	0.564	2
117	IB023	0.00	0.26	0.68	0.81	32.00	0.528	3
20	SR079	0.13	0.89	0.66	0.54	78.25	0.526	4
14	SR016	0.60	0.36	0.86	0.27	85.00	0.521	5
153		0.42	0.60	0.71	0.41	85.50	0.519	6
125	SR045	0.53	0.09	0.88	0.36	26.67	0.510	7
103	SW019	0.44	0.22	0.78	0.44	65.25	0.508	8
126	SR026	0.62	0.14	0.89	0.27	0.00	0.506	9
89	SR012	0.44	0.40	0.75	0.39	78.67	0.505	10
82	SR046	0.64	0.38	0.74	0.29	76.50	0.505	11
102	SW001	0.13	0.22	0.71	0.62	52.00	0.492	12
88	SR010	0.27	0.40	0.68	0.51	66.00	0.490	13
85	SR005	0.22	0.41	0.71	0.49	86.50	0.481	14
77	SR066	0.29	0.92	0.52	0.41	60.33	0.478	15
52	EF011	0.40	0.17	0.71	0.43	36.33	0.470	16
79	SR007	0.29	0.47	0.69	0.40	91.50	0.465	17
6	SR082	0.28	0.63	0.65	0.37	70.75	0.462	18
152	SR088	0.15	0.76	0.59	0.44	86.67	0.459	19
139	CC087	0.38	0.33	0.63	0.40	24.00	0.451	20
94	SR049	0.20	0.65	0.69	0.35	69.73	0.450	21
37	AC033	0.17	0.02	0.65	0.60	62.80	0.449	22
142	AC006	0.00	0.02	1.00	0.44	42.00	0.448	23
84	SR003	0.16	0.54	0.71	0.36	82.00	0.436	24
87	SR009	0.23	0.41	0.64	0.40	65.44	0.431	25
7	SR017	0.17	0.37	0.73	0.37	79.91	0.429	26
16	SR018	0.22	0.30	0.71	0.39	60.15	0.429	27
19	SR076	0.06	1.00	0.79	0.19	74.00	0.424	28
41	CC003	0.32	0.03	0.70	0.41	66.00	0.424	29
40	AC010	0.22	0.02	0.77	0.41	66.80	0.422	30

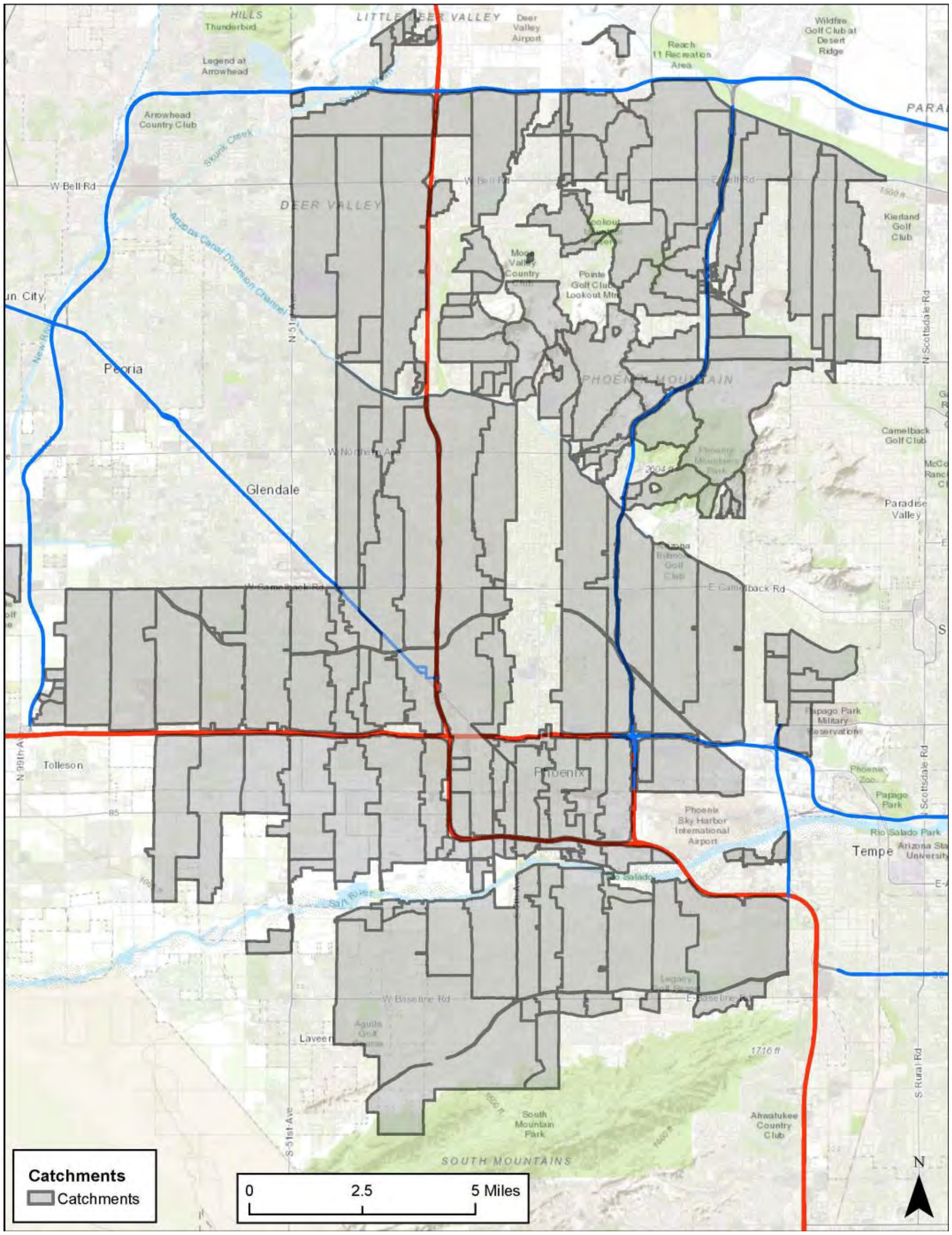

Figure 1. City of Phoenix catchments

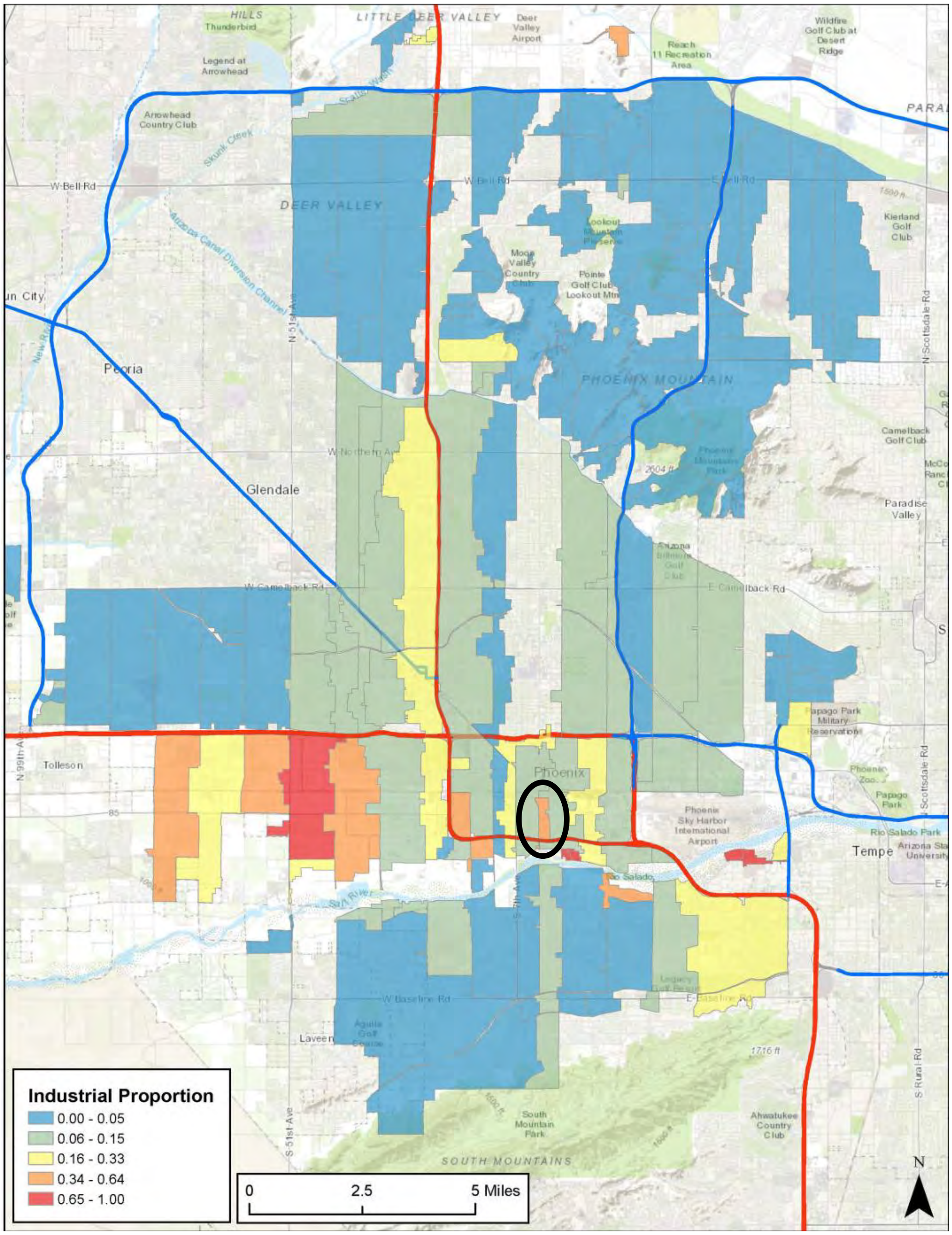

Figure 2. Proportion of industrial land use within each catchment. Our final selected catchment is circled.

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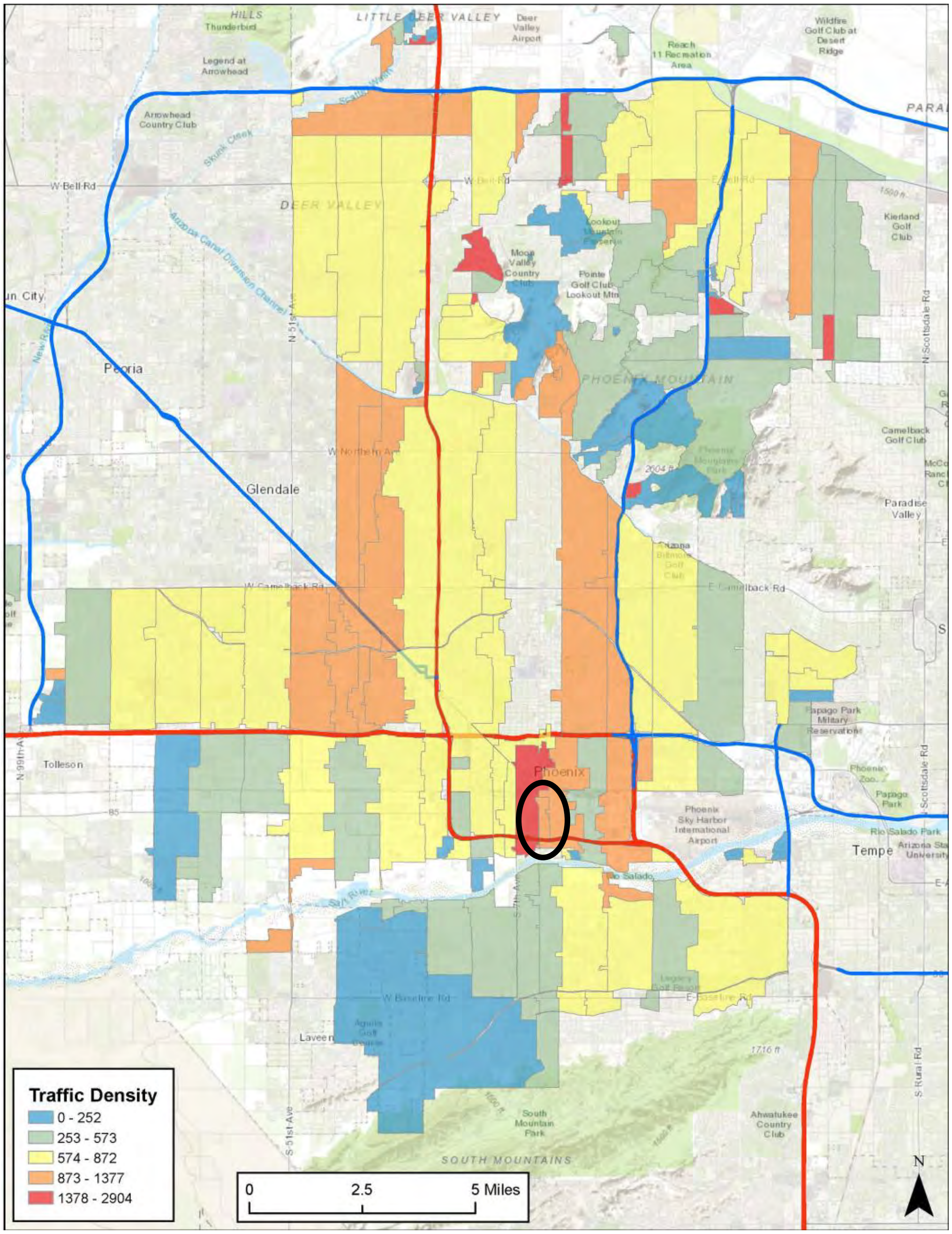

Figure 3. Density of traffic within each catchment. Our final selected catchment is circled.

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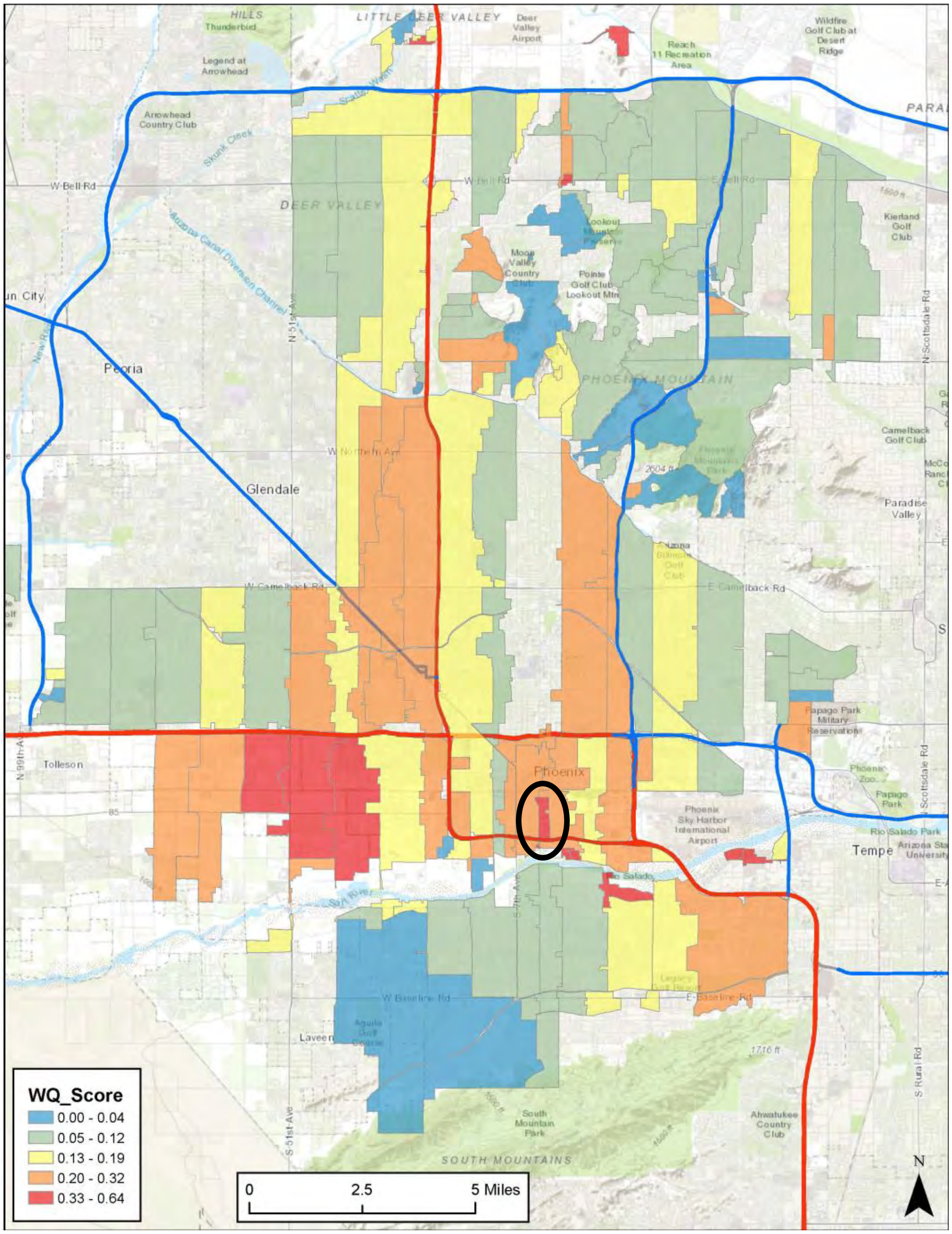

Figure 4. The overall stormwater quality score. Our final selected catchment is circled.

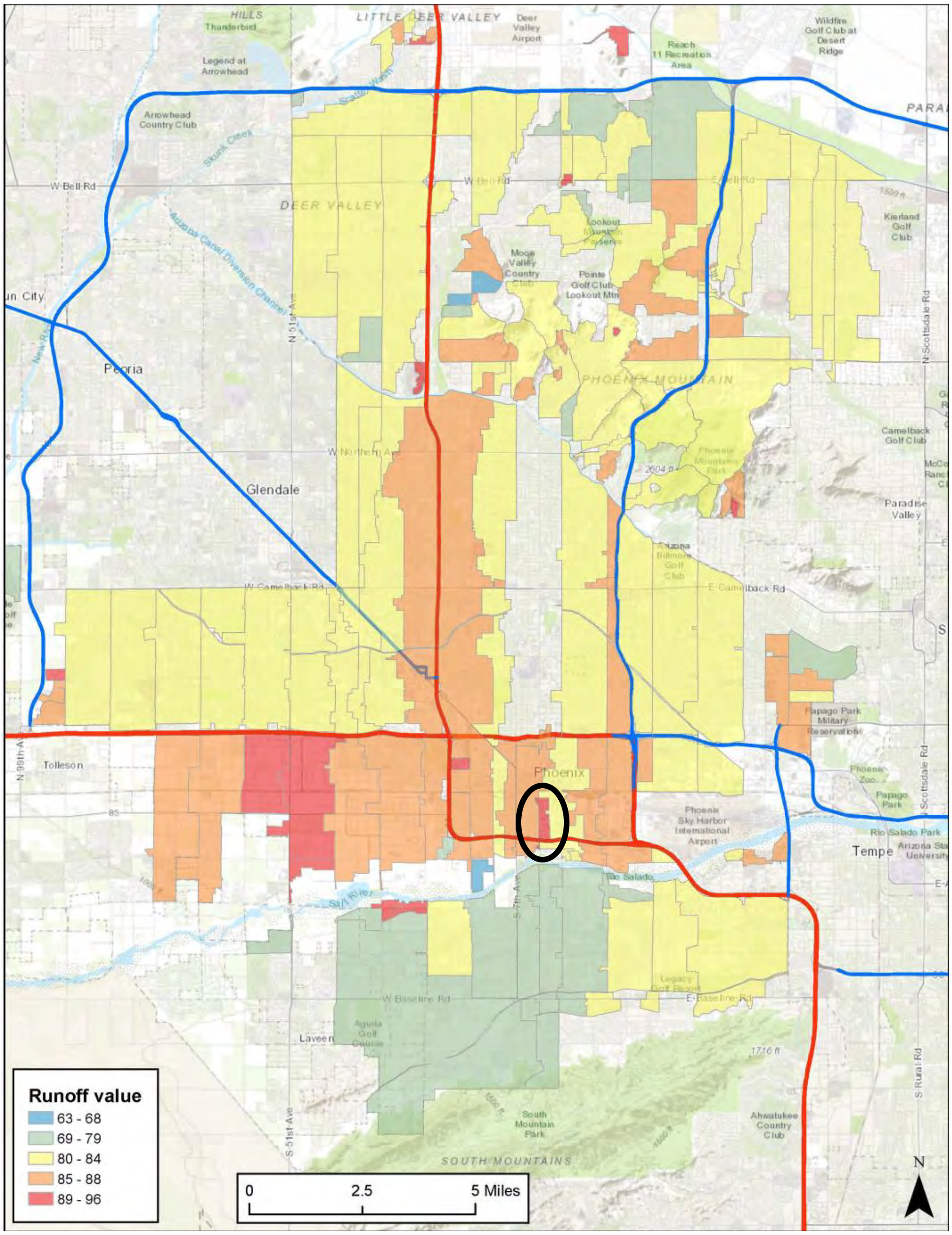

Figure 5. The average runoff values across catchments. Our final selected catchment is circled.

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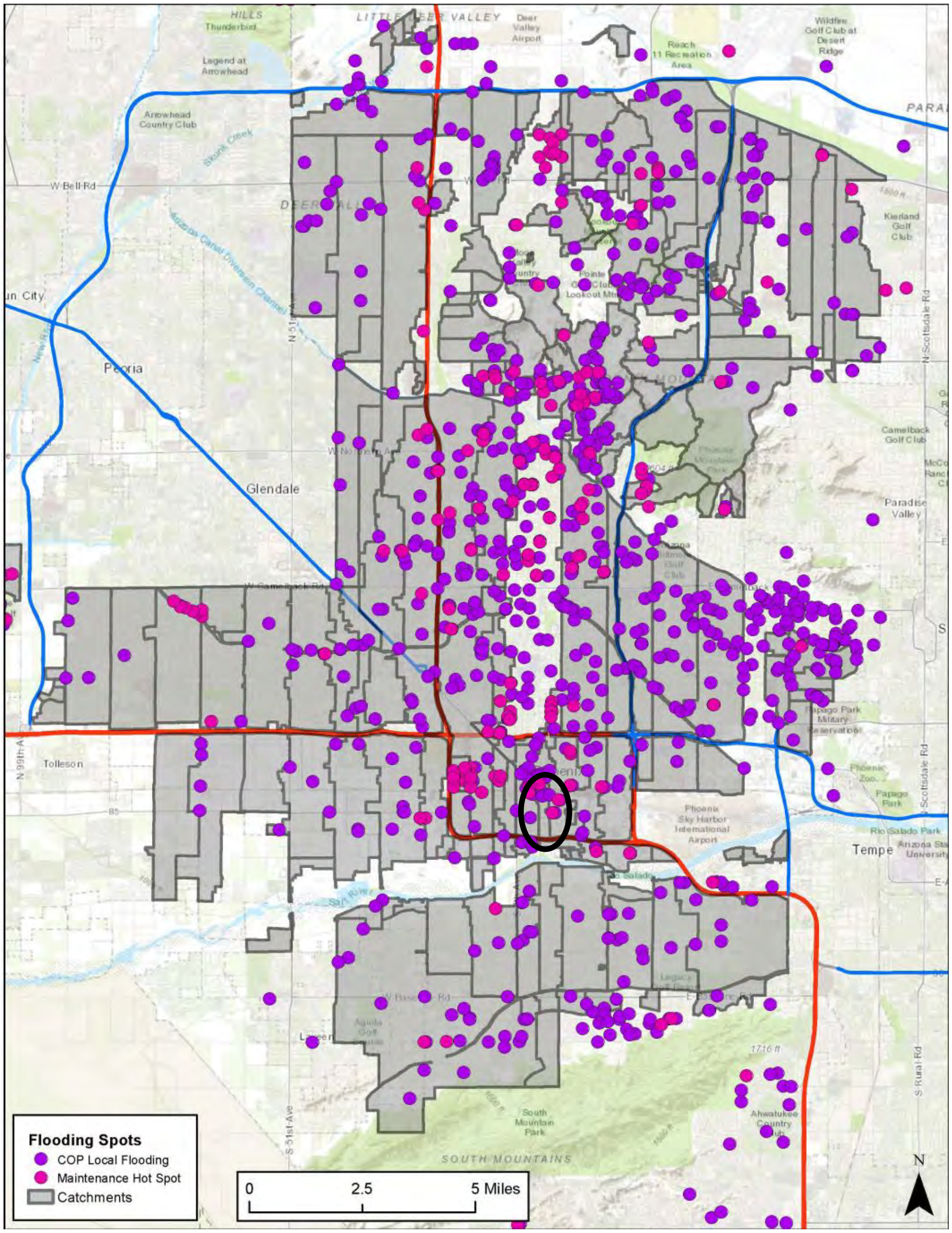

Figure 6. Localized flooding points and maintenance hot spots. Our final selected catchment is circled.

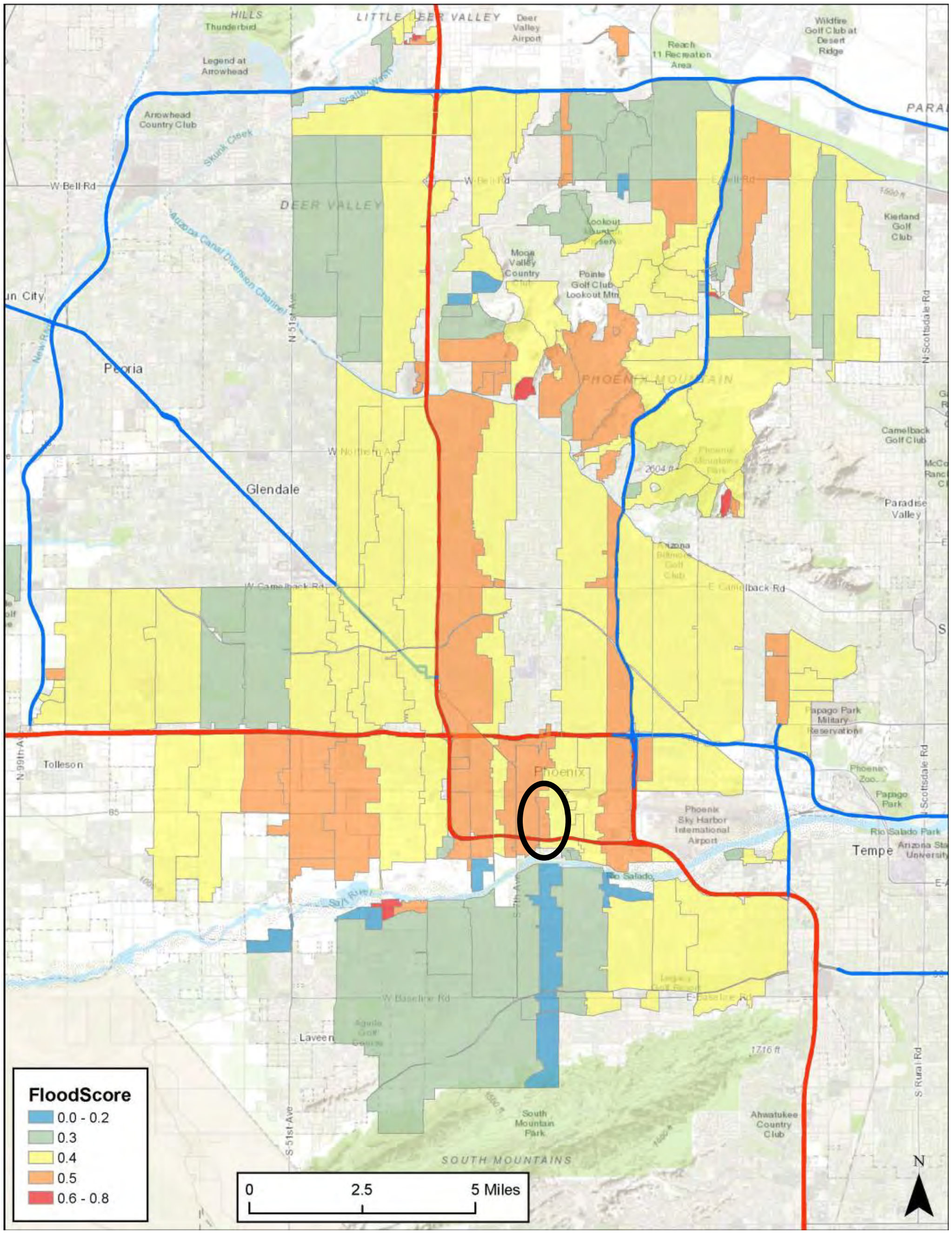

Figure 7. The overall flooding scores. Our final selected catchment is circled.

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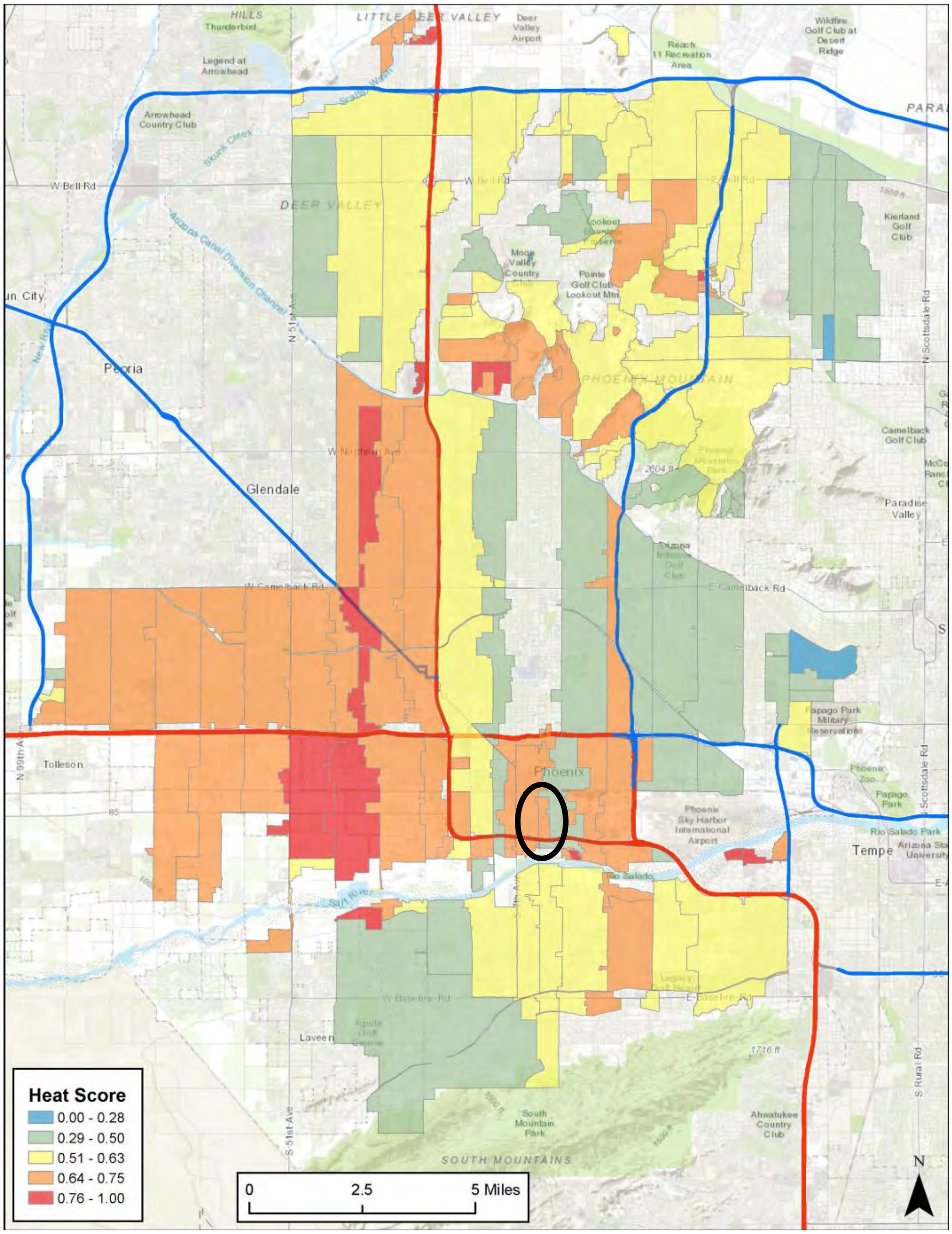

Figure 8. The overall heat scores. Our final selected catchment is circled.

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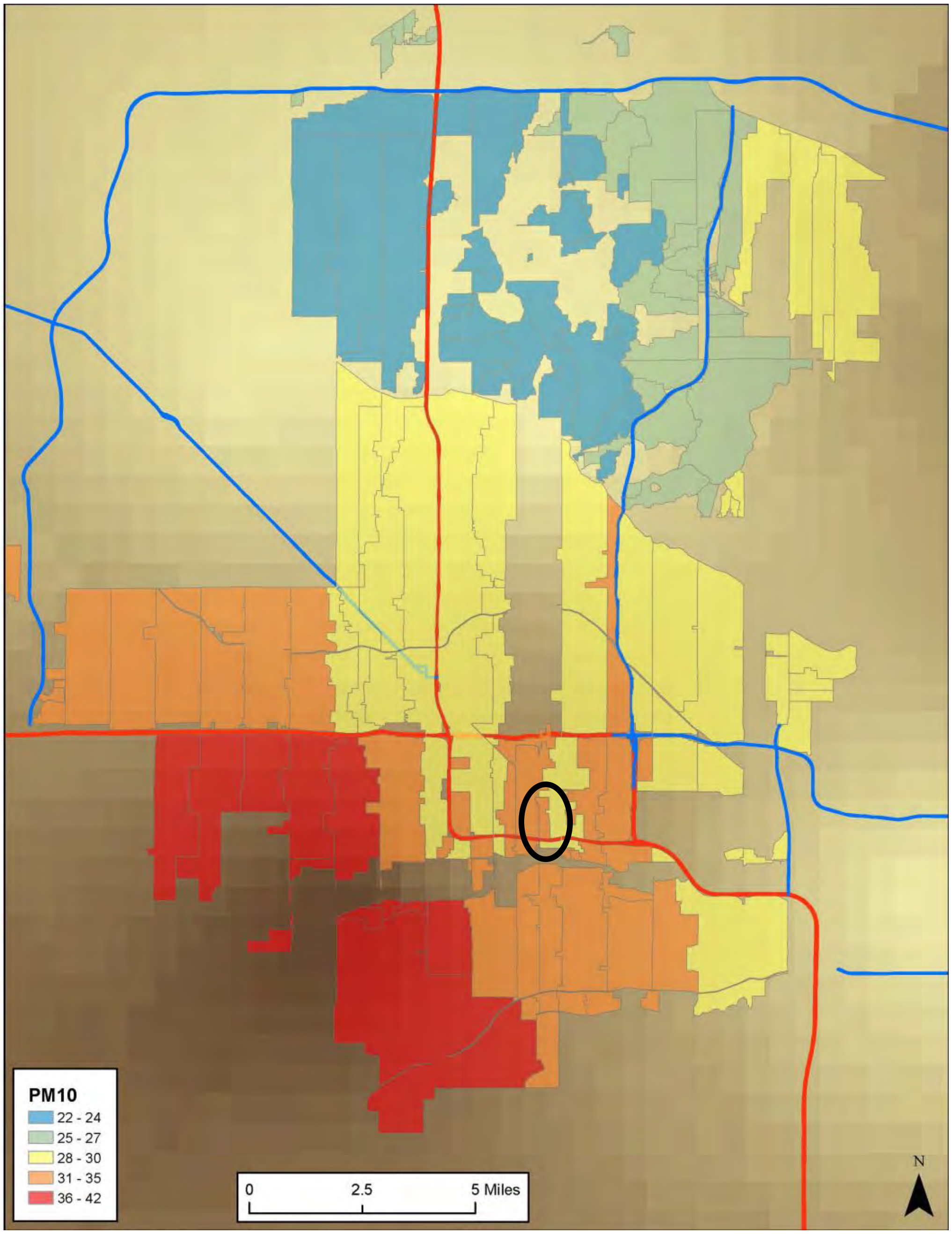

Figure 9. The average PM10 values across catchments with the continuous surface representing PM10 values in the background. Our final selected catchment is circled.

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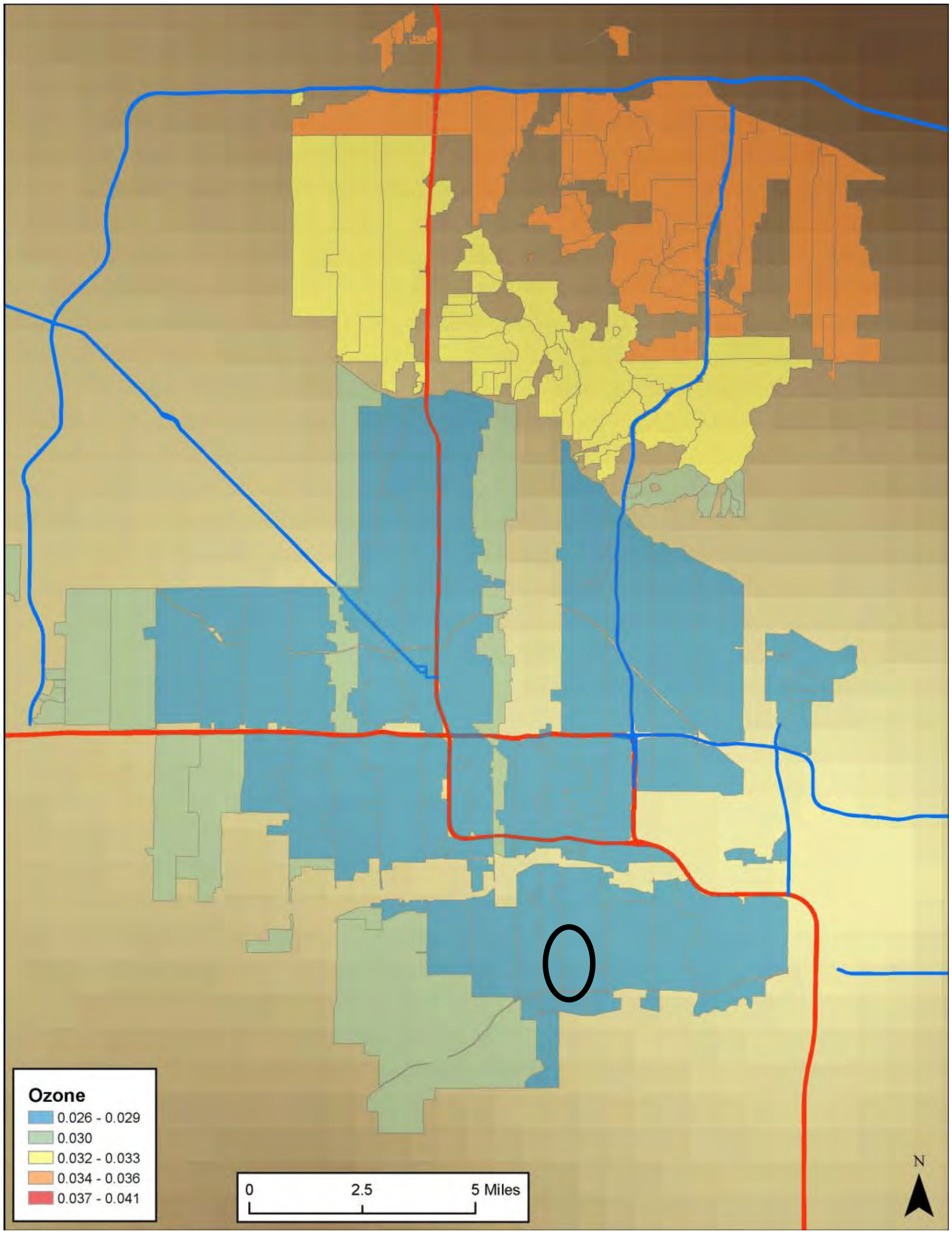

Figure 10. The average Ozone values across catchments with the continuous surface representing Ozone values in the background. Our final selected catchment is circled.

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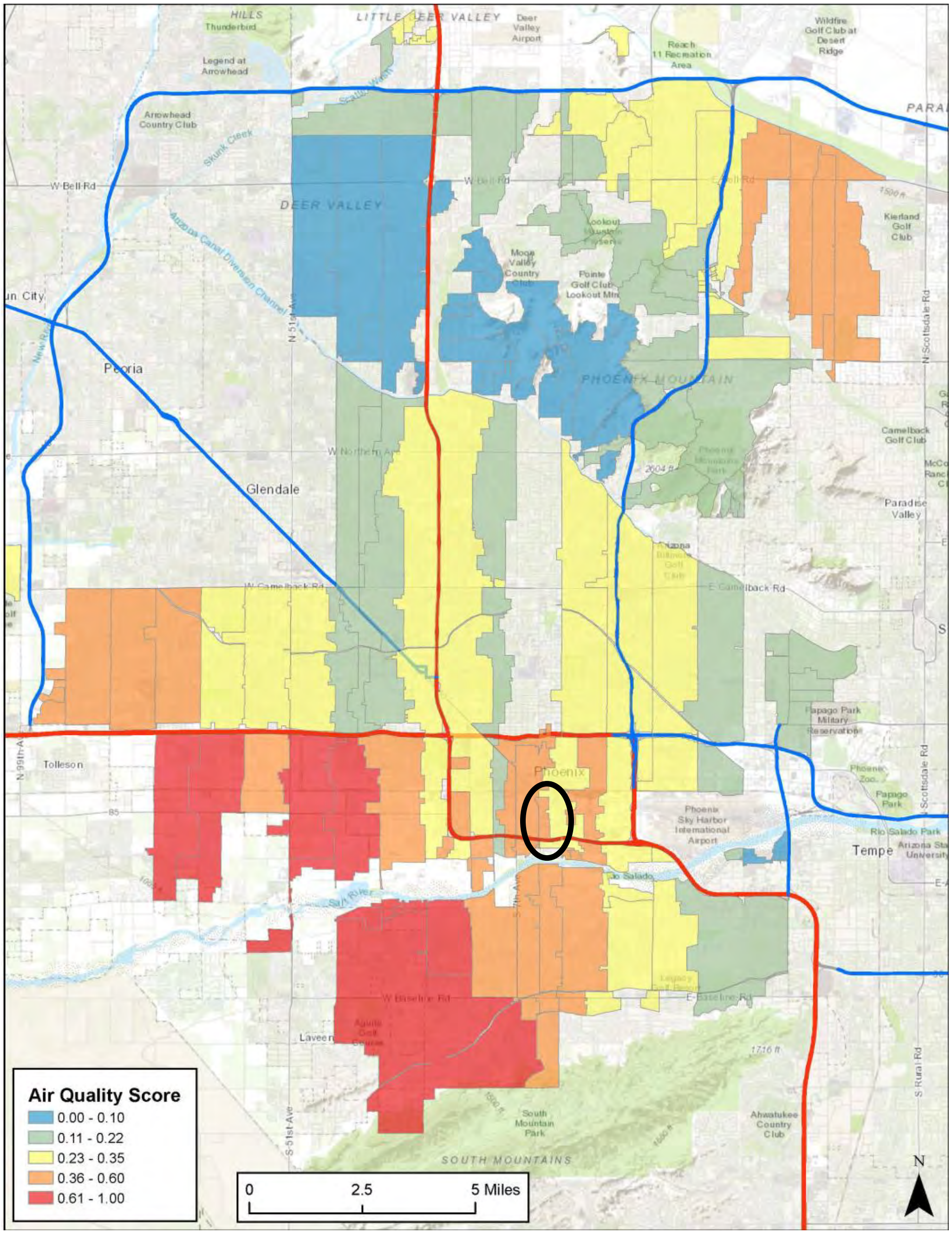

Figure 11. The overall air quality scores. Our final selected catchment is circled.

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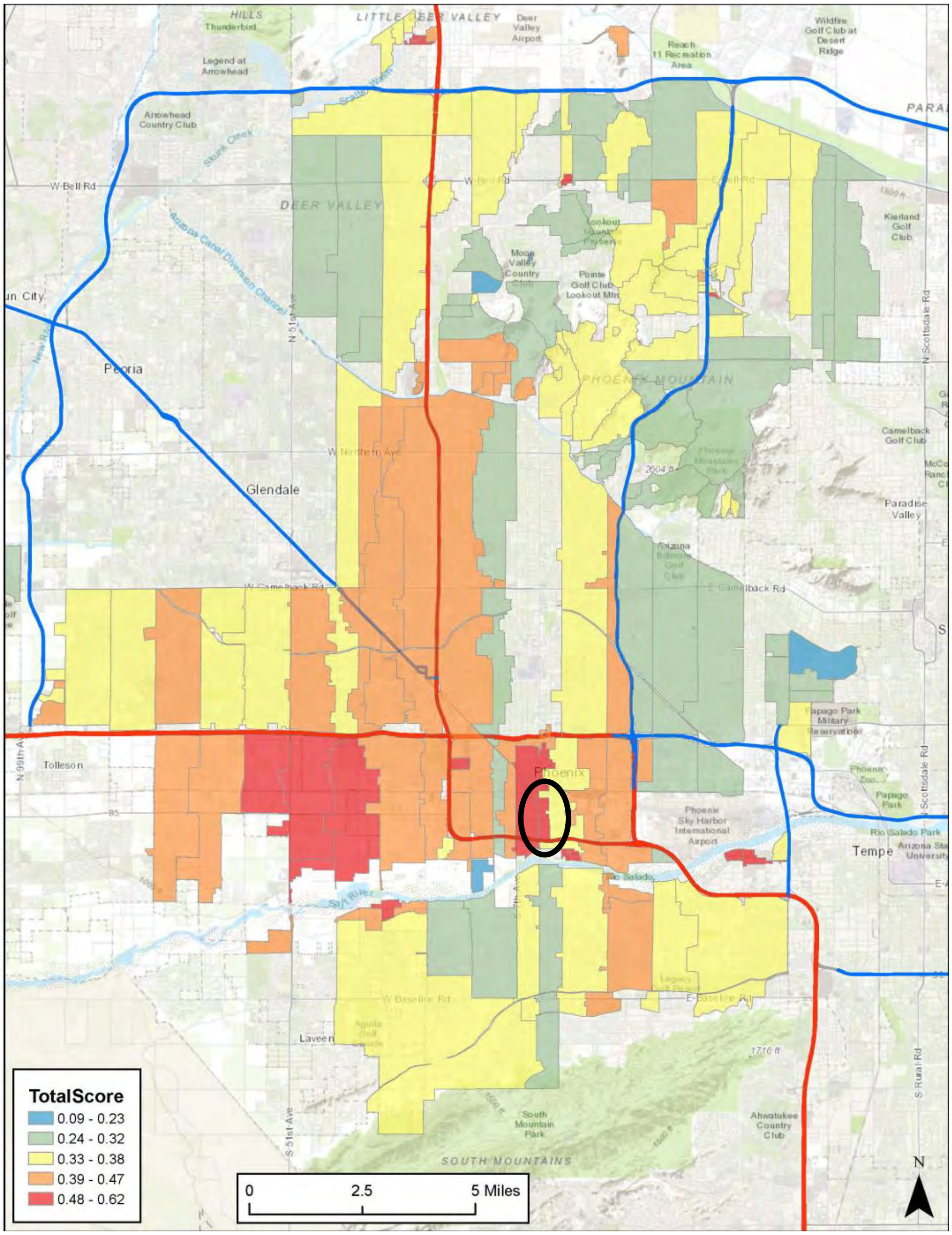

Figure 12. The overall total score across catchments. Our final selected catchment is circled.

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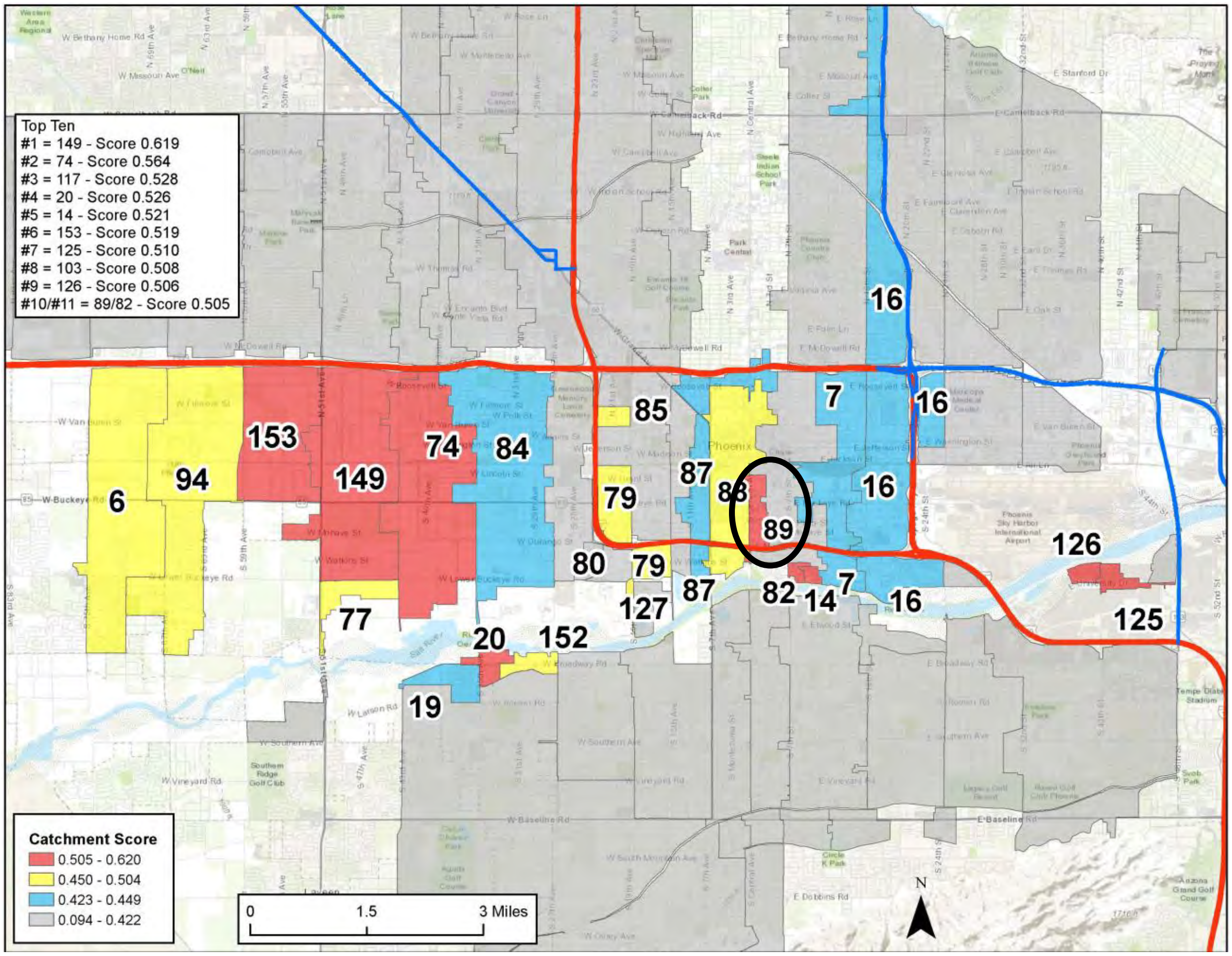

Figure 13. The top catchments. The colors in this figure correspond to the colors in Table 2. Our final selected catchment is circled.

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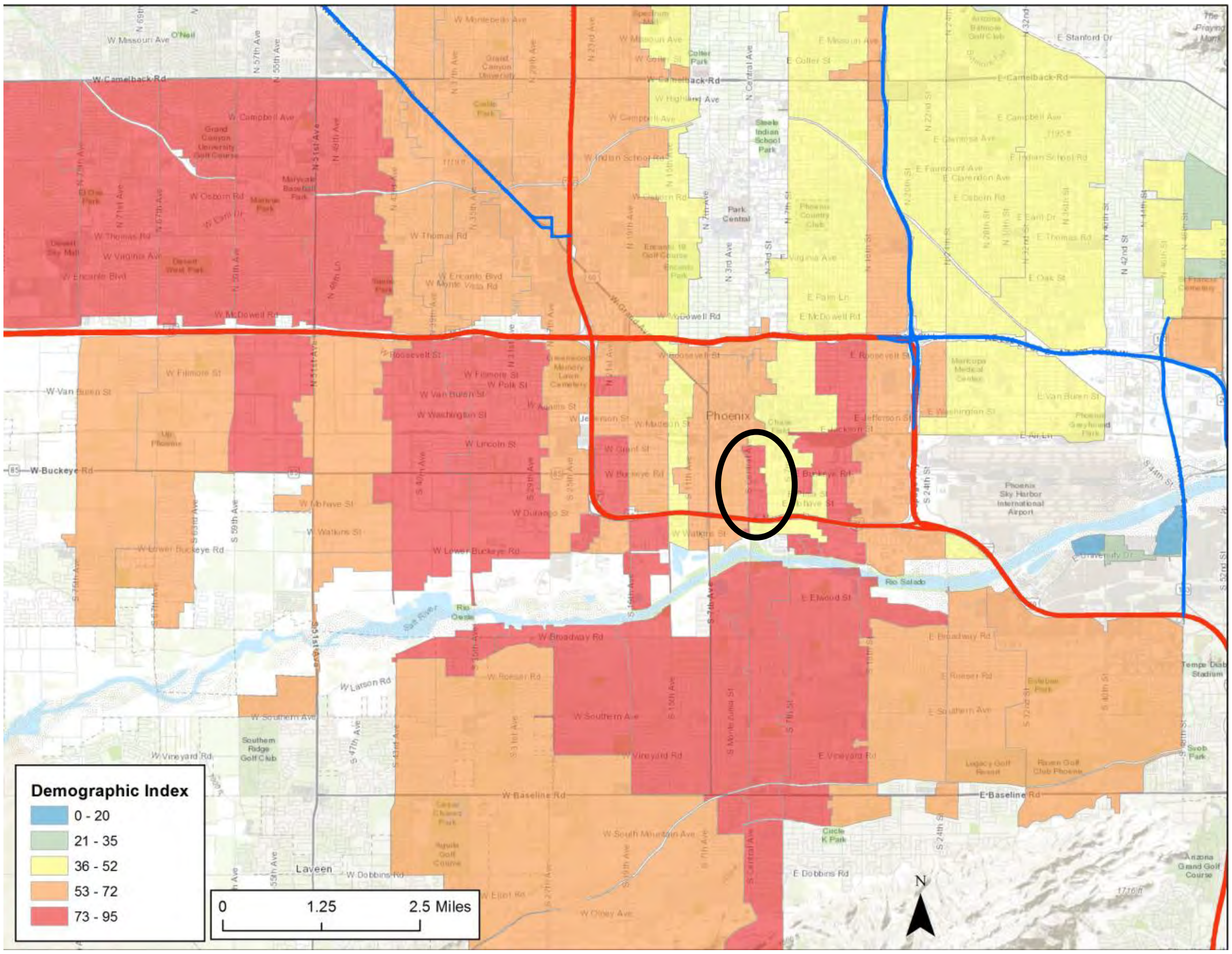

Figure 14. EJ Index average across catchments. Our final selected catchment is circled.

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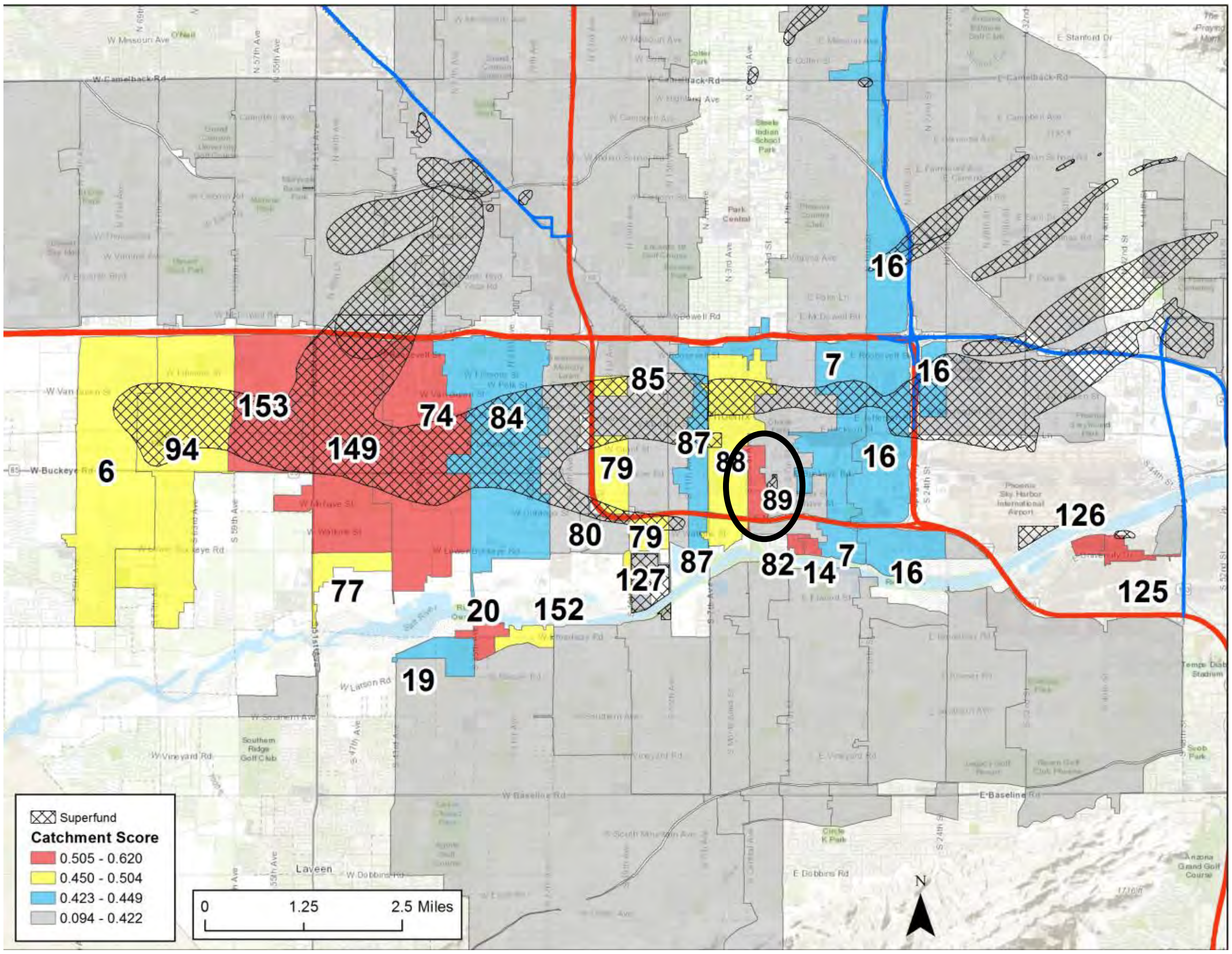

Figure 15. Superfund sites overlaid on top catchments. Our final selected catchment is circled.

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Appendix: Criteria weighting

Survey methodology: Project team members were asked to fill out a 3-question online (Qualtrics) survey. The survey asked them to compare the relative importance of four criteria – representing the primary LID benefits the study is focusing on – by rating, ranking, and pair-wise comparison methods. Team members had a week and a half to complete the survey. The aggregated results below were shared with all team members prior to the July monthly meeting. Ultimately 11 people participated in the survey, representing all project partners (BOR, TNC, City of Phoenix, Air Quality, Flood Control).

Question 1: Importance Rating:

1-not at all important
2-slightly important
3-moderately important
4-very important
5-extremely important

Aggregated results for all 11 responses

	Water Quality	Flooding	Air Quality	Heat
mean	3.909	4.455	3.455	4.091
stddev	0.701	0.688	1.036	0.701
mode	4 (very important)	5 (extremely important)	4 (very important)	4 (very important)
median	4 (very important)	5 (extremely important)	4 (very important)	4 (very important)

Question 2: Importance ranking

1-most important -> 4 least important

Aggregated results for all 11 responses

	Water Quality	Flooding	Air Quality	Heat
mean	2.455	1.545	3.273	2.727

Standard deviation	1.036	0.934	0.905	1.009
Rank	2	1	4	3

Question 3: Pair-wise comparisons

Aggregated weights for all 11 responses (possible model weights)

	Eigen vector method*	Arithmetic mean
water quality	0.16492471	0.244903
flooding	0.36670774	0.427663
air quality	0.09360485	0.124897
heat	0.14661986	0.202537

Individual preference weights (which are aggregated above):

I. Calculated using Dominant eigen values:

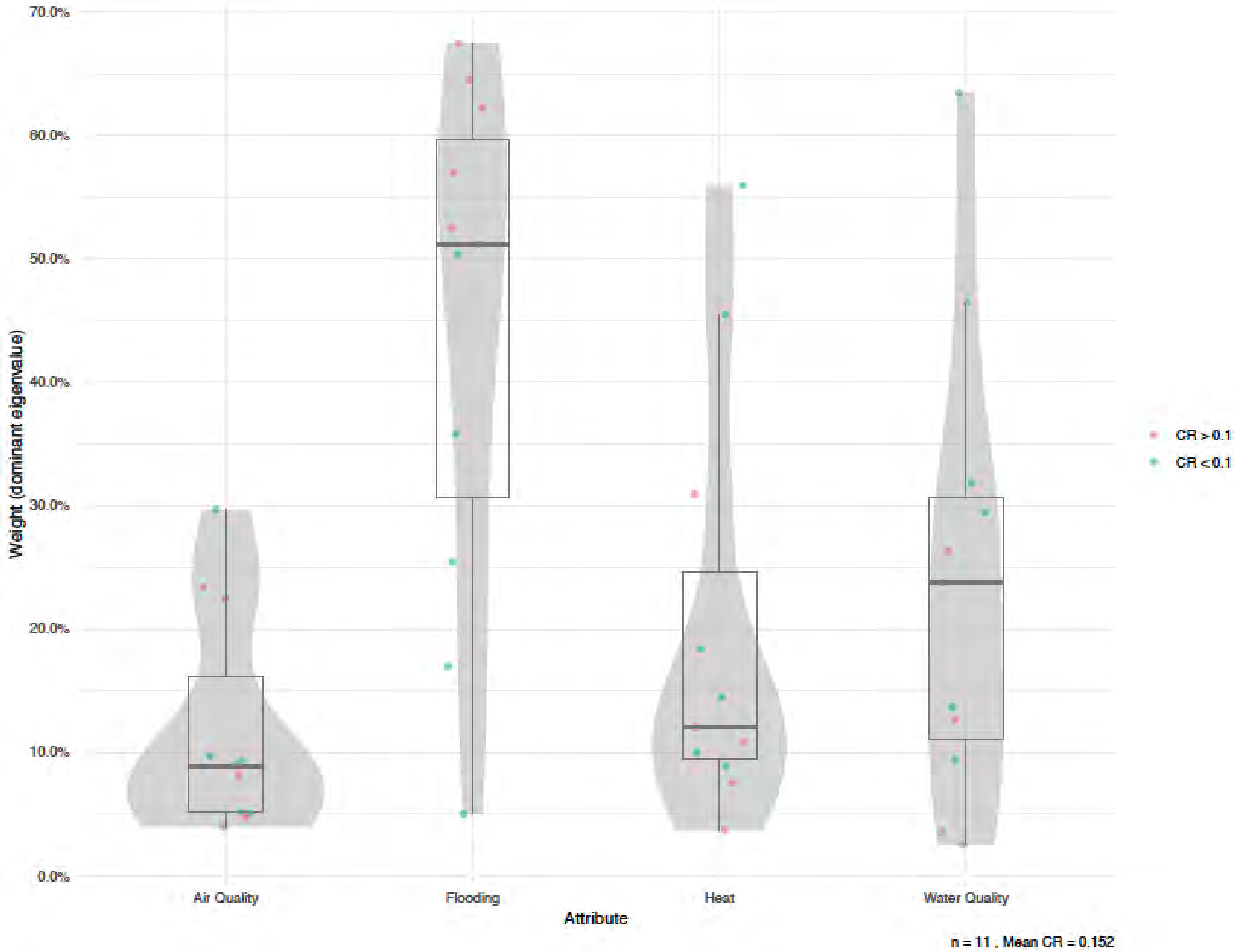
waterquality	flooding	airquality	heat
0.126365	0.524939	0.039263	0.309433
0.093861	0.049892	0.296611	0.559636
0.464242	0.254412	0.097485	0.183862
0.02501	0.675013	0.22496	0.075016
0.63448	0.169461	0.051636	0.144423
0.237461	0.645005	0.080625	0.036909
0.318205	0.503926	0.088935	0.088935
0.136899	0.358253	0.050055	0.454793
0.294801	0.511864	0.093243	0.100092
0.262404	0.570493	0.046781	0.120322
0.03512	0.622216	0.234122	0.108542

II. Calculated using arithmetic mean:

waterquality	flooding	airquality	heat

0.143324	0.51357	0.044099	0.299007
0.101201	0.052744	0.297563	0.548492
0.463421	0.251447	0.099408	0.185724
0.033933	0.605698	0.24338	0.116989
0.625647	0.175129	0.053506	0.145718
0.257804	0.588838	0.108258	0.0451
0.319036	0.501709	0.089627	0.089627
0.145145	0.364006	0.053315	0.437535
0.29979	0.49937	0.095168	0.105672
0.265645	0.554924	0.050963	0.128467
0.038984	0.596858	0.23858	0.125577

Graph showing the distribution of individual pair-wise comparison responses



6.11.19 Project Meeting: Finalizing weights

Final project team approved weights:

Criterion	Approved weight
water quality	0.224904
flooding	0.377663
air quality	0.124897
heat	0.272537

Methodology: Team members were asked to provide feedback on the aggregated weights. The group focused in on the arithmetic mean results. There was unanimous agreement that flooding should be the highest weighted criterion, as suggested by the survey results, and that air quality should be 4th. Team members from the City of Phoenix, however, disagreed that heat should be below water quality. They noted that there was strong “political will” around heat mitigation in the city, whereas water quality was less of a concern. The thought was that prioritizing heat would increase buy-in for LID. After some discussion, the group agreed to increase the weight for heat, while the weights for flooding and water quality were both decreased.

Appendix 4. Survey for Criteria Ranking

Survey

Survey methodology: Project team members were asked to fill out a 3-question online (Qualtrics) survey. The survey asked them to compare the relative importance of four criteria – representing the primary LID benefits the study is focusing on – by rating, ranking, and pair-wise comparison methods. Team members had a week and a half to complete the survey. The aggregated results below were shared with all team members prior to the July monthly meeting. Ultimately 11 people participated in the survey, representing all project partners (BOR, TNC, City of Phoenix, Air Quality, Flood Control).

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median	4 (very important)	5 (extremely important)	4 (very important)	4 (very important)

Question 2: Importance ranking

1-most important -> 4 least important

Aggregated results for all 11 responses

	Water Quality	Flooding	Air Quality	Heat
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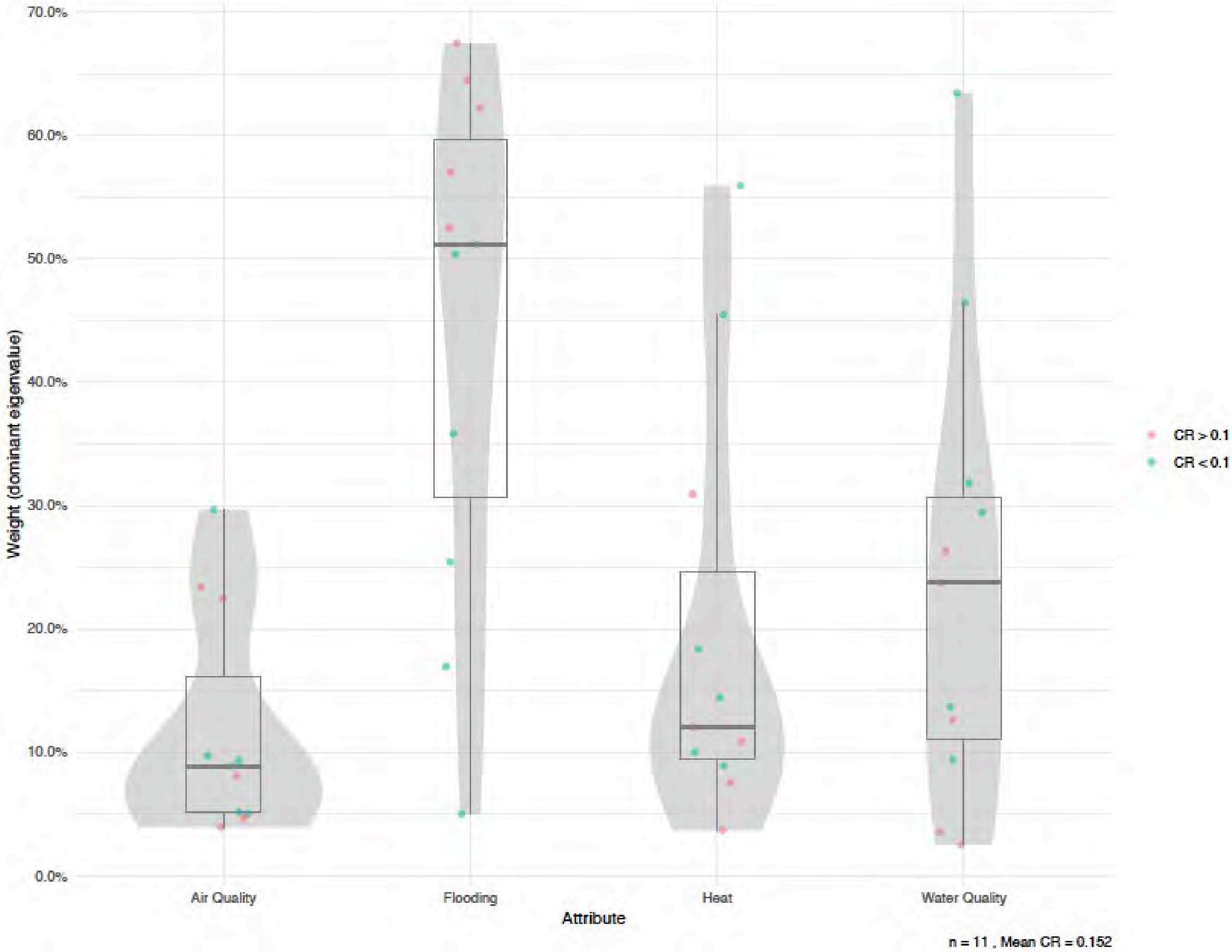
II. Calculated using arithmetic mean:

waterquality	flooding	airquality	heat
0.143324	0.51357	0.044099	0.299007
0.101201	0.052744	0.297563	0.548492
0.463421	0.251447	0.099408	0.185724
0.033933	0.605698	0.24338	0.116989
0.625647	0.175129	0.053506	0.145718
0.257804	0.588838	0.108258	0.0451
0.319036	0.501709	0.089627	0.089627
0.145145	0.364006	0.053315	0.437535
0.29979	0.49937	0.095168	0.105672
0.265645	0.554924	0.050963	0.128467
0.038984	0.596858	0.23858	0.125577

Graph showing the distribution of individual pair-wise comparison responses



<u>**6.11.19 Project Meeting: Finalizing weights**</u>

Final project team approved weights:

Criterion	Approved weight
water quality	0.224904
flooding	0.377663
air quality	0.124897
heat	0.272537

Methodology: Team members were asked to provide feedback on the aggregated weights. The group focused in on the arithmetic mean results. There was unanimous agreement that flooding should be the highest weighted criterion, as suggested by the survey results, and that air quality should be 4th. Team members from the City of Phoenix, however, disagreed that heat should be below water quality. They noted that there was strong "political will" around heat mitigation in the city, whereas water quality was less of a concern. The thought was that prioritizing heat would increase buy-in for LID. After some discussion, the group agreed to increase the weight for heat, while the weights for flooding and water quality were both decreased.

Appendix 5. LID Features and Treatment Train Details

Land Use Typ	LID Treatment Train Questionnaire	Selection	Notes/Comments
Residential	What percentage of surface area on a Residential roof would be captured/directed into a Cistern/Rain Barrel?	50%	
	What size of a cistern/rain barrel for Residential?	500 gallon (4' dia x 6' H	Because Residential areas are smaller it was determined by the group that 500 gallon cisterns would work. Also this determination was made with insight on the 1/2 inch rain event on the average size room leading to around 440 gallons of rain runoff. (Reference recording of meeting)
	For Residential; percentage of remaining roof area is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	50%	
	In Residential, what percentage of Driveway surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain)?	80%	The collective group wanted the most possible maximum and it was determined that 80% was appropriate.
	What percentage of yard/open space should Rain Gardens be applied in Residential?	50%	
	How many linear basins (WMG Style 4x10') and/or chicanes (9x20') added per lot of associated ROW with Residential?	1 linear basin per lot and 1 chicane every 4 lots	There was some discussion and it was important to clarify that each Residential lot would have 1 linear basin in front in the ROW and that every 4 lots there would be a traffic calming chicane.
Industrial	What percentage of surface area on an Industrial roof would be captured/directed into a Cistern/Rain Barrel?	25%	Collective Group agreed on 25% capture into a Rain Barrel
	What size of a cistern/rain barrel for Industrial?	3000 gallon (8.5' dia x 8.5 H)	
	For Industrial; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	50%	There was much discussion and based on the current Industrial land types on the study site, it we determined that there were less detention basins then originally thought thus the compromise came to agree on 50%.
	For Industrial, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain) and/or Infiltration Trench?	75%	There was much discussion and based on the current Industrial land types on the study site, it we determined that there were less detention basins then originally thought thus the compromise came to agree on 75%
	What percentage of landscaping/open space should Rain Gardens be applied in Industrial?	100% (Maximum)	After further discussion it was determined that the maximum available landscaping space should include rain gardens for Industrial, so 100% was chosen.
	For Industrial, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	10%	It was agreed upon 10% because some Industrial could utlize permeable pavement for future retention credits and there might be limited landscaping space. Another factor was considering industrial vehicle movement and larger impervious space leading to a smaller percentage of applicaiton compared to Commercial.
Commercial	What percentage of surface area on a Commercial roof would be captured/directed into a Cistern/Rain Barrel?	25%	Collective Group agreed on 25% capture into a Rain Barrel
	What size of a cistern/rain barrel for Commercial?	3000 gallon (8.5' dia x 8.5 H)	
	For Commercial; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	50%	*Need to cirlce back, the group was leaning towards 50% but depending on how this is represented in the model it could be 25%
	For Commercial, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain) and/or Infiltration Trench?	75%	
	What percentage of landscaping/open space should Rain Gardens be applied in Commercial?	100% (Maximum)	After further discussion it was determined that the maximum available landscaping space should include rain gardens for Commercial, so 100% was chosen.
	For Commercial, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	20%	It was agreed upon 20% because some Commerical could utlize permeable pavement for future retention credits and there might be limited landscaping space so a slightly larger percentage was provided compared to Public/School/Religious
Public/School	What percentage of surface area on a Public/School/Religious roof would be captured/directed into a Cistern/Rain Barrel?	50%	
	What size of a cistern/rain barrel for Public/School/Religious?	3000 gallon (8.5' dia x 8.5 H)	
	For Public/School/Religious; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	25%	
	In Public/School/Religious, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (ie. Grate Drain)?	50%	The collective group was split between 75% and 25% so it was agreed on 50%.
	What percentage of landscaping/open space should Rain Gardens be applied in Public/School/Religious?	50%	
	How many linear basins (WMG Style 4x10') and/or chicanes (9x20') added per lot of associated ROW with Public/School?Religious?	1 linear basin per lot and 1 chicane every 4 lots	
	For Public/School/Religious, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	10%	Based on cost and some limiting benefits for vegetation support the group went with the smaller amount
Central ROW	How many Bio-Retention planters installed on Central ROW? Each Landscaping ROW is about 10-15 ft. long, every 5-10 ft.	2 per landscaping ROW section	
Sizing	LID Feature Sizing: Infiltration Trench linear length?	10'	
	LID Feature Sizing: Depth for Rain Gardens/ Vegetative Swales/ Linear Basins/ Chicanes?	18 inches	Focusing on maximum capture, and there was discussion on 3 inch walled spaced for BMPs for design leading to the coconscious on 18 inches. It was also mentioned that the depth sizing for some of the listed LIDs could vary on this depth amount.
	LID Feature Sizing: Bio-Retention Planter Size	5x7'	Noted- Need to circle back to this question. It was agreeded upon at 5x7' for sizing because of its size demesions fit better for ROW application.

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
What percentage of surface area on a Residential roof would be captured/directed into a Cistern/Rain Barrel?	50%	4	
	75%	1	
	100%	0	
	25%	0	
	90%	0	
What size of a cistern/rain barrel for Residential?	1000 gallon (6' dia x 6' H)	2	
	3000 gallon (8.5' dia x 8.5 H)	1	
	500 gallon (4' dia x 6' H	2	Because Residential areas are smaller it was determined by the group that 500 gallon cisterns would work. Also this determination was made with insight on the 1/2 inch rain event on the average size room leading to around 440 gallons of rain runoff. (Reference recording of meeting)
	1500 gallon (8.5' dia x 8.5 H)	0	
For Residential; percentage of remaining roof area is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	50%	4	
	25%	1	
	10%	0	
	75%	0	
In Residential, what percentage of Driveway surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain)?	80%		The collective group wanted the most possible maximum and it was determined that 80% was appropriate.
	50%	4	
	30%	1	
	10%	0	
What percentage of yard/open space should Rain Gardens be applied in Residential?	50%	3	
	25%	1	
	75%	1	
	10%	0	
How many linear basins (WMG Style 4x10') and/or chicanes (9x20') added per lot of associated ROW with Residential?	1 linear basin per lot and 1 chicane every 4 lots	4	
	1 linear basins per lot	1	There was some discussion and it was important to clarify that each Residential lot would have 1 linear basin in front in the ROW and that every 4 lots there would be a traffic calming chicane.
	1 chicane every 4 lots	0	
	1 chicane every other lot	0	
	2 linear basins per lot	1	

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
What percentage of surface area on an Industrial roof would be captured/directed into a Cistern/Rain Barrel?	10%	1	
	75%	1	
	50%	1	
	25%	1	Collective Group agreed on 25% capture into a Rain Barrel
	0% (No Cistern)	1	
What size of a cistern/rain barrel for Industrial?	1000 gallon (6' dia x 6' H)	1	
	5000 gallon (8.5' dia x 13' H)	1	
	None	1	
	3000 gallon (8.5' dia x 8.5 H)	2	
For Industrial; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	10%	1	
	2%	1	
	25%	1	
	50%	1	There was much discussion and based on the current Industrial land types on the study site, it we determined that there were less detention basins then originally thought thus the compromise came to agree on 50%.
	90%	1	
For Industrial, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain) and/or Infiltration Trench?	90%	3	
	25%	1	
	75%	1	There was much discussion and based on the current Industrial land types on the study site, it we determined that there were less detention basins then originally thought thus the compromise came to agree on 75%
	50%	0	
What percentage of landscaping/open space should Rain Gardens be applied in Industrial?	100% (Maximum)		
	75%	3	After further discussion it was determined that the maximum available landscaping space should include rain gardens for Industrial, so 100% was chosen.
	10%	2	
	25%	1	
27. For Industrial, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	2%	2	

10%	1	It was agreed upon 10% because some Industrial could utlize permeable pavement for future retention credits and there might be limited landscaping space. Another factor was considering industrial vehicle movement and larger impervious space leading to a smaller percentage of applicaiton compared to Commercial.
25%	1	
50%	1	
20%	0	

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
What percentage of surface area on a Commercial roof would be captured/directed into a Cistern/Rain Barrel?	10%	1	
	75%	1	
	50%	1	
	25%	1	Collective Group agreed on 25% capture into a Rain Barrel
	0% (No Cistern)	1	
What size of a cistern/rain barrel for Commercial?	500 gallon (4' dia x 6' H	1	
	3000 gallon (8.5' dia x 8.5 H)	2	
	None	1	
	1000 gallon (6' dia x 6' H)	0	
13. For Commercial; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	25%	2	
	50%	2	*Need to cirlce back, the group was leaning towards 50% but depending on how this is represented in the model it could be 25%
	10%	1	
	75%	0	
For Commercial, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain) and/or Infiltration Trench?	75%	2	
	90%	2	
	25%	1	
	50%	0	
What percentage of landscaping/open space should Rain Gardens be applied in Commercial?	100% (Maximum)		
	50%	2	After further discussion it was determined that the maximum available landscaping space should include rain gardens for Commercial, so 100% was chosen.
	75%	2	
	25%	1	
For Commercial, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	50%	2	
	10%	1	
	20%	1	It was agreed upon 20% because some Commerical could utlize permeable pavement for future retention credits and there might be limited landscaping space so a slightly larger percentage was provided compared to Public/School/Religious
	25%	1	
	2%	0	

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
What percentage of surface area on a Public/School/Religious roof would be captured/directed into a Cistern/Rain Barrel?	50%	3	
	25%	1	
	75%	1	
	100%	0	
	90%	0	
What size of a cistern/rain barrel for Public/School/Religious?	3000 gallon (8.5' dia x 8.5 H)	3	
	10000 gallon (9' dia x 21' H)	1	
	1000 gallon (6' dia x 6' H)	1	
For Public/School/Religious; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	25%	3	
	50%	1	
	75%	1	
	10%	0	
In Public/School/Religious, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (ie. Grate Drain)?	25%	2	
	75%	2	
	90%	1	
	50%	0	The collective group was split between 75% and 25% so it was agreed on 50%.
20. What percentage of landscaping/open space should Rain Gardens be applied in Public/School/Religious?	50%	3	
	10%	1	
	25%	1	
	75%	0	
24. How many linear basins (WMG Style 4x10') and/or chicanes (9x20') added per lot of associated ROW with Public/School?Religious?	1 linear basin per lot and 1 chicane every 4 lots	3	
	1 linear basins per lot	1	
	1 chicane every 4 lots	0	
	1 chicane every other lot	0	
	2 linear basins per lot	1	
For Public/School/Religious, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	10%	2	
	25%	1	Based on cost and some limiting benefits for vegetation support the group went with the smaller amount
	5%	1	
	50%	1	
	2%	0	

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
How many Bio-Retention planters installed on Central ROW? Each Landscaping ROW is about 10-15 ft. long, every 5-10 ft.	2 per landscaping ROW section	3	
	1 per every other landscaping ROW section	1	
	1 per landscaping ROW section	1	

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
LID Feature Sizing: Infiltration Trench linear length?	10'	4	
	20'	1	
	5'	0	
	15'	0	
LID Feature Sizing: Depth for Rain Gardens/ Vegetative Swales/ Linear Basins/ Chicanes?	18 inches	3	
	12 inches	2	Focusing on maximum capture, and there was discussion on 3 inch walled spaced for BMPs for design leading to the coconscious on 18 inches. It was also mentioned that the depth sizing for some of the listed LIDs could vary on this depth amount.
	6 inches	0	
LID Feature Sizing: Bio-Retention Planter Size	5x5'	2	
	5x7'	2	Noted- Need to circle back to this question. It was agreeded upon at 5x7' for sizing because of its size demesions fit better for ROW application.
	10'10'	1	
	3x5'	0	
	Other	0	

LID Treatment Train Questionnaire	Answers:	Number of Responses	Notes/Comments
What percentage of surface area on a Residential roof would be captured/directed into a Cistern/Rain Barrel?	50%	4	
	75%	1	
	100%	0	
	25%	0	
	90%	0	
What percentage of surface area on a Public/School/Religious roof would be captured/directed into a Cistern/Rain Barrel?	50%	3	
	25%	1	
	75%	1	
	100%	0	
	90%	0	
What percentage of surface area on a Commercial roof would be captured/directed into a Cistern/Rain Barrel?	10%	1	
	75%	1	
	50%	1	
	25%	1	Collective Group agreed on 25% capture into a Rain Barrel
	0% (No Cistern)	1	
What percentage of surface area on an Industrial roof would be captured/directed into a Cistern/Rain Barrel?	10%	1	
	75%	1	
	50%	1	
	25%	1	Collective Group agreed on 25% capture into a Rain Barrel
	0% (No Cistern)	1	
What size of a cistern/rain barrel for Residential?	1000 gallon (6' dia x 6' H)	2	
	3000 gallon (8.5' dia x 8.5 H)	1	
	500 gallon (4' dia x 6' H	2	Because Residential areas are smaller it was determined by the group that 500 gallon cisterns would work. Also this determination was made with insight on the 1/2 inch rain event on the average size room leading to around 440 gallons of rain runoff. (Reference recording of meeting)
	1500 gallon (8.5' dia x 8.5 H)	0	
What size of a cistern/rain barrel for Public/School/Religious?	3000 gallon (8.5' dia x 8.5 H)	3	
	10000 gallon (9' dia x 21' H)	1	
	1000 gallon (6' dia x 6' H)	1	
What size of a cistern/rain barrel for Commercial?	500 gallon (4' dia x 6' H	1	
	3000 gallon (8.5' dia x 8.5 H)	2	
	None	1	
	1000 gallon (6' dia x 6' H)	0	
What size of a cistern/rain barrel for Industrial?	1000 gallon (6' dia x 6' H)	1	
	5000 gallon (8.5' dia x 13' H)	1	
	None	1	
	3000 gallon (8.5' dia x 8.5 H)	2	
For Residential; percentage of remaining roof area is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	50%	4	
	25%	1	
	10%	0	
	75%	0	

In Residential, what percentage of Driveway surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain)?	80%		The collective group wanted the most possible maximum and it was determined that 80% was appropriate.
	50%	4	
	30%	1	
	10%	0	
For Public/School/Religious; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	25%	3	
	50%	1	
	75%	1	
	10%	0	
In Public/School/Religious, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (ie. Grate Drain)?	25%	2	
	75%	2	
	90%	1	
	50%	0	The collective group was split between 75% and 25% so it was agreed on 50%.
For Commercial; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	25%	2	
	50%	2	*Need to cirlce back, the group was leaning towards 50% but depending on how this is represented in the model it could be 25%
	10%	1	
	75%	0	
For Commercial, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain) and/or Infiltration Trench?	75%	2	
	90%	2	
	25%	1	
	50%	0	
For Industrial; percentage of roof that is redirected to landscaping area (pervious surface and/or other LID treatment) via Disconnected Downspout? Keep in mind that in addition, a cistern/rain barrel will capture some percentage of the roof, as well.	10%	1	
	2%	1	
	25%	1	
	50%	1	There was much discussion and based on the current Industrial land types on the study site, it we determined that there were less detention basins then originally thought thus the compromise came to agree on 50%.
	90%	1	
For Industrial, what percentage of parking lot surface area (impervious) is diverted to rain garden (pervious) using Disconnected Downspout (Grate Drain) and/or Infiltration Trench?	90%	3	
	25%	1	
	75%	1	There was much discussion and based on the current Industrial land types on the study site, it we determined that there were less detention basins then originally thought thus the compromise came to agree on 75%
	50%	0	
LID Feature Sizing: Infiltration Trench linear length?	10'	4	
	20'	1	

	5'	0	
	15'	0	
LID Feature Sizing: Depth for Rain Gardens/ Vegetative Swales/ Linear Basins/ Chicanes?	18 inches	3	
	12 inches	2	Focusing on maximum capture, and there was discussion on 3 inch walled spaced for BMPs for design leading to the coconscious on 18 inches. It was also mentioned that the depth sizing for some of the listed LIDs could vary on this depth amount.
	6 inches	0	
What percentage of yard/open space should Rain Gardens be applied in Residential?	50%	3	
	25%	1	
	75%	1	
	10%	0	
20. What percentage of landscaping/open space should Rain Gardens be applied in Public/School/Religious?	50%	3	
	10%	1	
	25%	1	
	75%	0	
What percentage of landscaping/open space should Rain Gardens be applied in Commercial?	100% (Maximum)		
	50%	2	After further discussion it was determined that the maximum available landscaping space should include rain gardens for Commercial, so 100% was chosen.
	75%	2	
	25%	1	
What percentage of landscaping/open space should Rain Gardens be applied in Industrial?	100% (Maximum)		
	75%	3	After further discussion it was determined that the maximum available landscaping space should include rain gardens for Industrial, so 100% was chosen.
	10%	2	
	25%	1	
How many linear basins (WMG Style 4x10') and/or chicanes (9x20') added per lot of associated ROW with Residential?	1 linear basin per lot and 1 chicane every 4 lots	4	
	1 linear basins per lot	1	There was some discussion and it was important to clarify that each Residential lot would have 1 linear basin in front in the ROW and that every 4 lots there would be a traffic calming chicane.
	1 chicane every 4 lots	0	
	1 chicane every other lot	0	
	2 linear basins per lot	1	
How many linear basins (WMG Style 4x10') and/or chicanes (9x20') added per lot of associated ROW with Public/School?Religious?	1 linear basin per lot and 1 chicane every 4 lots	3	
	1 linear basins per lot	1	
	1 chicane every 4 lots	0	
	1 chicane every other lot	0	
	2 linear basins per lot	1	
For Public/School/Religious, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	10%	2	
	25%	1	Based on cost and some limiting benefits for vegetation support the group went with the smaller amount
	5%	1	
	50%	1	
	2%	0	

For Commercial, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	50%	2	
	10%	1	
	20%	1	It was agreed upon 20% because some Commerical could utlize permeable pavement for future retention credits and there might be limited landscaping space so a slightly larger percentage was provided compared to Public/School/Religious
	25%	1	
	2%	0	
For Industrial, what percentage of impervious areas (parking spaces, side walks, road/driveways) is converted to pervious using permeable pavement?	2%	2	
	10%	1	It was agreed upon 10% because some Industrial could utlize permeable pavement for future retention credits and there might be limited landscaping space. Another factor was considering industrial vehicle movement and larger impervious space leading to a smaller percentage of applicaiton compared to Commercial.
	25%	1	
	50%	1	
	20%	0	
LID Feature Sizing: Bio-Retention Planter Size	5x5'	2	
	5x7'	2	Noted- Need to circle back to this question. It was agreeded upon at 5x7' for sizing because of its size demesions fit better for ROW application.
	10'10'	1	
	3x5'	0	
	Other	0	
How many Bio-Retention planters installed on Central ROW? Each Landscaping ROW is about 10-15 ft. long, every 5-10 ft.	2 per landscaping ROW section	3	
	1 per every other landscaping ROW section	1	
	1 per landscaping ROW section	1	

Appendix 6. Surface Water Model Report

BUREAU OF RECLAMATION

Technical Service Center Memorandum Number ENV-2021-088

Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development: Surface Water Modeling

Lower Colorado Basin Region

U.S. Department of the Interior

July 2021

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover: Every Drop Counts artwork near catchment outfall; Credit: D. Tosline

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Lindsay A. Bearup, PhD, PE

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Technical Service Center
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Denver, CO 80225-0007

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Glendale, AZ 85306-4001

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Approved for public release; contact PXAO

13. SUPPLEMENTARY NOTES
This is not a feasibility study and implementation costs and exact feature locations were not considered.

14. ABSTRACT
This report details the stormwater modeling completed as part of the study titled “Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development”. It is a demonstration of the potential of low impact development approaches to manage stormwater runoff in Phoenix, AZ. The study demonstrates the ability of bioretention cells, rain gardens, cisterns, and similar features to increase infiltration and decrease runoff volumes and peak inflows in an urban catchment.

15. SUBJECT TERMS
Low Impact Development, Phoenix Arizona, Green Infrastructure

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Lindsay A. Bearup, PhD, PE
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BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Water Resources Engineering and Management Group, 86-688210

Technical Service Center Technical Memorandum

Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development: Surface Water Modeling

Prepared by: Lindsay A. Bearup, PhD, PE, Civil Engineer (Hydrologic) Group 86-68210 Date

Peer Reviewed by: Blair Greimann, PE, Hydraulic Engineer, Group 86-68240 Date

Acronyms and Abbreviations

cfs	Cubic feet per second
DOI	Department of the Interior
in	Inches
LID	Low Impact Development
Mgal	Million gallons
NRCS	Natural Resources Conservation Service
PCSWMM	Personal Computer Storm Water Management Model
Reclamation	Bureau of Reclamation
ROW	Right of Ways
SWMM	Stormwater Management Model
TSC	Technical Service Center
US EPA	United States Environmental Protection Agency

Contents

Tables

Figures

1 Introduction

1.1 About this Report

This report details the stormwater modeling completed as part of the study titled “Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development”. It is a demonstration of the potential of low impact development (LID) approaches to manage stormwater runoff in an urban catchment in Phoenix, AZ. This is not a feasibility study and implementation costs and exact feature locations were not considered. The information offered herein represents the opinion of the LID Floodplain study author(s). These theoretical LID treatment trains do not represent and should not be construed to represent the City of Phoenix determination, project or policy.

The Bureau of Reclamation’s (Reclamation) Technical Service Center (TSC) prepared this report to detail the assumptions, model development process, and results of stormwater modeling of LID features. It represents the TSC’s stormwater modeling and compliments the larger study team report.

1.2 Project Location

Catchment 89 is located between downtown Phoenix and the Salt River (Figure 1). This catchment scored highly in the Phase 1 GIS analysis that ranked which catchments would most benefit from LID installations based on four criteria: flooding, heat, stormwater quality, and air quality (Reclamation 2021). From the top scoring catchments, the team selected Catchment 89 for further analysis due to its variety of land uses and manageable size for the desired modeling approach.

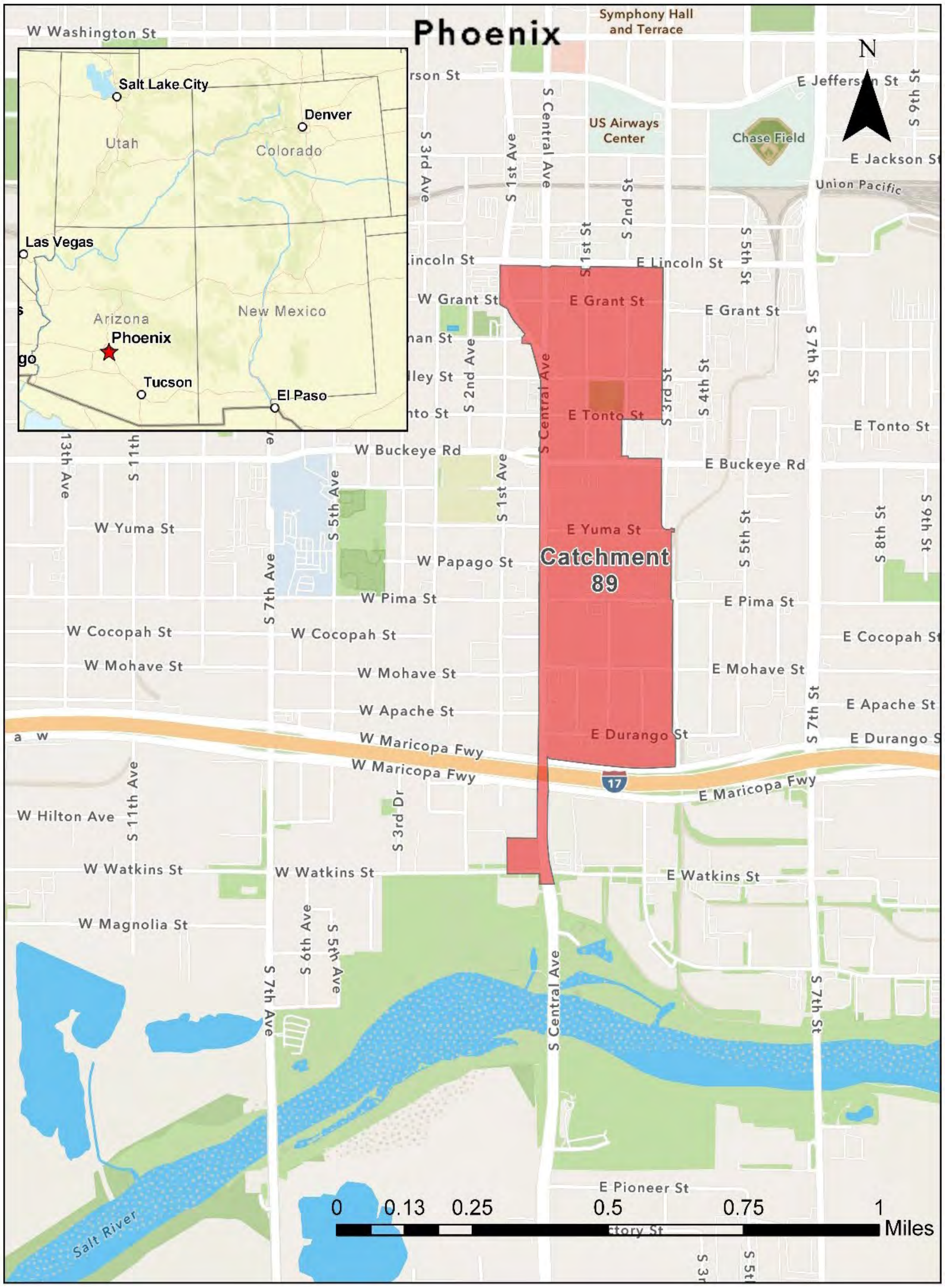

Figure 1 - Location map of Catchment 89.

2 Methods

2.1 Baseline PCSWMM Model Development

2.1.1 PCSWMM

The Personal Computer Storm Water Management Model (PCSWMM, www.pcswmm.com) provides a GIS-based interface and additional analysis tools to work with the US Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM, Rossman and Huber 2016). SWMM simulates stormwater runoff and storm sewer hydraulics and was developed specifically for land use planning. SWMM also includes default LID options that captured the range of features desired by project stakeholders, resulting in transparent and well-documented implementation of LID in the catchment.

This work uses PCSWMM version 7.4.3095 and SWMM version: 5.1.015.

2.1.2 Subcatchment Delineation

Project consultants at Geosyntec provided estimated subcatchments based on the digital elevation model (DEM) provided by the Flood Control District of Maricopa County (Flood Control District) and storm sewer network provided by the City of Phoenix. To protect the exact locations of this infrastructure, only the subcatchment and flow direction information were provided to Reclamation. The TSC used the Geosyntec initial subcatchments as well as Google Earth imagery and targeted field visit observations (See Attachment A) to estimate the locations of storm sewer inlets in the catchment. *Therefore, the stormsewer infrastructure is an estimate of reality and should be verified and corrected as needed if the model is used in future projects*.

From the initial subcatchments, the TSC trimmed areas to limit inflows from outside of the catchments when it could be justified by the features present or by review onsite (see Attachment A). This was done around Lincoln St. on the north end of Catchment 89. Boundaries were moved to align with rooflines, property lines and land uses to facilitate LID scenario implementation. These adjustments were only done when it appeared to be justified from aerial imagery. Flow directions from the 2 ft DEM aggregated to 10 ft were also evaluated to ensure changes were appropriate. Figure 2 depicts the final subcatchments used for this modeling analysis and the land use types in each subcatchment.

2.1.3 Subcatchment properties

Each subcatchment's properties are area weighted using the tools in PCSWMM and the GIS layers developed in the catchment ranking GIS analysis. The Flood Control District provided land cover shapefiles. Depression storage and Manning's n values that correspond to the land cover classes in those shapefiles were identified from PCSWMM lookup tables, resulting in Table 1.

Subcatchment	Residential	Industrial	Commerical	Public	LID Land Use
S1	0%	0%	100%	0%	C
S10	100%	0%	0%	0%	R
S11	100%	0%	0%	0%	R, C
S12	32%	0%	68%	0%	C
S13	98%	0%	2%	0%	R
S14	2%	0%	98%	0%	C
S15	0%	0%	0%	100%	P
S16	47%	0%	28%	25%	R, C, P
S17	49%	0%	32%	19%	R, C, P
S18	81%	0%	19%	0%	R, C
S19	100%	0%	0%	0%	R
S2	0%	0%	100%	0%	C
S20	0%	0%	0%	0%	street
S21	0%	2%	1%	0%	street
S22	0%	0%	0%	0%	street
S23	0%	0%	0%	0%	street
S24	0%	0%	0%	0%	street
S25	0%	0%	0%	0%	street
S26	0%	0%	0%	0%	street
S27	0%	0%	0%	0%	street
S28	0%	0%	13%	0%	street
S29	5%	82%	13%	0%	I
S3_a	0%	0%	0%	100%	P
S3_b	0%	0%	0%	100%	P
S3_c	0%	2%	0%	98%	P
S30	0%	0%	100%	0%	C
S31	0%	23%	0%	0%	street
S32	0%	0%	0%	0%	street
S33	0%	45%	0%	0%	street
S34	1%	0%	0%	0%	street
S35	0%	0%	100%	0%	C
S36	0%	100%	0%	0%	I
S37	0%	100%	0%	0%	I
S38	0%	100%	0%	0%	I
S39	0%	100%	0%	0%	I
S4	0%	0%	100%	0%	C
S40	0%	70%	30%	0%	C
S41	0%	1%	99%	0%	C
S42	0%	73%	27%	0%	C, I
S43	8%	0%	5%	1%	street
S44	0%	0%	100%	0%	C
S45	79%	5%	16%	0%	R
S46	94%	0%	6%	0%	R
S47	0%	88%	12%	0%	I
S48	0%	100%	0%	0%	I
S49	0%	15%	85%	0%	I
S5	76%	0%	0%	24%	R, P
S50	0%	100%	0%	0%	I
S51	0%	0%	0%	100%	P
S52	0%	39%	7%	54%	I, P
S53	0%	0%	6%	0%	street
S54	0%	100%	0%	0%	I
S6	0%	100%	0%	0%	I
S7	89%	11%	0%	0%	R
S8	2%	0%	98%	0%	C
S9	2%	0%	98%	0%	C

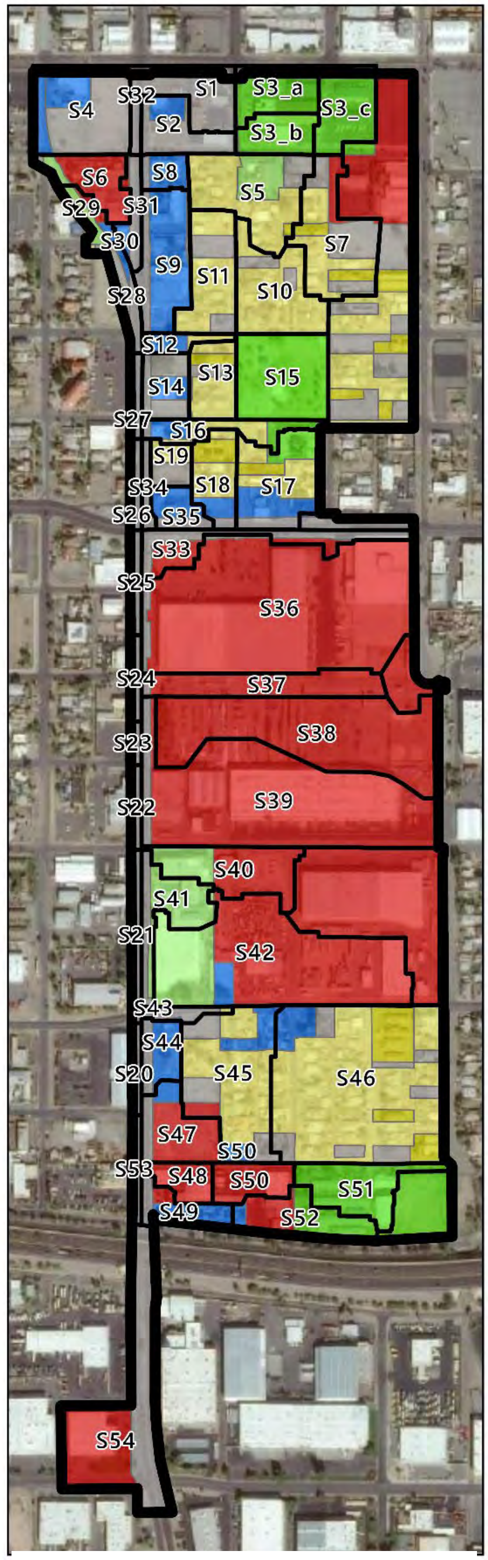

Figure 2 - Land use in Catchment 89, where yellow is residential (R), red is industrial (I), blue is commercial (C), and green is public/institutional (P).

Table 1 - Land cover properties used in the PCSWMM land cover lookup table.

Type Class	*Impervious Area (%)*	*Impervious Mannings N*	*Pervious Mannings N*	*Impervious Depression Storage (in)*	*Pervious Depression Storage (in)*
Desert Rangeland Bare Ground	0	0.015	0.05	0.05	0.1
Urban High Vegetation	0	0.015	0.4	0.05	0.2
Urban Low Vegetation	0	0.015	0.24	0.05	0.2
Unpaved road	0	0.015	0.02	0.05	0.15
Urban Bare Ground	0	0.015	0.05	0.05	0.1
Shade Structures	100	0.01	0.05	0.05	0.1
Asphalt	100	0.015	0.05	0.05	0.1
Concrete	100	0.016	0.05	0.05	0.1
Buildings	100	0.01	0.05	0.01	0.1

Soils in the catchment are mapped from the Natural Resources Conservation Service (NRCS) SSURGO database (NRCS 2021) as Gilman Loam (Mukey 53343), Glenbar Loam (Mukey 53348), and Glenbar Clay Loam (Mukey 53350). Soil parameters are from PCSWMM lookup tables by soil texture for suction and porosity (to derive deficit) and from the SSURGO dataset directly for hydraulic conductivity resulting in the properties provided in Table 2.

Table 2 - Soil properties used in the PCSWMM soil lookup table.

Soil ID (Mukey)	*Conductivity (in/hr)*	*Suction Head (in)*	*Initial Deficit*
53343	1.275	3.5	0.463
53348	0.385	3.5	0.463
53350	0.385	8.27	0.464

The *slope from DEM* tool in PCSWMM is used to define the catchment slope attributes. Flow lengths were developed in ArcGIS using the watershed delineation tools and the 10 ft DEM. Each subcatchment drains to the lowest junction within its limits that is identified as a storm drain, using the PCSWMM *set outlet* tool. If no infrastructure was within the limits of the subcatchment, it was set to drain directly to the downstream junction, assuming runoff hits the street and reaches the junction within the timestep. For this reason, this study focuses on runoff from the subcatchments, rather than inflow at the junctions.

Junction locations are derived from review of the subcatchments provided by Geosyntech and Google Earth Imagery. Rim elevations, or the elevation at the top of the manhole cover or stormwater inlet, are snapped to the 2ft DEM provided by the Flood Control District. Conduits connecting junctions are hypothetical in location, size and material. Pipes are sized by default PCSWMM tools to provide the smallest allowable pipe without surcharging under baseline conditions and therefore represent a hypothetical stormsewer network that may not represent actual flooding events from exceeding the stormsewer capacity.

2.1.4 Meteorology

The Flood Control District provided a precipitation timeseries from the Jackson St. at 7th Ave. gauge[1] with a 5-minute timestep. Precipitation data were provided from 1/29/1991 to 6/17/2020 supporting continuous simulation from 2/1/1991 through 1/31/2020, or a 29 year simulation. The largest daily total precipitation occurred on July 24, 1992 with 2.76 inches of rain that day. Other notable daily totals, as seen in Figure 3, occurred on July 14, 2002, September 8, 2014, and October 13, 2018, with 2.23, 2.64, 2.20 inches/day, respectively.

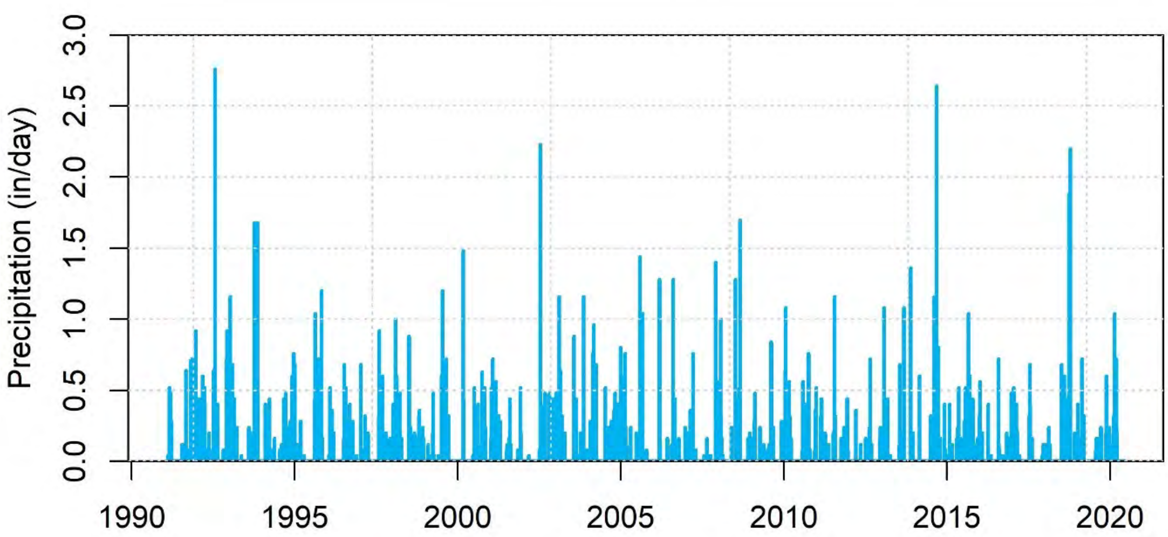

Figure 3 - Timeseries of daily precipitation totals at the Jackson St. at 7th Ave gauge.

The highest hourly rainfall intensity occurred on July 14, 2002, resulting in 1.87 inches of rain in one hour, while the most intense 5-minute rainfall occurred on August 28, 2008, with 0.39 inches of rain in 5 minutes.

Reference evapotranspiration inputs were taken from the monthly climate normals for the years 1988-2001 from the Phoenix Encanto AZMET station[2].

2.1.5 Summary of Modeling Setup

In addition to the parameters and inputs described above, the model used the following simulations settings:

- Simulation Length: 29 years (2/1/1991 through 1/31/2020),
- Infiltration Model: Green-Ampt,
- Routing Method: Dynamic Wave,
- Runoff Timestep: 5 minute for dry weather and 1 minute for wet weather,
- Routing Timestep: 5 seconds.

Baseline modeling resulted in very small continuity errors, with a 0% runoff error and a -0.2% routing error, suggesting the model was stable and the water budget was balanced.

[1] https://alert.fcd.maricopa.gov/alert/Rain/Master/4710.pdf
[2] https://cals.arizona.edu/azmet/data/15enor.pdf

2.2 LID Model Development

2.2.1 LID features

The project team identified a set of features that are desirable for each land use type, largely guided by the Greater Phoenix Metro Green Infrastructure & LID Handbook[3]. LID features available in PCSWMM and used in this study include (with descriptions modified from Rossman and Huber, 2016):

- *Bioretention Cell*: A vegetated surface depression with an engineered soil mixture over a gravel storage bed that stores, infiltrates, and evapotranspires captured rainfall and runoff. Here, bioretention cells were used as planters in parking lots, but only in certain land use types, due to their higher expense.
- *Rain Garden*: A type of bioretention feature without the gravel storage layer. In this study, rain gardens were also used as chicanes and linear basins in the street rights-of-way (ROWs). Chicanes are not currently permitted in Phoenix ROWs but were included here to show the possible benefit.
- *Infiltration Trench*: A gravel-filled ditch that captures, stores, and infiltrates runoff. Here, infiltration trenches were used in place of rain gardens, but only in certain land use types, due to their higher expense.
- *Rain Barrels / Cisterns*: Storage tanks that capture roof runoff during storm events. Here, rooftop collection was assumed to be used to water nearby vegetation between storms. Cisterns were set to drain at a constant rate equal to the average annual reference evaporation (0.2 in/day) by setting the drain coefficient to the corresponding velocity of 0.0085 in/hr (Table 3) and the drainage exponent to zero. As described in Rossman and Huber (2016), this approach normalizes the outflow flow to the area of the water tank, not the irrigated area. It is likely these features will drain faster if the water is applied to a larger area, providing more storage and thus this is a conservative estimate.The drainage water is applied to pervious area. This setup is designed to mimic an irrigation scenario, where the cistern water is applied to lawn or rain garden areas and therefore the cistern volume can be used to support trees or other vegetation between storms. The drain was set to have a 36 hour delay from the end of rain event until when the cistern water begins to deplete.
- *Rooftop Disconnection*: A method to reroute rooftop water from downspouts to permeable areas rather than to impervious areas or directly to the storm sewer to facilitate infiltration.
- *Permeable Pavement*: A type of paver or asphalt, concrete mix, that allows runoff to infiltrate the pavement layer to a gravel storage bed that infiltrates water. Here, permeable pavement was assumed to be used only in areas with light foot or automobile traffic. Permeable pavement in this study also includes an underdrain to avoid ponding in parking lots and walkways. This drain is offset from the bottom to allow more water to infiltrate prior to draining the storage layer.

Each LID feature requires a set of parameters to describe their storage and infiltration properties. Table 3 summarizes the parameters used for the LID features in this study.

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[3] https://sustainability-innovation.asu.edu/sustainable-cities/wp-content/uploads/sites/22/2019/04/LID2018-Book-04-11-19.pdf

Table 3 - LID feature parameters.

Feature	*Height (in)* [1]	*Surface Roughness*[2] *(n)*	*Surface Slope (%)*	*Soil Thickness (in)*	*Soil Porosity*[2] *(-)*	*Field Capacity*[2] *(-)*	*Wilting Point*[2] *(-)*	*Conductivity*[2] *(in/hr)*	*Conductivity Slope*[2]	*Suction head*[2] *(in)*	*Storage Thickness*[2] *(in)*	*Void Ratio*[2] *(voids/solids)*	*Seepage Rate*[4] *(in/hr)*	*Drain Coefficient (in/hr)*
Bio-retention planter	18	0	0	36[3]	0.52	0.15	0.08	4.7	10	1.9	18	0.3	0.6	-
Chicanes	18	0	0	36	0.52	0.15	0.08	4.7	10	1.9	-	-	0.6	-
Rain Barrel (residential)	72	-	-	-	-	-	-	-	-	-	-	-	-	0.0085
Cistern (non-residential)	100	-	-	-	-	-	-	-	-	-	-	-	-	0.0085
Disconnected Downspouts	0.075[2]	-	-	-	-	-	-	-	-	-	-	-	-	-
Infiltration Trench	18	0.02	1	-	-	-	-	-	-	-	90	0.3	0.6	-
Linear Basins	18	0.2	1	36	0.52	0.15	0.08	4.7	10	1.9	-	-	0.6	-
Pervious Pavement	0.05[2]	0.015	1	8[5]	0.2[5]	-	-	890[5]	-	-	12[3]	0.3	0.6	7.5 (4" pipe)[2]
Rain Garden	18	0	0	36	0.52	0.15	0.08	4.7	10	1.9	-	-	-	-

1. Determined by study team
2. PCSWMM lookup tables (mean value when a range is provided) or recommendations from the online manual (https://support.chiwater.com/77680/lid-control-editor)
3. LID handbook (ASU)
4. Based on properties used in the PCSWMM model development, including typical roughness values and area-weighted averages of underlying soil hydraulic conductivity
5. For Pervious Pavement, the thickness is the pavement thickness, the porosity is the pavement void ratio, and the conductivity is the pavement permeability.

2.2.2 LID Application

The project team formed a subteam to guide implementation of LID features in the catchment. The team selected one representative subcatchment for each land use and developed a possible layout of the desired LID features in the subcatchment to identify what was realistic for the area. From this exercise, the subteam determined how many features each unit of a land use could realistically support. This activity guided the development of a set of land-use specific assumptions that facilitated scaling the application up to other areas of the catchment with that land use.

In recognition that not all property owners would install LID features, three participation scenarios were considered: 25%, 50%, and 100% participation for each subcatchment. When the participation rate resulted in a partial property, it was rounded to the nearest whole number. Some subcatchments in non-residential areas only have 1-2 buildings. Here, participation rates were balanced to ensure at least 25, 50, or 100% capture over the entire basin, but uneven roof sizes result in greater capture for some scenarios. This is particularly impactful in the industrial areas, where building roofs span a large range of sizes (see Table 4).

Consistent with PCSWMM modeling practice, all LID footprints were removed from the catchment area to calculate the percent area captured and the subcatchment percent imperviousness was updated accordingly. To implement the features, all features start the continuous simulation empty. Catchments S20-S28, S31-S34, S43, and S53 are Central Avenue or other streets that the subteam determined did not have adequate space for LID features (Figure 2).

The application approach used in this study relied on the lumped nature of feature application in PCSWMM subcatchments to efficiently scale the number of LID features and the area they capture for different participation rates. As such, it does not identify specific feature locations or the specific area that drains to each feature. Some other important real-world considerations were also excluded from this analysis. Clogging was not evaluated in this assessment but is an important consideration for LID implementation and maintenance. Similarly, the model does not account for the vegetated volume of the feature, per common PCSWMM modeling practice, although, it would reduce the surface storage volume. The no-LID, or baseline, simulation also does not account for existing stormwater infrastructure or regulations because detailed design information was not available for the detention basin located in subcatchment S38 and no other existing features were identified in the catchment.

Like any modeling study, this effort has simplifications and limitations; however, it is illustrative of the potential benefits of LID usage in an urban catchment. The following sections and Table 5 - Table 8 provide details on the application of LID features for each of the four main land use types in the catchment: residential, commercial, industrial, and public (which includes parks, religious institutions, and schools). This application of LIDs resulted in the number of features summarized by land use in Table 4. Refer to Figure 2 for the distribution of land uses across the catchment.

Table 4 – Number or area (in square feet) of features aggregated by land use for each participation scenario.

Feature	Residential			Public			Commercial			Industrial		
	25%	50%	100%	25%	50%	100%	25%	50%	100%	25%	50%	100%
Disconnected Downspouts (sq. ft)	25500	50250	96750	6826	14204	27929	27147	49936	99779	110222	166725	314279
Cisterns / Rain Barrels (#)	34	67	129	3	6	11	6	14	27	4	8	15
Rain Gardens (#)	68	134	258	23	40	77	37	62	110	105	200	387
Linear Basins (#)	34	67	129	12	22	42	-	-	-	-	-	-
Chicanes (#)	27	27	27	12	12	12	-	-	-	-	-	-
Infiltration Trenches (#)	-	-	-	-	-	-	4	12	28	28	58	121
Bioretention (#)	-	-	-	18	33	63	14	17	26	33	57	107
Pervious Pavement Area (sq. ft)	-	-	-	4672	9344	18688	11683	23366	46733	21094	42187	84374

2.2.2.1 Residential Areas

Table 5 - Characteristics of LID application in residential areas.

Feature	*Size*	*Application Rate*	*Capture Area*	*Treatment Train Participation / Notes*
Cistern	6' High, 11.14 Sq. Ft Area (500 gallons)	1 per participating house	50% of a participating house's roof; residential roof size is assumed to be 1500 sq ft, based on the average of obstructions in the residential areas.	Drain flow sent to pervious area
Rain Garden - Driveway	8'x4'x18" deep	1 per participating house	80% of participating house's driveway; assume 400 square feet. + 20% of yard is captured	
Rain Garden - Yard	8'x4'x18" deep	1 per participating house	30% of yard is captured; assume lot is 6500 square feet and yard is 3900	
Disconnected Downspouts	NA	Per participating house	50% of a participating house's roof to pervious area	Drains to permeable area with no limit on roof drain flow rate.
ROW Basin	2'x10'x18" Deep	1 per participating house	Captures the sidewalk and 12' of frontage assumed to be 33% impervious	
Chicane	8'x20'x18" Deep	1 per 4 total houses	Captures half of the road with 80% efficiency, assuming 600 square feet per participating lot.	

Assumptions:

- No impervious area was removed to put in rain gardens because the most feasible location for rain gardens in residential lots were in the existing lawns/bare ground.
- Only the chicanes remove impervious area in residential areas. Chicane sizing is consistent with Greater Phoenix Metro Green Infrastructure & Lid Handbook (2019) and to remove 1 parallel parking space. 8x20'. Note that the same number of chicanes are applied for all participation rates, assuming they would be installed in the ROW not on each lot, but the drainage area is scaled assuming lot-by-lot curb cuts and flow redirection.
- Rain gardens and ROW basins are sized to capture at least the 0.5" storm but initial sizing does not account for the volume occupied by vegetation.

2.2.2.2 Commercial Areas

Table 6 - Characteristics of LID application in commercial areas.

Feature	*Size*	*Application Rate*	*Area Treated*	*Treatment Train Participation / Notes*
Cistern	100"High, 48.125 Sq. Ft Area (3000 gallons)	1 for every participating building	25% of surface area on roof captured	Drain flow sent to pervious area
Pervious Pavement	20% of non-roof impervious area		20% of Parking Lots	Modified from non-roof impervious to facilitate application in the model Based on original parking lot area and included in new pervious area
Rain Garden	5'x7'x18" deep		70% of Parking Lots	
Infiltration Trench	3.5'x10'x18" deep	Every 4th rain garden		
Bio-Retention	5'x7'x18" deep		10% of Parking Lots	10% conversion of impervious area
Disconnected Downspouts	NA		50% of roof	Drains to permeable area with no limited on roof drain systems flow rate.

Assumptions:

- Cisterns are large enough to capture more than the 0.5" storm even from the largest building
- Because subcatchments typically only have 1-2 commercial buildings, participation rates were balanced to ensure at least 25, 50, or 100% capture over the entire basin, but uneven roof sizes result in greater capture for some scenarios.
- Features that capture runoff from parking lots (Pervious Pavement and Rain Gardens) are scaled by percent of participations since parking lot ownership is unknown and the number of rain gardens applied is based on capturing the 0.5" storm off the collection area.

2.2.3 Industrial Areas

Table 7 - Characteristics of LID application in industrial areas.

Feature	*Size*	*Application Rate*	*Area Treated*	*Treatment Train Participation / Notes*
Cistern	100"High, 48.125 Sq. Ft Area (3000 gallons)	1 for every participating building	10% of surface area on roof captured	Drain flow sent to pervious area
Pervious Pavement	10% of Parking Lots		10% of Parking Lots	Modified from non-roof impervious to facilitate application in the model Based on original parking lot area and included in new pervious area
Rain Garden	5'x7'x18" deep		75% of Parking Lots	
Infiltration Trench	3.5'x10'x18" deep	Every 4th rain garden		
Bio-Retention	5'x7'x18" deep		25% of Parking Lots	10% conversion of impervious area
Disconnected Downspouts	NA		50% of roof	Drains to permeable area with no limit on roof drain systems flow rate.

Assumptions:

- Because subcatchments typically only have 1-2 industrial buildings, participation rates were balanced to ensure at least 25, 50, or 100% capture over the entire basin, but uneven roof sizes result in greater capture for some scenarios

2.2.4 Public Areas

Table 8 - Characteristics of LID application in public areas.

Feature	*Size*	*Application Rate*	*Area Treated*	*Treatment Train Participation / Notes*
Cistern	100"High, 48.125 Sq. Ft Area (3000 gallons)	1 for every participating building	50% of surface area on roof captured	Drain flow sent to pervious area
Pervious Pavement	10% of Parking Lots		10% of Parking Lots	Modified from non-roof impervious to facilitate application in the model Based on original parking lot area and included in new pervious area
Rain Garden	5'x7'x18" deep		50% of Parking Lots	
Infiltration Trench	3.5'x10'x18" deep	Every 4th rain garden		
Bio-Retention	5'x7'x18" deep		50% of Parking Lots	10% conversion of impervious area
Disconnected DS	NA		25% of roof	Drains to permeable area with no limited on roof drain systems flow rate.
ROW Basin	2'x10'x18" Deep	1 per 50' of frontage	Captures the sidewalk and 12' of frontage assumed to be 33% impervious	
Chicane	8'x20'x18" Deep	1 per 4 ROW basins	Captures half of the road with 80% efficiency, assuming 600 square feet per participating 50' of frontage.	

Assumptions:

- Because subcatchments typically have few public buildings, participation rates were balanced to ensure at least 25, 50, or 100% capture over the entire basin, but uneven roof sizes result in greater capture for some scenarios.
- If public areas are in subcatchments that include ROW and Chicane treatments, these LIDs are also applied to the Public Area ROWs as described in Table 8.

3 Results

3.1 Runoff Volume Reduction

Continuous modeling uses a multi-year precipitation timeseries and has the benefit of assessing different storm events combined with different initial conditions, such as how much of the storage volume in the LID features has not yet drained from previous storms. Looking at the results over the long-term simulation therefore provides a realistic picture of average LID performance over a range of conditions. These long-term results are provided in Section 3.1.1. In contrast, event based analysis provides information on how the features perform for different types of storms, as discussed in Section 3.1.2 for typical large monsoon events, winter events.

3.1.1 Long-term reductions

The total outflow volume from the catchment stormsewer outlet decreased as the participation rate increased (Figure 4a), with the 12.2 million gallons (Mgal) per year in the baseline scenario, 10.3 Mgal/year in the 25% participation scenario, 8.7 Mgal/year in the 50% participation scenario, and 5.5 Mgal/year in the 100% participation scenario. Considering the volumes reduction, rather than the total volumes, removes any bias that is attributed to model setup and inputs that are consistent between scenarios. The outflow volume reduction ranged from a 16% reduction in the 25% participation scenario to 55% reduction in the 100% participation scenario (Figure 4b). This result is promising, in that it indicates a modest (25%) participation rate and reasonable LID application may result in a detectable decrease in outflow volume from a mixed-use urban catchment.

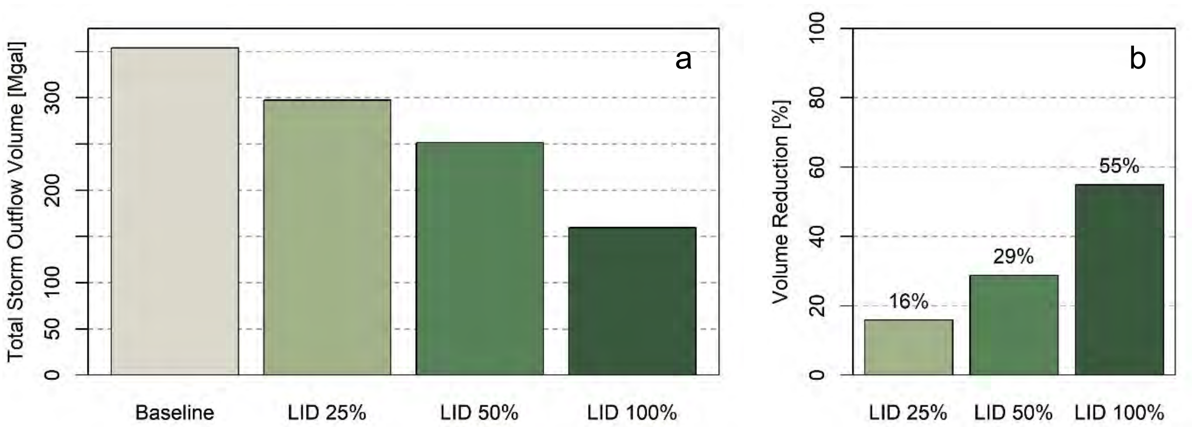


Figure 4 - Reduction in total catchment outflow volume over the 29-year simulations (a) and percent reduction (b).

Comparing the reduction in runoff by land use, as seen in Figure 5, illustrates that thoughtful placement of features can lead to effective runoff reduction across the land uses included in this study. Public areas exhibited a slightly larger reduction in runoff, likely due to the greater potential for LID application developed in the public areas for Catchment 89.

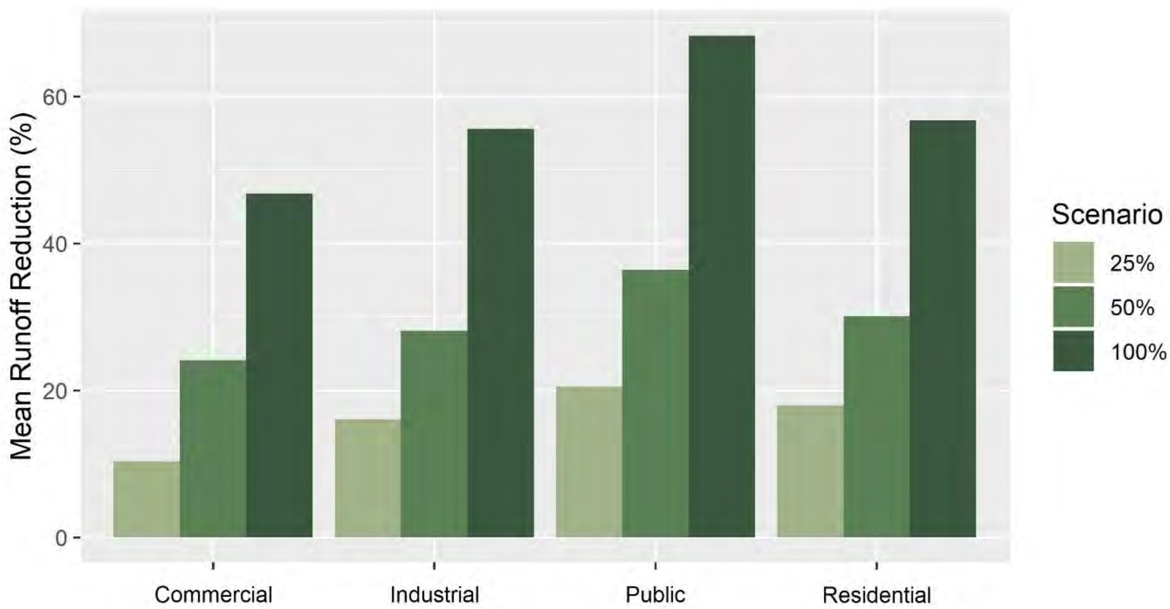


Figure 5 - Mean reduction in runoff from each land use.

3.1.2 Event-based reductions

3.1.2.1 Monsoon Events

The North American Monsoon (monsoon) season is characterized by thunderstorms and intense rain events. In this study, events occurring between June 15th and September 30th were assumed to occur in the monsoon season, consistent with the current National Weather Service definition[4]. Precipitation amounts represent the largest rolling total over the duration window (2, 6, or 24 hour), but may not reflect the full duration of any storm event. The maximum daily storm was 2.84” (Table 9) and occurred on July 24, 1992, as described in Section 2.1.4. This section also describes the most intense events in the simulation period and they all also occurred during the monsoon period, consistent with the nature of monsoon events.

Runoff from large monsoon events was captured consistently across storm durations (Figure 6). Some of the 2-hour storms showed lower reduction percentages, as seen by the lower tails on the 2-hour violin plots, may be related to the intensity of these shorter events. Large events are defined here as storms falling in the 85th-95th percentile of all monsoon events

[4] https://www.weather.gov/fgz/Monsoon

recorded during the simulation period, representing 25, 19, and 18 storms for the 2-, 6-, and 24-hour durations respectively.

Table 9 - Percentiles of precipitation, in inches ("), for three storm durations in the monsoon season

Storm Duration	*50th*	*85th*	*90th*	*95th*	*Maximum*
2 hour	0.12"	0.48"	0.64"	0.95"	2.23"
6 hour	0.16"	0.60"	0.72"	1.04"	2.64"
24 hour	0.16"	0.72"	0.95"	1.22"	2.84"

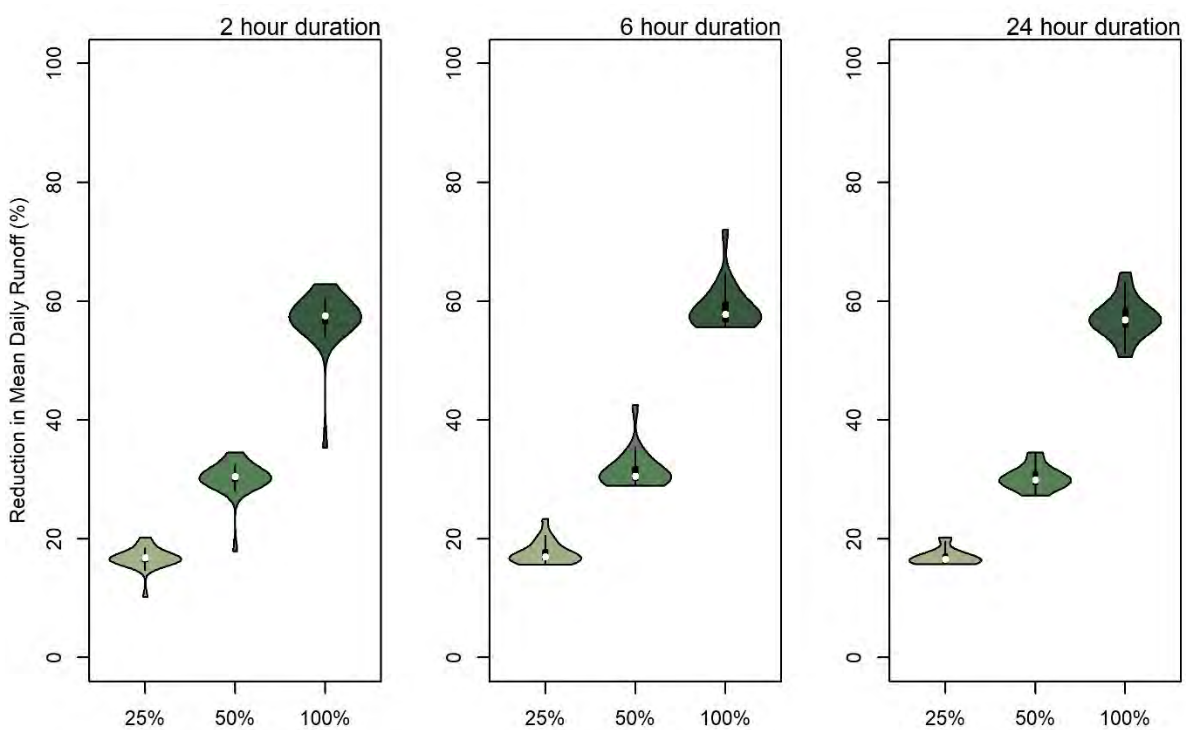


Figure 6 - Percent reduction in runoff over the 85th-95th percentile of monsoon events for the 2, 6, and 24-hour duration.

3.1.2.2 Winter Storm Events

After the monsoon season, the region experiences precipitation events that are more sustained and widespread but less intense. In this study, events occurring between October 1st and March 30th were assumed to occur in the winter season. While there is no standard definition for the season that these precipitation events occur, for the purpose of this study, this period considered the end of the monsoon season through the end of the month with the last event that produced one inch of precipitation in a day at the Jackson St. at 7th Ave gauge. Storms during this period were generally less intense than the monsoons, particularly for 2-hour durations (Table 10).

Evaluation of catchment runoff from the 85th-95th percentile of winter storms (representing 53, 30, and 32 storms for the 2-, 6-, and 24-hour durations respectively) indicated very similar percentages of runoff reduction as monsoon events. Most median reductions, represented by open circles, were within 2% for each storm durations and participation rate (Figure 7). For this analysis, this similarity suggests that the participation rate and associated LID storage capacity is more influential than storm type on the overall catchment average daily runoff reduction.

Table 10 - Percentiles of precipitation, in inches ("), for three storm durations during the winter season.

Storm Duration	*50th*	*85th*	*90th*	*95th*	*Maximum*
2 hour	0.08”	0.24”	0.28”	0.40”	1.44”
6 hour	0.16”	0.44”	0.48”	0.60”	2.20”
24 hour	0.24”	0.65”	0.80”	1.03”	2.20”

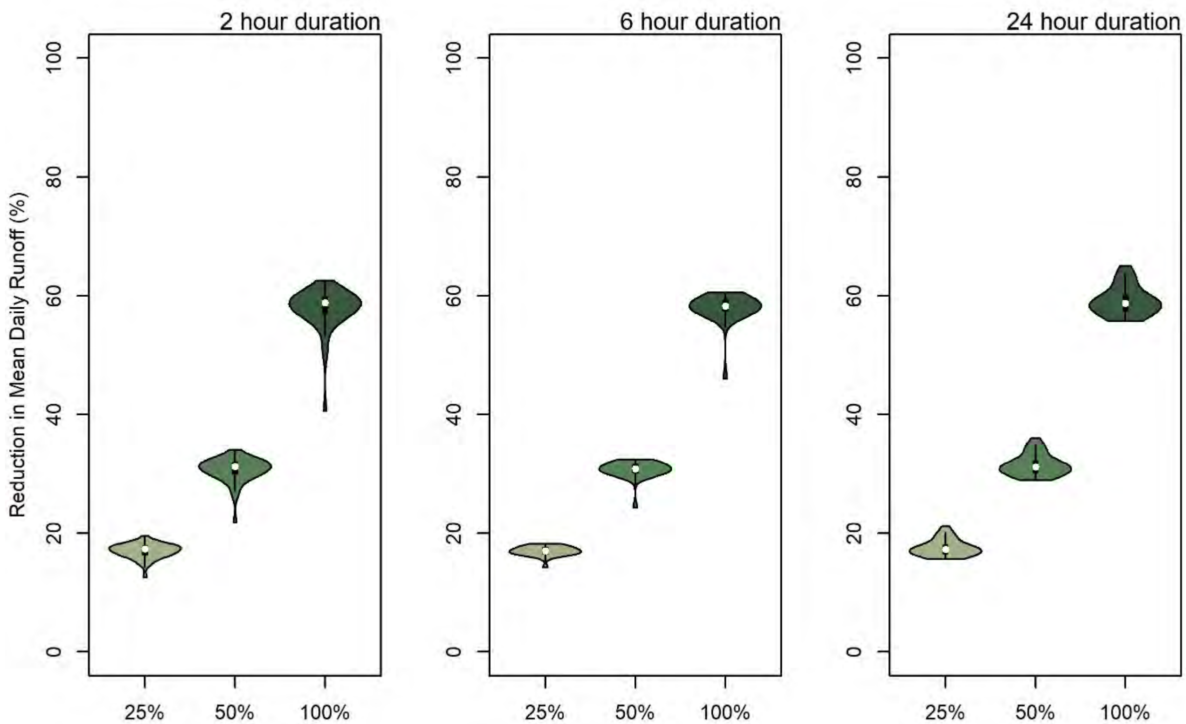


Figure 7 - Percent reduction in runoff over the 85th-95th percentile of winter events for the 2, 6, and 24 hour duration.

3.2 Change in Peak Flows

The impact of LID features on peak outflows from the catchment stormsewer is small. For the highest outflows over each simulation period, the 100% participation scenario only reduced the peak outflow by 6% relative to the baseline scenario (Figure 8a). This result is consistent with the LID design assumptions that sized features for 0.5” of precipitation, resulting in reduced ability to capture larger storms and reduced peak flows. If the primary goal of LID implementation is to reduce peak outflows for the largest event, than larger features should be considered.

Despite modest reductions at the stormsewer outlet, some subcatchments exhibited larger reductions in peak flows, which may suggest the potential for targeted LID placement to mitigate flooding at particular hotspots, although more study with actual storm sewer infrastructure sizes are needed to confirm this finding. As seen in the right panel of Figure 8, most runoff reductions were around 20% or less, relative to the baseline study. The median reduction in peak runoff ranged from 4.6-20.7% across participation scenarios. A few catchments consistently exhibited large decreases in peak runoff, with the top three largest reductions in the full participation scenario occurring in subcatchments S5, S17, and S15. These basins all have a high percent (>60%) of impervious area treated.

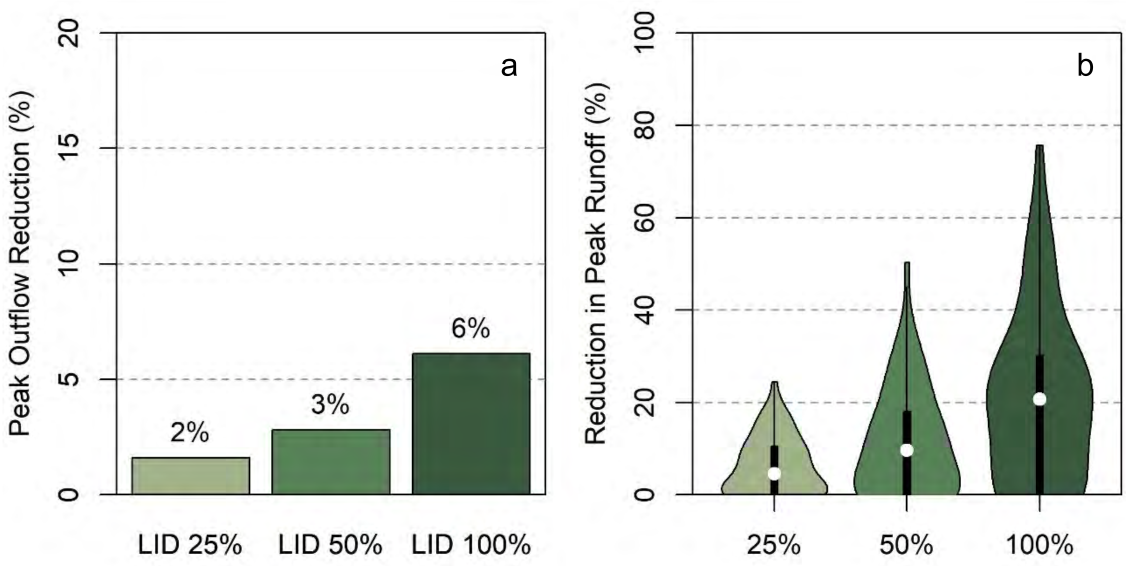
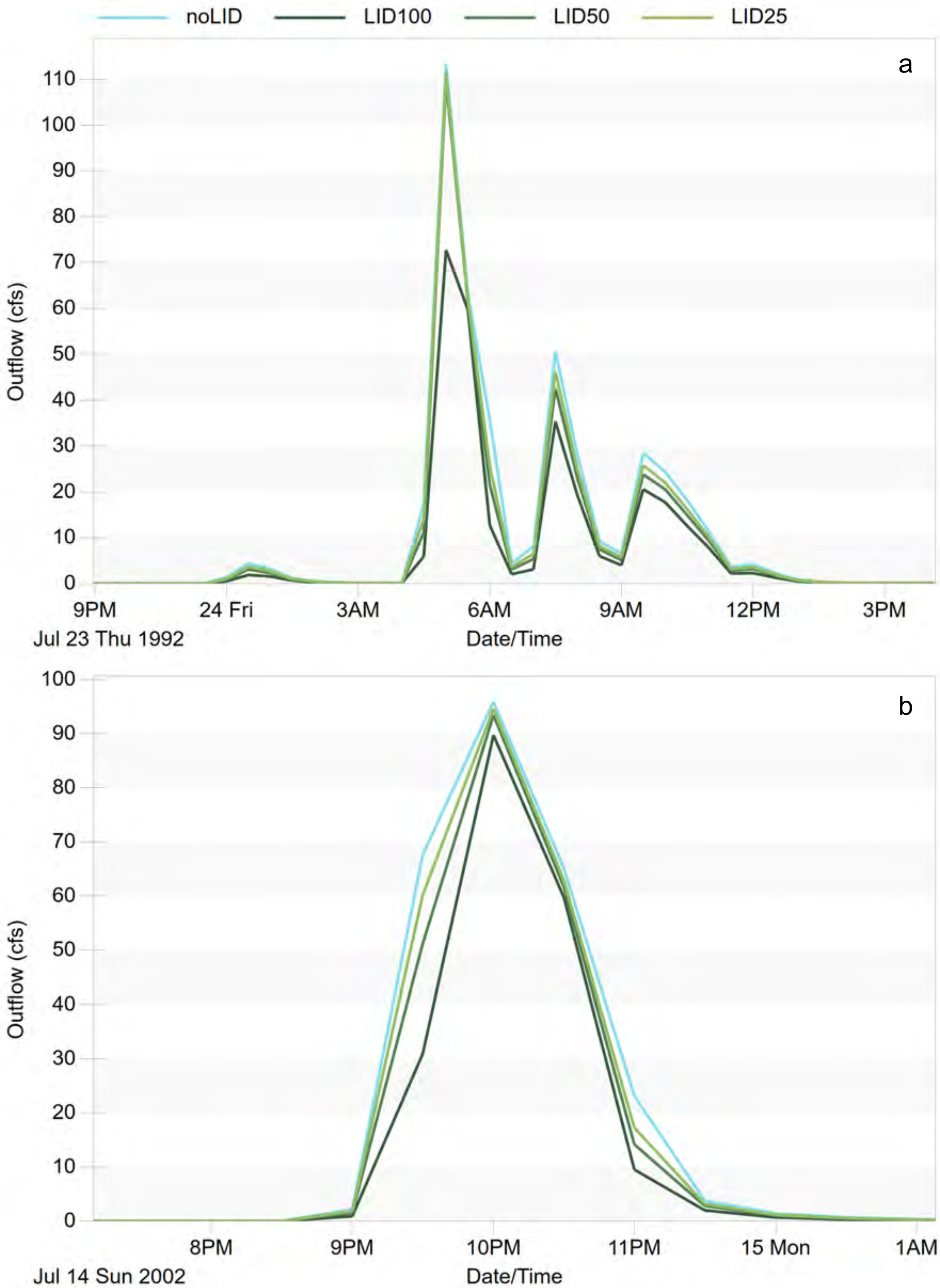


Figure 8 - Relative reduction in catchment stormsewer peak outflows (a) and the distribution of peak runoff across all subcatchment (b).

Smaller storms and those with a longer time since the last runoff event are likely to be more effective at reducing peak flows, particularly in the 100% participation scenario, which has more capacity to store runoff. Table 11 summarizes the percent reduction by participation rate for four select storms (a-d) and the number of days since the last runoff event. Generally, longer periods between events provide more time for the LID features to infiltrate or evapotranspire water, thus renewing the storage capacity and the ability of features to reduce stormwater runoff peaks. For example, comparing the storms on July 14, 2002 (Figure 9b) and on August 12, 2014 (Figure 9d), both storms peaked at over 90 cubic feet per second (cfs); however, the August storm had a much higher reduction in peak outflow. Not only did the July storm have more total precipitation, it also occurred just 2 days after another rain event (Table 11), emphasizing the need to consider storm patterns when evaluating the effectiveness of LID designs. The exact time required to restore storage capacity is a function of infiltration rates and feature design, both of which are hypothetical in this study.

Table 11 - Percent reduction in peak outflow for select storms and three LID participation levels.

	Participation Rate			*Days since last*	
Storm Event	**25%**	**50%**	**100%**	*runoff event*	*Description*
a. July 24, 1992	1.5	3.1	35.9	13	Largest daily precipitation total, with 2.84 in/day
b. July 14, 2002	1.4	2.6	6.4	2	Largest hourly total with 1.87 in/hour, and 2.23 total in over 2 hours.
c. Aug. 28, 2008	3.4	2.9	13.8	3	Highest intensity storm with 0.39 in/ 5 min
d. Aug. 12, 2014	15.0	39.4	95.8	17	Short but intense storm with 1.16 inches that fell over 1.5 hours.


noLID
LID100
LID50
LID25
a
Outflow (cfs)
110
100
90
80
70
60
50
40
30
20
10
0
9PM
24 Fri
3AM
6AM
9AM
12PM
3PM
Jul 23 Thu 1992
Date/Time
b
Outflow (cfs)
100
90
80
70
60
50
40
30
20
10
0
8PM
9PM
10PM
11PM
15 Mon
1AM
Jul 14 Sun 2002
Date/Time

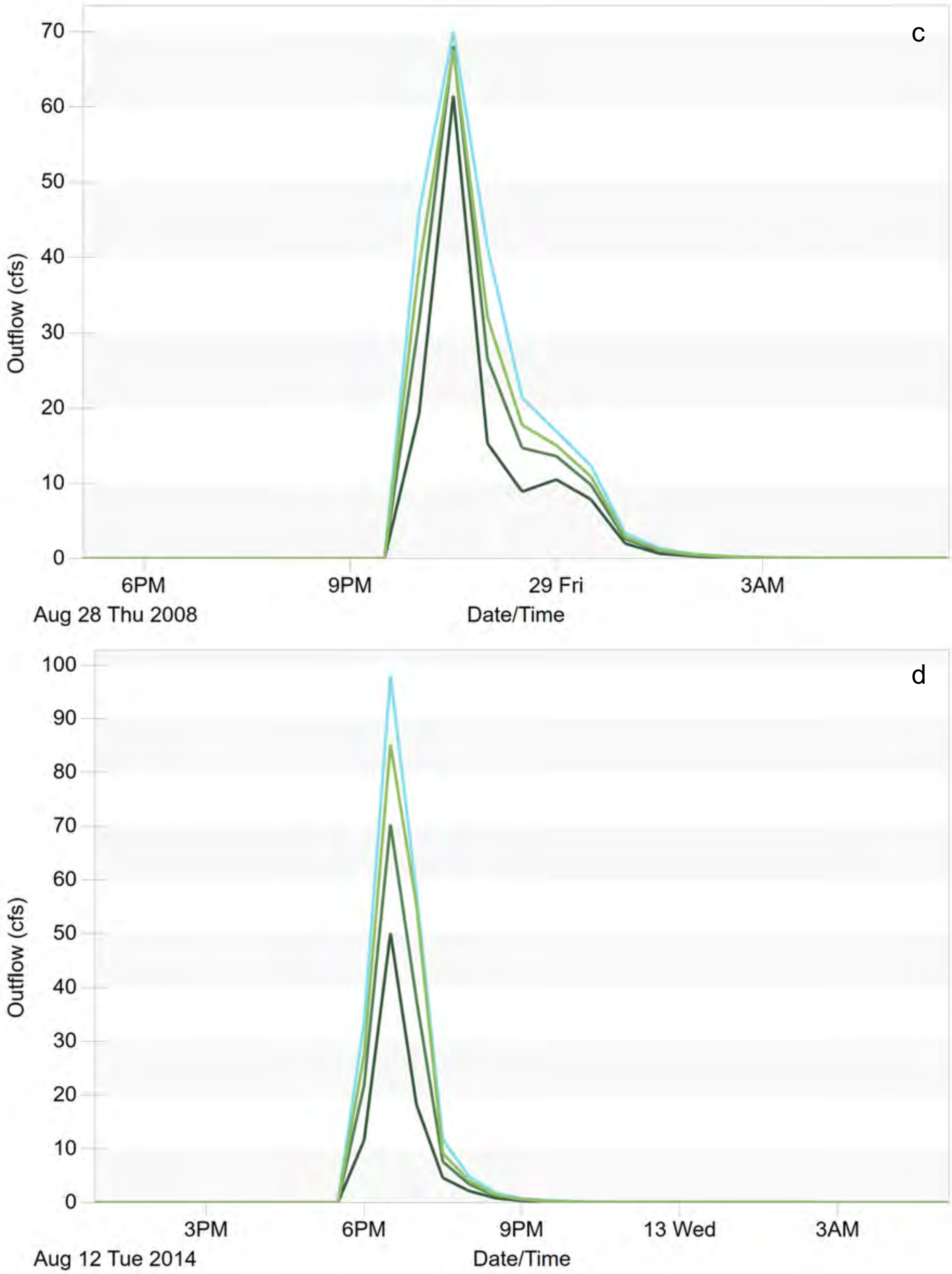


Figure 9 - System outflow for select storms (a-d) and all participation scenarios.

3.3 Change in Infiltration

Rain gardens infiltrated the most water over the simulation, consistent with the broader application of this feature type across all land uses and resulting in a higher total number of rain gardens, relative to similar features such as bioretention cell (Table 4). For example, as implemented here for the 100% participation scenario, there are 832 rain gardens employed, compared to 196 bio-retention features. While the additional rock storage layer in bioretention features provides the ability to store more water, the long-term simulation suggests rain gardens can be as effective if they are deployed at a higher rate due to the lower cost to install each feature. As these features were sized to capture the first flush (or first 0.5”) of precipitation in surface storage and that represents over 85% of the 2-hour storm events at the Jackson St at 7th Ave. gauge, the added subsurface storage in the bioretention areas is only utilized in the larger, but less likely events, and thus contributes less to average annual infiltration values.

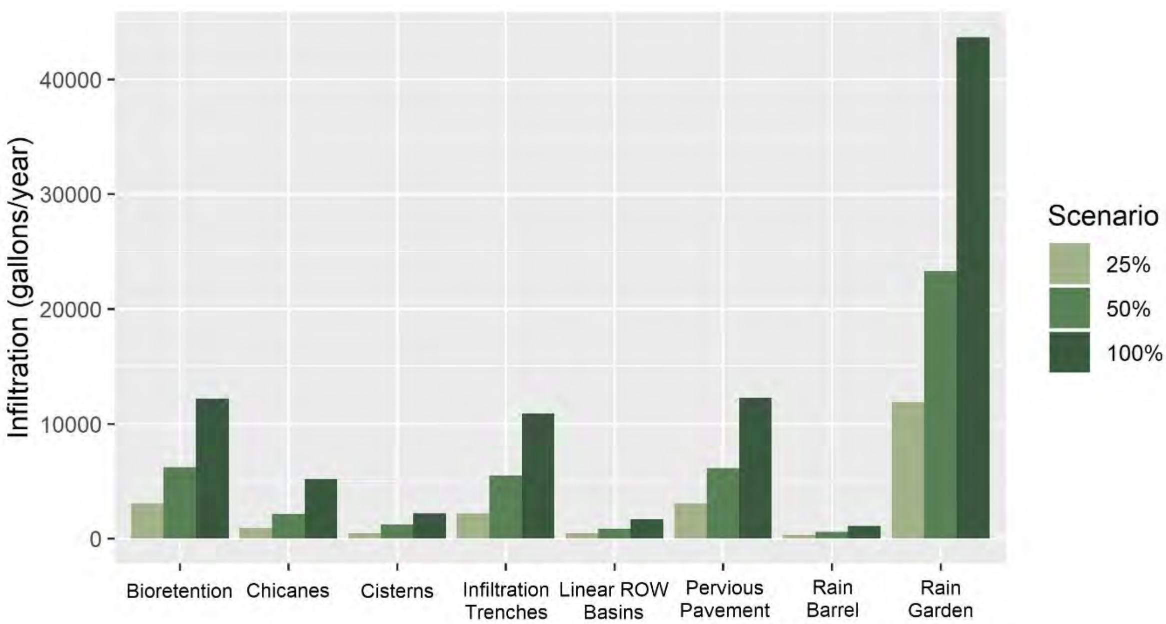


Figure 10 - Average annual infiltration by LID feature type

4 Summary and Future Opportunities

Here, we reported the results of PCSWMM surface water modeling for three LID participation scenarios over Catchment 89 in Phoenix, Arizona. In summary:

- LID features were more effective at reducing total volumes and less effective at peak flow reductions for the largest storms, but peak flow reduction varied based on storm size and time since last runoff event;
- Careful design and feature selection can result in considerable volume reductions even under the 25% participation scenario;
- Rain gardens can be an effective feature to encourage infiltration, particularly if they are more widely adopted and can be implemented over a larger area.

Future work in this catchment could do a full design of specific LID features, complete with infiltration testing, to determine exact locations and feasibility and develop a plan for implementing them in the catchment. The model used in this study could be further developed and calibrated with correct infrastructure and infiltration rates to support LID implementation in Catchment 89. Public outreach programs may help to increase the participation rates, particularly for residential areas in the catchment that are not required to offset development impacts similar to industrial areas.

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Rossman, L.A. & Huber W.C. (2016) Storm Water Management Model Reference Manual Volume III – Water Quality. National Risk Management Laboratory Office of Research and Development, U.S. Environmental Protection Agency. Available here: https://www.openswmm.org/ReferenceDocumentation

U.S. Bureau of Reclamation and Coauthors (2021) Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development.

Appendix 7. Urban Heat Assessment

Low Impact Development Floodplain Student Project:

Modeling the Impacts of Planning Low Impact Development on Urban Heat

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Arizona State University

May 2, 2021

Culminating Applied Project; Master of Urban and Environmental Planning

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Committee: Sara Meerow (Chair), David Hondula, Peter Crank, Anna Bettis (Client)

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Executive Summary

This study contributes to a larger study, *Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development,* conducted as a partnership between the Bureau of Reclamation, The Nature Conservancy, City of Phoenix, Flood Control District of Maricopa County, Maricopa Department of Air Quality, and Arizona State University. The larger study focuses on how green stormwater infrastructure (GSI)/low impact development (LID)[1] can benefit the City of Phoenix by infiltrating stormwater, improving water quality, and mitigating air pollution and urban heat. The main goal of the larger study is "to assess the quantifiable benefits of theoretical LID installations including increased stormwater infiltration and flood hazard mitigation, reduced urban heat island impacts and improved air and stormwater quality" (Tosline & Bettis, 2021).

A stormwater catchment located south of Downtown Phoenix, Arizona (Figure 1) was selected by the project team as the study site through a systematic selection process using a Geographic Information System (GIS) spatial analysis. The project team developed different scenarios for theoretical LID implementation within the stormwater catchment, and then modeled these scenarios using the PCSWMM surface water model to better understand the existing and future co-benefits of LID. The scenarios included 25% LID implementation, 50% implementation and 100% LID implementation for the catchment area.

Utilizing these scenarios, this project provides insight into the potential cooling benefits of LID implementation in the stormwater catchment and Phoenix more broadly. As one of the hottest cities in the US, Phoenix is actively seeking cooling strategies (Hondula et al., 2019). Spatial and statistical modeling are used to examine the relationship between LID features from the overall study and the built environment. Examples of LID features from the larger study include bioretention swales, permeable pavement, stormwater harvesting basins, and tree pits.[1] While the analysis is limited by data availability and technical requirements, it uses the best available data to examine the relationship between temperatures and LID features in Phoenix. Under a full participation scenario, meaning the catchment site incorporates 100% LID treatment using the various LID features from the larger study, this assessment estimates that some parts of the stormwater catchment could see as much as a 4ºF decrease in land surface temperature.

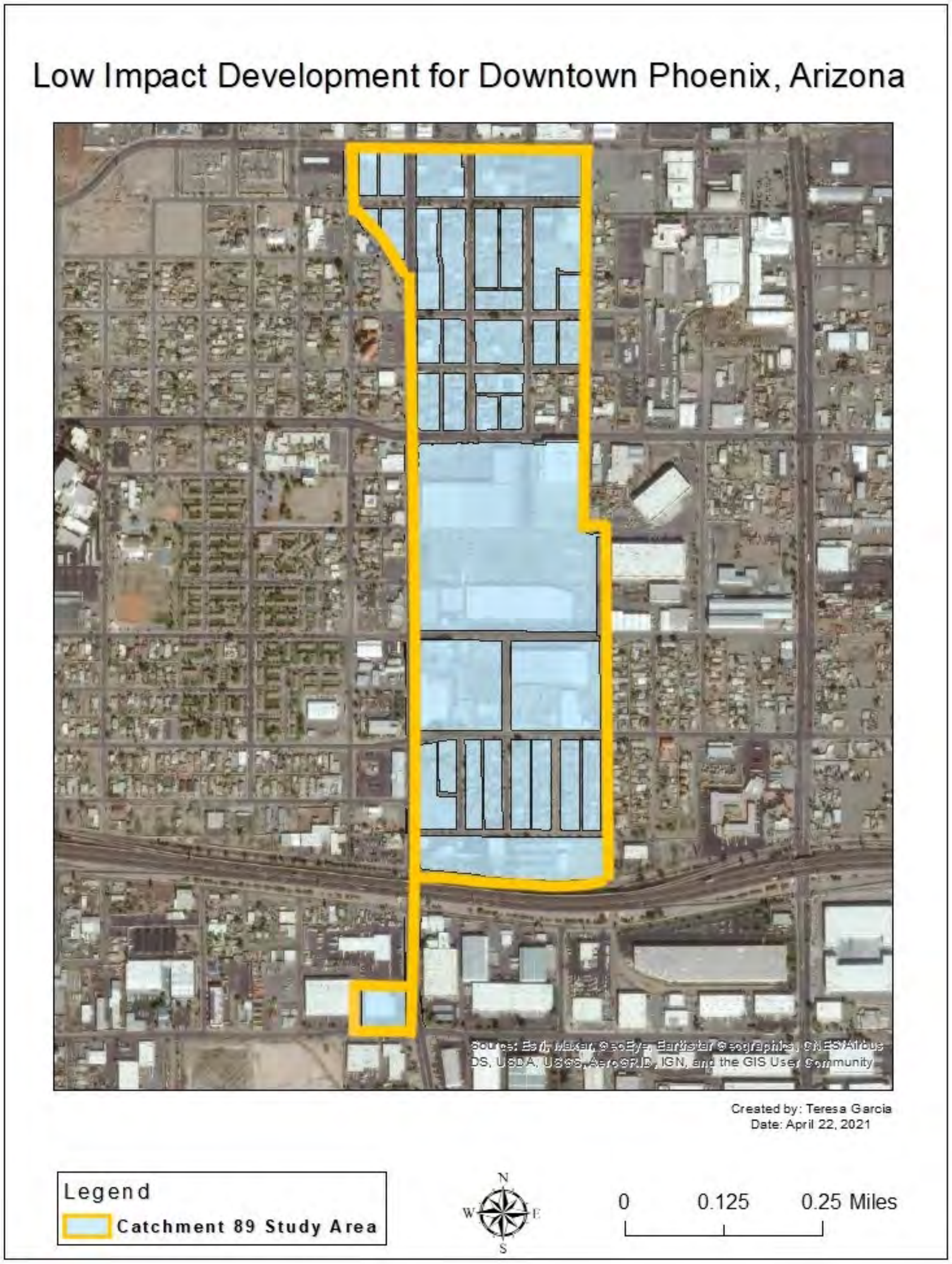


Figure 1: Aerial Map of Stormwater Catchment 89, located south of Downtown Phoenix. The area is from Lincoln Street to Van Buren Street and Central Avenue to 3rd Street. The polygons (blue) indicate the subcatchment areas within catchment 89.

1. Introduction

Green stormwater infrastructure (GSI), also known as low impact development (LID), has been examined as potential strategy to help infiltrate stormwater runoff and mitigate flood risk in a cost-effective manner. Planners and developers have studied ways to incorporate it into new and existing city plans. It has become more popular over time in many cities due to its ability to manage stormwater runoff, while providing other benefits such as localized cooling (Meerow 2020). The world is rapidly urbanizing, resulting in increased temperatures around urban cores. Implementation of LID can play a role in creating more comfortable urban environments by reducing the effect of the urban heat island, which according to EPA.gov, are "urbanized areas that experience higher temperatures than outlying areas" (para. 1). As Meerow et al. (2020, p. 2) state, "Urbanization can negatively affect residents' health and wellbeing. Green stormwater infrastructure (GSI) is increasingly advocated as a win-win strategy for addressing multiple urban problems. Literature quantifying GSI benefits is growing, but it is unclear how it performs in arid and semi-arid cities."

LID limits stormwater runoff, increases impervious surfaces, and when used to support vegetation, provide shading, which can mitigate the urban heat island effect (EPA, 2012). One potential benefit of LID is its ability to cool surrounding areas. This is an important planning priority because cities are warming due to a combination of the urban heat island effect and rising temperatures due to global-scale climate change. Implementing LID in underdeveloped areas can also protect open spaces and bioretention areas, which can limit the number of impervious surfaces that are added in a community (EPA, 2012).

This study analyzes the impact of LID on temperatures in a catchment area south of Downtown Phoenix using statistical analysis of LST and NDVI, in combination with land use/land cover data. Section 2 of this report, examines literature that focuses on LID and its cooling benefits. This helps support the hypothesis that LID implementation will help to mitigate heat in Phoenix. Section 3 describes the methodology used to assess LID scenarios, including detailing the different definitions and data sources. The 4th section lays out the results from statistical analyses of the data. The 5th section discusses the findings of the data, including recommendations for LID implementation and limitations to the study. The final section is the conclusion, where a general overview of the study's purpose and findings is presented.

2. Literature Review

The literature review assesses different methodologies for examining how green infrastructure can increase cooling benefits in areas most impacted by the urban heat island effect. This literature review includes examples from previous studies conducted in cities with a similar climate, including those pertaining to the development of scenarios, data models, tree cover, and vegetation.

2.1 Literature Methodology

The academic database, Scopus, identified studies to support this literature review. The following keywords were used in the Boolean search:

("green infrastructure" OR "low impact development" OR "water sensitive design" OR "water sensitive urban design" OR "sustainable urban drainage" OR "nature-based solution" OR "best management practice*" OR "stormwater control measure*" OR "sponge city" OR "stormwater quality improvement device" OR "integrated urban water management" OR "source control" OR "tree*") AND "urban heat" AND "model")*

The results contained 290 related articles, with the most recent articles published in 2021. Although many articles provided tremendous insight on the relationship between the urban heat island effect and LID, many were eliminated from the search due to dissimilar climate and dissimilar variables in the studies. After narrowing down the results, 8 studies were selected to support findings for this study. In addition, 3 more articles were added to the results via external sources. The table below (Table 1) consists of the 11 articles used to perform this literature review, including specific measured variables:

Table 1: Revised Scopus results showing relevant literature used for this study.

Authors	Article Title	Reference	Methodology	Measured Variables
Ronchi S., Salata S., Arcidiacono A.	Which urban design parameters provide climate-proof cities? An application of the Urban Cooling InVEST Model in the city of Milan comparing historical planning morphologies	(Ronchi et al., 2020)	High spatial resolution modeling	Tree density, tree cover, territorial surface, permeability ratio
Antoszewski P., Świerk D., Krzyżaniak M.	Statistical review of quality parameters of blue-green infrastructure elements important in mitigating the effect of the urban heat island in the temperate climate (C) zone	(Antoszewski et al., 2020)	Literature Review	Parameters: mitigation strategies, impact on green infrastructure, city
Zhang Y., Qin H., Zhang J., Hu Y.	An in-situ measurement method of evapotranspiration from typical LID facilities based on	(Zhang et al., 2020)	3T Model-regression models & equations, pilot LID facilities (green roof	Air temperatures, humidity, surface temperature, heat flux

[1] Articles provided by Dr. Sara Meerow of Arizona State University

	the three-temperature model		module, permeable concrete, permeable brick pavement	
Augusto B., Roebeling P., Rafael S., Ferreira J., Ascenso A., Bodilis C.	Short and medium-to long-term impacts of nature-based solutions on urban heat	(Augusto et al., 2020)	Case study: nature-based solutions	Energy, heat fluxes and temperature (based on meteorlogical data)
Aboelata A., Sodoudi S.	Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo	(Aboelata & Sodoudi, 2019)	ENVI-Met Model	Best vegetation scenario, temperature, humidity, solar radiation
Reinwald F., Ring Z., Kraus F., Kainz A., Tötzer T., Damyanovic D.	Green Resilient City - A framework to integrate the Green and Open Space Factor and climate simulations into everyday planning to support a green and climate-sensitive landscape and urban development	(Reinwald et al., 2019)	Climate Simulation Models	Green and open space factors,
Rötzer T., Rahman M.A., Moser-Reischl A., Pauleit S., Pretzsch H.	Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions	(Rötzer et al., 2019)	Process-based model	Climate, plant development, water balance, surface runoff

Stone B., Vargo J., Liu P., Hu Y., Russell A.	Climate change adaptation through urban heat management in Atlanta, Georgia	(Stone et al., 2013)	Land cover scenarios, meteorological modeling	Land cover, air temperature
Middel A., Chhetri N.	* Cool Urban Spaces Project: Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix	(Middel & Chhetri, 2014)	ENVI-Met Model, land cover scenarios	Temperature, humidity, wind, solar radiation
Broadbent A., Coutts A., Nice K., Demuzere M., Krayenhoff E., Tapper N., Wouters H.	* The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET v1.0): an efficient and user-friendly model of city cooling	(Broadbent et al., 2019)	Land cover simulations (including land cover scenarios), The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET)	Surface & air temperature, heat mitigation scenarios
Ibsen, P. C., Borowy, D., Dell, T., Greydanus, H., Gupta, N., Hondula, D. M., … Jenerette, G. D.	*Greater aridity increases the magnitude of urban nighttime vegetation-derived air cooling.	(Ibsen et al., 2021)	Linear Regression Models, microclimate analysis, GIS	Vapor pressure deficit (VPD), nighttime air temperatures, vegeation-derived nighttime cooling, normalized difference vegetation index (NDVI), transpiration

2.2 Discussion and Findings

Of the 11 articles, 4 utilized land cover and climate scenarios in the methodology. The studies looked at the relationship between land cover types, surface temperature, air temperature, and humidity. Stone et al. (2013) performed a study in Atlanta, Georgia, using 3 different land cover scenarios: one in the urban center, one in the suburban ring and one in exurban zone. Authors utilized meteorological data and the Weather Research and Forecasting mesoscale model (WRF) and discovered correlations between land cover and temperature. According to the study, “A transition to a fully forested center creates a negative heat island (i.e., center-city temperatures fall below that of the far periphery), while a transition to a fully impervious center increases heat island intensity by more than 60%” (Stone et al., 2013, p. 7785). Another study that used scenarios was Broadbent et. al (2019), where The Air-temperature Response to Green/blue-infrastructure Evaluation Tool (TARGET) model was used to analyze surface temperatures. Although the tool had limitations, especially with converted surface temperature variables, the study ultimately proved that this tool could help city planners determine the cooling benefits that come with LID development.

Another common methodology used was the ENVI-met model. According to envi-met.com (2020), the ENVI-met model is described as “software that allows you to create sustainable living conditions in a constantly changing environment”. A study conducted by Middel and Chhetri (2014) used three different landscaping scenarios for Phoenix in the model: “mesic (sprinkler-irrigated grass and lush vegetation), xeric (decomposing granite mulch, low-water use vegetation) and oasis (a mix between mesic and xeric)” (p. 4). Each scenario included a percentage of tree canopy cover (Figure 2); one of the variables that are utilized in previous studies.

Figure 2: Image from *Cool Urban Spaces Project: Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix*, indicating different landscaping scenarios.

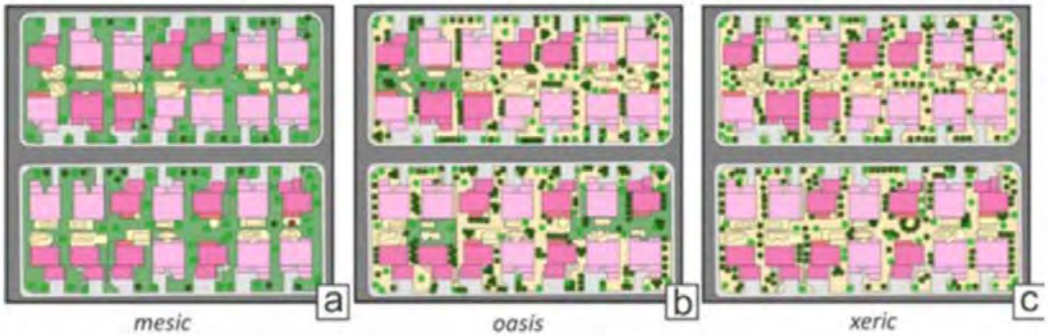


Figure 3: Typical Phoenix residential neighborhood (Middel et al., 2014a).

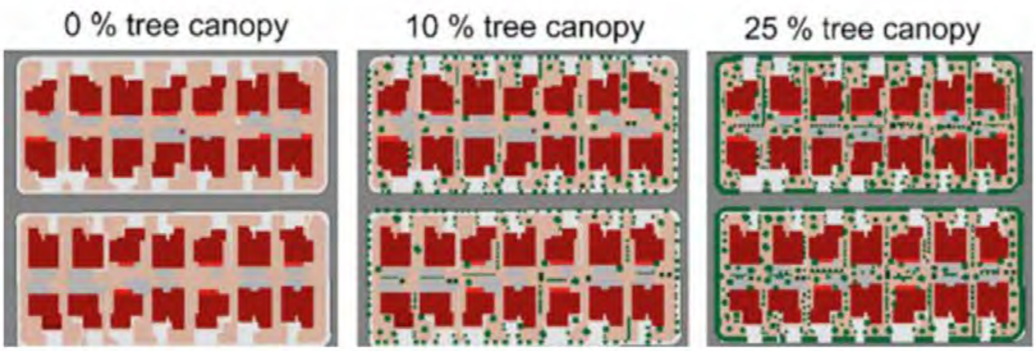


Figure 4: Tree canopy cover.

The study areas were based on model configuration parameters from a recent study on the impact of urban form and landscaping types on the midafternoon microclimate (Middel & Chhetri, 2014, p. 4). Based on the ENVI-model calculations, land cover plays a crucial role in decreasing the urban heat island effect and this model provides a deeper perception into how various land cover types can influence the temperature in the urban core. Temperatures in the canopied areas were cooler than the 0% tree canopy scenario, however the 25% canopy scenario proved to be cooler due to increased tree cover.

Another study that employed the ENVI-Met model was a study performed by Aboelata and Sodoudi (2019), who emphasized the use of urban greenery to create vegetation scenarios. The study states “urban greenery has been proposed as one of the most effective urban strategies to improve thermal performance, especially in high density built up urban areas” (p. 1). To support this claim, Aboelata and Sodoudi performed an ENVI-Met model analysis, which modeled tree heights and canopy sizes in each scenario. The variables measured included air temperature, wind speed, humidity, and physiological equivalent temperature (PET) (Aboelata & Sodoudi, 2019, p. 2). This study found a relationship between tree cover and the hour of the day. The scenario that included 50% of land cover cooled the area more than the 30% and 70% + grass scenarios. The hottest temperatures occurred between the hours of 7PM and 8PM due to the rise in latent heat after the sun reaches the highest peak. The most effective cooling occurred with the 50% land cover scenario. This scenario, compared to the other two, “is preferable to scenario 30% trees +70% grass as grass needs more water than trees” (p. 4). Latent heat plays a role in determining which scenario will work best based on how much energy is needed to evaporate water on the surface (NC State University, n.d). The more water present: the more energy will be needed for it to evaporate, further increasing the urban temperatures as the day goes on. Therefore, incorporating grass into the built environment may go against the cooling benefits of green infrastructure; urban greenery must be planned strategically.

The final methodology that was notable was linear regression models used in Ibsen et al.’s study (2021). This methodology incorporated GIS and microclimate analysis to study the urban nighttime vegetation cooling in eight cities across the country, including Phoenix. Ibsen et al. concluded that if policymakers were to green a neighborhood in Phoenix so it resembled a tree-lined street with a park, it “would result in approximately 1.3º C of cooling” (Ibsen et al., 2021, p. 9). Ibsen et al.’s research indicates “as daytime VPD increases, urban vegetation transpiration increases, which in addition to increasing immediate latent heat flux, reduces leaf surface temperature and eventual reradiation of stored heat energy” (p. 7). Nighttime air temperature, transpiration, heat flux and NDVI are important variables to incorporate to achieve the overall goal of this study. The variables can determine which factors of urban heat island will show more promising results.

2.3 Proposed Methodology Based on Literature

Based on the assessment of available literature and taking into consideration technical knowledge and time constraints, the proposed methodology that will serve the study *Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development* best is linear regression modeling. Incorporating software that allows for the analysis of spatial datasets, such as GIS, and GeoDa, would enhance the scenario-based study of this stormwater catchment area. This methodology can aid in determining which factors of green stormwater infrastructure would enhance cooling benefits by considering multiple variables including land use/landcover, NDVI, and temperature.

The first step of this methodology is to gather accurate meteorological data of the stormwater catchment site. Understanding existing conditions can help determine the short- and long-term impacts created by heat fluxes and urban temperatures (Augusto et al., 2020). Measuring variables, such as land surface temperature, will generate results in the linear regression model that will closely resemble the relationships seen in the previous studies. Local climate data can help researchers recognize trends in the selected stormwater catchment; Remotely sensed images, analyzed using GIS software, can give a better insight into which areas are hottest and how placement of green stormwater infrastructure will make a difference in the area.

The second step is to gather information about the existing characteristics of the site. Some examples include the number of impervious surfaces and vegetation cover. This will help determine how much change in vegetation and imperviousness will occur under different theoretical LID scenarios. The final step is to use linear regression modeling to predict what the change in temperature would be under those different LID scenarios compared to the baseline scenario.

This proposed methodology has limitations to be aware of. First, it uses simple statistical models of very complex systems to estimate temperature impacts. These models aggregate the relationship between, for example, NDVI and LST across the entire study area, obscuring heterogeneity. Other limitations include not accounting for the growth of the city (Augusto et al., 2020), excluding consistent rainfall, and the inability to measure long-term effects (Broadbent et al., 2019). Although these limitations exist, the linear regression models can provide valuable data to support the relationship between LID and local temperatures. This methodology will assist in gathering evidence on the cooling potential of green stormwater infrastructure (GSI)/ low impact development (LID) in arid and semi-arid climates. This information can assist planners, policymakers, and developers in weighing the costs and benefits of LID in Phoenix.

3. Data Sources

Data for the project study area (which includes all the different catchments delineated by the City of Phoenix, and more specifically catchment 89) were compiled using various data sources including PCSWMM model results provided by the study team as well as land use, land cover, land surface temperature, and NDVI.

3.1 Definitions

The first variable, *land use*, is defined as the way in which land is utilized by people (EPA, 2018). The next variable, *land cover*, describes the physical land type, for example where it is covered by vegetation, a road, or is just bare ground (US Department of Commerce, 2009). Various land cover types are present in the study area and were taken into consideration when calculating results. These were further examined for the hypothetical LID scenarios. The third variable is *land surface temperature (LST)*, which is how hot the surface of the earth is to the touch in a specific location (Carlowicz, 2021). Although Ibsen et. al utilizes air temperature as one of the main variables, LST is used for this study because it is available across the entire study area from remotely sensed images, whereas air temperature has to be modeled or sensed. LST differs from air temperature due to the amount of solar radiation that flows through the surface. As the day goes on, the amount of incoming shortwave radiation overpowers the amount of longwave radiation that is emitted back into the atmosphere. The longwave radiation cannot balance itself in the net radiation equation, which makes it difficult for the surface to cool at night, contributing to the urban heat island effect. Therefore, this causes the ground temperature to be warmer as the day goes on (*Geography NM*, 2011). The final variable in the study is the *normalized difference vegetation index (NDVI)*, a measurement that examines the reflection of sunlight off vegetation using visible and infrared imagery. The range of values can be anywhere between -1 and 1, where a value of -1 indicates less reflective vegetation and 1 indicates denser, more reflective vegetation (Carlowicz, 2021). Data sources and resolutions for each variable are provided below (Table 2) to examine other definitions and findings to support the outcome of this study.

Table 2: Data Source Table for defined variables, including citations and resolutions to help enhance the definitions.

Description	Source	Date	Resolution	Link or citation
Land cover	NAIP	2016	1 meter	Zhang, Y. and B. Turner II. 2020. Land-cover mapping of the central Arizona region based on 2015 National Agriculture Imagery Program (NAIP) imagery ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/e671ed549a55fda3338b177a2ad54487. Accessed 2021-05-01.
Land cover	Metro Phoenix Area Drainage Master Plan	2021		Bolen, S. (2021, April 7). Metro Phoenix Area Drainage Master Study/Plan Update. Phoenix; Flood Control District of Maricopa County
Land surface temperature	Landsat	Median value for summer months 2018	30 meters	Stuhlmacher, M. and L. Watkins. 2019. Remotely-sensed Land Surface Temperature (LST) for the central Arizona region during summer months over five-year periods: 1985-2015 ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/c526299a0e4e4f7d6e921aac18

				528e24 (Accessed 2021-04-14).
NDVI	Landsat	Median value for summer months 2018	30 meters	Stuhlmacher, M. and L. Watkins. 2019. Remotely-sensed Land Surface Temperature (LST) for the central Arizona region during summer months over five-year periods: 1985-2015 ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/c526299a0e4e4f7d6e921aac18528e24 (Accessed 2021-04-14).
Land use	Maricopa Area Governments Land Use	2016		

3.2 Calculating Relationships Between the Four Variables

Different datasets were combined to calculate descriptive statistics on the variations of land surface temperatures and NDVI for different land uses and land covers across the larger study area (all delineated catchments) in Phoenix and specifically for catchment 89. ArcPro was used to perform zonal statistics on the datasets to calculate the minimum, maximum, mean, and standard deviation of LST and NDVI for each land cover type across the larger study area. Land uses were assigned to each parcel in the broader study area and then the "Spatial Join" tool in ArcGIS was used to calculate the mean NDVI and LST for each parcel. A spatial join adds attributes from one spatial layer (in this case a grid of NDVI and LST values) to another (parcels in the study area) based on their shared location.

For catchment 89 a “Spatial Join” was also used to calculate the average LST and NDVI value for all areas intersecting each land cover polygon, and then these results were summarized for each land cover type. These results for catchment 89 were used to create regression models and scatterplot graphs.

3.3 Estimating Cooling Benefits for Stormwater Catchment 89

Stormwater Catchment 89 is south of Downtown Phoenix, located north of Watkins Street (including the I-17), south of Van Buren Street, east of Central Ave and west of 3rd Street (Figure 1). To estimate LID cooling benefits, we assembled the baseline scenario information on 56 subcatchments (out of 154 total) within Stormwater Catchment 89 by using stormwater modeling data, which included detailed land cover found in the Metro Phoenix Area Drainage Master Plan (Bolen, 2021). ArcGIS was used to calculate the percent of each area in the subcatchment that was classified as vegetated (urban high and low vegetation) using the Tabulate Intersection toolbox. Impervious areas, such as buildings, asphalt, and concrete, were calculated using the Tabulate Intersection toolbox as well. From there, the Spatial Join tool was used to find the average LST and NDVI of each subcatchment; these results represent the mean of all the LST and NDVI values across each of the subcatchments.

Once the means and standard deviation values were calculated, the maximum and minimum values for Stormwater Catchment 89 were calculated for each land cover type and entered on an Excel spreadsheet. The maximum and minimum values were then calculated, alongside the average LST and average NDVI. Those values were entered on another Excel spreadsheet.

The spreadsheets were used for the GeoDa linear regression model. Four regression models were performed for Stormwater Catchment 89: percent impervious vs. NDVI, percent impervious vs. LST, percent vegetated vs. NDVI and percent vegetated vs. LST. Percent impervious and percent vegetated served as the independent variables while NDVI and LST were the dependent variables. The models created regression coefficients (B) that were used in a later calculation. Scatterplot graphs were created for each of the four regression models. More detailed findings will be discussed in the next section.

The study team developed three scenarios as part of the stormwater model, representing different levels of participation: 25%, 50%, and 100%, with 100% representing all possible parcels receiving LID treatments. As part of the PCSWMM modeling, the project team calculated the area of each of the 56 subcatchments within Stormwater Catchment 89 that would be converted from impervious to pervious for each hypothetical LID scenario. The calculations were then used to determine the percent change in imperviousness for each subcatchment. In some places, for example on residential lots, hypothetical LID treatments are commonly applied to areas that are already pervious (e.g. gravel yards), therefore the total area that would be treated is much larger than the percent change in imperviousness might suggest. However, because it was not possible to individually evaluate how adding LID would change land cover on these already pervious areas, only areas that change from impervious to pervious in the model are assessed. This means that the results are likely a fairly conservative estimate of cooling benefits. If pervious, but unvegetated areas were converted to vegetated rain gardens, the new vegetation would likely have additional cooling effects. We did assume that areas that were converted from impervious to impervious areas would be vegetated in the LID scenario (being converted into, e.g., rain gardens), we used these areas to calculate the percent change in vegetated land cover for each of the three participation scenarios.

To estimate the theoretical reduction in each subcatchment's average LST, the percent change in imperviousness and percent change in vegetation were multiplied by the regression coefficients (B) to represent the relationship between percent impervious and LST and percent vegetated and LST: the calculations were performed on an Excel spreadsheet.

4. Results: Findings from Regression Models and Calculations

4.1 Data Tables: Land Use, Land Cover, and Land Surface Temperature

The following tables are the results of the calculations for NAIP-derived land cover of the entire study area (Table 3), a detailed land cover dataset of Stormwater Catchment 89 from the Metro Phoenix Area Drainage Master Plan (Table 4), and land use types within the entire study area (Table 5).

Table 3: Land cover calculations of LST and NDVI for the entire study area.

Land Cover	LST (Degrees F)				NDVI			
	MIN	MAX	MEAN	STD	MIN	MAX	MEAN	STD
Building	92.21	169.19	118.05	6.38	-0.23	0.74	0.17	0.09
Road	89.99	170.85	118.84	5.81	-0.45	0.83	0.15	0.09
Soil	86.95	164.38	117.13	5.40	-0.63	0.85	0.17	0.09
Tree	88.67	148.14	113.13	6.21	-0.75	0.83	0.25	0.14
Grass	89.68	149.44	110.63	7.41	-0.75	0.85	0.33	0.18
Shrub	87.36	134.86	115.48	5.45	-0.50	0.84	0.20	0.09
Active Cropland	88.05	155.79	106.73	11.64	-0.04	0.86	0.42	0.25
Inactive Cropland	87.68	159.37	108.47	12.39	-0.39	0.86	0.34	0.23
Orchard	92.64	124.31	105.02	7.25	0.08	0.81	0.43	0.19
Lake	87.73	142.29	109.61	9.79	-1.00	0.82	0.10	0.23
Canal	93.54	147.59	115.95	5.56	-0.75	0.71	0.10	0.09
Swimming Pool	97.81	135.05	114.76	4.85	-0.28	0.70	0.21	0.09
Seasonal River	89.82	135.21	113.78	6.18	-0.64	0.74	0.23	0.10

Table 4: Land cover calculations of NDVI and LST variables for Stormwater Catchment 89.

Land Cover	LST Min (F)	LST Max (F)	LST Avg (F)	LST StdDev (F)	NDVI Min	NDVI Max	NDVI Avg	NDVI StdDev
Asphalt	111.77	127.54	119.39	3.47	0.03	0.31	0.11	0.05
Buildings	103.18	130.94	118.03	4.33	0.01	0.59	0.15	0.08
Concrete	107.08	138.95	119.22	4.19	0.01	0.46	0.13	0.06
Desert Rangeland Bare Ground	120.99	120.99	120.99	0.00	0.11	0.11	0.11	0.00
Rock Riprap	115.56	121.95	119.17	2.90	0.07	0.15	0.12	0.03
Shade Structures	104.97	151.24	118.52	4.16	-0.02	0.56	0.13	0.07
Unpaved road	102.57	126.83	116.67	4.54	0.04	0.58	0.18	0.09
Urban Bare Ground	102.57	146.65	117.74	5.20	-0.01	0.67	0.15	0.10
Urban High Vegetation	102.57	146.65	116.59	4.73	-0.01	0.67	0.18	0.10
Urban Low Vegetation	106.40	113.25	108.89	2.19	0.32	0.46	0.39	0.05

Table 5: Parcel land use calculations of NDVI and LST Variables for the entire study area.

Land Use	Min LST (F)	Max LST (F)	Average of LST (F)	StdDev of LST (F)	Min NDVI	Max NDVI	Average of NDVI	StdDev of NDVI
Agriculture	93.14	124.91	106.94	9.99	0.04	0.76	0.38	0.23
Commercial	101.22	134.81	120.58	4.04	0.02	0.61	0.13	0.07
Industrial	102.54	145.69	122.63	3.95	-0.02	0.55	0.09	0.05
Mixed Use	112.68	124.50	122.20	2.36	0.03	0.19	0.06	0.03
Multi Family	96.89	133.49	116.73	4.29	-0.02	0.64	0.17	0.08
Office	99.58	132.90	117.72	4.47	0.00	0.59	0.17	0.08
Open Space	96.08	127.83	111.95	5.94	0.06	0.66	0.26	0.12
Other Employment	95.14	131.81	117.84	4.65	0.01	0.68	0.17	0.09
Single Family	95.09	128.94	117.38	4.25	0.04	0.66	0.19	0.08
Transportation	99.85	129.02	118.68	5.38	0.04	0.62	0.16	0.10
Vacant	101.20	131.71	118.71	4.47	0.03	0.58	0.14	0.07

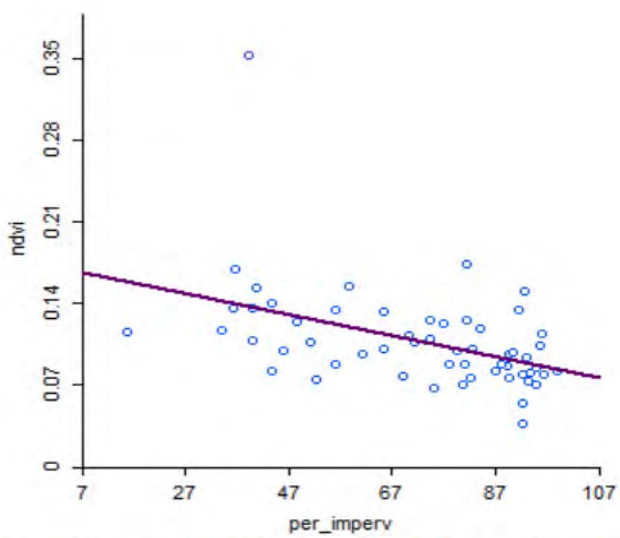
4.2 Examining the Relationship Between Vegetation and LST for the Subcatchments in Stormwater Catchment 89 Using Linear Regression Models

Linear regression models showcase the four variables and their relationships with vegetation and surface temperature using the 56 subcatchments within Stormwater Catchment 89 as the unit of analysis. The regression models show the relationship between percent impervious and NDVI (Figures 3 and 4; B=-0.00089), percent impervious versus LST (Figures 5 and 6; B=-0.06), percent vegetated versus NDVI (Figures 7 and 8; B=0.0051) and percent vegetated versus LST (Figures 9 and 10; B=-0.27). We used 0.06 and 0.27 and then multiplied them by the vegetation and impervious changes based on the three scenarios in the study (Table 5)[2].

Figure 3: GeoDa regression table for percent impervious vs. NDVI.

```
>>04/15/21 00:38:45
REGRESSION
----------
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set            :  subcatchments_redone
Dependent Variable  :         ndvi  Number of Observations:   56
Mean dependent var  :     0.108245  Number of Variables   :    2
S.D. dependent var  :    0.0433569  Degrees of Freedom    :   54

R-squared           :     0.193903  F-statistic           :     12.9895
Adjusted R-squared  :     0.178975  Prob(F-statistic)     : 0.000683192
Sum squared residual:    0.0848577  Log likelihood        :     102.319
Sigma-square        :   0.00157144  Akaike info criterion :    -200.638
S.E. of regression  :    0.0396414  Schwarz criterion     :    -196.588
Sigma-square ML     :   0.00151532
S.E of regression ML:    0.0389271

-----------------------------------------------------------------------------
       Variable      Coefficient       Std.Error    t-Statistic   Probability
-----------------------------------------------------------------------------
          CONSTANT      0.172724       0.0186584        9.25719      0.00000
        per_imperv  -0.000899295     0.000249521       -3.60409      0.00068
-----------------------------------------------------------------------------

REGRESSION DIAGNOSTICS
MULTICOLLINEARITY CONDITION NUMBER   6.899544
TEST ON NORMALITY OF ERRORS
TEST                  DF           VALUE             PROB
Jarque-Bera            2           566.8233          0.00000

DIAGNOSTICS FOR HETEROSKEDASTICITY
RANDOM COEFFICIENTS
TEST                  DF           VALUE             PROB
Breusch-Pagan test     1            19.5019          0.00001
Koenker-Bassett test   1             2.3843          0.12256
============================== END OF REPORT ================================
```

Figure 4: GeoDa scatterplot for percent impervious vs. NDVI.



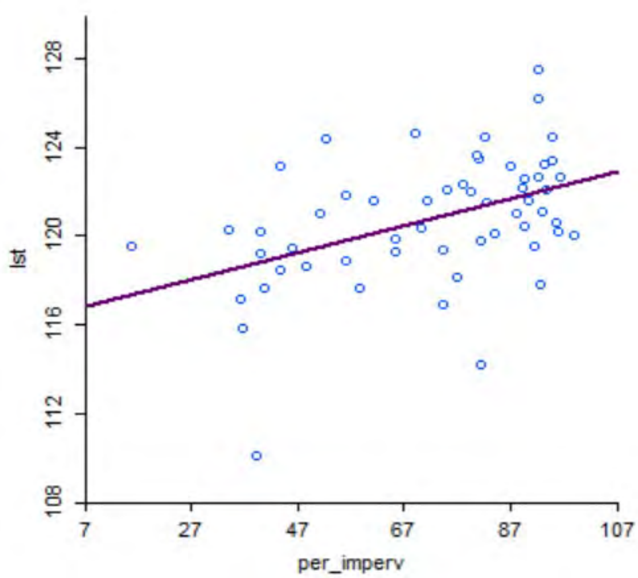
#obs	R^2	const a	std-err a	t-stat a	p-value a	slope b	std-err b	t-stat b	p-value b
56	0.194	0.173	0.019	9.257	0.000	-0.001	0.000	-3.604	0.001
0	0	0	0	0	0	0	0	0	0
56	0.194	0.173	0.019	9.257	0.000	-0.001	0.000	-3.604	0.001

Chow test for sel/unsel regression subsets: can't compute

Figure 5: GeoDa regression table for percent impervious vs. LST.

```
>>04/15/21 10:33:12
REGRESSION
----------
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set            :  subcatchments_redone
Dependent Variable  :          lst  Number of Observations:   56
Mean dependent var  :      120.739  Number of Variables    :    2
S.D. dependent var  :      2.88431  Degrees of Freedom     :   54

R-squared           :     0.196363  F-statistic            :      13.1945
Adjusted R-squared  :     0.181481  Prob(F-statistic)      : 0.000625664
Sum squared residual:      374.395  Log likelihood         :     -132.659
Sigma-square        :      6.93324  Akaike info criterion  :      269.319
S.E. of regression  :      2.63311  Schwarz criterion      :       273.37
Sigma-square ML     :      6.68563
S.E of regression ML:      2.58566

-----------------------------------------------------------------------------
       Variable      Coefficient      Std.Error    t-Statistic   Probability
-----------------------------------------------------------------------------
          CONSTANT       116.422        1.23935        93.9381     0.00000
        per_imperv     0.0602037       0.016574        3.63243     0.00063
-----------------------------------------------------------------------------

REGRESSION DIAGNOSTICS
MULTICOLLINEARITY CONDITION NUMBER    6.899544
TEST ON NORMALITY OF ERRORS
TEST                  DF           VALUE             PROB
Jarque-Bera            2            10.4022          0.00551

DIAGNOSTICS FOR HETEROSKEDASTICITY
RANDOM COEFFICIENTS
TEST                  DF           VALUE             PROB
Breusch-Pagan test     1             1.0811          0.29844
Koenker-Bassett test   1             0.5959          0.44015
============================== END OF REPORT ================================
```

Figure 6: GeoDa scatterplot for percent impervious vs. LST.



#obs	R^2	const a	std-err a	t-stat a	p-value a	slope b	std-err b	t-stat b	p-value b
56	0.196	116.422	1.239	93.938	0	0.060	0.017	3.632	0.001
0	0	0	0	0	0	0	0	0	0
56	0.196	116.422	1.239	93.938	0	0.060	0.017	3.632	0.001

Chow test for sel/unsel regression subsets: can't compute

Figure 7: GeoDa regression table for percent vegetated vs. NDVI.

```
>>04/15/21 10:42:44
REGRESSION
----------
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set            :  subcatchments_redone
Dependent Variable  :        ndvi  Number of Observations:  56
Mean dependent var  :    0.108245  Number of Variables   :   2
S.D. dependent var  :   0.0433569  Degrees of Freedom    :  54

R-squared           :    0.548563  F-statistic           :     65.6181
Adjusted R-squared  :    0.540203  Prob(F-statistic)     :6.79305e-011
Sum squared residual:   0.0475227  Log likelihood        :     118.553
Sigma-square        : 0.000880049  Akaike info criterion :    -233.105
S.E. of regression  :   0.0296656  Schwarz criterion     :    -229.055
Sigma-square ML     : 0.000848619
S.E of regression ML:   0.0291311

-----------------------------------------------------------------------------
       Variable      Coefficient      Std.Error    t-Statistic   Probability
-----------------------------------------------------------------------------
          CONSTANT     0.0832741     0.00502172       16.5828      0.00000
           per_veg     0.0051886    0.000640528        8.1005      0.00000
-----------------------------------------------------------------------------

REGRESSION DIAGNOSTICS
MULTICOLLINEARITY CONDITION NUMBER   2.044361
TEST ON NORMALITY OF ERRORS
TEST                  DF           VALUE             PROB
Jarque-Bera            2           164.2541          0.00000

DIAGNOSTICS FOR HETEROSKEDASTICITY
RANDOM COEFFICIENTS
TEST                  DF           VALUE             PROB
Breusch-Pagan test     1            32.1121          0.00000
Koenker-Bassett test   1             6.4994          0.01079
============================== END OF REPORT ================================
```

Figure 8: GeoDa scatterplot for percent vegetated vs. NDVI.

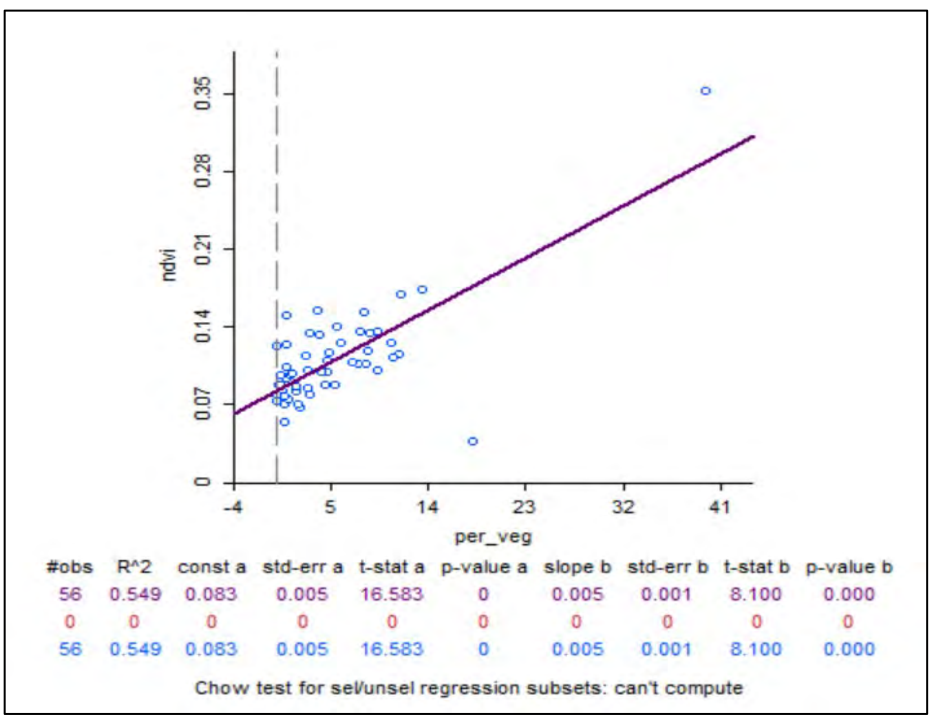
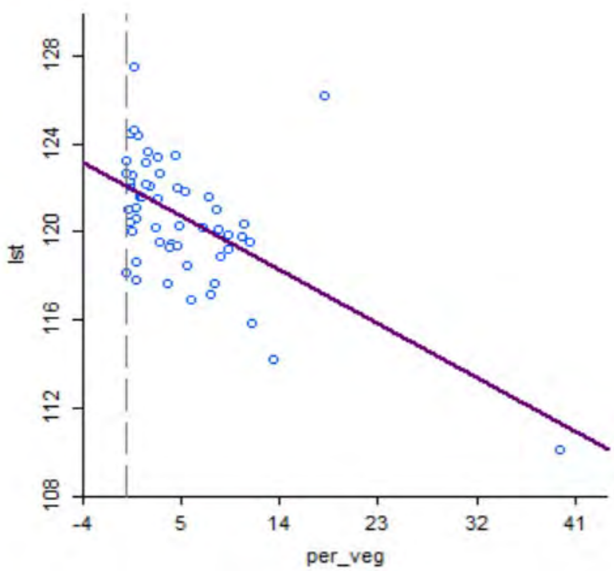


Figure 9: GeoDa regression table for percent vegetated vs. LST.

```
>>04/15/21 10:45:12
REGRESSION
----------
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set            :  subcatchments_redone
Dependent Variable  :          lst  Number of Observations:   56
Mean dependent var  :      120.739  Number of Variables   :    2
S.D. dependent var  :      2.88431  Degrees of Freedom    :   54

R-squared           :     0.338203  F-statistic           :      27.596
Adjusted R-squared  :     0.325947  Prob(F-statistic)     :2.59802e-006
Sum squared residual:      308.315  Log likelihood        :    -127.222
Sigma-square        :      5.70955  Akaike info criterion :     258.444
S.E. of regression  :      2.38947  Schwarz criterion     :     262.495
Sigma-square ML     :      5.50563
S.E of regression ML:      2.34641

-----------------------------------------------------------------------------
       Variable      Coefficient      Std.Error     t-Statistic   Probability
-----------------------------------------------------------------------------
          CONSTANT      122.043        0.404482       301.726      0.00000
           per_veg    -0.271025       0.0515924      -5.25319      0.00000
-----------------------------------------------------------------------------

REGRESSION DIAGNOSTICS
MULTICOLLINEARITY CONDITION NUMBER   2.044361
TEST ON NORMALITY OF ERRORS
TEST                      DF          VALUE              PROB
Jarque-Bera                2           22.5257           0.00001

DIAGNOSTICS FOR HETEROSKEDASTICITY
RANDOM COEFFICIENTS
TEST                      DF          VALUE              PROB
Breusch-Pagan test         1            1.9437           0.16326
Koenker-Bassett test       1            0.8511           0.35624
============================== END OF REPORT ================================
```

Figure 10: GeoDa scatterplot for percent vegetated vs. LST.



#obs	R^2	const a	std-err a	t-stat a	p-value a	slope b	std-err b	t-stat b	p-value b
56	0.338	122.043	0.404	301.726	0	-0.271	0.052	-5.253	0.000
0	0	0	0	0	0	0	0	0	0
56	0.338	122.043	0.404	301.726	0	-0.271	0.052	-5.253	0.000

Chow test for sel/unsel regression subsets: can't compute

Table 6: Subcatchment data results of the scenario-based measurements multiplied by the regression coefficients.

Subcatchment Name	Subcatchment Area (ac)	LST Reduction 25% Vegetation Change	LST Reduction 50% Vegetation Change	LST Reduction 100% Vegetation Change	LST Reduction 25% Impervious Change	LST Reduction 50% Impervious Change	LST Reduction 100% Impervious Change
S1	1.9418	1.57	2.09	3.14	0.35	0.46	0.70
S10	2.8392	0.07	0.07	0.07	0.02	0.02	0.02
S11	2.412	0.15	0.17	0.22	0.03	0.04	0.05
S12	0.533	0.11	0.15	0.22	0.02	0.03	0.05
S13	1.4616	0.07	0.07	0.07	0.02	0.02	0.02
S14	1.243	0.55	0.74	1.10	0.12	0.16	0.25
S15	3.1684	0.22	0.22	0.22	0.05	0.05	0.05
S16	1.3043	0.32	0.37	0.47	0.07	0.08	0.10
S17	2.9785	0.74	0.97	1.44	0.16	0.22	0.32
S18	1.5609	0.70	0.89	1.27	0.15	0.20	0.28
S19	0.7134	0.00	0.00	0.00	0.00	0.00	0.00
S2	1.5247	0.72	0.96	1.45	0.16	0.21	0.32
S20	0.3426	0.00	0.00	0.00	0.00	0.00	0.00
S21	0.6898	0.00	0.00	0.00	0.00	0.00	0.00
S22	0.3603	0.00	0.00	0.00	0.00	0.00	0.00
S23	0.1877	0.00	0.00	0.00	0.00	0.00	0.00
S24	0.3791	0.00	0.00	0.00	0.00	0.00	0.00
S25	0.48	0.00	0.00	0.00	0.00	0.00	0.00
S26	0.4206	0.00	0.00	0.00	0.00	0.00	0.00
S27	0.407	0.00	0.00	0.00	0.00	0.00	0.00
S28	0.766	0.00	0.00	0.00	0.00	0.00	0.00
S29	0.6728	0.22	0.26	0.35	0.05	0.06	0.08
S3_a	1.6764	1.73	2.08	2.77	0.38	0.46	0.62
S3_b	1.2188	0.81	0.94	1.20	0.18	0.21	0.27
S3_c	1.9377	2.63	3.15	4.20	0.58	0.70	0.93
S30	0.4404	0.76	1.01	1.52	0.17	0.23	0.34
S31	0.3233	0.00	0.00	0.00	0.00	0.00	0.00
S32	0.2674	0.00	0.00	0.00	0.00	0.00	0.00
S33	1.9047	0.00	0.00	0.00	0.00	0.00	0.00
S34	0.3666	0.00	0.00	0.00	0.00	0.00	0.00
S35	0.84	2.23	2.97	4.46	0.50	0.66	0.99
S36	13.374	1.10	1.32	1.77	0.25	0.29	0.39
S37	2.3493	2.37	2.84	3.79	0.53	0.63	0.84
S38	7.3745	1.45	1.75	2.33	0.32	0.39	0.52
S39	10.3292	1.26	1.52	2.02	0.28	0.34	0.45
S4	3.4508	0.22	0.30	0.44	0.05	0.07	0.10
S40	2.4912	0.23	0.30	0.45	0.05	0.07	0.10
S41	1.8488	1.33	1.77	2.66	0.30	0.39	0.59
S42	8.6343	1.24	1.52	2.07	0.28	0.34	0.46
S43	0.4243	0.00	0.00	0.00	0.00	0.00	0.00
S44	1.0503	1.89	2.52	3.77	0.42	0.56	0.84
S45	4.8503	0.06	0.06	0.06	0.01	0.01	0.01
S46	10.8217	0.09	0.09	0.09	0.02	0.02	0.02
S47	1.929	0.39	0.47	0.63	0.09	0.11	0.14
S48	0.8951	1.45	1.74	2.32	0.32	0.39	0.51
S49	1.0287	2.58	3.09	4.12	0.57	0.69	0.92
S5	3.4324	0.24	0.26	0.30	0.05	0.06	0.07
S50	1.1758	2.01	2.41	3.21	0.45	0.54	0.71
S51	2.1195	1.17	1.40	1.87	0.26	0.31	0.41
S52	1.9087	1.87	2.24	2.99	0.41	0.50	0.66
S53	0.4052	0.00	0.00	0.00	0.00	0.00	0.00
S54	5.3203	0.53	0.64	0.85	0.12	0.14	0.19
S6	1.5226	0.59	0.71	0.95	0.13	0.16	0.21
S7	3.2919	0.06	0.06	0.06	0.01	0.01	0.01
S8	0.6695	1.62	2.16	3.25	0.36	0.48	0.72
S9	2.7349	1.07	1.43	2.14	0.24	0.32	0.48
AVERAGE		0.69	0.85	1.18	0.15	0.19	0.26

4.3 Findings

Based on the average NDVI values for Stormwater Catchment 89's land cover, the highest NDVI value recorded was urban low vegetation (0.392). Second was unpaved road (0.179), then urban high vegetation (0.175). The lowest values recorded were asphalt (0.108), rock riprap (0.118), and desert range bare ground (0.112). Other land cover types consisted of values between 0.12 and 0.15. It is surprising that vegetated land covers do not have significantly higher average NDVI values, given that NDVI is supposed to be an index of vegetation. This calls into question the accuracy and usefulness of this indicator for the study at hand. This seemingly surprising result could be due to the fact that the grid size for the NDVI and LST is 30 meters, and there can be a mixture of land covers within each cell in a dense urban area. Despite this limitation, the data does suggest that vegetated land covers are associated with higher NDVI values, which we do find correlates with a lower LST.

This is important as Ibsen et al. (2021) found that one unit (from 0 to 1) change in NDVI is associated with a mean 4.25 ºC reduction in nighttime cooling. Although the focus for their study was air temperature, their results support how both air and land surface temperature correlate with higher NDVI values. Ibsen et al. (2021) compared different cities across the country based on their climate and vegetation gradients and found that "land surface cooling is a key component of urban heat health issues, and while out of the purview of this study of air temperatures it should not be ignored in future urban heat mitigation plants" (2021). The study also stated, "the linear relationships between vegetation and air temperature in all cities (figure 2(a) imply that adding vegetation in these cities results in a continuous cooling effect" (Ibsen et al., 2021).

The LST values for land covers in Stormwater Catchment 89 indicate that urban low vegetation is associated with the lowest mean LST (108.88 ºF). This strengthens the relationship between high NDVI values and lower LST values. Values for average LST across the different land cover types ranged from 116.58 ºF to 120.98 ºF; with desert rangeland bare ground having the highest value. Second was asphalt (119.39 ºF) and third was concrete (119.22 ºF); this evidence supports that lower NDVI values correlate with higher LST values.

A comparison of average LST and NDVI values for land use data for the entire study area (all catchments in Phoenix) also yielded promising results, with agriculture generating an average NDVI value of 0.38 and an average LST value of 106.94 ºF. Agriculture has a high percentage of pervious materials, such as grass and pastures that prevent excess stormwater runoff. Since stormwater can properly infiltrate in these materials, it reduces the land surface temperature, limiting the urban heat island effect. Compare the agriculture land use to industrial (which is a very common land use in this portion of Downtown Phoenix), the average NDVI value is 0.09 and an average LST value is 122.63 ºF. Mixed-use is another land use that shows a low NDVI value (0.06) and a high LST value (122.20 ºF); this may be the lack of vegetated areas within mixed use land use.

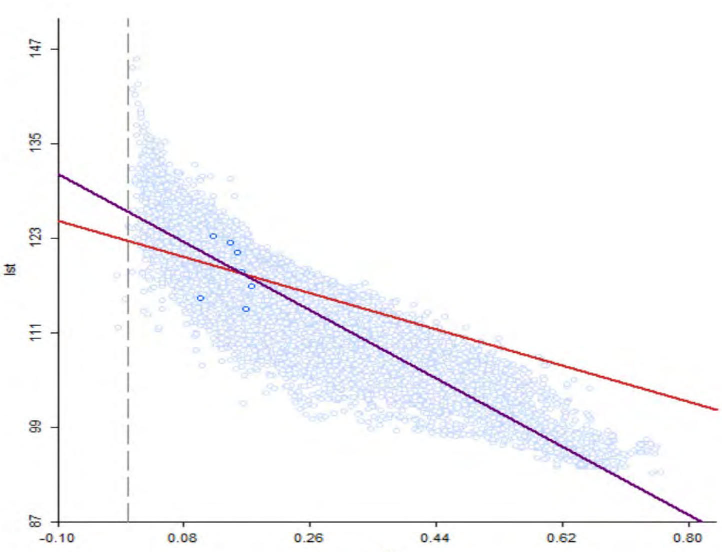
Table 6 shows the average change in percent impervious and change in percent vegetated for each of the subcatchments within Stormwater Catchment 89 under the three theoretical scenarios. The first set of yellow columns were calculated by multiplying the percent change in vegetation by the regression coefficient for the relationship between percent vegetation and LST that was calculated in GeoDa (B=0.27). The average reductions in LST reduction for each subcatchment were 0.69 (25% participation scenario), 0.85 (50% participation scenario), and 1.18 (100%). As a reminder, this assumes that all areas identified as part of the PCSWMM modeling as converting from impervious to pervious would be vegetated. The second set of yellow columns were calculated by multiplying the percent change in imperviousness under the different LID participation scenarios by the regression coefficient for the relationship between percent imperviousness and LST (B=0.06). The average reduction in LST for all subcatchments was 0.15º F (25% participation), 0.19 º F (50% participation), 0.26 º F (100% participation). Although the values are rather small, they indicate that even using conservative estimates of how LID implementation would change vegetation and imperviousness of the ground cover within each subcatchment, the theoretical scenarios would lead to overall reductions in average LST. Again, it is important to note that the land surface temperature reductions would likely be greater if the scenarios were implemented in the catchment because this only considers the areas that are converted from impervious to pervious, while LID could add more vegetation to current pervious (e.g. gravel or bare ground) areas. It would also likely reduce land surface temperatures more in the areas immediately surrounding the LID features, whereas this temperature reduction estimate is an average for the whole subcatchment.

To further support the findings of the 4 relationships above, GeoDa was used to analyze the relationship between LST (dependent variable) and NDVI (independent variable) for the entire city of Phoenix (Figures 10 and 11). This model suggests that an increase in NDVI from 0 to 1 would reduce land surface temperatures by 48 degrees Fahrenheit. Thus in general, more vegetation is associated with lower surface temperatures.

<u>Figure 11:</u> GeoDa Regression Table for Percent Impervious vs. NDVI of Entire Study Area

```
>>04/07/21 19:57:45
REGRESSION
----------
SUMMARY OF OUTPUT: ORDINARY LEAST SQUARES ESTIMATION
Data set              :  (My Calculations) parcels_lst_ndvi_csv
Dependent Variable    :          lst  Number of Observations:211480
Mean dependent var    :      117.484  Number of Variables   :    2
S.D. dependent var    :      4.67433  Degrees of Freedom    :211478

R-squared             :     0.755662  F-statistic           :      654037
Adjusted R-squared    :     0.755661  Prob(F-statistic)     :           0
Sum squared residual:1.12901e+006  Log likelihood        :     -477188
Sigma-square          :      5.33866  Akaike info criterion :      954380
S.E. of regression    :      2.31056  Schwarz criterion     :      954401
Sigma-square ML       :      5.33861
S.E of regression ML:        2.31054

-----------------------------------------------------------------------------
       Variable      Coefficient       Std.Error    t-Statistic   Probability
-----------------------------------------------------------------------------
          CONSTANT       126.293       0.0119954        10528.4      0.00000
              ndvi      -48.0598       0.0594265       -808.726      0.00000
-----------------------------------------------------------------------------

REGRESSION DIAGNOSTICS
MULTICOLLINEARITY CONDITION NUMBER   4.555372
TEST ON NORMALITY OF ERRORS
TEST                  DF           VALUE                 PROB
Jarque-Bera            2         38489.6835              0.00000

DIAGNOSTICS FOR HETEROSKEDASTICITY
RANDOM COEFFICIENTS
TEST                  DF           VALUE                 PROB
Breusch-Pagan test     1           247.6862              0.00000
Koenker-Bassett test   1           139.1749              0.00000
============================== END OF REPORT ================================
```

<u>Figure 12:</u> GeoDa Scatterplot for Percent Impervious vs. NDVI of Entire Study Area.



#obs	R^2	const a	std-err a	t-stat a	p-value a	slope b	std-err b	t-stat b	p-value b
211480	0.756	126.293	0.012	10528.400	0	-48.060	0.059	-808.726	0
7	0.035	122.530	8.865	13.821	0.000	-25.437	59.560	-0.427	0.687
211473	0.756	126.293	0.012	10528.467	0	-48.060	0.059	-808.739	0

Chow test for sel/unsel regression subsets: distrib=F(2,211476), ratio=0.3298, p-val=0.7191

5. Discussion

5.1 Recommendations for Implementing LID

Phoenix is increasingly becoming warmer, making mitigation of urban heat island effects one of the top priorities of the City (Tosline & Bettis, 2021). LID has been shown to have cooling benefits in cities that utilize it, however it is important to quantify the cooling benefit that can be expected. This stormwater catchment area is primarily industrial but is also includes residential land use. This study suggests that adding LID features to manage stormwater runoff would also help to reduce land surface temperatures, and based on the literature, likely air temperatures as well. Although the 100% participation scenario would be preferable from a cooling perspective, LID still provides cooling benefits in the lowest participation scenario. Ultimately planning is complex and involves tradeoffs and planning for LID is no exception.

5.2 Limitations and Avenues for Future Research

While this study supports the overall project goals by examining the relationship between land use/land cover, vegetation, and LST and estimating the cooling benefits of three different LID scenarios in a Phoenix stormwater catchment, there are limitations to consider. First, as already noted, the percent change in vegetation for each subcatchment and corresponding reductions of LST in the different participation scenarios is likely an underestimate, because it does not ‘count’ areas that are already pervious (e.g. gravel yards), but not vegetated. If these areas were converted to rain gardens and vegetation were added they would likely be cooler.

Other variables were also not considered for this study, such as air temperature, solar radiation, and soil moisture values from the additional stormwater retention and infiltration that would result from the implementation of new LID features. A study performed by Tosline et al. (2020) found that even an unvegetated LID installation in Phoenix reduced temperatures for a longer period following a rainfall event than an area without LID. They state, “although we cannot establish statistical confidence for this result, it means that the treatment creates roughly 3ºC of microclimate effect for at least two days after the rainfall event as compared with pre-treatment” (Tosline et al., 2020, p. 54). Future studies should use more sophisticated modeling techniques, such as ENVI-Met to examine these scenarios for more accurate estimates.

Another limitation is the size of the stormwater catchment area. It would be valuable to run the same statistical models on the entire city of Phoenix, which would have more data and likely provide a more accurate estimate of the relationship. A set number of data points, land cover and land uses exist in this stormwater catchment area; comparing those models to relationships across the larger study area (Figures 10 & 11) is helpful. For example, if further research could examine what the average change in NDVI value would be when adding LID features, it would be possible to use the model of the relationship between NDVI and LST across Phoenix to estimate what the corresponding change in LST would be. This would also make it possible to use the Ibsen et al. (2021) model to predict air temperatures. Our team did not have this information available, but this is an area that could be examined by future research.

6. Conclusion

LID has been shown to help mitigate urban heat island effects in many cities. Although not the only solution to limiting the effects of rising temperatures, LID is an important step cities can take to mitigate urban heat. The results of this study suggest that increased vegetation, reduced imperviousness, and higher NDVI is associated with lower land surface temperatures. Although there were many limitations to this study, the results suggest that adding LID, especially with vegetation, could have a cooling benefit in Phoenix.

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These past two years have been quite a whirlwind. Adding a pandemic on top of everything has created more obstacles than I could have ever imagined. With that being said, I would like to thank my committee members: Dr. Sara Meerow, Dr. David Hondula and Peter Crank. This committee has been nothing but supportive through my journey with this project and were always available whenever I needed a helping hand. A special thank you to Dr. Sara Meerow, who has served as an incredible committee chair and always ensured that I was going to succeed with this project. I would also like to thank the members of the Bureau of Reclamation, The Nature Conservancy, The City of Phoenix, and Flood Control District of Maricopa County, and the Maricopa County Department of Air Quality for allowing me to be a part of this project. My career goal is to combine my knowledge and passion for meteorology and urban planning into one and I was able to do just that with this project! To my amazing classmates and professors, thank you for motivating me to pursue my dreams. Although I spent my last year seeing you all through a computer screen, you have been wonderful and I know, someday, we are going to change the world!

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Appendix

[1] LID features from *Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development*

Bioretention basins and planters	Systems that collect and filter stormwater through a variety of media, including vegetation, mulch, rocks, and sand.
Curb openings	Cuts in the pavement that direct stormwater runoff from paved areas to green infrastructure that can absorb the water or channel it elsewhere.
Domed overflow structures	These work like buried water silos for storing and discharging stormwater runoff; the dome is usually accessible from ground level.
Grade control structures	A structure built across a drainage way to protect against erosion.
Infiltration trenches	Linear indentation that collects stormwater and allow it to seep into the ground quickly; they typically are filled with natural materials such as grass or stone.
(Non-tree) vegetation	All planted vegetation aside from trees and vegetation planted as part of another intervention, such as a grade control structure.
Permeable pavement	Pavers or concrete that allows water to drain through it.
Sediment traps	Systems that collect sediment and other debris from runoff, often used with other features.
Stormwater harvesting basins	Stormwater harvesting basins, or rain gardens, are often landscaped and set at a lower grade than surrounding non-permeable surface, they usually include subsurface storage.
Trees and tree pits	Trees that are planted in pits that are surrounded by non-permeable surface, such as the typical street tree.
Vegetated or rock swales	Open channels lined with vegetation and/or rock in order to slow the flow of runoff.
Other	Any feature that does not fit into one of the other categories.

[2] Subcatchment Spreadsheet Indicating Scenario-Based Calculations and Their Regression Coefficients.

Subcatchme	Subcatchme	25_change_	50_change_	100_change	Regression	25_reductio	50_reductio	100_reduction_	25_change_in_pe	50_change_	100_change	Regression	25_reductio	50_reductio	100_reduct
S1	1.9418	5.78916	7.71888	11.57832	0.27	1.57	2.09	3.14	5.789160153	7.71888	11.57832	0.06	0.35	0.46	0.70
S10	2.8392	0.258742	0.258742	0.258742	0.27	0.07	0.07	0.07	0.258741517	0.258742	0.258742	0.06	0.02	0.02	0.02
S11	2.412	0.549841	0.631599	0.795114	0.27	0.15	0.17	0.22	0.549841091	0.631599	0.795114	0.06	0.03	0.04	0.05
S12	0.533	0.410897	0.547863	0.821795	0.27	0.11	0.15	0.22	0.410897307	0.547863	0.821795	0.06	0.02	0.03	0.05
S13	1.4616	0.251306	0.251306	0.251306	0.27	0.07	0.07	0.07	0.251306416	0.251306	0.251306	0.06	0.02	0.02	0.02
S14	1.243	2.035088	2.713451	4.070176	0.27	0.55	0.74	1.10	2.035087953	2.713451	4.070176	0.06	0.12	0.16	0.25
S15	3.1684	0.811503	0.811503	0.811503	0.27	0.22	0.22	0.22	0.811503032	0.811503	0.811503	0.06	0.05	0.05	0.05
S16	1.3043	1.19334	1.375686	1.740376	0.27	0.32	0.37	0.47	1.193340358	1.375686	1.740376	0.06	0.07	0.08	0.10
S17	2.9785	2.712931	3.576134	5.302541	0.27	0.74	0.97	1.44	2.712930579	3.576134	5.302541	0.06	0.16	0.22	0.32
S18	1.5609	2.570419	3.270346	4.6702	0.27	0.70	0.89	1.27	2.57041907	3.270346	4.6702	0.06	0.15	0.20	0.28
S19	0.7134	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S2	1.5247	2.667959	3.557279	5.335918	0.27	0.72	0.96	1.45	2.667959248	3.557279	5.335918	0.06	0.16	0.21	0.32
S20	0.3426	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S21	0.6898	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S22	0.3603	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S23	0.1877	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S24	0.3791	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S25	0.48	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S26	0.4206	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S27	0.407	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S28	0.766	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S29	0.6728	0.796307	0.955568	1.274091	0.27	0.22	0.26	0.35	0.796306897	0.955568	1.274091	0.06	0.05	0.06	0.08
S3_a	1.6764	6.389168	7.667002	10.22267	0.27	1.73	2.08	2.77	6.389167975	7.667002	10.22267	0.06	0.38	0.46	0.62
S3_b	1.2188	2.986621	3.463398	4.41695	0.27	0.81	0.94	1.20	2.986621368	3.463398	4.41695	0.06	0.18	0.21	0.27
S3_c	1.9377	9.688268	11.62592	15.50123	0.27	2.63	3.15	4.20	9.688267968	11.62592	15.50123	0.06	0.58	0.70	0.93
S30	0.4404	2.804707	3.739609	5.609413	0.27	0.76	1.01	1.52	2.804706715	3.739609	5.609413	0.06	0.17	0.23	0.34
S31	0.3233	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S32	0.2674	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S33	1.9047	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S34	0.3666	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S35	0.84	8.225518	10.96736	16.45104	0.27	2.23	2.97	4.46	8.225518169	10.96736	16.45104	0.06	0.50	0.66	0.99
S36	13.374	4.073084	4.887701	6.516935	0.27	1.10	1.32	1.77	4.073084153	4.887701	6.516935	0.06	0.25	0.29	0.39
S37	2.3493	8.741467	10.48976	13.98635	0.27	2.37	2.84	3.79	8.741467331	10.48976	13.98635	0.06	0.53	0.63	0.84
S38	7.3745	5.36565	6.43878	8.58504	0.27	1.45	1.75	2.33	5.365649916	6.43878	8.58504	0.06	0.32	0.39	0.52
S39	10.3292	4.661039	5.593246	7.457662	0.27	1.26	1.52	2.02	4.661038636	5.593246	7.457662	0.06	0.28	0.34	0.45
S4	3.4508	0.817673	1.09023	1.635346	0.27	0.22	0.30	0.44	0.817672813	1.09023	1.635346	0.06	0.05	0.07	0.10
S40	2.4912	0.831301	1.108401	1.662602	0.27	0.23	0.30	0.45	0.831300835	1.108401	1.662602	0.06	0.05	0.07	0.10
S41	1.8488	4.908068	6.54409	9.816136	0.27	1.33	1.77	2.66	4.908067835	6.54409	9.816136	0.06	0.30	0.39	0.59
S42	8.6343	4.583412	5.601564	7.63787	0.27	1.24	1.52	2.07	4.583411781	5.601564	7.63787	0.06	0.28	0.34	0.46
S43	0.4243	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S44	1.0503	6.963772	9.285029	13.92754	0.27	1.89	2.52	3.77	6.963771862	9.285029	13.92754	0.06	0.42	0.56	0.84
S45	4.8503	0.227188	0.227188	0.227188	0.27	0.06	0.06	0.06	0.227187674	0.227188	0.227188	0.06	0.01	0.01	0.01
S46	10.8217	0.339419	0.339419	0.339419	0.27	0.09	0.09	0.09	0.339419369	0.339419	0.339419	0.06	0.02	0.02	0.02
S47	1.929	1.455927	1.747112	2.329483	0.27	0.39	0.47	0.63	1.455926673	1.747112	2.329483	0.06	0.09	0.11	0.14
S48	0.8951	5.339755	6.407705	8.543607	0.27	1.45	1.74	2.32	5.339754581	6.407705	8.543607	0.06	0.32	0.39	0.51
S49	1.0287	9.507886	11.40946	15.21262	0.27	2.58	3.09	4.12	9.507885843	11.40946	15.21262	0.06	0.57	0.69	0.92
S5	3.4324	0.890795	0.961941	1.104234	0.27	0.24	0.26	0.30	0.89079486	0.961941	1.104234	0.06	0.05	0.06	0.07
S50	1.1758	7.411479	8.893775	11.85837	0.27	2.01	2.41	3.21	7.411478905	8.893775	11.85837	0.06	0.45	0.54	0.71
S51	2.1195	4.307183	5.16862	6.891493	0.27	1.17	1.40	1.87	4.307183222	5.16862	6.891493	0.06	0.26	0.31	0.41
S52	1.9087	6.892194	8.270633	11.02751	0.27	1.87	2.24	2.99	6.892194087	8.270633	11.02751	0.06	0.41	0.50	0.66
S53	0.4052	0	0	0	0.27	0.00	0.00	0.00	0	0	0	0.06	0.00	0.00	0.00
S54	5.3203	1.952786	2.343343	3.124457	0.27	0.53	0.64	0.85	1.952785636	2.343343	3.124457	0.06	0.12	0.14	0.19
S6	1.5226	2.181134	2.61736	3.489814	0.27	0.59	0.71	0.95	2.181133608	2.61736	3.489814	0.06	0.13	0.16	0.21
S7	3.2919	0.22316	0.22316	0.22316	0.27	0.06	0.06	0.06	0.223159548	0.22316	0.22316	0.06	0.01	0.01	0.01
S8	0.6695	5.989524	7.986032	11.97905	0.27	1.62	2.16	3.25	5.989523862	7.986032	11.97905	0.06	0.36	0.48	0.72
S9	2.7349	3.954849	5.273132	7.909697	0.27	1.07	1.43	2.14	3.954848697	5.273132	7.909697	0.06	0.24	0.32	0.48
AVERAGE						**0.69**	**0.85**	**1.18**					**0.15**	**0.19**	**0.26**

Appendix 8. Air Quality Assessment

School of Geographical Sciences and Urban Planning
Arizona State University

Air Quality Impacts of Green Infrastructure:
Low Impact Development Floodplain Student Project

Ferguson, Corey

Submitted May 3, 2021
Updated November 23, 2021

Culminating Applied Project; Master of Urban and Environmental Planning
School of Geographical Sciences and Urban Planning; Arizona State University
Tempe, Arizona; 85287

Content

0.0 Executive Summary

This study analyzed the impacts of Low Impact Development (LID) on air quality improvements for one stormwater catchment in Phoenix, Arizona through a scientific modeling approach, using the modeling software i-Tree Eco. This research was part of the larger study, "Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development". Working collaboratively with the larger study partners, this assessment focused specifically on the benefits of LID to improve local air quality in an underserved and vulnerable area of the city. Previous research regarding LID and air quality relationships in arid and semi-arid climates is limited. This research provides additional empirical evidence about these relationships and advances the understanding of LID application in the context of Phoenix. Such findings seek to inform the future planning practices of the City to improve the urban ecosystem in tandem with equitable development.

As determined by the larger study, theoretical LID treatment scenarios were used to understand the various impacts of LID across the catchment. Specifically, these treatment scenarios included 25, 50, and 100 percent participation of the catchment area in LID conversion. To understand the air quality implications of these conversions, water infiltration volume was translated to the amount of new vegetation supported across each different rate of LID participation and then input into the i-Tree Eco model to quantify air quality affects. The i-Tree suites are open-access software programs specific to calculating ecosystem benefits of trees and other vegetation. In the literature review, i-Tree Eco was recognized for its abilities to quantify air quality benefits from vegetation and was thus utilized in this study to help achieve the study goals. New trees supported by stormwater capture were added to the baseline model to create unique treatment scenario models for each rate of LID participation.

Results from the model runs indicate that LID vegetation does lead to an improvement in air quality through increases in pollution removal rates and health benefits. These results, while positive, were relatively moderate and difficult to discern across the treatment scenario models. Variations were observed in the type of LID and its associated impacts on air quality, where grasses provided stronger evidence of benefits than the observed trees and shrubs in terms of pollution removal and biogenic volatile organic compound emissions. The i-Tree Eco reports also outline relationships between specific tree species and air pollution removal rates as well as overall net benefits. Although, cost of implementation was unknown.

Acknowledgement of and active mitigation against this and other limitations of the study, throughout the project scope, provide informed results for future LID implementation for the City of Phoenix and other arid and semi-arid climates. This research and its results create a platform for deeper investigation into the intersection of LID design, vegetation species selection, and participation optimization to advise policy and planning practices towards environmental and social equity. Targeted LID application has the potential to maximize the observed benefits of this research and scale them to larger, citywide systems of urban life.

1.0 Introduction to Project Scope

Green stormwater infrastructure or low-impact development (henceforth referred to as “LID”) employs the use of natural processes to curb stormwater runoff in urban areas of high flood risk or abundant impervious surfaces. LID features, such as rain gardens and vegetation, help to capture stormwater at its source during weather events, working to improve groundwater infiltration and limit the ‘gray’ infrastructure needed for proper stormwater alleviation. Traditional planning of LID has been isolated to this one-dimensional application for stormwater management. However, intentional LID application can enhance other, larger systems of urban life (Whitman and Eisenhauer, 2020).

As articulated by the American Planning Association, planners have begun to recognize, understand, and amplify the co-benefits of LID application within cities for improved human and biophysical environments. Such co-benefits include improved water quality, mitigated urban heat impacts, and local air pollution removal. LID features such as trees, grasses, and gardens can also expand urban access to natural shade, green spaces, and community agriculture (Whitman and Eisenhauer, 2020). Planners can employ LID to address inequities in green space allocation, urban resilience to climate change, healthy food access, systemic health impairments, and overall quality of life. Specifically, air quality benefits through these practices can be significant. However, much is still needed to be understood about air quality impacts across different LID features and vegetation type. This study seeks to bridge this gap, through quantitative scientific modeling, to inform successful environmental planning efforts to improve local air quality through LID application.

This project is being conducted within the larger study, “Identifying Key Areas in the City of Phoenix for Infiltration and Retention Using Low Impact Development”. This specific study is co-managed by the Bureau of Reclamation (Reclamation) and The Nature Conservancy to assess opportunities for LID implementation within arid and semi-arid climates. Other study partners include the City of Phoenix, Flood Control District of Maricopa County and Maricopa Air Quality Department, and Arizona State University. To inform effective decision-making, this larger study is looking specifically at the impacts and co-benefits of theoretical LID installation for a particular catchment site in Phoenix, Arizona (See Figure 1). Based on infiltration rates derived from Reclamation modeling projections using the Personal Computer Storm Water Management Model (PCSWMM), the larger study will focus on the potential for using LID treatment scenarios within the catchment to slow and infiltrate surface water flows. These infiltration rates will also determine the LID vegetation able to be supported within each scenario to quantify the impacts of LID improvements on local air quality. As the focus of this study, understanding the co-benefits of LID on local air quality first requires a literature review to identify existing knowledge in the field, gaps in this knowledge, and previously performed methodologies applicable to the current study. Using this review, the study then selected an appropriate methodology, performed said methodology, and analyzed the results. These results articulate the impacts of LID on air quality for the catchment of interest, under specific theoretical treatment scenarios, to aid in the larger study's review of informed implementation for LID in Phoenix to improve air quality.

2.0 Literature Review of LID Air Quality Benefits Assessment

As part of the larger study goals, an overarching literature review has already been performed to understand the impacts of LID in arid and semi-arid climates on hydrologic performance, water quality, urban heat, and air quality. This review exposed the lack of empirical knowledge on the impacts of LID on air quality in arid and semi-arid climates (Meerow et al., 2020). Out of the 28 sources identified, only three pertained to air quality (Meerow et al., 2020). Within these three studies, trees were the primary focus for LID assessment and were generally found to mitigate urban air pollution, with some tree species having the potential to contribute to the problem as well through biogenic volatile organic compounds (bVOCs) (Meerow et al., 2020). Additionally, all three studies quantified their findings through modeling methodologies that capture the concentrations of various air pollutants before and after LID installation (Meerow et al., 2020). Among these methodologies, two of the studies utilized i-Tree Eco modeling to perform such assessments (Kim and Coseo, 2018; Jayasooriya et al., 2017).

The previous literature review intended to articulate best practices and considerations from prior studies to be drawn upon in preparing the methodology of the current study on air quality impacts. However, a narrowed understanding of only three studies on the impacts of LID on air quality lacks comprehension of available approaches to quantifying this complex phenomenon. Therefore, an additional literature review, expanding the scope beyond LID treatments in only arid and semi-arid climates and focusing the application of LID on only air quality improvements, was necessary to determine the most applicable methodology for this LID study on air quality impacts in Phoenix.

The literature review of LID air quality benefits assessment builds upon the previous review to identify an appropriate methodology for this study based on qualitative and quantitative reasoning. This review contributes to a wider perspective on the modeling techniques used in other LID air quality studies. Modeling was observed as the most common approach for LID evaluation in the previous literature review (Meerow et al., 2020) and supports the current approach of the larger project team to simulate theoretical treatment scenarios. As noted, this subsequent literature review broadens its search beyond only arid and semi-arid climates, having already identified studies pertaining to LID performance and associated methodologies within these regions. The wider scope on LID applications across all climates creates a larger sample for analyzing and comparing a variety of modeling approaches. Additionally, rather than considering all impacts of LID, this review focuses specifically on air quality impacts. By both expanding and narrowing the scope of the search, the supplemental literature review produced a total of 18 sources (16 new, 2 from the previous review) on modeling methodologies for air quality impacts of various LID treatments.

2.1 Methodology

Consistent with the previous literature review's keywords and search engines (Meerow et al., 2020), this literature review used the academic search engine Scopus and the following Boolean search input to retrieve relevant, open access studies for further review:

["green infrastructure" OR "low impact development" OR "water sensitive urban design" OR "sponge city" OR "stormwater control" OR "nature-based solution"] AND ["air quality" OR "particulate matter" OR "air pollution" OR "ozone" OR "carbon dioxide"]

The search yielded 366 results, with 93 searches available via open access. In order to target the review more specifically to methodologies and modeling techniques, an additional Boolean search was performed:

["green infrastructure" OR "low impact development" OR "water sensitive urban design" OR "sponge city" OR "nature-based solution"] AND ["air quality" OR "particulate matter" OR "air pollution" OR "ozone" OR "carbon dioxide"] AND ["model" OR "modeling"]

This more specific search yielded 119 results, with 31 searches available via open access. All of the 31 open access searches were reviewed for relevancy and application to this study's scope and goals, eliminating those that did not involve LID air quality assessments (such as studies focused on urban heat or water quality), those that did not reference a methodology or modeling approach towards the quantification of air quality benefits, and those that focus on air quality improvements through methods outside of LID treatment. Ultimately, 18 sources were selected for further analysis and review.

2.2 Findings

The 18 identified sources (as outlined in Table 1) are consistent with the findings from the original literature review. Trees were predominately assessed in air pollution removal and i-Tree models were the most referenced modeling technique among the sample studies (Baró et al., 2014; Kim and Coseo, 2018; Reynolds et al., 2017; Jayasooriya et al., 2017). However, distinctions between the original review and this search were observed.

For instance, while urban trees remained the most prominent LID treatment assessed, LID treatments in the form of parks (Newman et al., 2020; Kim and Coseo, 2018), wetland and riparian restoration (Zhang et al., 2020; Newman et al., 2020), green roofs and living walls (Viecco et al., 2018; Abhijith et al., 2017; Jayasooriya et al., 2017), bioswales and rain gardens (Newman et al., 2020), hedges (Hewitt et al., 2020; Abhijith et al., 2017), and grasses (Jeanjean et al., 2016) were also considered for impacts on air quality. Pollution parameters for the selected studies ranged from ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) to bVOCs and particulate matter 2.5 and 10.

Study locations spanned climates from arid and semi-arid locales (Kim and Coseo, 2018; Viecco et al., 2018); to the United Kingdom (Nemitz et al., 2020; Jeanjean et al., 2016), Italy (Marando et al., 2016), and Spain (Baró et al., 2014; Pecero-Casimiro et al., 2020); to Eastern China (Zhang et al., 2019; Chen et al., 2016) and Australia (Jayasooriya et al., 2017). These additions to the study literature provide further insight into the diverse treatments, parameters, and locations of other LID air quality studies, aiding in developing the research structure for this particular study.

The methods literature review also appropriately highlights variations within the methodologies of the 18 studies, such as the different applications of the i-Tree models as well as alternative modeling software and research approaches. Out of the 18 studies analyzed, 4 studies prioritized the open-access i-Tree modeling software. While i-Tree Eco was used to calculate similar pollution parameters for urban trees and LID systems in Barcelona, Spain (Baró et al., 2014), Melbourne, Australia (Jayasooriya et al., 2017), and Phoenix, AZ (Kim and Coseo, 2018), i-Tree Streets was used in conjunction with i-Tree Canopy to quantify carbon sequestration for urban tree systems in Medellin, Colombia (Reynolds et al., 2017). The i-Tree Eco model provides assessment on a broader range of LID treatments and at a greater scale than i-Tree Streets, which focuses unilaterally on street trees. The i-Tree Canopy model in conjunction with i-Tree Streets allows for a wider, systematic commutation of an area’s urban forest; however, is limited to urban tree assessment where i-Tree Eco is not (Jayasooriya et al., 2017).

Other research methodologies observed in the literature review include ENVI-met and other simulation modeling software, LiDAR imaging, ArcGIS, qualitative literature assessments, participatory design workshops, field sampling, and lab experiments. ENVI-met was well represented in the sample of studies, developing microclimate simulations and sensitivity studies to inform additional modeling processes, such as chemistry transport models (Simon et al., 2019; Nemitz et al., 2020) and Surface Dynamic deposition models (Yang et al., 2019), to understand air pollution removal rates for urban tree systems. Open access modeling software OpenFoam, in conjunction with LiDAR imaging, was used in Leicester, UK (Jeanjean et al., 2016) to quantify the impacts of LID on air quality for urban trees and urban grasses, both separately and together. LiDAR imaging was also used in conjunction with an Aerobiological Index to assess risk potential for pollen allergies through dispersion and deposition (Pecero-Casimiro et al., 2020). ArcGIS provided mapping capabilities of field data from air quality monitoring stations (Chen et al., 2016) and remote sensing (Marando et al., 2016) to illustrate land use cover analyses and seasonal pollution distributions. Qualitative literature assessments were performed (Abhijith et al., 2017; Hewitt et al., 2020) and results synthesized to articulate aggregated impacts and LID best practices for pollution reduction as well as considerations for LID planning and treatment design based on the anticipated urban form. Participatory design strategies were also employed to understand the community context of LID in Manchester, TX (Newman et al., 2020), informed by community feedback, field data, and the Green Value Calculator. Additional studies prioritized field data

Table 1 - Literature Review of LID Air Quality Benefit Assessments

Article	Reference	Location	Methodology	Parameters	LID Treatment
Potential and limitation of air pollution mitigation by vegetation and uncertainties of deposition-based evaluations: Air pollution mitigation by vegetation	Nemitz et al., 2020	UK (countrywide)	Atmospheric Chemistry and Transport Modeling (ACTM)	PM 2.5, NOx, NO2, NH3, O3, SO2, and bVOC	Vegetation (not specified) across the country and urban vegetation across the country
Measuring multi-scale urban forest carbon flux dynamics using an integrated eddy covariance technique	Zhang et al., 2019	Shanghai, China; Feng Xian University Campus	EddyPro 5.1.1 software	CO2 and carbon sequestration/sink	Urban forest, evergreen trees/urban study area
Urban trees and their impact on local Ozone concentration-A microclimate modeling study	Simon et al., 2019	Mainz, Germany; other German urban areas	ENVI-met and box model	O3 and bVOC (isoprene)	Urban and suburban trees in different modeling scenarios
Exploring the potential for air pollution mitigation by urban green infrastructure for high density urban environment	Yang et al., 2019	Not specified; case study in Taiyuan, China	ENVI-Met and Systems Dynamics model	PM 10, dry deposition	Urban trees, boreal deciduous and evergreens
Citizen science-informed community master planning: Land use and built environment changes to increase flood resilience and decrease contaminant exposure	Newman et al., 2020	Manchester, TX (Houston)	Field samples, participatory community outreach, Green Values Calculator, design development	PAHs and metalloids, indoor and outdoor dust	Urban parks, wetlands/riparian restoration, smaller-scale implementation (bioswales, rain gardens, etc.)
Contribution of ecosystem services to air quality and climate change mitigation policies: The case of urban forests in Barcelona, Spain	Baró et al., 2014	Barcelona, Spain	i-Tree Eco model	O3, CO, NO2, PM 10, and SO2; bVOCs; carbon sequestration, dry deposition	Urban trees
Urban park systems to support sustainability: The role of urban park systems in hot arid urban climates	Kim and Coseo, 2018	Phoenix, AZ	i-Tree Eco model	O3, CO, NO2, PM 10, PM 2.5, and SO2; carbon sequestration	Urban trees/tree cover in urban park system
Green infrastructure practices for improvement of urban air quality	Jayasooriya et al., 2017	Melbourne, Australia	i-Tree Eco model	O3, CO, NO2, PM 10, PM 2.5, and SO2	Urban Trees, green roofs and green walls
Does "greening" of neotropical cities considerably mitigate carbon dioxide emissions? The case of Medellin, Colombia	Reynolds et al., 2017	Medellin, Colombia	i-Tree Streets and i-Tree Canopy models	CO2 and carbon sequestration	Urban trees and tree canopy
Potential of particle matter dry deposition on green roofs and living walls vegetation for mitigating urban atmospheric pollution in semiarid climates	Viecco et al., 2018	Chile (countrywide)	Lab experiments and field samples data collection	PM 2.5 and PM 10, dry deposition	Sedums and Succulents, Green Roofs and Living Walls
The removal efficiencies of several temperate tree species at adsorbing airborne particulate matter in urban forests and roadsides	Kwak et al., 2019	Seoul, South Korea	Lab experiments and leaf surface samples; Leaf Area Index	PM 2.5 and PM 10	Urban forest and roadsides (street trees); five tree species most commonly found in SK
Unexpected air quality impacts from implementation of green infrastructure in urban environments: A Kansas City case study	Zhang et al., 2020	Kansas City, MO/KS	Land Surface Modeling, WRF-CMAQ coupled model	PM 2.5 and O3, summertime	Urban reforestation, wetland restoration
Modelling the effectiveness of urban trees and grass on PM2.5 reduction via dispersion and deposition at a city scale	Jeanjean et al., 2016	Leicester, UK	LiDAR 3D imaging and OpenFOAM model (CFD)	PM 2.5	Urban trees and grasses, separate and together
Producing urban aerobiological risk map for Cupressaceae family in the SW Iberian peninsula from LiDAR technology	Pecero-Casimiro et al., 2020	Iberian Peninsula (Portugal and Spain)	LiDAR imaging and the AIROT Index, visualized through Kriging Analysis Mapping	Pollen	Ornamental trees and plants from the Cupressaceae family
Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review	Abhijith et al., 2017	Not specified; urban street canyons and open road	Literature review and synthesis	Not specified; air pollution in general, several studies investigating several different gases and PM	Trees and hedges, green walls and green roofs; urban street canyons and open road
Using green infrastructure to improve urban air quality (GI4AQ)	Hewitt et al., 2020	Not specified; general policy guidelines, mostly applied to the UK	Literature review and synthesis	Not specified; air pollution in general, several studies investigating several different gases and PM	Trees and hedges, urban canopy and green oases
Do green spaces affect the spatiotemporal changes of PM2.5 in Nanjing?	Chen et al., 2016	Nanjing, China	Monitoring stations, field samples; land use cover analysis, ArcGIS	PM 2.5, seasonal distribution	Urban green cover and vegetation;
Removal of PM10 by forests as a nature-based solution for air quality improvement in the Metropolitan city of Rome	Marando et al., 2016	Rome, Italy; larger European context	Remote Sensing and ArcGIS; monitoring stations, field samples, and aerial imaging	PM 10, dry deposition and seasonal distinctions	Urban and peri-urban forests; trees: evergreen and deciduous species

sampling (Chen et al., 2016; Marando et al., 2016) and lab experimentation (Kwak et al., 2019; Viecco et al., 2018) to directly quantify air pollution deposition rates for various LID treatments and specific species.

2.3 Discussion

The literature review of LID air quality benefits assessment builds upon the information gleaned from the previous literature review for this study and exposes further gaps in available knowledge on the impacts of LID on air quality. Many of the reviewed studies focused predominately on urban trees when assessing the impacts of LID on air quality. Other LID treatments, such as green roofs and green walls, were studied and quantified, but required modifications to direct modeling inputs to achieve an appropriate analysis (Jayasooriya et al., 2017). Field sampling and lab experiments have also been conducted for some of these alternative treatments as a more direct technique to quantify impacts on pollutant removal (Kwak et al., 2019; Viecco et al., 2018); however, the application of such approaches is not always feasible \and requires physical samples to be completed.

A majority of the studies selected performed analyses on such physical and existing systems, with very few providing research on hypothetical and detailed LID treatment scenarios such as the ones in this study. This suggests that more research on the intentional and future planning of LID treatments is necessary. Theoretical modeling scenarios, in partnership with decision-makers, can inform the effective planning of LID implementation by exposing the tradeoffs and potential benefits of such systems before enduring the impacts and investments for implementation. Additionally, there is still much to learn about the relationships between LID and air quality in arid and semi-arid climates. While the expanded literature review exposed more methodologies and research findings, empirical evidence on LID in arid and semi-arid climates like Phoenix remained small. Research conducted by Viecco et al. (2018) on green roofs and living walls in semi-arid Chile adds to the climate-contextual knowledge base of the study and provides information on alternative LID treatment options outside the common urban and street tree configurations previously studied in Phoenix. However, continued investigation into the implications of LID co-benefits in arid and semi-arid climates is still needed.

There is also limited empirical evidence on the general quantification of LID benefits on air quality. Much of the research on such benefits is limited to qualitative inference and conceptual understandings. While there is an accepted understanding that LID contributes to air pollutant removal and positive sequestration, empirical evidence observed from this sample of studies questions the direct and universal impacts of LID on air quality. Studies calculated increases in pollutants from higher bVOC emissions (Simon et al., 2019) and during wet and nocturnal deposition (Zhang et al., 2020) for certain tree species while others concluded that LID implementation should be a tertiary option for air pollution mitigation (Hewitt et al., 2020) due to the relatively marginal impact of LID deposition (Baró et al., 2014). Many of the studies within the small sample size were also more tangential than directly applicable to the interests and intentions of this research. This highlights a need for further research and quantitative evidence (through modeling and/or field measurements) to understand the specific impacts of LID on removing air pollutants. Of the studies observed, modeling methodologies appeared to provide successful calculations for the intended research parameters. However, many of the modeling methodologies also utilized nuanced approaches to model creation and execution. This provides a difficult comparison across methodologies and reproduction results. While every modeling approach has its limitations and prescribed assumptions, using a previously performed modeling approach or software for this study can progress the overall understanding of varied LID impacts by providing a platform for comparison with existing research across climate, scale, and treatment type.

In identifying these gaps and needs within the current literature on LID and air quality, this research presents an opportunity to further understand the relationships between LID treatments, vegetation, and local air quality as well as the quantitative assessment of these relationships. With an expanded understanding of the potential methodologies to achieve these goals, this study selected a modeling approach using the i-Tree Eco methodology.

2.4 Limitations of the Literature Review

While the literature review did yield a total of 18 results for deeper study and analysis, the Boolean search yielded 119 results, with 88 of these outside of open access. 88 potential additions to the study is significant and, with more time and access to these restricted studies, could have yielded vastly different results. Additionally, this literature review only performed searches within one academic search engine. Widening the scope to include others, such as Web of Science, could have yielded more open access studies and a more comprehensive understanding of the existing literature on LID air quality assessment. However, within the time and financial constraints of this study, the performed literature review achieved its purpose of widening the existing portfolio of information from 3 to 18 studies and provided a larger understanding of the different approaches to LID and air quality research methodologies. In doing so, conclusions were drawn that supported the original review’s findings and presented wider evidence and justification for choosing i-Tree Eco.

3.0 Selected Methodology

After reviewing the previous methodologies and research approaches of similar studies, this research will be best served using the i-Tree Eco model for its calculation of air quality impacts from LID treatments. As demonstrated in Baró et al. (2014), Jayasooriya et al. (2017), and Kim and Coseo (2018), i-Tree Eco presents the greatest opportunity to quantify relationships between the local context, specific vegetation, and interested pollutant parameters while developing justifiable recommendations for targeted LID treatment implementation.

The i-Tree program is a peer-reviewed software suite from the United States Department of Agriculture (USDA) Forest Service that is informed and periodically updated by the "cooperator" team as well as through public and professional feedback from users. Led by the USDA Forest Service, the cooperator team consists of the professional entities Davey Tree Expert Company, Arbor Day Foundation, Society of Municipal Arborists, International Society of Arboriculture, Casey Trees, and State University of New York College of Environmental Science and Forestry (i-Tree Eco User's Manual v.6, 2020). Beginning in 2006, this team developed the i-Tree program to assist local urban forest management across the country by calculating ecosystem impacts of LID treatments for sixteen United States reference cities and climate zones (McPherson, 2010). Glendale/Phoenix, Arizona represented one of these original flagship cities surveyed for national application. In 2014, the cooperator team performed an additional community forest assessment for the City of Phoenix to advance the internal knowledge and scope of the original reference city survey (Davey Resource Group, 2014). This embedded, validated, and updated local context within the i-Tree program suite provides efficiency and confidence when using i-Tree Eco to understand the implications of LID in Phoenix today. As a reference city, application for Phoenix already includes local air quality measurements and meteorological data for the region, updated most recently in 2016 (i-Tree Eco User's Manual v.6, 2020), as well as a comprehensive database of vegetation species common to the area. Together, these programmatic advantages contribute to a direct and accurate assessment of pollution removal results for this study.

3.1 Implementation Steps

According to previous application by Jayasooriya et al. (2017) and in agreement with the latest user manual (i-Tree Eco User's Manual v.6, 2020), i-Tree Eco can be broken down into four main stages of implementation. The first stage is to determine the planning and setup of the project study, including the field sampling procedure for the study area. This requires a decision to perform either a random, stratified, or grid plot sampling method (Jayasooriya et al., 2017) or a complete inventory of the entire project area (i-Tree Eco User's Manual v.6, 2020). Data collection and analysis opportunities differ within i-Tree Eco depending on the sampling procedure. Plot-based sampling assessments allow the model to account for shrub, grassland, and other ground cover characteristics and impacts on air quality while a complete inventory assessment is isolated to tree impact analysis (i-Tree Eco User's Manual v.6, 2020). To maximize LID analysis and model capabilities, this study utilizes a plot-based sampling assessment.

The second step is to collect field data. The stormwater catchment of interest is located within the City of Phoenix, between E. Lincoln Street and Arizona Highway 60 and between Central Avenue and S. 3rd Street (Figure 1). Using vegetation to measure LID impact on air quality, species type and diameter breast height (DBH) must be determined for every unit of vegetation (trees, shrubs, etc.) sampled as well as the percent measured and percent covered in a plot-based sample analysis (i-Tree Eco User's Manual v.6, 2020). Required data (as outlined in Table 2 based on previous studies and user manuals) must be collected to its fullest as missing information will be aggregated with program data defaults and regression averages, under- or overestimating the final results (i-Tree Eco User's Manual v.6, 2020). In a related i-Tree Eco study by Kim and Coseo (2018), random sampling of the urban park system in Phoenix was selected as the sampling procedure and involved physical data collection over three months in the summertime. While this study is focused on a single catchment, detailed information on proposed plant species and land cover must still be collected for accurate analysis. Existing site conditions and current land uses within the catchment as well as proposed LID treatment scenarios and intended LID covering will provide the foundation for collecting the required data and creating the estimates.

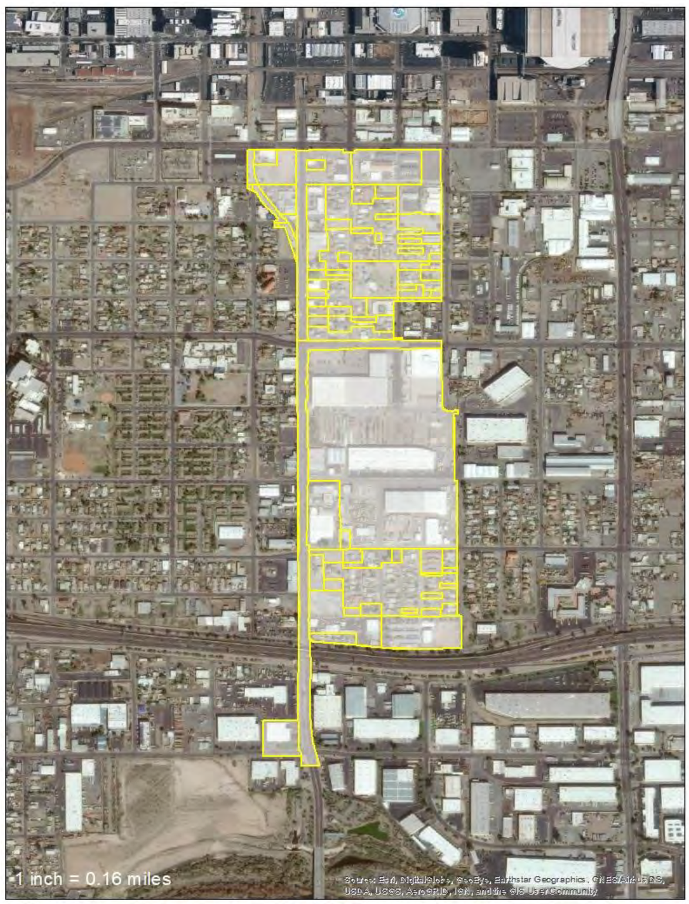


Figure 1. Site Boundary of Catchment 89 in the City of Phoenix

Supplemental analyses within the model can also be conducted, such as energy savings, avian habitat, life assessment forecasts, and pest detection; however, each requires additional data collection and input (i-Tree Eco User's Manual v.6, 2020). Meteorological and air quality data are also requested at this step. As mentioned, i-Tree already provides this data for United States studies and specifically for the Phoenix context. This data was last updated with reported information from 2016. Opportunities for manual input of more current and context-specific data are available from local air quality recording stations. However, time restrictions for the study were considered and no optional data collection was pursued.

The third step involves inputting the field data into the modeling system, either by paper or by a programmatic online form (i-Tree Eco User's Manual v.6, 2020). The i-Tree Eco manual recommends using the Mobile Data Collector online form while out in the field for a smooth and fast transition from field collection to model calculation. The fourth and final step of the i-Tree Eco process is to run the model and analyze the results, usually delivered within a day of submission (i-Tree Eco User's Manual v.6, 2020). Results from the i-Tree Eco model contain, among other reports, a breakdown of pollution removal rates by vegetation species, LID treatment, and seasonal distribution (i-Tree Eco User's Manual v.6, 2020; Jayasooriya et al., 2017). Jayasooriya et al. (2017) articulates the corresponding metrics and formulas of these results within the context of a dry deposition calculation while the i-Tree website provides further information on this dry deposition process as well as detailed bVOC emissions calculations.

Table 2 – Required Data Inputs for i-Tree Eco

Additional Data Collection		*Y/N*
Tree Information	Species	**Yes**, will need to determine; for different LID treatment scenarios
	Land Use	**Yes**, will need to determine; for different LID treatment scenarios
	Diameter Breast Height	**Yes**, will need to calculate; both height and from where it was measured for each tree species sampled; potentially for different projection timelines of treatment maturity
	Crown Dieback Percentage	**Yes**, will need to calculate; for each tree species sampled; i-Tree Eco offers a predetermined range of dieback percentages
	Total Height	**Yes**, will need to calculate; for each tree species sampled
	Percent Impervious	**Yes**, will need to calculate; for different LID treatment scenarios
Shrub Information	Species	**Yes**, will need to determine; for different LID treatment scenarios
	Height	**Yes**, will need to calculate; for each shrub species sampled; potentially for different projection timelines of treatment maturity
	Percent Shrub Area	**Yes**, will need to determine; for different LID treatment scenarios
Plot Information	Ground Cover	**Yes**, will need to determine; for different LID treatment scenarios; i-Tree Eco offers 11 predetermined ground covers available for use
	Land Use	**Yes**, will need to determine; for different LID treatment scenarios; i-Tree Eco offers 13 predetermined land use covers available for use
	Percent Tree Cover	**Yes**, will need to determine; for different LID treatment scenarios
	Percent Shrub Cover	**Yes**, will need to determine; for different LID treatment scenarios
	Percent Measured	**Yes**, will need to determine sample or complete assessment
Weather and Air Quality Information	Meteorological Data	No, provided by i-Tree program; if comfortable with using regional data from 2016
	Air Quality/Pollution Data	No, provided by i-Tree program; if comfortable with using regional data from 2016
**If additional analyses are pursued, additional data may be needed to be collected; refer to i-Tree Eco User's Manuel v.6, 2020 for detailed forms on data collection and recording.*		

3.2 Execution of Data Collection and Processing

In order to compare results from the modeled treatment scenarios, a baseline model was performed to provide a foundation for results understanding for the specific context. The baseline model also provided an opportunity to understand existing vegetation species to translate into more informed and appropriate hypothetical scenarios.

Field work was performed and data was collected from the identified stormwater catchment for the baseline and treatment models, as defined by the above stages of implementation. These models used the same plot configurations as defined by the larger study team for the PCSWMM (Figures 2-5) to create a plot-based sampling assessment that matches overall study inputs and results. This type of assessment, as mentioned, provides a greater opportunity to analyze a wider range of LID features and allows for data collection on only a portion of the total site. While only a single catchment, the site is larger and more populated with vegetation than previously anticipated. Therefore, the chosen method of a plot-based sample assessment provided reasonable collection requirements and results.

These plots, as shown in Figures 2-5, represent a typical parcel for the four land uses analyzed in the study (residential, public, commercial, and industrial). The images show the proposed LID treatment for each land use through these typical "examples". It was determined by the larger study to treat all parcels of each land use under these assumptions and treatment criteria. Each of these four plots were used as inputs for overall land use and total catchment aggregation in the PCSWMM. Therefore, these same plots were chosen for consistency as sample plots within this study. Field data from these plots was then input into i-Tree Eco and scaled by area of overall land use type to calculate catchment wide benefits of LID implementation.

Figure 2. Example Residential LID Treatment

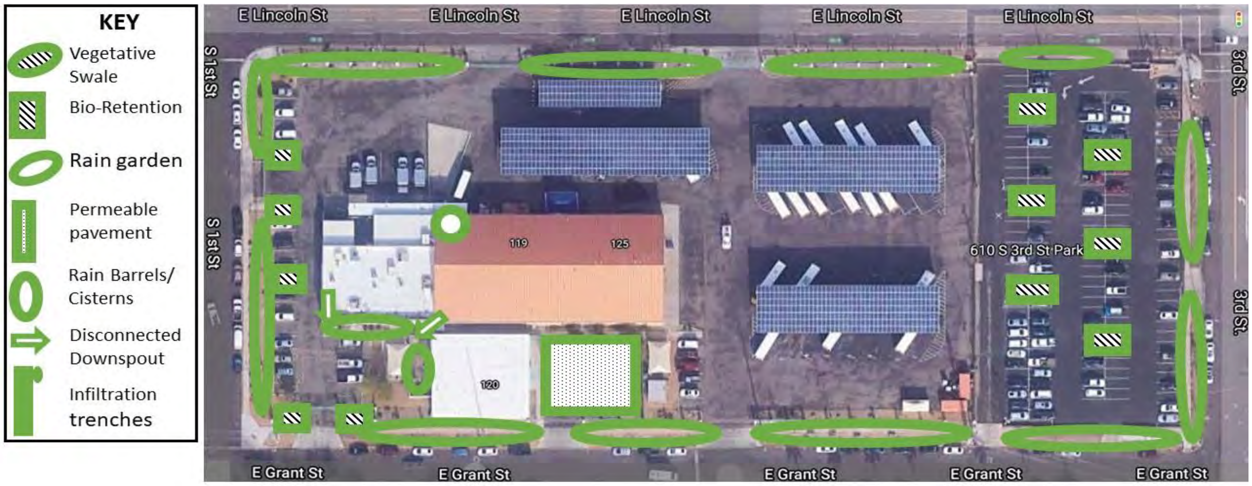
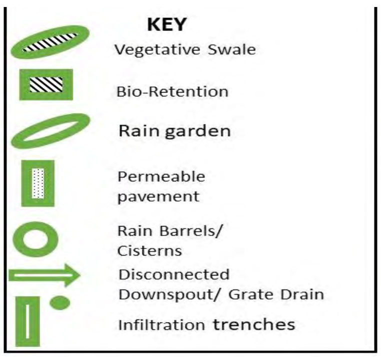
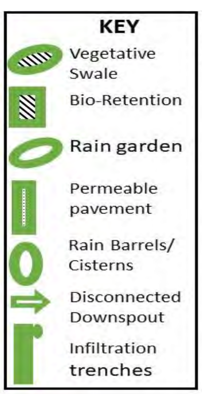


Figure 3. Example Public School and Downtown Parking LID Treatment



The information offered herein represents the opinion of the LID Floodplain study author(s). It does not represent and should not be construed to represent the City of Phoenix determination or policy.

Figure 4. Example Commercial LID Treatment



Example industrial potential LID treatment

Industrial lands are required to have significant stormwater manage ment protocols in place. (Detention basins, retain x% of stormwater runoff on site). It could be argued that further LID treatments will not influence the peak stormwater flow in these areas for smaller storms. However, GI/LID is a solutions multiplier tool so other benefits will occur with LID application and thus the argument to include these features for the study still stands.

The information offered herein represents the opinion of the LID Floodplain study author(s). It does not represent and should not be construed to represent the City of Phoenix determination or policy.

Figure 5. Example Industrial LID Treatment

3.2.1 Baseline Model

On Saturday, March 20, 2021, researchers went out to the site and recorded existing vegetation among the four sample land use plots chosen by the larger study to develop a baseline understanding of the site's characteristics and vegetation composition. The residential sample plot was located between 725 and 713 S. 1st St. and between 726 and 714 S. 2nd St. while public land use was captured at E. Lincoln St. to Grant St. and 1st St to 3rd St., commercial at E. Lincoln St. to Grant St. and Central Ave. to 1st St., and industrial at Buckeye Rd. to E. Papago St. and Central Ave. to 3rd St. These four plots each contained a variety of existing trees and shrubs that were recorded and brought into i-Tree Eco for analysis. For each vegetation, as highlighted in Table 2, several factors were examined and recorded. These included species type, land use, diameter breast height, crown health and related measurements, total height, percent impervious, and percent of canopy missing. To identify species type, the mobile app PlantNet was used to take pictures of the existing vegetation and develop informed understandings of species type. These "identified" species were then cross-referenced with Maricopa County and i-Tree Eco tree species lists to confirm the viability of the app's suggestions. Diameter Breast Height was measured using a piece of string and a ruler to calculate the circumference of the tree or shrub and then divided by π (3.14) to achieve diameter value. Crown dieback was estimated using the scale provided by i-Tree Eco to assess health from Excellent (0%) to Dead (100%). Total height of the species, if larger than the researcher, was determined through informed estimation and verified with information on average and expected heights of the species. Percent impervious (the amount of impervious surface behind the recorded feature) and percent missing (the amount of surface area missing or dead within the recorded feature) were both able to be estimated confidently through an informed perspective and physical site investigation.

This information, collected for each vegetation at each of the four sample plots (with less inputs required for shrub data), was then input into i-Tree Eco to generate the baseline results. In total, over 250 tree and shrub species were recorded across these four plots within the catchment site.

3.2.2 Treatment Scenario Model

The treatment scenario model builds off the baseline model by adding additional LID features supported by the modeled infiltration rates from the PCSWMM to the existing LID structure of the sample plots. The infiltration rates help to determine how much new vegetation could be supported on the site through improved stormwater capture. Changes to the treatment scenario model therefore include new tree species supported by the infiltration volumes as well as increased pervious ground cover and new ground cover types to include other LID interventions. These changes are adjusted based on the three different participation rates of LID implementation used within the PCSWMM of 25 percent participation across the catchment, 50 percent, and 100 percent, or complete participation. Taking the total volume of stormwater captured from the three participation rates, gallons of water retained per year for each scenario was used to justify new tree implementation and ground cover adjustments. As shown in Figures 2-5, these scenarios are designed for area allocation of new LID features, not specifically the exact LID feature composition. This study then bridges the gap in design and context by providing information on specific vegetation afforded for each area of LID allocation and the related benefits for air quality improvement. Within this, there were three additional considerations that needed to be made.

The first was to select which new tree species would be chosen as the optimal additive tree for modeling purposes. Several considerations factored into this decision. The search began by identifying native tree species outlined by the City of Phoenix through previous LID research that are preferred for the City's urban environment (GI/LID Handbook). These species were cross-referenced with available i-Tree species data and Maricopa County Tree Selection criteria to identify those species that are able to be input into the model with supporting maturity averages for expected height, canopy density, and diameter breast height. From here, this short list grew even shorter by eliminating those that contained anything other than low water use and low to moderate bVOCs (as defined by Maricopa County). These five species types were then presented to the larger project team and assessed based on previous knowledge and engagement with these species, previous City planting practices, and other competing tree characteristics to arrive at the "optimal" tree input for the model. The five tree species up for consideration are identified in Table 3.

Table 3 – Tree Selection Short List

Scientific Name	*Common Name*	*Native*	*Canopy*	*Height*	*Water Use*	*bVOC Emissions*	*Allergies*	*Notes*
Chilopsis linearis	Desert willow	Yes	10-20'	15-30'	Low	Mod	Low	Deciduous tree – no shade in the winter; little shade to begin with; could be higher water use
Parkinsonia florida	Blue paloverde	Yes	15-20	25'	Low	Mod	High	Variety in its application, can be cut to size, large; grows quite slow; maintenance concerns and pruning demand; high allergy concerns; recommended by City of Phoenix
Acacia farnesiana	Sweet acacia	Yes	15-25'	15-25'	Low	Mod	Low	Heavily found in other literature review within the Phoenix Area; currently not included in sample
Celtis reticulata	Western hackberry	Yes	25-30'	25-35'	Low	Low	Mod	Deciduous tree – no shade in the winter; not planted very often by the City of Phoenix
Lysiloma watsonii	Feather bush/ Desert fern	Yes	12-15'	15'-20'	Mod	Low	Low	Strong shade producer; low allergies; recommended by City of Phoenix

For this model, *Lysiloma watsonii* (common name Feather bush or Desert Fern, henceforth referred to as "Desert fern") was selected for its dense and wide canopy which aids in improved air pollution removal, low water use, moderate bVOC emissions, low allergy potential, lower maintenance demand, and preference within the City of Phoenix for planting purposes. However, it is worth mentioning that all five species received support for potential implementation, contributing to the conversation that there is not one optimal tree for this process and that several of the available native species within the City of Phoenix portfolio could and should be utilized during physical implementation.

The second decision that needed to be made was how to determine the water required to support a Desert Fern. Several resources were found to determine water demand for tree species, with varying degrees of sophistication. The Maricopa County Tree Selection criteria that informed the tree selection process determined its understanding of water use from the digital resource Water Use It Wisely (WUIW). This online platform provides resources for water conservation and best practices when watering vegetation. To keep consistent with other measures of analysis already embedded within selecting the Desert fern for implementation, water consumption calculations for this study were derived from WUIW as well. WUIW identifies canopy width as the strongest contributing factor to water demand by determining how large the root zone is and thus how much water is needed to completely wet the root zone with each watering to maintain a healthy tree specimen (Water Use It Wisely, 2021). Using the provided ratios, a Desert fern, with a typical canopy width of 12-15 feet (Maricopa County Tree Selection Criteria), requires approximately 115 gallons of water (at 14 feet) per watering (Water Use It Wisely, 2021).

While this calculation removes the variability and context of species, it provides an even stronger understanding of water consumption of new LID implementation regardless of species type. This aids in the application of results to any of the other tree species identified for potential implementation and treats water consumption as neutral within the model calculations, defined only by canopy width and watering scheduling. WUIW also provided insight on a watering schedule for desert adaptive plants over the course of the year (Figure 6). Such a schedule was used to aggregate how many gallons of water are required by a Desert Fern per year. This calculation yielded 3,795 gallons of water per year for one Desert Fern. This typical tree species requirement can then be used with the total volume of water retained by the new LID features across the catchment to find out how many Desert ferns can be supported by the various participation rates over a year.

How Much & How Often Water to the outer edge of the plant's canopy and to the depth indicated. Watering frequency will vary depending on season, plant type, weather and soil.		**Seasonal Frequency — Days Between Waterings**				**Water This Deeply** (Typical Root Depth)
		Spring Mar - May	Summer May - Oct	Fall Oct - Dec	Winter Dec - Mar	
Trees	Desert adapted	14-30 days	7-21 days	14-30 days	30-60 days	24-36 inches
	High water use	7-12 days	7-10 days	7-12 days	14-30 days	24-36 inches
Shrubs	Desert adapted	14-30 days	7-21 days	14-30 days	30-45 days	18-24 inches
	High water use	7-10 days	5-7 days	7-10 days	10-14 days	18-24 inches

Figure 6. Watering Schedule from WUIW, taken from Maricopa County Tree Selection criteria

The third considerations for LID adjustments within the treatment scenario model is understanding how much of each land use's current ground cover should be converted from impervious to pervious features. This required translating the LID features and their application considered within the PCSWMM criteria to the sample plot level for i-Tree calculation. The changes in ground cover from the baseline calculation to the different participation rates is shown in Table 4.

Table 4 – Ground Cover Conversion Adjustments

Residential	Baseline	25%	50%	100%
Ground Cover	*Percent Coverage*			
Building	21	21	21	21
Rock	52	52	51	51
Other Impr.	27	27	27	27
Unmain. Grass	0	0	1	1
Commercial	**Baseline**	**25%**	**50%**	**100%**
Ground Cover	*Percent Coverage*			
Building	13	13	13	13
Rock	9	9	9	9
Tar	65	49	33	0
Other Impr.	13	13	13	13
Unmain. Grass	0	16	32	65
Public	**Baseline**	**25%**	**50%**	**100%**
Ground Cover	*Percent Coverage*			
Building	13	13	13	13
Rock	3	3	3	3
Tar	65	49	33	0
Other Impr.	19	19	19	18
Unmain. Grass	0	16	32	66
Industrial	**Baseline**	**25%**	**50%**	**100%**
Ground Cover	*Percent Coverage*			
Building	28	28	28	28
Rock	10	8	5	0
Tar	31	23	16	0
Other Impr.	31	31	31	31
Unmain. Grass	0	10	20	41
**Rock relates to pervious rock surfaces such as gravel, brick, or flagstone walkways or patios; Other Impr. relates to other impervious surfaces outside of buildings and tar; Unmain. Grass relates to unmaintained grass and the most representative class for rain gardens, linear basins, and bio-retention swales*				

Adjustments to the residential land use included the addition of two rain gardens and one right-of-way linear basin per participating residential lot, but of which would contain new tree growth. The rain gardens were calculated at an area of 32 sq ft each and the linear basin at 20 sq ft. These areas were then applied to the sample plot, where 100 percent participation of LID implementation included all eight of the residential lots implementing two rain gardens and one linear basin. 50 percent participation and 25 percent scenarios included only four and two residential lots, respectively. The PCSWMM notes that no impervious areas were removed in the residential land use calculations for new rain gardens because the most feasible location for these features would be in the existing lawns and bare ground. Residential ground cover, therefore, did not change significantly at the sample plot level due to the controlled conversion of already pervious surfaces, the relatively small size of the LID features included, and the relatively small size of the sample plot within the larger residential area. As shown in Table 4, Unmaintained Grass (natural grass that is not manicured or regularly maintained) was selected out of the available ground covers in i-Tree Eco to represent new rain gardens, linear basins, and bio-retention swales (as applied to the other land uses), yielding a minimal one percent conversion of the baseline i-Tree selected ground cover, Rock (pervious landscaping/ground cover), to the new Unmaintained Grass at 50 and 100 percent participation and no change at the 25 percent participation.

Commercial adjustments to the baseline model included converting 75 percent of the parking lot (represented by Tar) to rain gardens and the other 25 percent of the parking lot to bio-retention swales at 100 percent participation. It is important to note that these calculations are different from the Urban Heat Assessment conversions. In this assessment's conversions, both rain gardens and bio-retention swales were again captured under Unmaintained Grass. The participation rates for these larger land uses, where only one lot was identified in each, were more difficult to capture by feature since the PCSWMM based its application off full participation from the number of participating lots. However, to still articulate 25, 50, and 100 percent participation within the sample plot and individual lots, adjusted percentages of each conversion were used to correspond to the different participation levels. Public land use adjustments were the same as commercial, with an additional one percent ground cover conversion impact from linear basin frontage (only physically captured within the model at the 100 percent level due to the small size of the feature). Industrial land use adjustments include similar conversion of the parking lots as well as complete landscape conversion (Rock) to rain gardens (Unmaintained Grass). To accomplish varying levels of participation, the Rock and Tar compositions across the plot were subtracted in accordance with each participation rate and added to the new Unmaintained Grass cover.

These three considerations inform the treatment scenario model with the appropriate changes and additions. With these adjustments in place and the new model run, the treatment scenario model can then be compared to the baseline model to determine the overall improvements of new LID implementation on local air quality. Within this comparison also exists recommendations for the City of Phoenix to consider when implementing LID, including most performative tree species for LID features. Using the literature review, baseline model results, and other native vegetation resources, the treatment scenario model provides evidence on which tree species to incorporate in LID treatments and the visible impacts such intent can have on the larger community. These models together provide a preview of what larger scale implementation of LID could do for the City of Phoenix.

3.3 Limitations of Selected Methodology

This section takes a critical approach to dissecting the limitations posed by the selected methodology and the steps taken to ensure informed and accurate results. These limitations help to create a context-specific lens for understanding the model results.

When considering the drawbacks regarding the i-Tree program to conduct LID and air quality research, the structural limitations for using the i-Tree Eco model over alternative methods were mitigated in this research by study location and its objectives. Nemitz et al. (2020) emphasizes the inability for i-Tree Eco to calculate wet deposition or concentrations of air pollution as air pollution data is aggregated equally across the study area. However, wet deposition rates for air quality control in arid and semi-arid climates are only applicable during rain events after dust storms. Wet deposition in Phoenix is also less of a concern than in more humid environments that must account for impacts from morning dew. The relatively isolated scope of the study to a single catchment additionally lessens the impact of unaccounted concentration changes, improving the efficacy of results. Nemitz et al. (2020) also recognizes the benefits of i-Tree Eco to produce detailed observations of vegetation and species impact through its modeling capabilities, something this study is heavily interested in. As a general methods approach, scientific modeling has weaknesses as well due to assumptions and modifications made. However, when contextualizing the potential impacts of LID treatment scenarios to inform future implementation, modeling such as this offers a reasonably accurate and accessible way to understand air quality implications for many different possible configuration scenarios (Jayasooriya et al., 2017).

Limitations exist in the data collection process for this model as well. Restrictions on time, money, and access to recommended equipment and complete study areas required estimations on certain model calculations such as tree height, diameter breast height, and species type in certain situations. Some of the LID features collected for the baseline model were unidentifiable from a species perspective or unable to be accessed for precise measuring due to private land ownership, which in-turn influences the treatment scenario model and overall comparisons. Out of the 250 species recorded for the baseline model, 18 required informed estimation for missing information. This 7 percent of model data was calculated based on visual estimations from outside property boundaries, surrounding species context, and informed estimations using previously collected data and species averages. Equipment recommended by i-Tree Eco for determined tree height and crown height measurements were also unobtainable for the study. However, calculations for such data were made based on other measuring techniques like measuring the accessible surrounding site context and then applying that understanding to the feature of interest. These adaptations of data collection were made through informed and calculated decisions and, while not traditional to the i-Tree Eco data collection process, provide a concrete foundation for understanding the existing context of the site for comparative study.

When translating the PCSWMM results to the treatment scenario model for calculation, assumptions were made and limitations were met when incorporating the new data into the i-Tree Eco model. Conversion of total catchment water capture and tree sustainability to the individual plot level for modeling purposes required an assumption that total trees for each participation rate would be divided among the four land uses based on the number of rain gardens included in each land use. Water volumes were examined by feature, meaning that the total volume calculated for new tree accommodations was the total volume captured by all new LID features combined. These features, as shown in Figures 2-5, range from rain gardens and bioswales to cisterns and disconnected downspouts. The larger study team concluded that new tree implementation would presumably be limited to the rain gardens. However, water collected from all of the other features would also be directed to these gardens to support new tree growth. Therefore, while total water consumption and subsequent tree sustainability is not isolated to rain gardens, for calculation purposes, the total trees supported was divided among the land uses as a percentage of rain gardens within each land use at the different participation rates. This was chosen to prioritize where new tree allocation would be targeted based on the plantable space of the available rain gardens. The number of trees associated with each land use was then aggregated down to the sample plot level based on area percentages of the sample plot associated with the total land use.

Within the tree selection process and new tree implementation, this study acknowledges that the practice of monoculture planting, planting hundreds of one tree type, is unrealistic, inefficient, and problematic. It is also worth noting the assumption of full maturity for the newly planted trees as such benefits received from this growth will take several years to achieve. However, for modeling purposes, these assumptions were the most systematic way to understand the benefits of new LID impacts on catchment characteristics. Vegetation species identification was also subject to error and could potentially alter the informed results. Triangulation of data found from PlantNet, i-Tree Eco, and Maricopa County helps to mitigate the chances for error; however, lack of expertise in species identification led to assumptions in species selection. Additionally, when calculating the ground cover conversion for each participation rate, the inability to measure participation rates by number of participating lots (outside of the residential plot) for each of the sample plots resulted in modified calculations within each lot for LID percentages applied by lot. This resulted in relatively small impacts to the residential sample plot ground cover composition, but very significant conversions for commercial, public, and industrial. However, this understanding was considered throughout the ground cover calculations and appropriate percentages of LID conversion were still applied within each lot. This discrepancy in land use conversion was more so a reflection of the nature of modeling residential lots within the PCSWMM as compared to the other land use types, where full parking lot conversion is expected at 100 percent participation. While this presents a limitation within the treatment scenarios themselves, it also means that if the LID scenarios were implemented, the reality would likely differ from the modeled benefits.

In total, while this modeling approach has significant limitations, which are important to disclose and discuss, the i-Tree Eco model still provided the most applicable methodology for the study goals; a simple yet comprehensive and fast yet articulate interpretation of LID impacts on air quality within Phoenix. This model aids in addressing the research intent to quantify air quality implications of LID treatment scenarios within arid and semi-arid climates and contributes to the growing conversation around LID co-benefits and air quality impacts. The results of the selected methodology are discussed next.

4.0 Results

After all the data was input for both the baseline and the three treatment scenario models, the data was then input into the model and submitted for processing. When the results were retrieved, findings on both the existing structure of the catchment and the implications of LID implementation were compared.

4.1 Existing Context Composition

In order to ground the treatment scenario results in context, existing conditions must be understood. The baseline model results were fundamental to understanding the current urban forest composition of the catchment site. The i-Tree Eco software calculated total catchment conditions using the sample plot data described above. Based on the species collected from the sample plots, Silver Wattle or Mimosa Trees (*Acacia Dealbata*) were the most common, found predominately in the residential land uses. Beefwood (*Grevillea striata*) was the second most common, found predominately in the industrial and residential land uses. Figure 7 shows the breakdown of the tree species found among the sample plots and their proportion to total trees identified. Shrubs were also common among the four land uses, with Texas barometer bush or Texas ranger (*Leucophyllum frutescens*) and Fairy duster (*Calliandra eriophylla*) being the two dominate species found in the catchment. Figure 8 provides a detailed report on tree species characteristics by land use. This summary highlights the leaf area, leaf biomass, and condition of the vegetation. Leaf area is a key component of air pollution removal, as identified in the literature review (Kwak et al, 2019), with larger leaf surface area allowing for higher rates of deposition. High leaf area of the residential land use appears significant compared to the other land uses. The high leaf area in residential come primarily from the large Beefwood specie and the frequent Mimosa Trees. This summary also informs the overall condition of the current urban forest for the catchment. Overall health condition of the species average just under 80 percent of full health, signaling a relatively healthy to moderately healthy tree population across the site. Industrial land uses showed the highest condition average at just over 90 percent. Conditions of species play a large role in determining the health of canopy density as well as available leaf area, both of which strongly influence air pollution removal capacity. The i-Tree Eco report for the baseline model also provides insight on average diameter breast height for the species identified to aid in understanding the size and relative age of the found vegetation. Diameter breast height (DBH) for the catchment does not exceed 18 inches and is clustered in the smaller DBH ranges, signaling a smaller, potentially younger vegetation population across the site. Overall, the results indicate that the catchment includes a diversity of species, in good condition, with potential to grow.

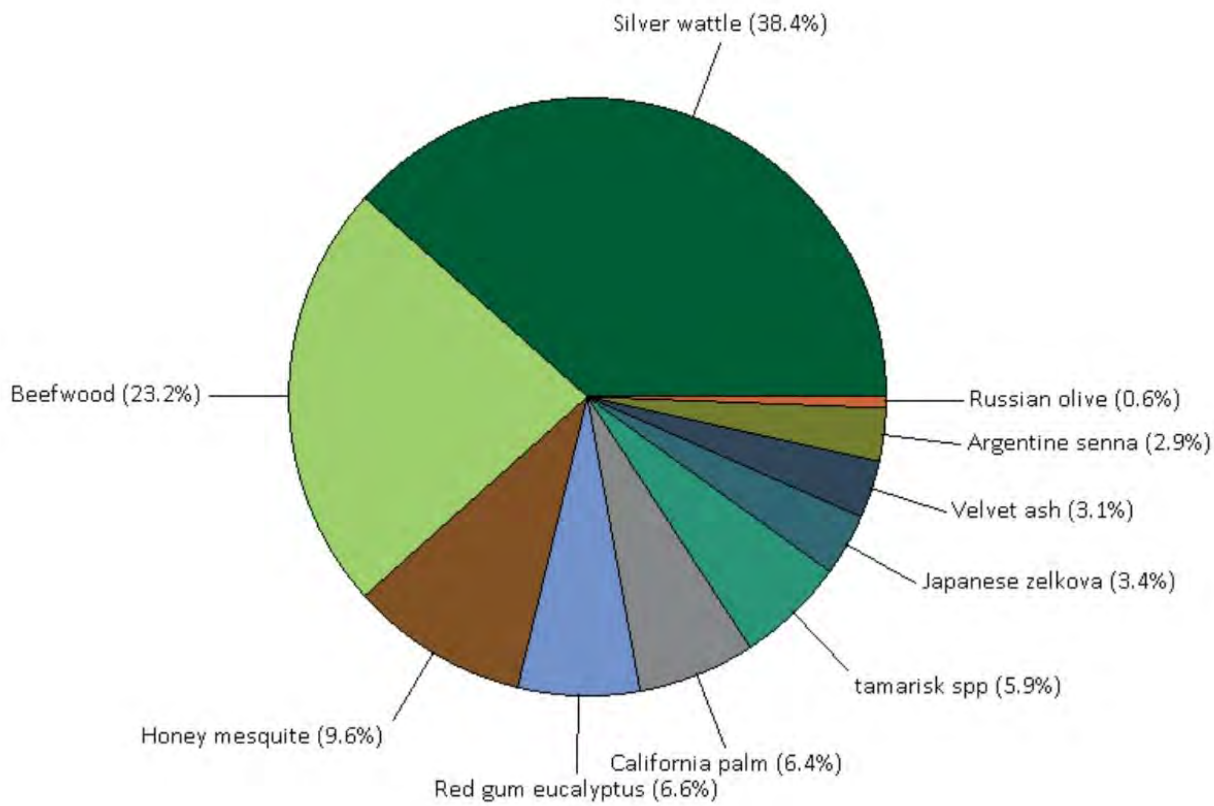


Figure 7. Tree Species Composition; retrieved from i-Tree Eco Baseline Model Results

The baseline model, apart from its analysis, also includes information on the pollution records used from the most recent software data in 2016. These rates, broken down by pollutant, are shown in Figure 9. CO, NO_2, O_3, and SO_2 are articulated by parts per million (PPM). CO appears to be the most significant of the four pollutants in terms of quantity; however, CO also represents potentially the least harmful of the pollutants in terms of public health. The other pollutants have undergone adjustments in federal standards to reflect more severe health concerns at lower levels of concentrations based on medical and epidemiological research. Particulate Matter 2.5 is also recorded in this pollution data (Figure 9) and graphed

Structure Summary by Stratum and Species

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

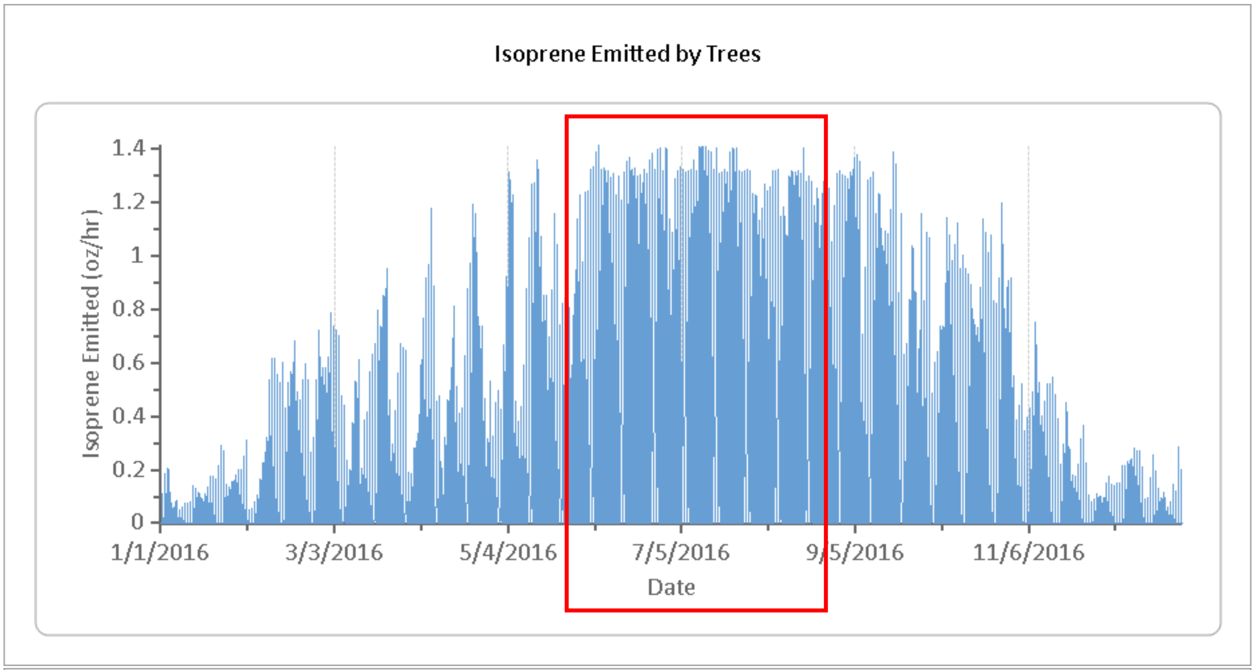
i-Tree Eco

Stratum	Species	Trees Number	SE	Leaf Area (ac)	SE	Leaf Biomass (ton)	SE	Tree Dry Weight Biomass (ton)	SE	Average Condition (%)
Residential	Silver wattle	212	±0	3.424	±0.000	3.692	±0.000	8.306	±0.000	71.17
	Velvet ash	18	±0	0.002	±0.000	0.000	±0.000	0.116	±0.000	13.00
	Beefwood	53	±0	4.404	±0.000	2.389	±0.000	46.202	±0.000	94.50
	Honey mesquite	18	±0	0.064	±0.000	0.024	±0.000	0.725	±0.000	82.50
	Total	**301**	**±0**	**7.893**	**±0.000**	**6.106**	**±0.000**	**55.349**	**±0.000**	**72.53**
Public Land and Schools	Silver wattle	3	±0	0.099	±0.000	0.107	±0.000	0.289	±0.000	94.50
	Russian olive	3	±0	0.031	±0.000	0.007	±0.000	0.571	±0.000	94.50
	Red gum eucalyptus	10	±0	0.000	±0.000	0.000	±0.000	0.289	±0.000	0.00
	Honey mesquite	37	±0	0.057	±0.000	0.022	±0.000	0.468	±0.000	94.50
	Total	**54**	**±0**	**0.187**	**±0.000**	**0.136**	**±0.000**	**1.617**	**±0.000**	**76.78**
Commercial	tamarisk spp	34	±0	1.003	±0.000	0.382	±0.000	12.092	±0.000	94.50
	California palm	14	±0	0.036	±0.000	0.025	±0.000	1.747	±0.000	94.50
	Japanese zelkova	19	±0	0.031	±0.000	0.009	±0.000	1.962	±0.000	37.50
	Total	**67**	**±0**	**1.069**	**±0.000**	**0.416**	**±0.000**	**15.801**	**±0.000**	**78.21**
Industrial	Silver wattle	3	±0	0.064	±0.000	0.069	±0.000	0.793	±0.000	82.50
	Red gum eucalyptus	27	±0	1.029	±0.000	0.635	±0.000	3.907	±0.000	87.30
	Beefwood	79	±0	0.759	±0.000	0.412	±0.000	74.242	±0.000	94.50
	Argentine senna	16	±0	0.023	±0.000	0.019	±0.000	0.115	±0.000	94.50
	California palm	22	±0	0.054	±0.000	0.037	±0.000	2.655	±0.000	94.50
	Total	**147**	**±0**	**1.928**	**±0.000**	**1.172**	**±0.000**	**81.712**	**±0.000**	**92.94**
Study Area		**569**	**±0**	**11.078**	**±0.000**	**7.829**	**±0.000**	**154.479**	**±0.000**	**78.88**

Figure 8. Tree Structure Summary; retrieved from i-Tree Eco Baseline Model Results

in micrograms per cubic meter. These charts were prescribed by the i-Tree Eco report and the differences in units of measurement make for a difficult comparison between $PM_{2.5}$ and the other pollutants. However, it is possible to compare the seasonal fluctuations of the five pollutants. CO, NO_2, SO_2, and $PM_{2.5}$ are highest in the winter, when leaf area index is lowest, conditions are drier, days are shorter, and skies are clearer within the board, alluvial topography of the Phoenix Valley. These four pollutants also exhibit decreases in concentrations during the summertime when dispersion is improved by storm systems mixing

Figure 9. Clockwise from Top Left: CO; NO_2; SO_2; $PM_{2.5}$; O_3 levels for the area based on 2016 Pollution Records; retrieved from i-Tree Eco Baseline Model Results



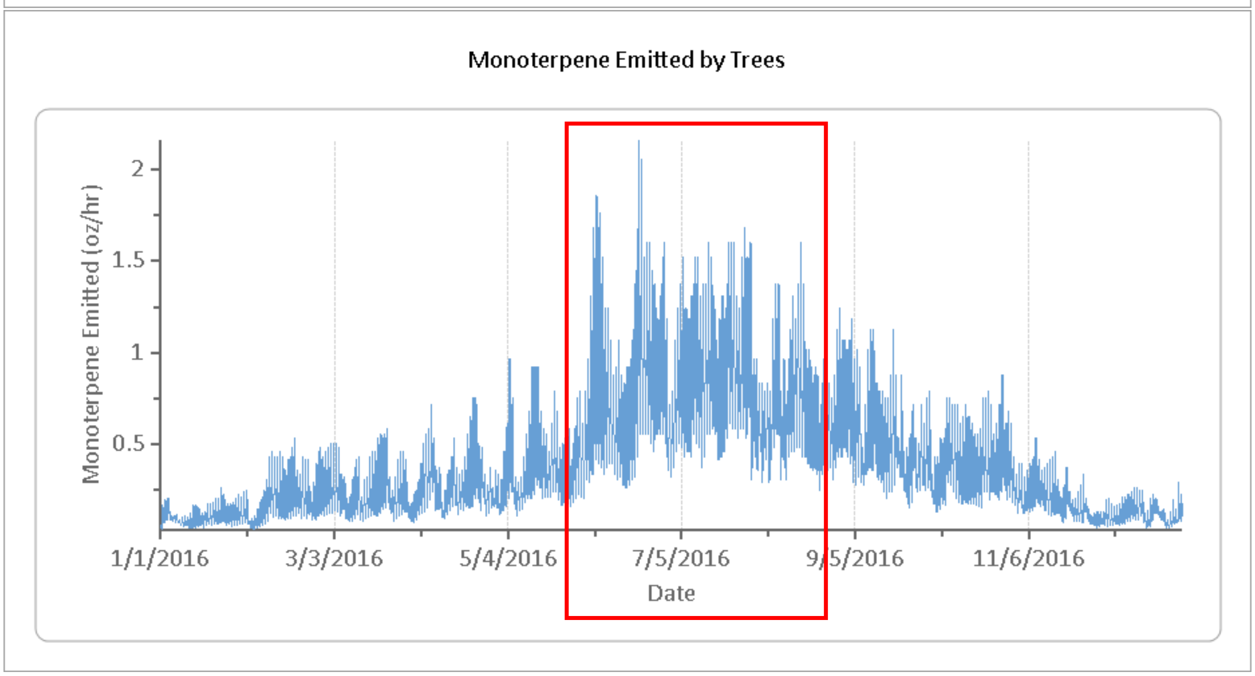


Figure 10. Isoprene and Monoterpene bVOC concentrations based on 2016 Pollution Records; retrieved from i-Tree Eco Baseline Model Results

and moving through. O_3, which is generated by ample heat and sunlight, trends the opposite of the others and peaks in the middle of summer during July. This is supported in the seasonal relationships of Monoterpene and Isoprene, both biogenic volatile organic compounds and both higher in concentration during the summers when biomass is higher (Figure 10). When these bVOCs are combined with NO or NO_2 they create additional ozone pollution.

These structural relationships and concentration counts of the five pollutants are important for understanding what to prioritize in local air pollution mitigation and what the observed removal rates for each pollutant means for the overall site and air quality improvements. For the larger study team, O_3 and $PM_{2.5}$ were the main pollutants of interest when quantifying removal potential and thus were explored in greater depth below then some of the others.

Total Catchment			
Land Use	*25%*	*50%*	*100%*
Residential	162	288	461
Public	38	75	129
Commercial	83	150	248
Industrial	297	537	898
Total New Trees	580	1050	1736
Sample Plot			
Land Use	*25%*	*50%*	*100%*
Residential	9	16	26
Public	11	22	38
Commercial	17	31	52
Industrial	109	197	329
Total New Trees	147	267	445

Figure 11. New Tree Additions based on Participation Rates for each Treatment Model

Pollution data and existing tree composition are consistent throughout the baseline and treatment models. Where the treatment models vary is in tree count, ground cover, and the subsequent impact on air quality benefits. Figure 11 highlights the additive calculations of new trees for each level of participation, for both the total catchment and the sample plots, based on the methodology outlined in the previous section. As mentioned, the average Desert fern, at 15' canopy width, 15" DBH, and 20' total height, was selected as the "optimal" new tree input for all of the new trees included. Figure 11 is helpful in understanding the characteristics of tree composition by participation rate, compared to the baseline composition outlined above. The tree counts represent new trees added to the 101 trees already observed within the sample plots and the 569 trees estimated for the total catchment area. These new tree counts represent a significant number of trees to be added across the site. To provide context for these numbers, when broken down, the residential additions amount to about three new trees per residential lot. The treatment models also reflect the subsequent conversion of impervious surfaces to pervious from the proposed LID implementation. Table 4 in the previous section highlights the observed differences in ground cover across the baseline and participation rates. Understanding the existing context and the model inputs allows for a clearer interpretation of the results on air quality impact.

4.2 Air Quality Impacts

4.2.1 Pollution Removal Rates

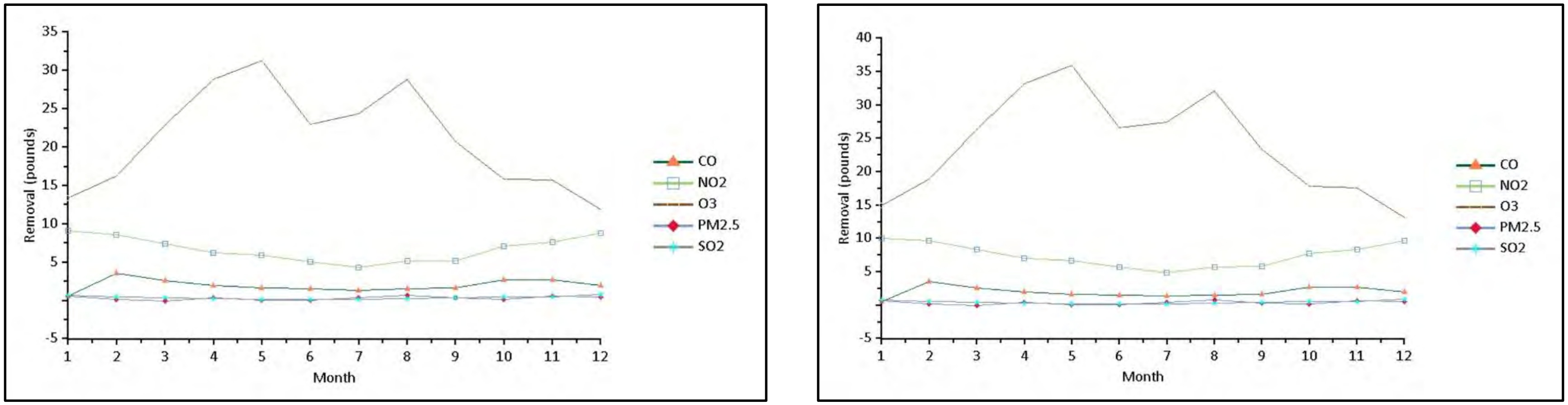


Figure 12. Baseline and 25% Participation Air Pollutant Removal Rates by Trees and Shrubs; retrieved from i-Tree Eco Baseline Model Results

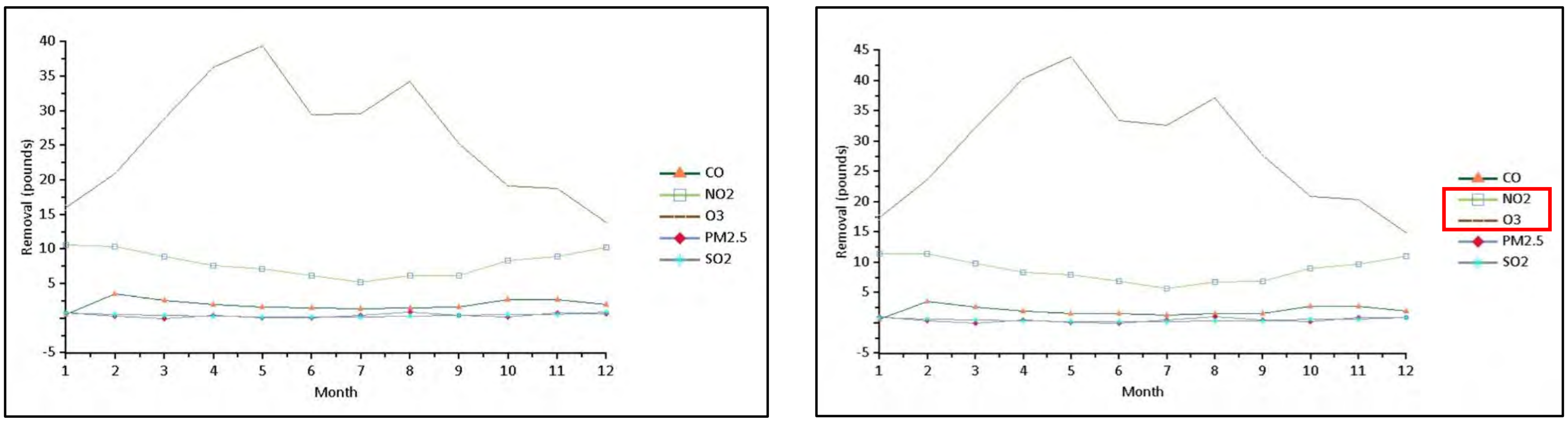


Figure 13. 50% and 100% Participation Air Pollutant Removal Rates by Trees and Shrubs; retrieved from i-Tree Eco Model Results

With this understanding of the pollutants and concentrations used within the model, the impacts of LID implementation on pollution removal rates can be contextually understood. The first four graphs in Figures 12 and 13 illustrate the removal rates of each pollutant (CO, NO_2, O_3, $PM_{2.5}$, SO_2) by trees and shrubs within the different participation models. These graphs show the relative improvements in air quality from the addition of the LID features, specifically the new Desert ferns. The improvements from baseline to 100 participation are expressed in pounds removed with significant variations in scale across the charts. O_3 concentrations stand out as the largest and most volatile in pounds removed while the other pollutants appear to remain much lower and more constant. To control for scale and directly compare across the scenarios, Figure 14 isolates the two pollutant parameters of most interest to the larger study, O_3 and $PM_{2.5}$, in closer detail.

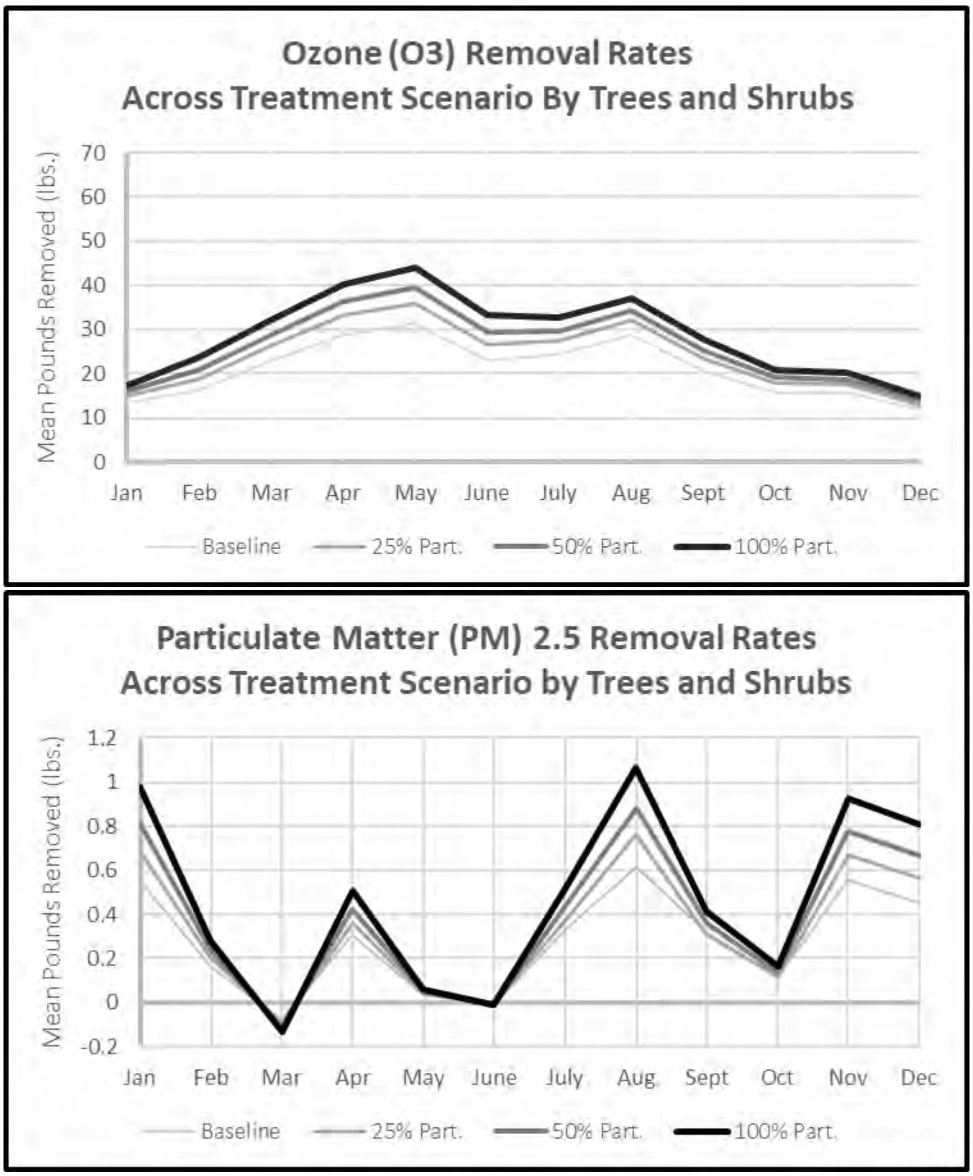


Figure 14. Pollution removal rates for O_3 and $PM_{2.5}$ across participation scenarios by trees and shrubs.

It can be seen here that both O_3 and $PM_{2.5}$ show an increase in removal with increasing LID participation, while mostly in proportional increments. This is to say that greater implementation of LID or one participation scenario over another does not yield exponential advantages or greater economies of scale. This is reiterated when observing the total annual pounds removed by trees and shrubs across the different participation levels and compared to the baseline (Figure 15). While several hundred more pounds of O_3 were removed in each model than $PM_{2.5}$, it is most effective to analyze these results within each pollutant rather than across the aisle as different volumes of different pollutants create different outcomes. Through this lens, we can see that each additional implementation of LID garners a similar removal rate for the two pollutants as implementation reaches 100 percent participation.

PM 2.5 Total Annual Removal

Participation Model	Pounds Removed	Value in Dollars
Baseline Model	3.4	$517.51
25% Participation	4.0	$608.84
50% Participation	4.7	$715.39
100% Participation	5.6	$852.38

Ozone Total Annual Removal

Participation Model	Pounds Removed	Value in Dollars
Baseline Model	252.6	$197.03
25% Participation	287.1	$223.94
50% Participation	311.8	$243.20
100% Participation	344.3	$268.55

Figure 15. Total pounds removed annually for $PM_{2.5}$ and O_3 by Trees and Shrubs.

Figure 15 also highlights the value of each removal rate for O_3 and $PM_{2.5}$ in terms of US dollars. Using metrics found within i-Tree Eco, O_3 values were calculated using a price point of $0.78 per pound whereas $PM_{2.5}$ values were calculated using a price point of $152.21 per pound. These differences in market value correlate with the potency of one unit of pollutant as well as the costs associated with each. $PM_{2.5}$, while low in total volume, has a clear monetary advantage when removed and signifies that even a marginal change in pollutant volume has a significant impact on associated costs and harm. Values like these are not absolute and should be considered as a rough estimate of removal potential. However, these values do add color to the context of pollution removal totals for the catchment site, especially for those that seem marginal or insignificant.

Another takeaway from the overall results is the reduced concentrations of NO_2. This is essential to mitigating potential negative impacts of urban tree implementation, as NO_2 can create O_3 particles when combined with bVOCs. However, the degree at which NO_2 and overall O_3 concentrations are being removed against the addition of new bVOC emissions should be explored to fully understand the positive and negative implications of new tree plantings. Figures 16 and 17 highlight the impacts of bVOCs across species and land use within the baseline and complete participation models. In Figure 16, Mimosa trees and Red Gum Eucalyptus are found to contribute the most to emissions. The addition of the Desert fern also yields relatively moderate emissions. However, when considering the large quantity of these trees, the impact of one individual tree is much smaller. Both the 25 and 50 percent participation models showed lower emissions from the Desert fern than the 100 percent model due to the smaller quantity of trees being "planted". This tradeoff in emissions also supports the recommended implementation process of including a diversity of species, not just one to scale, in order to mitigate any harmful effects from monocropping.

Figure 17 also shows the total bVOCs per pound per year decreasing in the 100 percent participation model when compared to the baseline numbers. This is explained through the differences in concentrations of Monoterpene versus Isoprene for different species and the Desert fern. Isoprene has an average Maximum Incremental Reactivity (MIR), used to express impacts of VOCs towards ozone production, of 10 compared to the average MIR of Monoterpenes of 3-4 (Carter, 2010). This means that Isoprene is two and half time more harmful towards ozone production than Monoterpenes, creating a larger concern for Isoprene production within species selection. The introduction of the Desert Fern in Figure 15 creates zero Isoprene emissions and showcases the value of planting low-emitting species like the Desert fern. Figure 16; however, highlights the concern with unintentional planting. As mentioned in the existing composition, Mimosa trees were most common in the residential sample plot. Red Gum Eucalyptus was most common around Public lands or Schools. These trees account for significant bVOC emissions and harmful ozone production impacts in areas with the most human activity. This understanding of species' externalities can inform better solutions to mitigate compounding exposure in vulnerable land uses.

VOC Emissions of Trees by Species

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

i-Tree Eco

Species Name	Monoterpene (lb/yr)	Isoprene (lb/yr)	Total VOCs (lb/yr)
Argentine senna	0.1	0.0	0.1
Beefwood	9.9	0.0	9.9
California palm	0.0	4.4	4.4
Honey mesquite	0.0	0.0	0.0
Japanese zelkova	0.0	0.0	0.0
Red gum eucalyptus	42.4	135.7	178.2
Russian olive	0.0	0.0	0.0
Silver wattle	166.1	0.7	166.7
tamarisk spp	0.3	0.0	0.3
Velvet ash	0.0	0.0	0.0
Total	**218.8**	**140.8**	**359.6**

Species Name	Monoterpene (lb/yr)	Isoprene (lb/yr)	Total VOCs (lb/yr)
Argentine senna	0.1	0.0	0.1
Beefwood	9.9	0.0	9.9
California palm	0.0	3.0	3.0
Feather bush	35.3	0.0	35.3
Honey mesquite	0.0	0.0	0.0
Japanese zelkova	0.0	0.0	0.0
Red gum eucalyptus	42.4	92.2	134.6
Russian olive	0.0	0.0	0.0
Silver wattle	166.1	0.5	166.5
tamarisk spp	0.3	0.0	0.3
Velvet ash	0.0	0.0	0.0
Total	**254.0**	**95.7**	**349.7**

Figure 16. VOC Emissions by Tree Species for Baseline and 100 Percent Participation Models; retrieved from i-Tree Eco Model Results

VOC Emissions of Trees by Stratum

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

i-Tree Eco

Stratum	Monoterpene (lb/yr)	Isoprene (lb/yr)	Total VOCs (lb/yr)
Commercial	0.3	1.8	2.0
Industrial	46.9	138.4	185.3
Public Land and Schools	4.6	0.0	4.6
Residential	166.9	0.7	167.6
Study Area	**218.8**	**140.8**	**359.6**

Stratum	Monoterpene (lb/yr)	Isoprene (lb/yr)	Total VOCs (lb/yr)
Commercial	5.3	1.2	6.5
Industrial	65.2	94.0	159.2
Public Land and Schools	7.2	0.0	7.3
Residential	176.3	0.4	176.7
Study Area	**254.0**	**95.7**	**349.7**

Figure 17. VOC Emissions by Land Use for Baseline and 100 Percent Participation Models; retrieved from i-Tree Eco Model Results

This current analysis of total catchment pollution removal also only considers the benefits of trees and shrubs. As outlined in the methodology, LID application also creates a conversion in existing ground cover and the introduction of "unmaintained grass", in the form of rain gardens, linear basins, and bioswales. Figures 18 and 19 highlight the removal potential of unmaintained grass on catchment pollutant concentrations. Immediately, one acknowledges the seemingly blank chart of the baseline model. As no grass was found within the sample plot, the i-Tree model aggregated this finding across the catchment. This is not to say that the catchment does not contain any grass, especially when there is a public park located within the study area. However, these limitations of the model do not eliminate the findings from improved pervious conversions. The "introduction" of grass to the model drastically improves air pollution removal rates across the site. Grasses, similar at least on the surface to trees and shrubs, capture more pounds of O_3 and NO_2 production but have a smaller impact on $PM_{2.5}$ and SO_2 concentrations. However, when looking more closely at the isolated results of O_3 and $PM_{2.5}$ as previously explored (Figures 20, 21), O_3 removal rates are much higher at complete participation for grasses than for trees and shrubs. Whereas $PM_{2.5}$ removal is much lower among grasses than the totals observed from trees and shrubs.

One of the biggest differences between the results of the two vegetations is the amounts removed for each pollutant across participation scenario. As no grass was the baseline model, each scenario and introduction of more grass offers a much more visual removal potential with LID implementation (Figure 18, 19). And while trees and shrubs showcased a fairly proportional increase in pollution removal potential, grasses display a more exponential impact on each pollutant, where increasing implementation offers accelerating benefits for pollution removal per application (Figure 20, 21). With this, grasses appear to exhibit a stronger relationship with pollution removal than shown by trees, with more grass area contributing to substantially more pollution removal at each level (Figure 22).

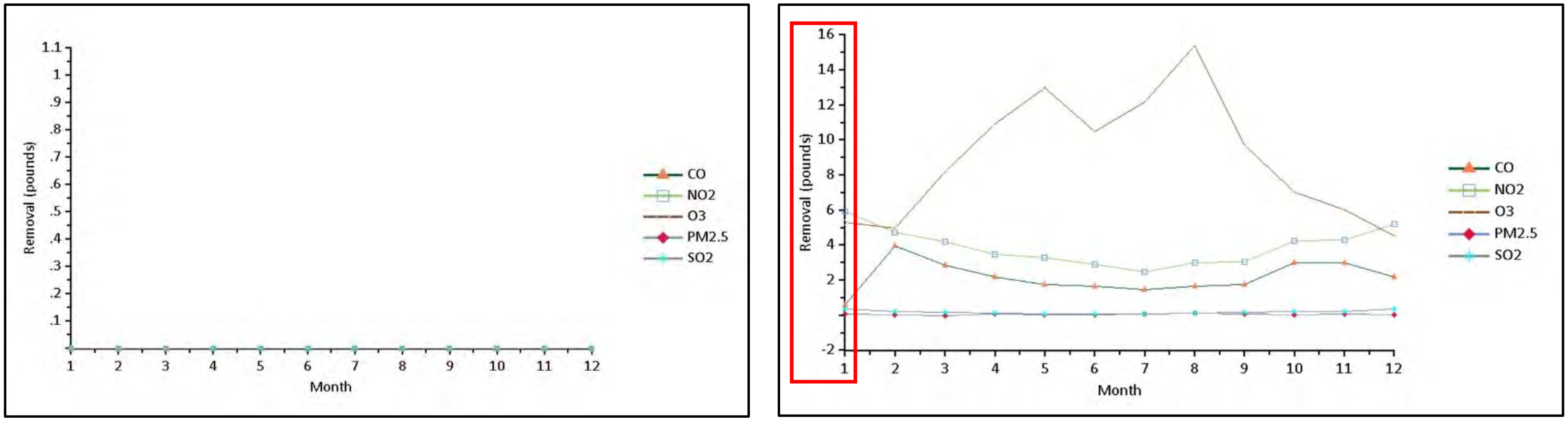


Figure 18. Air Pollutant Removal Rates by Grass for Baseline and 25 Percent Participation Models; retrieved from i-Tree Eco Baseline Model Results

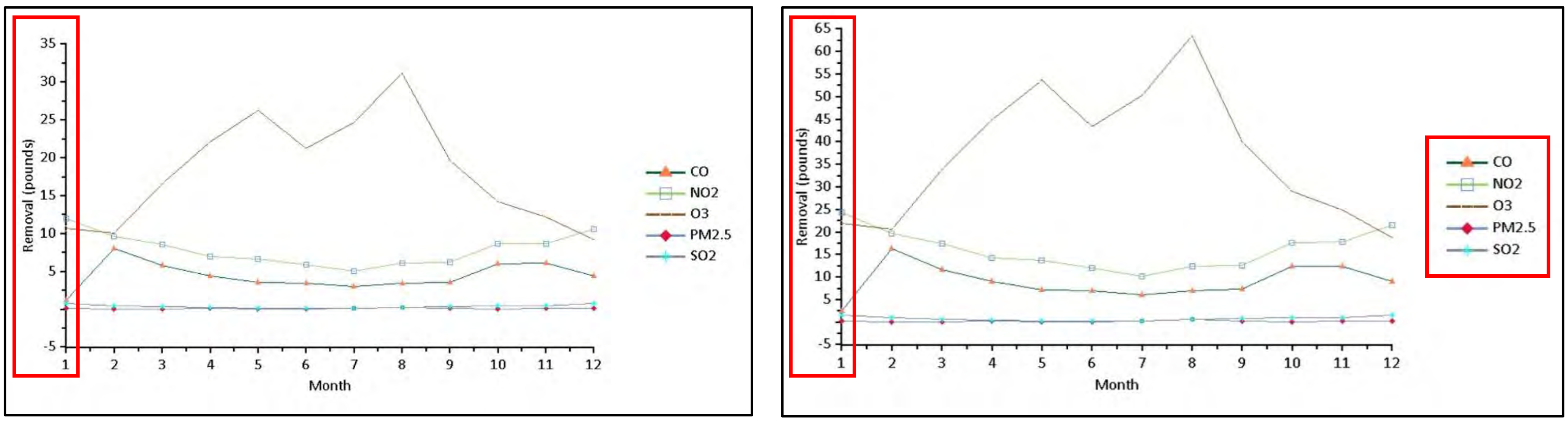


Figure 19. Air Pollutant Removal Rates by Grass for 50 and 100 Percent Participation Models; retrieved from i-Tree Eco Model Results

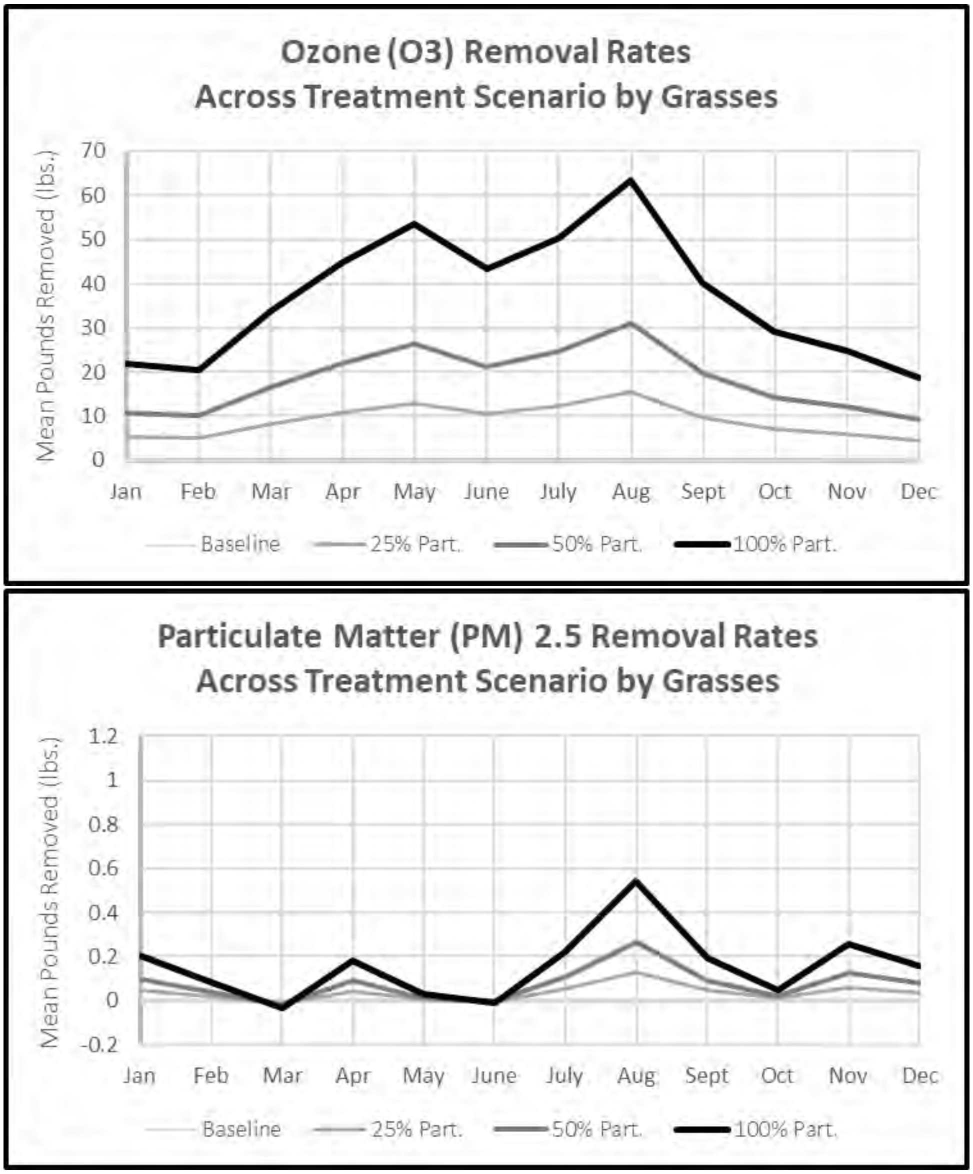


Figure 20. Pollution removal rates for O_3 and $PM_{2.5}$ across participation scenarios by trees and shrubs.

However, the application of grasses as mentioned previously is not directly comparable to the application of trees and shrubs and thus should be understood when contextualizing their value. For instance, it is important to control for area and scale of implementation when interpreting these results. Grass introduction within the conversion process accounts for much more land coverage and conversion than new tree introduction in each participation scenario, creating more opportunity for removal potential. Overall, the observed results of grass and its effectiveness in air pollution removal highlight the opportunities for grass cover in LID implementation to improve air quality as well as surface land temperatures. These results provide strong evidence for a deeper investigation into the opportunities for grasses to improve air quality, both through a targeted literature review and further modeling or research efforts.

Grasses have some unique benefits over tree planting, such as not emitting offsetting bVOCs and contributing to the higher removal of O_3. However, these benefits must also be considered with their tradeoffs, like the lack of other co-benefits produced by trees like shade and the overall water consumption of water intensive grasses. Therefore, rain gardens that provide grass coverage through stormwater capture can yield significant benefits and mitigate these tradeoffs through a combination of tree and grass application, as shown in Figure 21.

PM 2.5 Total Annual Removal

Participation Model	Pounds Removed by Trees and Shrubs	Pounds Removed by Grasses	Collective PM2.5 Removal (Value in $)
Baseline Model	3.4	0.0	3.4 ($517.51)
25% Participation	4.0	0.5	4.5 ($684.95)
50% Participation	4.7	0.9	5.6 ($852.38)
100% Participation	5.6	1.9	7.5 ($1,141.58)

Ozone Total Annual Removal

Participation Model	Pounds Removed by Trees and Shrubs	Pounds Removed by Grasses	Collective Ozone Removal (Value in $)
Baseline Model	252.6	0.0	252.6 ($197.03)
25% Participation	287.1	107.7	394.8 ($307.95)
50% Participation	311.8	218.1	529.9 ($413.32)
100% Participation	344.3	444.2	788.5 ($615.03)

Figure 21. Total pounds removed annually for $PM_{2.5}$ and O_3 across vegetation.

In summation, Table 5 highlights the overall estimated air pollution removal rates for all observed vegetation across the different treatment scenarios. These numbers represent an aggregation of the five measured pollutants outlined above (Figure 21) for the baseline and three participation models. Table 5 helps to understand the current and potential impacts of LID investment within the catchment area at a comprehensive, yet simplified view. While it is still important to consider the limitations and variability within the results as discussed, these numbers provide a comparison across treatment and highlight the increasing benefits of air pollution removal with increased investment. Table 5 also provides metrics for understanding the value of each investment over the years, in the short-term and the long-term.

Table 5. i-Tree Eco Aggregation in Pounds of Pollution Removed per Year

Participation Model	Pounds Removed by Trees and Shrubs	Pounds Removed by Grasses	Collective/Total Pollution Removal
Baseline Model	363.9	0.0	363.9
25% Participation	408.4	183.1	591.5
50% Participation	440.6	370.9	811.5
100% Participation	483.5	755.7	1,239.2

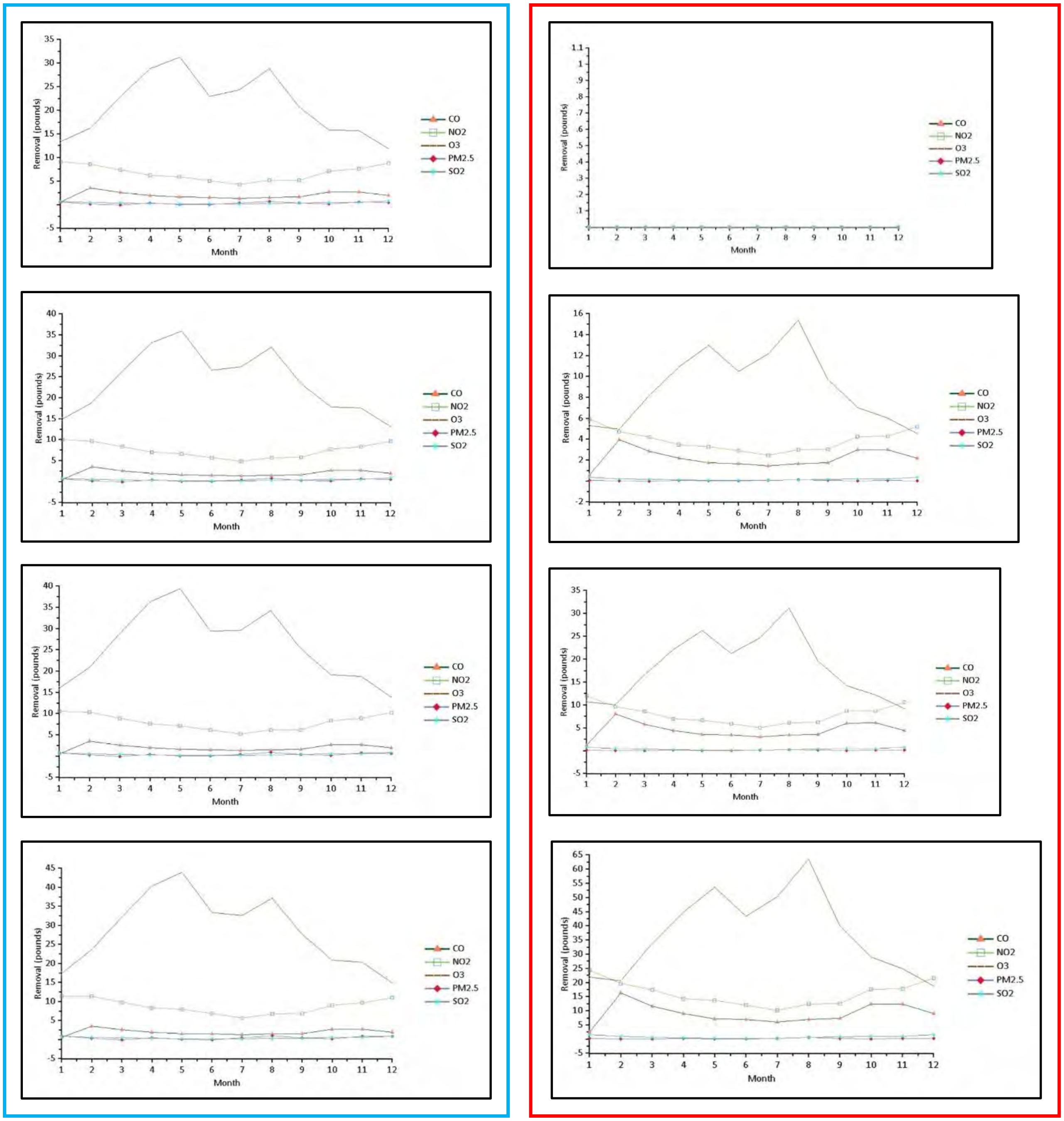


Figure 22. Comparison of Air Pollutant Removal Rates across models (from Baseline to Complete Participation) by Trees and Shrubs (Blue) and Grasses (Red); retrieved from i-Tree Eco Model Results

4.2.2 Health Impacts

Pollution removal rates such as these can also be translated into improvements in health. One of the main interests in this study area was its relationship to socio-economic status and opportunities for addressing environmental justice challenges and contributing to social equity. In many urban contexts, including Phoenix, underserved communities are disproportionately exposed to environmental hazards, with documented negative health implications. Articulating these removal rates beyond dollar values and contextualizing the social value of such removal in terms of health equity can provide a deeper level of impact for the intentional LID application within the City where needed most. The i-Tree Eco reports provide information on health benefits across the four models. Figure 22 shows the comparison between the baseline and 100 percent participation results of LID application to reduce instances of asthma exacerbation and hospitalization. While these results appear marginal now, continued investigation into different beneficial tree species and their implementation could elevate the health impacts of LID to an even greater effect. The values attributed to these improvements could also be reinvested in equitable ways to multiple health justice advancements. As mentioned with bVOCs, introducing LID features that mitigate their own emissions to provide the maximum benefit toward pollution reduction can go a long way in improving these disparities. There is a greater need to understand the existing health inequities in the area of interest and the opportunities to provide targeted LID application to address these concerns.

Air Quality Health Impacts and Values Summary: Trees, Shrubs, Grass/Herbaceous

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

i-Tree Eco

	NO2 Incidence (Reduction/yr)	NO2 Value ($/yr)	O3 Incidence (Reduction/yr)	O3 Value ($/yr)	PM2.5 Incidence (Reduction/yr)	PM2.5 Value ($/yr)	SO2 Incidence (Reduction/yr)	SO2 Value ($/yr)
Acute Bronchitis					0.000	0.00		
Acute Myocardial Infarction					0.000	1.26		
Acute Respiratory Symptoms	0.009	0.27	0.052	4.48	0.026	2.56	0.000	0.01
Asthma Exacerbation	0.121	10.14			0.027	2.16	0.002	0.15
Chronic Bronchitis					0.000	5.38		
Emergency Room Visits	0.000	0.03	0.000	0.01	0.000	0.02	0.000	0.00
Hospital Admissions	0.000	4.86	0.000	1.55			0.000	0.20
Hospital Admissions, Cardiovascular					0.000	0.25		
Hospital Admissions, Respiratory					0.000	0.11		
Lower Respiratory Symptoms					0.001	0.04		
Mortality			0.000	188.57	0.000	498.26		
School Loss Days			0.025	2.43				
Upper Respiratory Symptoms					0.001	0.02		
Work Loss Days					0.004	0.73		
Total	**0.130**	**15.30**	**0.077**	**197.03**	**0.059**	**510.78**	**0.002**	**0.35**

	NO2 Incidence (Reduction/yr)	NO2 Value ($/yr)	O3 Incidence (Reduction/yr)	O3 Value ($/yr)	PM2.5 Incidence (Reduction/yr)	PM2.5 Value ($/yr)	SO2 Incidence (Reduction/yr)	SO2 Value ($/yr)
Acute Bronchitis					0.000	0.01		
Acute Myocardial Infarction					0.000	2.81		
Acute Respiratory Symptoms	0.036	1.14	0.153	13.12	0.058	5.71	0.001	0.02
Asthma Exacerbation	0.504	42.30			0.059	4.82	0.006	0.51
Chronic Bronchitis					0.000	11.99		
Emergency Room Visits	0.000	0.13	0.000	0.03	0.000	0.03	0.000	0.01
Hospital Admissions	0.001	21.09	0.000	4.60			0.000	0.73
Hospital Admissions, Cardiovascular					0.000	0.56		
Hospital Admissions, Respiratory					0.000	0.24		
Lower Respiratory Symptoms					0.002	0.09		
Mortality			0.000	563.18	0.000	1,111.68		
School Loss Days			0.071	6.97				
Upper Respiratory Symptoms					0.001	0.05		
Work Loss Days					0.010	1.62		
Total	**0.541**	**64.67**	**0.225**	**587.90**	**0.131**	**1,139.63**	**0.007**	**1.27**

EPA Environmental Benefits Mapping and Analysis Program http://www.epa.gov/airquality/benmap/index.html
Incidence: the total number of adverse health effects avoided in a year due to a change in pollution concentration
Value: the economic value that is associated with the incidence of adverse health effects

Figure 22. Air Quality Health Impacts for the Current and Potential LID Application at 100 Percent Participation; retrieved from i-Tree Eco Model Results

4.2.3 Net Benefits

In summary, i-Tree Eco also provides an analysis of the net benefits of the different models. These benefits are absent of costs; however, can be interpreted for their larger benefits. As shown in Figure 23, which details the total benefits of each model from baseline to complete participation, total benefits continue to increase with participation and offer a substantial increase in benefits from the existing context. A majority of these benefits come through a significant increase in carbon sequestration with each tree planting. Callegary et al. (2021) relates this increase in sequestration to an increase in water retention. Air pollution removal rates also continue to increase; however, not at the scale or rate of carbon sequestered. The smaller removal benefits of air pollution can be coordinated with lessons learned in previous studies through the literature review. Hewitt et al. (2020) emphasizes the tertiary application of LID to reduce pollution and that to truly impact air pollution, one must address pollution at its source. However, these complementary benefits of LID application do progress the narrative of nexus thinking, where cities can address climate change advancements through CO2 reduction and air pollution hazards simultaneously with LID.

Net Annual Benefits for all Trees

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

i-Tree Eco

Benefits	Total $ (USD)	$ (USD)/tree	$ (USD)/capita
Energy	0.00	0.00	0.00
Gross Carbon Sequestration	111.31	0.20	0.00
Pollution Removal	471.63	0.83	0.00
Avoided Runoff	184.33	0.32	0.00
Total Benefits	**767.28**	**1.35**	**0.00**

Benefits	Total $ (USD)	$ (USD)/tree	$ (USD)/capita
Energy	0.00	0.00	0.00
Gross Carbon Sequestration	2,846.05	2.49	0.00
Pollution Removal	614.91	0.54	0.00
Avoided Runoff	234.54	0.20	0.00
Total Benefits	**3,695.50**	**3.23**	**0.00**

Benefits	Total $ (USD)	$ (USD)/tree	$ (USD)/capita
Energy	0.00	0.00	0.00
Gross Carbon Sequestration	5,069.05	3.14	0.00
Pollution Removal	737.71	0.46	0.00
Avoided Runoff	272.94	0.17	0.00
Total Benefits	**6,079.70**	**3.77**	**0.00**

Benefits	Total $ (USD)	$ (USD)/tree	$ (USD)/capita
Energy	0.00	0.00	0.00
Gross Carbon Sequestration	8,357.63	3.63	0.01
Pollution Removal	914.88	0.40	0.00
Avoided Runoff	327.19	0.14	0.00
Total Benefits	**9,599.70**	**4.17**	**0.01**

Figure 23. Baseline, 25%, 50%, and 100% Participation Net Annual Benefits for all Trees; retrieved from i-Tree Eco Model Results

This summation calculation also provides context on the proportional relationship between the three treatment scenarios. The 25 and 50 percent participation scenarios provide more than these percentages in benefits relative to the total benefits of 100 percent participation. The 25 percent participation scenario actually represents approximately 38 percent of the benefits while 50 percent participation contains over 63 percent. This provides a stronger context for the City of Phoenix to understand and consider the appropriate participation level of implementation for LID based on budget and net benefits.

4.3 Other Findings

The i-Tree report offers several more comparisons on related benefits of tress and LID. Based on temperature data from 2016, potential evapotranspiration for each scenario is calculated to determine the relative cooling benefits of the implemented vegetation (Figure 24). Results for such calculations vary slightly among the participation rates and represent only a small increase beyond the baseline conditions. This confirms the findings from the partner Urban Heat study, where small, yet consistent land surface temperature differences were observed.

The i-Tree report also evaluates oxygen production and carbon sequestration among the existing and additive vegetation. These two measurements, while outside the traditional scope of air quality parameters, provide another dimension towards overall air quality improvement. As shown in Figure 25, Oxygen was found to increase significantly over the participation rates, with residential and industrial land uses yielding the largest gains. These two areas, especially residential, can benefit from improvements in oxygen production that can lead to health protection and benefits in poor air quality areas.

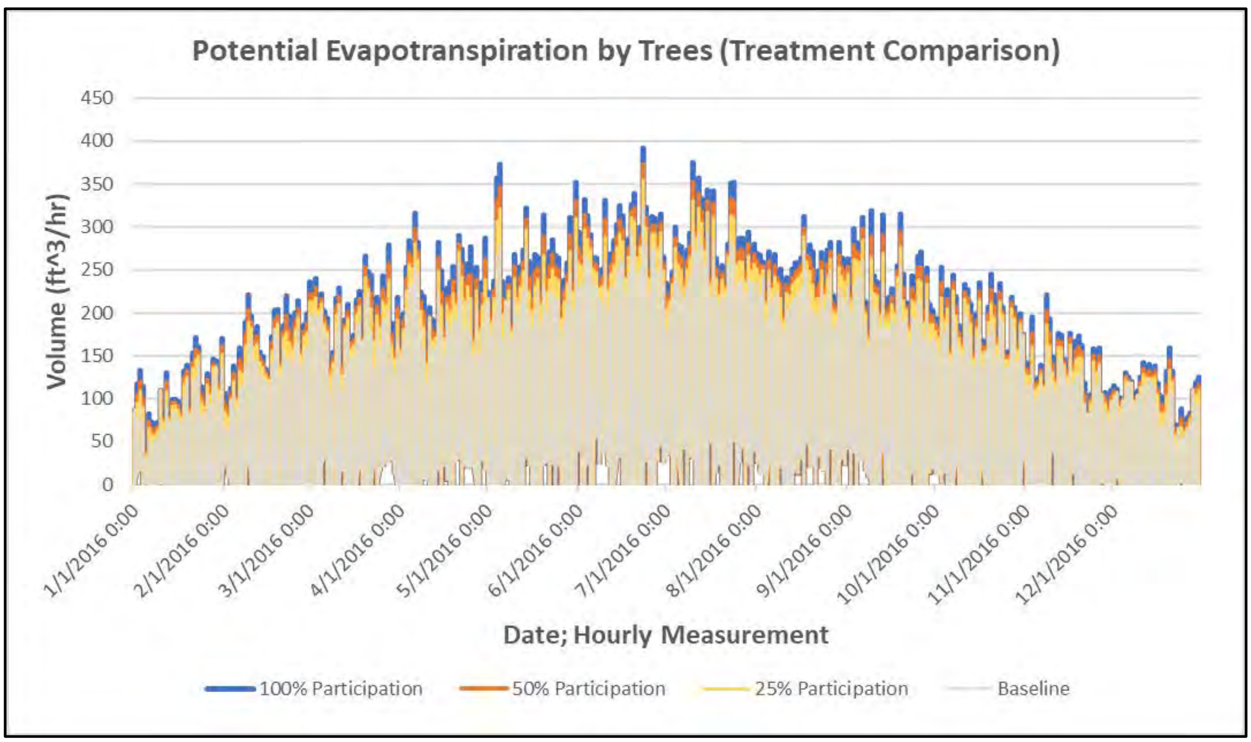


Figure 24. Evapotranspiration Comparison across the Four Models; retrieved from i-Tree Eco Model Results

Oxygen Production of Trees by Stratum

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

Stratum	Oxygen Production (ton/yr)
Residential	0.3
Public Land and Schools	0.2
Commercial	0.0
Industrial	0.2
Study Area	**0.6**

Stratum	Oxygen Production (ton/yr)
Residential	11.2
Public Land and Schools	2.7
Commercial	5.6
Industrial	20.6
Study Area	**40.2**

Stratum	Oxygen Production (ton/yr)
Residential	19.8
Public Land and Schools	5.3
Commercial	10.2
Industrial	37.1
Study Area	**72.3**

Stratum	Oxygen Production (ton/yr)
Residential	31.9
Public Land and Schools	9.0
Commercial	17.1
Industrial	61.8
Study Area	**119.9**

Figure 25. Clockwise From Top Left: Oxygen Production by Land Use for Baseline, 25, 100, and 50 Percent Participation; retrieved from i-Tree Eco Model Results

Carbon sequestration, as discussed within the net benefits of the models, can also work to improve air quality by mitigating greenhouse gas emissions and advancing climate action agendas. CO2 reduction is broken down by species type and land use in Figures 26 and 27, respectively. By land use, residential and industrial again are significant benefactors of CO2 reduction and carbon storage due to the higher concentration of trees, and the correlated increase in water retention, in these land uses (Callegary et al., 2021). By species type, the Desert fern (Feather bush) is significant due to the sheer quantity in the 100 percent participation model as well as the Beefwood, due to its larger size and DBH. These comparisons by species add another dimension of understanding for tree selection criteria for the City of Phoenix, where intentional efforts can work to mitigate air pollution and CO2 emissions collectively, as supported by the net benefits analysis. The i-Tree model provides several more calculations outside the scope of this project and merits deeper investigation. Many of the data criteria to effectively evaluate these other calculations was omitted in this study's methodology and results are mostly based on estimations and rough aggregations. More time and resources could be applied to understand these relationships from LID vegetation application in a more informed manner in future research.

4.4 Limitations of Results and Analyses

As with the methodology, there were many limitations and assumptions embedded within these results. First, many of the graphs and data representations from the i-Tree reports were static and unable to be adjusted. This was a major limitation for illustrating results as the graphic scales for several of these comparisons were inconsistent. The analysis and discussion of these figures was intended to mitigate any of this potential misunderstanding, but more control of report results would have been beneficial when making illustrative comparisons across models. Additionally, the previous limitations and assumptions discussed in this report are embedded within the interpreted results. These compounding limitations further limit the widespread applicability of the results and what is being observed. This report has taken significant strides to disclose and mitigate these limitations; however, structural and unavoidable limitations do impact the analytics of the outlined results. Some of the data during the data collection was also left blank, due to inability to acquire such data. The lack of costs associated with the model also provide limitations in assessing the cost verses the benefits for each participation rate. The feasibility of complete participation and its expected benefits may not outweigh the costs of implementation, maintenance, and other potential costs without further research to assess this. With these limitations in mind and the described results from above, the study provides a lens of critical discussion around these results and a path forward for future research.

Carbon Storage of Trees by Species

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

Species	Carbon Storage (ton)	Carbon Storage (%)	CO_2 Equivalent (ton)
Silver wattle	4.7	6.1%	17.2
Russian olive	0.3	0.4%	1.0
Red gum eucalyptus	2.1	2.7%	7.7
Velvet ash	0.1	0.1%	0.2
Beefwood	60.2	78.0%	220.8
Honey mesquite	0.6	0.8%	2.2
Argentine senna	0.1	0.1%	0.2
tamarisk spp	6.0	7.8%	22.2
California palm	2.2	2.8%	8.1
Japanese zelkova	1.0	1.3%	3.6
Total	**77.2**	**100%**	**283.2**

Species	Carbon Storage (ton)	Carbon Storage (%)	CO_2 Equivalent (ton)
Silver wattle	4.7	0.5%	17.2
Russian olive	0.3	0.0%	1.0
Red gum eucalyptus	2.1	0.2%	7.7
Velvet ash	0.1	0.0%	0.2
Beefwood	60.2	6.0%	220.8
Feather bush	925.9	92.3%	3,395.2
Honey mesquite	0.6	0.1%	2.2
Argentine senna	0.1	0.0%	0.2
tamarisk spp	6.0	0.6%	22.2
California palm	2.2	0.2%	8.1
Japanese zelkova	1.0	0.1%	3.6
Total	**1,003.1**	**100%**	**3,678.5**

Due to limits of available models, i-Tree Eco will limit carbon storage to a maximum of 7,500 kg (16,534.7 lbs) and not estimate additional storage for any tree beyond a diameter of 254 cm (100 in). Whichever limit results in lower carbon storage is used.

Figure 26. Carbon Storage by Land Use between the Baseline (Top) and 100 Percent Participation Model (Bottom); retrieved from i-Tree Eco Model Results

Carbon Storage of Trees by Stratum

Location: Phoenix, Maricopa, Arizona, United States of America
Project: Baseline, Series: 1, Year: 2021
Generated: 4/16/2021

Stratum	Carbon Storage (ton)	Carbon Storage (%)	CO_2 Equivalent (ton)
Residential	27.7	35.8%	101.5
Public Land and Schools	0.8	1.0%	3.0
Commercial	7.9	10.2%	29.0
Industrial	40.9	52.9%	149.8
Study Area	**77.2**	**100%**	**283.2**

Stratum	Carbon Storage (ton)	Carbon Storage (%)	CO_2 Equivalent (ton)
Residential	112.7	29.3%	413.2
Public Land and Schools	20.6	5.4%	75.7
Commercial	51.3	13.4%	188.2
Industrial	199.5	51.9%	731.7
Study Area	**384.2**	**100%**	**1,408.8**

Stratum	Carbon Storage (ton)	Carbon Storage (%)	CO_2 Equivalent (ton)
Residential	178.8	28.2%	655.7
Public Land and Schools	40.5	6.4%	148.5
Commercial	87.1	13.7%	319.4
Industrial	327.6	51.7%	1,201.4
Study Area	**634.0**	**100%**	**2,324.9**

Stratum	Carbon Storage (ton)	Carbon Storage (%)	CO_2 Equivalent (ton)
Residential	273.3	27.2%	1,002.0
Public Land and Schools	69.3	6.9%	254.3
Commercial	140.7	14.0%	516.1
Industrial	519.8	51.8%	1,906.1
Study Area	**1,003.1**	**100%**	**3,678.5**

Figure 27. Carbon Storage by Species across the Baseline (Top), 25, 50, and 100 Percent Participation Models (Bottom); retrieved from i-Tree Eco Model Results

5.0 Discussion

The results demonstrate that an overall improvement of air quality can be achieved through vegetation increases in LID implementation. The purpose of this study was to highlight these benefits and articulate the relationship between these factors for future planning initiatives. Several key takeaways were observed as were opportunities for deeper investigation.

One of the biggest takeaways in terms of air pollution reduction was the advantages of grasses. Representing rain gardens, linear basins, and bioswales as unmaintained grass in the model ground covers elevated pollution reduction rates significantly with each increase in participation. These results, coupled with the lack of bVOC emissions, allowed low-lying grass vegetations to absorb and mitigate more of the air quality concerns of the catchment than available with the observed and modeled trees or shrubs. The percentage of grass ground cover conversion may have been unrealistically high in the participation scenarios, but the afforded insight offers an aspiration towards these observed rates within future planning agendas and large-scale programming. Planners should also continue to challenge the narrative that such parking lot conversions are infeasible for cities like Phoenix. As the threats of climate change continue to emerge and strengthen, a more radical urban vision is necessary to sustain the health and wellbeing of our cities. Results from studies like this should not be automatically overlooked based on the current climate of things and should always be considered for the opportunities a more radical approach could provide. This study in particular can help pave the path for more comprehensive and creative endeavors in arid and semi-arid LID implementation.

As such an example, the application of LID and grass cover on building roof surfaces and walls could provide a particular benefit for the City of Phoenix or similar landscapes based on the observed results. Green roof and living wall planning efforts may be scarce in the Phoenix region and the eventual application of such technologies may be different than examples elsewhere, but deeper research into the feasibility of converting these impervious surfaces could have immense benefits for urban air quality. Jayasooriya et al. (2017) demonstrates these findings in Australia through i-Tree Eco. A similar study of these LID features within Phoenix could be modeled again through i-Tree Eco and understood to warrant a deeper investigation into physical implementation. Experimental green roofs already happening within the Valley could also be studied for their air quality impacts based on the connections illustrated in this current study.

Another takeaway from the pollution removal potential within this study was the overall lack of movement in $PM_{2.5}$, CO, and SO_2 across the participation rates, especially within the observed and modeled trees and shrubs. O_3 and NO_2 provided the biggest improvements, while still minimal, across the treatment scenarios. However, the other three primary pollutants still need to be addressed. These results are interesting as previous studies have specifically identified the benefit of trees to reduce $PM_{2.5}$ concentrations (McDonald et al., 2016; Jeanjean et al., 2016). The relative lack of movement within this study for these concentrations could be attributed to the specific trees found and selected for the model runs. Potential modeling scenarios that include different species and/or different combinations of implementation could be tested to understand the impacts of different vegetation towards the removal of $PM_{2.5}$, CO, and SO_2, which additionally contributes to $PM_{2.5}$ production. Understanding what works and what does not can aid in the development of a comprehensive LID implementation plan that addresses all of the major pollutants and not just a few. With more time and resources, these avenues of investigation would be exciting to explore.

The overall balance and general predictability of the observed results was also surprising. The scaling application of participation, while not directly applied to the i-Tree Eco model as intended, created incremental results based seemingly on quantity. Perhaps the scale of the site was too small to observe any peaks, or the application of a one-size-fits-all Desert fern was too simplistic, but the results provided little insight into the optimal level of participation within the catchment. As noted within the net benefits, some differences were observed for various levels of participation. Benefits declined at the complete participation level compared to the 25 percent and 50 percent participation. More opportunity to reconfigure the model to test some of these initial interpretations could lead to a stronger understanding of how best to optimize the results, where air quality improvements and toll of implementation are considered together. Inversely, the model results could be correct in assuming total revegetation is the way to achieve optimization. However, realistic and social considerations for people and industries that live on site as well as local resource limitation must continue to be included to find a path forward that is sustainable for all. Lower participation rates may bridge this gap and provide both social cohabitation and improved benefits towards air quality and stormwater retention.

Outside of this, the results from the Desert fern chosen for LID optimization proved to be well informed. Especially impressive was the overall reduction in bVOCs through the implementation of the Desert fern. Other parameters with less than impressive results could also be an indication that other species aside from the Desert fern should be considered. A variety of tree species, within and beyond the tree list of Table 3, could address all of these issues collectively and provide a pathway for LID implementation based on targeted criteria and species "superpower". Where the Desert fern did not improve CO or $PM_{2.5}$ as needed, Paloverdes or Hackberries could provide a different result based on variations in canopy size, density, and DBH. Additionally, collaborative LID vegetation, like grasses and trees working together, can compound on the co-benefits of strategic LID planning. Future application could involve specific tree species selection to craft the urban environment that best fits the intended outcome, where reductions in pollution rates are matched with shade production, carbon sequestration, and emissions considerations.

5.1 Limitations and Other Future Considerations

A significant limitation of the model and its results that requires future consideration is the assumed maturity of the tree species. This points to the importance of tree maintenance and care, given that the maximum co-benefits of trees are reached when the tree is at maturity. For one, to reach this level of observed results will take time, while the challenges facing communities are pressing. Two, a model representation of the growth across years could yield interesting and informative results regarding the deposition of pollutants over time and the implications by species. Such a modeling practice could be done within i-Tree and only requires more time and thought regarding the growth patterns by species. Another limitation of the selected model and methodology is the lack of spatial association between species. This does not allow for species grouping and canopy density development to improve leaf area indices and air pollution deposition. The i-Tree software could allow for this relationship through model manipulation, but the current model does not account for these interactions. Understanding these benefits through the modeling benefits of i-Tree to discern impacts by species and strata can lead to more strategies for LID implementation beyond species type and quantity. A final future consideration is that these models only begin to touch on the intersections between LID planning, health, and social equity. As highlighted above, i-Tree provides information on health benefits and incidence reductions; however, understanding more of the underlying community context related to health can help ground the results in social structures and justice concerns. This intersectionality of LID application can inform the equitable distribution of its co-benefits and target specific concerns through intentional species and feature selection.

6.0 Conclusion

With the world's population living in urban areas expected to exponentially increase over the next thirty years, understanding and maximizing the application of LID to improve air quality will be critical to maintaining livable spaces within already vulnerable cities. This study utilized i-Tree Eco for modeling to demonstrate the relationships between air quality and LID implementation with trees and vegetation in an arid and semi-arid urban climate for informed planning purposes. Results from this study can help to advance better decision making around intentional LID application to address air quality concerns and amplify these positive co-benefits across urban spaces for future generations.

The results from the treatment scenario models provide insight into the intensity of LID participation and the tradeoffs or limitations on air quality improvement. However, these results also indicate that full participation may not yield the most benefits proportionately. To fully understand this, further research is needed to assess the costs of implementation to deliver sound recommendations towards optimization and best-fit participation models. This research provides an initial foundation for future investigation, looking closer at the relationships between a combination of tree species for use in LID projects, how these species influence air quality over their growing cycle, and the intersections between LID planning and social equity to maximize observed co-benefits based on context-specific needs. As outlined in the literature review, this research provides an additional perspective and results for LID application in arid and semi-arid climates and expands planning research on air quality relationships and LID projects that include trees. The methodology, while complex and specific to the larger project goals, can provide insight for future i-Tree Eco studies on the limitations and assumptions that exist and the potential methods for mitigation and resolution. As the City of Phoenix considers the investment in and opportunities for LID around the city, results from this study can be reproduced for other locations of interest. Additional applications of LID can then be compared to this model to identify other opportunities for future research on this topic.

Overall, this study has provided a deeper, more critical insight into the impacts of LID on air quality and the relationships between species type, participation scale, and urban planning.

This study highlights the power of comprehensive LID planning to improve systems of health, resilience, equity, and urban identity (Whitman and Eisenhauer, 2020) through improvements in water retention, vegetation, and local air quality. Cities are the future and targeted LID application will play an integral role in creating safe and livable spaces for all.

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8.0 Appendix

Content List

- Literature Review Excel Spreadsheet
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Air Quality Methodology Literature Review: Quantifying the Impacts of Green Infrastructure on Air Quality Improvements					
Article	*Reference*	*Location*	*Methodology*	*Parameters*	*LID Treatment*
Potential and limitation of air pollution mitigation by vegetation and uncertainties of deposition-based evaluations: Air pollution mitigation by vegetation	Nemitz et al., 2020	UK (countrywide)	Atmospheric Chemistry and Transport Modeling (ACTM)	PM 2.5, NOx, NO2, NH3, O3, SO2, and bVOC	Vegetation (not specified) across the country and urban vegetation across the country
Measuring multi-scale urban forest carbon flux dynamics using an integrated eddy covariance technique	Zhang et al., 2019	Shanghai, China; Feng Xian University Campus	EddyPro 5.1.1 software	CO2 and carbon sequestration/sink	Urban forest, evergreen trees/urban study area
Urban trees and their impact on local Ozone concentration-A microclimate modeling study	Simon et al., 2019	Mainz, Germany; other German urban areas	ENVI-met and box model	O3 and bVOC (isoprene)	Urban and suburban trees in different modeling scenarios
Exploring the potential for air pollution mitigation by urban green infrastructure for high density urban environment	Yang et al., 2019	Not specified; case study in Taiyuan, China	ENVI-Met and Systems Dynamics model	PM 10, dry deposition	Urban trees, boreal deciduous and evergreens
Citizen science-informed community master planning: Land use and built environment changes to increase flood resilience and decrease contaminant exposure	Newman et al., 2020	Manchester, TX (Houston)	Field samples, participatory community outreach, Green Values Calculator, design development	PAHs and metalloids, indoor and outdoor dust	Urban parks, wetlands/riparian restoration, smaller-scale implementation (bioswales, rain gardens, etc.)
Contribution of ecosystem services to air quality and climate change mitigation policies: The case of urban forests in Barcelona, Spain	Baró et al., 2014	Barcelona, Spain	i-Tree Eco model	O3, CO, NO2, PM 10, and SO2; bVOCs; carbon sequestration, dry deposition	Urban trees
Urban park systems to support sustainability: The role of urban park systems in hot arid urban climates	Kim and Coseo, 2018	Phoenix, AZ	i-Tree Eco model	O3, CO, NO2, PM 10, PM 2.5, and SO2; carbon sequestration	Urban trees/tree cover in urban park system
Green infrastructure practices for improvement of urban air quality	Jayasooriya et al., 2017	Melbourne, Australia	i-Tree Eco model	O3, CO, NO2, PM 10, PM 2.5, and SO2	Urban Trees, green roofs and green walls
Does "greening" of neotropical cities considerably mitigate carbon dioxide emissions? The case of Medellin, Colombia	Reynolds et al., 2017	Medellin, Colombia	i-Tree Streets and i-Tree Canopy models	CO2 and carbon sequestration	Urban trees and tree canopy
Potential of particle matter dry deposition on green roofs and living walls vegetation for mitigating urban atmospheric pollution in semiarid climates	Viecco et al., 2018	Chile (countrywide)	Lab experiments and field samples data collection	PM 2.5 and PM 10, dry deposition	Sedums and Succulents, Green Roofs and Living Walls
The removal efficiencies of several temperate tree species at adsorbing airborne particulate matter in urban forests and roadsides	Kwak et al., 2019	Seoul, South Korea	Lab experiments and leaf surface samples; Leaf Area Index	PM 2.5 and PM 10	Urban forest and roadsides (street trees); five tree species most commonly found in SK
Unexpected air quality impacts from implementation of green infrastructure in urban environments: A Kansas City case study	Zhang et al., 2020	Kansas City, MO/KS	Land Surface Modeling, WRF-CMAQ coupled model	PM 2.5 and O3, summertime	Urban reforestation, wetland restoration
Modelling the effectiveness of urban trees and grass on PM2.5 reduction via dispersion and deposition at a city scale	Jeanjean et al., 2016	Leicester, UK	LiDAR 3D imaging and OpenFOAM model (CFD)	PM 2.5	Urban trees and grasses, separate and together
Producing urban aerobiological risk map for Cupressaceae family in the SW Iberian peninsula from LiDAR technology	Pecero-Casimiro et al., 2020	Iberian Peninsula (Portugal and Spain)	LiDAR imaging and the AIROT Index, visualized through Kriging Analysis Mapping	Pollen	Ornamental trees and plants from the Cupressaceae family
Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review	Abhijith et al., 2017	Not specified; urban street canyons and open road	Literature review and synthesis	Not specified; air pollution in general, several studies investigating several different gases and PM	Trees and hedges, green walls and green roofs; urban street canyons and open road
Using green infrastructure to improve urban air quality (GI4AQ)	Hewitt et al., 2020	Not specified; general policy guidelines, mostly applied to the UK	Literature review and synthesis	Not specified; air pollution in general, several studies investigating several different gases and PM	Trees and hedges, urban canopy and green oases
Do green spaces affect the spatiotemporal changes of PM2.5 in Nanjing?	Chen et al., 2016	Nanjing, China	Monitoring stations, field samples; land use cover analysis, ArcGIS	PM 2.5, seasonal distribution	Urban green cover and vegetation;
Removal of PM10 by forests as a nature-based solution for air quality improvement in the Metropolitan city of Rome	Marando et al., 2016	Rome, Italy; larger European context	Remote Sensing and ArcGIS; monitoring stations, field samples, and aerial imaging	PM 10, dry deposition and seasonal distinctions	Urban and peri-urban forests; trees: evergreen and deciduous species

Required Data Inputs for i-Tree Eco		
Additional Data Collection		*Y/N*
Tree Information	Species	**Yes**, will need to determine; for different LID treatment scenarios
	Land Use	**Yes**, will need to determine; for different LID treatment scenarios
	Diameter Breast Height	**Yes**, will need to calculate; both height and from where it was measured for each tree species sampled; potentially for different projection timelines of treatment maturity
	Crown Dieback Percentage	**Yes**, will need to calculate; for each tree species sampled; i-Tree Eco offers a predetermined range of dieback percentages
	Total Height	**Yes**, will need to calculate; for each tree species sampled
	Percent Impervious	**Yes**, will need to calculate; for different LID treatment scenarios
Shrub Information	Species	**Yes**, will need to determine; for different LID treatment scenarios
	Height	**Yes**, will need to calculate; for each shrub species sampled; potentially for different projection timelines of treatment maturity
	Percent Shrub Area	**Yes**, will need to determine; for different LID treatment scenarios
Plot Information	Ground Cover	**Yes**, will need to determine; for different LID treatment scenarios; i-Tree Eco offers 11 predetermined ground covers available for use
	Land Use	**Yes**, will need to determine; for different LID treatment scenarios; i-Tree Eco offers 13 predetermined land use covers available for use
	Percent Tree Cover	**Yes**, will need to determine; for different LID treatment scenarios
	Percent Shrub Cover	**Yes**, will need to determine; for different LID treatment scenarios
	Percent Measured	**Yes**, will need to determine sample or complete assessment
Weather and Air Quality Information	Meteorological Data	No, provided by i-Tree program; if comfortable with using regional data from 2016
	Air Quality/Pollution Data	No, provided by i-Tree program; if comfortable with using regional data from 2016

**If additional analyses are pursued, additional data may be needed to be collected; refer to i-Tree Eco User's Manuel v.6, 2020 for detailed forms on data collection and recording.*

Vegetation that required estimation due to inaccessibility (highlighted)

i-Tree Field Data Collection; Collected on Saturday, March 20, 2021

Land Use: Residential (725 S 1st St to 713 S 1st St; 714 S 2nd St to 726 S 2nd St; and ally)

Species (**S**)	DBH (in.)	DBH Ht. (ft.)	Crown % Dieback	Total Ht. (ft.) (**S**)	Top Ht.	Base Ht.	Width N/S	Width E/W	% Missing (**S**)	% Impervious	**% Shrub Area**	Planted or Ingrowth
Silver Wattle/Mimosa (Acacia Dealbata)	1.75	4.5	Dying	12	12	6	6	3		100		Planted
Silver Wattle/Mimosa (Acacia Dealbata)	0.56	1	Dying	5.5	5.5	0.75	4.75	2		100		Planted
Silver Wattle/Mimosa (Acacia Dealbata)	2.07	2	Good	10	10	3	7	16		100		Planted
Silver Wattle/Mimosa (Acacia Dealbata)	2.87	1	Good	10	10	2	8	16		100		Planted
Silver Wattle/Mimosa (Acacia Dealbata)	0.48	2	Fair	10	10	1	9	10		100		Planted
DBH2	0.80	2										
DBH3	1.27	2										
Silver Wattle/Mimosa (Acacia Dealbata)	0.80	1	Fair	6	6	2	4	7		100		Planted
Silver Wattle/Mimosa (Acacia Dealbata)	9.55	4.5	Poor	30	30	10	20	20		100		Planted
Honey mesquite (Prosopis glandulosa)	4.14	1	Fair	12	12	2	10	15		100		Planted
DBH2	1.43	1										
Arizona Ash (Fraxinus velutina)	2.00	1	Dying	7	7	0.5	6.5	5		100		Planted
Silver Whittle (Acacia Dealbata)	9.55	4.5	Fair	45	45	20	25	35		100		Planted
Texas barometer bush (Leucophyllum frutescens)				2.5					0		100	
Texas barometer bush (Leucophyllum frutescens)				2.5					0		100	
Texas barometer bush (Leucophyllum frutescens)				2.5					0		100	
Texas barometer bush (Leucophyllum frutescens)				2.5					0		100	
Texas barometer bush (Leucophyllum frutescens)				2.5					0		100	
Texas barometer bush (Leucophyllum frutescens)				2.5					0		100	
Silver Wattle/Mimosa (Acacia Dealbata)	9.55	4.5	Fair	20	20	12	8	15		100		Ingrowth
Silver Wattle/Mimosa (Acacia Dealbata)	9.55	4.5	Fair	30	30	12	18	20		100		Ingrowth
Silver Wattle/Mimosa (Acacia Dealbata)	9.55	4.5	Good	30	30	12	18	35		100		Ingrowth
Silver Wattle/Mimosa (Acacia Dealbata)	1.75	2	Good	10	10	3	7	8		100		Ingrowth
Beefwood (Grevillea striata)	12.42	4.5	Good	50	50	0	50	20		100		Ingrowth
Beefwood (Grevillea striata)	12.42	4.5	Good	30	30	0	30	15		100		Ingrowth
Beefwood (Grevillea striata)	12.42	4.5	Good	20	20	0	20	10		100		Ingrowth

Land Use: Public Schools (E. Lincoln St to Grant St. and 1st to 3rd St.)

Species (**S**)	DBH (in.)	DBH Ht. (ft.)	Crown % Dieback	Total Ht. (ft.) (**S**)	Top Ht.	Base Ht.	Width N/S	Width E/W	% Missing (**S**)	% Impervious	**% Shrub Area**	Planted or Ingrowth
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Good	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Fair	8	8	1	7	10		100		Planted
Honey mesquite (Prosopis glandulosa)	2.55	0.5	Dying	8	8	1	7	10		100		Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					75		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					15		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					15		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					75		100	Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Dead	25	20	10	10	20	100	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Dead	25	20	10	10	20	100	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Dead	25	20	10	10	20	100	100		Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				4					0		100	Planted
Fairy duster (Calliandra eriophylla)				4					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted

Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				1					25		100	Planted
Silver Wattle/Mimosa (Acacia Dealbata)	9.55	4.5	Good	25	25	10	15	25	0	100		Planted
Russian olive (Elaeagnus angustifolia)	7.96	4.5	Good	18	18	6	12	15	0	100		Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		`	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted

Land Use: Commercial (E. Lincoln St. to Grant St. and Central Ave. to 1st St.)

Species (**S**)	DBH (in.)	DBH Ht. (ft.)	Crown % Dieback	Total Ht. (ft.) (**S**)	Top Ht.	Base Ht.	Width N/S	Width E/W	% Missing (**S**)	% Imprevious	**% Shrub Area**	Planted or Ingrowth
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				3					0		100	Planted
Fairy duster (Calliandra eriophylla)				2					10		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				3					50		100	Planted
Fairy duster (Calliandra eriophylla)				3					50		100	Planted
Fairy duster (Calliandra eriophylla)				3					50		100	Planted
Fairy duster (Calliandra eriophylla)				3					50		100	Planted
Fairy duster (Calliandra eriophylla)				3					50		100	Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	70	70	60	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	70	70	60	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	70	70	60	10	10	0	100		Planted
Japanese zelkova (Zelkova serrata)	7.32	4.5	Poor	24	14	8	6	12	75	100		Planted
Japanese zelkova (Zelkova serrata)	7.32	4.5	Poor	24	14	8	6	12	75	100		Planted
Japanese zelkova (Zelkova serrata)	7.32	4.5	Poor	24	14	8	6	12	75	100		Planted
Japanese zelkova (Zelkova serrata)	7.32	4.5	Poor	24	14	8	6	12	75	100		Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted

Texas barometer bush (Leucophyllum frutescens)				2					0		100	Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted
Tamarisk (Tamarix)	7.96	4.5	Good	30	30	10	20	20	0	100		Planted

Land Use: Industrial (Buckeye Rd to Papago St. and Central Ave to 3rd St.)

Species (**S**)	DBH (in.)	DBH Ht. (ft.)	Crown % Dieback	Total Ht. (ft.) (**S**)	Top Ht.	Base Ht.	Width N/S	Width E/W	% Missing (**S**)	% Imprevious	**% Shrub Area**	Planted or Ingrowth
Red gum eucalyptus (Eucalyptus camaldulensis)	17.20	4.5	Good	50	50	20	30	20	0	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	17.20	4.5	Good	50	50	20	30	20	0	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	17.20	4.5	Good	50	50	20	30	20	0	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	17.20	4.5	Good	50	50	20	30	20	0	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Fair	30	30	15	15	10	25	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Fair	30	30	15	15	10	25	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Fair	30	30	15	15	10	25	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Fair	30	30	15	15	10	25	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Fair	30	30	15	15	10	25	100		Planted
Red gum eucalyptus (Eucalyptus camaldulensis)	6.69	4.5	Fair	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	12.42	4.5	Good	40	40	20	20	10	10	100		Planted
Beefwood (Grevillea striata)	12.42	4.5	Good	40	40	20	20	10	10	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Beefwood (Grevillea striata)	13.22	4.5	Good	30	30	15	15	10	25	100		Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted

Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					25		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
Fairy duster (Calliandra eriophylla)				2					50		100	Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Good	60	60	50	10	10	0	100		Planted
California Palm (Washingtonia filifera)	12.42	4.5	Dead	60	60	50	0	0	0	100		Planted
Fairy duster (Calliandra eriophylla)				3					10		100	Planted
Fairy duster (Calliandra eriophylla)				3					10		100	Planted
Fairy duster (Calliandra eriophylla)				3					10		100	Planted
Fairy duster (Calliandra eriophylla)				3					10		100	Planted
Silver Wattle/Mimosa (Acacia Dealbata)	17.83	3	Fair	35	35	20	15	20	15	100		Planted
Oleander (Nerium oleander)				4					20		100	Planted
Oleander (Nerium oleander)				4					20		100	Planted
Oleander (Nerium oleander)				4					20		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					60		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					60		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				4					40		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					60		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					60		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					60		100	Planted
Texas barometer bush (Leucophyllum frutescens)				3					60		100	Planted
Argentine senna (Senna corymbosa)	2.71	2	Good	10	10	2	8	6	10	100		Planted
Argentine senna (Senna corymbosa)	2.71	2	Good	10	10	2	8	6	10	100		Planted
Argentine senna (Senna corymbosa)	2.71	2	Good	10	10	2	8	6	10	100		Planted
Argentine senna (Senna corymbosa)	2.71	2	Good	10	10	2	8	6	10	100		Planted
Argentine senna (Senna corymbosa)	2.71	2	Good	10	10	2	8	6	10	100		Planted
Argentine senna (Senna corymbosa)	2.71	2	Good	10	10	2	8	6	10	100		Planted

Land Use: Industrial (Buckeye Rd to Papago St. and Central Ave to 3rd St.)

Species (**S**)	DBH (in.)	DBH Ht. (ft.)	Crown % Dieback	Total Ht. (ft.) (**S**)	Top Ht.	Base Ht.	Width N/S	Width E/W	% Missing (**S**)	% Imprevious	**% Shrub Area**	Planted or Ingrowth
Feather bush/Desert Fern (Lysiloma watsonii)	15.00	4.5	Good	20	20	10	10	15	0	100	0	Planted

Scientific Name	Common Name
Parkinsonia praecox	Sonoran palo verde
Acacia constricta	Whitethorn acacia
Acacia greggii	Catclaw acacia
Atriplex canescens	Four winged saltbrush
Baccharis sarothroides	Desertbroom
Calliandra eriophylla	Fairy duster
Hymenoclea salsola	Burrobrush
Justicia californica	Beloperone
Larrea tridentata	Creosote bush
Lycium andersonii	Water jacket
Eucalyptus microtheca	Coolibah tree
Eucalyptus spathulata	Narrow-leaved gimlet
Leucophyllum frutescens	Texas barometer bush
Maytenus phyllanthoides	Florida mayten
Phoenix dactylifera	Date palm
Senna artemisioides	Wormwood senna

Native Tree Species mentioned in the LID handbook with information on Height and Canopy Width

Native Tree Species mentioned in the LID handbook

Non-native Tree Species mentioned in the LID handbook with information on Height and Canopy Width

Non-native Tree Species mentioned in the LID handbook

Tecoma stans	Ginger-thomas
Washingtonia filifera	California palm
Abarema	abarema spp
Abarema cochliocarpos	Abarema cochliocarpos
Abarema glauca	Abarema glauca
Abarema jupunba	Frijolillo
Abarema langsdorfii	pau gamba
Abatia	abatia spp
Abatia parviflora	Abatia parviflora
Abelia	abelia spp
Abelia chinensis	Abelia
Abelia triflora	Indian abelia
Abelia x grandiflora	Glossy abelia
Abeliophyllum	Abeliophyllum spp
Abelmoschus	Abelmoschus spp
Abies	fir spp
Abies alba	European silver fir
Abies amabilis	Pacific silver fir
Abies balsamea	Balsam fir
Abies bracteata	Bristlecone fir
Abies cephalonica	Greek Fir
Abies cilicica	Syrian Fir
Abies concolor	White fir
Abies concolor v. lowiana	Sierra white fir
Abies delavayi	Delavay's Fir
Abies fargesii	Farges Fir
Abies firma	Momi Fir
Abies forrestii v. georgei	George's Fir
Abies fraseri	Fraser fir
Abies grandis	Grand fir
Abies holophylla	Manchurian fir
Abies homolepis	Japanese fir
Abies koreana	Korean Fir
Abies lasiocarpa	Subalpine fir
Abies magnifica	California red fir
Abies nordmanniana	Nordmann fir
Abies numidica	Algerian Fir
Abies pinsapo	Spanish fir
Abies procera	Noble fir
Abies religiosa	Sacred fir
Abies veitchii	Veitch's Silver Fir
Abies x borisii-regis	Bulgarian fir
Abies x masjoannis	Masjoannis fir
Abies x phanerolepis	Bracted balsam fir
Abies x shastensis	Shasta red fir
Abutilon	Indian mallow spp
Abutilon berlandieri	Berlandier indian mallow

Trees Commonly Available in Arizona December 2017	**Common Name**	*Canopy Size/Shade production (width) (Reference 1,3)*	*Annual Growth Rate (Reference 1)*	*Powerline Friendly (height) [SRP/APS recommdation*	*Root Damage Potential (Reference 1)*	*Sonoran Desert Native YES- NO-*	*Invasive (Reference 8) NO- YES-*	*BVOC Emissions/Ozone contribution*	*Allergenic LOW- MOD- HIGH-*	*Water Use LOW- MOD- HIGH-*	*Edible Fruit Producing Trees (Reference 19)*
Chilopsis linearis	Desert willow	10-20'	24-36"	15-30'	low	Yes(16)	No	mod(9)	low(21)	low(4)	No
Parkinsonia florida	Blue palo verde	15-20	36"	25'	low	Yes (16)	No	mod(9)	high(28)	low(4)	Yes
Parkinsonia hybrids *	Desert museum palo verde	25'	30"	25'	low	Yes(18)	No	mod(9)	high(28)	low(7)	Yes
Parkinsonia Microphylla	Yellow palo verde or Little-leaf palo verde/Foothills Palo Verde	20'	36"	20'	low	Yes(16)	No	mod(9)	high(28)	low(7)	Yes
Parkinsonia praecox	Sonoran palo verde/Palo Brea	20'	36"	20'	low	Yes(7)	No	mod(9)	high(28)	low(4)	Yes
Vachellia farnesiana	Desert sweet acacia	15-25'	24-36"	15-25'	low	Yes(22)	No	mod(9)	low(22)	low(22)	No
Lysiloma watsonii	Feather bush/desert fern	12-15'	24"	12-15'	low	Yes(22)	No	mod(9)	low(1)	low(4)	No
Celtis reticulata	Netleaf/Western hackberry/Canyon Hackberry	25-30'	24"	25-35'	low	Yes(16)	No	low(9)	mod(26)	low(23)	Yes
Fraxinus velutina	Arizona ash or Velvet ash	30'-40	36"	30-50'	mod	Yes(16)	No	low(9)	high(20)	mod(23)	No
Olneya tesota	Desert Ironwood	15-30'	12"	15-30'	low	Yes(16)	No	high(10)	low(21)	low(4)	Yes
Prosopis velutina	Velvet mesquite	30'	24"	30'	low	Yes(16)	Yes	mod(9)	mod(20)	low(4)	Yes

Tree Characteristics Definitions

Canopy Size/Shade Production- The hot summer weather in Arizona results in high air conditioner use. Choosing a shade providing tree can reduce energy use, which can have positive economic and environmental impacts. High shade providing trees have a canopy of over 40 ft. when full grown. A low shade tree has little to no shade with a canopy of under 25ft. Trees with moderate shade generally have a canopy between 25-40'.

Annual Growth Rate- Trees grow at different rates. Slow growing trees grow 12" or less per year; trees that grow 13-24" per year are considered moderate growers. Trees that grow 25" or more in a year are considered fast growers.

Powerline Friendly–Trees planted too close to power lines create fire and safety hazards and cause power outages. The growth characteristics of trees (canopy size and height) are an important consideration when planting a tree. Generally, trees that grow to less than 20ft when mature are considered powerline friendly. Trees that grow taller than 20ft can be powerline friendly, but must be planted a safe distance away from the powerlines. Generally, trees that grow no more than 40 feet tall should be planted 20-50 feet from a powerline. Trees that grow taller than 40 feet should be planted at least 50 feet from powerlines.

Root Damage Potential-Trees with invasive root systems have the potential to cause damage, especially to underground infrastructure. Planting a tree with invasive roots can cause damage to sewers, waterlines, powerlines, sidewalks, pavement, and foundations of homes. Choosing a non-invasive root system can help reduce the risks of damaging underground infrastructure.

Sonoran Desert Native- Sonoran Desert Native trees are indigenous to the Sonoran Desert. Since native plants are adapted to the conditions of their environment, they require less water and maintenance. They also provide habitat for birds and other forms of wildlife.

Invasive- Invasive trees are non-native to an area and can be harmful to the surrounding ecosystems. They have the ability to grow quickly and can displace native species. Invasive species can-potentially cause health problems to people and animals. Invasive species have been identified on an invasive species list and/or noxious weed law in North America.

Biogenic Volatile Organic Compound Emissions/Ozone Forming Potential (BVOCs) - All trees have the potential to emit BVOCs, which contribute to the production of ground level ozone. Ground level ozone is a harmful air pollutant that affects all of us and can lead to potential health problems. In general, trees that emit BVOCs at lower rates contribute less to ground level ozone. A tree is considered low BVOC if it emits <1 µg/g dry leaf wt/hr. Moderate is between 1-10, µg/g dry leaf wt/hr , and high is >10 µg/g dry leaf wt/hr.

Allergenic- Allergenic trees contribute to common allergy symptoms at different times of the year. Trees that are highly allergenic can produce pollen that can trigger allergies. Choosing a low/non allergenic tree can eliminate much of this hazard.

Water Use- Given our desert climate, low water use trees are well-adapted to the weather conditions in Arizona. Low water use trees can survive with little to no additional watering. Water is scarce in the desert and these low water use trees can help preserve our water resources. Moderate water use trees generaly require watering every 1-3 weeks during the growing season after establishment. High water use trees require additional watering ranging from daily to weekly.

WATER USE IT WISELY

LANDSCAPE WATERING GUIDELINES

How Much & How Often Water to the outer edge of the plant's canopy and to the depth indicated. Watering frequency will vary depending on season, plant type, weather and soil.		Seasonal Frequency — Days Between Waterings Spring Mar - May	Summer May - Oct	Fall Oct - Dec	Winter Dec - Mar	Water This Deeply (Typical Root Depth)
Trees	Desert adapted	14-30 days	7-21 days	14-30 days	30-60 days	24-36 inches
	High water use	7-12 days	7-10 days	7-12 days	14-30 days	24-36 inches
Shrubs	Desert adapted	14-30 days	7-21 days	14-30 days	30-45 days	18-24 inches
	High water use	7-10 days	5-7 days	7-10 days	10-14 days	18-24 inches

Edible Fruit Producing trees- Edible fruit producing trees can have a positive or negative impact depending on where the tree is planted. Planting fruit bearing trees at a home could be a benefit because it-could provide food foor humans and/or wildlife. However, planting a fruit bearing tree in densely populated residential or commercial areas may require additional maintenance because of the potential for the fruit/pods to become a nuisance.

December, 2017

Scientific Name	*Common Name*	*Native*	*Canopy*	*Heigh t*	*Water Use*	*bVOC Emissions*	*Allergies*	*Notes*
Chilopsis linearis	Desert willow	Yes	10-20'	15-30'	Low	Mod	Low	Deciduous tree – no shade in the winter; little shade to begin with; could be higher water use
Parkinsonia florida	Blue paloverde	Yes	15-20	25'	Low	Mod	High	Variety in its application, can be cut to size, large; grows quite slow; maintenance concerns and pruning demand; high allergy concerns; recommended by City of Phoenix
Acacia farnesiana	Sweet acacia	Yes	15-25'	15-25'	Low	Mod	Low	Heavily found in other literature review within the Phoenix Area; currently not included in sample
Celtis reticulata	Western hackberry	Yes	25-30'	25-35'	Low	Low	Mod	Deciduous tree – no shade in the winter; not planted very often by the City of Phoenix
Lysiloma watsonii	Feather bush/ Desert fern	Yes	12-15'	15'-20'	Mod	Low	Low	Strong shade producer; low allergies; recommended by City of Phoenix

Things you can change		
Precip	5.1	inch/yr

*This volume is the annual average of the sum of precip from all storms, including only the first 0.5" of rain over the period I am running the model (1991-2020)

(does not include pervious pavement)

Subcatchment	Surfrace Area Captured (sq ft)			Volume Captured (ft3/year)			Volume Captured (gal/year)		
	25%	50%	100%	25%	50%	100%	25%	50%	100%
S1	10524	18685	37370	4473	7941	15882	33455	59400	118799
S10	10100	25250	45450	4293	10731	19316	32108	80270	144486
S11	10530	26109	47168	4475	11096	20046	33473	83001	149947
S12	159	2765	3083	68	1175	1310	505	8791	9802
S13	10100	20200	35350	4293	8585	15024	32108	64216	112378
S14	1837	9291	12964	781	3949	5510	5838	29537	41213
S15	9931	24265	42708	4221	10313	18151	31570	77139	135770
S16	7809	10512	19940	3319	4467	8474	24826	33416	63389
S17	14900	52701	81701	6332	22398	34723	47366	167537	259727
S18	12480	25735	50694	5304	10937	21545	39672	81812	161157
S19	4250	5050	9300	1806	2146	3953	13511	16054	29565
S2	2953	8924	17848	1255	3793	7585	9388	28369	56737
S20	0	0	0	0	0	0	0	0	0
S21	0	0	0	0	0	0	0	0	0
S22	0	0	0	0	0	0	0	0	0
S23	0	0	0	0	0	0	0	0	0
S24	0	0	0	0	0	0	0	0	0
S25	0	0	0	0	0	0	0	0	0
S26	0	0	0	0	0	0	0	0	0
S27	0	0	0	0	0	0	0	0	0
S28	0	0	0	0	0	0	0	0	0
S29	467	815	813	198	347	345	1484	2592	2584
S3_a	9331	18373	53070	3966	7809	22555	29664	58409	168709
S3_b	13366	16787	24477	5681	7135	10403	42491	53366	77811
S3_c	16355	31945	60831	6951	13577	25853	51993	101553	193381
S30	897	1794	4840	381	762	2057	2851	5702	15385
S31	0	0	0	0	0	0	0	0	0
S32	0	0	0	0	0	0	0	0	0
S33	0	0	0	0	0	0	0	0	0
S34	0	0	0	0	0	0	0	0	0
S35	5016	10033	22420	2132	4264	9529	15947	31893	71273
S36	131172	166106	248502	55748	70595	105614	416995	528050	789989
S37	17891	30673	29399	7604	13036	12495	56876	97509	93459
S38	34473	59040	56465	14651	25092	23998	109588	187687	179504
S39	78745	146321	181756	33467	62187	77246	250331	465155	577803
S4	2049	4097	14937	871	1741	6348	6512	13024	47483
S40	1504	9892	19785	639	4204	8409	4780	31448	62896
S41	9300	15888	31775	3952	6752	13504	29564	50506	101013
S42	57899	94849	138776	24607	40311	58980	184060	301526	441170
S43	0	0	0	0	0	0	0	0	0
S44	8430	13740	27481	3583	5840	11679	26800	43681	87361
S45	20200	35350	70700	8585	15024	30048	64216	112378	224755
S46	60600	116150	232300	25755	49364	98728	192647	369241	738482
S47	2447	4270	31808	1040	1815	13518	7778	13575	101117
S48	7939	10987	14611	3374	4669	6210	25239	34926	46447
S49	8521	14641	14101	3621	6223	5993	27088	46545	44826
S5	18987	36590	78790	8070	15551	33486	60361	116318	250473
S50	7592	13094	18728	3227	5565	7959	24135	41626	59535
S51	14579	28987	57290	6196	12320	24348	46348	92151	182126
S52	16300	27731	43538	6927	11786	18504	51817	88157	138407
S53	0	0	0	0	0	0	0	0	0
S54	9051	33901	33768	3847	14408	14351	28774	107773	107349
S6	10868	13014	20942	4619	5531	8900	34550	41373	66575
S7	15150	30300	55550	6439	12878	23609	48162	96324	176593
S8	2911	9219	15042	1237	3918	6393	9255	29308	47818
S9	14748	29496	65888	6268	12536	28002	46884	93768	209456

		Totals	2201010	3985105	6586749
Gallons per Tree per Year (GTY)	3795	Total Trees Supported	580	1050	1736

Land Uses	Participation Rates		
	25	50	100
R	68	134	258
C	35	70	139
I	125	250	503
P	16	35	72
Total	244	489	972
R	0.278688525	0.27402863	0.265432099
C	0.143442623	0.143149284	0.143004115
I	0.512295082	0.511247444	0.517489712
P	0.06557377	0.071574642	0.074074074
Trees	579.9762269	1050.093621	1735.638708
R	162	288	461
C	83	150	248
I	297	537	898
P	38	75	129
Total	580	1050	1736
Area	Total	Sample	
R	28.14	1.59	0.056503198
C	12.35	2.58	0.208906883
I	60.28	22.1	0.366622429
P	19.16	5.67	0.295929019
Trees per Sample			
R	9	16	26
P	11	22	38
C	17	31	52
I	109	197	329
		Total	445

Total Catchment			
Land Use	*25%*	*50%*	*100%*
Residential	162	288	461
Public	38	75	129
Commercial	83	150	248
Industrial	297	537	898
Total New Trees	580	1050	1736
Sample Plot			
Land Use	*25%*	*50%*	*100%*
Residential	9	16	26
Public	11	22	38
Commercial	17	31	52
Industrial	109	197	329
Total New Trees	147	267	445

Sample Plot Ground Cover Calculations and Percentages

	Area (sq ft)			
Residential	69269.4			
Trees (radius)	Area	Shrub (L)	Shrub (W)	Area
7	153.86	30	7	210
16	803.84	34	2	68
9	254.34		Total	278
6	113.04		Percentage	0.004013316
10	314			
28	2461.76	Plantable Area		
9	254.34	10.7639104	460	4951.398784
5	78.5		343.35	3695.788636
6	113.04		295.12	3176.645237
24	1808.64		68.86	741.2028701
19	1133.54		26.43	284.4901519
10	314		270	2906.255808
19	1133.54		73.6	792.2238054
5	78.5		252.52	2718.102654
5	78.5		88.41	951.6373185
5	78.5		379.69	4086.94914
5	78.5		44.37	477.5947044
5	78.5		90.45	973.5956957
5	78.5		11.23	120.8787138
4	50.24		18.88	203.2226284
Total	9457.68	Total	2422.91	26079.98615
Percentage	0.136534747	Percentage	0.034978071	0.376500824
Buildings				
	1328	Rock	0.517048887	
	783	Other	0.275095985	
	2778			
	963			
	1491			
	2131			
	1861			
	1418			
	1645			
Total	14398			
Percentage	0.207855128			

	Area (ac)	sq ft to ac	Area (sq ft)
Public	5.67	43560	246985.2
Trees (radius)	Area	Shrub	Area
6	113.04	2	12.56
15	706.5	4	50.24
5	78.5		
8	200.96		
7	153.86		
6	113.04		
6	113.04		
Total	1478.94		
Percentage	0.00598797		
Rock	0.031835349		
Building	0.127473225		
Tar	0.64214374		
Other	0.198547686		

	Area (ac)	Area (sq ft)	
Commercial	2.58	112384.8	
	Rock	Building	Tar
	1894	3162	88176
	5458	3981	
	3795	2630	
		5367	
Total	11147	15140	73036
Percentage	0.099186	0.134715727	0.6498744

		Area (ac)	Area (sq ft)	
Industrial		22.1	962676	
Number	Total Area	Building	269473	0.27992076
38	477.28	Tar	301358	0.31304198
11	552.64	Rock		0.1
Total	1029.92	Other		0.30703726
Percentage	0.004169966			
Plantable				
	876			
	339			
	1026			
	855			
	276			
	182			
	343			
	1079			
	378			
Total	5354			
Percentage	0.021677412			

Personal Calculations		
	#	Size (ft 2)
Rain Gardens	2	32
ROW Basin	1	20
		1
		0.5
		0.25
Rain Gardens		
Prev Pave	20 of impr	
Rain Gardens	75 of tar	
Bioswale	25 of tar	
	#	Size
ROW Basin	43	20

Residential	Baseline	25%	50%	100%
Ground Cover	*Percent Coverage*			
Building	21	21	21	21
Rock	52	52	51	51
Other Impr.	27	27	27	27
Unmain. Grass	0	0	1	1

Commercial	Baseline	25%	50%	100%
Ground Cover	*Percent Coverage*			
Building	13	13	13	13
Rock	9	9	9	9
Tar	65	49	33	0
Other Impr.	13	13	13	13
Unmain. Grass	0	16	32	65

Public	Baseline	25%	50%	100%
Ground Cover	*Percent Coverage*			
Building	13	13	13	13
Rock	3	3	3	3
Tar	65	49	33	0
Other Impr.	19	19	19	18
Unmain. Grass	0	16	32	66

Industrial	Baseline	25%	50%	100%
Ground Cover	*Percent Coverage*			
Building	28	28	28	28
Rock	10	8	5	0
Tar	31	23	16	0
Other Impr.	31	31	31	31
Unmain. Grass	0	10	20	41

**Rock relates to pervious rock surfaces such as gravel, brick, or flagstone walkways or patios; Other Impr. relates to other impervious surfaces outside of buildings and tar; Unmain. Grass relates to unmaintained grass and the most representative class for rain gardens, linear basins, and bio-retention swales*

i-Tree
Ecosystem Analysis

Baseline

Urban Forest Effects and Values
April 2021

Summary

Understanding an urban forest's structure, function and value can promote management decisions that will improve human health and environmental quality. An assessment of the vegetation structure, function, and value of the Baseline urban forest was conducted during 2021. Data from 4 field plots located throughout Baseline were analyzed using the i-Tree Eco model developed by the U.S. Forest Service, Northern Research Station.

- Number of trees: 569
- Tree Cover: 5.3 %
- Most common species of trees: Silver wattle, Beefwood, Honey mesquite
- Percentage of trees less than 6" (15.2 cm) diameter: 37.4%
- Pollution Removal: 363.9 pounds/year ($739/year)
- Carbon Storage: 77.24 tons ($13.2 thousand)
- Carbon Sequestration: 1305 pounds ($111/year)
- Oxygen Production: 1262 pounds/year
- Avoided Runoff: 4.181 thousand cubic feet/year ($279/year)
- Building energy savings: $0/year
- Carbon Avoided: 0 tons/year ($0/year)
- Structural values: $665 thousand

Ton: short ton (U.S.) (2,000 lbs)
Monetary values $ are reported in US Dollars throughout the report except where noted.
Pollution removal and avoided runoff estimates are reported for trees and shrubs. All other ecosystem service estimates are reported for trees.

For an overview of i-Tree Eco methodology, see Appendix I. Data collection quality is determined by the local data collectors, over which i-Tree has no control. Additionally, some of the plot and tree information may not have been collected, so not all of the analyses may have been conducted for this report.

Table of Contents

I. Tree Characteristics of the Urban Forest

The urban forest of Baseline has an estimated 569 trees with a tree cover of 5.3 percent. The three most common species are Silver wattle (38.4 percent), Beefwood (23.2 percent), and Honey mesquite (9.6 percent).

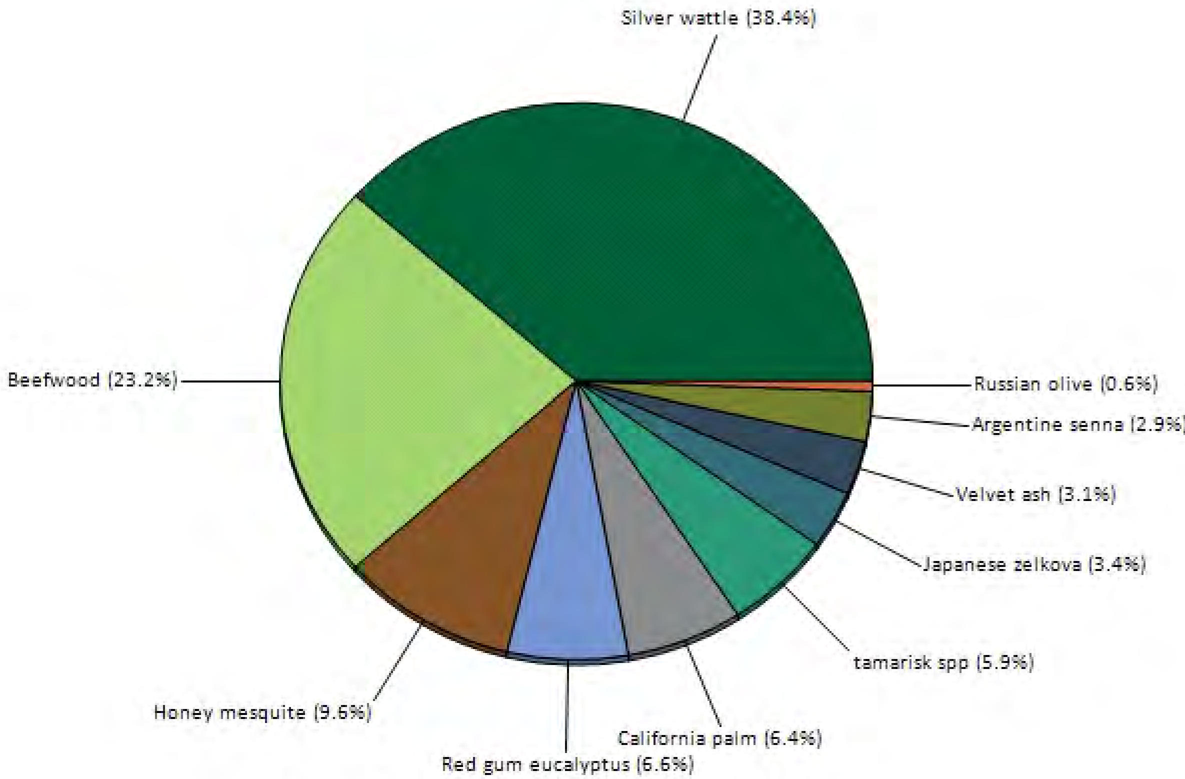

Figure 1. Tree species composition in Baseline

The overall tree density in Baseline is 5 trees/acre (see Appendix III for comparable values from other cities). For stratified projects, the highest tree densities in Baseline occur in Residential followed by Commercial and Public Land and Schools.

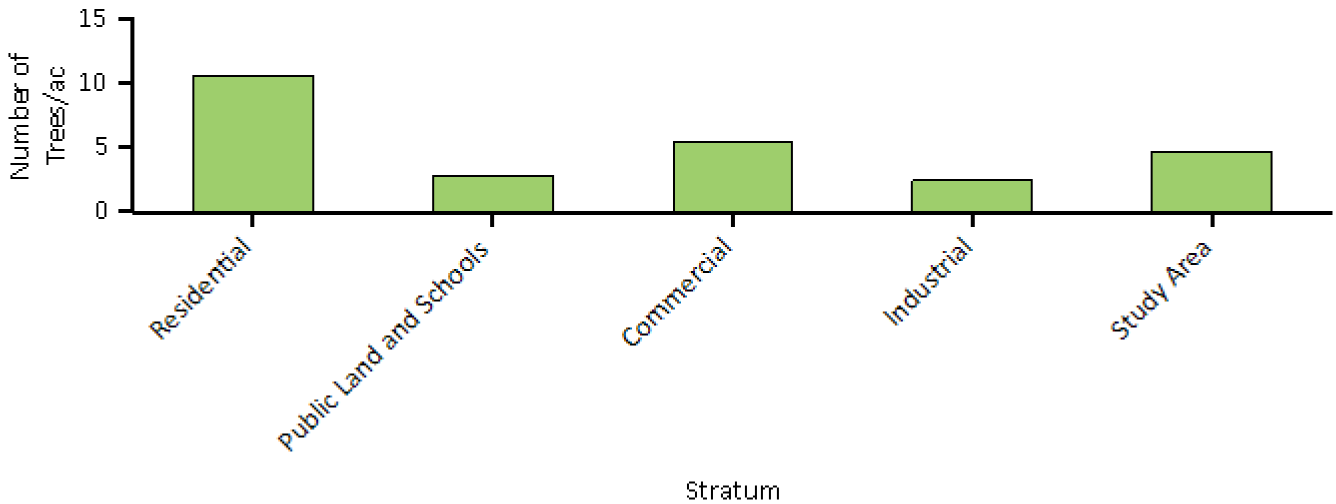

Figure 2. Number of trees/ac in Baseline by stratum

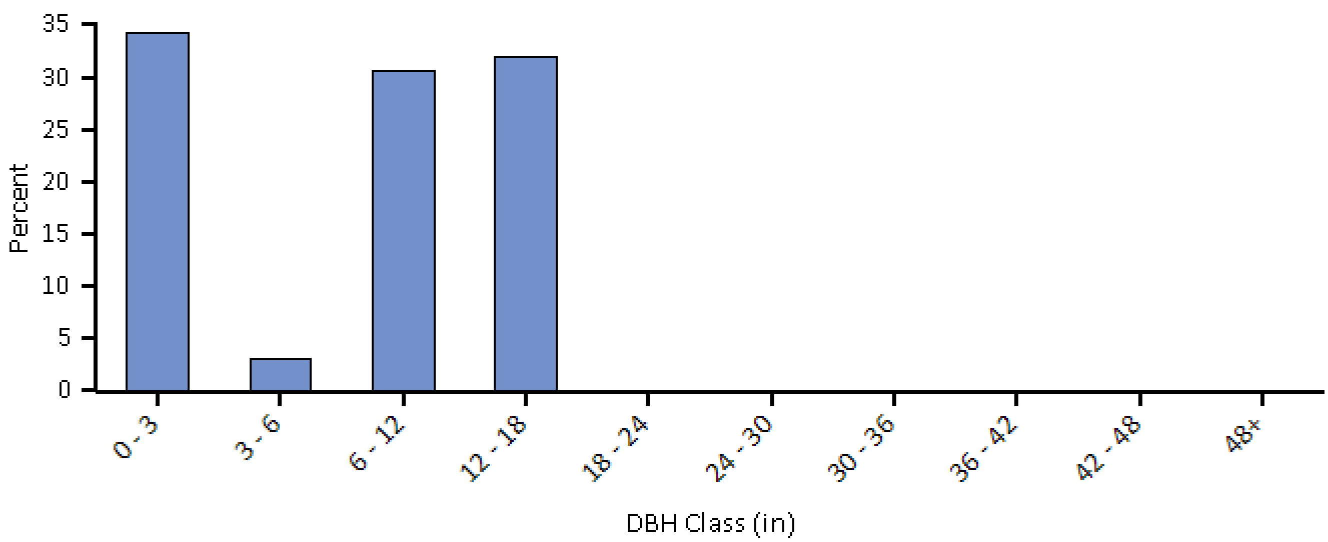

Figure 3. Percent of tree population by diameter class (DBH - stem diameter at 4.5 feet)

Urban forests are composed of a mix of native and exotic tree species. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease, but it can also pose a risk to native plants if some of the exotic species are invasive plants that can potentially out-compete and displace native species. In Baseline, about 19 percent of the trees are species native to North America, while 19 percent are native to Arizona. Species exotic to North America make up 81 percent of the population. Most exotic tree species have an origin from Australia (68 percent of the species).

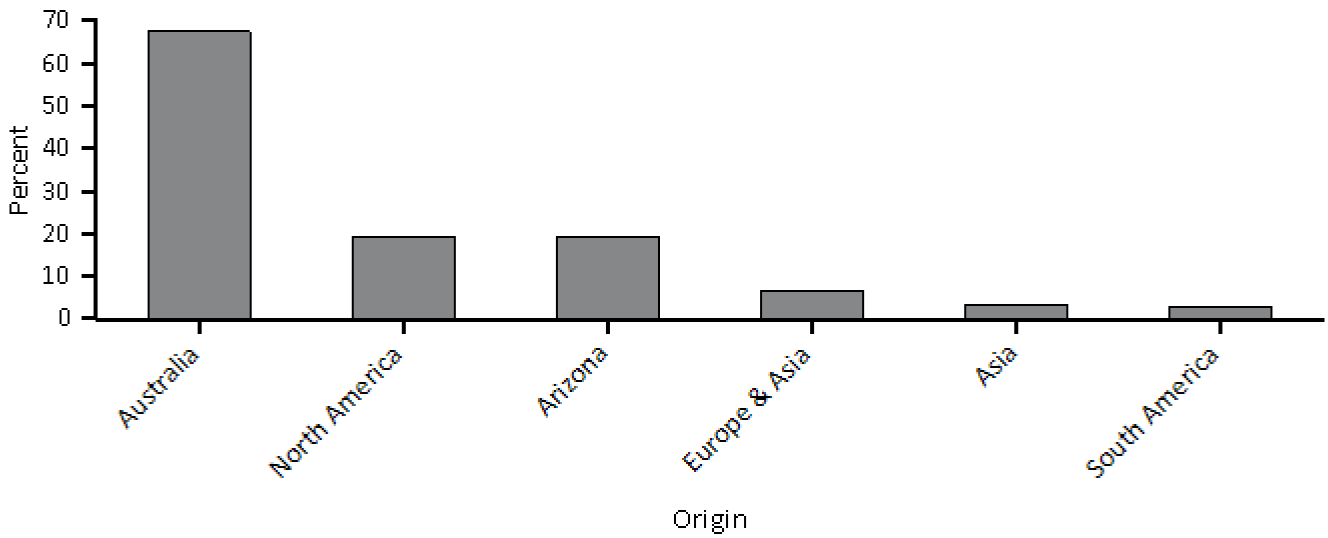

Figure 4. Percent of live tree population by area of native origin, Baseline

Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and general lack of natural enemies. These abilities enable them to displace native plants and make them a threat to natural areas. One of the 10 tree species in Baseline are identified as invasive on the state invasive species list (Arizona Wildland Invasive Plant Working Group 2005). This invasive species (Russian olive) comprises 0.6 percent of the tree population though it may only cause a minimal level of impact (see Appendix V for a complete list of invasive species).

II. Urban Forest Cover and Leaf Area

Many tree benefits equate directly to the amount of healthy leaf surface area of the plant. Trees cover about 5.3 percent of Baseline and provide 11.08 acres of leaf area. Total leaf area is greatest in Residential followed by Industrial and Commercial.

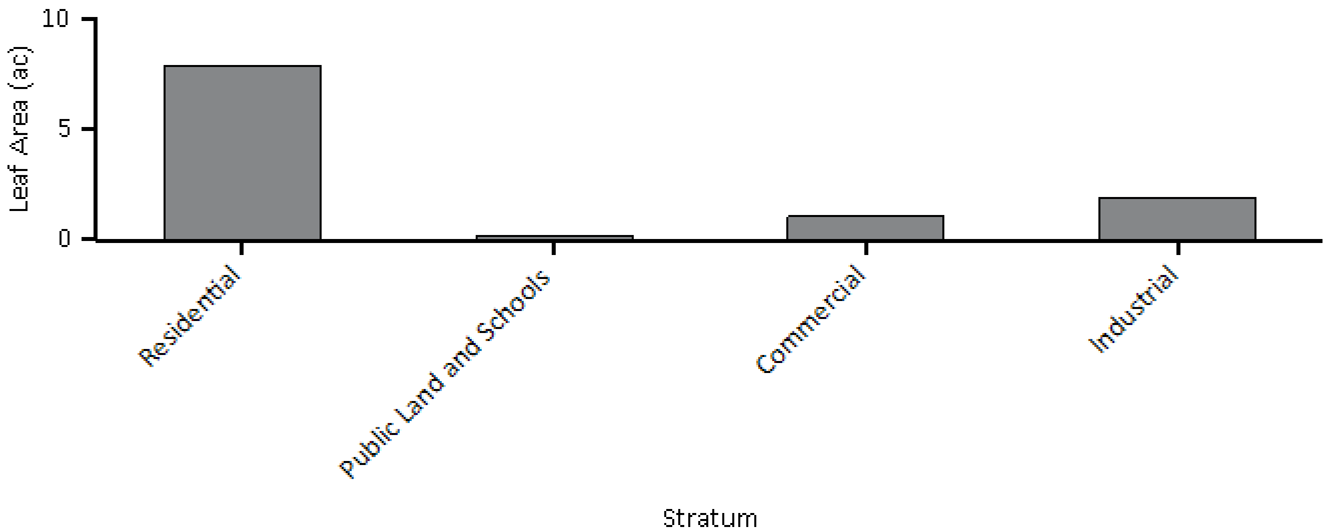

Figure 5. Leaf area by stratum, Baseline

In Baseline, the most dominant species in terms of leaf area are Beefwood, Silver wattle, and Red gum eucalyptus. The 10 species with the greatest importance values are listed in Table 1. Importance values (IV) are calculated as the sum of percent population and percent leaf area. High importance values do not mean that these trees should necessarily be encouraged in the future; rather these species currently dominate the urban forest structure.

Table 1. Most important species in Baseline

Species Name	*Percent Population*	*Percent Leaf Area*	*IV*
Silver wattle	38.4	32.4	70.8
Beefwood	23.2	46.6	69.8
Red gum eucalyptus	6.6	9.3	15.9
tamarisk spp	5.9	9.0	14.9
Honey mesquite	9.6	1.1	10.7
California palm	6.4	0.8	7.2
Japanese zelkova	3.4	0.3	3.6
Velvet ash	3.1	0.0	3.1
Argentine senna	2.9	0.2	3.1
Russian olive	0.6	0.3	0.9

Common ground cover classes (including cover types beneath trees and shrubs) in Baseline include other impervious, buildings, rock, water, unmaintained grass, duff/mulch, and bare soil, impervious covers such as tar, and cement, and herbaceous covers such as grass, and herbs (Figure 6). The most dominant ground cover types are Tar (32.7 percent) and Other Impervious (26.3 percent).

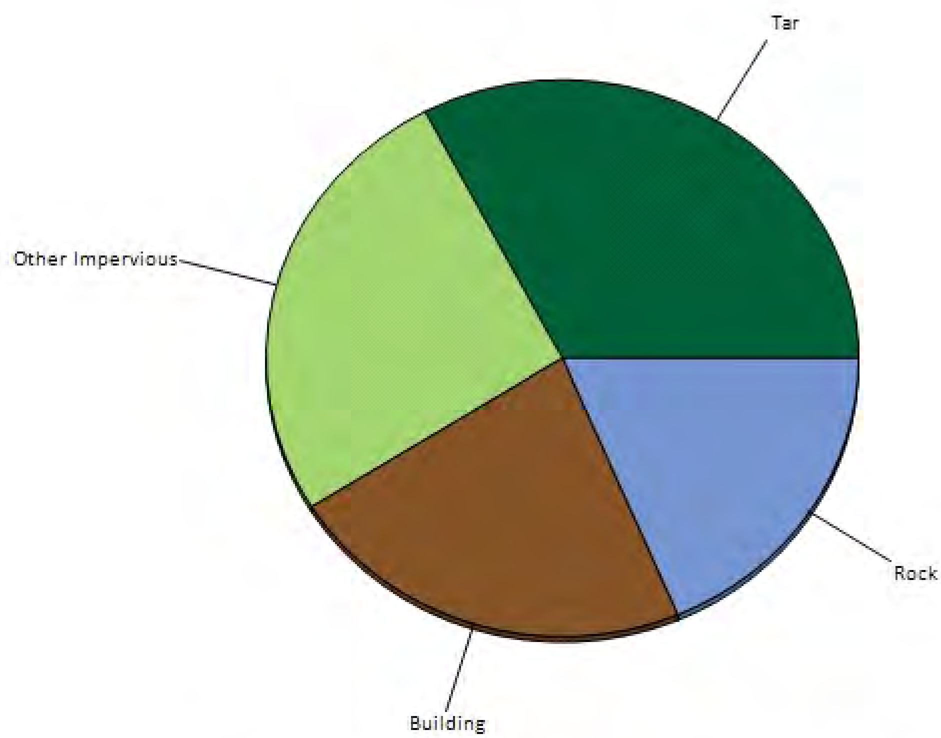

Figure 6. Percent of land by ground cover classes, Baseline

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees and shrubs in Baseline was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees and shrubs remove 363.9 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5)[2], and sulfur dioxide (SO2)) per year with an associated value of $739 (see Appendix I for more details).

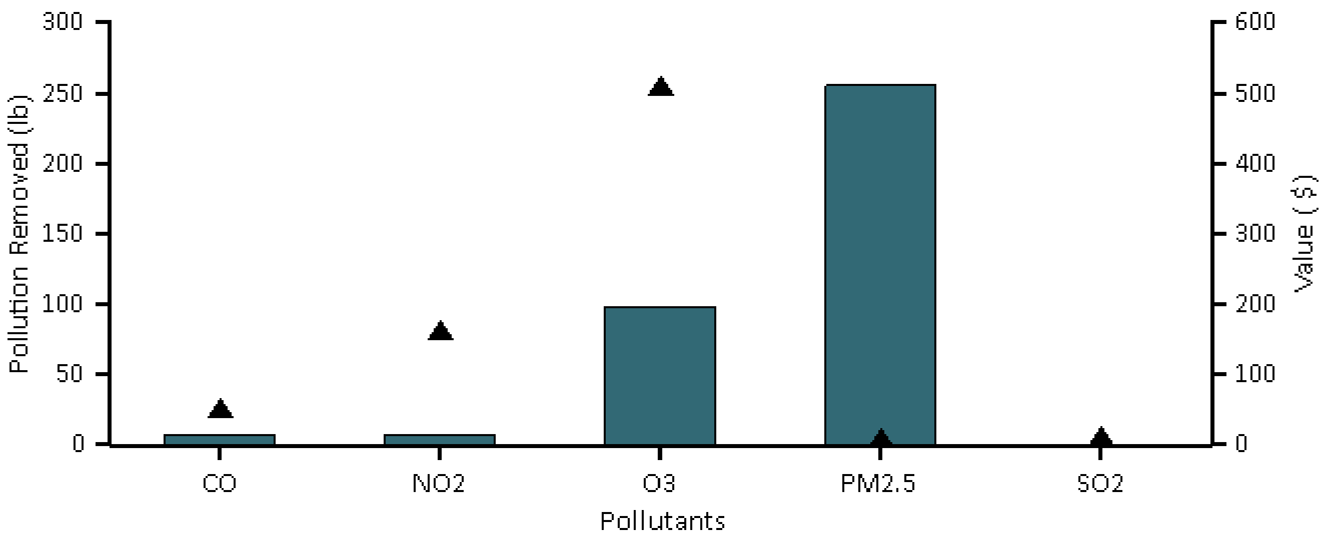

Figure 7. Annual pollution removal (points) and value (bars) by urban trees, Baseline

[1] Particulate matter less than 10 microns is a significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 when particulate matter is deposited on leaf surfaces. This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2021, trees in Baseline emitted an estimated 359.6 pounds of volatile organic compounds (VOCs) (140.8 pounds of isoprene and 218.8 pounds of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Ninety- six percent of the urban forest's VOC emissions were from Red gum eucalyptus and Silver wattle. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

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[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Baseline trees is about 1305 pounds of carbon per year with an associated value of $111. Net carbon sequestration in the urban forest is about 473.2 pounds. See Appendix I for more details on methods.

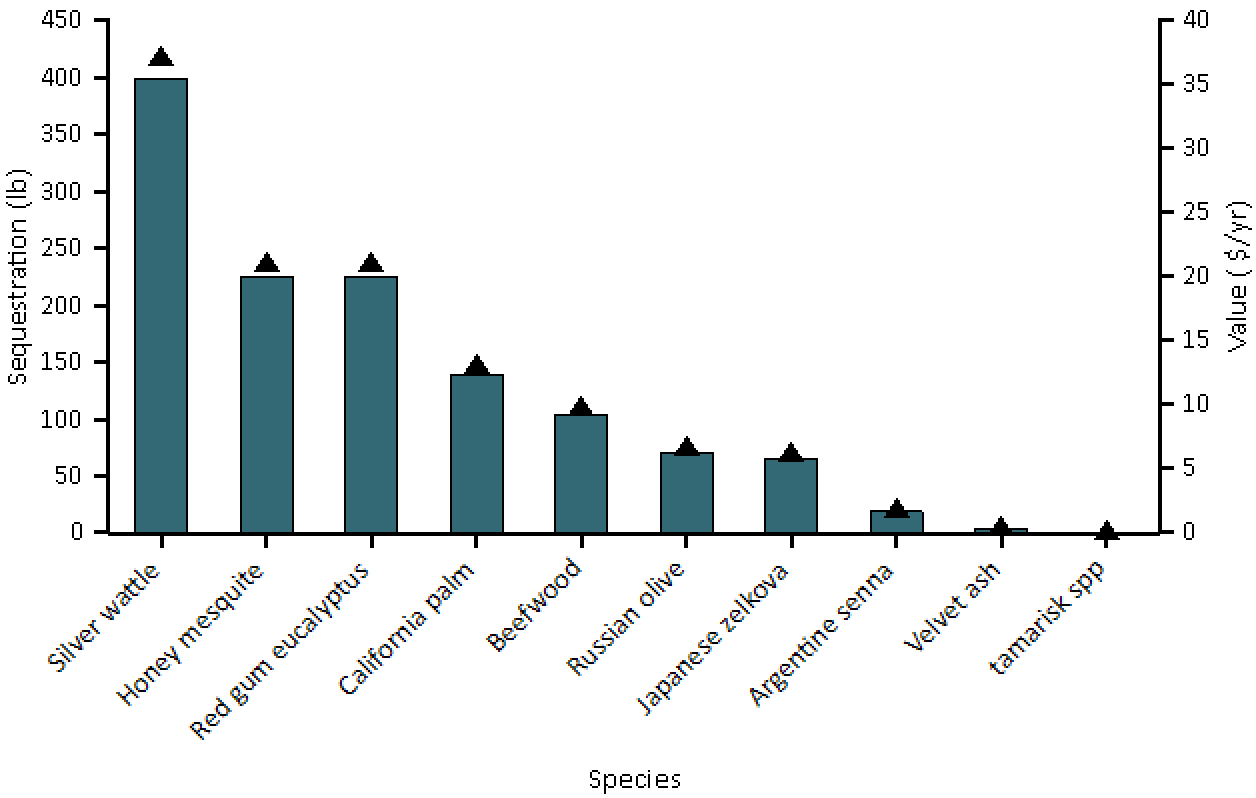


Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Baseline

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Baseline are estimated to store 77.2 tons of carbon ($13.2 thousand). Of the species sampled, Beefwood stores the most carbon (approximately 78% of the total carbon stored) and Silver wattle sequesters the most (approximately 31.9% of all sequestered carbon.)

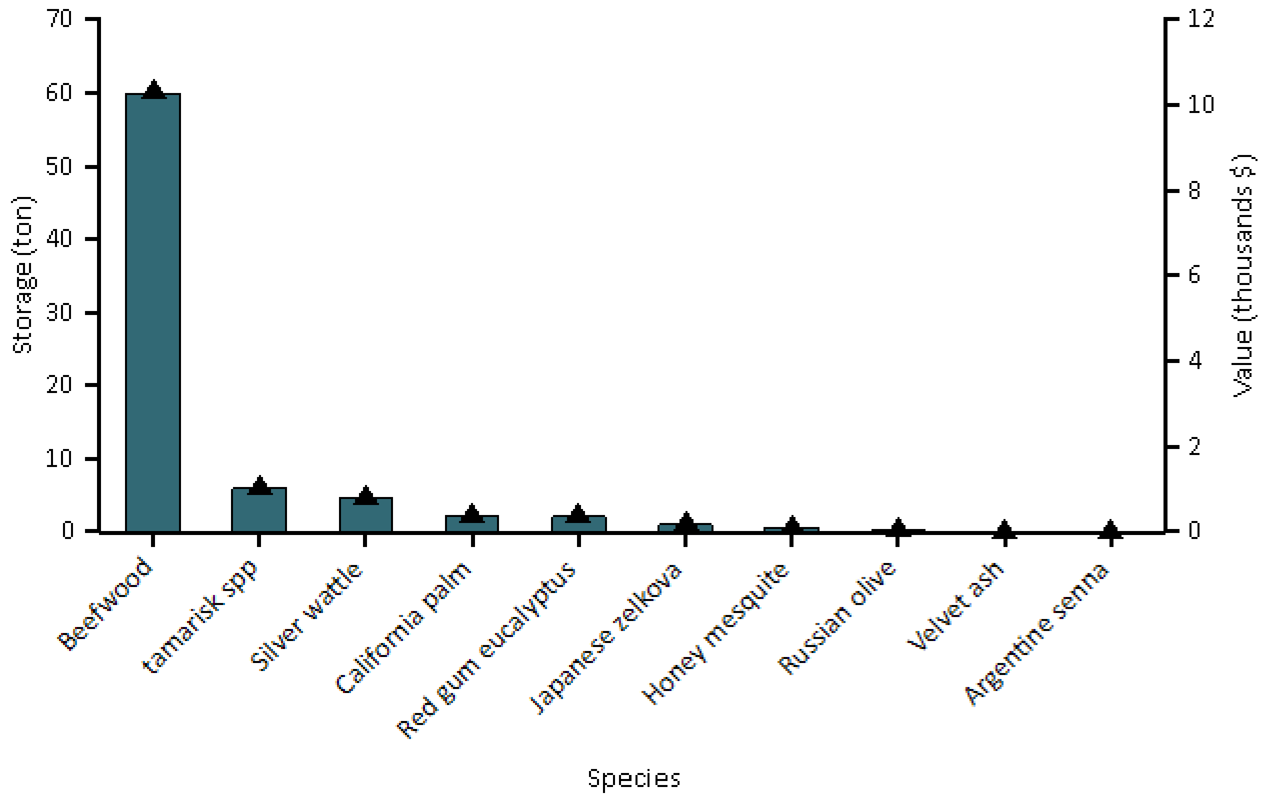


Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Baseline

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Baseline are estimated to produce 1262 pounds of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 20 oxygen production species.

Species	*Oxygen (pound)*	*Net Carbon Sequestration (pound/yr)*	*Number of Trees*	*Leaf Area (acre)*
Silver wattle	792.54	297.20	218	3.59
Honey mesquite	598.45	224.42	55	0.12
Red gum eucalyptus	364.59	136.72	37	1.03
California palm	342.13	128.30	36	0.09
Russian olive	191.21	71.71	3	0.03
Argentine senna	50.02	18.76	16	0.02
Japanese zelkova	-12.64	-4.74	19	0.03
Velvet ash	-35.31	-13.24	18	0.00
tamarisk spp	-120.14	-45.05	34	1.00
Beefwood	-909.01	-340.88	132	5.16

[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Baseline help to reduce runoff by an estimated 4.18 thousand cubic feet a year with an associated value of $280 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Baseline, the total annual precipitation in 2016 was 6.8 inches.

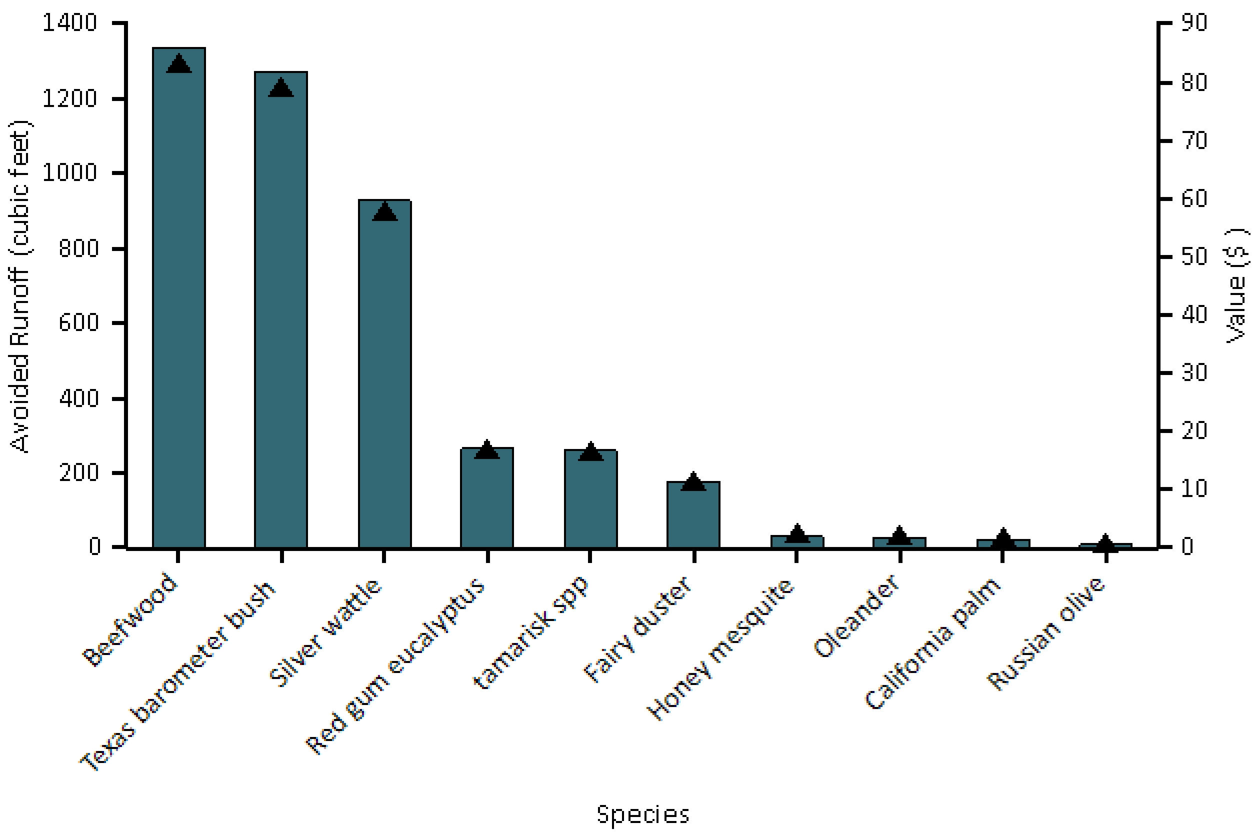


Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Baseline

VII. Trees and Building Energy Use

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space conditioned residential buildings (McPherson and Simpson 1999).

Trees in Baseline are estimated to reduce energy-related costs from residential buildings by $0 annually. Trees also provide an additional $0 in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 0 pounds of carbon emissions).

Note: negative numbers indicate that there was not a reduction in carbon emissions and/or value, rather carbon emissions and values increased by the amount shown as a negative value.[5]

Table 3. Annual energy savings due to trees near residential buildings, Baseline

	Heating	*Cooling*	*Total*
MBTU[a]	0	N/A	0
MWH[b]	0	0	0
Carbon Avoided (pounds)	0	0	0

[a]MBTU - one million British Thermal Units

[b]MWH - megawatt-hour

Table 4. Annual savings [a]($) in residential energy expenditure during heating and cooling seasons, Baseline

	Heating	*Cooling*	*Total*
MBTU[b]	0	N/A	0
MWH[c]	0	0	0
Carbon Avoided	0	0	0

[b]Based on the prices of $131.6 per MWH and $16.3480800457637 per MBTU (see Appendix I for more details)

[c]MBTU - one million British Thermal Units

[c]MWH - megawatt-hour

[5] Trees modify climate, produce shade, and reduce wind speeds. Increased energy use or costs are likely due to these tree-building interactions creating a cooling effect during the winter season. For example, a tree (particularly evergreen species) located on the southern side of a residential building may produce a shading effect that causes increases in heating requirements.

VIII. Structural and Functional Values

Urban forests have a structural value based on the trees themselves (e.g., the cost of having to replace a tree with a similar tree); they also have functional values (either positive or negative) based on the functions the trees perform.

The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees (Nowak et al 2002a). Annual functional values also tend to increase with increased number and size of healthy trees. Through proper management, urban forest values can be increased; however, the values and benefits also can decrease as the amount of healthy tree cover declines.

Urban trees in Baseline have the following structural values:

- Structural value: $665 thousand
- Carbon storage: $13.2 thousand

Urban trees in Baseline have the following annual functional values:

- Carbon sequestration: $111
- Avoided runoff: $279
- Pollution removal: $739
- Energy costs and carbon emission values: $0

(Note: negative value indicates increased energy cost and carbon emission value)

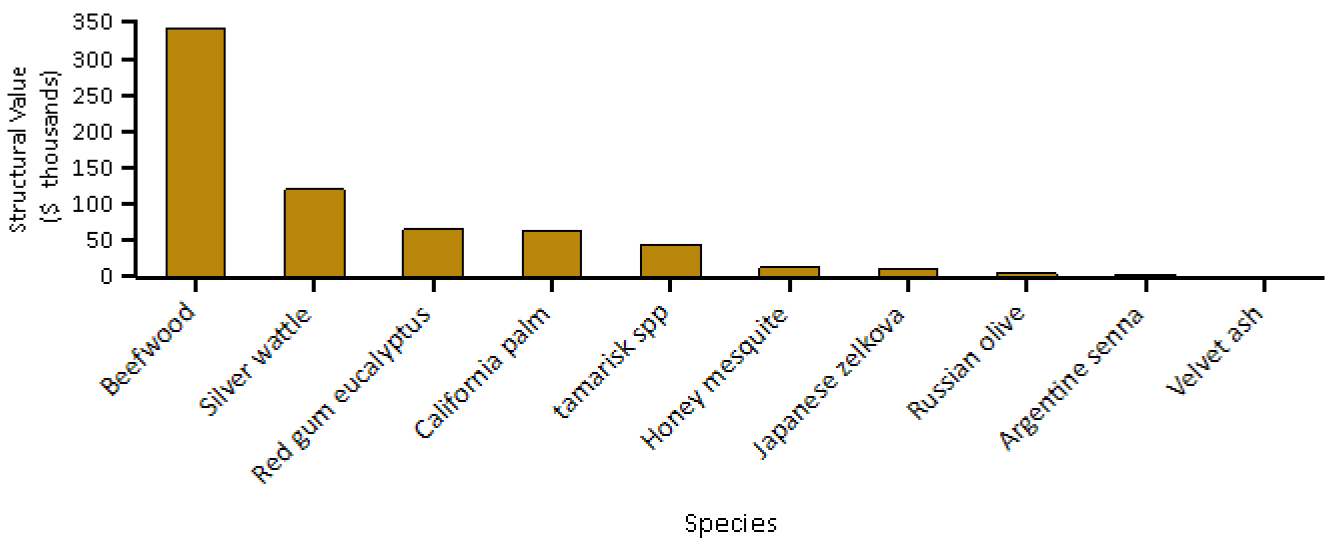


Figure 11. Tree species with the greatest structural value, Baseline

IX. Potential Pest Impacts

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, structural value and sustainability of the urban forest. As pests tend to have differing tree hosts, the potential damage or risk of each pest will differ among cities.Thirty-six pests were analyzed for their potential impact and compared with pest range maps (Forest Health Technology Enterprise Team 2014) for the conterminous United States to determine their proximity to Maricopa County. One of the thirty-six pests analyzed are located within the county. For a complete analysis of all pests, see Appendix VII.

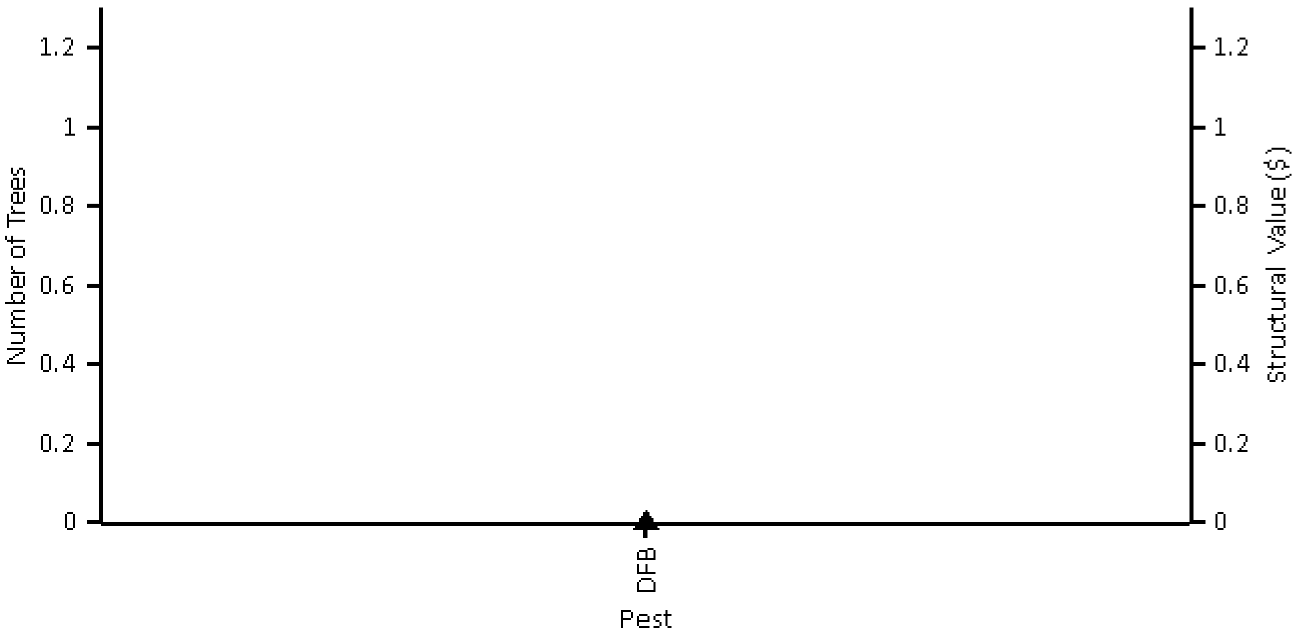


Figure 12. Number of trees at risk (points) and associated compensatory value (bars) for most threatening pests located in the county, Baseline

Douglas-fir beetle (DFB) (Schmitz and Gibson 1996) is a bark beetle that infests Douglas-fir trees throughout the western United States, British Columbia, and Mexico. Potential loss of trees from DFB is 0.0 percent ($0 in structural value).

Appendix I. i-Tree Eco Model and Field Measurements

i-Tree Eco is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects (Nowak and Crane 2000), including:

- Urban forest structure (e.g., species composition, tree health, leaf area, etc.).
- Amount of pollution removed hourly by the urban forest, and its associated percent air quality improvement throughout a year.
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power sources.
- Structural value of the forest, as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by pests, such as Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

Typically, all field data are collected during the leaf-on season to properly assess tree canopies. Typical data collection (actual data collection may vary depending upon the user) includes land use, ground and tree cover, individual tree attributes of species, stem diameter, height, crown width, crown canopy missing and dieback, and distance and direction to residential buildings (Nowak et al 2005; Nowak et al 2008).

During data collection, trees are identified to the most specific taxonomic classification possible. Trees that are not classified to the species level may be classified by genus (e.g., ash) or species groups (e.g., hardwood). In this report, tree species, genera, or species groups are collectively referred to as tree species.

<u>Tree Characteristics:</u>

Leaf area of trees was assessed using measurements of crown dimensions and percentage of crown canopy missing. In the event that these data variables were not collected, they are estimated by the model.

An analysis of invasive species is not available for studies outside of the United States. For the U.S., invasive species are identified using an invasive species list (Arizona Wildland Invasive Plant Working Group 2005)for the state in which the urban forest is located. These lists are not exhaustive and they cover invasive species of varying degrees of invasiveness and distribution. In instances where a state did not have an invasive species list, a list was created based on the lists of the adjacent states. Tree species that are identified as invasive by the state invasive species list are cross-referenced with native range data. This helps eliminate species that are on the state invasive species list, but are native to the study area.

<u>Air Pollution Removal:</u>

Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 2.5 microns. Particulate matter less than 10 microns (PM10) is another significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988; Baldocchi et al 1987). As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature (Bidwell and Fraser 1972; Lovett 1994) that were adjusted depending on leaf phenology and leaf area.

Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere (Zinke 1967). Recent updates (2011) to air quality modeling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values (Hirabayashi et al 2011; Hirabayashi et al 2012; Hirabayashi 2011).

Trees remove PM2.5 when particulate matter is deposited on leaf surfaces (Nowak et al 2013). This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors. Generally, PM2.5 removal is positive with positive benefits. However, there are some cases when net removal is negative or resuspended particles lead to increased pollution concentrations and negative values. During some months (e.g., with no rain), trees resuspend more particles than they remove. Resuspension can also lead to increased overall PM2.5 concentrations if the boundary layer conditions are lower during net resuspension periods than during net removal periods. Since the pollution removal value is based on the change in pollution concentration, it is possible to have situations when trees remove PM2.5 but increase concentrations and thus have negative values during periods of positive overall removal. These events are not common, but can happen.

For reports in the United States, default air pollution removal value is calculated based on local incidence of adverse health effects and national median externality costs. The number of adverse health effects and associated economic value is calculated for ozone, sulfur dioxide, nitrogen dioxide, and particulate matter less than 2.5 microns using data from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) (Nowak et al 2014). The model uses a damage-function approach that is based on the local change in pollution concentration and population. National median externality costs were used to calculate the value of carbon monoxide removal (Murray et al 1994).

For international reports, user-defined local pollution values are used. For international reports that do not have local values, estimates are based on either European median externality values (van Essen et al 2011) or BenMAP regression equations (Nowak et al 2014) that incorporate user-defined population estimates. Values are then converted to local currency with user-defined exchange rates.

For this analysis, pollution removal value is calculated based on the prices of $1,327 per ton (carbon monoxide), $1,560 per ton (ozone), $381 per ton (nitrogen dioxide), $170 per ton (sulfur dioxide), $304,416 per ton (particulate matter less than 2.5 microns).

<u>Carbon Storage and Sequestration:</u>

Carbon storage is the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation. To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak 1994). To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

Carbon sequestration is the removal of carbon dioxide from the air by plants. To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year x+1.

Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. For international reports that do not have local values, estimates are based on the carbon value for the United States (U.S. Environmental Protection Agency 2015, Interagency Working Group on Social Cost of Carbon 2015) and converted to local currency with user-defined exchange rates.

For this analysis, carbon storage and carbon sequestration values are calculated based on $171 per ton.

Oxygen Production:

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights: net O2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of the urban forest account for decomposition (Nowak et al 2007). For complete inventory projects, oxygen production is estimated from gross carbon sequestration and does not account for decomposition.

Avoided Runoff:

Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis.

The value of avoided runoff is based on estimated or user-defined local values. For international reports that do not have local values, the national average value for the United States is utilized and converted to local currency with user-defined exchange rates. The U.S. value of avoided runoff is based on the U.S. Forest Service's Community Tree Guide Series (McPherson et al 1999; 2000; 2001; 2002; 2003; 2004; 2006a; 2006b; 2006c; 2007; 2010; Peper et al 2009; 2010; Vargas et al 2007a; 2007b; 2008).

For this analysis, avoided runoff value is calculated based on the price of $0.07 per ft^3.

Building Energy Use:

If appropriate field data were collected, seasonal effects of trees on residential building energy use were calculated based on procedures described in the literature (McPherson and Simpson 1999) using distance and direction of trees from residential structures, tree height and tree condition data. To calculate the monetary value of energy savings, local or custom prices per MWH or MBTU are utilized.

For this analysis, energy saving value is calculated based on the prices of $131.60 per MWH and $16.35 per MBTU.

Structural Values:

Structural value is the value of a tree based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree). Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information (Nowak et al 2002a; 2002b). Structural value may not be included for international projects if there is insufficient local data to complete the valuation procedures.

Potential Pest Impacts:

The complete potential pest risk analysis is not available for studies outside of the United States. The number of trees at risk to the pests analyzed is reported, though the list of pests is based on known insects and disease in the United States.

For the U.S., potential pest risk is based on pest range maps and the known pest host species that are likely to

experience mortality. Pest range maps for 2012 from the Forest Health Technology Enterprise Team (FHTET) (Forest Health Technology Enterprise Team 2014) were used to determine the proximity of each pest to the county in which the urban forest is located. For the county, it was established whether the insect/disease occurs within the county, is within 250 miles of the county edge, is between 250 and 750 miles away, or is greater than 750 miles away. FHTET did not have pest range maps for Dutch elm disease and chestnut blight. The range of these pests was based on known occurrence and the host range, respectively (Eastern Forest Environmental Threat Assessment Center; Worrall 2007).

Relative Tree Effects:

The relative value of tree benefits reported in Appendix II is calculated to show what carbon storage and sequestration, and air pollutant removal equate to in amounts of municipal carbon emissions, passenger automobile emissions, and house emissions.

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (Carbon Dioxide Information Analysis Center 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (g/mi) for CO, NOx, VOCs, PM10, SO2 for 2010 (Bureau of Transportation Statistics 2010; Heirigs et al 2004), PM2.5 for 2011-2015 (California Air Resources Board 2013), and CO2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (Federal Highway Administration 2013) to determine average emissions per vehicle.

Household emissions are based on average electricity kWh usage, natural gas Btu usage, fuel oil Btu usage, kerosene Btu usage, LPG Btu usage, and wood Btu usage per household in 2009 (Energy Information Administration 2013; Energy Information Administration 2014)

- CO2, SO2, and NOx power plant emission per KWh are from Leonardo Academy 2011. CO emission per kWh assumes 1/3 of one percent of C emissions is CO based on Energy Information Administration 1994. PM10 emission per kWh from Layton 2004.
- CO2, NOx, SO2, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from Leonardo Academy 2011.
- CO2 emissions per Btu of wood from Energy Information Administration 2014.
- CO, NOx and SOx emission per Btu based on total emissions and wood burning (tons) from (British Columbia Ministry 2005; Georgia Forestry Commission 2009).

Appendix II. Relative Tree Effects

The urban forest in Baseline provides benefits that include carbon storage and sequestration, and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average municipal carbon emissions, average passenger automobile emissions, and average household emissions. See Appendix I for methodology.

Carbon storage is equivalent to:

- Amount of carbon emitted in Baseline in 0 days
- Annual carbon (C) emissions from 55 automobiles
- Annual C emissions from 22 single-family houses

Carbon monoxide removal is equivalent to:

- Annual carbon monoxide emissions from 0 automobiles
- Annual carbon monoxide emissions from 0 single-family houses

Nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 6 automobiles
- Annual nitrogen dioxide emissions from 3 single-family houses

Sulfur dioxide removal is equivalent to:

- Annual sulfur dioxide emissions from 22 automobiles
- Annual sulfur dioxide emissions from 0 single-family houses

Annual carbon sequestration is equivalent to:

- Amount of carbon emitted in Baseline in 0.0 days
- Annual C emissions from 0 automobiles
- Annual C emissions from 0 single-family houses

Appendix III. Comparison of Urban Forests

A common question asked is, "How does this city compare to other cities?" Although comparison among cities should be made with caution as there are many attributes of a city that affect urban forest structure and functions, summary data are provided from other cities analyzed using the i-Tree Eco model.

I. City totals for trees

City	*% Tree Cover*	*Number of Trees*	*Carbon Storage (tons)*	*Carbon Sequestration (tons/yr)*	*Pollution Removal (tons/yr)*
Toronto, ON, Canada	26.6	10,220,000	1,221,000	51,500	2,099
Atlanta, GA	36.7	9,415,000	1,344,000	46,400	1,663
Los Angeles, CA	11.1	5,993,000	1,269,000	77,000	1,975
New York, NY	20.9	5,212,000	1,350,000	42,300	1,676
London, ON, Canada	24.7	4,376,000	396,000	13,700	408
Chicago, IL	17.2	3,585,000	716,000	25,200	888
Phoenix, AZ	9.0	3,166,000	315,000	32,800	563
Baltimore, MD	21.0	2,479,000	570,000	18,400	430
Philadelphia, PA	15.7	2,113,000	530,000	16,100	575
Washington, DC	28.6	1,928,000	525,000	16,200	418
Oakville, ON , Canada	29.1	1,908,000	147,000	6,600	190
Albuquerque, NM	14.3	1,846,000	332,000	10,600	248
Boston, MA	22.3	1,183,000	319,000	10,500	283
Syracuse, NY	26.9	1,088,000	183,000	5,900	109
Woodbridge, NJ	29.5	986,000	160,000	5,600	210
Minneapolis, MN	26.4	979,000	250,000	8,900	305
San Francisco, CA	11.9	668,000	194,000	5,100	141
Morgantown, WV	35.5	658,000	93,000	2,900	72
Moorestown, NJ	28.0	583,000	117,000	3,800	118
Hartford, CT	25.9	568,000	143,000	4,300	58
Jersey City, NJ	11.5	136,000	21,000	890	41
Casper, WY	8.9	123,000	37,000	1,200	37
Freehold, NJ	34.4	48,000	20,000	540	22

II. Totals per acre of land area

City	*Number of Trees/ac*	*Carbon Storage (tons/ac)*	*Carbon Sequestration (tons/ac/yr)*	*Pollution Removal (lb/ac/yr)*
Toronto, ON, Canada	64.9	7.8	0.33	26.7
Atlanta, GA	111.6	15.9	0.55	39.4
Los Angeles, CA	19.6	4.2	0.16	13.1
New York, NY	26.4	6.8	0.21	17.0
London, ON, Canada	75.1	6.8	0.24	14.0
Chicago, IL	24.2	4.8	0.17	12.0
Phoenix, AZ	12.9	1.3	0.13	4.6
Baltimore, MD	48.0	11.1	0.36	16.6
Philadelphia, PA	25.1	6.3	0.19	13.6
Washington, DC	49.0	13.3	0.41	21.2
Oakville, ON , Canada	78.1	6.0	0.27	11.0
Albuquerque, NM	21.8	3.9	0.12	5.9
Boston, MA	33.5	9.1	0.30	16.1
Syracuse, NY	67.7	10.3	0.34	13.6
Woodbridge, NJ	66.5	10.8	0.38	28.4
Minneapolis, MN	26.2	6.7	0.24	16.3
San Francisco, CA	22.5	6.6	0.17	9.5
Morgantown, WV	119.2	16.8	0.52	26.0
Moorestown, NJ	62.1	12.4	0.40	25.1
Hartford, CT	50.4	12.7	0.38	10.2
Jersey City, NJ	14.4	2.2	0.09	8.6
Casper, WY	9.1	2.8	0.09	5.5
Freehold, NJ	38.3	16.0	0.44	35.3

Appendix IV. General Recommendations for Air Quality Improvement

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmosphere environment. Four main ways that urban trees affect air quality are (Nowak 1995):

- Temperature reduction and other microclimate effects
- Removal of air pollutants
- Emission of volatile organic compounds (VOC) and tree maintenance emissions
- Energy effects on buildings

The cumulative and interactive effects of trees on climate, pollution removal, and VOC and power plant emissions determine the impact of trees on air pollution. Cumulative studies involving urban tree impacts on ozone have revealed that increased urban canopy cover, particularly with low VOC emitting species, leads to reduced ozone concentrations in cities (Nowak 2000). Local urban management decisions also can help improve air quality.

Urban forest management strategies to help improve air quality include (Nowak 2000):

Strategy	*Result*
Increase the number of healthy trees	Increase pollution removal
Sustain existing tree cover	Maintain pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone and carbon monoxide formation
Sustain large, healthy trees	Large trees have greatest per-tree effects
Use long-lived trees	Reduce long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduce pollutants emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduce pollutant emissions
Plant trees in energy conserving locations	Reduce pollutant emissions from power plants
Plant trees to shade parked cars	Reduce vehicular VOC emissions
Supply ample water to vegetation	Enhance pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improve tree health
Utilize evergreen trees for particulate matter	Year-round removal of particles

Appendix V. Invasive Species of the Urban Forest

The following inventoried tree species were listed as invasive on the Arizona invasive species list (Arizona Wildland Invasive Plant Working Group 2005):

Species Name[a]	*Number of Trees*	*% of Trees*	*Leaf Area (ft²)*	*Percent Leaf Area*
Russian olive	3	0.6	0.0	0.3
Total	**3**	**0.59**	**0.00**	**0.28**

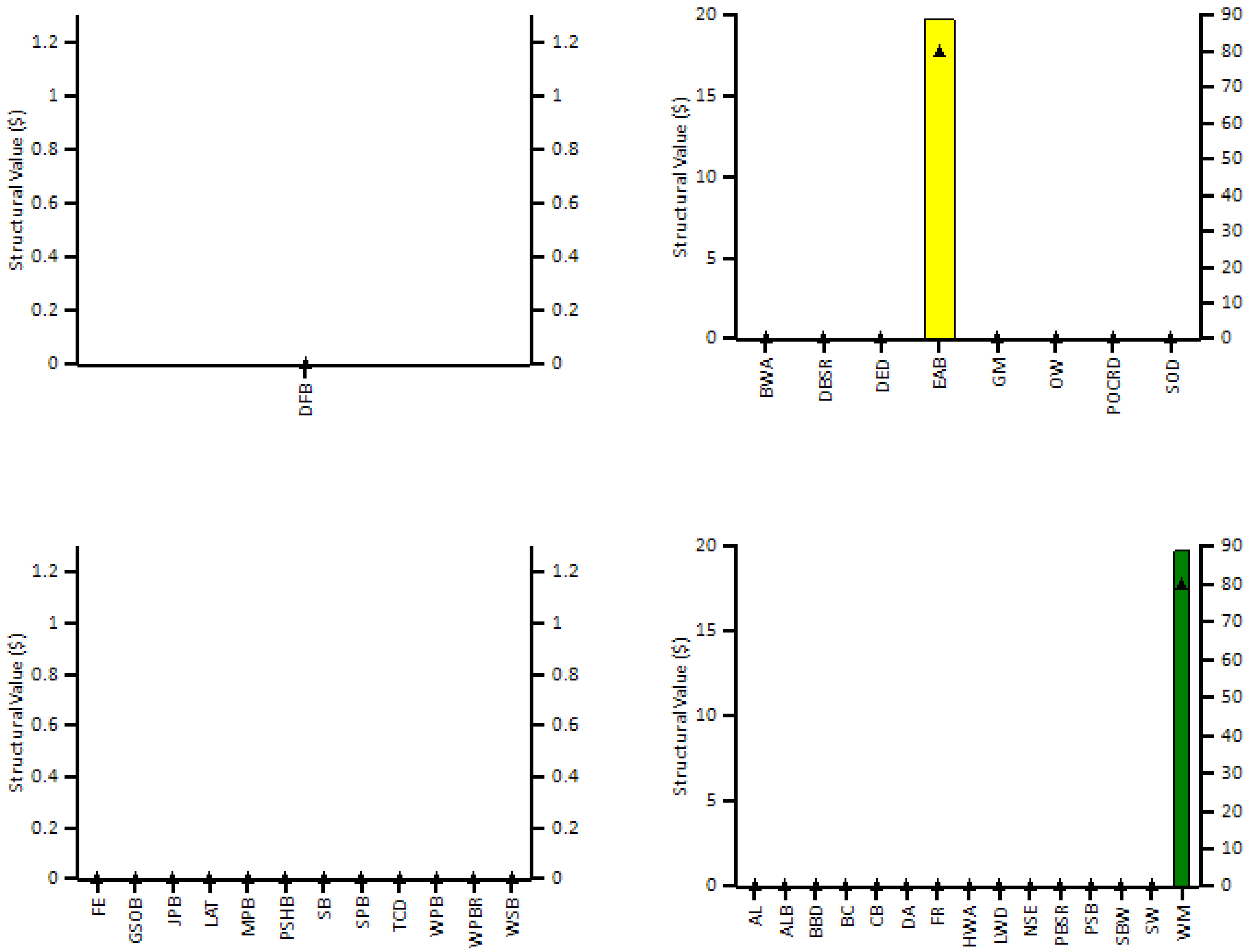
[a]Species are determined to be invasive if they are listed on the state's invasive species list

Appendix VI. Potential Risk of Pests

Thirty-six insects and diseases were analyzed to quantify their potential impact on the urban forest. As each insect/ disease is likely to attack different host tree species, the implications for {0} will vary. The number of trees at risk reflects only the known host species that are likely to experience mortality.

Code	Scientific Name	Common Name	Trees at Risk (#)	Value ($)
AL	Phyllocnistis populiella	Aspen Leafminer	0	0.00
ALB	Anoplophora glabripennis	Asian Longhorned Beetle	0	0.00
BBD	Neonectria faginata	Beech Bark Disease	0	0.00
BC	Sirococcus clavigignenti juglandacearum	Butternut Canker	0	0.00
BWA	Adelges piceae	Balsam Woolly Adelgid	0	0.00
CB	Cryphonectria parasitica	Chestnut Blight	0	0.00
DA	Discula destructiva	Dogwood Anthracnose	0	0.00
DBSR	Leptographium wageneri var. pseudotsugae	Douglas-fir Black Stain Root Disease	0	0.00
DED	Ophiostoma novo-ulmi	Dutch Elm Disease	0	0.00
DFB	Dendroctonus pseudotsugae	Douglas-Fir Beetle	0	0.00
EAB	Agrilus planipennis	Emerald Ash Borer	18	88.82
FE	Scolytus ventralis	Fir Engraver	0	0.00
FR	Cronartium quercuum f. sp. Fusiforme	Fusiform Rust	0	0.00
GM	Lymantria dispar	Gypsy Moth	0	0.00
GSOB	Agrilus auroguttatus	Goldspotted Oak Borer	0	0.00
HWA	Adelges tsugae	Hemlock Woolly Adelgid	0	0.00
JPB	Dendroctonus jeffreyi	Jeffrey Pine Beetle	0	0.00
LAT	Choristoneura conflictana	Large Aspen Tortrix	0	0.00
LWD	Raffaelea lauricola	Laurel Wilt	0	0.00
MPB	Dendroctonus ponderosae	Mountain Pine Beetle	0	0.00
NSE	Ips perturbatus	Northern Spruce Engraver	0	0.00
OW	Ceratocystis fagacearum	Oak Wilt	0	0.00
PBSR	Leptographium wageneri var. ponderosum	Pine Black Stain Root Disease	0	0.00
POCRD	Phytophthora lateralis	Port-Orford-Cedar Root Disease	0	0.00
PSB	Tomicus piniperda	Pine Shoot Beetle	0	0.00
PSHB	Euwallacea nov. sp.	Polyphagous Shot Hole Borer	0	0.00
SB	Dendroctonus rufipennis	Spruce Beetle	0	0.00
SBW	Choristoneura fumiferana	Spruce Budworm	0	0.00
SOD	Phytophthora ramorum	Sudden Oak Death	0	0.00
SPB	Dendroctonus frontalis	Southern Pine Beetle	0	0.00
SW	Sirex noctilio	Sirex Wood Wasp	0	0.00
TCD	Geosmithia morbida	Thousand Canker Disease	0	0.00
WM	Operophtera brumata	Winter Moth	18	88.82
WPB	Dendroctonus brevicomis	Western Pine Beetle	0	0.00
WPBR	Cronartium ribicola	White Pine Blister Rust	0	0.00
WSB	Choristoneura occidentalis	Western Spruce Budworm	0	0.00

In the following graph, the pests are color coded according to the county's proximity to the pest occurrence in the United States. Red indicates that the pest is within the county; orange indicates that the pest is within 250 miles of the county; yellow indicates that the pest is within 750 miles of the county; and green indicates that the pest is outside of these ranges.



Note: points - Number of trees, bars - Structural value

Based on the host tree species for each pest and the current range of the pest (Forest Health Technology Enterprise Team 2014), it is possible to determine what the risk is that each tree species in the urban forest could be attacked by an insect or disease.

Spp. Risk	Risk Weight	Species Name	AL	ALB	BBD	BC	BWA	CB	DA	DBSR	DED	DFB	EAB	FE	FR	GM	GSOB	HWA	JPB	LAT	LWD	MPB	NSE	OW	PBSR	POCRD	PSB	PSHB	SB	SBW	SOD	SPB	SW	TCD	WM	WPB	WPBR	WSB
	3	Velvet ash																																				

Note:
Species that are not listed in the matrix are not known to be hosts to any of the pests analyzed.

Species Risk:

- Red indicates that tree species is at risk to at least one pest within county
- Orange indicates that tree species has no risk to pests in county, but has a risk to at least one pest within 250 miles from the county
- Yellow indicates that tree species has no risk to pests within 250 miles of county, but has a risk to at least one pest that is 250 and 750 miles from the county
- Green indicates that tree species has no risk to pests within 750 miles of county, but has a risk to at least one pest that is greater than 750 miles from the county

Risk Weight:
Numerical scoring system based on sum of points assigned to pest risks for species. Each pest that could attack tree species is scored as 4 points if red, 3 points if orange, 2 points if yellow and 1 point if green.

Pest Color Codes:

- Red indicates pest is within Maricopa county
- Red indicates pest is within 250 miles county
- Yellow indicates pest is within 750 miles of Maricopa county
- Green indicates pest is outside of these ranges

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i-Tree
Ecosystem Analysis

25 Percent Participation

Urban Forest Effects and Values
April 2021

Summary

Understanding an urban forest's structure, function and value can promote management decisions that will improve human health and environmental quality. An assessment of the vegetation structure, function, and value of the Baseline urban forest was conducted during 2021. Data from 4 field plots located throughout Baseline were analyzed using the i-Tree Eco model developed by the U.S. Forest Service, Northern Research Station.

- Number of trees: 1,144
- Tree Cover: 5.3 %
- Most common species of trees: Feather bush, Silver wattle, Beefwood
- Percentage of trees less than 6" (15.2 cm) diameter: 18.6%
- Pollution Removal: 408.4 pounds/year ($889/year)
- Carbon Storage: 384.2 tons ($65.5 thousand)
- Carbon Sequestration: 16.69 tons ($2.85 thousand/year)
- Oxygen Production: 40.18 tons/year
- Avoided Runoff: 4.932 thousand cubic feet/year ($330/year)
- Building energy savings: $0/year
- Carbon Avoided: 0 tons/year ($0/year)
- Structural values: $2.65 million

Ton: short ton (U.S.) (2,000 lbs)
Monetary values $ are reported in US Dollars throughout the report except where noted.
Pollution removal and avoided runoff estimates are reported for trees and shrubs. All other ecosystem service estimates are reported for trees.

For an overview of i-Tree Eco methodology, see Appendix I. Data collection quality is determined by the local data collectors, over which i-Tree has no control. Additionally, some of the plot and tree information may not have been collected, so not all of the analyses may have been conducted for this report.

Table of Contents

I. Tree Characteristics of the Urban Forest

The urban forest of Baseline has an estimated 1,144 trees with a tree cover of 5.3 percent. The three most common species are Feather bush (50.3 percent), Silver wattle (19.1 percent), and Beefwood (11.6 percent).

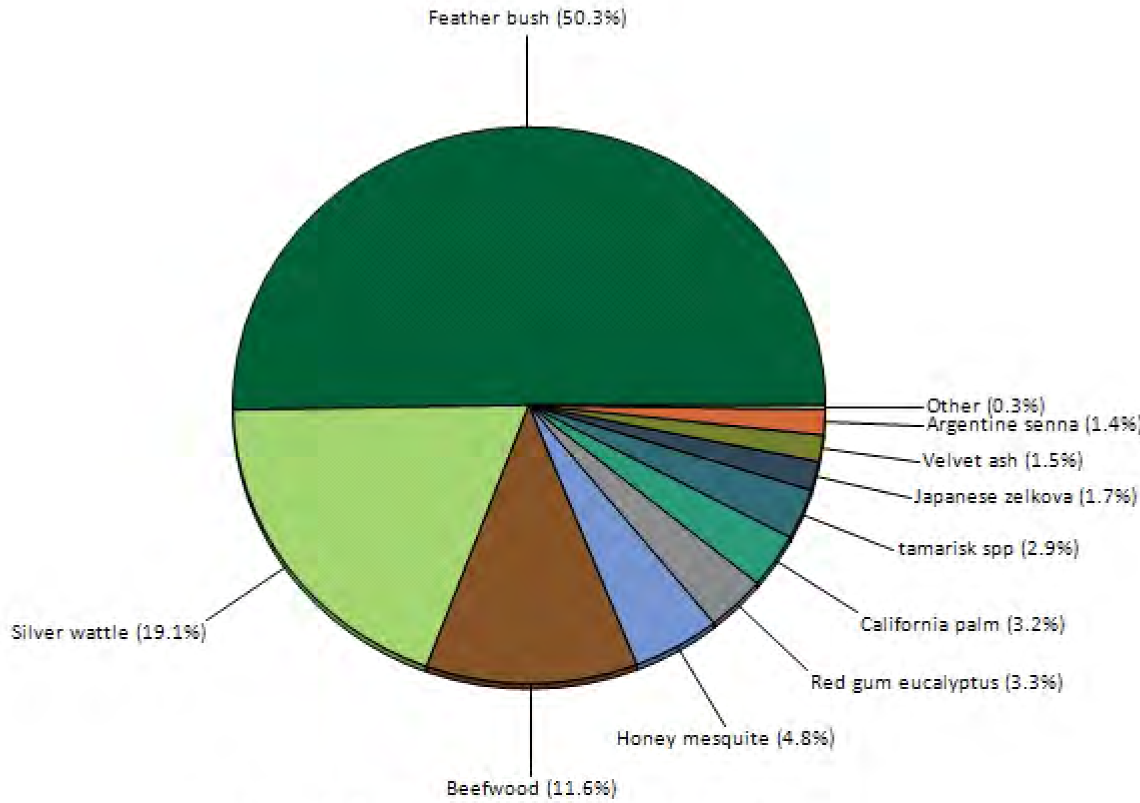


Figure 1. Tree species composition in Baseline

The overall tree density in Baseline is 10 trees/acre (see Appendix III for comparable values from other cities). For stratified projects, the highest tree densities in Baseline occur in Residential followed by Commercial and Industrial.

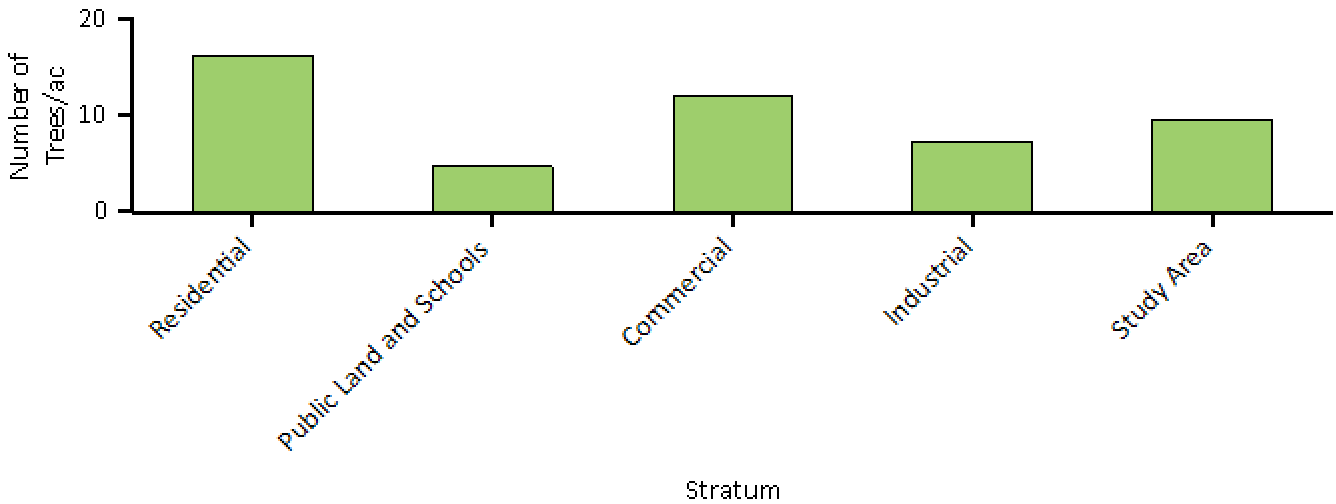


Figure 2. Number of trees/ac in Baseline by stratum

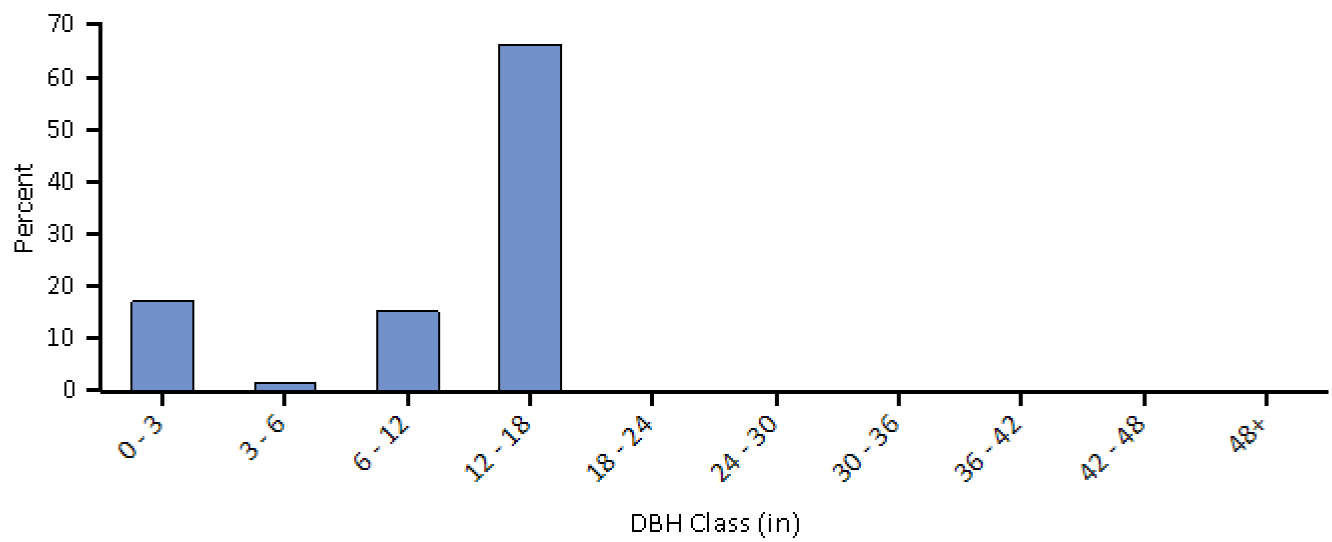


Figure 3. Percent of tree population by diameter class (DBH - stem diameter at 4.5 feet)

Urban forests are composed of a mix of native and exotic tree species. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease, but it can also pose a risk to native plants if some of the exotic species are invasive plants that can potentially out-compete and displace native species. In Baseline, about 60 percent of the trees are species native to North America, while 60 percent are native to Arizona. Species exotic to North America make up 40 percent of the population. Most exotic tree species have an origin from Australia (33 percent of the species).

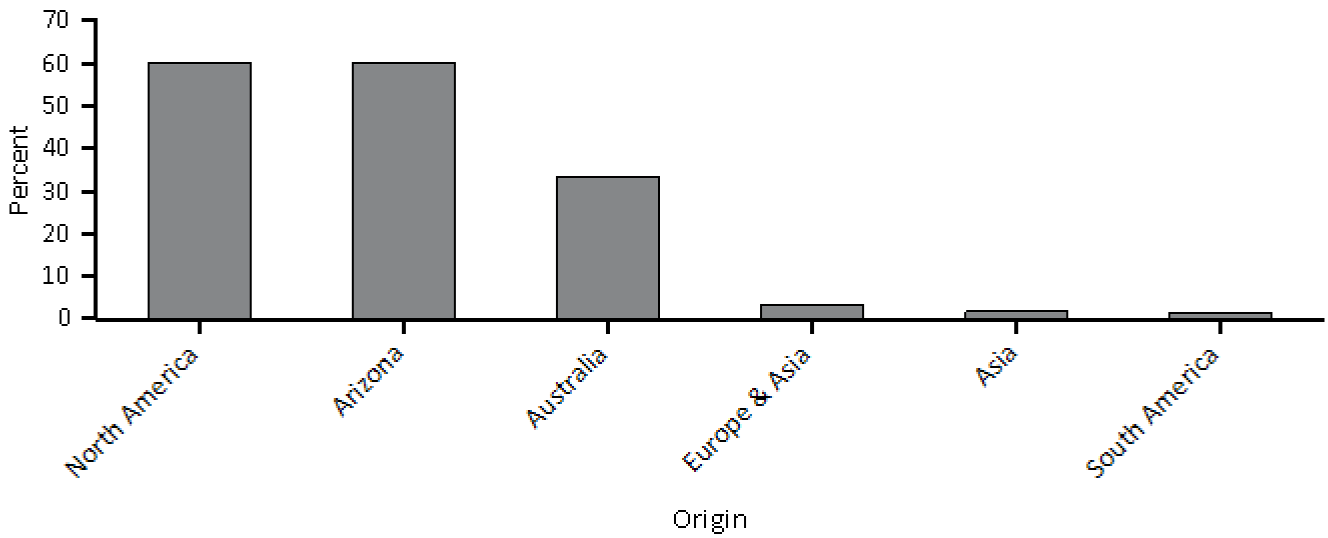


Figure 4. Percent of live tree population by area of native origin, Baseline

Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and general lack of natural enemies. These abilities enable them to displace native plants and make them a threat to natural areas. One of the 11 tree species in Baseline are identified as invasive on the state invasive species list (Arizona Wildland Invasive Plant Working Group 2005). This invasive species (Russian olive) comprises 0.3 percent of the tree population though it may only cause a minimal level of impact (see Appendix V for a complete list of invasive species).

II. Urban Forest Cover and Leaf Area

Many tree benefits equate directly to the amount of healthy leaf surface area of the plant. Trees cover about 5.3 percent of Baseline and provide 15.38 acres of leaf area. Total leaf area is greatest in Residential followed by Industrial and Commercial.

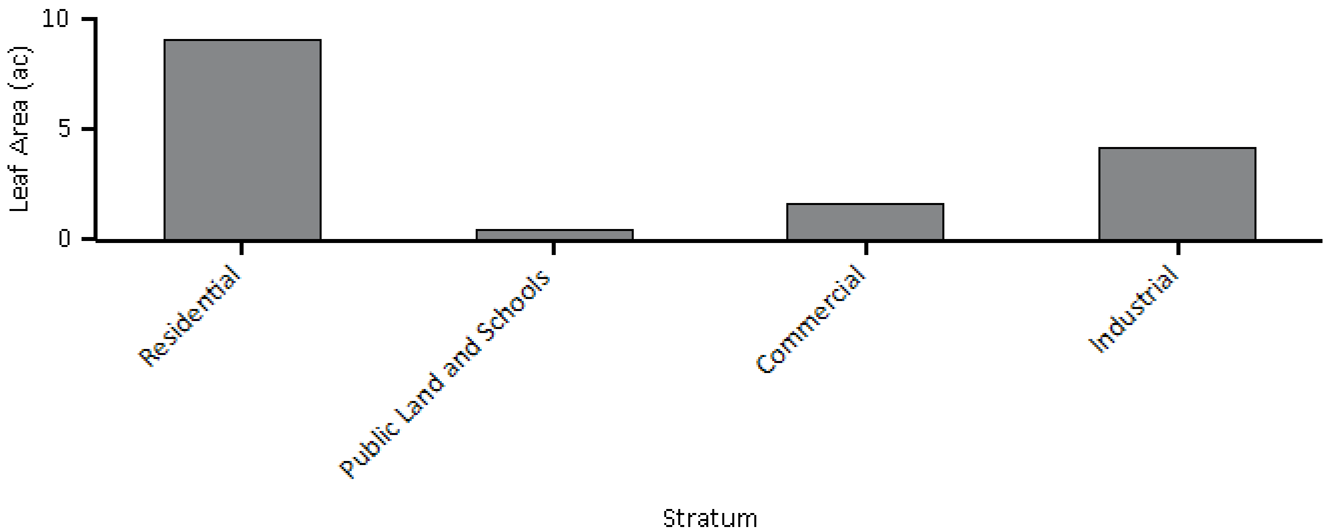


Figure 5. Leaf area by stratum, Baseline

In Baseline, the most dominant species in terms of leaf area are Beefwood, Feather bush, and Silver wattle. The 10 species with the greatest importance values are listed in Table 1. Importance values (IV) are calculated as the sum of percent population and percent leaf area. High importance values do not mean that these trees should necessarily be encouraged in the future; rather these species currently dominate the urban forest structure.

Table 1. Most important species in Baseline

Species Name	*Percent Population*	*Percent Leaf Area*	*IV*
Feather bush	50.3	28.0	78.2
Beefwood	11.6	33.6	45.1
Silver wattle	19.1	23.3	42.4
Red gum eucalyptus	3.3	6.7	10.0
tamarisk spp	2.9	6.5	9.4
Honey mesquite	4.8	0.8	5.6
California palm	3.2	0.6	3.7
Japanese zelkova	1.7	0.2	1.9
Argentine senna	1.4	0.1	1.6
Velvet ash	1.5	0.0	1.6

Common ground cover classes (including cover types beneath trees and shrubs) in Baseline include other impervious, buildings, rock, unmaintained grass, water, duff/mulch, and bare soil, impervious covers such as tar, and cement, and herbaceous covers such as grass, and herbs (Figure 6). The most dominant ground cover types are Other Impervious (26.3 percent) and Tar (24.4 percent).

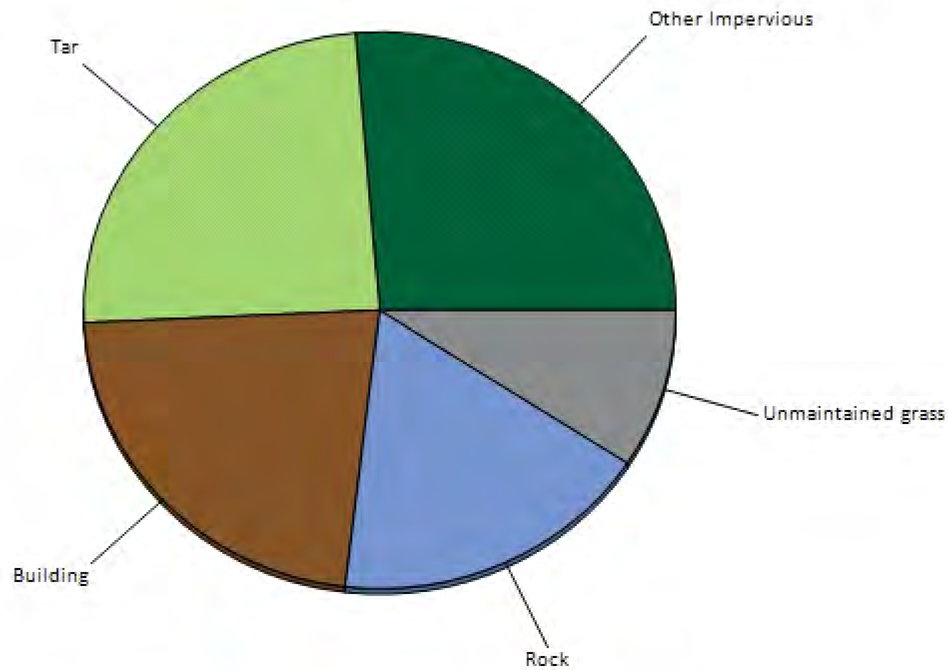


Figure 6. Percent of land by ground cover classes, Baseline

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees and shrubs in Baseline was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees and shrubs remove 408.4 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5)[2], and sulfur dioxide (SO2)) per year with an associated value of $889 (see Appendix I for more details).

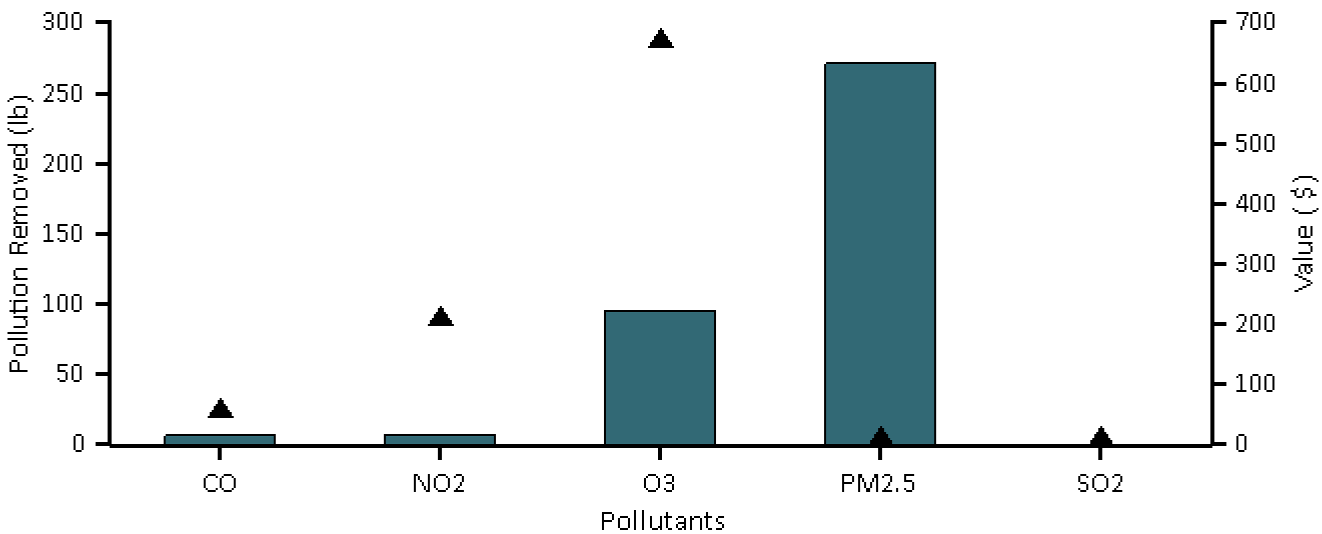


Figure 7. Annual pollution removal (points) and value (bars) by urban trees, Baseline

[1] Particulate matter less than 10 microns is a significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 when particulate matter is deposited on leaf surfaces. This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2021, trees in Baseline emitted an estimated 353.2 pounds of volatile organic compounds (VOCs) (122.8 pounds of isoprene and 230.5 pounds of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Ninety- three percent of the urban forest's VOC emissions were from Silver wattle and Red gum eucalyptus. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Baseline trees is about 16.69 tons of carbon per year with an associated value of $2.85 thousand. Net carbon sequestration in the urban forest is about 15.07 tons. See Appendix I for more details on methods.

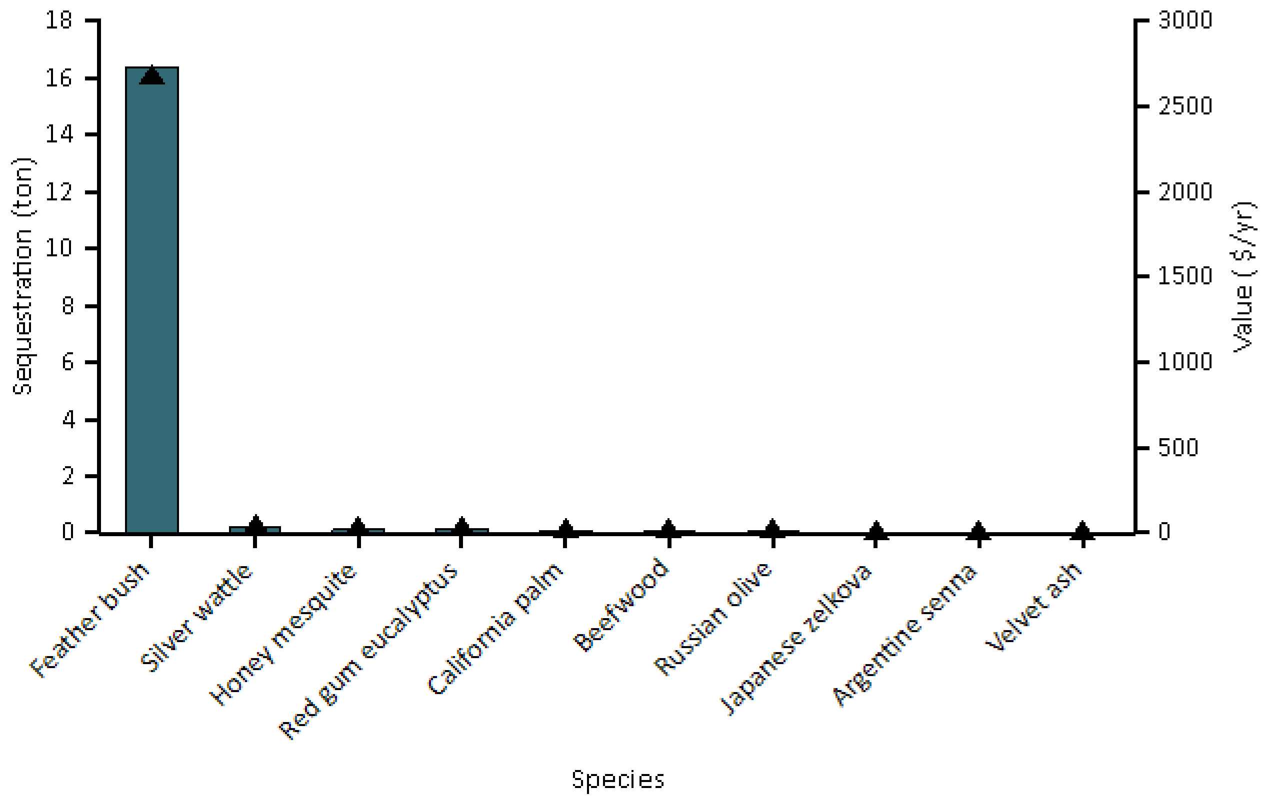


Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Baseline

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Baseline are estimated to store 384 tons of carbon ($65.5 thousand). Of the species sampled, Feather bush stores and sequesters the most carbon (approximately 79.9% of the total carbon stored and 96.1% of all sequestered carbon.)

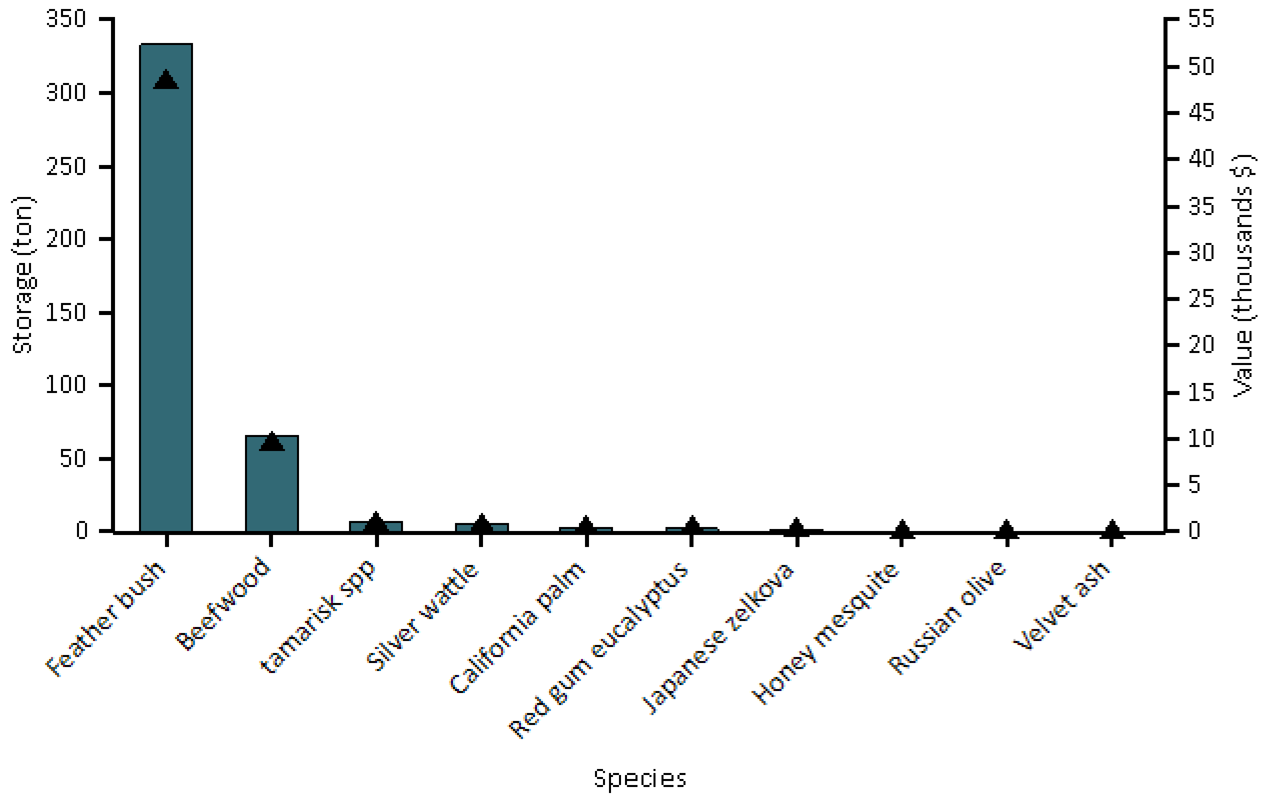


Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Baseline

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Baseline are estimated to produce 40.18 tons of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 20 oxygen production species.

Species	*Oxygen (ton)*	*Net Carbon Sequestration (ton/yr)*	*Number of Trees*	*Leaf Area (acre)*
Feather bush	39.55	14.83	575	4.31
Silver wattle	0.40	0.15	218	3.59
Honey mesquite	0.30	0.11	55	0.12
Red gum eucalyptus	0.18	0.07	37	1.03
California palm	0.17	0.06	36	0.09
Russian olive	0.10	0.04	3	0.03
Argentine senna	0.03	0.01	16	0.02
Japanese zelkova	-0.01	0.00	19	0.03
Velvet ash	-0.02	-0.01	18	0.00
tamarisk spp	-0.06	-0.02	34	1.00
Beefwood	-0.45	-0.17	132	5.16

[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Baseline help to reduce runoff by an estimated 4.93 thousand cubic feet a year with an associated value of $330 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Baseline, the total annual precipitation in 2016 was 6.8 inches.

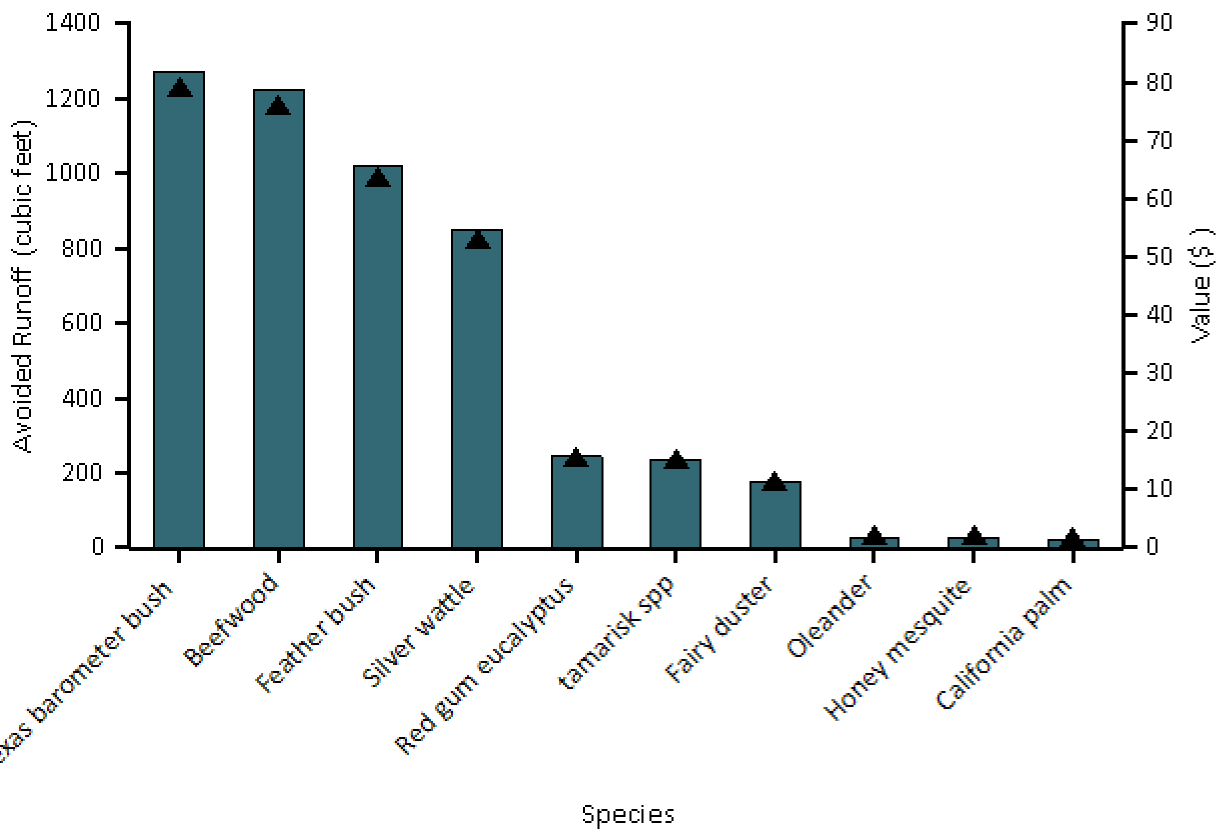


Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Baseline

VII. Trees and Building Energy Use

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space conditioned residential buildings (McPherson and Simpson 1999).

Trees in Baseline are estimated to reduce energy-related costs from residential buildings by $0 annually. Trees also provide an additional $0 in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 0 pounds of carbon emissions).

Note: negative numbers indicate that there was not a reduction in carbon emissions and/or value, rather carbon emissions and values increased by the amount shown as a negative value.[5]

Table 3. Annual energy savings due to trees near residential buildings, Baseline

	Heating	*Cooling*	*Total*
MBTU[a]	0	N/A	0
MWH[b]	0	0	0
Carbon Avoided (pounds)	0	0	0

[a]MBTU - one million British Thermal Units

[b]MWH - megawatt-hour

Table 4. Annual savings [a]($) in residential energy expenditure during heating and cooling seasons, Baseline

	Heating	*Cooling*	*Total*
MBTU[b]	0	N/A	0
MWH[c]	0	0	0
Carbon Avoided	0	0	0

[b]Based on the prices of $131.6 per MWH and $16.3480800457637 per MBTU (see Appendix I for more details)

[c]MBTU - one million British Thermal Units

[c]MWH - megawatt-hour

[5] Trees modify climate, produce shade, and reduce wind speeds. Increased energy use or costs are likely due to these tree-building interactions creating a cooling effect during the winter season. For example, a tree (particularly evergreen species) located on the southern side of a residential building may produce a shading effect that causes increases in heating requirements.

VIII. Structural and Functional Values

Urban forests have a structural value based on the trees themselves (e.g., the cost of having to replace a tree with a similar tree); they also have functional values (either positive or negative) based on the functions the trees perform.

The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees (Nowak et al 2002a). Annual functional values also tend to increase with increased number and size of healthy trees. Through proper management, urban forest values can be increased; however, the values and benefits also can decrease as the amount of healthy tree cover declines.

Urban trees in Baseline have the following structural values:

- Structural value: $2.65 million
- Carbon storage: $65.5 thousand

Urban trees in Baseline have the following annual functional values:

- Carbon sequestration: $2.85 thousand
- Avoided runoff: $330
- Pollution removal: $889
- Energy costs and carbon emission values: $0

(Note: negative value indicates increased energy cost and carbon emission value)

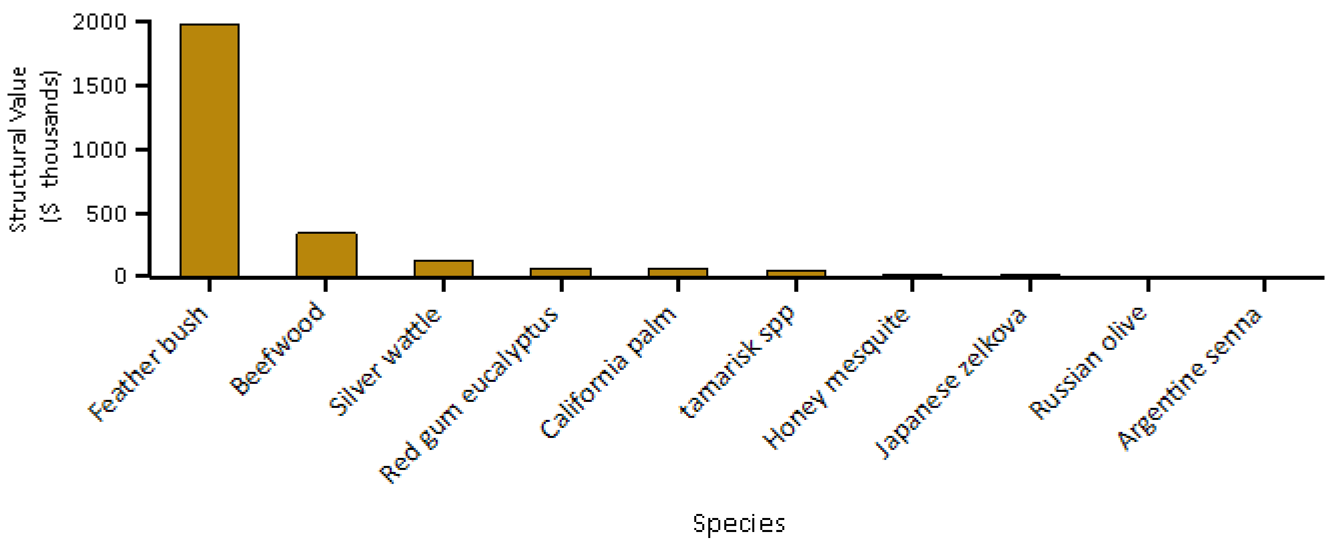


Figure 11. Tree species with the greatest structural value, Baseline

IX. Potential Pest Impacts

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, structural value and sustainability of the urban forest. As pests tend to have differing tree hosts, the potential damage or risk of each pest will differ among cities.Thirty-six pests were analyzed for their potential impact and compared with pest range maps (Forest Health Technology Enterprise Team 2014) for the conterminous United States to determine their proximity to Maricopa County. One of the thirty-six pests analyzed are located within the county. For a complete analysis of all pests, see Appendix VII.

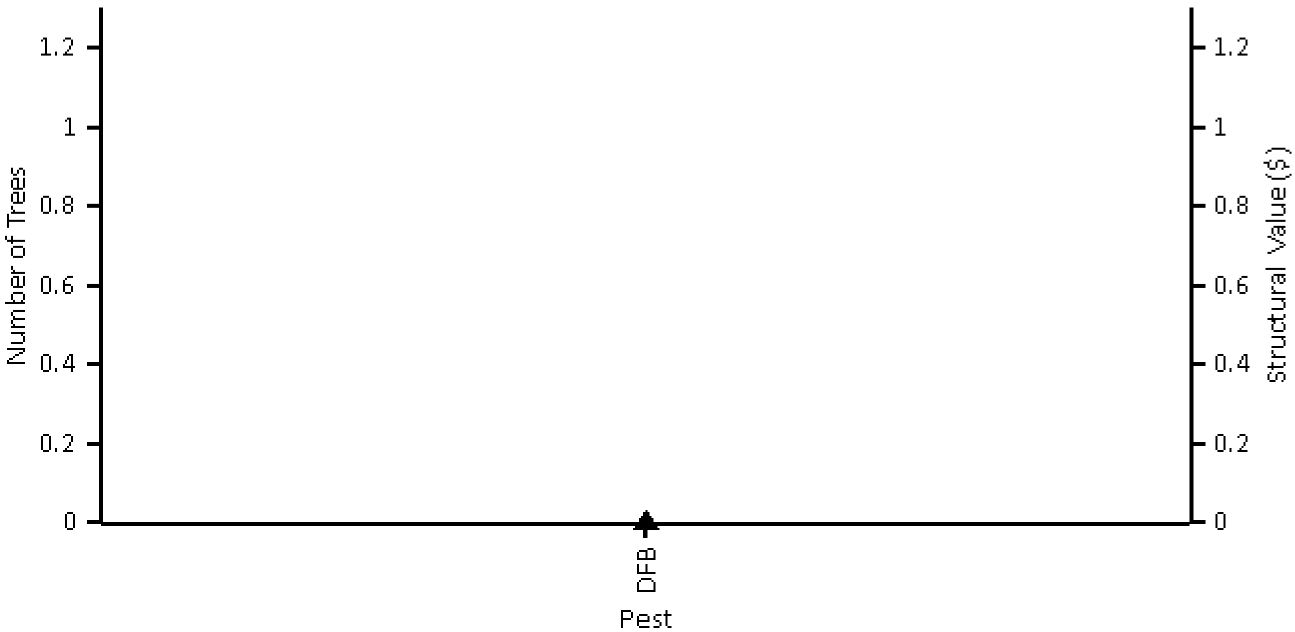


Figure 12. Number of trees at risk (points) and associated compensatory value (bars) for most threatening pests located in the county, Baseline

Douglas-fir beetle (DFB) (Schmitz and Gibson 1996) is a bark beetle that infests Douglas-fir trees throughout the western United States, British Columbia, and Mexico. Potential loss of trees from DFB is 0.0 percent ($0 in structural value).

Appendix I. i-Tree Eco Model and Field Measurements

i-Tree Eco is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects (Nowak and Crane 2000), including:

- Urban forest structure (e.g., species composition, tree health, leaf area, etc.).
- Amount of pollution removed hourly by the urban forest, and its associated percent air quality improvement throughout a year.
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power sources.
- Structural value of the forest, as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by pests, such as Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

Typically, all field data are collected during the leaf-on season to properly assess tree canopies. Typical data collection (actual data collection may vary depending upon the user) includes land use, ground and tree cover, individual tree attributes of species, stem diameter, height, crown width, crown canopy missing and dieback, and distance and direction to residential buildings (Nowak et al 2005; Nowak et al 2008).

During data collection, trees are identified to the most specific taxonomic classification possible. Trees that are not classified to the species level may be classified by genus (e.g., ash) or species groups (e.g., hardwood). In this report, tree species, genera, or species groups are collectively referred to as tree species.

<u>Tree Characteristics:</u>

Leaf area of trees was assessed using measurements of crown dimensions and percentage of crown canopy missing. In the event that these data variables were not collected, they are estimated by the model.

An analysis of invasive species is not available for studies outside of the United States. For the U.S., invasive species are identified using an invasive species list (Arizona Wildland Invasive Plant Working Group 2005)for the state in which the urban forest is located. These lists are not exhaustive and they cover invasive species of varying degrees of invasiveness and distribution. In instances where a state did not have an invasive species list, a list was created based on the lists of the adjacent states. Tree species that are identified as invasive by the state invasive species list are cross-referenced with native range data. This helps eliminate species that are on the state invasive species list, but are native to the study area.

<u>Air Pollution Removal:</u>

Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 2.5 microns. Particulate matter less than 10 microns (PM10) is another significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988; Baldocchi et al 1987). As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature (Bidwell and Fraser 1972; Lovett 1994) that were adjusted depending on leaf phenology and leaf area.

Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere (Zinke 1967). Recent updates (2011) to air quality modeling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values (Hirabayashi et al 2011; Hirabayashi et al 2012; Hirabayashi 2011).

Trees remove PM2.5 when particulate matter is deposited on leaf surfaces (Nowak et al 2013). This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors. Generally, PM2.5 removal is positive with positive benefits. However, there are some cases when net removal is negative or resuspended particles lead to increased pollution concentrations and negative values. During some months (e.g., with no rain), trees resuspend more particles than they remove. Resuspension can also lead to increased overall PM2.5 concentrations if the boundary layer conditions are lower during net resuspension periods than during net removal periods. Since the pollution removal value is based on the change in pollution concentration, it is possible to have situations when trees remove PM2.5 but increase concentrations and thus have negative values during periods of positive overall removal. These events are not common, but can happen.

For reports in the United States, default air pollution removal value is calculated based on local incidence of adverse health effects and national median externality costs. The number of adverse health effects and associated economic value is calculated for ozone, sulfur dioxide, nitrogen dioxide, and particulate matter less than 2.5 microns using data from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) (Nowak et al 2014). The model uses a damage-function approach that is based on the local change in pollution concentration and population. National median externality costs were used to calculate the value of carbon monoxide removal (Murray et al 1994).

For international reports, user-defined local pollution values are used. For international reports that do not have local values, estimates are based on either European median externality values (van Essen et al 2011) or BenMAP regression equations (Nowak et al 2014) that incorporate user-defined population estimates. Values are then converted to local currency with user-defined exchange rates.

For this analysis, pollution removal value is calculated based on the prices of $1,327 per ton (carbon monoxide), $1,555 per ton (ozone), $373 per ton (nitrogen dioxide), $169 per ton (sulfur dioxide), $316,613 per ton (particulate matter less than 2.5 microns).

Carbon Storage and Sequestration:

Carbon storage is the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation. To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak 1994). To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

Carbon sequestration is the removal of carbon dioxide from the air by plants. To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year x+1.

Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. For international reports that do not have local values, estimates are based on the carbon value for the United States (U.S. Environmental Protection Agency 2015, Interagency Working Group on Social Cost of Carbon 2015) and converted to local currency with user-defined exchange rates.

For this analysis, carbon storage and carbon sequestration values are calculated based on $171 per ton.

Oxygen Production:

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights: net O2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of the urban forest account for decomposition (Nowak et al 2007). For complete inventory projects, oxygen production is estimated from gross carbon sequestration and does not account for decomposition.

Avoided Runoff:

Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis.

The value of avoided runoff is based on estimated or user-defined local values. For international reports that do not have local values, the national average value for the United States is utilized and converted to local currency with user-defined exchange rates. The U.S. value of avoided runoff is based on the U.S. Forest Service's Community Tree Guide Series (McPherson et al 1999; 2000; 2001; 2002; 2003; 2004; 2006a; 2006b; 2006c; 2007; 2010; Peper et al 2009; 2010; Vargas et al 2007a; 2007b; 2008).

For this analysis, avoided runoff value is calculated based on the price of $0.07 per ft^3.

Building Energy Use:

If appropriate field data were collected, seasonal effects of trees on residential building energy use were calculated based on procedures described in the literature (McPherson and Simpson 1999) using distance and direction of trees from residential structures, tree height and tree condition data. To calculate the monetary value of energy savings, local or custom prices per MWH or MBTU are utilized.

For this analysis, energy saving value is calculated based on the prices of $131.60 per MWH and $16.35 per MBTU.

Structural Values:

Structural value is the value of a tree based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree). Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information (Nowak et al 2002a; 2002b). Structural value may not be included for international projects if there is insufficient local data to complete the valuation procedures.

Potential Pest Impacts:

The complete potential pest risk analysis is not available for studies outside of the United States. The number of trees at risk to the pests analyzed is reported, though the list of pests is based on known insects and disease in the United States.

For the U.S., potential pest risk is based on pest range maps and the known pest host species that are likely to

experience mortality. Pest range maps for 2012 from the Forest Health Technology Enterprise Team (FHTET) (Forest Health Technology Enterprise Team 2014) were used to determine the proximity of each pest to the county in which the urban forest is located. For the county, it was established whether the insect/disease occurs within the county, is within 250 miles of the county edge, is between 250 and 750 miles away, or is greater than 750 miles away. FHTET did not have pest range maps for Dutch elm disease and chestnut blight. The range of these pests was based on known occurrence and the host range, respectively (Eastern Forest Environmental Threat Assessment Center; Worrall 2007).

<u>Relative Tree Effects:</u>

The relative value of tree benefits reported in Appendix II is calculated to show what carbon storage and sequestration, and air pollutant removal equate to in amounts of municipal carbon emissions, passenger automobile emissions, and house emissions.

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (Carbon Dioxide Information Analysis Center 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (g/mi) for CO, NOx, VOCs, PM10, SO2 for 2010 (Bureau of Transportation Statistics 2010; Heirigs et al 2004), PM2.5 for 2011-2015 (California Air Resources Board 2013), and CO2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (Federal Highway Administration 2013) to determine average emissions per vehicle.

Household emissions are based on average electricity kWh usage, natural gas Btu usage, fuel oil Btu usage, kerosene Btu usage, LPG Btu usage, and wood Btu usage per household in 2009 (Energy Information Administration 2013; Energy Information Administration 2014)

- CO2, SO2, and NOx power plant emission per KWh are from Leonardo Academy 2011. CO emission per kWh assumes 1/3 of one percent of C emissions is CO based on Energy Information Administration 1994. PM10 emission per kWh from Layton 2004.
- CO2, NOx, SO2, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from Leonardo Academy 2011.
- CO2 emissions per Btu of wood from Energy Information Administration 2014.
- CO, NOx and SOx emission per Btu based on total emissions and wood burning (tons) from (British Columbia Ministry 2005; Georgia Forestry Commission 2009).

Appendix II. Relative Tree Effects

The urban forest in Baseline provides benefits that include carbon storage and sequestration, and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average municipal carbon emissions, average passenger automobile emissions, and average household emissions. See Appendix I for methodology.

Carbon storage is equivalent to:
- Amount of carbon emitted in Baseline in 0 days
- Annual carbon (C) emissions from 272 automobiles
- Annual C emissions from 111 single-family houses

Carbon monoxide removal is equivalent to:
- Annual carbon monoxide emissions from 0 automobiles
- Annual carbon monoxide emissions from 0 single-family houses

Nitrogen dioxide removal is equivalent to:
- Annual nitrogen dioxide emissions from 6 automobiles
- Annual nitrogen dioxide emissions from 3 single-family houses

Sulfur dioxide removal is equivalent to:
- Annual sulfur dioxide emissions from 25 automobiles
- Annual sulfur dioxide emissions from 0 single-family houses

Annual carbon sequestration is equivalent to:
- Amount of carbon emitted in Baseline in 0.0 days
- Annual C emissions from 0 automobiles
- Annual C emissions from 0 single-family houses

Appendix III. Comparison of Urban Forests

A common question asked is, "How does this city compare to other cities?" Although comparison among cities should be made with caution as there are many attributes of a city that affect urban forest structure and functions, summary data are provided from other cities analyzed using the i-Tree Eco model.

I. City totals for trees

City	*% Tree Cover*	*Number of Trees*	*Carbon Storage (tons)*	*Carbon Sequestration (tons/yr)*	*Pollution Removal (tons/yr)*
Toronto, ON, Canada	26.6	10,220,000	1,221,000	51,500	2,099
Atlanta, GA	36.7	9,415,000	1,344,000	46,400	1,663
Los Angeles, CA	11.1	5,993,000	1,269,000	77,000	1,975
New York, NY	20.9	5,212,000	1,350,000	42,300	1,676
London, ON, Canada	24.7	4,376,000	396,000	13,700	408
Chicago, IL	17.2	3,585,000	716,000	25,200	888
Phoenix, AZ	9.0	3,166,000	315,000	32,800	563
Baltimore, MD	21.0	2,479,000	570,000	18,400	430
Philadelphia, PA	15.7	2,113,000	530,000	16,100	575
Washington, DC	28.6	1,928,000	525,000	16,200	418
Oakville, ON , Canada	29.1	1,908,000	147,000	6,600	190
Albuquerque, NM	14.3	1,846,000	332,000	10,600	248
Boston, MA	22.3	1,183,000	319,000	10,500	283
Syracuse, NY	26.9	1,088,000	183,000	5,900	109
Woodbridge, NJ	29.5	986,000	160,000	5,600	210
Minneapolis, MN	26.4	979,000	250,000	8,900	305
San Francisco, CA	11.9	668,000	194,000	5,100	141
Morgantown, WV	35.5	658,000	93,000	2,900	72
Moorestown, NJ	28.0	583,000	117,000	3,800	118
Hartford, CT	25.9	568,000	143,000	4,300	58
Jersey City, NJ	11.5	136,000	21,000	890	41
Casper, WY	8.9	123,000	37,000	1,200	37
Freehold, NJ	34.4	48,000	20,000	540	22

II. Totals per acre of land area

City	*Number of Trees/ac*	*Carbon Storage (tons/ac)*	*Carbon Sequestration (tons/ac/yr)*	*Pollution Removal (lb/ac/yr)*
Toronto, ON, Canada	64.9	7.8	0.33	26.7
Atlanta, GA	111.6	15.9	0.55	39.4
Los Angeles, CA	19.6	4.2	0.16	13.1
New York, NY	26.4	6.8	0.21	17.0
London, ON, Canada	75.1	6.8	0.24	14.0
Chicago, IL	24.2	4.8	0.17	12.0
Phoenix, AZ	12.9	1.3	0.13	4.6
Baltimore, MD	48.0	11.1	0.36	16.6
Philadelphia, PA	25.1	6.3	0.19	13.6
Washington, DC	49.0	13.3	0.41	21.2
Oakville, ON , Canada	78.1	6.0	0.27	11.0
Albuquerque, NM	21.8	3.9	0.12	5.9
Boston, MA	33.5	9.1	0.30	16.1
Syracuse, NY	67.7	10.3	0.34	13.6
Woodbridge, NJ	66.5	10.8	0.38	28.4
Minneapolis, MN	26.2	6.7	0.24	16.3
San Francisco, CA	22.5	6.6	0.17	9.5
Morgantown, WV	119.2	16.8	0.52	26.0
Moorestown, NJ	62.1	12.4	0.40	25.1
Hartford, CT	50.4	12.7	0.38	10.2
Jersey City, NJ	14.4	2.2	0.09	8.6
Casper, WY	9.1	2.8	0.09	5.5
Freehold, NJ	38.3	16.0	0.44	35.3

Appendix IV. General Recommendations for Air Quality Improvement

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmosphere environment. Four main ways that urban trees affect air quality are (Nowak 1995):

- Temperature reduction and other microclimate effects
- Removal of air pollutants
- Emission of volatile organic compounds (VOC) and tree maintenance emissions
- Energy effects on buildings

The cumulative and interactive effects of trees on climate, pollution removal, and VOC and power plant emissions determine the impact of trees on air pollution. Cumulative studies involving urban tree impacts on ozone have revealed that increased urban canopy cover, particularly with low VOC emitting species, leads to reduced ozone concentrations in cities (Nowak 2000). Local urban management decisions also can help improve air quality.

Urban forest management strategies to help improve air quality include (Nowak 2000):

Strategy	*Result*
Increase the number of healthy trees	Increase pollution removal
Sustain existing tree cover	Maintain pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone and carbon monoxide formation
Sustain large, healthy trees	Large trees have greatest per-tree effects
Use long-lived trees	Reduce long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduce pollutants emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduce pollutant emissions
Plant trees in energy conserving locations	Reduce pollutant emissions from power plants
Plant trees to shade parked cars	Reduce vehicular VOC emissions
Supply ample water to vegetation	Enhance pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improve tree health
Utilize evergreen trees for particulate matter	Year-round removal of particles

Appendix V. Invasive Species of the Urban Forest

The following inventoried tree species were listed as invasive on the Arizona invasive species list (Arizona Wildland Invasive Plant Working Group 2005):

Species Name[a]	*Number of Trees*	*% of Trees*	*Leaf Area (ft²)*	*Percent Leaf Area*
Russian olive	3	0.3	0.0	0.2
Total	**3**	**0.30**	**0.00**	**0.20**

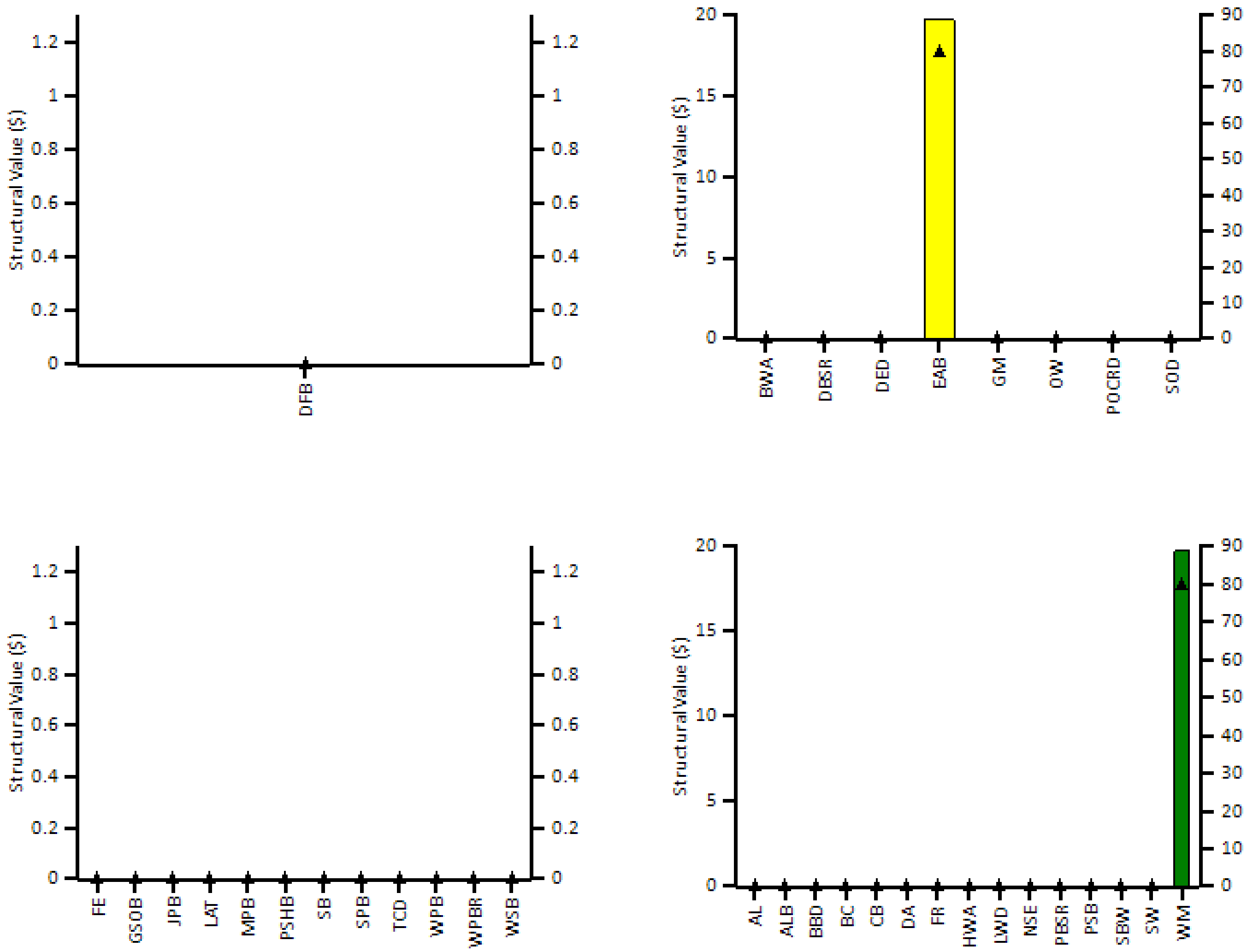
[a]Species are determined to be invasive if they are listed on the state's invasive species list

Appendix VI. Potential Risk of Pests

Thirty-six insects and diseases were analyzed to quantify their potential impact on the urban forest. As each insect/disease is likely to attack different host tree species, the implications for {0} will vary. The number of trees at risk reflects only the known host species that are likely to experience mortality.

Code	Scientific Name	Common Name	Trees at Risk (#)	Value ($)
AL	Phyllocnistis populiella	Aspen Leafminer	0	0.00
ALB	Anoplophora glabripennis	Asian Longhorned Beetle	0	0.00
BBD	Neonectria faginata	Beech Bark Disease	0	0.00
BC	Sirococcus clavigignenti juglandacearum	Butternut Canker	0	0.00
BWA	Adelges piceae	Balsam Woolly Adelgid	0	0.00
CB	Cryphonectria parasitica	Chestnut Blight	0	0.00
DA	Discula destructiva	Dogwood Anthracnose	0	0.00
DBSR	Leptographium wageneri var. pseudotsugae	Douglas-fir Black Stain Root Disease	0	0.00
DED	Ophiostoma novo-ulmi	Dutch Elm Disease	0	0.00
DFB	Dendroctonus pseudotsugae	Douglas-Fir Beetle	0	0.00
EAB	Agrilus planipennis	Emerald Ash Borer	18	88.82
FE	Scolytus ventralis	Fir Engraver	0	0.00
FR	Cronartium quercuum f. sp. Fusiforme	Fusiform Rust	0	0.00
GM	Lymantria dispar	Gypsy Moth	0	0.00
GSOB	Agrilus auroguttatus	Goldspotted Oak Borer	0	0.00
HWA	Adelges tsugae	Hemlock Woolly Adelgid	0	0.00
JPB	Dendroctonus jeffreyi	Jeffrey Pine Beetle	0	0.00
LAT	Choristoneura conflictana	Large Aspen Tortrix	0	0.00
LWD	Raffaelea lauricola	Laurel Wilt	0	0.00
MPB	Dendroctonus ponderosae	Mountain Pine Beetle	0	0.00
NSE	Ips perturbatus	Northern Spruce Engraver	0	0.00
OW	Ceratocystis fagacearum	Oak Wilt	0	0.00
PBSR	Leptographium wageneri var. ponderosum	Pine Black Stain Root Disease	0	0.00
POCRD	Phytophthora lateralis	Port-Orford-Cedar Root Disease	0	0.00
PSB	Tomicus piniperda	Pine Shoot Beetle	0	0.00
PSHB	Euwallacea nov. sp.	Polyphagous Shot Hole Borer	0	0.00
SB	Dendroctonus rufipennis	Spruce Beetle	0	0.00
SBW	Choristoneura fumiferana	Spruce Budworm	0	0.00
SOD	Phytophthora ramorum	Sudden Oak Death	0	0.00
SPB	Dendroctonus frontalis	Southern Pine Beetle	0	0.00
SW	Sirex noctilio	Sirex Wood Wasp	0	0.00
TCD	Geosmithia morbida	Thousand Canker Disease	0	0.00
WM	Operophtera brumata	Winter Moth	18	88.82
WPB	Dendroctonus brevicomis	Western Pine Beetle	0	0.00
WPBR	Cronartium ribicola	White Pine Blister Rust	0	0.00
WSB	Choristoneura occidentalis	Western Spruce Budworm	0	0.00

In the following graph, the pests are color coded according to the county's proximity to the pest occurrence in the United States. Red indicates that the pest is within the county; orange indicates that the pest is within 250 miles of the county; yellow indicates that the pest is within 750 miles of the county; and green indicates that the pest is outside of these ranges.



Note: points - Number of trees, bars - Structural value

Based on the host tree species for each pest and the current range of the pest (Forest Health Technology Enterprise Team 2014), it is possible to determine what the risk is that each tree species in the urban forest could be attacked by an insect or disease.

Spp. Risk	Risk Weight	Species Name	AL	ALB	BBD	BC	BWA	CB	DA	DBSR	DED	DFB	EAB	FE	FR	GM	GSOB	HWA	JPB	LAT	LWD	MPB	NSE	OW	PBSR	POCRD	PSB	PSHB	SB	SBW	SOD	SPB	SW	TCD	WM	WPB	WPBR	WSB
	3	Velvet ash																																				

Note:
Species that are not listed in the matrix are not known to be hosts to any of the pests analyzed.

Species Risk:

- Red indicates that tree species is at risk to at least one pest within county
- Orange indicates that tree species has no risk to pests in county, but has a risk to at least one pest within 250 miles from the county
- Yellow indicates that tree species has no risk to pests within 250 miles of county, but has a risk to at least one pest that is 250 and 750 miles from the county
- Green indicates that tree species has no risk to pests within 750 miles of county, but has a risk to at least one pest that is greater than 750 miles from the county

Risk Weight:
Numerical scoring system based on sum of points assigned to pest risks for species. Each pest that could attack tree species is scored as 4 points if red, 3 points if orange, 2 points if yellow and 1 point if green.

Pest Color Codes:

- Red indicates pest is within Maricopa county
- Red indicates pest is within 250 miles county
- Yellow indicates pest is within 750 miles of Maricopa county
- Green indicates pest is outside of these ranges

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i-Tree
Ecosystem Analysis

50 Percent Participation

Urban Forest Effects and Values
April 2021

Summary

Understanding an urban forest's structure, function and value can promote management decisions that will improve human health and environmental quality. An assessment of the vegetation structure, function, and value of the Baseline urban forest was conducted during 2021. Data from 4 field plots located throughout Baseline were analyzed using the i-Tree Eco model developed by the U.S. Forest Service, Northern Research Station.

- Number of trees: 1,612
- Tree Cover: 5.3 %
- Most common species of trees: Feather bush, Silver wattle, Beefwood
- Percentage of trees less than 6" (15.2 cm) diameter: 13.2%
- Pollution Removal: 440.6 pounds/year ($1.01 thousand/year)
- Carbon Storage: 634 tons ($108 thousand)
- Carbon Sequestration: 29.72 tons ($5.07 thousand/year)
- Oxygen Production: 72.33 tons/year
- Avoided Runoff: 5.507 thousand cubic feet/year ($368/year)
- Building energy savings: $0/year
- Carbon Avoided: 0 tons/year ($0/year)
- Structural values: $4.27 million

Ton: short ton (U.S.) (2,000 lbs)
Monetary values $ are reported in US Dollars throughout the report except where noted.
Pollution removal and avoided runoff estimates are reported for trees and shrubs. All other ecosystem service estimates are reported for trees.

For an overview of i-Tree Eco methodology, see Appendix I. Data collection quality is determined by the local data collectors, over which i-Tree has no control. Additionally, some of the plot and tree information may not have been collected, so not all of the analyses may have been conducted for this report.

Table of Contents

I. Tree Characteristics of the Urban Forest

The urban forest of Baseline has an estimated 1,612 trees with a tree cover of 5.3 percent. The three most common species are Feather bush (64.7 percent), Silver wattle (13.6 percent), and Beefwood (8.2 percent).

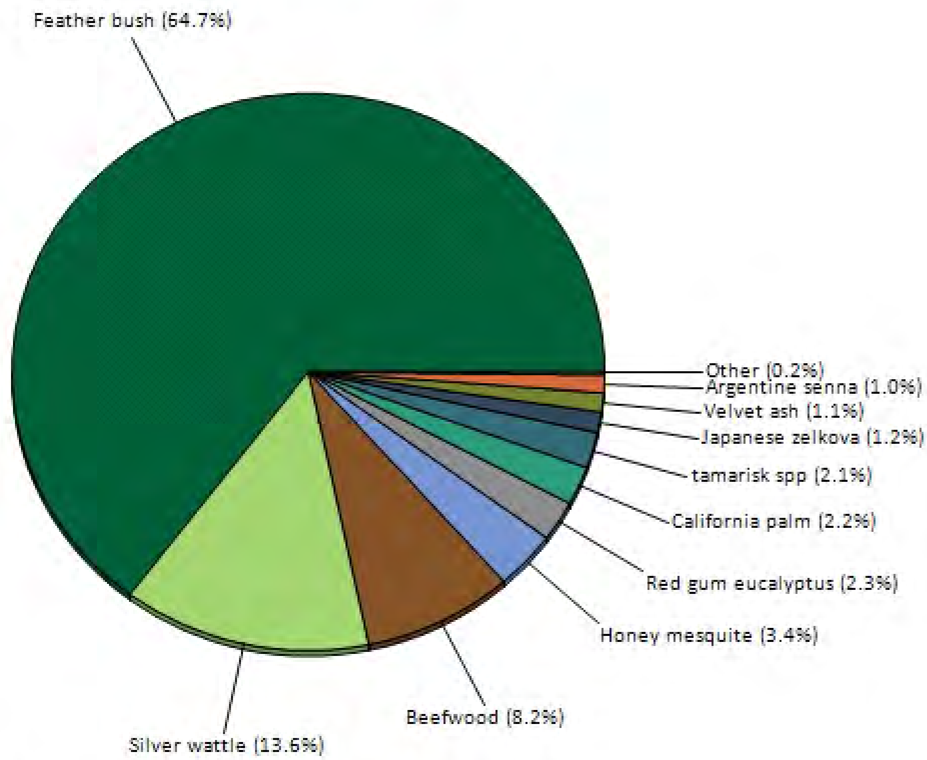


Figure 1. Tree species composition in Baseline

The overall tree density in Baseline is 13 trees/acre (see Appendix III for comparable values from other cities). For stratified projects, the highest tree densities in Baseline occur in Residential followed by Commercial and Industrial.

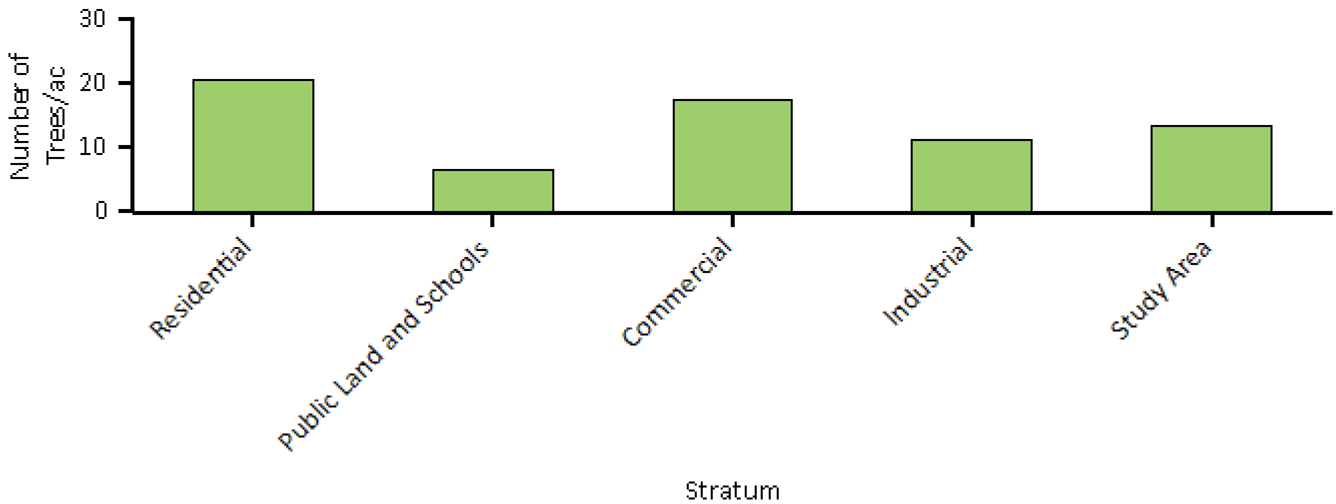


Figure 2. Number of trees/ac in Baseline by stratum

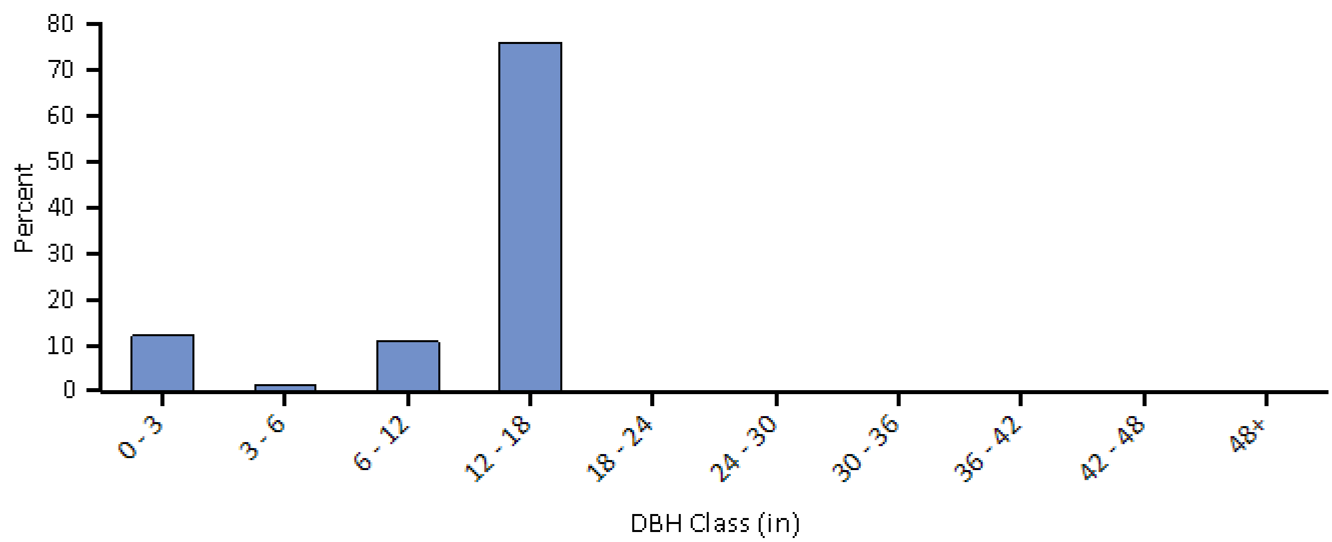


Figure 3. Percent of tree population by diameter class (DBH - stem diameter at 4.5 feet)

Urban forests are composed of a mix of native and exotic tree species. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease, but it can also pose a risk to native plants if some of the exotic species are invasive plants that can potentially out-compete and displace native species. In Baseline, about 72 percent of the trees are species native to North America, while 72 percent are native to Arizona. Species exotic to North America make up 28 percent of the population. Most exotic tree species have an origin from Australia (24 percent of the species).

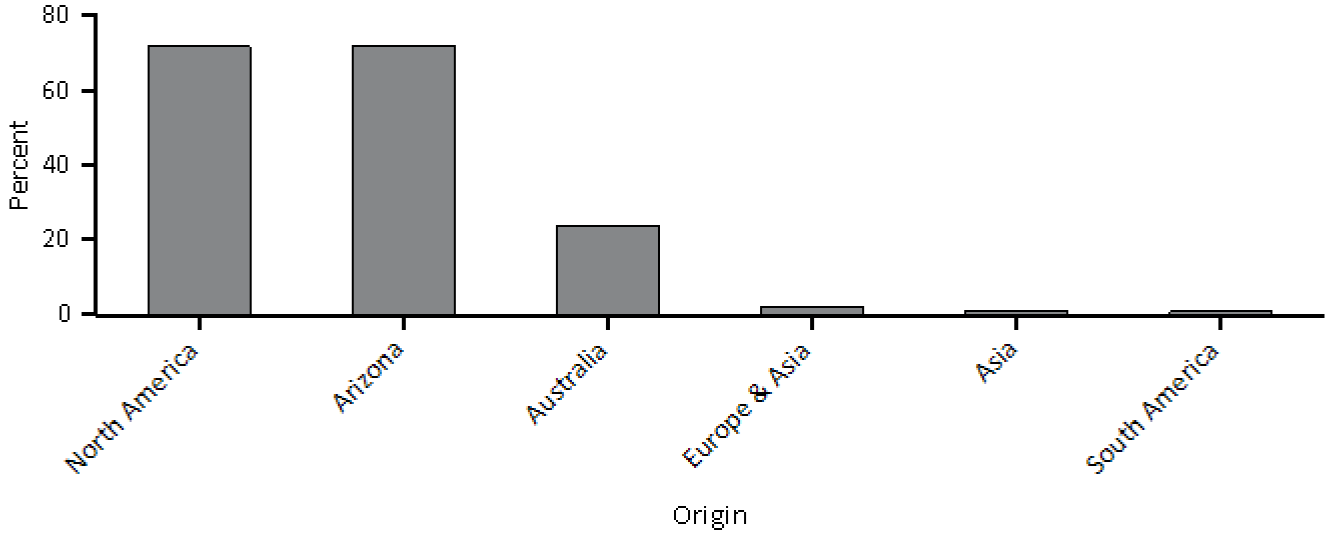


Figure 4. Percent of live tree population by area of native origin, Baseline

Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and general lack of natural enemies. These abilities enable them to displace native plants and make them a threat to natural areas. One of the 11 tree species in Baseline are identified as invasive on the state invasive species list (Arizona Wildland Invasive Plant Working Group 2005). This invasive species (Russian olive) comprises 0.2 percent of the tree population though it may only cause a minimal level of impact (see Appendix V for a complete list of invasive species).

II. Urban Forest Cover and Leaf Area

Many tree benefits equate directly to the amount of healthy leaf surface area of the plant. Trees cover about 5.3 percent of Baseline and provide 18.89 acres of leaf area. Total leaf area is greatest in Residential followed by Industrial and Commercial.

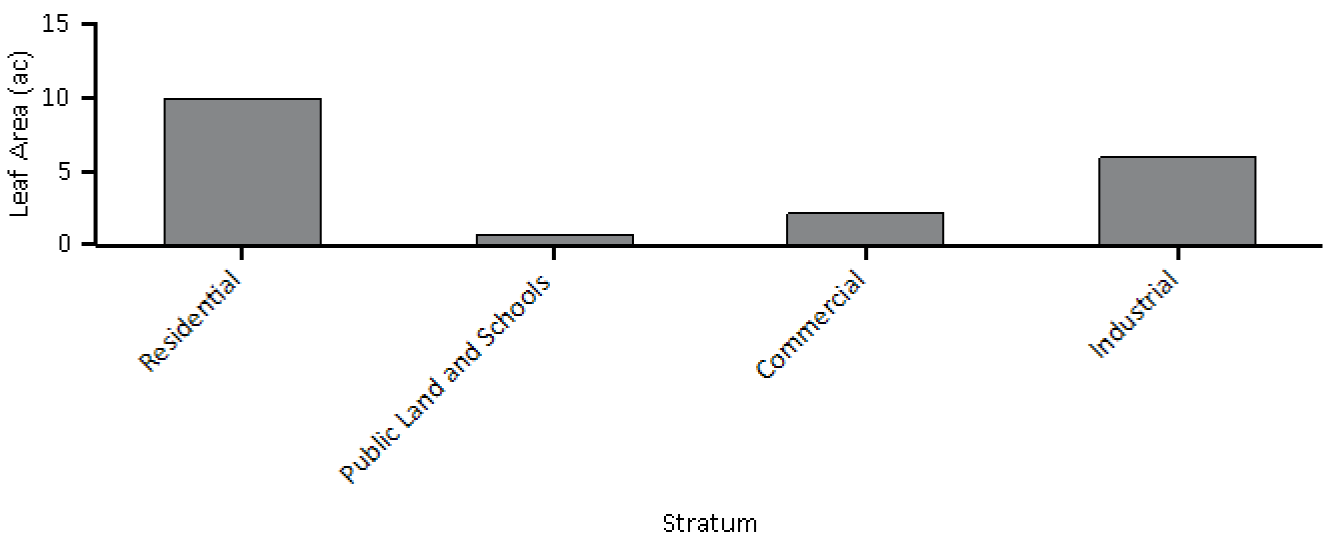


Figure 5. Leaf area by stratum, Baseline

In Baseline, the most dominant species in terms of leaf area are Feather bush, Beefwood, and Silver wattle. The 10 species with the greatest importance values are listed in Table 1. Importance values (IV) are calculated as the sum of percent population and percent leaf area. High importance values do not mean that these trees should necessarily be encouraged in the future; rather these species currently dominate the urban forest structure.

Table 1. Most important species in Baseline

Species Name	*Percent Population*	*Percent Leaf Area*	*IV*
Feather bush	64.7	41.4	106.0
Beefwood	8.2	27.3	35.5
Silver wattle	13.5	19.0	32.5
Red gum eucalyptus	2.3	5.4	7.8
tamarisk spp	2.1	5.3	7.4
Honey mesquite	3.4	0.6	4.0
California palm	2.2	0.5	2.7
Japanese zelkova	1.2	0.2	1.4
Argentine senna	1.0	0.1	1.1
Velvet ash	1.1	0.0	1.1

Common ground cover classes (including cover types beneath trees and shrubs) in Baseline include other impervious, buildings, unmaintained grass, rock, water, duff/mulch, and bare soil, impervious covers such as tar, and cement, and herbaceous covers such as grass, and herbs (Figure 6). The most dominant ground cover types are Other Impervious (26.3 percent) and Building (22.4 percent).

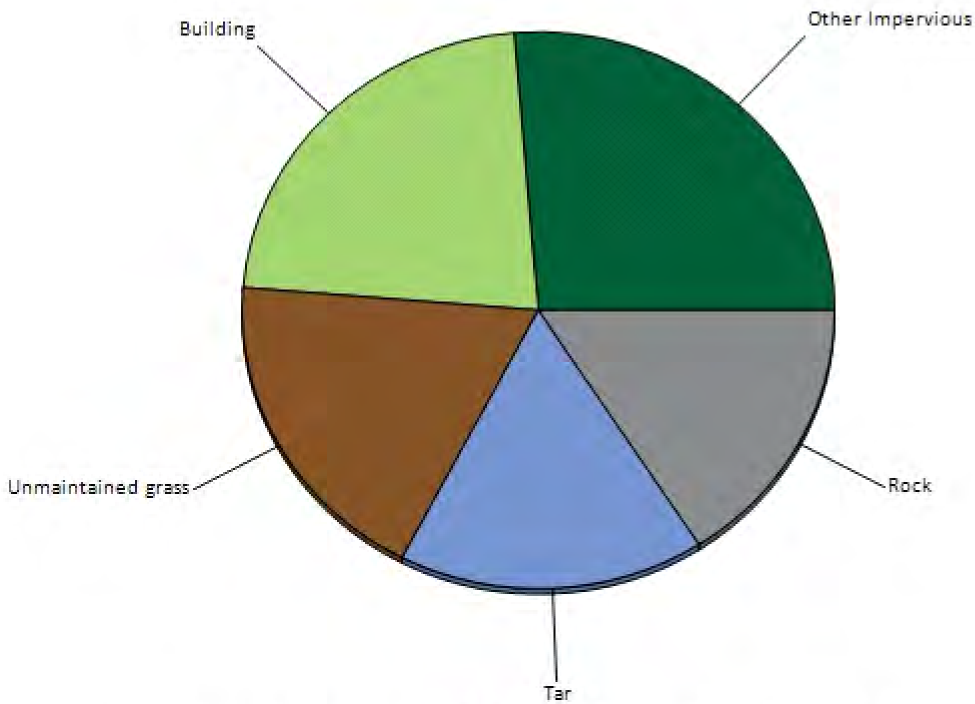


Figure 6. Percent of land by ground cover classes, Baseline

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees and shrubs in Baseline was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees and shrubs remove 440.6 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5)[2], and sulfur dioxide (SO2)) per year with an associated value of $1.01 thousand (see Appendix I for more details).

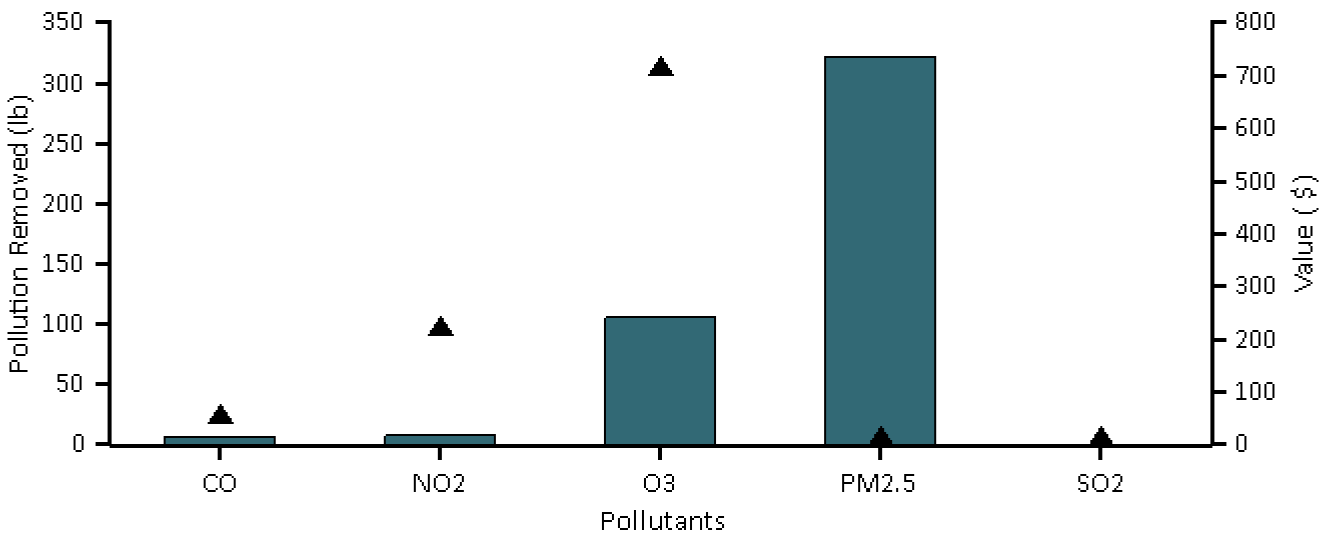


Figure 7. Annual pollution removal (points) and value (bars) by urban trees, Baseline

[1] Particulate matter less than 10 microns is a significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 when particulate matter is deposited on leaf surfaces. This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2021, trees in Baseline emitted an estimated 350.5 pounds of volatile organic compounds (VOCs) (110.5 pounds of isoprene and 240 pounds of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Ninety percent of the urban forest's VOC emissions were from Silver wattle and Red gum eucalyptus. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Baseline trees is about 29.72 tons of carbon per year with an associated value of $5.07 thousand. Net carbon sequestration in the urban forest is about 27.12 tons. See Appendix I for more details on methods.

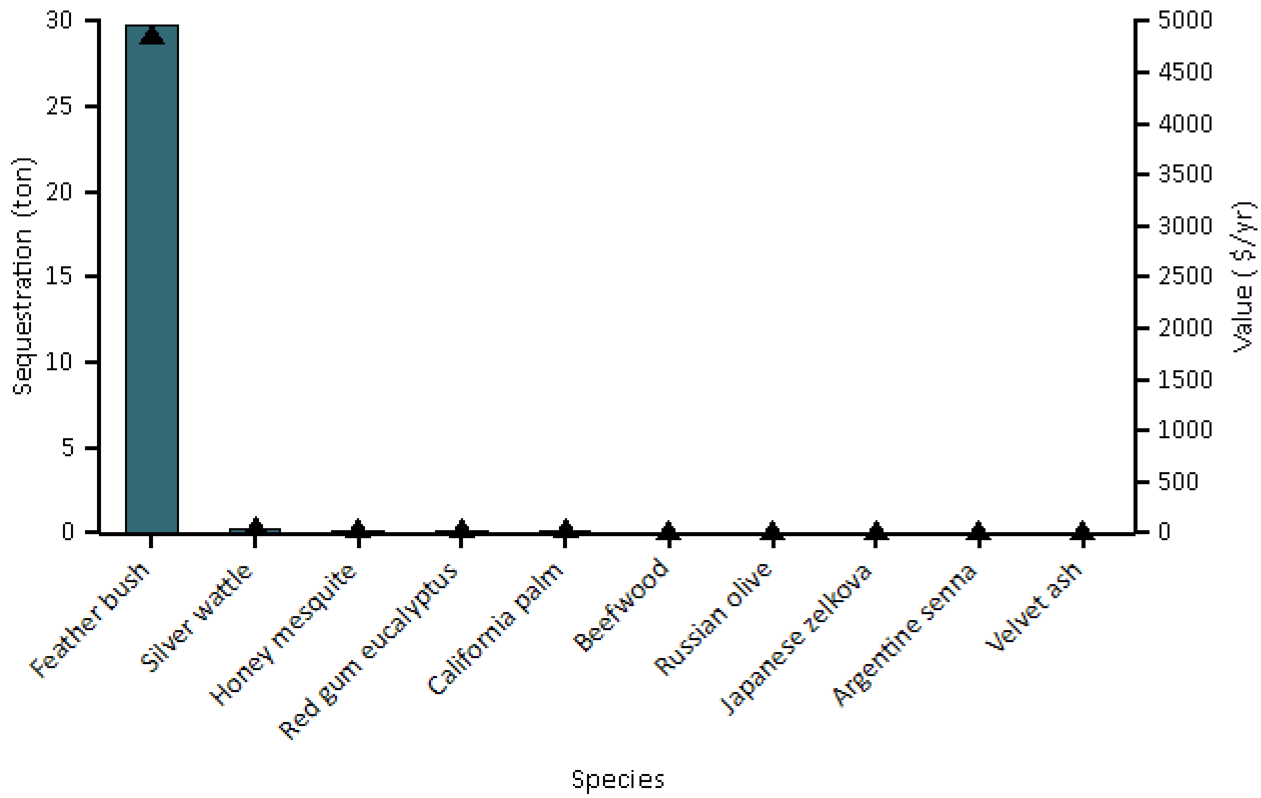


Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Baseline

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Baseline are estimated to store 634 tons of carbon ($108 thousand). Of the species sampled, Feather bush stores and sequesters the most carbon (approximately 87.8% of the total carbon stored and 97.8% of all sequestered carbon.)

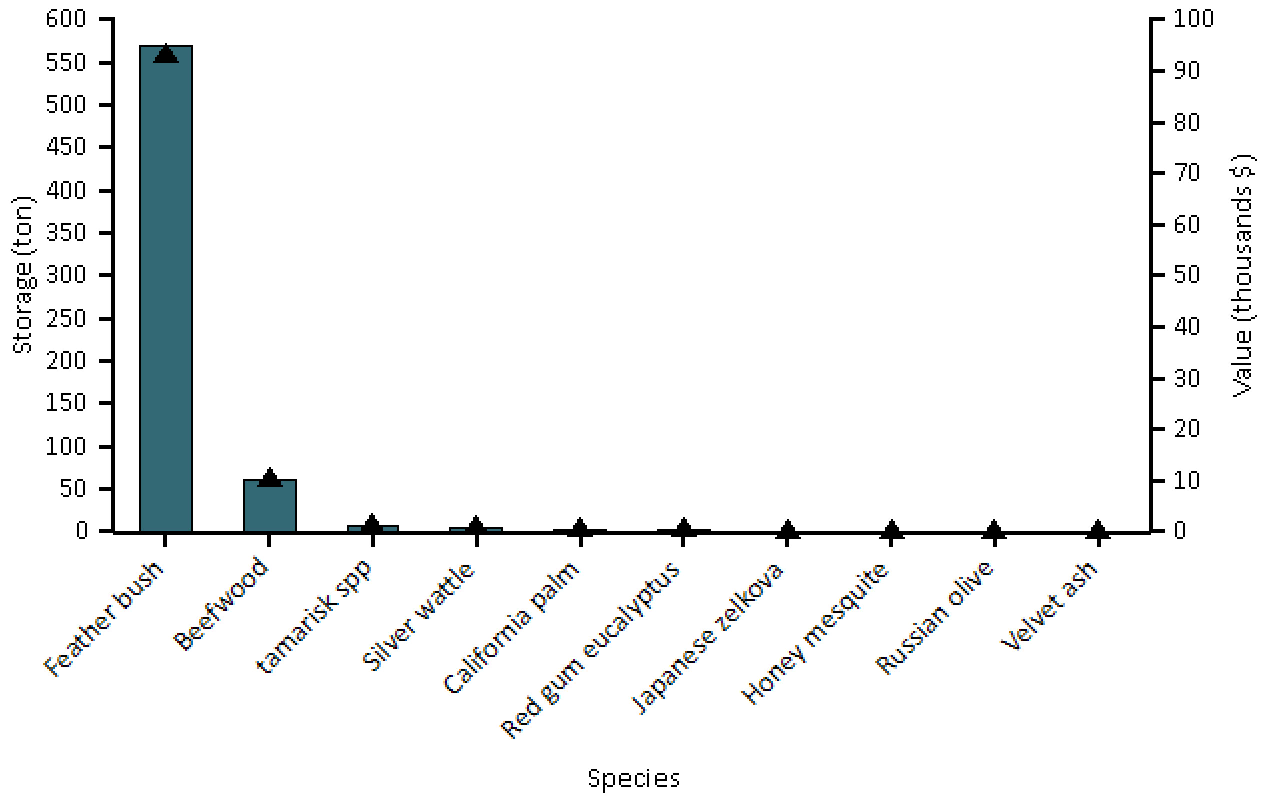


Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Baseline

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Baseline are estimated to produce 72.33 tons of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 20 oxygen production species.

Species	*Oxygen (ton)*	*Net Carbon Sequestration (ton/yr)*	*Number of Trees*	*Leaf Area (acre)*
Feather bush	71.70	26.89	1,043	7.81
Silver wattle	0.40	0.15	218	3.59
Honey mesquite	0.30	0.11	55	0.12
Red gum eucalyptus	0.18	0.07	37	1.03
California palm	0.17	0.06	36	0.09
Russian olive	0.10	0.04	3	0.03
Argentine senna	0.03	0.01	16	0.02
Japanese zelkova	-0.01	0.00	19	0.03
Velvet ash	-0.02	-0.01	18	0.00
tamarisk spp	-0.06	-0.02	34	1.00
Beefwood	-0.45	-0.17	132	5.16

[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Baseline help to reduce runoff by an estimated 5.51 thousand cubic feet a year with an associated value of $370 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Baseline, the total annual precipitation in 2016 was 6.8 inches.

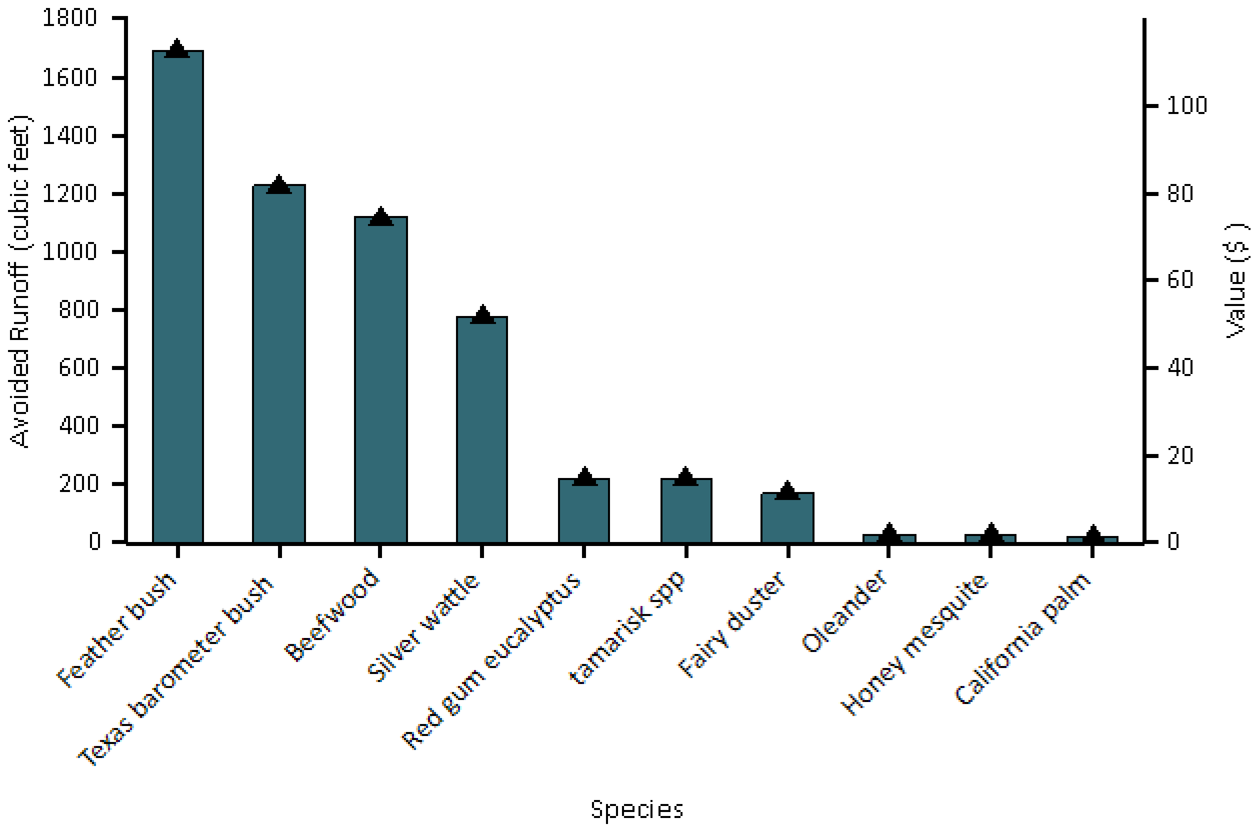


Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Baseline

VII. Trees and Building Energy Use

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space conditioned residential buildings (McPherson and Simpson 1999).

Trees in Baseline are estimated to reduce energy-related costs from residential buildings by $0 annually. Trees also provide an additional $0 in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 0 pounds of carbon emissions).

Note: negative numbers indicate that there was not a reduction in carbon emissions and/or value, rather carbon emissions and values increased by the amount shown as a negative value.[5]

Table 3. Annual energy savings due to trees near residential buildings, Baseline

	Heating	*Cooling*	*Total*
MBTU[a]	0	N/A	0
MWH[b]	0	0	0
Carbon Avoided (pounds)	0	0	0

[a]MBTU - one million British Thermal Units

[b]MWH - megawatt-hour

Table 4. Annual savings [a]($) in residential energy expenditure during heating and cooling seasons, Baseline

	Heating	*Cooling*	*Total*
MBTU[b]	0	N/A	0
MWH[c]	0	0	0
Carbon Avoided	0	0	0

[b]Based on the prices of $131.6 per MWH and $16.3480800457637 per MBTU (see Appendix I for more details)

[c]MBTU - one million British Thermal Units

[c]MWH - megawatt-hour

[5] Trees modify climate, produce shade, and reduce wind speeds. Increased energy use or costs are likely due to these tree-building interactions creating a cooling effect during the winter season. For example, a tree (particularly evergreen species) located on the southern side of a residential building may produce a shading effect that causes increases in heating requirements.

VIII. Structural and Functional Values

Urban forests have a structural value based on the trees themselves (e.g., the cost of having to replace a tree with a similar tree); they also have functional values (either positive or negative) based on the functions the trees perform.

The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees (Nowak et al 2002a). Annual functional values also tend to increase with increased number and size of healthy trees. Through proper management, urban forest values can be increased; however, the values and benefits also can decrease as the amount of healthy tree cover declines.

Urban trees in Baseline have the following structural values:

- Structural value: $4.27 million
- Carbon storage: $108 thousand

Urban trees in Baseline have the following annual functional values:

- Carbon sequestration: $5.07 thousand
- Avoided runoff: $368
- Pollution removal: $1.01 thousand
- Energy costs and carbon emission values: $0

(Note: negative value indicates increased energy cost and carbon emission value)

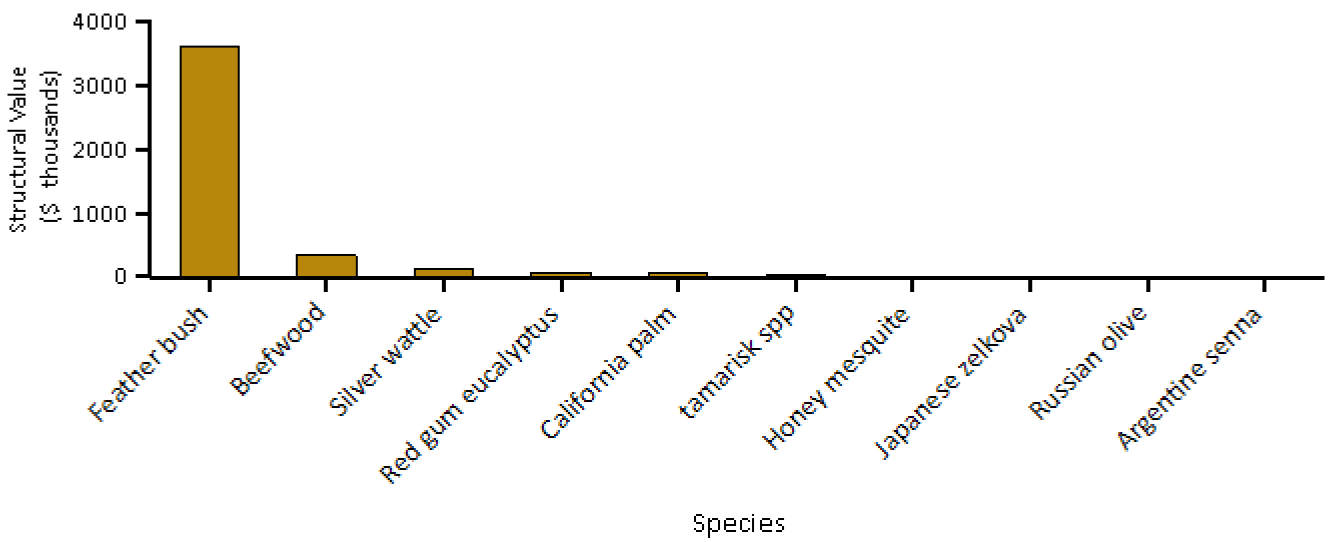


Figure 11. Tree species with the greatest structural value, Baseline

IX. Potential Pest Impacts

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, structural value and sustainability of the urban forest. As pests tend to have differing tree hosts, the potential damage or risk of each pest will differ among cities.Thirty-six pests were analyzed for their potential impact and compared with pest range maps (Forest Health Technology Enterprise Team 2014) for the conterminous United States to determine their proximity to Maricopa County. One of the thirty-six pests analyzed are located within the county. For a complete analysis of all pests, see Appendix VII.

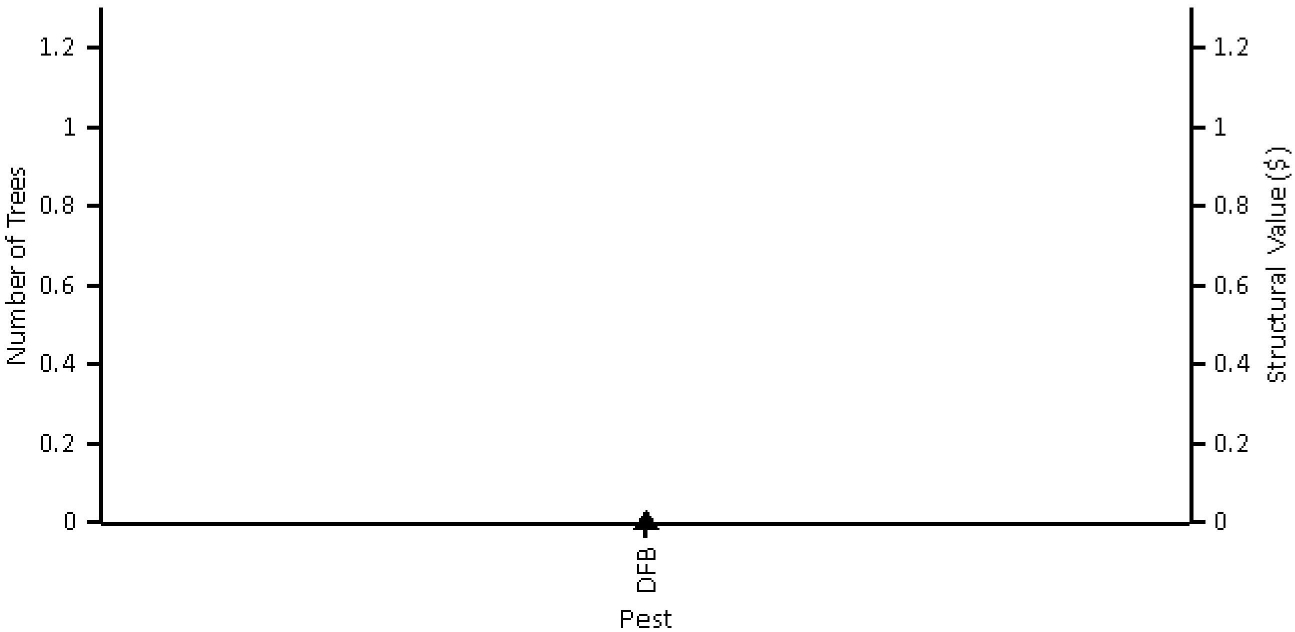


Figure 12. Number of trees at risk (points) and associated compensatory value (bars) for most threatening pests located in the county, Baseline

Douglas-fir beetle (DFB) (Schmitz and Gibson 1996) is a bark beetle that infests Douglas-fir trees throughout the western United States, British Columbia, and Mexico. Potential loss of trees from DFB is 0.0 percent ($0 in structural value).

Appendix I. i-Tree Eco Model and Field Measurements

i-Tree Eco is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects (Nowak and Crane 2000), including:

- Urban forest structure (e.g., species composition, tree health, leaf area, etc.).
- Amount of pollution removed hourly by the urban forest, and its associated percent air quality improvement throughout a year.
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power sources.
- Structural value of the forest, as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by pests, such as Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

Typically, all field data are collected during the leaf-on season to properly assess tree canopies. Typical data collection (actual data collection may vary depending upon the user) includes land use, ground and tree cover, individual tree attributes of species, stem diameter, height, crown width, crown canopy missing and dieback, and distance and direction to residential buildings (Nowak et al 2005; Nowak et al 2008).

During data collection, trees are identified to the most specific taxonomic classification possible. Trees that are not classified to the species level may be classified by genus (e.g., ash) or species groups (e.g., hardwood). In this report, tree species, genera, or species groups are collectively referred to as tree species.

Tree Characteristics:

Leaf area of trees was assessed using measurements of crown dimensions and percentage of crown canopy missing. In the event that these data variables were not collected, they are estimated by the model.

An analysis of invasive species is not available for studies outside of the United States. For the U.S., invasive species are identified using an invasive species list (Arizona Wildland Invasive Plant Working Group 2005)for the state in which the urban forest is located. These lists are not exhaustive and they cover invasive species of varying degrees of invasiveness and distribution. In instances where a state did not have an invasive species list, a list was created based on the lists of the adjacent states. Tree species that are identified as invasive by the state invasive species list are cross-referenced with native range data. This helps eliminate species that are on the state invasive species list, but are native to the study area.

Air Pollution Removal:

Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 2.5 microns. Particulate matter less than 10 microns (PM10) is another significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988; Baldocchi et al 1987). As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature (Bidwell and Fraser 1972; Lovett 1994) that were adjusted depending on leaf phenology and leaf area.

Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere (Zinke 1967). Recent updates (2011) to air quality modeling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values (Hirabayashi et al 2011; Hirabayashi et al 2012; Hirabayashi 2011).

Trees remove PM2.5 when particulate matter is deposited on leaf surfaces (Nowak et al 2013). This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors. Generally, PM2.5 removal is positive with positive benefits. However, there are some cases when net removal is negative or resuspended particles lead to increased pollution concentrations and negative values. During some months (e.g., with no rain), trees resuspend more particles than they remove. Resuspension can also lead to increased overall PM2.5 concentrations if the boundary layer conditions are lower during net resuspension periods than during net removal periods. Since the pollution removal value is based on the change in pollution concentration, it is possible to have situations when trees remove PM2.5 but increase concentrations and thus have negative values during periods of positive overall removal. These events are not common, but can happen.

For reports in the United States, default air pollution removal value is calculated based on local incidence of adverse health effects and national median externality costs. The number of adverse health effects and associated economic value is calculated for ozone, sulfur dioxide, nitrogen dioxide, and particulate matter less than 2.5 microns using data from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) (Nowak et al 2014). The model uses a damage-function approach that is based on the local change in pollution concentration and population. National median externality costs were used to calculate the value of carbon monoxide removal (Murray et al 1994).

For international reports, user-defined local pollution values are used. For international reports that do not have local values, estimates are based on either European median externality values (van Essen et al 2011) or BenMAP regression equations (Nowak et al 2014) that incorporate user-defined population estimates. Values are then converted to local currency with user-defined exchange rates.

For this analysis, pollution removal value is calculated based on the prices of \$1,327 per ton (carbon monoxide), \$1,549 per ton (ozone), \$367 per ton (nitrogen dioxide), \$168 per ton (sulfur dioxide), \$316,627 per ton (particulate matter less than 2.5 microns).

<u>Carbon Storage and Sequestration:</u>

Carbon storage is the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation. To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak 1994). To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

Carbon sequestration is the removal of carbon dioxide from the air by plants. To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year x+1.

Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. For international reports that do not have local values, estimates are based on the carbon value for the United States (U.S. Environmental Protection Agency 2015, Interagency Working Group on Social Cost of Carbon 2015) and converted to local currency with user-defined exchange rates.

For this analysis, carbon storage and carbon sequestration values are calculated based on $171 per ton.

Oxygen Production:

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights: net O2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of the urban forest account for decomposition (Nowak et al 2007). For complete inventory projects, oxygen production is estimated from gross carbon sequestration and does not account for decomposition.

Avoided Runoff:

Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis.

The value of avoided runoff is based on estimated or user-defined local values. For international reports that do not have local values, the national average value for the United States is utilized and converted to local currency with user-defined exchange rates. The U.S. value of avoided runoff is based on the U.S. Forest Service's Community Tree Guide Series (McPherson et al 1999; 2000; 2001; 2002; 2003; 2004; 2006a; 2006b; 2006c; 2007; 2010; Peper et al 2009; 2010; Vargas et al 2007a; 2007b; 2008).

For this analysis, avoided runoff value is calculated based on the price of $0.07 per ft^3.

Building Energy Use:

If appropriate field data were collected, seasonal effects of trees on residential building energy use were calculated based on procedures described in the literature (McPherson and Simpson 1999) using distance and direction of trees from residential structures, tree height and tree condition data. To calculate the monetary value of energy savings, local or custom prices per MWH or MBTU are utilized.

For this analysis, energy saving value is calculated based on the prices of $131.60 per MWH and $16.35 per MBTU.

Structural Values:

Structural value is the value of a tree based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree). Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information (Nowak et al 2002a; 2002b). Structural value may not be included for international projects if there is insufficient local data to complete the valuation procedures.

Potential Pest Impacts:

The complete potential pest risk analysis is not available for studies outside of the United States. The number of trees at risk to the pests analyzed is reported, though the list of pests is based on known insects and disease in the United States.

For the U.S., potential pest risk is based on pest range maps and the known pest host species that are likely to

experience mortality. Pest range maps for 2012 from the Forest Health Technology Enterprise Team (FHTET) (Forest Health Technology Enterprise Team 2014) were used to determine the proximity of each pest to the county in which the urban forest is located. For the county, it was established whether the insect/disease occurs within the county, is within 250 miles of the county edge, is between 250 and 750 miles away, or is greater than 750 miles away. FHTET did not have pest range maps for Dutch elm disease and chestnut blight. The range of these pests was based on known occurrence and the host range, respectively (Eastern Forest Environmental Threat Assessment Center; Worrall 2007).

Relative Tree Effects:

The relative value of tree benefits reported in Appendix II is calculated to show what carbon storage and sequestration, and air pollutant removal equate to in amounts of municipal carbon emissions, passenger automobile emissions, and house emissions.

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (Carbon Dioxide Information Analysis Center 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (g/mi) for CO, NOx, VOCs, PM10, SO2 for 2010 (Bureau of Transportation Statistics 2010; Heirigs et al 2004), PM2.5 for 2011-2015 (California Air Resources Board 2013), and CO2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (Federal Highway Administration 2013) to determine average emissions per vehicle.

Household emissions are based on average electricity kWh usage, natural gas Btu usage, fuel oil Btu usage, kerosene Btu usage, LPG Btu usage, and wood Btu usage per household in 2009 (Energy Information Administration 2013; Energy Information Administration 2014)

- CO2, SO2, and NOx power plant emission per KWh are from Leonardo Academy 2011. CO emission per kWh assumes 1/3 of one percent of C emissions is CO based on Energy Information Administration 1994. PM10 emission per kWh from Layton 2004.
- CO2, NOx, SO2, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from Leonardo Academy 2011.
- CO2 emissions per Btu of wood from Energy Information Administration 2014.
- CO, NOx and SOx emission per Btu based on total emissions and wood burning (tons) from (British Columbia Ministry 2005; Georgia Forestry Commission 2009).

Appendix II. Relative Tree Effects

The urban forest in Baseline provides benefits that include carbon storage and sequestration, and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average municipal carbon emissions, average passenger automobile emissions, and average household emissions. See Appendix I for methodology.

Carbon storage is equivalent to:

- Amount of carbon emitted in Baseline in 0 days
- Annual carbon (C) emissions from 449 automobiles
- Annual C emissions from 184 single-family houses

Carbon monoxide removal is equivalent to:

- Annual carbon monoxide emissions from 0 automobiles
- Annual carbon monoxide emissions from 0 single-family houses

Nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 7 automobiles
- Annual nitrogen dioxide emissions from 3 single-family houses

Sulfur dioxide removal is equivalent to:

- Annual sulfur dioxide emissions from 26 automobiles
- Annual sulfur dioxide emissions from 0 single-family houses

Annual carbon sequestration is equivalent to:

- Amount of carbon emitted in Baseline in 0.0 days
- Annual C emissions from 0 automobiles
- Annual C emissions from 0 single-family houses

Appendix III. Comparison of Urban Forests

A common question asked is, "How does this city compare to other cities?" Although comparison among cities should be made with caution as there are many attributes of a city that affect urban forest structure and functions, summary data are provided from other cities analyzed using the i-Tree Eco model.

I. City totals for trees

City	*% Tree Cover*	*Number of Trees*	*Carbon Storage (tons)*	*Carbon Sequestration (tons/yr)*	*Pollution Removal (tons/yr)*
Toronto, ON, Canada	26.6	10,220,000	1,221,000	51,500	2,099
Atlanta, GA	36.7	9,415,000	1,344,000	46,400	1,663
Los Angeles, CA	11.1	5,993,000	1,269,000	77,000	1,975
New York, NY	20.9	5,212,000	1,350,000	42,300	1,676
London, ON, Canada	24.7	4,376,000	396,000	13,700	408
Chicago, IL	17.2	3,585,000	716,000	25,200	888
Phoenix, AZ	9.0	3,166,000	315,000	32,800	563
Baltimore, MD	21.0	2,479,000	570,000	18,400	430
Philadelphia, PA	15.7	2,113,000	530,000	16,100	575
Washington, DC	28.6	1,928,000	525,000	16,200	418
Oakville, ON , Canada	29.1	1,908,000	147,000	6,600	190
Albuquerque, NM	14.3	1,846,000	332,000	10,600	248
Boston, MA	22.3	1,183,000	319,000	10,500	283
Syracuse, NY	26.9	1,088,000	183,000	5,900	109
Woodbridge, NJ	29.5	986,000	160,000	5,600	210
Minneapolis, MN	26.4	979,000	250,000	8,900	305
San Francisco, CA	11.9	668,000	194,000	5,100	141
Morgantown, WV	35.5	658,000	93,000	2,900	72
Moorestown, NJ	28.0	583,000	117,000	3,800	118
Hartford, CT	25.9	568,000	143,000	4,300	58
Jersey City, NJ	11.5	136,000	21,000	890	41
Casper, WY	8.9	123,000	37,000	1,200	37
Freehold, NJ	34.4	48,000	20,000	540	22

II. Totals per acre of land area

City	*Number of Trees/ac*	*Carbon Storage (tons/ac)*	*Carbon Sequestration (tons/ac/yr)*	*Pollution Removal (lb/ac/yr)*
Toronto, ON, Canada	64.9	7.8	0.33	26.7
Atlanta, GA	111.6	15.9	0.55	39.4
Los Angeles, CA	19.6	4.2	0.16	13.1
New York, NY	26.4	6.8	0.21	17.0
London, ON, Canada	75.1	6.8	0.24	14.0
Chicago, IL	24.2	4.8	0.17	12.0
Phoenix, AZ	12.9	1.3	0.13	4.6
Baltimore, MD	48.0	11.1	0.36	16.6
Philadelphia, PA	25.1	6.3	0.19	13.6
Washington, DC	49.0	13.3	0.41	21.2
Oakville, ON , Canada	78.1	6.0	0.27	11.0
Albuquerque, NM	21.8	3.9	0.12	5.9
Boston, MA	33.5	9.1	0.30	16.1
Syracuse, NY	67.7	10.3	0.34	13.6
Woodbridge, NJ	66.5	10.8	0.38	28.4
Minneapolis, MN	26.2	6.7	0.24	16.3
San Francisco, CA	22.5	6.6	0.17	9.5
Morgantown, WV	119.2	16.8	0.52	26.0
Moorestown, NJ	62.1	12.4	0.40	25.1
Hartford, CT	50.4	12.7	0.38	10.2
Jersey City, NJ	14.4	2.2	0.09	8.6
Casper, WY	9.1	2.8	0.09	5.5
Freehold, NJ	38.3	16.0	0.44	35.3

Appendix IV. General Recommendations for Air Quality Improvement

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmosphere environment. Four main ways that urban trees affect air quality are (Nowak 1995):

- Temperature reduction and other microclimate effects
- Removal of air pollutants
- Emission of volatile organic compounds (VOC) and tree maintenance emissions
- Energy effects on buildings

The cumulative and interactive effects of trees on climate, pollution removal, and VOC and power plant emissions determine the impact of trees on air pollution. Cumulative studies involving urban tree impacts on ozone have revealed that increased urban canopy cover, particularly with low VOC emitting species, leads to reduced ozone concentrations in cities (Nowak 2000). Local urban management decisions also can help improve air quality.

Urban forest management strategies to help improve air quality include (Nowak 2000):

Strategy	*Result*
Increase the number of healthy trees	Increase pollution removal
Sustain existing tree cover	Maintain pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone and carbon monoxide formation
Sustain large, healthy trees	Large trees have greatest per-tree effects
Use long-lived trees	Reduce long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduce pollutants emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduce pollutant emissions
Plant trees in energy conserving locations	Reduce pollutant emissions from power plants
Plant trees to shade parked cars	Reduce vehicular VOC emissions
Supply ample water to vegetation	Enhance pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improve tree health
Utilize evergreen trees for particulate matter	Year-round removal of particles

Appendix V. Invasive Species of the Urban Forest

The following inventoried tree species were listed as invasive on the Arizona invasive species list (Arizona Wildland Invasive Plant Working Group 2005):

Species Name[a]	*Number of Trees*	*% of Trees*	*Leaf Area (ft²)*	*Percent Leaf Area*
Russian olive	3	0.2	0.0	0.2
Total	**3**	**0.21**	**0.00**	**0.16**

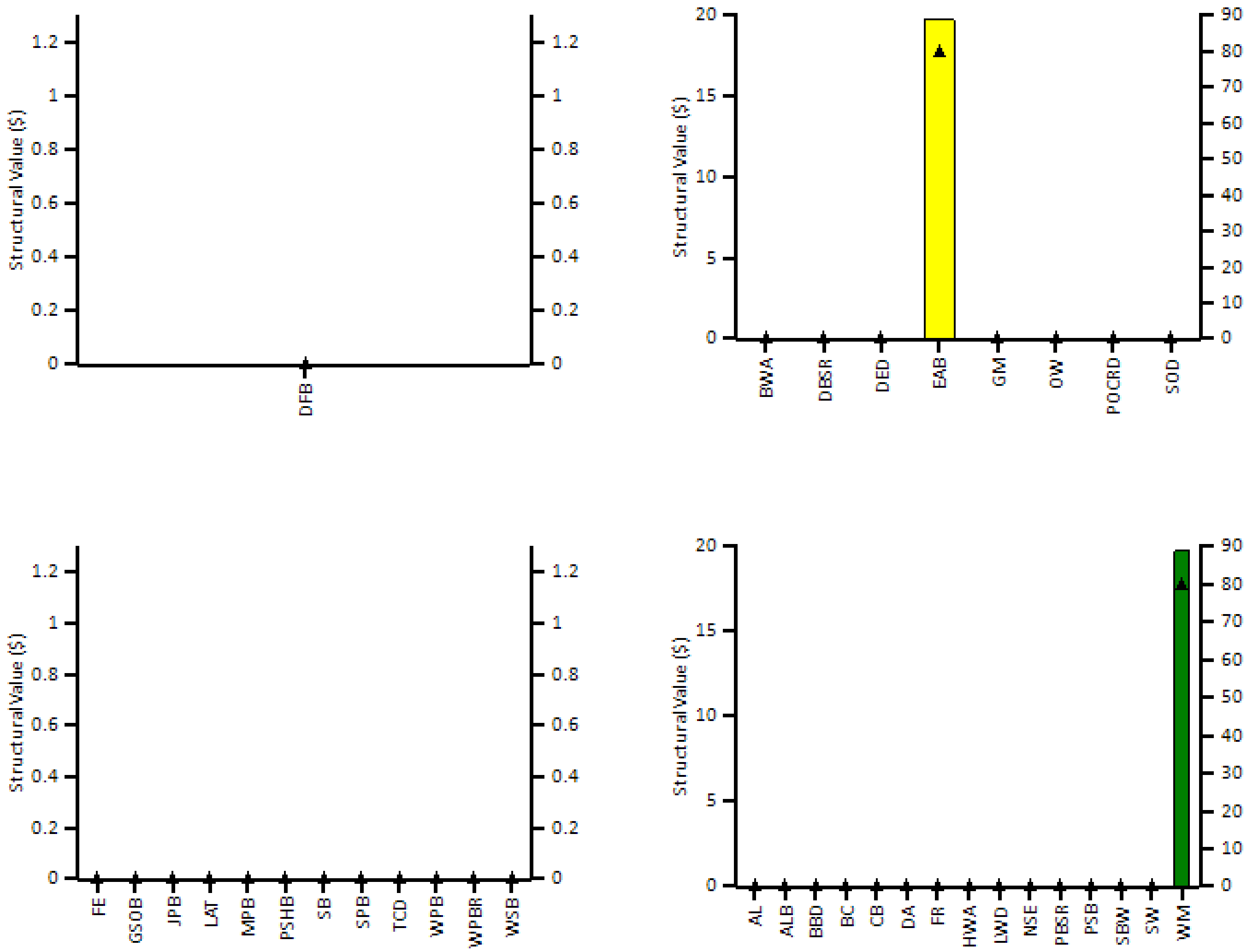
[a]Species are determined to be invasive if they are listed on the state's invasive species list

Appendix VI. Potential Risk of Pests

Thirty-six insects and diseases were analyzed to quantify their potential impact on the urban forest. As each insect/ disease is likely to attack different host tree species, the implications for {0} will vary. The number of trees at risk reflects only the known host species that are likely to experience mortality.

Code	Scientific Name	Common Name	Trees at Risk (#)	Value ($)
AL	Phyllocnistis populiella	Aspen Leafminer	0	0.00
ALB	Anoplophora glabripennis	Asian Longhorned Beetle	0	0.00
BBD	Neonectria faginata	Beech Bark Disease	0	0.00
BC	Sirococcus clavigignenti juglandacearum	Butternut Canker	0	0.00
BWA	Adelges piceae	Balsam Woolly Adelgid	0	0.00
CB	Cryphonectria parasitica	Chestnut Blight	0	0.00
DA	Discula destructiva	Dogwood Anthracnose	0	0.00
DBSR	Leptographium wageneri var. pseudotsugae	Douglas-fir Black Stain Root Disease	0	0.00
DED	Ophiostoma novo-ulmi	Dutch Elm Disease	0	0.00
DFB	Dendroctonus pseudotsugae	Douglas-Fir Beetle	0	0.00
EAB	Agrilus planipennis	Emerald Ash Borer	18	88.82
FE	Scolytus ventralis	Fir Engraver	0	0.00
FR	Cronartium quercuum f. sp. Fusiforme	Fusiform Rust	0	0.00
GM	Lymantria dispar	Gypsy Moth	0	0.00
GSOB	Agrilus auroguttatus	Goldspotted Oak Borer	0	0.00
HWA	Adelges tsugae	Hemlock Woolly Adelgid	0	0.00
JPB	Dendroctonus jeffreyi	Jeffrey Pine Beetle	0	0.00
LAT	Choristoneura conflictana	Large Aspen Tortrix	0	0.00
LWD	Raffaelea lauricola	Laurel Wilt	0	0.00
MPB	Dendroctonus ponderosae	Mountain Pine Beetle	0	0.00
NSE	Ips perturbatus	Northern Spruce Engraver	0	0.00
OW	Ceratocystis fagacearum	Oak Wilt	0	0.00
PBSR	Leptographium wageneri var. ponderosum	Pine Black Stain Root Disease	0	0.00
POCRD	Phytophthora lateralis	Port-Orford-Cedar Root Disease	0	0.00
PSB	Tomicus piniperda	Pine Shoot Beetle	0	0.00
PSHB	Euwallacea nov. sp.	Polyphagous Shot Hole Borer	0	0.00
SB	Dendroctonus rufipennis	Spruce Beetle	0	0.00
SBW	Choristoneura fumiferana	Spruce Budworm	0	0.00
SOD	Phytophthora ramorum	Sudden Oak Death	0	0.00
SPB	Dendroctonus frontalis	Southern Pine Beetle	0	0.00
SW	Sirex noctilio	Sirex Wood Wasp	0	0.00
TCD	Geosmithia morbida	Thousand Canker Disease	0	0.00
WM	Operophtera brumata	Winter Moth	18	88.82
WPB	Dendroctonus brevicomis	Western Pine Beetle	0	0.00
WPBR	Cronartium ribicola	White Pine Blister Rust	0	0.00
WSB	Choristoneura occidentalis	Western Spruce Budworm	0	0.00

In the following graph, the pests are color coded according to the county's proximity to the pest occurrence in the United States. Red indicates that the pest is within the county; orange indicates that the pest is within 250 miles of the county; yellow indicates that the pest is within 750 miles of the county; and green indicates that the pest is outside of these ranges.



Note: points - Number of trees, bars - Structural value

Based on the host tree species for each pest and the current range of the pest (Forest Health Technology Enterprise Team 2014), it is possible to determine what the risk is that each tree species in the urban forest could be attacked by an insect or disease.

Spp. Risk	Risk Weight	Species Name	AL	ALB	BBD	BC	BWA	CB	DA	DBSR	DED	DFB	EAB	FE	FR	GM	GSOB	HWA	JPB	LAT	LWD	MPB	NSE	OW	PBSR	POCRD	PSB	PSHB	SB	SBW	SOD	SPB	SW	TCD	WM	WPB	WPBR	WSB
	3	Velvet ash																																				

Note:
Species that are not listed in the matrix are not known to be hosts to any of the pests analyzed.

Species Risk:

- Red indicates that tree species is at risk to at least one pest within county
- Orange indicates that tree species has no risk to pests in county, but has a risk to at least one pest within 250 miles from the county
- Yellow indicates that tree species has no risk to pests within 250 miles of county, but has a risk to at least one pest that is 250 and 750 miles from the county
- Green indicates that tree species has no risk to pests within 750 miles of county, but has a risk to at least one pest that is greater than 750 miles from the county

Risk Weight:
Numerical scoring system based on sum of points assigned to pest risks for species. Each pest that could attack tree species is scored as 4 points if red, 3 points if orange, 2 points if yellow and 1 point if green.

Pest Color Codes:

- Red indicates pest is within Maricopa county
- Red indicates pest is within 250 miles county
- Yellow indicates pest is within 750 miles of Maricopa county
- Green indicates pest is outside of these ranges

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i-Tree
Ecosystem Analysis

100 Percent Participation

Urban Forest Effects and Values
April 2021

Summary

Understanding an urban forest's structure, function and value can promote management decisions that will improve human health and environmental quality. An assessment of the vegetation structure, function, and value of the Baseline urban forest was conducted during 2021. Data from 4 field plots located throughout Baseline were analyzed using the i-Tree Eco model developed by the U.S. Forest Service, Northern Research Station.

- Number of trees: 2,304
- Tree Cover: 5.3 %
- Most common species of trees: Feather bush, Silver wattle, Beefwood
- Percentage of trees less than 6" (15.2 cm) diameter: 9.2%
- Pollution Removal: 483.5 pounds/year ($1.19 thousand/year)
- Carbon Storage: 1003 tons ($171 thousand)
- Carbon Sequestration: 49 tons ($8.36 thousand/year)
- Oxygen Production: 119.9 tons/year
- Avoided Runoff: 6.318 thousand cubic feet/year ($422/year)
- Building energy savings: $0/year
- Carbon Avoided: 0 tons/year ($0/year)
- Structural values: $6.67 million

Ton: short ton (U.S.) (2,000 lbs)
Monetary values $ are reported in US Dollars throughout the report except where noted.
Pollution removal and avoided runoff estimates are reported for trees and shrubs. All other ecosystem service estimates are reported for trees.

For an overview of i-Tree Eco methodology, see Appendix I. Data collection quality is determined by the local data collectors, over which i-Tree has no control. Additionally, some of the plot and tree information may not have been collected, so not all of the analyses may have been conducted for this report.

Table of Contents

I. Tree Characteristics of the Urban Forest

The urban forest of Baseline has an estimated 2,304 trees with a tree cover of 5.3 percent. The three most common species are Feather bush (75.3 percent), Silver wattle (9.5 percent), and Beefwood (5.7 percent).

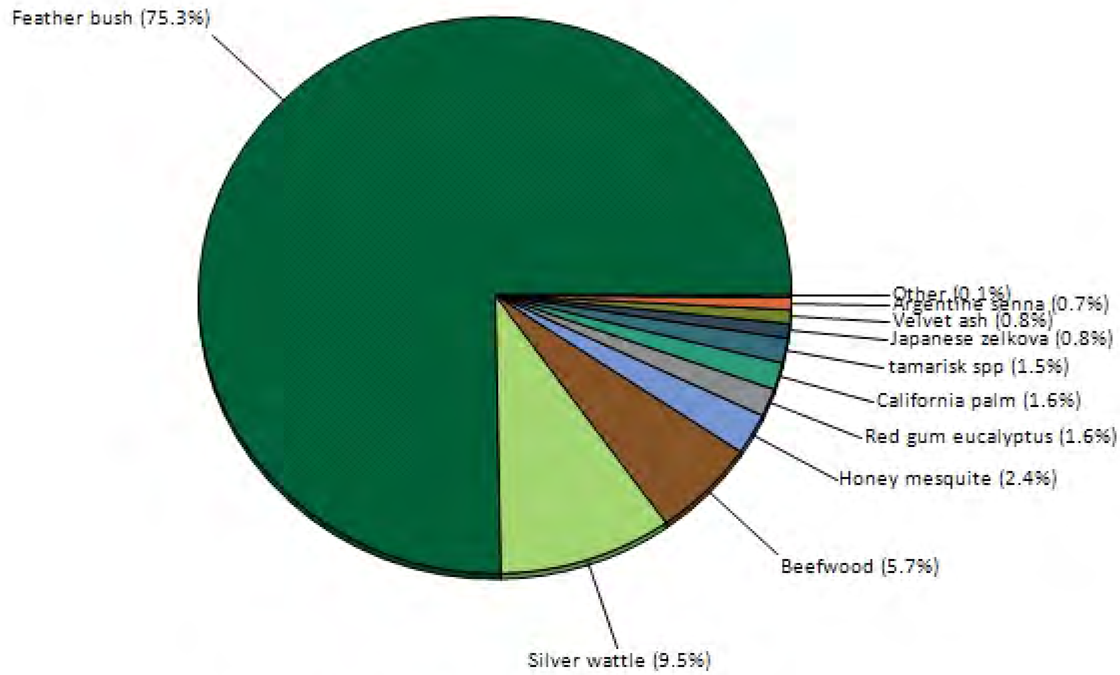


Figure 1. Tree species composition in Baseline

The overall tree density in Baseline is 19 trees/acre (see Appendix III for comparable values from other cities). For stratified projects, the highest tree densities in Baseline occur in Residential followed by Commercial and Industrial.

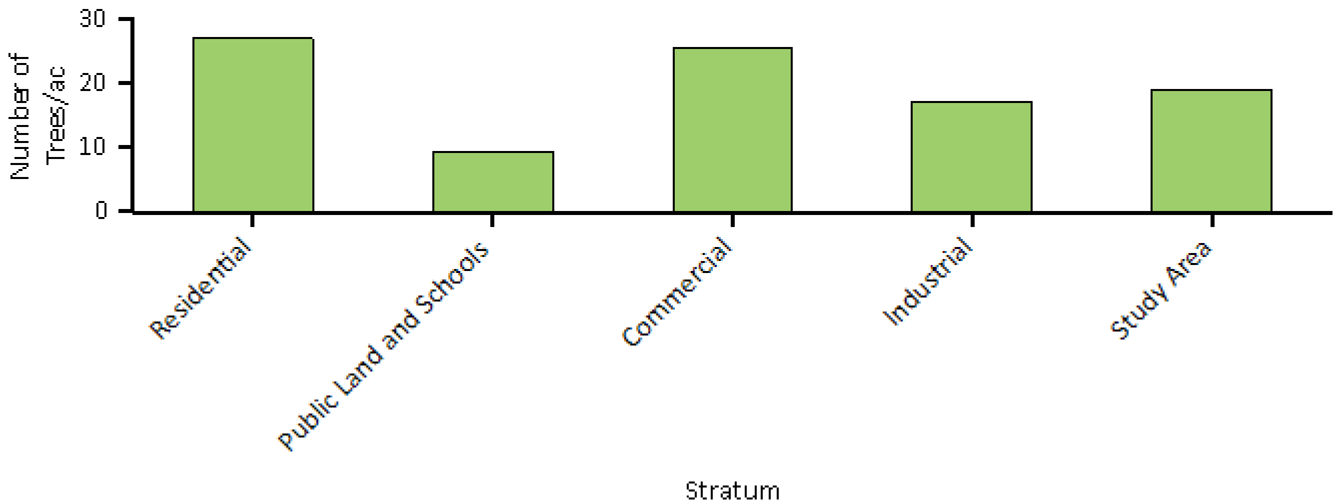


Figure 2. Number of trees/ac in Baseline by stratum

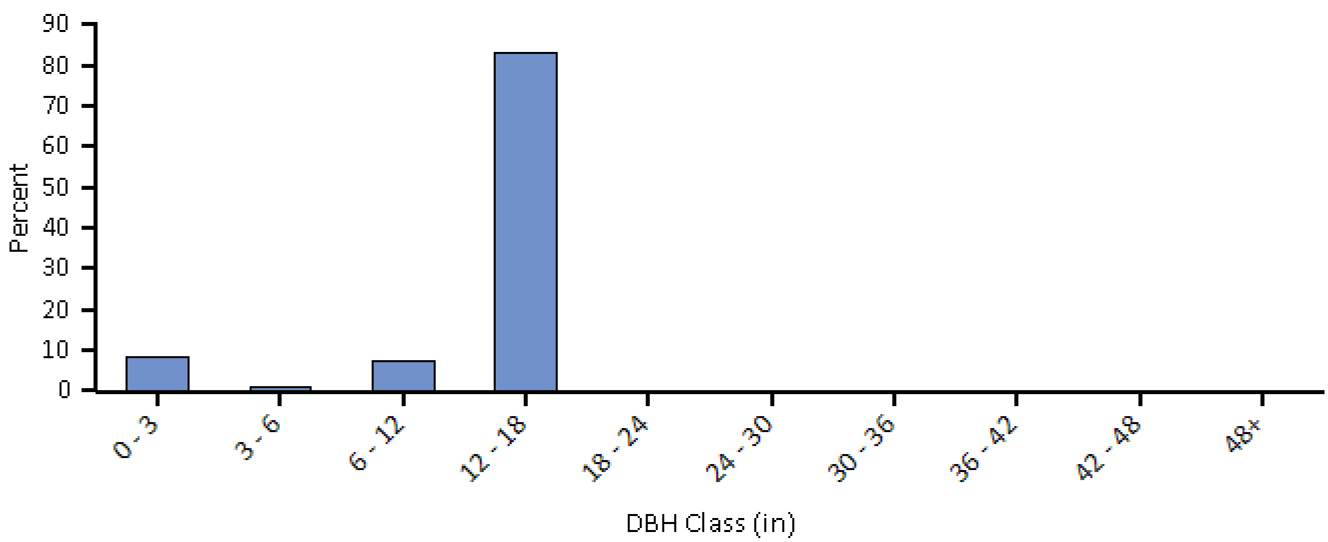


Figure 3. Percent of tree population by diameter class (DBH - stem diameter at 4.5 feet)

Urban forests are composed of a mix of native and exotic tree species. Thus, urban forests often have a tree diversity that is higher than surrounding native landscapes. Increased tree diversity can minimize the overall impact or destruction by a species-specific insect or disease, but it can also pose a risk to native plants if some of the exotic species are invasive plants that can potentially out-compete and displace native species. In Baseline, about 80 percent of the trees are species native to North America, while 80 percent are native to Arizona. Species exotic to North America make up 20 percent of the population. Most exotic tree species have an origin from Australia (16 percent of the species).

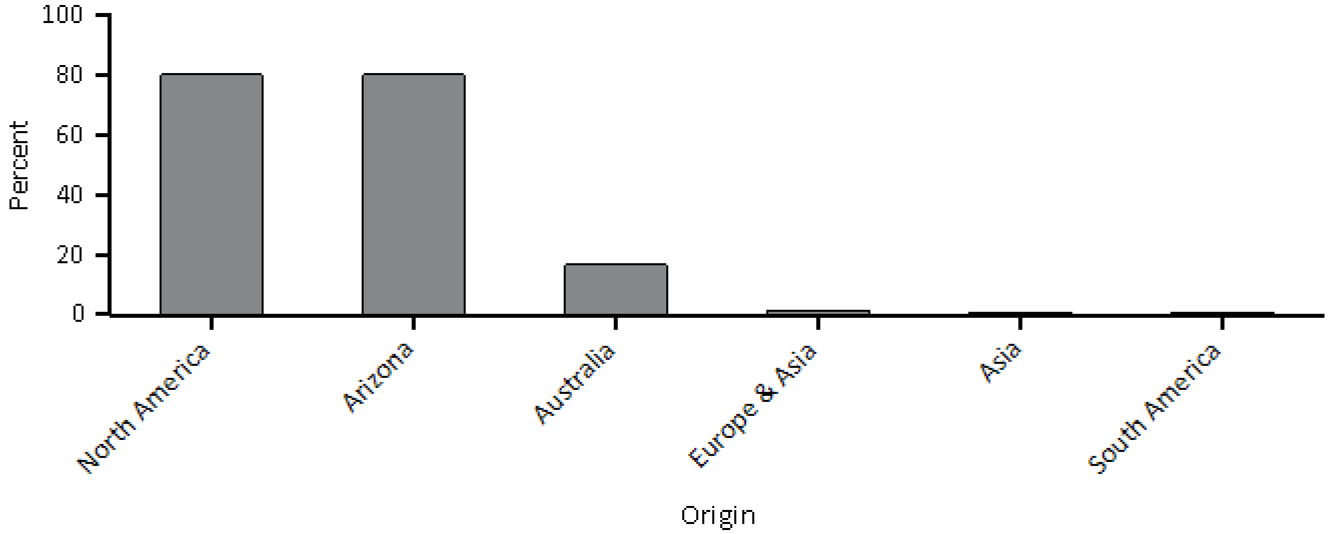


Figure 4. Percent of live tree population by area of native origin, Baseline

Invasive plant species are often characterized by their vigor, ability to adapt, reproductive capacity, and general lack of natural enemies. These abilities enable them to displace native plants and make them a threat to natural areas. One of the 11 tree species in Baseline are identified as invasive on the state invasive species list (Arizona Wildland Invasive Plant Working Group 2005). This invasive species (Russian olive) comprises 0.1 percent of the tree population though it may only cause a minimal level of impact (see Appendix V for a complete list of invasive species).

II. Urban Forest Cover and Leaf Area

Many tree benefits equate directly to the amount of healthy leaf surface area of the plant. Trees cover about 5.3 percent of Baseline and provide 24.07 acres of leaf area. Total leaf area is greatest in Residential followed by Industrial and Commercial.

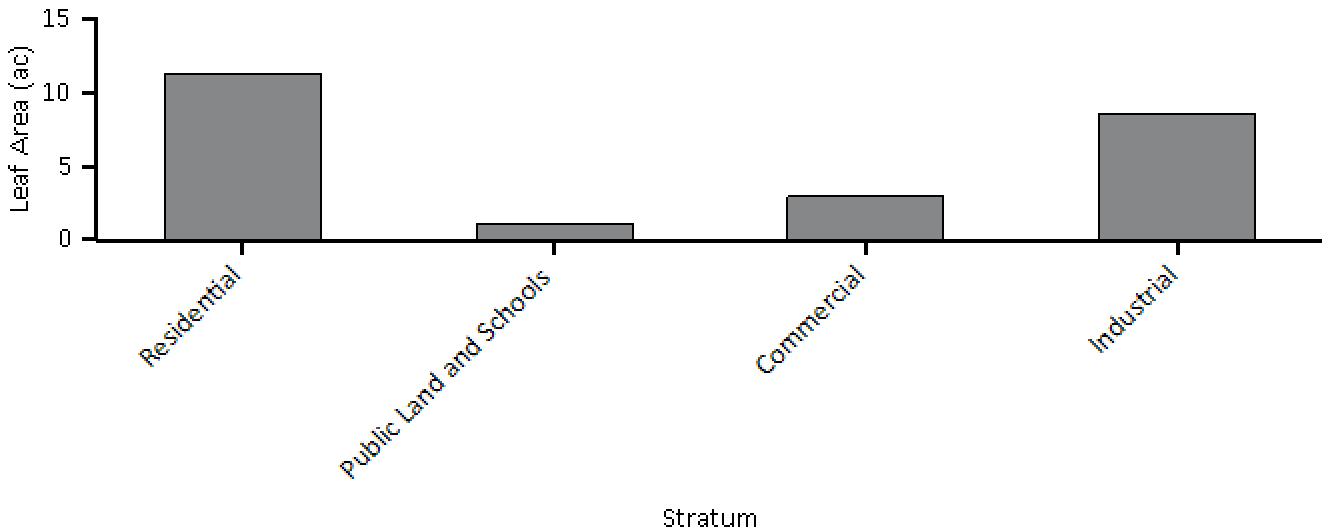


Figure 5. Leaf area by stratum, Baseline

In Baseline, the most dominant species in terms of leaf area are Feather bush, Beefwood, and Silver wattle. The 10 species with the greatest importance values are listed in Table 1. Importance values (IV) are calculated as the sum of percent population and percent leaf area. High importance values do not mean that these trees should necessarily be encouraged in the future; rather these species currently dominate the urban forest structure.

Table 1. Most important species in Baseline

Species Name	*Percent Population*	*Percent Leaf Area*	*IV*
Feather bush	75.3	54.0	129.3
Beefwood	5.7	21.5	27.2
Silver wattle	9.5	14.9	24.4
Red gum eucalyptus	1.6	4.3	5.9
tamarisk spp	1.5	4.2	5.6
Honey mesquite	2.4	0.5	2.9
California palm	1.6	0.4	1.9
Japanese zelkova	0.8	0.1	1.0
Argentine senna	0.7	0.1	0.8
Velvet ash	0.8	0.0	0.8

Common ground cover classes (including cover types beneath trees and shrubs) in Baseline include unmaintained grass, other impervious, buildings, rock, water, duff/mulch, and bare soil, impervious covers such as tar, and cement, and herbaceous covers such as grass, and herbs (Figure 6). The most dominant ground cover types are Unmaintained Grass (38.1 percent) and Other Impervious (26.1 percent).

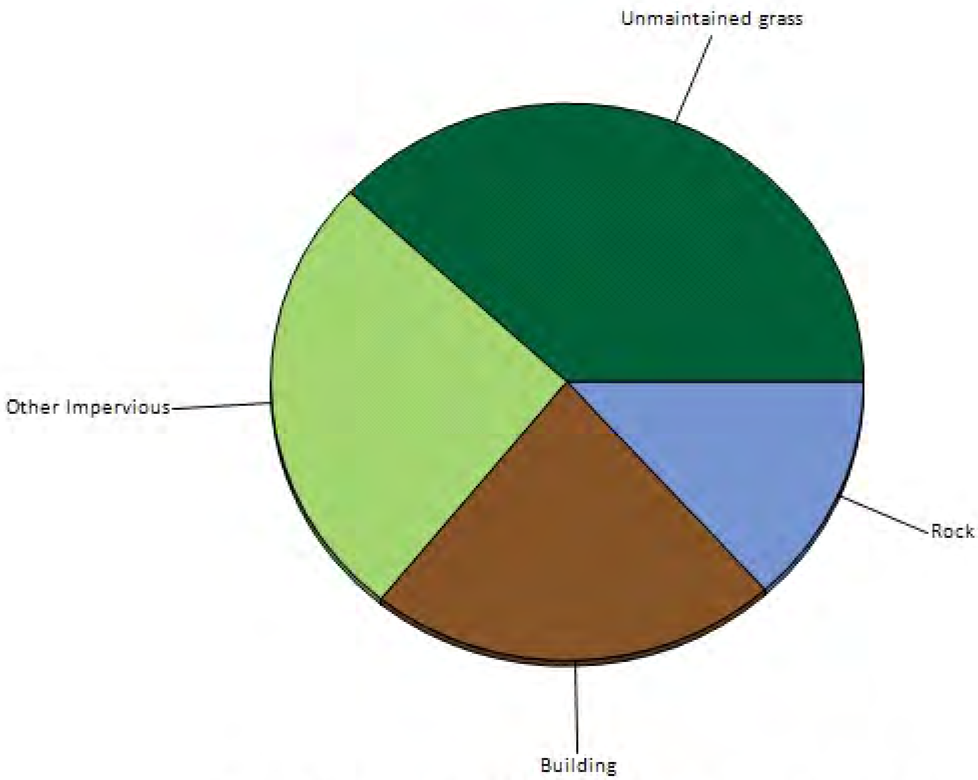


Figure 6. Percent of land by ground cover classes, Baseline

III. Air Pollution Removal by Urban Trees

Poor air quality is a common problem in many urban areas. It can lead to decreased human health, damage to landscape materials and ecosystem processes, and reduced visibility. The urban forest can help improve air quality by reducing air temperature, directly removing pollutants from the air, and reducing energy consumption in buildings, which consequently reduces air pollutant emissions from the power sources. Trees also emit volatile organic compounds that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak and Dwyer 2000).

Pollution removal[1] by trees and shrubs in Baseline was estimated using field data and recent available pollution and weather data available. Pollution removal was greatest for ozone (Figure 7). It is estimated that trees and shrubs remove 483.5 pounds of air pollution (ozone (O3), carbon monoxide (CO), nitrogen dioxide (NO2), particulate matter less than 2.5 microns (PM2.5)[2], and sulfur dioxide (SO2)) per year with an associated value of $1.19 thousand (see Appendix I for more details).

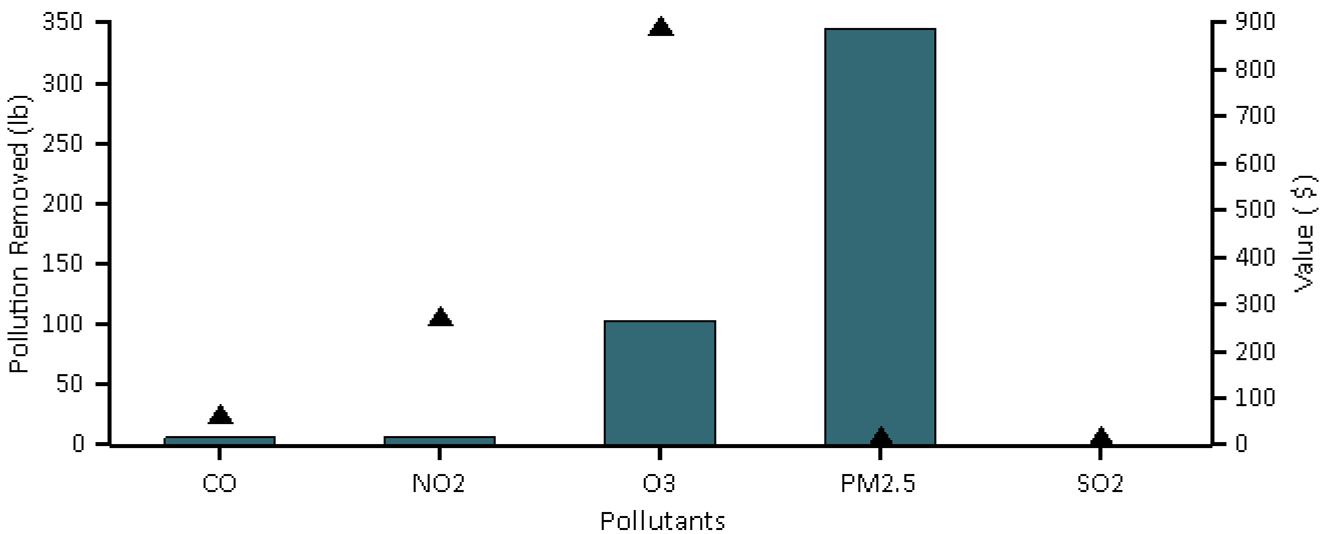


Figure 7. Annual pollution removal (points) and value (bars) by urban trees, Baseline

[1] Particulate matter less than 10 microns is a significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

[2] Trees remove PM2.5 when particulate matter is deposited on leaf surfaces. This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors (see Appendix I for more details).

In 2021, trees in Baseline emitted an estimated 349.7 pounds of volatile organic compounds (VOCs) (95.66 pounds of isoprene and 254 pounds of monoterpenes). Emissions vary among species based on species characteristics (e.g. some genera such as oaks are high isoprene emitters) and amount of leaf biomass. Eighty- six percent of the urban forest's VOC emissions were from Silver wattle and Red gum eucalyptus. These VOCs are precursor chemicals to ozone formation.[3]

General recommendations for improving air quality with trees are given in Appendix VIII.

[3] Some economic studies have estimated VOC emission costs. These costs are not included here as there is a tendency to add positive dollar estimates of ozone removal effects with negative dollar values of VOC emission effects to determine whether tree effects are positive or negative in relation to ozone. This combining of dollar values to determine tree effects should not be done, rather estimates of VOC effects on ozone formation (e.g., via photochemical models) should be conducted and directly contrasted with ozone removal by trees (i.e., ozone effects should be directly compared, not dollar estimates). In addition, air temperature reductions by trees have been shown to significantly reduce ozone concentrations (Cardelino and Chameides 1990; Nowak et al 2000), but are not considered in this analysis. Photochemical modeling that integrates tree effects on air temperature, pollution removal, VOC emissions, and emissions from power plants can be used to determine the overall effect of trees on ozone concentrations.

IV. Carbon Storage and Sequestration

Climate change is an issue of global concern. Urban trees can help mitigate climate change by sequestering atmospheric carbon (from carbon dioxide) in tissue and by altering energy use in buildings, and consequently altering carbon dioxide emissions from fossil-fuel based power sources (Abdollahi et al 2000).

Trees reduce the amount of carbon in the atmosphere by sequestering carbon in new growth every year. The amount of carbon annually sequestered is increased with the size and health of the trees. The gross sequestration of Baseline trees is about 49 tons of carbon per year with an associated value of $8.36 thousand. Net carbon sequestration in the urban forest is about 44.96 tons. See Appendix I for more details on methods.

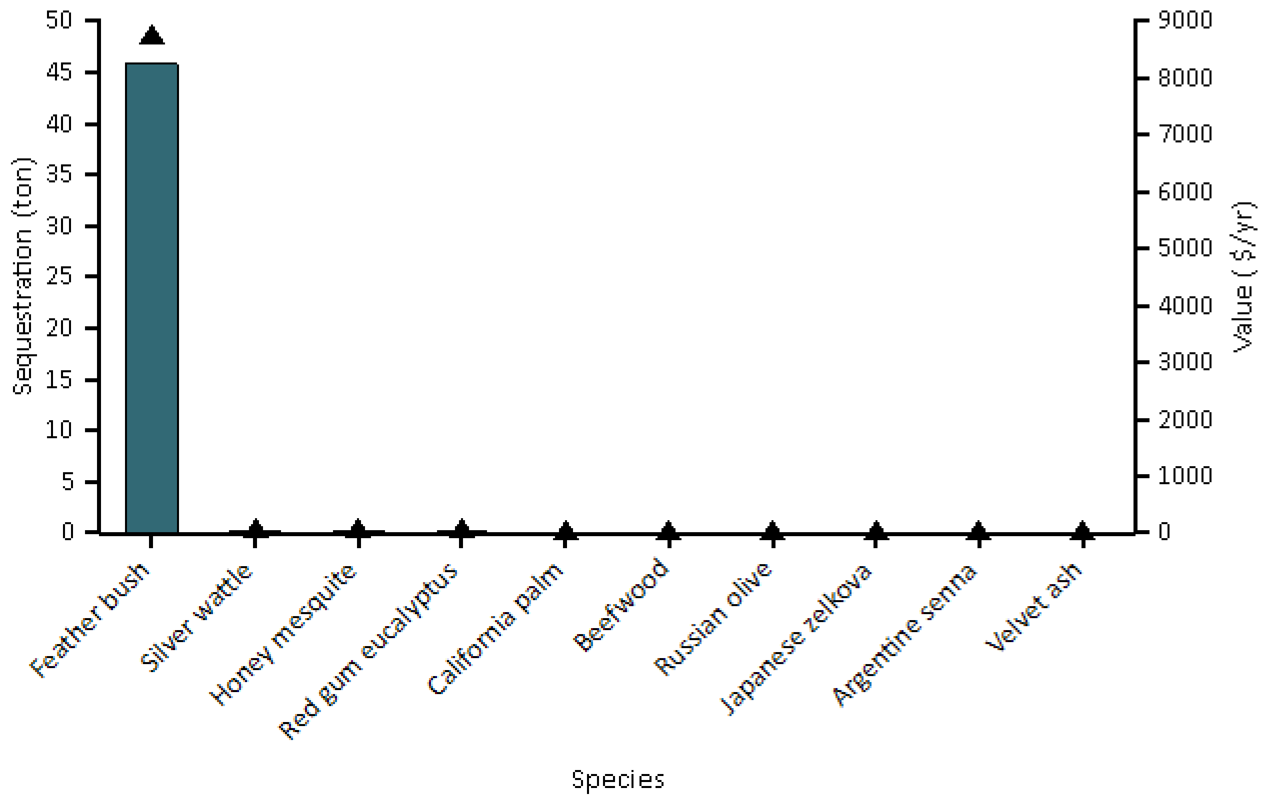


Figure 8. Estimated annual gross carbon sequestration (points) and value (bars) for urban tree species with the greatest sequestration, Baseline

Carbon storage is another way trees can influence global climate change. As a tree grows, it stores more carbon by holding it in its accumulated tissue. As a tree dies and decays, it releases much of the stored carbon back into the atmosphere. Thus, carbon storage is an indication of the amount of carbon that can be released if trees are allowed to die and decompose. Maintaining healthy trees will keep the carbon stored in trees, but tree maintenance can contribute to carbon emissions (Nowak et al 2002c). When a tree dies, using the wood in long-term wood products, to heat buildings, or to produce energy will help reduce carbon emissions from wood decomposition or from fossil-fuel or wood-based power plants.

Trees in Baseline are estimated to store 1000 tons of carbon ($171 thousand). Of the species sampled, Feather bush stores and sequesters the most carbon (approximately 92.3% of the total carbon stored and 98.7% of all sequestered carbon.)

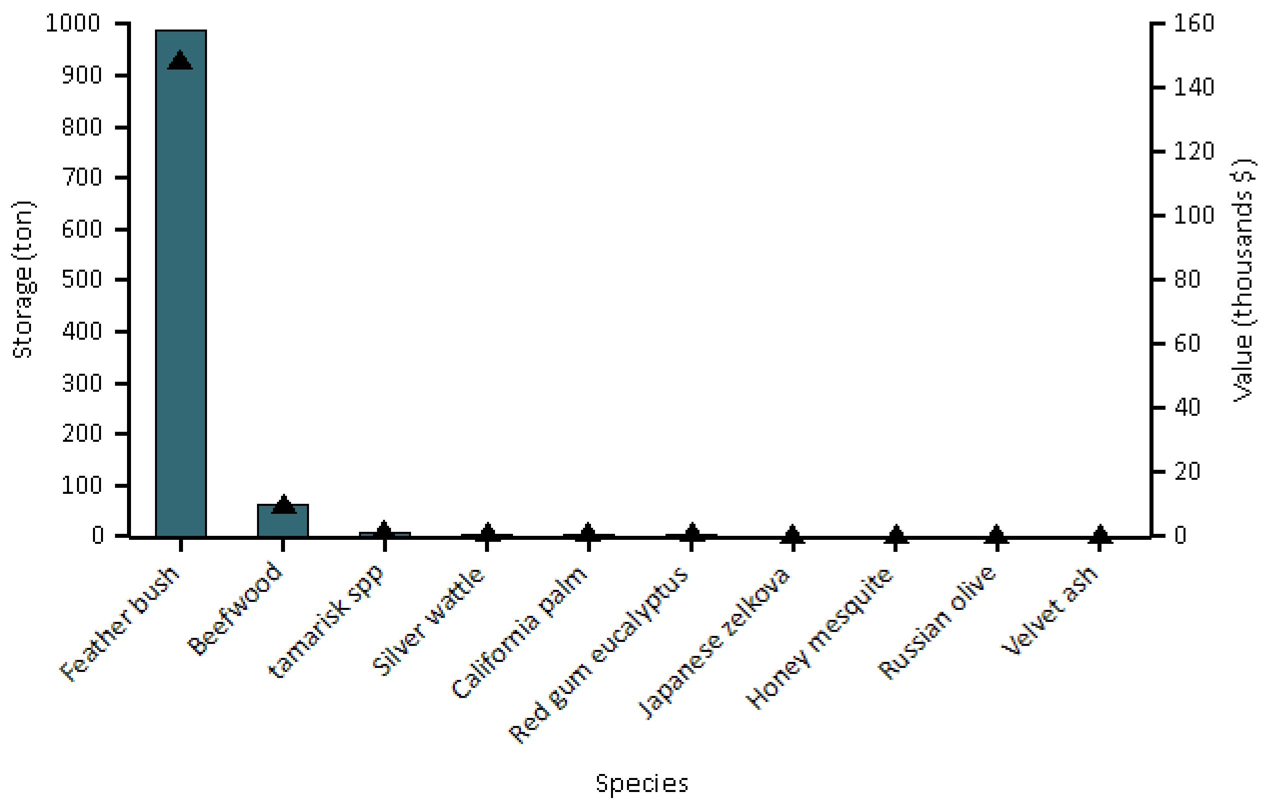


Figure 9. Estimated carbon storage (points) and values (bars) for urban tree species with the greatest storage, Baseline

V. Oxygen Production

Oxygen production is one of the most commonly cited benefits of urban trees. The net annual oxygen production of a tree is directly related to the amount of carbon sequestered by the tree, which is tied to the accumulation of tree biomass.

Trees in Baseline are estimated to produce 119.9 tons of oxygen per year.[4] However, this tree benefit is relatively insignificant because of the large and relatively stable amount of oxygen in the atmosphere and extensive production by aquatic systems. Our atmosphere has an enormous reserve of oxygen. If all fossil fuel reserves, all trees, and all organic matter in soils were burned, atmospheric oxygen would only drop a few percent (Broecker 1970).

Table 2. The top 20 oxygen production species.

Species	*Oxygen (ton)*	*Net Carbon Sequestration (ton/yr)*	*Number of Trees*	*Leaf Area (acre)*
Feather bush	119.26	44.72	1,735	12.99
Silver wattle	0.40	0.15	218	3.59
Honey mesquite	0.30	0.11	55	0.12
Red gum eucalyptus	0.18	0.07	37	1.03
California palm	0.17	0.06	36	0.09
Russian olive	0.10	0.04	3	0.03
Argentine senna	0.03	0.01	16	0.02
Japanese zelkova	-0.01	0.00	19	0.03
Velvet ash	-0.02	-0.01	18	0.00
tamarisk spp	-0.06	-0.02	34	1.00
Beefwood	-0.45	-0.17	132	5.16

[4] A negative estimate, or oxygen deficit, indicates that trees are decomposing faster than they are producing oxygen. This would be the case in an area that has a large proportion of dead trees.

VI. Avoided Runoff

Surface runoff can be a cause for concern in many urban areas as it can contribute pollution to streams, wetlands, rivers, lakes, and oceans. During precipitation events, some portion of the precipitation is intercepted by vegetation (trees and shrubs) while the other portion reaches the ground. The portion of the precipitation that reaches the ground and does not infiltrate into the soil becomes surface runoff (Hirabayashi 2012). In urban areas, the large extent of impervious surfaces increases the amount of surface runoff.

Urban trees and shrubs, however, are beneficial in reducing surface runoff. Trees and shrubs intercept precipitation, while their root systems promote infiltration and storage in the soil. The trees and shrubs of Baseline help to reduce runoff by an estimated 6.32 thousand cubic feet a year with an associated value of $420 (see Appendix I for more details). Avoided runoff is estimated based on local weather from the user-designated weather station. In Baseline, the total annual precipitation in 2016 was 6.8 inches.

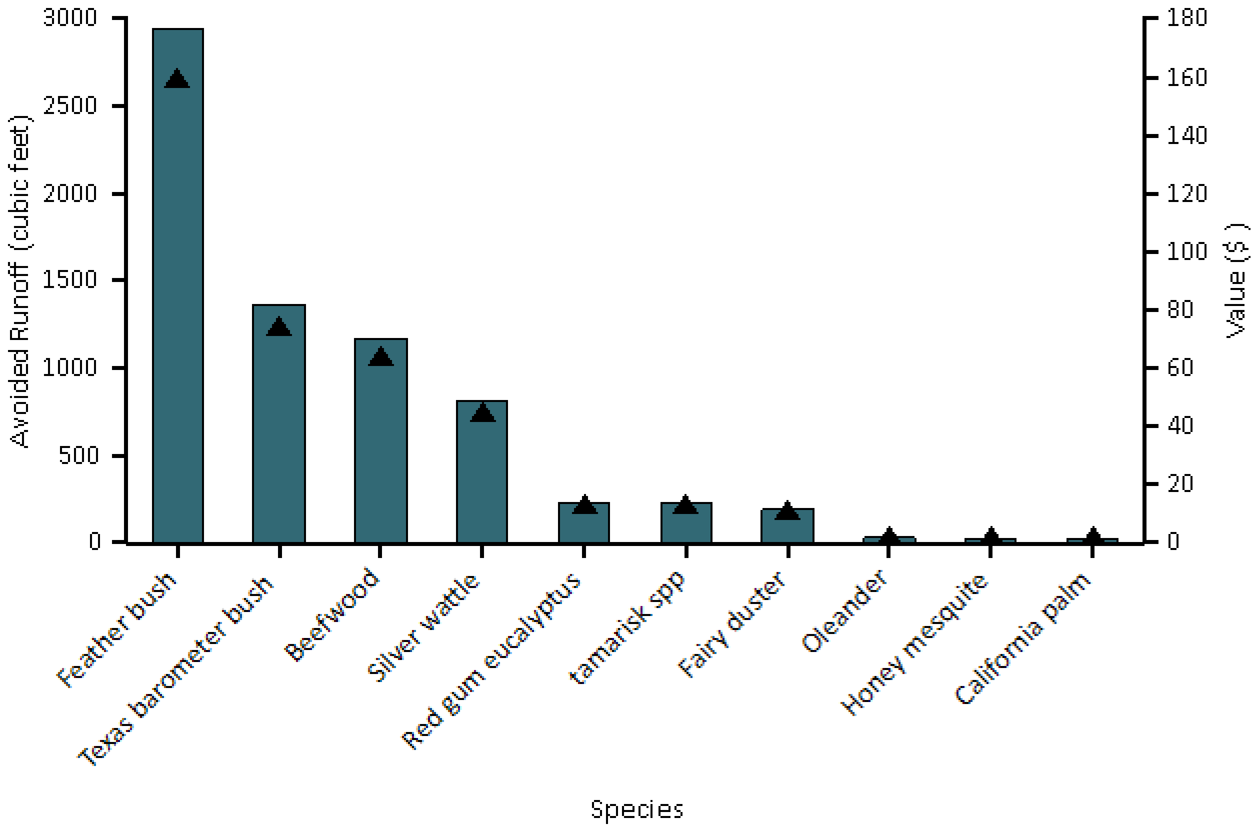


Figure 10. Avoided runoff (points) and value (bars) for species with greatest overall impact on runoff, Baseline

VII. Trees and Building Energy Use

Trees affect energy consumption by shading buildings, providing evaporative cooling, and blocking winter winds. Trees tend to reduce building energy consumption in the summer months and can either increase or decrease building energy use in the winter months, depending on the location of trees around the building. Estimates of tree effects on energy use are based on field measurements of tree distance and direction to space conditioned residential buildings (McPherson and Simpson 1999).

Trees in Baseline are estimated to reduce energy-related costs from residential buildings by $0 annually. Trees also provide an additional $0 in value by reducing the amount of carbon released by fossil-fuel based power plants (a reduction of 0 pounds of carbon emissions).

Note: negative numbers indicate that there was not a reduction in carbon emissions and/or value, rather carbon emissions and values increased by the amount shown as a negative value.[5]

Table 3. Annual energy savings due to trees near residential buildings, Baseline

	Heating	*Cooling*	*Total*
MBTU[a]	0	N/A	0
MWH[b]	0	0	0
Carbon Avoided (pounds)	0	0	0

[a]MBTU - one million British Thermal Units
[b]MWH - megawatt-hour

Table 4. Annual savings [a]($) in residential energy expenditure during heating and cooling seasons, Baseline

	Heating	*Cooling*	*Total*
MBTU[b]	0	N/A	0
MWH[c]	0	0	0
Carbon Avoided	0	0	0

[b]Based on the prices of $131.6 per MWH and $16.3480800457637 per MBTU (see Appendix I for more details)
[c]MBTU - one million British Thermal Units
[c]MWH - megawatt-hour

[5] Trees modify climate, produce shade, and reduce wind speeds. Increased energy use or costs are likely due to these tree-building interactions creating a cooling effect during the winter season. For example, a tree (particularly evergreen species) located on the southern side of a residential building may produce a shading effect that causes increases in heating requirements.

VIII. Structural and Functional Values

Urban forests have a structural value based on the trees themselves (e.g., the cost of having to replace a tree with a similar tree); they also have functional values (either positive or negative) based on the functions the trees perform.

The structural value of an urban forest tends to increase with a rise in the number and size of healthy trees (Nowak et al 2002a). Annual functional values also tend to increase with increased number and size of healthy trees. Through proper management, urban forest values can be increased; however, the values and benefits also can decrease as the amount of healthy tree cover declines.

Urban trees in Baseline have the following structural values:

- Structural value: $6.67 million
- Carbon storage: $171 thousand

Urban trees in Baseline have the following annual functional values:

- Carbon sequestration: $8.36 thousand
- Avoided runoff: $422
- Pollution removal: $1.19 thousand
- Energy costs and carbon emission values: $0

(Note: negative value indicates increased energy cost and carbon emission value)

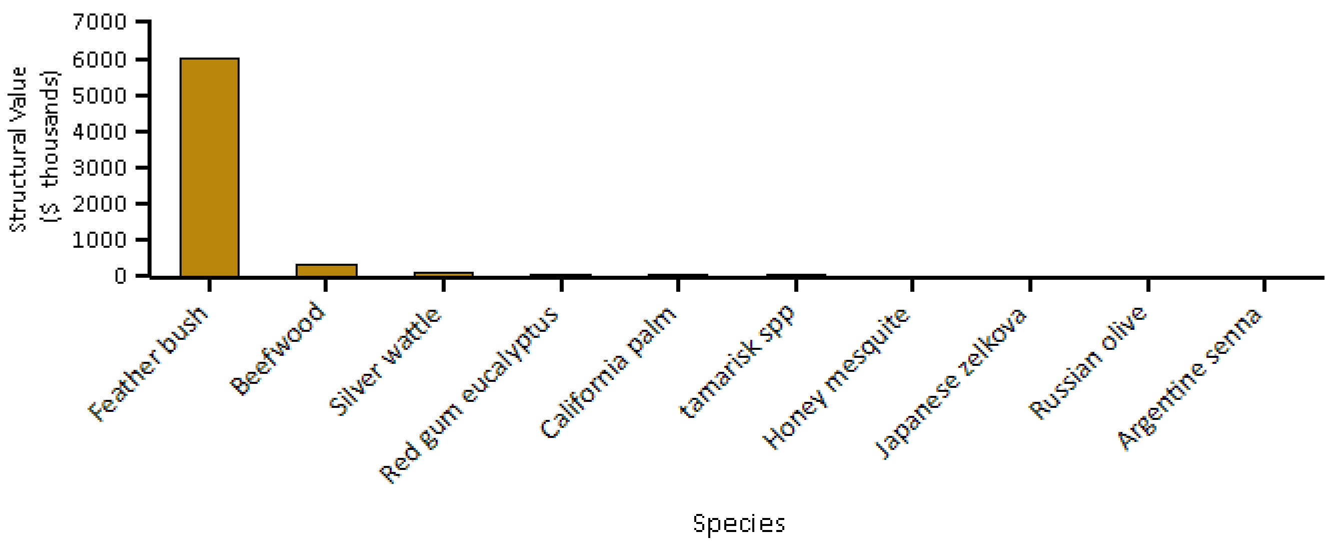


Figure 11. Tree species with the greatest structural value, Baseline

IX. Potential Pest Impacts

Various insects and diseases can infest urban forests, potentially killing trees and reducing the health, structural value and sustainability of the urban forest. As pests tend to have differing tree hosts, the potential damage or risk of each pest will differ among cities.Thirty-six pests were analyzed for their potential impact and compared with pest range maps (Forest Health Technology Enterprise Team 2014) for the conterminous United States to determine their proximity to Maricopa County. One of the thirty-six pests analyzed are located within the county. For a complete analysis of all pests, see Appendix VII.

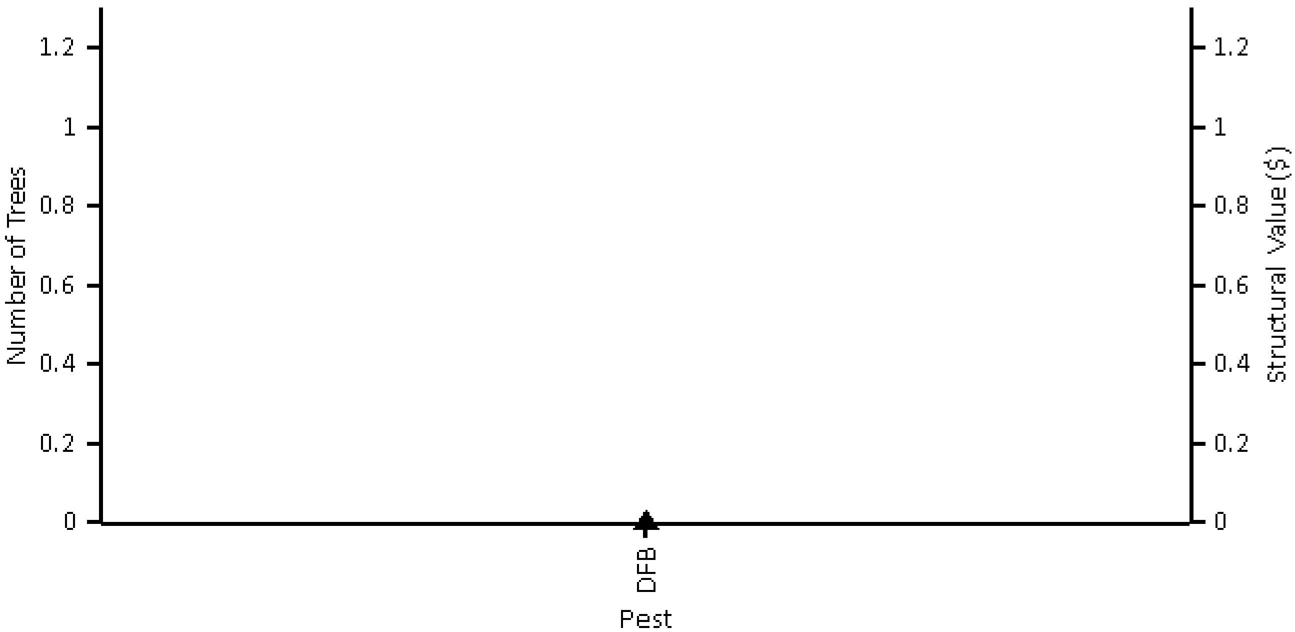


Figure 12. Number of trees at risk (points) and associated compensatory value (bars) for most threatening pests located in the county, Baseline

Douglas-fir beetle (DFB) (Schmitz and Gibson 1996) is a bark beetle that infests Douglas-fir trees throughout the western United States, British Columbia, and Mexico. Potential loss of trees from DFB is 0.0 percent ($0 in structural value).

Appendix I. i-Tree Eco Model and Field Measurements

i-Tree Eco is designed to use standardized field data from randomly located plots and local hourly air pollution and meteorological data to quantify urban forest structure and its numerous effects (Nowak and Crane 2000), including:

- Urban forest structure (e.g., species composition, tree health, leaf area, etc.).
- Amount of pollution removed hourly by the urban forest, and its associated percent air quality improvement throughout a year.
- Total carbon stored and net carbon annually sequestered by the urban forest.
- Effects of trees on building energy use and consequent effects on carbon dioxide emissions from power sources.
- Structural value of the forest, as well as the value for air pollution removal and carbon storage and sequestration.
- Potential impact of infestations by pests, such as Asian longhorned beetle, emerald ash borer, gypsy moth, and Dutch elm disease.

Typically, all field data are collected during the leaf-on season to properly assess tree canopies. Typical data collection (actual data collection may vary depending upon the user) includes land use, ground and tree cover, individual tree attributes of species, stem diameter, height, crown width, crown canopy missing and dieback, and distance and direction to residential buildings (Nowak et al 2005; Nowak et al 2008).

During data collection, trees are identified to the most specific taxonomic classification possible. Trees that are not classified to the species level may be classified by genus (e.g., ash) or species groups (e.g., hardwood). In this report, tree species, genera, or species groups are collectively referred to as tree species.

Tree Characteristics:

Leaf area of trees was assessed using measurements of crown dimensions and percentage of crown canopy missing. In the event that these data variables were not collected, they are estimated by the model.

An analysis of invasive species is not available for studies outside of the United States. For the U.S., invasive species are identified using an invasive species list (Arizona Wildland Invasive Plant Working Group 2005)for the state in which the urban forest is located. These lists are not exhaustive and they cover invasive species of varying degrees of invasiveness and distribution. In instances where a state did not have an invasive species list, a list was created based on the lists of the adjacent states. Tree species that are identified as invasive by the state invasive species list are cross-referenced with native range data. This helps eliminate species that are on the state invasive species list, but are native to the study area.

Air Pollution Removal:

Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and particulate matter less than 2.5 microns. Particulate matter less than 10 microns (PM10) is another significant air pollutant. Given that i-Tree Eco analyzes particulate matter less than 2.5 microns (PM2.5) which is a subset of PM10, PM10 has not been included in this analysis. PM2.5 is generally more relevant in discussions concerning air pollution effects on human health.

Air pollution removal estimates are derived from calculated hourly tree-canopy resistances for ozone, and sulfur and nitrogen dioxides based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi 1988; Baldocchi et al 1987). As the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, removal rates (deposition velocities) for these pollutants were based on average measured values from the literature (Bidwell and Fraser 1972; Lovett 1994) that were adjusted depending on leaf phenology and leaf area.

Particulate removal incorporated a 50 percent resuspension rate of particles back to the atmosphere (Zinke 1967). Recent updates (2011) to air quality modeling are based on improved leaf area index simulations, weather and pollution processing and interpolation, and updated pollutant monetary values (Hirabayashi et al 2011; Hirabayashi et al 2012; Hirabayashi 2011).

Trees remove PM2.5 when particulate matter is deposited on leaf surfaces (Nowak et al 2013). This deposited PM2.5 can be resuspended to the atmosphere or removed during rain events and dissolved or transferred to the soil. This combination of events can lead to positive or negative pollution removal and value depending on various atmospheric factors. Generally, PM2.5 removal is positive with positive benefits. However, there are some cases when net removal is negative or resuspended particles lead to increased pollution concentrations and negative values. During some months (e.g., with no rain), trees resuspend more particles than they remove. Resuspension can also lead to increased overall PM2.5 concentrations if the boundary layer conditions are lower during net resuspension periods than during net removal periods. Since the pollution removal value is based on the change in pollution concentration, it is possible to have situations when trees remove PM2.5 but increase concentrations and thus have negative values during periods of positive overall removal. These events are not common, but can happen.

For reports in the United States, default air pollution removal value is calculated based on local incidence of adverse health effects and national median externality costs. The number of adverse health effects and associated economic value is calculated for ozone, sulfur dioxide, nitrogen dioxide, and particulate matter less than 2.5 microns using data from the U.S. Environmental Protection Agency's Environmental Benefits Mapping and Analysis Program (BenMAP) (Nowak et al 2014). The model uses a damage-function approach that is based on the local change in pollution concentration and population. National median externality costs were used to calculate the value of carbon monoxide removal (Murray et al 1994).

For international reports, user-defined local pollution values are used. For international reports that do not have local values, estimates are based on either European median externality values (van Essen et al 2011) or BenMAP regression equations (Nowak et al 2014) that incorporate user-defined population estimates. Values are then converted to local currency with user-defined exchange rates.

For this analysis, pollution removal value is calculated based on the prices of $1,327 per ton (carbon monoxide), $1,539 per ton (ozone), $362 per ton (nitrogen dioxide), $167 per ton (sulfur dioxide), $317,976 per ton (particulate matter less than 2.5 microns).

Carbon Storage and Sequestration:

Carbon storage is the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation. To calculate current carbon storage, biomass for each tree was calculated using equations from the literature and measured tree data. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak 1994). To adjust for this difference, biomass results for open-grown urban trees were multiplied by 0.8. No adjustment was made for trees found in natural stand conditions. Tree dry-weight biomass was converted to stored carbon by multiplying by 0.5.

Carbon sequestration is the removal of carbon dioxide from the air by plants. To estimate the gross amount of carbon sequestered annually, average diameter growth from the appropriate genera and diameter class and tree condition was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year x+1.

Carbon storage and carbon sequestration values are based on estimated or customized local carbon values. For international reports that do not have local values, estimates are based on the carbon value for the United States (U.S. Environmental Protection Agency 2015, Interagency Working Group on Social Cost of Carbon 2015) and converted to local currency with user-defined exchange rates.

For this analysis, carbon storage and carbon sequestration values are calculated based on $171 per ton.

Oxygen Production:

The amount of oxygen produced is estimated from carbon sequestration based on atomic weights: net O_2 release (kg/yr) = net C sequestration (kg/yr) × 32/12. To estimate the net carbon sequestration rate, the amount of carbon sequestered as a result of tree growth is reduced by the amount lost resulting from tree mortality. Thus, net carbon sequestration and net annual oxygen production of the urban forest account for decomposition (Nowak et al 2007). For complete inventory projects, oxygen production is estimated from gross carbon sequestration and does not account for decomposition.

Avoided Runoff:

Annual avoided surface runoff is calculated based on rainfall interception by vegetation, specifically the difference between annual runoff with and without vegetation. Although tree leaves, branches, and bark may intercept precipitation and thus mitigate surface runoff, only the precipitation intercepted by leaves is accounted for in this analysis.

The value of avoided runoff is based on estimated or user-defined local values. For international reports that do not have local values, the national average value for the United States is utilized and converted to local currency with user-defined exchange rates. The U.S. value of avoided runoff is based on the U.S. Forest Service's Community Tree Guide Series (McPherson et al 1999; 2000; 2001; 2002; 2003; 2004; 2006a; 2006b; 2006c; 2007; 2010; Peper et al 2009; 2010; Vargas et al 2007a; 2007b; 2008).

For this analysis, avoided runoff value is calculated based on the price of $0.07 per ft³.

Building Energy Use:

If appropriate field data were collected, seasonal effects of trees on residential building energy use were calculated based on procedures described in the literature (McPherson and Simpson 1999) using distance and direction of trees from residential structures, tree height and tree condition data. To calculate the monetary value of energy savings, local or custom prices per MWH or MBTU are utilized.

For this analysis, energy saving value is calculated based on the prices of $131.60 per MWH and $16.35 per MBTU.

Structural Values:

Structural value is the value of a tree based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree). Structural values were based on valuation procedures of the Council of Tree and Landscape Appraisers, which uses tree species, diameter, condition, and location information (Nowak et al 2002a; 2002b). Structural value may not be included for international projects if there is insufficient local data to complete the valuation procedures.

Potential Pest Impacts:

The complete potential pest risk analysis is not available for studies outside of the United States. The number of trees at risk to the pests analyzed is reported, though the list of pests is based on known insects and disease in the United States.

For the U.S., potential pest risk is based on pest range maps and the known pest host species that are likely to

experience mortality. Pest range maps for 2012 from the Forest Health Technology Enterprise Team (FHTET) (Forest Health Technology Enterprise Team 2014) were used to determine the proximity of each pest to the county in which the urban forest is located. For the county, it was established whether the insect/disease occurs within the county, is within 250 miles of the county edge, is between 250 and 750 miles away, or is greater than 750 miles away. FHTET did not have pest range maps for Dutch elm disease and chestnut blight. The range of these pests was based on known occurrence and the host range, respectively (Eastern Forest Environmental Threat Assessment Center; Worrall 2007).

<u>Relative Tree Effects:</u>

The relative value of tree benefits reported in Appendix II is calculated to show what carbon storage and sequestration, and air pollutant removal equate to in amounts of municipal carbon emissions, passenger automobile emissions, and house emissions.

Municipal carbon emissions are based on 2010 U.S. per capita carbon emissions (Carbon Dioxide Information Analysis Center 2010). Per capita emissions were multiplied by city population to estimate total city carbon emissions.

Light duty vehicle emission rates (g/mi) for CO, NOx, VOCs, PM10, SO2 for 2010 (Bureau of Transportation Statistics 2010; Heirigs et al 2004), PM2.5 for 2011-2015 (California Air Resources Board 2013), and CO2 for 2011 (U.S. Environmental Protection Agency 2010) were multiplied by average miles driven per vehicle in 2011 (Federal Highway Administration 2013) to determine average emissions per vehicle.

Household emissions are based on average electricity kWh usage, natural gas Btu usage, fuel oil Btu usage, kerosene Btu usage, LPG Btu usage, and wood Btu usage per household in 2009 (Energy Information Administration 2013; Energy Information Administration 2014)

- CO2, SO2, and NOx power plant emission per KWh are from Leonardo Academy 2011. CO emission per kWh assumes 1/3 of one percent of C emissions is CO based on Energy Information Administration 1994. PM10 emission per kWh from Layton 2004.
- CO2, NOx, SO2, and CO emission per Btu for natural gas, propane and butane (average used to represent LPG), Fuel #4 and #6 (average used to represent fuel oil and kerosene) from Leonardo Academy 2011.
- CO2 emissions per Btu of wood from Energy Information Administration 2014.
- CO, NOx and SOx emission per Btu based on total emissions and wood burning (tons) from (British Columbia Ministry 2005; Georgia Forestry Commission 2009).

Appendix II. Relative Tree Effects

The urban forest in Baseline provides benefits that include carbon storage and sequestration, and air pollutant removal. To estimate the relative value of these benefits, tree benefits were compared to estimates of average municipal carbon emissions, average passenger automobile emissions, and average household emissions. See Appendix I for methodology.

Carbon storage is equivalent to:

- Amount of carbon emitted in Baseline in 0 days
- Annual carbon (C) emissions from 710 automobiles
- Annual C emissions from 291 single-family houses

Carbon monoxide removal is equivalent to:

- Annual carbon monoxide emissions from 0 automobiles
- Annual carbon monoxide emissions from 0 single-family houses

Nitrogen dioxide removal is equivalent to:

- Annual nitrogen dioxide emissions from 8 automobiles
- Annual nitrogen dioxide emissions from 3 single-family houses

Sulfur dioxide removal is equivalent to:

- Annual sulfur dioxide emissions from 28 automobiles
- Annual sulfur dioxide emissions from 0 single-family houses

Annual carbon sequestration is equivalent to:

- Amount of carbon emitted in Baseline in 0.0 days
- Annual C emissions from 0 automobiles
- Annual C emissions from 0 single-family houses

Appendix III. Comparison of Urban Forests

A common question asked is, "How does this city compare to other cities?" Although comparison among cities should be made with caution as there are many attributes of a city that affect urban forest structure and functions, summary data are provided from other cities analyzed using the i-Tree Eco model.

I. City totals for trees

City	*% Tree Cover*	*Number of Trees*	*Carbon Storage (tons)*	*Carbon Sequestration (tons/yr)*	*Pollution Removal (tons/yr)*
Toronto, ON, Canada	26.6	10,220,000	1,221,000	51,500	2,099
Atlanta, GA	36.7	9,415,000	1,344,000	46,400	1,663
Los Angeles, CA	11.1	5,993,000	1,269,000	77,000	1,975
New York, NY	20.9	5,212,000	1,350,000	42,300	1,676
London, ON, Canada	24.7	4,376,000	396,000	13,700	408
Chicago, IL	17.2	3,585,000	716,000	25,200	888
Phoenix, AZ	9.0	3,166,000	315,000	32,800	563
Baltimore, MD	21.0	2,479,000	570,000	18,400	430
Philadelphia, PA	15.7	2,113,000	530,000	16,100	575
Washington, DC	28.6	1,928,000	525,000	16,200	418
Oakville, ON , Canada	29.1	1,908,000	147,000	6,600	190
Albuquerque, NM	14.3	1,846,000	332,000	10,600	248
Boston, MA	22.3	1,183,000	319,000	10,500	283
Syracuse, NY	26.9	1,088,000	183,000	5,900	109
Woodbridge, NJ	29.5	986,000	160,000	5,600	210
Minneapolis, MN	26.4	979,000	250,000	8,900	305
San Francisco, CA	11.9	668,000	194,000	5,100	141
Morgantown, WV	35.5	658,000	93,000	2,900	72
Moorestown, NJ	28.0	583,000	117,000	3,800	118
Hartford, CT	25.9	568,000	143,000	4,300	58
Jersey City, NJ	11.5	136,000	21,000	890	41
Casper, WY	8.9	123,000	37,000	1,200	37
Freehold, NJ	34.4	48,000	20,000	540	22

II. Totals per acre of land area

City	*Number of Trees/ac*	*Carbon Storage (tons/ac)*	*Carbon Sequestration (tons/ac/yr)*	*Pollution Removal (lb/ac/yr)*
Toronto, ON, Canada	64.9	7.8	0.33	26.7
Atlanta, GA	111.6	15.9	0.55	39.4
Los Angeles, CA	19.6	4.2	0.16	13.1
New York, NY	26.4	6.8	0.21	17.0
London, ON, Canada	75.1	6.8	0.24	14.0
Chicago, IL	24.2	4.8	0.17	12.0
Phoenix, AZ	12.9	1.3	0.13	4.6
Baltimore, MD	48.0	11.1	0.36	16.6
Philadelphia, PA	25.1	6.3	0.19	13.6
Washington, DC	49.0	13.3	0.41	21.2
Oakville, ON , Canada	78.1	6.0	0.27	11.0
Albuquerque, NM	21.8	3.9	0.12	5.9
Boston, MA	33.5	9.1	0.30	16.1
Syracuse, NY	67.7	10.3	0.34	13.6
Woodbridge, NJ	66.5	10.8	0.38	28.4
Minneapolis, MN	26.2	6.7	0.24	16.3
San Francisco, CA	22.5	6.6	0.17	9.5
Morgantown, WV	119.2	16.8	0.52	26.0
Moorestown, NJ	62.1	12.4	0.40	25.1
Hartford, CT	50.4	12.7	0.38	10.2
Jersey City, NJ	14.4	2.2	0.09	8.6
Casper, WY	9.1	2.8	0.09	5.5
Freehold, NJ	38.3	16.0	0.44	35.3

Appendix IV. General Recommendations for Air Quality Improvement

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmosphere environment. Four main ways that urban trees affect air quality are (Nowak 1995):

- Temperature reduction and other microclimate effects
- Removal of air pollutants
- Emission of volatile organic compounds (VOC) and tree maintenance emissions
- Energy effects on buildings

The cumulative and interactive effects of trees on climate, pollution removal, and VOC and power plant emissions determine the impact of trees on air pollution. Cumulative studies involving urban tree impacts on ozone have revealed that increased urban canopy cover, particularly with low VOC emitting species, leads to reduced ozone concentrations in cities (Nowak 2000). Local urban management decisions also can help improve air quality.

Urban forest management strategies to help improve air quality include (Nowak 2000):

Strategy	*Result*
Increase the number of healthy trees	Increase pollution removal
Sustain existing tree cover	Maintain pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone and carbon monoxide formation
Sustain large, healthy trees	Large trees have greatest per-tree effects
Use long-lived trees	Reduce long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduce pollutants emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduce pollutant emissions
Plant trees in energy conserving locations	Reduce pollutant emissions from power plants
Plant trees to shade parked cars	Reduce vehicular VOC emissions
Supply ample water to vegetation	Enhance pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improve tree health
Utilize evergreen trees for particulate matter	Year-round removal of particles

Appendix V. Invasive Species of the Urban Forest

The following inventoried tree species were listed as invasive on the Arizona invasive species list (Arizona Wildland Invasive Plant Working Group 2005):

Species Name[a]	*Number of Trees*	*% of Trees*	*Leaf Area (ft^2)*	*Percent Leaf Area*
Russian olive	3	0.1	0.0	0.1
Total	**3**	**0.15**	**0.00**	**0.13**

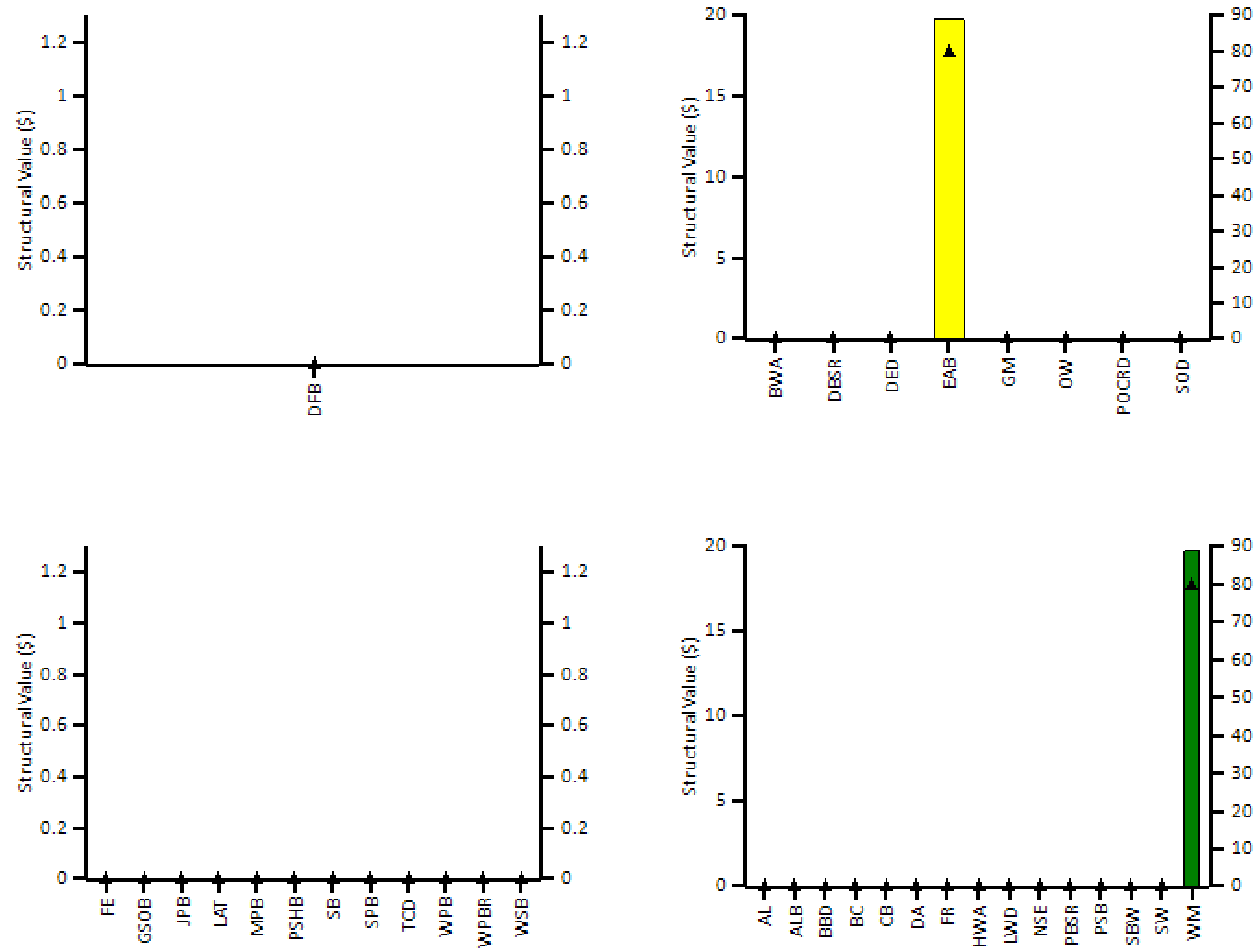
[a]Species are determined to be invasive if they are listed on the state's invasive species list

Appendix VI. Potential Risk of Pests

Thirty-six insects and diseases were analyzed to quantify their potential impact on the urban forest. As each insect/ disease is likely to attack different host tree species, the implications for {0} will vary. The number of trees at risk reflects only the known host species that are likely to experience mortality.

Code	Scientific Name	Common Name	Trees at Risk (#)	Value ($)
AL	Phyllocnistis populiella	Aspen Leafminer	0	0.00
ALB	Anoplophora glabripennis	Asian Longhorned Beetle	0	0.00
BBD	Neonectria faginata	Beech Bark Disease	0	0.00
BC	Sirococcus clavigignenti juglandacearum	Butternut Canker	0	0.00
BWA	Adelges piceae	Balsam Woolly Adelgid	0	0.00
CB	Cryphonectria parasitica	Chestnut Blight	0	0.00
DA	Discula destructiva	Dogwood Anthracnose	0	0.00
DBSR	Leptographium wageneri var. pseudotsugae	Douglas-fir Black Stain Root Disease	0	0.00
DED	Ophiostoma novo-ulmi	Dutch Elm Disease	0	0.00
DFB	Dendroctonus pseudotsugae	Douglas-Fir Beetle	0	0.00
EAB	Agrilus planipennis	Emerald Ash Borer	18	88.82
FE	Scolytus ventralis	Fir Engraver	0	0.00
FR	Cronartium quercuum f. sp. Fusiforme	Fusiform Rust	0	0.00
GM	Lymantria dispar	Gypsy Moth	0	0.00
GSOB	Agrilus auroguttatus	Goldspotted Oak Borer	0	0.00
HWA	Adelges tsugae	Hemlock Woolly Adelgid	0	0.00
JPB	Dendroctonus jeffreyi	Jeffrey Pine Beetle	0	0.00
LAT	Choristoneura conflictana	Large Aspen Tortrix	0	0.00
LWD	Raffaelea lauricola	Laurel Wilt	0	0.00
MPB	Dendroctonus ponderosae	Mountain Pine Beetle	0	0.00
NSE	Ips perturbatus	Northern Spruce Engraver	0	0.00
OW	Ceratocystis fagacearum	Oak Wilt	0	0.00
PBSR	Leptographium wageneri var. ponderosum	Pine Black Stain Root Disease	0	0.00
POCRD	Phytophthora lateralis	Port-Orford-Cedar Root Disease	0	0.00
PSB	Tomicus piniperda	Pine Shoot Beetle	0	0.00
PSHB	Euwallacea nov. sp.	Polyphagous Shot Hole Borer	0	0.00
SB	Dendroctonus rufipennis	Spruce Beetle	0	0.00
SBW	Choristoneura fumiferana	Spruce Budworm	0	0.00
SOD	Phytophthora ramorum	Sudden Oak Death	0	0.00
SPB	Dendroctonus frontalis	Southern Pine Beetle	0	0.00
SW	Sirex noctilio	Sirex Wood Wasp	0	0.00
TCD	Geosmithia morbida	Thousand Canker Disease	0	0.00
WM	Operophtera brumata	Winter Moth	18	88.82
WPB	Dendroctonus brevicomis	Western Pine Beetle	0	0.00
WPBR	Cronartium ribicola	White Pine Blister Rust	0	0.00
WSB	Choristoneura occidentalis	Western Spruce Budworm	0	0.00

In the following graph, the pests are color coded according to the county's proximity to the pest occurrence in the United States. Red indicates that the pest is within the county; orange indicates that the pest is within 250 miles of the county; yellow indicates that the pest is within 750 miles of the county; and green indicates that the pest is outside of these ranges.



Note: points - Number of trees, bars - Structural value

Based on the host tree species for each pest and the current range of the pest (Forest Health Technology Enterprise Team 2014), it is possible to determine what the risk is that each tree species in the urban forest could be attacked by an insect or disease.

Spp. Risk	Risk Weight	Species Name	AL	ALB	BBD	BC	BWA	CB	DA	DBSR	DED	DFB	EAB	FE	FR	GM	GSOB	HWA	JPB	LAT	LWD	MPB	NSE	OW	PBSR	POCRD	PSB	PSHB	SB	SBW	SOD	SPB	SW	TCD	WM	WPB	WPBR	WSB
	3	Velvet ash																																				

Note:
Species that are not listed in the matrix are not known to be hosts to any of the pests analyzed.

Species Risk:
- Red indicates that tree species is at risk to at least one pest within county
- Orange indicates that tree species has no risk to pests in county, but has a risk to at least one pest within 250 miles from the county
- Yellow indicates that tree species has no risk to pests within 250 miles of county, but has a risk to at least one pest that is 250 and 750 miles from the county
- Green indicates that tree species has no risk to pests within 750 miles of county, but has a risk to at least one pest that is greater than 750 miles from the county

Risk Weight:
Numerical scoring system based on sum of points assigned to pest risks for species. Each pest that could attack tree species is scored as 4 points if red, 3 points if orange, 2 points if yellow and 1 point if green.

Pest Color Codes:
- Red indicates pest is within Maricopa county
- Red indicates pest is within 250 miles county
- Yellow indicates pest is within 750 miles of Maricopa county
- Green indicates pest is outside of these ranges

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Appendix 9. Surface Water Quality Assessment

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DRAFT Memorandum

Date: 6 July 2021

To: Anna Bettis, MSUS PMP, Nature Conservancy in Arizona

From: Aaron Poresky, P.E. (OR) and Christian Nilsen, P.E. (WA)

Subject: Water Quality Analysis for City of Phoenix Low Impact Development Study
Geosyntec Project: PNW0432, Phase 5

INTRODUCTION

The Bureau of Reclamation and The Nature Conservancy along with local partners the City of Phoenix, Flood Control District of Maricopa County, and Maricopa County Air Quality Department are working to identify and prioritize catchments in most need of Low Impact Development (LID)/Green Stormwater Infrastructure (GSI) improvements. This study is referred to as the Phoenix LID study in this technical memorandum.

As part of this effort, the Bureau of Reclamation developed a continuous simulation hydrologic and hydraulic model. Geosyntec then performed a water quality analysis to estimate the performance of potential LID scenarios. The purpose of this memorandum is to summarize the methodology, inputs, and results of this water quality analysis.

METHODOLOGY

The Bureau of Reclamation developed hydrologic and hydraulic models of the study area using the Stormwater Management Model (SWMM) version 5.1. Model versions included a baseline condition (without LID) and three hypothetical scenarios representing 25%, 50%, and 100% of maximum LID participation. The SWMM model represented the LID features using the “LID Controls” editor. Details of these models are provided in the modeling report prepared by the Bureau of Reclamation.

The SWMM models were provided to Geosyntec. These models produce report files, containing results for each SWMM catchment and the types of LID features in each catchment. Results represent cumulative values for the period-of-record modeled. The report file provides sufficient information to construct a water balance for each catchment and LID type, including:

- Runoff volume from each catchment, broken down by pervious and impervious area
- Volumes of catchment runoff tributary to each LID type (a subset of the total catchment runoff volume)
- Volumes that leave each LID type via infiltration, evapotranspiration, treated discharge through underdrains, and overflow or bypass

We queried the report file to develop a long-term water balance of each catchment and LID type.

We developed representative runoff concentrations for each catchment based on the mix of dominant land uses in each catchment. The modeled pollutants were total suspended solids, total copper, and total lead. Combining the representative land use runoff concentrations with the runoff volumes, we calculated the pollutant loading from each catchment and the pollutant loading incident to each type of LID feature in each catchment.

Finally, for BMPs that contain an underdrain discharging treated water, we developed estimates of BMP treatment efficiencies to estimate the concentration reduction of the water that is treated.

For water lost to infiltration or evapotranspiration, the associated pollutant load was considered to be removed by the BMP and not discharged downstream into the storm drain network

Figure 1 illustrates the conceptual model used for this analysis. We implemented this analysis framework using a spreadsheet that reads the SWMM report files and outputs result summaries.

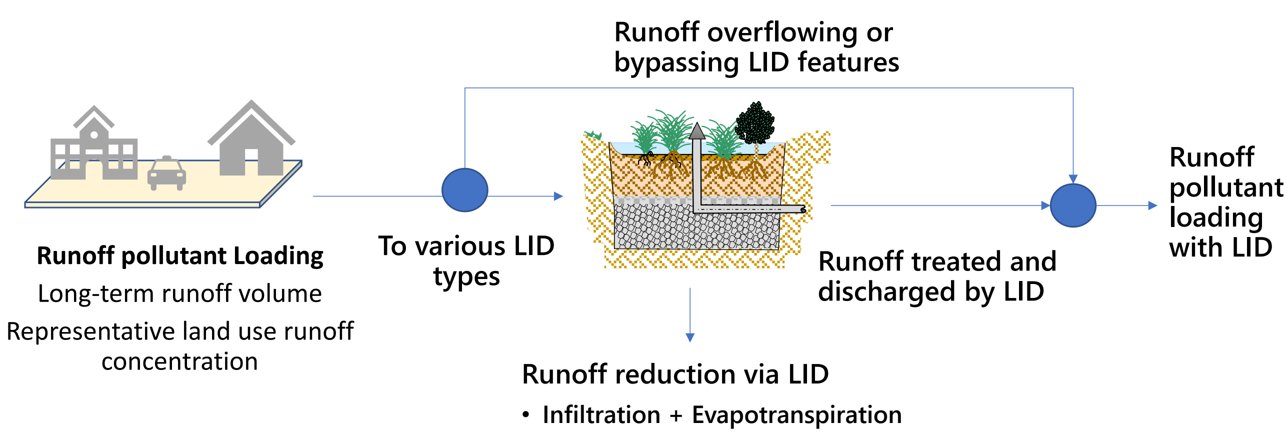


Figure 1. Conceptual Model for Stormwater Quality Analysis

INPUTS

Model Scenarios

The water quality analysis was conducted for four scenarios: baseline, 25% participation, 50% participation, and 100% participation. The model report files were produced by the Bureau of Reclamation and transmitted to Geosyntec. These were used as primary inputs to determine runoff volumes and LID hydrologic performance.

Land Use Assignments and Land Use Runoff Concentrations

Earlier phases of the study classified the dominant land use breakdown of each SWMM catchment. For each of the dominant land uses present, Geosyntec consulted relevant monitoring studies to develop a representative concentration for each land use for the study pollutants. For TSS and Total Copper, the primary source was the National Stormwater Quality Database (https://bmpdatabase.org/nsqdstat.html). We filtered the data to those most representative of Arizona. Where land use data were available from Arizona studies, those data were used. Where land use data were not available from Arizona, data from California were used. Sources and summary statistics are shown in Table 1.

Table 1. Land Use Event Mean Concentrations from National Stormwater Quality Database

Land Use in NSQD	State Filter	Total Suspended Solids			Total Copper		
		Number of Sites	Number of EMCs	Mean EMC, mg/L	Number of Sites	Number of EMCs	Mean EMC, ug/L
Residential	AZ	4	43	**122**	4	44	**18**
Commercial	AZ	2	23	**132**	2	35	**17**
Industrial	AZ	9	165	**297**	3	60	**93**
Public/ Institutional	CA	1	51	**94**	1	54	**22**
Freeway	CA	16	183	**138**	16	182	**60**
Surface Street[1]	-	-	-	**135**	-	-	**39**

1 - There is not a NSQD category for surface streets. A representative EMC was constructed based on the average of freeway and commercial concentrations.

Runoff concentrations for lead have reduced over time with the phase-out of leaded gasoline and gradual drawdown in lead sources within the landscape. Older sampling data from the NSQD no longer reflect modern lead concentrations. Instead, we used recent storm drain outfall monitoring collected in Orange County, CA (https://ocgov.app.box.com/VSDR/WQIPClearinghouse/folder/130628955382; See Item 5). These data did not now show differences in concentration by land use. This is expected given the very limited remaining sources of lead in the landscape. Summary statistics are shown in Table 2.

Table 2. Land Use Event Mean Concentrations from South Orange County California Wet Weather Outfall Monitoring Program

Land Use	Total Lead		
	Number of Sites	**Number of EMCs**	**Mean EMC, ng/L**
Mixed Urban Land Use	14	83	**2.1**
Street[1]	NA	NA	**3.3**

1 - Estimate developed by South Orange County Stormwater Program from multiple lines of evidence.

Combining these concentrations with the land use distribution of each catchment resulted in a representative concentration for each catchment. In cases where there were multiple land uses within a catchment, an area-weighted approach was used. Volume-weighting may produce somewhat more accurate results but was not possible based on the spatial resolution of SWMM output. Land use distributions and runoff concentrations are provided in Table A-1 (Attachment A).

Representative BMP Removal Efficiency

The suite of LID features used in the modeling scenarios had relatively minor reliance on treatment and release processes. Therefore, BMP removal efficiencies were not an important part of this analysis. However, systems with more reliance on treatment could potentially be used in areas where infiltration is not feasible. Therefore, using the statistical analysis tool for the International Stormwater BMP Database (https://bmpdatabase.org/bmpstat.html), we calculated the following representative reductions in concentration for types of LID that may be used in other study areas (Table 4). The calculated reductions will tend to differ for different influent concentrations; at low influent concentrations, the relative removal may be lower. Additional detail is provided in Table A-2 (Attachment A), including sample counts used to estimate BMP performance and concentration reduction results for different ranges of influent concentration.

Table 3. Representative Concentration Reductions for LID Types

LID Type	BMP Database Category	Representative Concentration Reduction[1]		
		TSS	Total Copper	Total Lead
BioretentionPlanter	Bioretention[2]	78%	49%	73%
LinearBasins				
RainGarden				
Chicanes				
PerviousPavement	Pervious Pavement[2]	68%	33%	50%
RainBarrel-Residential	Retention Pond (Wet Pond)	75%	50%	70%
Cistern				

1 – Based on a comparison of median influent and effluent. See Table 5 for representative concentration reduction at different influent concentrations.
2 – Concentration reduction applies to treated water; therefore, this only applies to LID variations that have underdrains.

SUMMARY OF RESULTS

Load Reduction Effectiveness of LID Types

The runoff volume multiplied by concentration equals load. Therefore, the load reduction achieved by LID accounts for reduction of runoff volume as well as change in concentration.

For the stormwater runoff draining to LID features, a portion of the load is removed, and a portion is discharged or bypassed. Table 5 summarizes the portion of the load removed as a fraction of the load draining to the BMP. This is not the total load from the study area as portions of the area were not routed to LID features.

Table 4. Load Reduction Effectiveness of LID Types (for water draining to each type)

	Average Long-Term Load Reduction of Water Draining to LID Type (%)		
LID Type	**TSS**	**Total Copper**	**Total Lead**
BioretentionPlanter	95	95	95
Chicanes	99	99	99
Cistern	32	27	35
DisconnectedRoof	100	100	100
InfiltrationTrench	95	95	95
LinearBasins	97	97	97
PerviousPavement	100	100	100
RainBarrel-Residential	14	12	16
RainGarden	95	95	95

Note that cisterns and rain barrels also include the dispersion of water over landscaping after water is captured or overflows. Therefore, the total performance of these features is higher than indicated in this table. This is not tracked explicitly in SWMM and cannot be reported at the scale of each LID feature. However, it is accounted for in the summaries in the following sections.

Overall Comparison of Scenarios

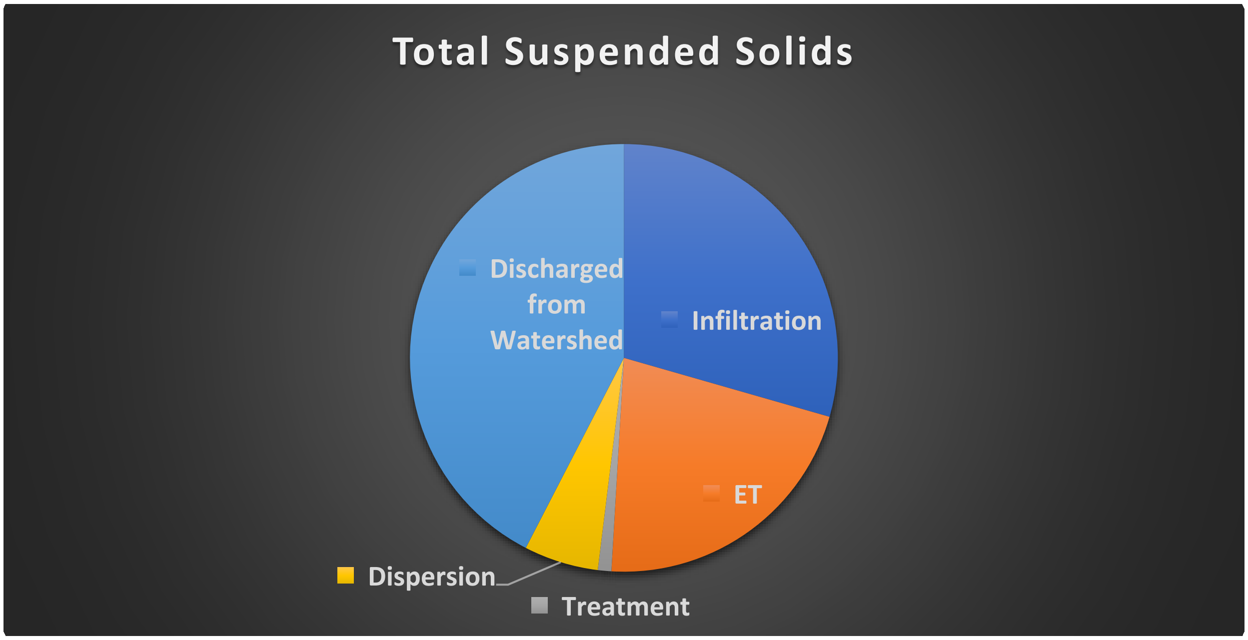
Table 5 summarizes the modeled load reduction for the study area as a whole for each level of participation. Load reduction is attributable primarily to volume reduction (via infiltration or evapotranspiration), therefore the relative load reduction is quite similar between pollutants.

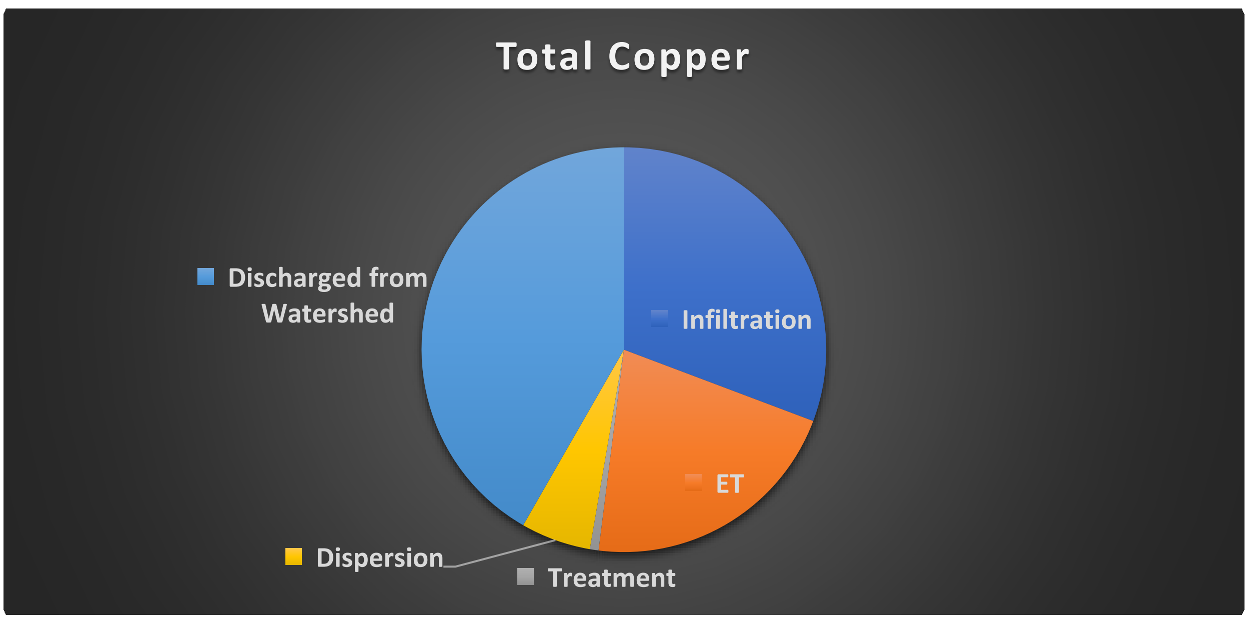
Table 5. Study Area Load Reduction

Scenario	TSS	Total Copper	Total Lead
Baseline Runoff Mass Load (lbs/yr)	21,600	5.7	0.23
100% Participation			
Load to Outlet (lbs/yr)	8,300	2.1	0.10
Total Load Reduction (%)	62%	63%	56%
50% Participation			
Load to Outlet (lbs/yr)	14,700	4.0	0.16
Total Load Reduction (%)	32%	30%	33%
25% Participation			
Load to Outlet (lbs/yr)	17,300	4.7	0.18
Total Load Reduction (%)	20%	18%	21%

Load Reduction by LID Unit Process

Figure 2 (multi-part figure below) illustrates the LID unit process responsible for removal of pollutant loads. This is categorized by water balance component. Actual fate of pollutants (e.g., deposition, particle filtration, sorption) differs by pollutant. Dispersion refers to water that discharges or overflows from Cisterns and Rain Barrels onto pervious surfaces and does not runoff. Much of this water is evapotranspired; some may infiltrate. Results are for the 100% participation scenario. For lower implementation, the portion discharged from the watershed increases, and the other components decrease approximately proportionally.


Total Suspended Solids
Discharged from Watershed
Infiltration
ET
Dispersion
Treatment


Total Copper
Discharged from Watershed
Infiltration
ET
Dispersion
Treatment

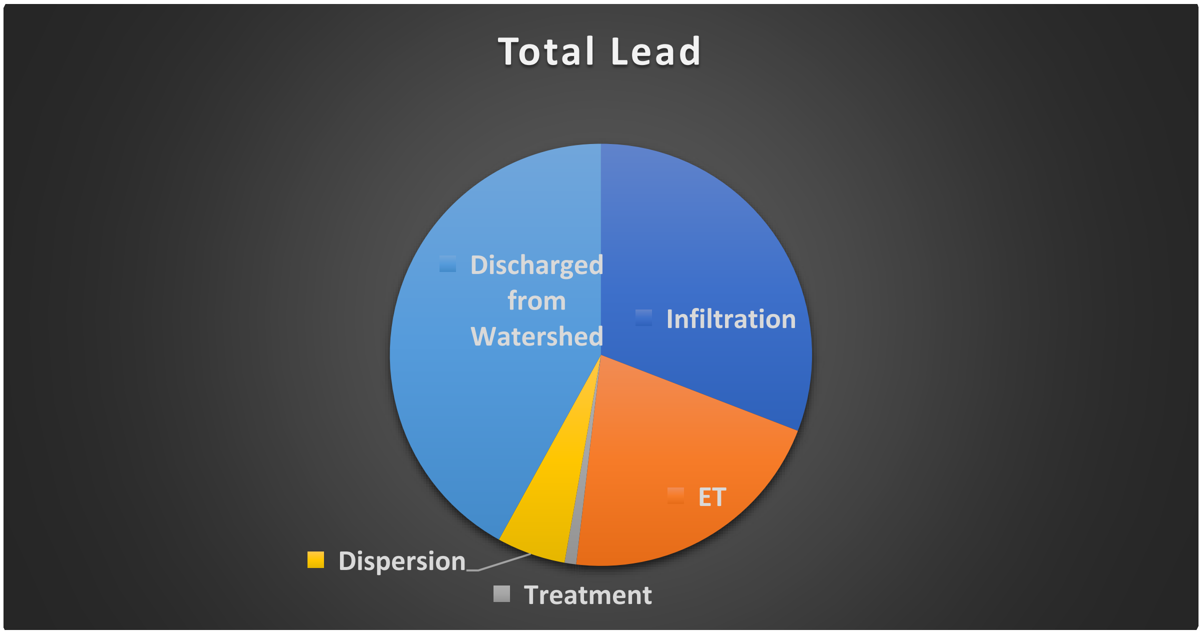


Figure 2. Load Reduction by LID Unit Process, 100% Participation Scenario

Load Reduction by LID Type

Figure 3 illustrates the portion of load reduction attributable to each type of LID feature for the overall study area. This plot is for the 100% participation scenario for total copper as a representative pollutant. A similar distribution applies to other pollutants and implementation scenarios. Note, dispersion is a component of the overall performance of rain barrels and cisterns, so these processes should be considered together.

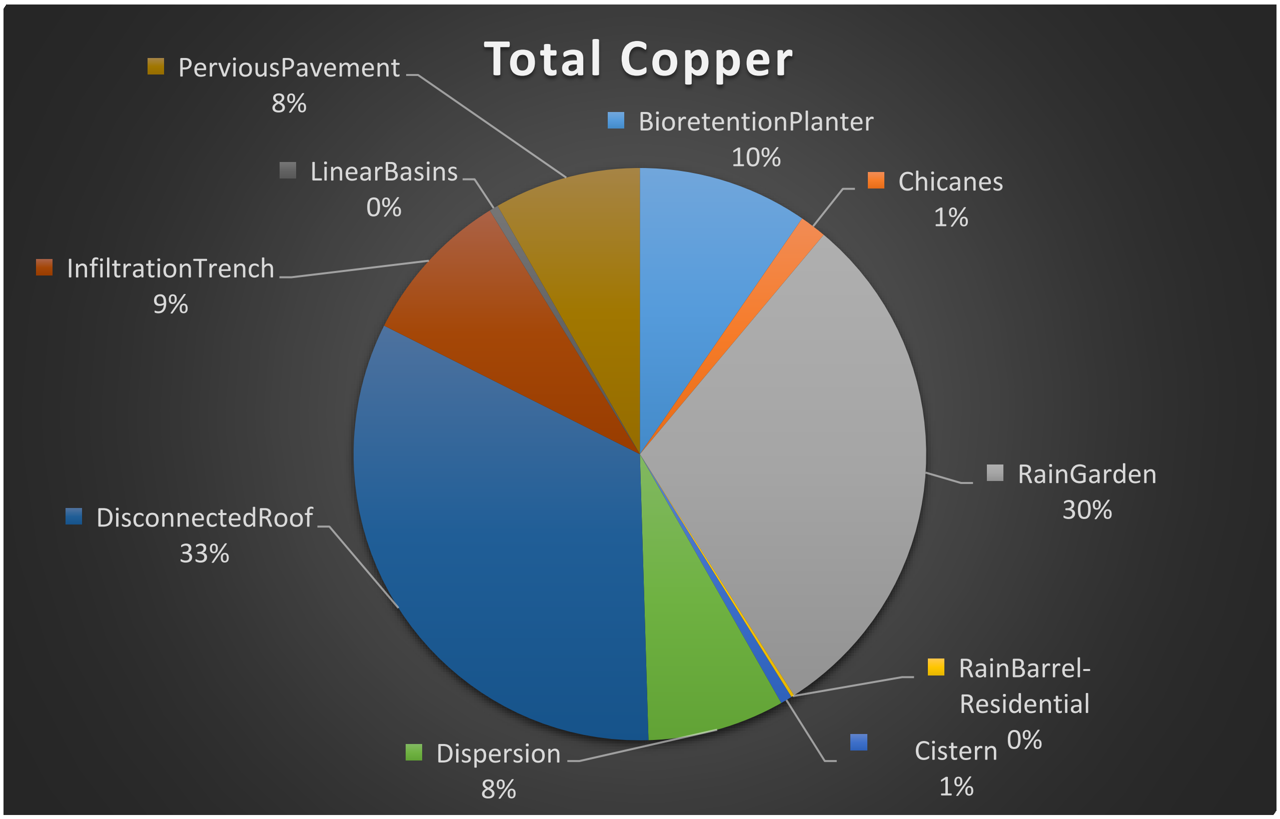


Figure 3. Load Reduction by LID Feature Type, 100% Participation Scenario, Total Copper

Load Reduction by Catchment

Table A-3 (Attachment A) reports the load reduction for each catchment, accounting for the area treated by LID as well as the effectiveness of the LID to remove pollutants. This table is for the 100 percent participation scenario.

INTERPRETATION

Several observations can be made from the results of the water quality analysis:

- For the areas draining to LID features, a very high percentage of load was typically removed. The exception was cisterns and rain barrels, which tend to drain slowly between storm events and therefore may produce more bypass. However, these systems were also combined with dispersion over pervious areas when bypass occurs, which has the effect of increasing overall performance beyond what is achieved within the cistern or rain barrel alone.

- Volume reduction processes, including infiltration, ET, and dispersion (which is a combination of infiltration and ET), account for the vast majority of the load reduction. LID systems can also provide effective removal of the pollutants of concern via treatment and discharge; however, this process did not play a significant role in the suite of LID features modeled.

- Results were relatively consistent across pollutants. This is expected due to the prevalence of volume reduction processes, which affect all pollutants relatively similarly.

- The maximum participation scenario resulted in about 60% load reduction of each pollutant. Lesser participation scaled approximately linearly, with 30% load reduction for the 50% participation scenario and about 20% load reduction for the 25% participation scenario.

- Overall, the most important factor in the effectiveness of LID controls was the amount of area that could be treated by these controls. In catchments where LID controls could be placed to treat a high fraction of the area, they were effective in achieving high levels of load reduction. The weighted watershed average of 60% load reduction accounts for areas that could not be treated.

This analysis did not directly account for elevated source areas that may exist within land uses and catchments; instead, it assumed uniform pollutant concentrations throughout each catchment. At the time of implementation, placement of LID should also consider specific pollutant source areas if they are known at that time.

* * * * *

ATTACHMENT A- SUPPLEMENTAL TABLES

Attachment A – Supplemental Tables

Table A-1. Land Use Distribution and Representative Runoff Concentration by Subcatchment

Catchment	Land Use Distribution					Representative Concentration, mg/L		
	Residential	Industrial	Commercial	Public	Street	TSS	Cu	Pb
S1	0%	0%	100%	0%	0%	132	0.017	0.002
S2	0%	0%	100%	0%	0%	132	0.017	0.002
S3_a	0%	0%	0%	100%	0%	94	0.022	0.002
S3_b	0%	0%	0%	100%	0%	94	0.022	0.002
S3_c	0%	2%	0%	98%	0%	98	0.024	0.002
S4	0%	0%	100%	0%	0%	132	0.017	0.002
S5	76%	0%	0%	24%	0%	115	0.019	0.002
S6	0%	100%	0%	0%	0%	297	0.092	0.002
S7	89%	11%	0%	0%	0%	140	0.026	0.002
S8	2%	0%	98%	0%	0%	132	0.017	0.002
S9	2%	0%	98%	0%	0%	132	0.017	0.002
S10	100%	0%	0%	0%	0%	122	0.018	0.002
S11	100%	0%	0%	0%	0%	122	0.018	0.002
S12	32%	0%	68%	0%	0%	129	0.018	0.002
S13	98%	0%	2%	0%	0%	122	0.018	0.002
S14	2%	0%	98%	0%	0%	132	0.017	0.002
S15	0%	0%	0%	100%	0%	94	0.022	0.002
S16	47%	0%	28%	25%	0%	118	0.019	0.002
S17	49%	0%	32%	19%	0%	120	0.019	0.002
S18	81%	0%	19%	0%	0%	124	0.018	0.002
S19	100%	0%	0%	0%	0%	122	0.018	0.002
S20	0%	0%	0%	0%	100%	135	0.039	0.003
S21	0%	2%	1%	0%	97%	137	0.039	0.003
S22	0%	0%	0%	0%	100%	135	0.039	0.003
S23	0%	0%	0%	0%	100%	135	0.039	0.003
S24	0%	0%	0%	0%	100%	135	0.039	0.003
S25	0%	0%	0%	0%	100%	136	0.039	0.003
S26	0%	0%	0%	0%	100%	135	0.039	0.003
S27	0%	0%	0%	0%	100%	135	0.039	0.003
S28	0%	0%	13%	0%	87%	135	0.036	0.003
S29	5%	82%	13%	0%	0%	267	0.079	0.002
S30	0%	0%	100%	0%	0%	132	0.017	0.002
S31	0%	23%	0%	0%	77%	172	0.051	0.003

Attachment A – Supplemental Tables

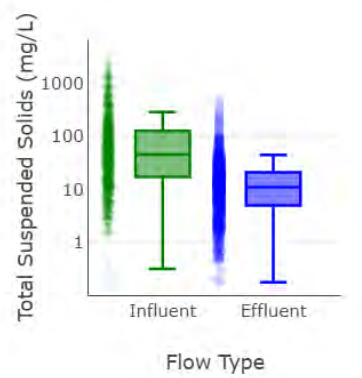
Catchment	Land Use Distribution					Representative Concentration, mg/L		
	Residential	**Industrial**	**Commercial**	**Public**	**Street**	**TSS**	**Cu**	**Pb**
S32	0%	0%	0%	0%	100%	135	0.039	0.003
S33	0%	45%	0%	0%	55%	207	0.063	0.003
S34	1%	0%	0%	0%	99%	135	0.039	0.003
S35	0%	0%	100%	0%	0%	132	0.017	0.002
S36	0%	100%	0%	0%	0%	297	0.093	0.002
S37	0%	100%	0%	0%	0%	297	0.093	0.002
S38	0%	100%	0%	0%	0%	297	0.093	0.002
S39	0%	100%	0%	0%	0%	297	0.093	0.002
S40	0%	70%	30%	0%	0%	247	0.070	0.002
S41	0%	1%	99%	0%	0%	134	0.018	0.002
S42	0%	73%	27%	0%	0%	252	0.072	0.002
S43	8%	0%	5%	1%	86%	134	0.036	0.003
S44	0%	0%	100%	0%	0%	132	0.017	0.002
S45	79%	5%	16%	0%	0%	132	0.022	0.002
S46	94%	0%	6%	0%	0%	122	0.018	0.002
S47	0%	88%	12%	0%	0%	278	0.084	0.002
S48	0%	100%	0%	0%	0%	297	0.093	0.002
S49	0%	15%	85%	0%	0%	157	0.029	0.002
S50	0%	100%	0%	0%	0%	297	0.093	0.002
S51	0%	0%	0%	100%	0%	94	0.022	0.002
S52	0%	39%	7%	54%	0%	176	0.049	0.002
S53	0%	0%	6%	0%	94%	135	0.037	0.003
S54	0%	100%	0%	0%	0%	297	0.093	0.002

Attachment A – Supplemental Tables

Table A-2. BMP Performance Summary Data from the International Stormwater BMP Database

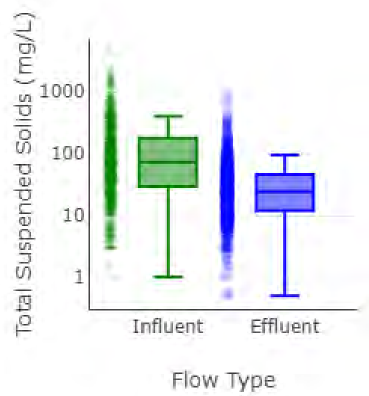
Bioretention, TSS

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	864	693	
Percent of NDs (%)	0	5	
25th Percentile (mg/L)	17	4.0	77%
*Median (mg/L)	45	10	78%
75th Percentile (mg/L)	127	20	84%
Mean (mg/L)	142	19	87%



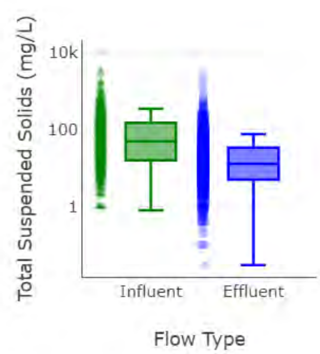
Permeable Pavement, TSS

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	901	700	
Percent of NDs (%)	0.44	1.29	
25th Percentile (mg/L)	29	12	59%
*Median (mg/L)	72	23	68%
75th Percentile (mg/L)	176	45	74%
Mean (mg/L)	176	44	75%



Wet Pond, TSS

Statistic	Influent	Effluent	Comparison
Number of EMCs	1201	1193	
Percent of NDs (%)	1	3	
25th Percentile (mg/L)	15	5	67%
*Median (mg/L)	49	12	75%
75th Percentile (mg/L)	149	33	78%
Mean (mg/L)	157	43	72%

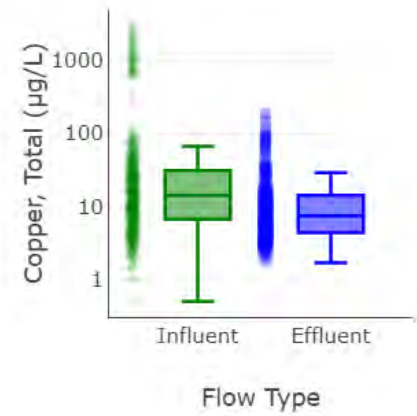


Note: Box plots show median (horizontal line), interquartile range (box limits), and fences (lower and upper quartiles minus and plus 1.5 times the interquartile range, respectively).

Attachment A – Supplemental Tables

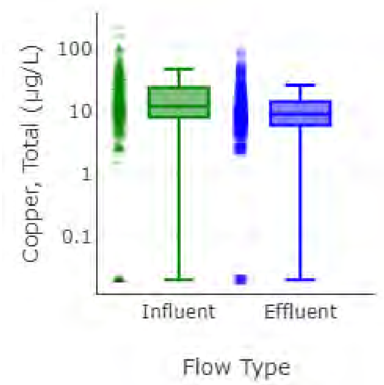
Bioretention, Total Copper

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	537	476	
Percent of NDs (%)	0.37%	2.5%	
25th Percentile (µg/L)	6.7	4.1	38%
Median (µg/L)	14.2	7.3	49%
75th Percentile (µg/L)	31	14	55%
Mean (µg/L)	129	16	87%



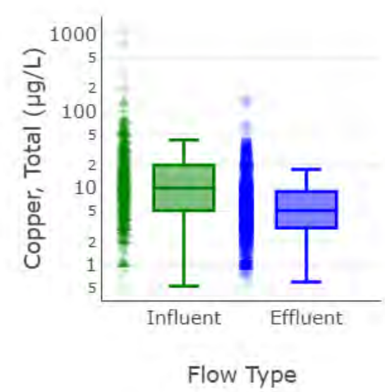
Permeable Pavement, Total Copper

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	551	392	
Percent of NDs (%)	2.2	11	
25th Percentile (µg/L)	8	5	38%
*Median (µg/L)	12	8	33%
75th Percentile (µg/L)	23	13	43%
Mean (µg/L)	19	12	39%



Wet Pond, Total Copper

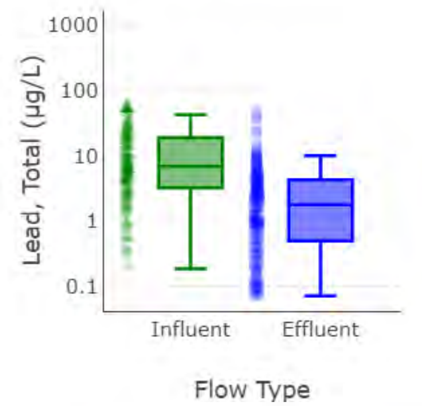
Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	938	926	
Percent of NDs (%)	9	17	
25th Percentile (µg/L)	5	3	40%
*Median (µg/L)	10	5	50%
75th Percentile (µg/L)	20	10	50%
Mean (µg/L)	20	8	60%



Attachment A – Supplemental Tables

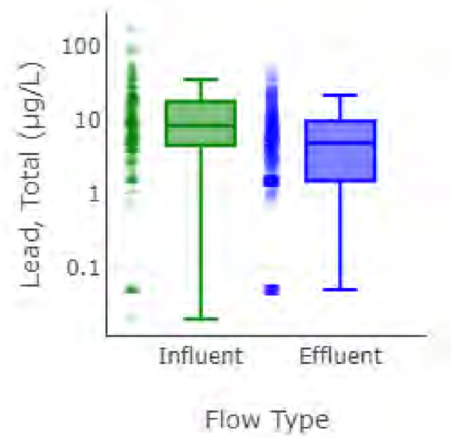
Bioretention, Total Lead

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	350	296	
Percent of NDs (%)	14	35	
25th Percentile (µg/L)	2.5	0.7	72%
*Median (µg/L)	6.0	1.6	73%
75th Percentile (µg/L)	16	3.4	79%
Mean (µg/L)	15	3.3	78%



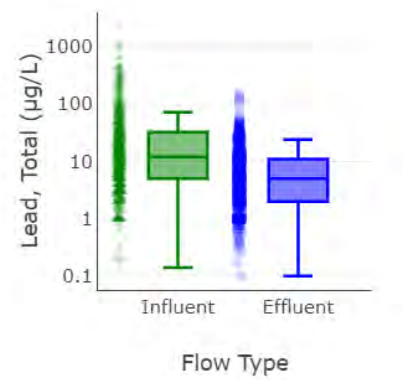
Permeable Pavement, Total Lead

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	529	377	
Percent of NDs (%)	38	50	
25th Percentile (µg/L)	2.5	1.5	40%
*Median (µg/L)	5.0	2.5	50%
75th Percentile (µg/L)	12	5.7	53%
Mean (µg/L)	11	5.3	50%



Wet Pond, Total Lead

Statistic	Influent Samples	Effluent Samples	Reduction in Concentration
Number of EMCs	836	858	
Percent of NDs (%)	19	28	
25th Percentile (µg/L)	3	1	67%
*Median (µg/L)	10	3	70%
75th Percentile (µg/L)	29	10	65%
Mean (µg/L)	39	8	79%



Attachment A – Supplemental Tables

Table A-3. Load Reduction by Catchment, 100% Participation Scenario

Catchment	Has LIDs?	Total Subcatchment Load Reduction Fraction		
		TSS	Total Copper	Total Lead
S1	yes	57%	57%	57%
S2	yes	47%	44%	45%
S3_a	yes	73%	69%	72%
S3_b	yes	48%	43%	45%
S3_c	yes	74%	72%	72%
S4	yes	26%	14%	18%
S5	yes	75%	75%	77%
S6	yes	75%	80%	50%
S7	yes	42%	33%	48%
S8	yes	57%	40%	48%
S9	yes	47%	27%	66%
S10	yes	50%	53%	52%
S11	yes	66%	56%	60%
S12	yes	29%	19%	23%
S13	yes	74%	64%	70%
S14	yes	50%	50%	50%
S15	yes	60%	68%	64%
S16	yes	21%	12%	39%
S17	yes	83%	80%	85%
S18	yes	65%	68%	67%
S19	yes	70%	73%	72%
S20	no	0%	0%	0%
S21	no	0%	0%	0%
S22	no	0%	0%	0%
S23	no	0%	0%	0%
S24	no	0%	0%	0%
S25	no	0%	0%	0%
S26	no	0%	0%	0%
S27	no	0%	0%	0%
S28	no	0%	0%	0%
S29	yes	14%	15%	5%
S30	yes	31%	17%	23%
S31	no	0%	0%	0%
S32	no	0%	0%	0%

Attachment A – Supplemental Tables

Catchment	Has LIDs?	Total Subcatchment Load Reduction Fraction		
		TSS	Total Copper	Total Lead
S33	no	0%	0%	0%
S34	no	0%	0%	0%
S35	yes	63%	45%	76%
S36	yes	79%	89%	64%
S37	yes	85%	86%	77%
S38	yes	89%	89%	81%
S39	yes	72%	72%	58%
S40	yes	57%	74%	42%
S41	yes	31%	16%	49%
S42	yes	64%	62%	67%
S43	no	0%	0%	0%
S44	yes	47%	28%	65%
S45	yes	30%	20%	44%
S46	yes	66%	68%	68%
S47	yes	51%	52%	49%
S48	yes	78%	80%	55%
S49	yes	76%	80%	74%
S50	yes	82%	88%	69%
S51	yes	52%	42%	73%
S52	yes	69%	67%	78%
S53	no	0%	0%	0%
S54	yes	28%	28%	28%

Appendix 10. Decision Support Tool Memo

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Memorandum

Date: June 24, 2021

To: Anna Bettis, MSUS PMP, Nature Conservancy in Arizona

From: Christian Nilsen, PE

Subject: DRAFT Options for development of a decision-support tool; City of Phoenix Low Impact Development Study

1. INTRODUCTION

The Bureau of Reclamation and The Nature Conservancy along with local partners the City of Phoenix, Flood Control District of Maricopa County, and Maricopa County Air Quality Department are working to identify and prioritize catchments in most need of Low Impact Development (LID)/Green Stormwater Infrastructure (GSI) improvements. This study is referred to as the Phoenix LID study in this technical memorandum. Partners and stakeholders have identified multiple objectives to be evaluated under this study. These objectives include reduction in urban flooding, improvements in stormwater quality, improvements in air quality, and reduction in urban health island effects.

Comparison of LID/GSI alternatives is a common challenge for stormwater planners. Studies often need to evaluate multiple goals using a mix of quantitative and qualitative criteria. In addition, diverse stakeholder preferences and values should be embedded within the decision-making process to defend decisions and justify investments in public infrastructure. For these reasons, stormwater managers often utilize Multi-criteria Decision Analysis (MCDA) methods to support decision-making to evaluate trade-offs of alternatives in a systematic and transparent manner.

This technical memorandum describes general MCDA approaches, and reviews available tools and methodologies for stormwater managers. It reviews the methodologies implemented for the Phoenix LID study and provides recommendations for choosing a decision support system for future studies.

2. MULTI-CRITERIA DECISION ANALYSIS

MCDA can be a useful tool for the selection of a preferred alternative when seeking to incorporate stakeholder values with engineering and scientific studies. It provides a structured methodology to balance scientific findings with qualitative goals and objectives. Figure 1 provides a general framework for the MCDA Process.

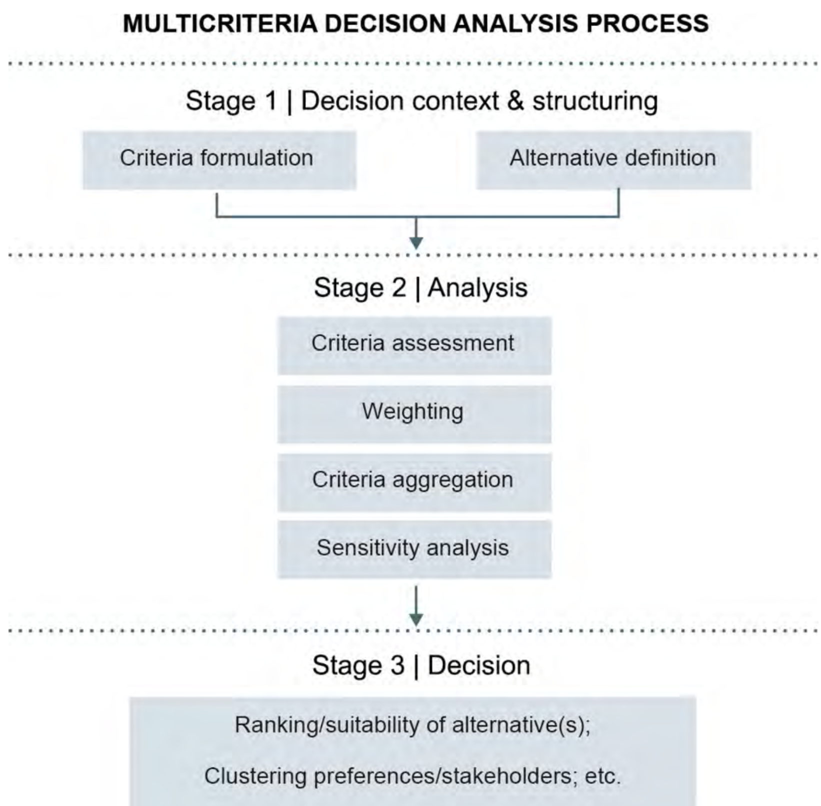

Figure 1. Generalized MCDA Process

From: *Adem Esmail, B, Geneletti, D. Multi-criteria decision analysis for nature conservation: A review of 20 years of applications. Methods Ecol Evol. 2018; 9: 42– 53*

As shown above, the MCDA process can be divided into the following steps:

- Stage 1 – Decision context & structuring
    - Criteria formulation – Identification of measurable benchmarks to evaluate possible alternatives against.
    - Alternative definition – Development of alternatives to consider to meet study objectives.

- Stage 2 – Analysis
    - Criteria Assessment – Quantification of the performance of alternatives against criteria. This stage is typically informed by models or calculations.
    - Weighting – Assigning relative importance of each criterion based on stakeholder inputs.
    - Criteria Aggregation – Combination of weights and criteria to assess the overall performance of each alternative.
    - Sensitivity Analysis – Evaluation of the relationships between inputs and results. This step can be especially important when large uncertainty exists in criteria Assessment
- Stage 3 – Decision
    - Ranking/Suitability of alternatives – Using the information from previous steps to rank alternatives, leading to the preferred alternative.
    - Clustering of preferences – An optional step to gain further insight on decisions by grouping stakeholder preferences or broadening the number of stakeholders.

3. PHOENIX LID STUDY DECISION SUPPORT PROCESS

The Phoenix LID study performed its decision analysis in two phases: 1) Identification of priority watershed, and 2) evaluation of alternatives related to the level of LID adoption.

3.1 Identification of priority watershed

The study team performed an initial prioritization using spatial data to determine the highest priority watershed to study stormwater interventions.

3.1.1 Criteria and weighting

This evaluation used the methodology shown in Table 1 to assign metrics for each identified criterion.

Table 1. Criteria and Metrics adopted for the Phoenix LID Study

Criterion	Metrics
Flooding	Average Runoff, number of flooding hotspots
Heat	Median surface temperature
Stormwater quality	Proportion of Industrial Land use, Traffic Volume
Air quality	Particulate Matter (PM10), Ozone

Next, a study team was convened to provide input on preferred weights of criteria. From that assessment, the following weights were assigned to criteria:

3.1.2 Clustering preferences/reranking

The study time then included assessments based on professional judgment, environmental justices, legacy contamination, infiltration, land use, and catchment size. Information from subsequent public stakeholder meetings was incorporated to arrive at the final priority catchment selection.

3.2 Alternatives Analysis

Once a preferred catchment was selected, the Phoenix LID stakeholder group identified alternatives based on the level of adoption of LID in the priority catchment. These alternatives were then evaluated against the criteria identified in the catchment selection phase to assess the performance of each alternative.

4. REVIEW OF AVAILABLE TOOLS

4.1 General MCDA and approaches

In general, the two most common types of MCDA approaches used in natural resources studies can be classified as value-based or outranking methods.

Value-based methods use quantitative measurements to determine if criteria are fulfilled, and weight those criteria based on stakeholder preferences. This is the most common approach due to its ease of understanding and ease of implementation. The most common type of value-based method is a weighted-sum method. This is the approach used in the catchment prioritization step of this study.

Outranking methods use pairwise comparisons of each alternative/criteria combination to find the strength of preferring one alternative over another. An added strength of this method is that it can account for indifferences and incompatibilities among alternatives. However, this methodology is not as readily understood by non-practitioners and is not used as widely as value-based methods.

4.2 Stormwater Specific tools

Several stormwater-specific decision support tools are available to help stormwater practitioners prioritize actions for stormwater. These tools have stormwater functions

4.2.1 Integrated Decision Support Tool (iDST)

The Integrated Decision Support Tool (iDST), provides a modeling and optimization framework of stormwater control measures. Optimization is based on the calculation of life-cycle costs, including avoided costs of grey infrastructure. Benefits are evaluated based on the monetization of life-cycle costs and environmental costs/benefits.

iDST is being developed by a team that includes university researchers and the Nature Conservancy. It is in the final stages of development, although some modules are currently available.

4.2.2 Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs (CLASIC)

Like iDST, the Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs (CLASIC) tool uses a life-cycle cost framework to calculate the benefits of SCMs. It estimates peak-flow reduction and water quality improvement to assess the performance of scenarios. It calculates scores for select co-benefits including economic, social, and environmental benefits. These are used in an integrated MCDA module to help prioritize alternatives. It is intended to be used as a screening tool and does not provide site-specific design of SCMs.

4.2.3 System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN)

The System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), is a modeling-focused tool that combines modules related to watershed processes, SCM processes, and stormwater conveyance networks with a cost-optimization module. It does not directly calculate co-benefits, but can be used alongside other tools to do so.

4.2.4 Comparison of existing tools

Table 1 provides a summary of existing tools reviewed for this technical memo.

Table 2. Summary of Existing Tools

Tool	Intended Application	Modeling Engine	Co-benefits assessed	MCDA Methodology	Homepage
CLASIC	Watershed scale	SWMM	Economic (avoided infrastructure costs; costs from illnesses, impacts from nuisance floods, property values,) Social (Air quality, mental health, urban heat) Environmental (Ecosystem services, groundwater flow, carbon sequestration)	Value-based weighted-sum; includes lifecycle costs	https://clasic.erams.com/
iDST	Watershed scale; site scale	SWMM	Environmental, Economic, Institutional, and Social Categories	Value-based MCDA; Includes criteria assessment. Does not include weighting.	https://idst.mines.edu/
SUSTAIN	Watershed scale, site scale	SWMM, HSPF	Cost optimization only	Cost optimization only	https://www.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain

5. CONCLUSIONS AND RECOMMENDATIONS

Several approaches to structured decision-making for stormwater have been presented in this technical memorandum. Although these approaches vary in their complexity and implementation, they follow a general framework for arriving at a ranked alternatives list based on explicitly defined criteria. When selecting a decision support framework, it is important to identify tools and methodologies that allow decision-makers to understand the tradeoffs of selecting alternatives.

The Phoenix LID Study followed a frequently applied approach for evaluating and prioritizing alternatives for green stormwater infrastructure. Alternatives and criteria were objectively developed, weighting was informed by stakeholder values, and ranking followed a structured methodology. Although some of the approaches identified in this memo can help quantify criteria, and add structure to decisions, no additional decision support system is recommended for the Phoenix LID study.

If this study were to expand in scope, or if additional studies were to be conducted, study proponents should follow these recommendations to select a decision support system:

- Identify the scale of the study. Are general watershed-scale approaches adequate, or do site-specific SCMs need to be identified?
- Identify important co-benefits. Criteria should be targeted to the benefits and co-benefits that are most important to stakeholders. Select an approach that incorporates methods to adequately estimate these.
- Identify who will be making the ultimate decision. Decision support systems should give proponents, stakeholders, and public officials. the tools to make the best-informed decisions. Decision-making for public infrastructure is multi-faceted, involving community, regulatory and political drivers. Tools should inform decision-makers - not make decisions for them.
- Evaluation and ranking of alternatives should be as transparent as possible, with input from diverse stakeholders – especially those who will be most affected by decisions. Ultimately the choice of a specific tool is not as important as listening to stakeholders and choosing based on a clear understanding of their objectives and values.

* * * * *