Designing and Implementing Ecological Monitoring of Aridland Urban Ecological Infrastructure (UEI): A Case-Study of Design Process and Outcomes

by

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ABSTRACT

Cities are increasingly using nature-based approaches to address urban sustainability challenges. These solutions leverage the ecological processes associated with existing or newly constructed Urban Ecological Infrastructure (UEI) to address issues through ecosystem services (e.g. stormwater retention or treatment). The growing use of UEI to address urban sustainability challenges can bring together teams of urban researchers and practitioners to co-produce UEI design, monitoring and maintenance. However, this co-production process received little attention in the literature, and has not been studied in the Phoenix Metro Area.

I examined several components of a co-produced design process and related project outcomes associated with a small-scale UEI project – bioswales installed at the Arizona State University (ASU) Orange Mall and Student Pavilion in Tempe, AZ. Specifically, I explored the social design process and ecohydrological and biogeochemical outcomes associated with development of an ecohydrological monitoring protocol for assessing post-construction landscape performance of this site. The monitoring protocol design process was documented using participant observation of collaborative project meetings, and semi-structured interviews with key researchers and practitioners. Throughout this process, I worked together with researchers and practitioners to co-produced a suite of ecohydrological metrics to monitor the performance of the bioswales (UEI) constructed at Orange Mall, with an emphasis on understanding stormwater dynamics. I then installed and operated monitoring equipment from Summer 2018 to Spring 2019 to generate data that can be used to assess system performance with respect to the co-identified performance metrics.

The co-production experience resulted in observable change in attitudes both at the individual and institutional level with regards to the integration and use of urban ecological research to assess and improve UEI design. My ecological monitoring demonstrated that system performance met design goals with regards to stormwater capture, and water quality data suggest the system's current design has some capacity for stormwater treatment. These data and results are being used by practitioners at ASU and their related design partners to inform future design and management of UEI across the ASU campus. More broadly, this research will provide insights into improving the monitoring, evaluation, and performance efficacy associated with collaborative stormwater UEI projects, independent of scale, in arid cities.

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1.1 General Introduction

As cities grow larger in both population and spatial extent, so has the strain they put on resources and infrastructure (Grimm et al. 2008; Grove 2009; Childers et al. 2015). As an example, water resources and related infrastructure in aridland southwestern US cities face growing challenges related to extreme events, and decreasing water supply and increasing demand (Larson et al. 2013). Cities cope with these challenges through the use of infrastructure – the components of urban systems that provide the services essential to sustain critical social and biophysical systems (Neuman and Smith 2010). Traditionally these approaches have largely consisted of "gray" infrastructure approaches—engineered infrastructure that is designed to be fail-safe and to control environmental hazards within constrained limits (Ahern 2011, 2013). However, grey infrastructure approaches are increasingly met with issues associated with adaptive rigidity and systemic failure in the face of increasingly uncertain climate and record-setting hazardous events.

In response, many cities are increasingly using "design with nature" solutions, and engaging the "design-ecology nexus" (sensu Childers et al. 2015). These solutions leverage the ecosystem functions associated with existing or newly constructed ecosystem structures to provide a service or benefit to people (Grimm 2016). Many different terms exist to classify these ecosystem service-based approaches including "green", "nature-based", "hybrid" and others (Hansen & Pauleit, 2014, Andersson et al., 2014, Grimm 2016). In the interest of maintaining focus on the urban and ecological processes associated with this infrastructure, I will be referring to it instead as urban ecological infrastructure (UEI) (Childers et al. in review). This emerging classification simply defines UEI as any component of a city that is capable of supporting ecological structure and function, and thus providing ecosystem services. Importantly, this broad definition expands on the traditional terrestrial-based definition of green infrastructure to also include aquatic (blue) and wetland (turquoise, *sensu* Childers et al. 2015) features. Examples of UEI include bioswales, treatment wetlands, shade trees, urban parks, and residential yards, and even front porch flower pots. In addition, UEI and the ecosystems associated with it often have novel structure and function relative to their non-urban counterparts (McDonnell and Pickett 1990). UEI has several key characteristics, which include: 1) typically some level of human management of ecological structure and function, 2) ubiquity in the urban landscape, 3) the provision of a variety of services (and disservices) (Larsen et al. 2015, Grimm et al. 2016), and 4) high potential for adaptive capacity relative to gray infrastructure approaches.

The growing use of UEI to address urban sustainability challenges often brings together teams of urban researchers and practitioners to co-produce UEI design, monitoring and maintenance. However, this co-production process has received little attention in the literature, and has not been studied in the Phoenix Metro Area. To address this, I examined several components of a co-produced design process and related project outcomes associated with a small-scale UEI project – bioswales installed at the Arizona State University (ASU) Orange Mall and Student Pavilion in Tempe, AZ. Specifically, I explored the social design process and ecohydrological and biogeochemical outcomes associated with development of an ecohydrological monitoring protocol for assessing post-construction landscape performance of this site.

Decision-makers and practitioners that fund and manage UEI projects are often interested in evaluating or measuring the benefits that stakeholders receive from these projects (Felson and Pickett 2005). However, they often do not have the resources to do so. Not coincidentally, UEI is increasingly a focus of study for urban ecological research agendas. Most notably, the growing movement towards an ecology *for* cities approach in urban ecological research advocates for a strong transdisciplinary integration of principles and practice related to urban design, resilience, and sustainability (Childers et al. 2015, Grove et al 2016, Pickett et al. 2016). This emphasis on deep integration across disciplines and problem-oriented research has also more recently been described as convergent or translational research (NSF 2018). As the convergence among urban ecologists, designers, and practitioners around UEI is increasing, so are needs and calls for more extensive research on these collaborative approaches, and more active involvement of urban ecology in the design and management of sustainable urban ecological systems (Lawton and Jones 1995, Felson et al. 2013, Steiner et al. 2013, Grose 2014).

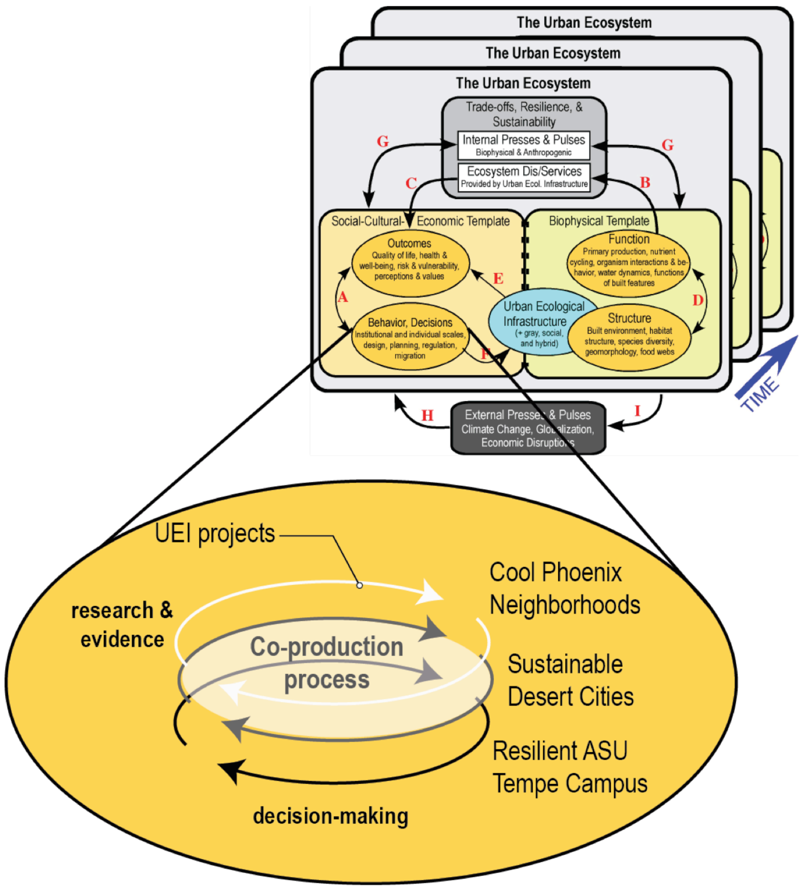
Importantly, the overlap of knowledge needs and research interests means that UEI projects often involve collaboration between urban practitioners and researchers to co-produce elements of both design (layout, materials, form, expectations) and research (questions and outcomes, experimental design). Important potential outcomes from this approach are: 1) rigorous translational processes that enhance and build adaptive and/or institutional capacity around UEI; 2) increased UEI efficacy; and 3) broader urban adaptive capacity, resilience, and sustainability (Armitage et al. 2011; Albrechts 2013; Voorberg et al. 2014).

Urban design is being increasingly integrated into urban research agendas. As an example, urban design is now a key interdisciplinary research theme (IRT) for the latest iteration of the Central Arizona Phoenix Long Term Ecological Research Program (CAP LTER 2018). CAP LTER's Urban Design IRT emphasizes a focus on integrating ecological and social science into the decision-making processes related to UEI (CAP LTER 2018). This includes explicit goals to co-produce data and results with practitioners and stakeholders, and utilize this information to power iterative feedback loops to support decision-making around the design, construction, and management stages of UEI development (see Figure 1).

Practitioners are also increasingly integrating and codifying these collaborative principles into UEI projects. This can take place via project certification programs that organizations managing UEI are pursuing. One such example is the Sustainable Sites Initiative (SITES). SITES is a certification program which emphasizes an alignment of land design and development practices with the protection and enhancement of ecosystem services (Lady Bird Johnson Wild Flower Center 2014). Most importantly, SITES and programs like it explicitly require the collection of ecological and hydrological data to assess pre-existing site conditions (e.g. ecosystem structure), project impacts, and post-construction performance (e.g. ecosystem function). SITES credit C9.3 also specifically emphasizes a collaborative, interdisciplinary approach to the data collection and evaluation process. As these frameworks for understanding UEI continue

Figure 1.

The CAP LTER Design IRT Conceptual Framework.



to gain traction, collaborative approaches to ecological monitoring of UEI will be increasingly important going forward.

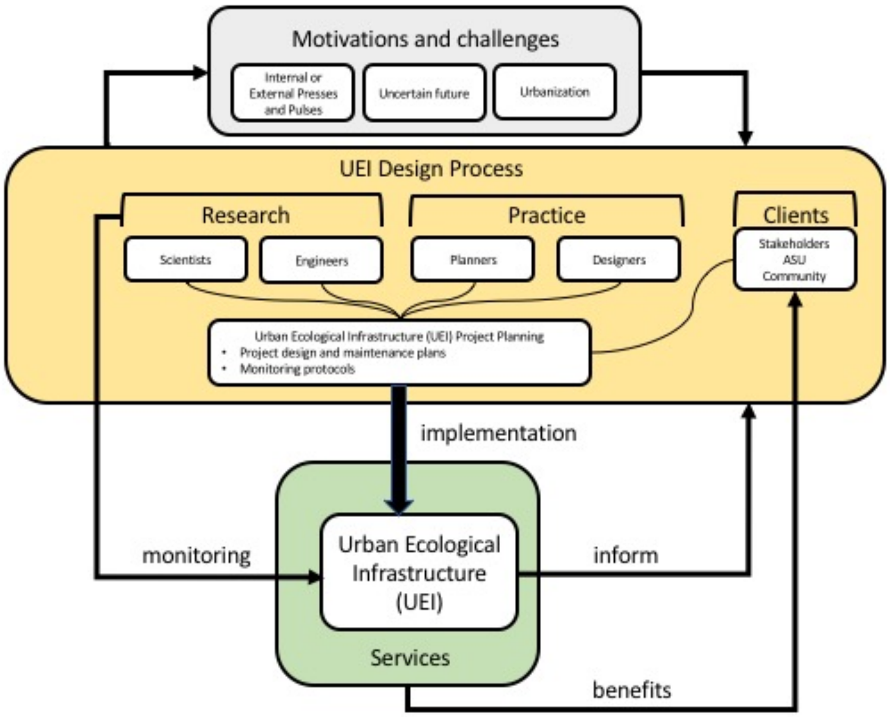
1.2 Knowledge Gaps and Conceptual Framework

In practice, urban researchers and practitioners have been working together for quite some time (Grose 2014). Many landscape architecture firms have staff with some degree of ecological training, and “designed experiments” conducted in conjunction with urban designers are an increasingly common approach in urban ecological research (Felson and Pickett 2005). Further, landscape designers and managers often cite an intuitive orientation towards UEI-based approaches, and the systems that urban ecologists study often include these highly designed and managed ecological features. As such, recent calls in the urban ecological literature for collaboration and research at the ecology-design nexus (e.g. Childers et al. 2015, Grove et al. 2016) may instead reflect persistent gaps in foundational understanding around how these processes unfold—how different actors conceptualize, navigate and contribute to the design process and to the co-production of knowledge. Because UEI is designed, built, and managed by people, the social processes driving project design, management and monitoring are critical to understanding or predicting ecosystem service outcomes from UEI projects. Recognizing that there is no one size fits all design method or process (Grose 2014), my research examined these phenomena within a particular case study to discover social and ecological processes and best practices that apply to UEI more broadly.

Beyond the practice and processes of design, knowledge gaps about the process of evaluating UEI project performance also persist. The relatively novel ecological structure, function, and urban contexts of many UEI projects create a need for co-produced ecological research to meet the site-specific knowledge needs of UEI designers and managers, and to advance urban ecology in general. As an example, we know surprisingly little about how particular configurations of UEI (e.g. novel bioswale designs) perform relative to their traditional gray infrastructure counterparts. Further, emerging research on UEI performance in aridland settings compared to mesic cities suggests that novel processes in dry climates may have significant impacts on system performance (Weller et al. 2016, Sanchez et al. 2016, Bois et al. 2017). Finally, few studies exist about the social processes that drive UEI design, management and monitoring outcomes (Armitage et al. 2011). In the context of the convergence between UEI research and practice, these gaps outline a translational research approach that I utilized to frame my central research question: *How does collaboration and co-production around aridland UEI monitoring unfold, and how does this collaborative process impact outcomes for UEI performance and evaluation?*

Figure 2.

Conceptual framework. My framework illustrates the co-production processes associated with UEI design, maintenance, and monitoring. My research will document the co-production process associated with the development of the monitoring protocol (yellow box, below), as well as to apply the protocol (monitor) and generate useful ecohydrological and biogeochemical data about project performance (inform).



My conceptual framework (Figure 2) provides a roadmap to address these knowledge gaps and operationalize research by mapping the phases of the design process and applying them to a specific case study. My research specifically focused on understanding the connections between the processes of UEI project planning (yellow box, Figure 2) and UEI monitoring (bottom-left arrow, Figure 2). Further, an explicit emphasis is placed on integrating outcomes of research and monitoring efforts (data and results) back into maintenance and management of the UEI projects being studied by developing collaborative partnerships with practitioners. In doing so, this framework contributes to understanding key points of intervention in the design process for the integration and use of socio-ecological research by putting them into practice. I used a combination of qualitative and quantitative methods to produce a holistic understanding of the design process and design outcomes related to project monitoring, and address these two specific research questions: 1) RQ1: Design Process: What are the processes and outcomes associated with the co-production of a monitoring protocol for a stormwater UEI project?; and 2) RQ2: Design Outcomes: How well does a stormwater management UEI project meet performance goals?

My research was motivated by my interest in understanding how UEI serves as a space of collaboration and knowledge production for urban researchers, designers, practitioners, and the public. I conducted this study in partnership with other stakeholders to allow the establishment of meaningful collaborative relationships which drive the "back end" of the iterative design feedback loop ("inform" in Figure 2). This allows for research and data to be used to iteratively improve UEI design and performance, even after a project has moved past the design and construction phases. Further, these relationships enable deeper, long-term integration of research at key intervention points to support future UEI projects.

More broadly, I am interested in contributing to the understanding and improvement of UEI design and performance in the PMA. By better understanding the mechanisms and processes associated with research and design co-production, this project contributes insights towards building adaptive capacity and improving performance efficacy of UEI projects. These include better understanding of the drivers, challenges and opportunities associated with the integration of research into UEI design and management, and the outcomes and best practices associated with co-production between UEI researchers and practitioners. More broadly, my work will support more effective UEI design and management in arid cities, and contribute to a better understanding of the design-ecology nexus.

1.4 ASU Orange Mall: A Case Study

The Arizona State University (ASU) Tempe Campus is located in the city of Tempe, AZ, centrally situated within the broader geographical context of the rapidly expanding greater Phoenix Metropolitan Area (PMA) (Figure 3). As of Fall 2017, the Tempe Campus was the primary home to approximately 52,000 enrolled students, and nearly 10,000 faculty, staff and administrators (ASU 2017). As such, ASU is one of the largest universities in the United States in terms of enrollment, personnel, and land area. This means that the physical size and scale of activity of the campus and the organizations which manage it provide broad comparability to analogous structures in cities and municipalities. Further, my research methods used to understand the design process and monitor UEI performance are built on common practices that provide comparability to other UEI sites, such as those studied by CAP LTER.

For nearly a decade, ASU has championed a strong mandate for sustainability awareness and education, incorporating sustainability themes into curriculum, branding, and university practices across its campuses. More recently, ASU has begun to incorporate sustainability principles into the physical structure of the campus. This is being accomplished through designing and incorporating new ecological structures and increased ecosystem function into the physical infrastructure of the campus, largely through the integration of UEI into current and future redevelopment projects. To support this work, ASU has chosen to pursue Sustainable SITES certification for these projects as well as for future landscaping projects across the university. While not all projects will ultimately become fully SITES certified, SITES guidelines have been explicitly acknowledged as guiding principles for all future landscaping development efforts across the ASU campuses. The first of these projects, the redevelopment of the Orange Mall, will serve as a case-study of UEI monitoring design and implementation.

In 2016, Arizona State University (ASU) began an effort to redevelop Orange Street, a high-traffic thoroughfare in the heart of the Tempe Campus in Tempe, AZ. Historically, Orange Street was a paved asphalt road largely used by automobiles, with foot traffic relegated to sidewalks. Orange Mall was identified by ASU as a high priority point of intervention to begin implementing sustainable UEI features into the campus due to its central location, high visibility, and large volume of foot traffic. Further, the Orange Mall area has historically served as a key drainage point for an 18-acre watershed extending north from Orange Mall across the campus. This hydrologic convergence resulted in drainage issues and on-going flooding at the Orange Mall site – a key impetus for the implementation of UEI.

The Orange Mall redevelopment project transformed the existing paved asphalt road (Orange Street) into a shaded pedestrian mall. This project coincided with the construction of the new Student Pavilion building, at the northwest corner of the Orange Mall. Initial planning and design phases for this project began in June 2016, and construction began in March 2017. Construction of landscape features associated with this project were completed by October 2017 (see Figure 4).

The design goals of the project included 1) social activation of the space via a variety of pedestrian-friendly structures such as benches, tables, lighting and power-outlets; 2) increased ecohydrological function via features such as vegetation and bioretention basins (bioswales) to capture and reuse stormwater for passive irrigation; and 3) management of site microclimate. In tackling the latter problems, practitioners, and other stakeholders involved in the redesign project emphasized a UEI-based solution that was focused on maximizing ecosystem functionality, sustainability, and resilience.

Additionally, an explicit overarching goal for project was to achieve Sustainable SITES certification. The process of applying for SITES certification for this project required the collaborative development and implementation of an ecohydrological monitoring protocol to evaluate post-construction landscape performance, the focus of this case-study. SITES credit C9.3 requires reporting of the monitoring protocol, the methods used to develop and implement it, results, and, interestingly, examples of how data were used to correct and improve UEI design (Lady Bird Johnson Wild Flower Center 2014). This co-production process took place across meetings held in Spring

2018, and monitoring equipment were procured and installed in Summer 2018. I participated in these meetings, contributed to the co-production process, and led the corresponding research and monitoring efforts.

Figure 3.

Location of study site within the city of Tempe, AZ

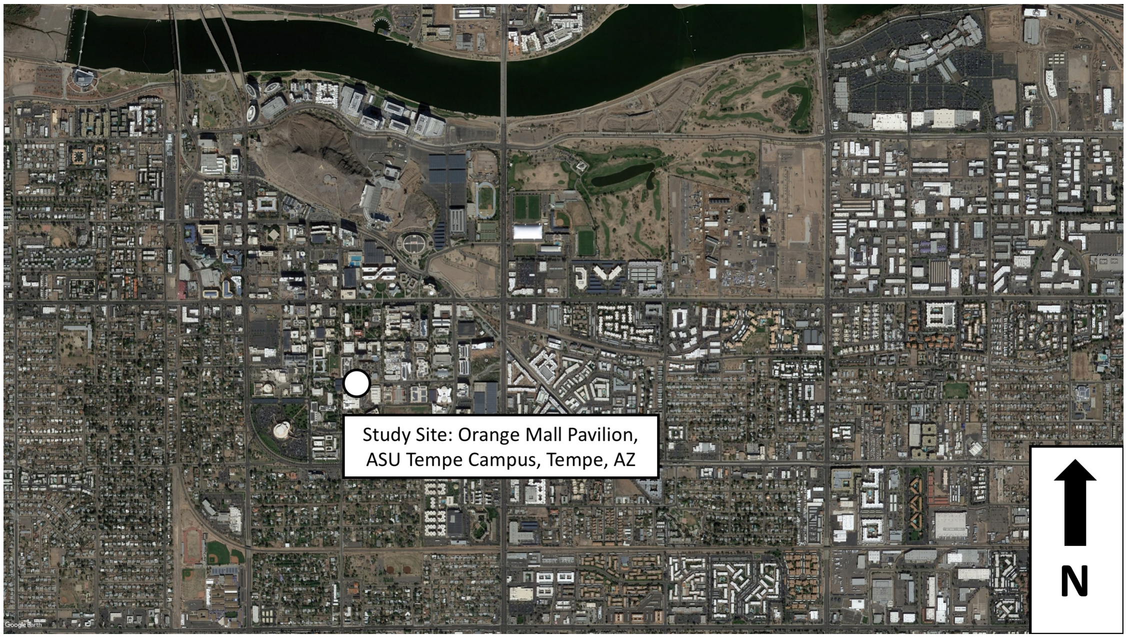


Figure 4.

Aerial imagery showing the ASU Orange Mall before (left) and after (right) construction.

METHODS

2.1 Site description

The redeveloped ASU Orange Mall is comprised of concrete and pavers interspersed with stand-alone vegetation and planted bioretention basins. The development introduced 525 m^2 of bioretention basin and ground cover, an approximate 12% increase in the overall amount of permeable surfaces across the site. The site contains a total of 7 basins, which are divided into two primary (east and west) basin systems (Figure 5).

The western half of the site contains 3 smaller basins – numbered west basin 1 through 3 (WB1-WB3), which are 90, 40, and 15 m^2 in size, respectively (total = 145m^2). The eastern half of the site contains 4 larger basins – labeled east basins 1 through 4 (EB1-EB4), which are 165, 110, 20, and 85 m^2 in size, respectively (total = 380m^2). Basins in each of the two subsystems are connected to each other by a series of shallow runnels that channel water between the individual basins with each system. An elevation gradient directs flow from both the east and west basin systems to converge at a final central collection box, where all stormwater combines and flows south via a concrete pipe to an off-site below-ground cistern. A variety of desert adapted native vegetation species (n = 11) were planted across all of the Orange Mall basins. Roughly 80% of the population is comprised of individuals from 5 species: Fan West Ash (*Fraxinus 'Fan-West'* hybrid), Tall Slipper Plant (*Pedilanthus bracteatus),* Desert Spoon (*Dasylirion wheeleri),* Mexican Petunia (*Ruellia brittoniani),* and Compact Jojoba (*Simmonsdsia chinensis 'vista')*.

Surface inflows to the basins are varied and dispersed. EB1 and EB2 both receive significant point-source inputs at their eastern terminus from curb cuts that drain surface flow from the remainder of Orange Street, while WB1 receives significant inputs from Student Pavilion roof drainage and asphalt roads to the north. However, the basins also receive inflow from surface runoff flowing off all of the concrete surfaces that surround them, making an accurate estimate of total inflow volumes or rates difficult. I installed monitoring equipment and positioned them to provide insights into the general hydrological dynamics of the site. These include characterizing water flow through the system and changes in water quality as water flows through each of the two systems of basins.

Figure 5.

The experimental design for the ecohydrological monitoring at Orange Mall.

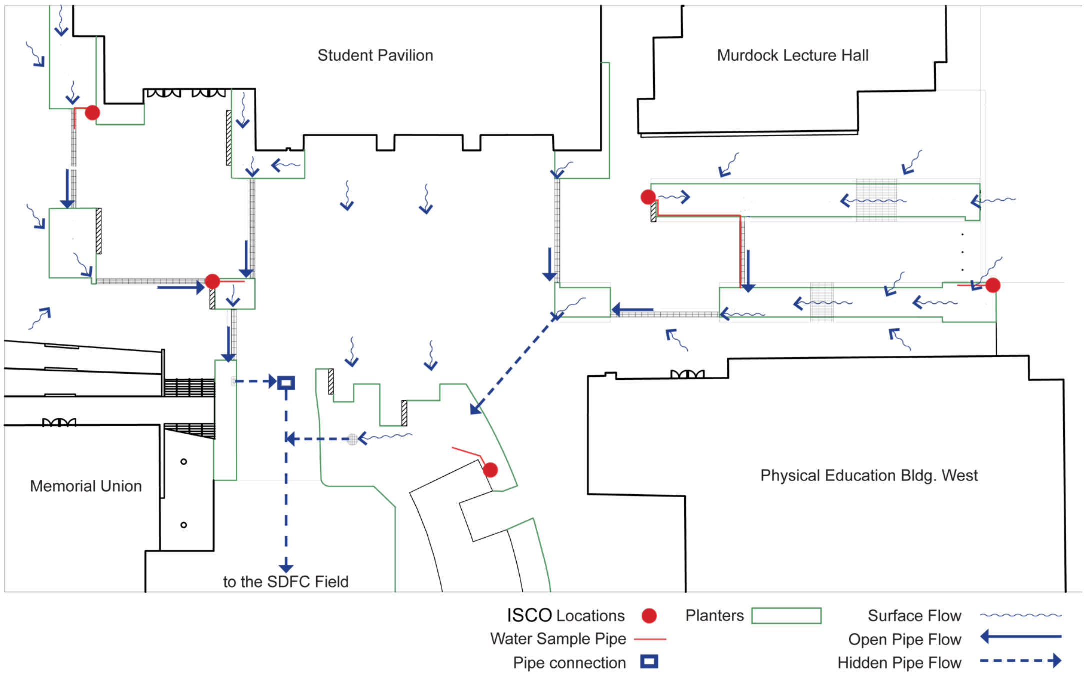
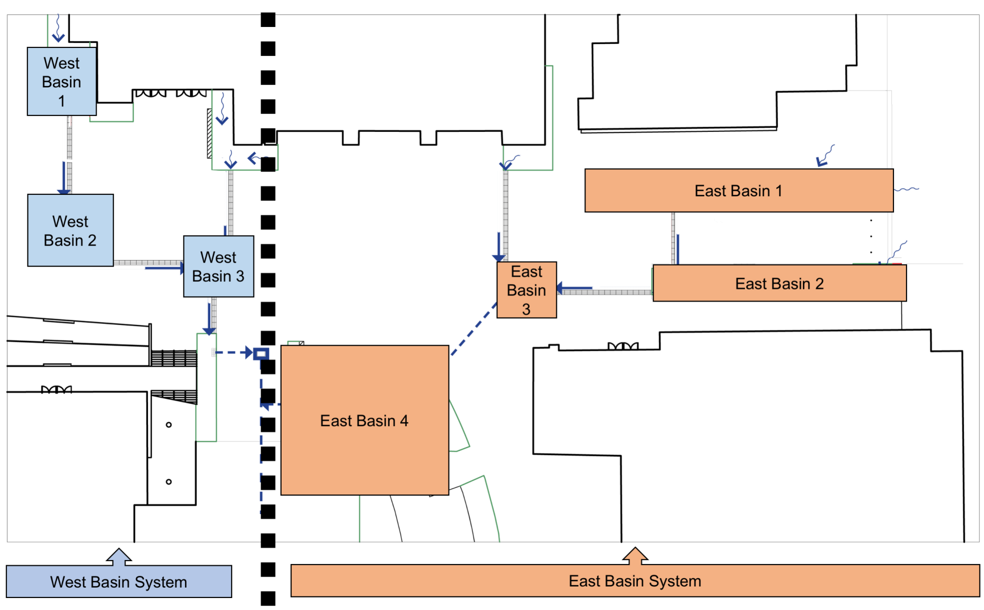


Figure 6.

Simplified experimental design. This rendering of experimental design shows the two major basin systems of Orange Mall.



2.2 - RQ1: The Design Process

In addition to ecological monitoring, qualitative methods were utilized to characterize the design process. In conjunction with the site-based field monitoring, these methods enabled a holistic understanding of how the system was designed, how the research protocol was developed, and the corresponding data on performance and design outcomes.

The actors that I studied in this stormwater UEI project fit into one of two categories: urban researchers or urban practitioners. Urban researchers included academic or research-based actors who work in the fields of urban ecology or urban design (e.g. faculty and students of ASU and CAP LTER). I defined urban practitioners as the non-academic actors, such as ASU designers or decision-makers and external consultants who are associated with decision-making related to this UEI project. While other groups, including sub-contractors, private organizations or community members and students, may have been important stakeholders and tangentially involved in or affected by this UEI project, my definition focused in on the dominant groups and institutions that were involved in the key design decisions of this project. Importantly, this particular case-study was and the methods I used were limited in scope to collecting data on the post-construction monitoring implementation and feedback phases (Figure 2).

Two primary qualitative data collection methods were utilized to study the design process related to the development of the monitoring protocol. First, during all meetings in Spring 2018 when the monitoring protocol and research design were being co-produced, I conducted participant observation of the dynamics between researchers and practitioners. During these meetings, researchers and practitioners worked together to co-produce a monitoring protocol that would be used to evaluate the performance of UEI at Orange Mall and generate data to fulfill SITES reporting mandates. Participant observation of these meetings included tracking various developments, participant dynamics and attitudes, and decision-making processes taking place in these meetings. Importantly, I was an active participant in this process. This included leading the discussion of possible research design and sampling options on behalf of the researchers. As such, my participant observation also included self-reflection on the experience of co-producing research with design practitioners.

Secondly, semi-structured, in-depth interviews were conducted with key research and practitioner personnel. My interview instrument was based on a more general CAP LTER Design IRT interview instrument that I developed with leaders and members of the CAP Design IRT in Summer 2017. My Orange Mall interview instrument operationalized these themes and included questions specific to my research interests for this UEI case-study (see Appendix A for interview instrument). Interviews were between 40-50 minutes in length, and focused on understanding the subjects' past experiences with UEI, the Orange Mall project narrative, unpacking the project and monitoring design process, and feedback on the motives, challenges and opportunities associated with UEI design (see Appendix B for details). Subjects interviewed include 1) ASU/CAP LTER researchers, 2) ASU designers and facilities management personnel, and 3) external consultants, landscape architects and engineers from consulting firms. I recorded interview audio with consent from participants, and interview recordings were transcribed. For all interviews, detailed notes were also taken on participant attitude and body language. For one interview where consent to recording was denied, notes were the sole source of interview data. Finally, I conducted these interviews with key project participants until saturation was reached and no new significant information was emerging.

I utilized an open coding framework for my initial review and content analysis of these interviews (Elo and Kyngas 2008). In this initial review I identified major emergent themes and developed an initial codebook. A second coding review was then conducted utilizing a provisional approach that uses specific co-production knowledge gaps as identified by the CAP LTER Design IRT and in the ecology-design literature to refine the codebook and content analysis. Finally, an intercoder reliability check was conducted utilizing a 10% coding sample to verify the validity of the codebook prior to final analysis. All content analysis was conducted using NVivo 12 Mac (Version 12.3.0, https://www.qsrinternational.com/nvivo/home). Importantly, all methods and protocols were submitted to and approved by the ASU Institutional Review Board (IRB; see Appendix A).

2.3 - RQ2: Design Outcomes

Throughout Spring 2018, researchers and practitioners worked together in workshop-style meetings to discuss and develop a monitoring protocol to assess site performance and design outcomes. The protocol included ecological, hydrological, and biogeochemical metrics that met the needs of my research goals, as well as data needs for SITES reporting (see Table 1 below). Unless otherwise noted, all analyses were conducted using R (version 3.3.3., http://cran.r-project.org/).

Table 1.

Co-produced Orange Mall ecological field monitoring protocol.

Data type	Metric	Equipment	Method
Hydrology	Water Quality	ISCO 6700/6712 auto-sampler + ISCO 720 bubbler module	Sample collection triggered by rain
	Water Quantity	V-notch weir + ONSET water level autologger	Autologging probe
Ecology	Transpiration	LICOR 6400XT Infrared Gas Analyzer (IRGA)	Direct, leaf-level measurements
	Climate	EarthNetworks and MCFDX meteorological stations	Data access/download
Biogeochemistry	Soil moisture	ONSET 10HS Soil Moisture Smart Sensor	Automatic data logger

2.3a - Water Quality

Designers and managers of the Orange Mall system were interested in achieving stormwater quality improvement for stormwater flow not being directly captured and retained within the basins. To measure this, I used five ISCO® 6712 automated pump samplers to collect up to 9 discrete stormwater samples per sampler during storm events between August 2018 and March 2019. I installed ISCO samplers at the inflow and outflow of the western half of the site, and at the inflow, mid-point, and outflow of the eastern half of the site (n = 5) (see Figure 5 for installation details). ISCO intake sampling lines were installed in the curb cuts or runnels providing inflow or outflow to the basins so that only flow between basins would be sampled, as opposed to standing water in the center of a basin. ISCO® 720 bubbler modules were installed and used to measure water stage and trigger sample collection based on water stage; bubbler lines were installed parallel to the ISCO® 6712 sampling lines. The samplers were programmed to draw samples at a water stage of 3.13cm or greater - the minimum depth required to inundate the strainer at the end of the sample line. The samplers were also programmed to sample at non-uniform fixed time intervals, with sampling occurring more frequently during the beginning of storms when water quality was expected to change most rapidly (i.e., first-flush effect; Lee et al. 2002). These fixed time sampling intervals were set to 0, 5, 10, 15, 30, 45, 60, 90, and 120 minutes following sampling program activation.

Stormwater samples were collected from the Orange Mall ISCOs within 12 hours of each event and transported to the ASU Wetland Ecosystem Ecology Lab for processing. Subsamples for dissolved organic carbon (DOC) and anion analysis were filtered through ashed Whatman GF/F® 47mm filters, and DOC samples were HCl acidified to pH = 2. Samples were then transported to the ASU Goldwater Environmental Lab for analysis. DOC samples were analyzed within 7 days on a Shimadzu TOC-VC/TN analyzer (detection limit 0.04 mg DOC/L and 0.004 mg TN/L). Unfiltered sub-samples were collected for total nitrogen (TN) and total phosphorus (TP). Nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) samples were centrifuged to remove particulates and along with TN and TP analyzed on a Lachat Quick Chem 8000 Flow Injection Analyzer (detection limit 0.85 µg NO_3-N/L and 3.01 µg NH_4-N/L). TN, TP, NO_3^-, NO_2^- and NH_4 samples were kept frozen after processing until analysis. All methods for stormwater collection and analysis were based on standard CAP LTER stormwater research to provide cross-site comparability.

2.3b – Water Quantity

To determine effluent discharge volumes from the basins, 90-degree v-notch weirs were constructed and installed at the outflow discharge points of the east and west basin systems (see Figure 1 for location details). ONSET HOBO U20L water level probes were installed 10 cm upstream from the weirs inside the discharge pipe/channel to measure water stage. I used the US Bureau of Reclamation (2001) Cone equation for v-notched weirs was to calculate discharge rates at the weirs using these water level measurements:

$$Q = 2.49h_1^{2.48}$$

where Q represents the flow rate in m^3/s, and h_1 represents the hydraulic head on the weir. Hydraulic head was derived by subtracting the total distance from the bottom of the channel to the bottom of the weir v-notch from the observed water stage. The resulting value represented the hydrological head of water overtopping the weir.

2.3c – Soil Moisture

In addition to water flow, soil moisture was identified as a useful metric for Orange Mall managers. Managers were interested in the ability to reuse captured stormwater to provide passive irrigation to vegetation planted in the basins. As such, I measured continuous soil moisture content to characterize the water retention capacity of soil amendments used in the basins. To do this, I collected soil moisture data in EB1 and EB2 using a series of ONSET HOBO 10HS Soil Moisture Probes connected to an ONSET USB Microstation datalogger, capturing continuous soil moisture data at a 5 minute resolution. Soil moisture readings were averaged across all sensors, as basin soil amendments were identical. ONSET HOBOWare (version 3.7.15, ONSET, Bourne, MA) was used to download data from all ONSET probes and loggers and transform raw data into the appropriate units.

2.3d - Transpiration

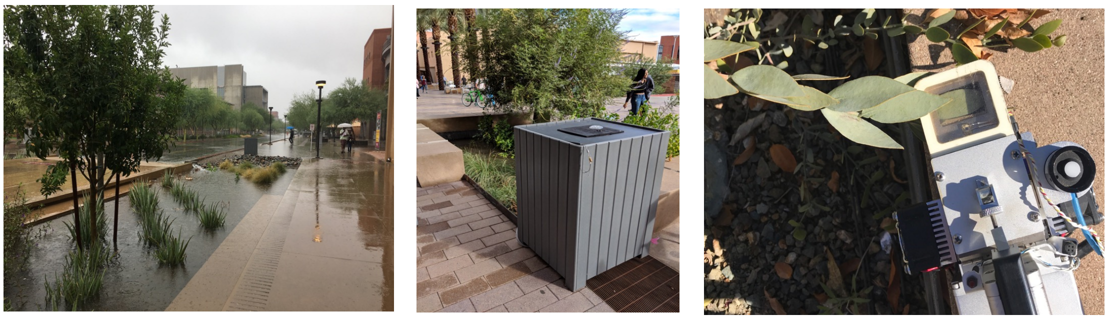
Orange Mall managers were also interested in understanding comparative transpiration rates for the various species of vegetation planted in the basins, given the important implications this has for stormwater and microclimate management. Leaf-specific transpiration rates were measured for the 5 dominant macrophyte species planted throughout the system using a LICOR LI-6400 handheld infrared gas analyzer (IRGA). Measurements were made on individual leaves or leaflets of *Pedilanthus bracteatus, Dasylirion wheeleri, Ruellia brittoniani,* and *Simmonsdsia chinensis 'vista'* plants. Gas flux data were collected continuously in 2-3 hour sampling sessions on a random selection of individuals from each species across all basins. For each individual, a spread of 3 leaves representing the entire height and width of the canopy were chosen and sampled using the IRGA. Several evening transpiration sampling sessions confirmed night-time transpiration to be negligible for all species.

2.3d – Meteorological Data

Daily rainfall data were collected from a Maricopa County Flood Control District (MCFDX) Rain Gauge located 0.63km south of Orange Mall (Station ID: 67500 – ASU South), as well as contemporary data from an EarthNetworks meteorological station on the ASU Tempe Campus located 0.30km north-east of Orange Mall (Station ID: TMPST). Rainfall data for these two stations were averaged to obtained an estimate of actual precipitation at Orange Mall, located roughly halfway between the two stations. These data were used to characterize each storm event and derive hydrographs describing the timing, amount and intensity of rainfall.

Figure 7.

Photos of bioswales and equipment at Orange Mall. From left to right: 1) a flooded bioswale after a rain event in October 2018; 2) an ISCO 6712 sampler deployed on-site and hidden within a protective enclosure; 3) a LI-COR 6400XT Infrared Gas Analyzer being used to measure transpiration on of a leaf.



RESULTS & DISCUSSION

3.1 RQ1: Design Process

Both participant observation and participation in key planning and research design meetings, and my semi-structured, in-depth interviews yielded a number of important insights into the design process. A total of 5 meetings in Spring 2018 were observed, and n = 12 interviews were conducted before saturation was reached and no new significant data were emerging from interviews. Interviews included 2 researchers, and 10 practitioners. The final codebook used for qualitative data analysis contained 5 top-level themes, including: Previous Experience, Design Process, Challenges, Opportunities, and Outcomes. Each of these top-level themes then contained a number of other codes for more specific themes that emerged. As an example, under the theme Challenges was interview content related to the challenges of integrating research in UEI design and management, which included codes such as "time," "resources," or "institutional." Table 2 provides a brief description of each top-level code, as well as examples of several subcodes. This sub-section begins with the narrative and overall dynamics of monitoring protocol development, follow by more specific data from interview themes.

3.1a Defining and understanding UEI

UEI was not an inherently new concept for project participants. All of the practitioners who were interviewed expressed previous experience with designing, managing, or researching UEI features. However, all practitioners chose to refer to UEI as either "green infrastructure" or "nature-based solutions." Yet, in many cases, when asked to define what they meant by these terms, practitioner definitions were remarkably similar to that of UEI. Common themes included an emphasis on ecosystem structures

Table 2.

Top-level codes and sub-codes used for coding analysis.

Top-Level Codes	Description	Example Sub-Codes
Previous Experience	Descriptions and anecdotes of previous experience working with UEI	“education,” “professional experience,” “solutions,” “definitions,” “monitoring”
Design Process	Descriptions and anecdotes about Orange Mall site and research design	“UEI drivers,” “UEI challenges,” “SITES,”
Challenges	Content related to challenges associated with monitoring UEI	“time,” “funding,” “institutional,” “organizational”
Opportunities	Content related to opportunities associated with monitoring UEI	“evidence,” “education,” “time”
Outcomes	Outcomes and results as a result of co-production experience	“individual learning,” “institutional learning,” “sustainability,” “evidence”

(e.g. bioswales, wetlands) and ecosystem functions (e.g. stormwater capture, water quality improvement). Notably, these definitions did not contain references to more enviro-political definitions (e.g. solar panels, recycling bins) that are also routinely defined as green infrastructure (Childers et al. in review).

Interestingly, practitioners often cited the use of UEI in previous work experience, mainly in private consulting landscape design projects in aridland settings. They noted an intuitive orientation towards UEI-based solutions, such as bioswales or infiltration basins, to manage flooding issues. This was the case without reliance on strong research-based evidence to inform these designs, particularly data from arid contexts. This was directly attributed to: 1) a lack of peer-reviewed evidence of site-scale UEI performance; 2) an unfamiliarity with or inability to access researchers or peer-reviewed literature; or 3) reliance on established designs and precedent. 75% of practitioners interviewed reported using these UEI-based techniques as part of common practice in the "field" [of landscape architecture] to achieve design solutions that were both aesthetically pleasing and functional. Examples include: "I think all of our projects up to that point had a lot of the principles built into them," but "we probably don't call [that] green infrastructure at that time."

On the other hand, researchers were familiar with the term UEI, which they attributed to co-involvement with CAP LTER and other similar urban research programs. All researchers had previous experience as practitioners including experience that spanned both private and public practice. These experiences also included, in some cases, work on monitoring UEI via designed-experiment research approaches.

3.1b Design Process

While plans for the Orange Mall redevelopment project included UEI features early on (bioretention basins), the decision to implement ecological monitoring of these features emerged late in the design and construction process. Initially, the focus for the project was on attaining SITES certification. Practitioners at Arizona State University were interested in SITES as an opportunity to formalize existing university-wide practices around landscape function and sustainability. However, SITES credit C9.3 requires monitoring of post-construction landscape performance (Lady Bird Johnson Wild Flower Center 2014). Practitioners at ASU decided to engage with researchers to meet this reporting goal.

As a result, in Spring 2018 researchers began to hold meetings with key ASU practitioners and external consultants involved in the design and management of Orange Mall. These workshop-style discussions were held to co-produce the monitoring protocol. Discussion included a review of the site design history, SITES documentation and mandates, resources (equipment, funding, etc.) available, and how these all align with the research interests of participants. My role in these meetings was to lead the discussion with regards to what resources were available for monitoring, and provide options and consultation on experimental design.

I began our initial meeting by asking practitioners what types of data would be most interesting or valuable for them in evaluating site performance and applying for SITES certification. Importantly, I made sure to frame our approach to this conversation to ensure that practitioners felt like equal partners, and had genuine agency in identifying which approaches would be best. Practitioners indicated that they were primarily interested in stormwater quality and quantity data to meet SITES reporting requirements. However, as SITES does not specify or require particular methodologies, practitioners did not specify any sampling strategies. Instead, practitioners deferred to researchers for suggestions on experimental design. In response, researchers suggested a suite of different methods that could be used to achieve this.

My role was to present the various equipment and protocols for monitoring that could be used at Orange Mall. Importantly, we as researchers were all affiliated with CAP LTER and so presented sampling equipment and methods which mirrored those used by CAP LTER at to evaluate the performance of other stormwater UEI; the goal of this approach being to enable cross-site comparability. Through collaborative and mutually respectful dialog, the group was able to decide on a final set of metrics, equipment, sampling, and analytical techniques to evaluate the performance of Orange Mall (Table 1). After the monitoring protocol was finalized, subsequent meetings were held to finalize the sampling strategy for the site. Printed copies of the Orange Mall final site plans were used as collaborative tools to physically map expected water flow across the site, and to sketch different sampling scenarios and adjust equipment locations in response to water flow dynamics, safety and ADA compliance, and aesthetic concerns. These interactive drawing sessions proved to be a particularly popular and effective method to communicate and collaborative with the practitioners I worked with.

Throughout this process, two key limitations arose with regards to the monitoring protocol development – funding and aesthetics. As monitoring was not initially included in the plan or budget for the Orange Mall redevelopment, ASU did not have any funding available to purchase monitoring equipment or pay for samples and data analysis. This challenge was overcome by using existing CAP research equipment.

Further, while ASU was excited about the integration of research into a high-profile landscaping project, the high visibility and foot-traffic associated with the site presented challenges with equipment aesthetics and security. ASU practitioners emphasized a need to minimize the visibility and appearance of research equipment, and where visible, blend equipment in with the overall site aesthetics. Ultimately, this challenge was overcome through the use of large trash bin enclosures provided by ASU which were modified to include lockable lids. These bins were used to house the ISCO pump samplers, data loggers, and other important equipment. I also buried any cables or sampling lines protruding from these bins a few centimeters below soil surfaces to minimize visibility and disturbance. Despite concerns about the appearance of research equipment, ASU practitioners were interested in raising awareness of the design goals and research at the Orange Mall site. Ultimately, ASU chose to install interpretive signage on these bins to accomplish this, as well as gain an additional SITES credit related to education and awareness. These interpretive signs highlighted research efforts and raised awareness of the potential for campus-wide benefits of the UEI approach used in the Orange Mall redevelopment.

Table 3.

Key themes and quotes: design process and outcomes associated with UEI co-production and monitoring.

Category	Theme	Example Quotes
Design Process	Monitoring	• "Orange Mall became that, and [ASU practitioner] and I talked about it a long time and we said, "If we don't do it now, we'll never do it. We have to. We have to see if this works. We have to know."
Outcomes	Capacity-building	• "…so there has been that carryover to Nelson, which is great—because again, we just have more knowledge—we have more understanding of what it is that we need to do." • "This has become a window of opportunity for our program, for me to hopefully take on the lead to start and build this research initiative into the campus design."
	Institutional learning	• "That was one of those things where we all, as a team, didn't see the pieces where they needed to go, and now I understand it as a site consultant"

3.1c Challenges

A number of challenges to the design and use of monitoring to evaluate UEI were reported by participants. By far the most universal challenge noted by practitioners was resources – particularly time and money. Representative responses included the sentiment that "there's no money, no time to even think about monitoring long-term," and "[monitoring is] a lower priority." Project timelines and budgets are often tight on both time and money, and as projects reach completion focus and resources are quickly shifted to the next upcoming project. Researchers also cited time as a challenge. When asked for more detail, however, explanations varied from those of practitioners. A key factor for researchers was "mismatches" in the alignment of the design process with other key cycles such as the academic "school year," or "funding cycles." These mismatches can significantly impact the availability of time, personnel, or funding to support the establishment or maintenance of research-based monitoring efforts.

There also appeared to be institutional factors that provided challenges to implementing UEI monitoring. Put simply, practitioners and urban ecologists think differently about site and research design. My observations of the co-production process and my interviews revealed low institutional capacity among practitioners regarding research design and implementation. So, although UEI was a consideration early in the design process for Orange Mall, researchers were not engaged with regards to UEI monitoring until after site construction. As a result the final Orange Mall site design featured a number of constraints that limited research design. Namely, a lack of on-site space for equipment installation or storage combined with the high visibility and foot traffic led to challenges when balancing monitoring design with Americans with

Disabilities Act (ADA) compliance, safety concerns, aesthetic considerations, and access to power for equipment. Engagement between researchers and practitioners earlier in the design process could alleviate these challenges.

Finally, nearly all participants spoke to the challenges of monitoring stormwater UEI in an arid context. As an example, one participant noted that “here [UEI] don’t get tested very often…if you have a bioretention basin, the chances of actually seeing it working are really low.” Despite significant investments of time and money, high interannual variability in rainfall can significantly impact the quantity of monitoring data and results. For example, while I was able to capture four storms in this study that were intense enough or of long enough duration to produce flow through Orange Mall, this location received virtually no rainfall during the same time period (August to February) in the previous year (2017-2018; Maricopa County Flood Control District 2019).

3.1d Opportunities and Outcomes

My participation in the monitoring design process and interviewing participants also revealed a number of positive opportunities associated with monitoring UEI. As a direct response to the challenges associated with finding or generating evidence about aridland stormwater UEI, participants also viewed this co-production process as a valuable opportunity to generate such evidence. Practitioners at ASU and external consultants have all expressed interest in using these data to inform future UEI design and management. One response in particular was revealing, with a practitioner stating “this Orange Mall project provides a really cool opportunity to do [monitoring] for this type of landscaping because there’s this intuitiveness of oh, yeah, we should use infiltration basins. Now there's a chance to actually test that and use that as evidence going forward."

I also observed evidence of learning and significant improvements in institutional capacity. One practitioner summarized it well: "We all, as a team, didn't see the pieces [of this project] and where they needed to go, and now I understand it." For context, in this example the practitioner is referring to understanding all of various components and processes associated with monitoring an UEI project. Practitioners repeatedly emphasized an improved ability to support and plan for monitoring integration into future projects as a result of the coproduction experiences associated with Orange Mall. Researchers, myself included, also became much more fluent in understanding and navigating the design process. This included the ability to read and work with planning and engineering disciplines and documents, anticipate needs and concerns associated with conducting research in high-traffic, high-profile sites.

Finally, although the high visibility and centrality of the site created challenges for research design, there are a number of important educational opportunities that emerged from UEI monitoring. As one ASU practitioner described it, "to be able demonstrate [UEI] in a very public and open way was also a very interesting and exciting benefit." ASU practitioners described how participation in this collaborative project increased their awareness of key student engagement opportunities associated with high-profile monitoring efforts on the campus. These include not only raising awareness via interpretive signage, but also actively engaging faculty and researchers, as well as students in their labs and courses, in the research and monitoring process.

Table 4.

Key themes and quotes: challenges and opportunities associated with UEI co-production and monitoring.

Category	Theme	Example Quotes
Challenges	Arid cities	• ”One of the things that, I think, we've discussed in the past is this idea that here they don't get tested very often. There's not even a—if you have a bioretention basin, the chances of them actually seeing it working are really low.”
	Institutional	• “You know, it was overwhelming. I’m not an engineer, but I mean I kept talking to the engineer and like, “This is what I want to do.” [Then he said] “Yeah, yeah, yeah, but that’s not how we do it.” • “[Contractors] are actually more integral…in ways that you don’t really think about until it’s too late. For example, not on the Orange Mall Project, but on the Nelson Project, which is also on campus. We just were not collaborative enough and there was a breakdown in communication.” • “If you’re new, yeah, it’s confusing until you get used to it”
	Resources	• “ [Usually] there’s no money, no time to even think about monitoring long-term, or really understanding how it perform. We will go back to the site to see, “Oh, wow, this is our design. Cool!
Opportunities	Evidence	• “This Orange Mall project provides a really cool opportunity to do that for this type of landscaping because there’s this intuitiveness of oh, yeah, we should use infiltration basins. Now there’s a chance to actually test that and use that as evidence going forward.”
	Education	• “Here especially at ASU, we have a huge educational component. So to be able to demonstrate that in a very public and open way is—was also a very interesting and exciting benefit.”

3.2 RQ2: Design Outcomes

Beyond reviewing the project narrative and interviews, a key goal of this project was to understand how the stormwater UEI at the Orange Mall performed. I implemented the co-produced monitoring protocol and used these methods to monitor site performance over a 7-month study period (August 2018 to February 2019). In this section I present these ecohydrologic and biogeochemical data and results on the design performance outcomes.

3.2a Storm Events

Throughout the study period the Orange Mall site experienced a total of 17 rain events. Out of these 17 events, only four fully inundated the basins to achieve flow throughout the system and activate the ISCO samplers, allowing the collection of water quality and flow data. This threshold for full activation of all basins was a storm intensity of 0.76mm of precipitation per hour. Less intense events partially inundated all basins, but did not achieve flow between basins and thus did not activate the ISCO sampling units. Further, this varied with basin location, size, and design. The west swale systems (WB1-3) flooded faster, and had one more event (n= 4) sampled for water quality than the east swale systems (EB1-4) (n = 3; see Figure 5). These water quality data will be presented along with other data on system performance with respect to hydrology (precipitation, outflow rates and volumes) and biogeochemistry (soil moisture) for each storm event.

The first storm to fully inundate and achieve flow between the Orange Mall basins occurred on 9/19/18 (Figure 8). This storm generated 3.00 mm of precipitation within 1 hour, (storm intensity = 3.0 mm precipitation hr^{-1}). Water flow rates as measured at the outflow of the east and west basin systems peaked at 0.0000429 m^3 s^{-1} and 0.000748 m^3 s^{-1}, respectively, with an estimated 1.379 m^3 of total outflow occurring during the storm event.

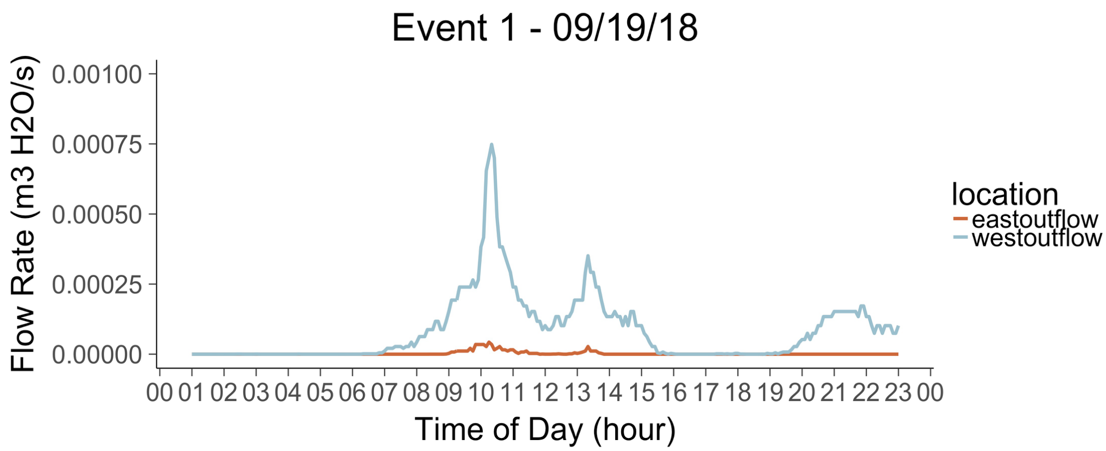
Table 5.

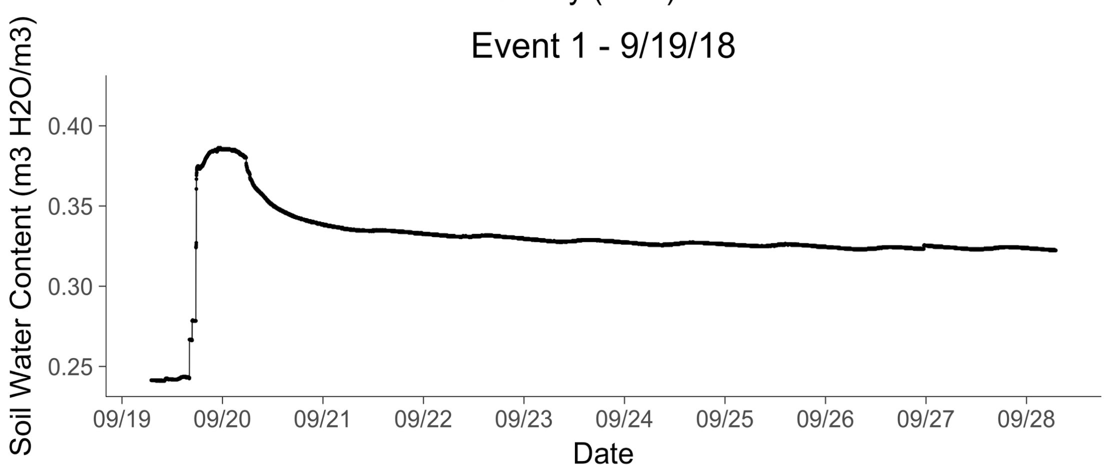
Characteristics of storms sampled in this study

Storm ID	Date	Total Precip (mm)	Total Precip (in)	Duration (h)	Intensity (mm hr^{-1})
1	9/19/18	3.00	0.12	1	2.9
2	10/8/18	5.08	0.20	3	1.69
3	10/13/18	18.79	0.74	7	2.68
4	1/16/19	3.05	0.12	4	0.76

Figure 8.

Ecohydrological and biogeochemical monitoring results for storm event 1.





The second storm to fully inundate and achieve flow between the Orange Mall basins occurred on 10/8/18 (Figure 9). This storm generated 5.08 mm of precipitation across 3 hours, for an overall storm intensity of 1.69 mm precipitation hr^{-1}. Resulting water flow rates as measured at the outflow of the west basin systems peaked at 0.000451 $m^3 s^{-1}$, with an estimated 0.857 m^3 of total outflow occurring during the storm event. This storm event did not produce measurable outflow from the east basin system.

The third and largest storm to fully inundate and achieve flow between the Orange Mall basins occurred on 10/13/18 (Figure 10). This storm generated 18.79 mm of precipitation across 7 hours, for an overall storm intensity of 2.68 mm precipitation hr^{-1}. Resulting water flow rates as measured at the outflow of the east and west basin systems peaked at 0.375 $m^3 s^{-1}$ and 0.177 $m^3 s^{-1}$, respectively, with an estimated 1623.083 m^3 of total outflow occurring during the storm event.

Figure 9.

Ecohydrological and biogeochemical monitoring results for storm event 2.

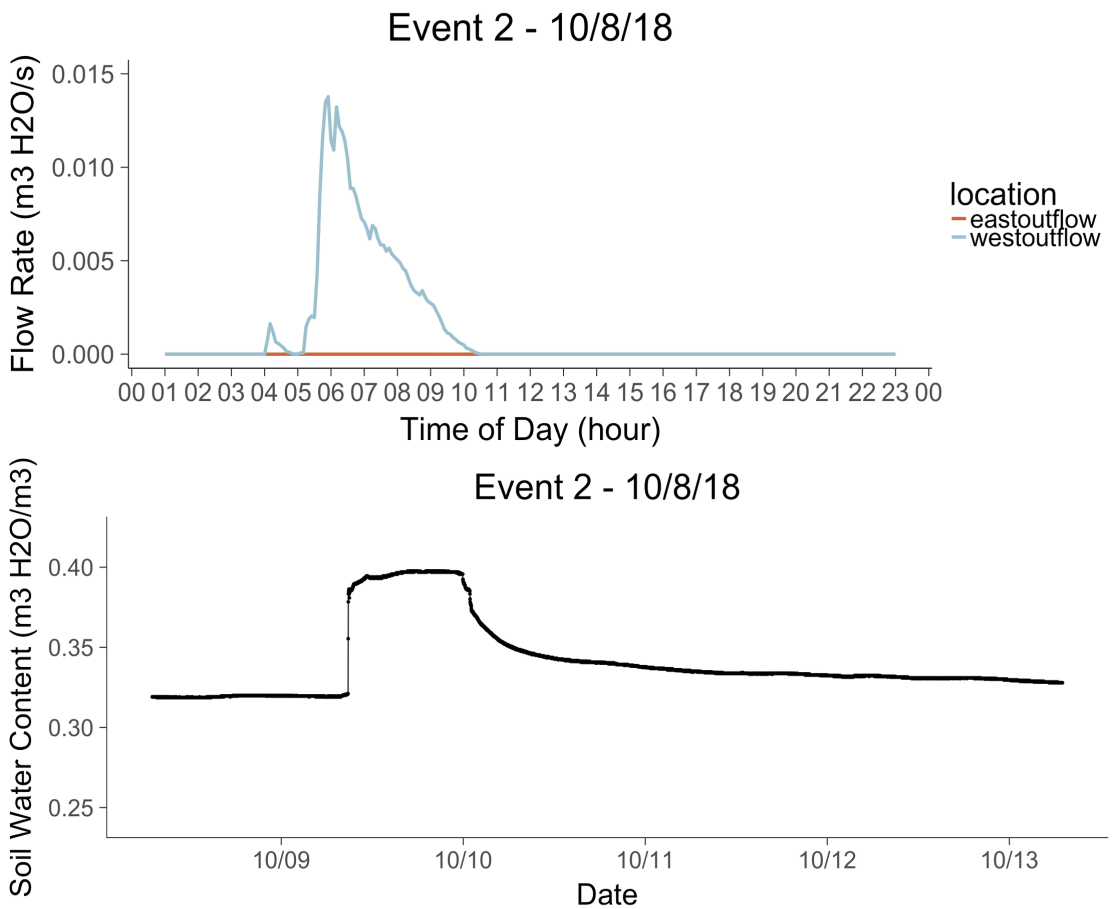
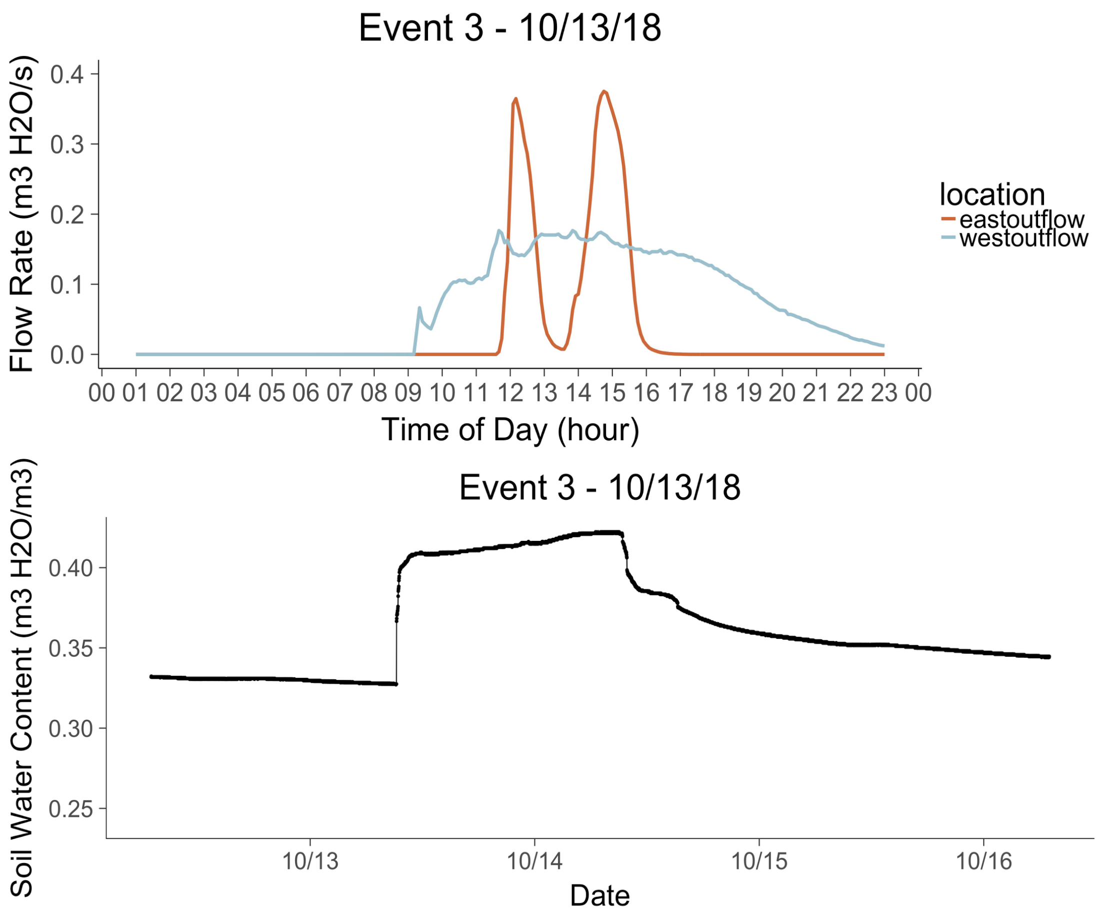


Figure 10.

Ecohydrological and biogeochemical monitoring results for storm event 3.



The last storm to fully inundate and achieve flow between the Orange Mall basins occurred on 1/16/19. This storm generated 5.08 mm of precipitation across 3 hours, for an overall storm intensity of 1.69 mm precipitation hr^{-1}. Water flow rates as measured at the outflow of the east and west basin systems peaked at 0.000210 m^3 s^{-1} and 0.00232 m^3 s^{-1}, respectively, with an estimated 14.801 m^3 of total outflow occurring during the storm event.

I averaged water quality data across all four storm events to understand the general dynamics of the system across a variety of storm events. Then, I calculated the change in concentration of each water quality analyte between each sampling location, for each basin system. These included the change in analyte concentration between the east basin system inflow and midpoint, east basin system midpoint and outflow, and the west basin system inflow and outflow. Between the inflow and midpoint of the east basin system, a net decrease in NH4, TP and NO3 was observed throughout the storm events, while TN showed a net increase (Figure 12). Comparatively, between the midpoint and outflow of the east basin system, a net increase in NO3 and TN was observed throughout the storm event, while TP was consistently reduced and change in NH4 was negligible (Figure 12). For the west basin system, a net increase in TP, NO3, and NH4 was observed, while for TN the system varied between a net source and sink throughout the storm (Figure 12). Across all storm events, TP concentrations ranged from 0.585 to 0.06 mg/L, TN concentrations from 0.346 to 3.168 mg/L, NO3 concentrations from 0.02 to 1.713 mg/L, and NH4 concentrations from 0.019 to 0.312 mg/L.

Figure 11.

Ecohydrological and biogeochemical monitoring results for storm event 4.

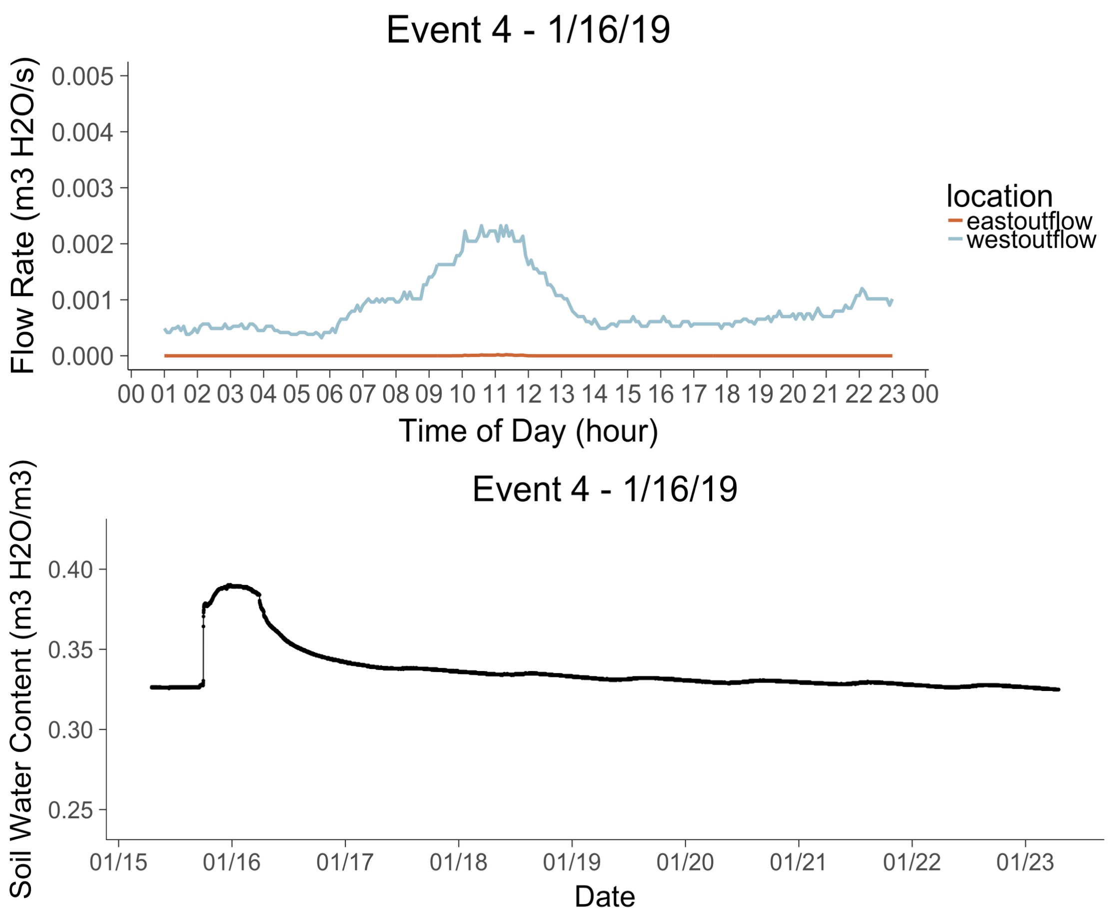
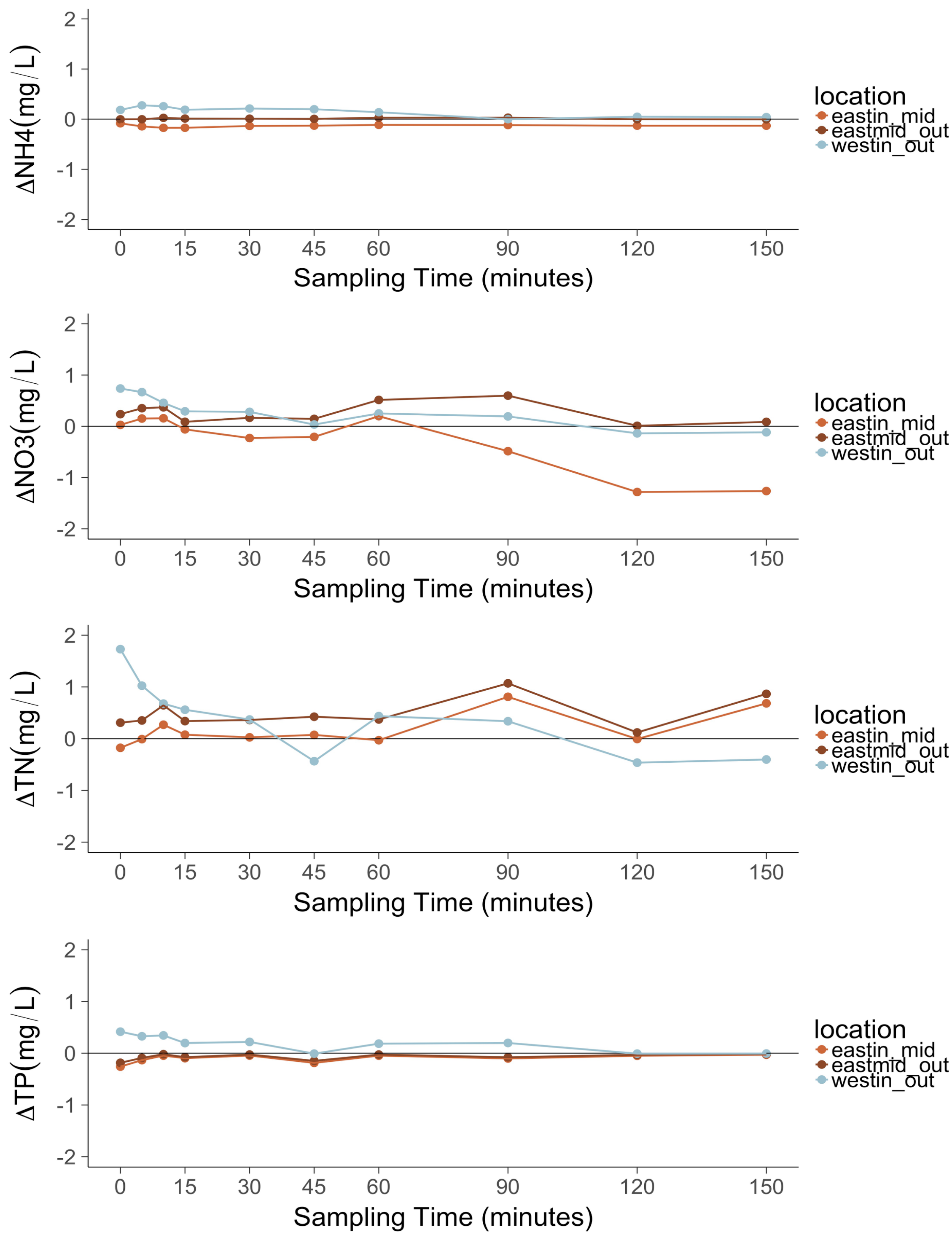


Figure 12.

Average change in water quality analyte concentrations between east basin inflow to midpoint (“eastin_mid”), east basin midpoint to outflow (“eastmid_out”) and west basin inflow and outflow (“westin_out”).



Soil moisture retention rates remained consistent across storm events. Baseline soil moisture was approximately 0.33 m^3 H_2O m^{-3}. Volumetric soil water content for event 1 peaked at 0.37 m^3 H_2O m^{-3} during the storm, and took approximately 7 days to return to baseline (Figure 8). Volumetric soil water content for event 2 peaked at 0.39 m^3 H_2O m^{-3} during the storm, and took approximately 5 days to return to baseline (Figure 9). Volumetric soil water content for event 3 took approximately 4 days to return to baseline (~0.33 m^3 H_2O m^{-3}) following a peak at 0.42 m^3 H_2O m^{-3} during the storm (Figure 10). Finally, volumetric soil water content for event 4 peaked at 0.38 m^3 H_2O m^{-3} during the storm, and took approximately 7 days to return to baseline (Figure 11).

Transpiration measurements showed a general increase in transpiration by the dominant Orange Mall vegetation species following a storm events. Transpiration rates measured in the days following storm events, when soil moisture was relatively high, were on average higher than those taken during baseline soil moisture conditions. Importantly, time of day was controlled for by consistently sampling between 10AM and 12PM. This increase was the case for all of the identified dominant Orange Mall vegetation species, although there was variation between species. As an example, Fan West Ash transpiration rates increased on average by 46% following a storm event, while transpiration rates for Tall Slipper plant dramatically increased by 76%.

Overall, the system met design goals with regards to stormwater capture - no storm events exceeded the capacity of the basins. Further, the majority of the events that occurred at the Orange Mall site were not intesnse enough to cause flow between the basins. The system overwhelmingly tended to capture rain events within each individual basin and manage this water through vertical water paths (infiltration, evaporation/transpiration,). With regards to water retention, on average soil moisture took just under 6 days following an event to return to baseline conditions (mean = 5.75 days). In conjunction with observed increases in transpiration following storm events, the vegetation in the basin systems appeared to actively reuse captured stormwater, and play an role in regulating soil moisture following storm events. The significant interspecies variation in transpiration rate responses to rain events may be an important consideration for UEI managers for future projects. However, my transpiration analysis did not account for overall plant biomass by species. A lack of well-established phenometric models for the species present at Orange Mall made biomass estimates difficult. Further, leaf structures for all species besides Fan West Ash were not conducive to estimating leaf area, a secondary approach for scaling leaf-level transpiration rates. Further research to effectively scale transpiration rates in both space and time would contribute to a clearer understanding of the role of vegetation relative to the whole system water budget.

However, an important tradeoff for achieving successful stormwater capture within the basins was challenges in monitoring water quality as water moved through the system. Effective stormwater capture by the Orange Mall basins for most events resulted in little flow between the basins, and thus a reduced number of opportunities to collect water quality samples. Despite a small sample size, the water quality data that were able to be collected provided insight into water quality improvement capacity. A pattern of net reduction of TP as water moved through the basin systems suggests effective capture of suspended particular matter, as TP is often particulate-bound. However, trends in the various species of nitrogen monitored (TN, NO3, and NH4) were less consistent. This may be due in part to the hydrology of the system, particularly the highly dispersed inflows. Surface and roof runoff patterns entering each of the basins was fairly homogenous throughout the site, providing pathways for organics and other pollutants to enter the system at any point.

My results indicate that the co-production process associated with monitoring Orange Mall resulted in important learning outcomes for all participants. Further, my data demonstrate that the system met design goals for stormwater capture, with no events that resulted in system failure (e.g. widespread flooding across the Orange Mall pavilion). Further, the system partially met design goals with regards to storm water quality improvement - my data demonstrated system capacity for storm water quality improvement for TP, although results for N species were less consistent.

CONCLUSION

To address key knowledge gaps associated with collaborative process around UEI, I conducted a holistic socioecological case-study of the co-production processes and outcomes associated with monitoring stormwater UEI at the ASU Orange Mall. I documented the design process, including challenges and opportunities associated with co-production of UEI monitoring, and UEI performance outcomes.

Challenges in co-production associated with monitoring included resources (time and money) and overall institutional capacity to support engagement between researchers and practitioners. Further, both groups frequently cited a lack of evidence to support best practices for design and collaboration for aridland UEI. However, the co-production process also resulted in a number of important positive outcomes and opportunities. The practice of collaborating led to better mutual understanding between researchers and practitioners. I observed positive changes in practitioner capacity to engage with and support research design, and researcher capacity to navigate the design process and anticipate practitioner needs and site constraints. This resulted in what practitioners described as "carryover" between projects, with the experiences, knowledge and evidence from the Orange Mall co-production and monitoring process feeding directly into improved collaboration and outcomes for design processes associated with future projects. Further, monitoring results on system performance in response to storm events can provide specific feedback on aspects of UEI site design to enable iterative improvement of existing projects, as well as improved designs for future projects.

This feedback loop in the design processes ("inform", Figure 2) associated with the ASU Tempe Campus has already begun. As a result of the successful collaborative relationship established via the Orange Mall project, ASU practitioners expressed interest in extending their engagement with the researchers (and myself) to a second, in-progress landscape redevelopment project on the Tempe Campus. This new collaboration is noteworthy for several reasons: 1) researchers engaged with project practitioners much earlier in the design process (before final construction was completed); 2) preliminary monitoring results from Orange Mall have directly influenced design and monitoring decisions for future UEI projects; and 3) funding and accommodations for research equipment, sampling, and analysis was included as part of site development budget and design plans. This exciting early-stage engagement relative to Orange Mall has enabled a more comprehensive co-production process. This includes the use of Before-After-Control-Reference-Intervention (BACRI) research design (Underwood, 1991, Walsh et al. 2015) to better understand site performance before and after UEI construction.

My case-study contributes foundational evidence to the understanding of UEI performance in aridland urban settings. Further, the relationships established via the collaborative approaches used to generate this evidence are an important first step to more deeply integrating research and monitoring into the UEI design process. Continuing to develop these relationships between researchers and practitioners is an important next step to improving institutional capacity, and building better mutual understanding and trust around the use of research and monitoring in understanding UEI performance. The use of feedback from case-studies and evidence from existing projects can enable more informed exploration of design scenarios for future UEI projects. This has important implications for better outcomes for aridland UEI performance, and sustainability and resilience more broadly.

REFERENCES

Ahern J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning, 100(4)*, 341-343. doi: 10.1016/j.landurbplan.2011.02.021

Ahern J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology, 28(6)*, 1203-1212. doi: 10.1007/s10980-012-9799-z

Albrechts L. (2013). Reframing strategic spatial planning by using a coproduction perspective. *Planning Theory, 12(1)*, 46–63 doi: 10.1177/1473095212452722

Anderson E., Barthel, S., Borgström, S., Colding, J., Elmqvist, T., Folke, C., & Gren, Å. (2014). Reconnecting cities to the biosphere: Stewardship of green infrastructure and urban ecosystem services. *Ambio, 43(4),* 445–453.

Arizona State University. (2017). Facts At A Glance. Available from: https://uoia.asu.edu/

Armitage, D., Berkes, F., Dale, A., Kocho-Schellenberg, E., & Patton, E. (2011). Co-management and the co- production of knowledge: learning to adapt in Canada's Arctic. *Global Environmental Change, 21(3)*, 995–1004. doi: 10.1016/j.gloenvcha.2011.04.006

Bettencourt L., Clarens, A., Das, S., Fitzgerald, G., Irwin, E., Pataki, D., & Nichols, L. (2018). Sustainable Urban Systems: Articulating a Long-Term Convergence Research Agenda. *National Science Foundation.*

Bois, P., Childers, D.L., Corlouer, T., Laurent, J., Massicot, A., Sanchez, C.A., & A Wanko. (2017). Confirming a plant-mediated "Biological Tide" in an aridland constructed treatment wetland. *Ecosphere 8(3),* doi: e01756.10.1002/ecs2.1756

Childers, D.L., Bois, P., Hartnett, H.E., McPhearson, T., and Metson, G.S., In review. Urban Ecological Infrastructure: An inclusive concept for the non-built urban environment. *Landscape and Urban Planning.*

Childers, D.L., Cadenasso, M.L., Grove, J.M., Marshall, V., McGrath, B., & Pickett, S.T.A. (2015). An ecology for cities: A transformational nexus of design and ecology to advance climate change resilience and urban sustainability. *Sustainability (Switzerland),* 7(4), 3774–3791. doi: 10.3390/su7043774

Elo S., Kyngas, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing, 62(1),* 107-115. doi: 10.1111/j.1365-2648.2007.04569.x

Felson, A.J., & Pickett, S.T.A. (2005). Designed experiments: new approaches to studying urban ecosystems. *The Ecological Society of America, 3(10),* 549–556. doi: 10.2307/3868611

Felson, A.J., Bradford, M.A., & Terway, T.M. (2013). Promoting Earth stewardship through urban design experiments. *Frontiers in Ecology and the Environment, 11(7),* 362-367. doi: 10.1890/130061

Grimm, N.B., Cook, E.M., Hale, R.L., & Iwaniec, D.M. (2016). A broader framing of ecosystem services in cities: Benefits and challenges of built, natural, or hybrid system function. Pp. 203-212 In: Seto, K. C., W. Solecki and C. Griffith eds., *The Routledge Handbook of Urbanization and Global Environmental Change*, Routledge.

Grose, M.J. (2014). Landscape and Urban Planning Gaps and futures in working between ecology and design for constructed ecologies. *Landscape and Urban Planning*, *132*, 69–78. doi: 10.1016/j.landurbplan.2014.08.011

Grove, J.M. (2009). Cities: managing densely settled social-ecological systems. Pages 281–294 in F. S. Chapin III, G. P. Kofinas, and C. Folke, editors. *Principles of ecosystem stewardship: resilience- based natural resource management in a changing world*. Springer, New York, New York, USA.

Grove, J.M., Childers, D.L., Galvin, M., Hines, S., Muñoz-Erickson, T., & Svendsen, E.S. (2016). Linking science and decision making to promote an ecology for the city: practices and opportunities. *Ecosystem Health and Sustainability,* 2(9), p.e01239. doi: 10.1002/ehs2.1239

Hansen, R., & Pauleit S. (2014). From multifunctionality to multiple ecosystem services? A conceptual framework for multifunctionality in green infrastructure planning for urban areas. *Ambio, 43(4),* 516–529. doi: 10.1007/s13280-014-0510-2

Lady Bird Johnson Wild Flower Center. 2014. SITES v2: Reference Guide For Sustainable Land Design and Development. The University of Texas, Austin, TX.

Larsen, L. (2015). Urban climate and adaptation strategies. *Frontiers in Ecology and the Environment, 13(9),* 486–492. doi: 10.1890/150103

Larson, K.L., Polsky, C., Gober, P., Chang, H., & Shandas, V. (2013). Vulnerability of water systems to the effects of climate change and urbanization: A comparison of phoenix, Arizona and Portland, Oregon (USA). *Environmental Management*, *52(1),* 179–195. doi: 10.1007/s00267-013-0072-2

Lawton, J.H., & Jones, C.G. (1995). Linking species and ecosystems: Organisms as ecosystem engineers. In C. Jones and J.H. Lawton (Eds.), *Linking Species & Ecosystems* New York, NY: Springer. Pp. 141-150.

Lee, J.H., Bang, K.W., Ketchum, L.H., Choe, J.S., Yu, M.J. (2002). First flush analysis of urban storm runoff. *Science of the Total Environment, 293(1)*, 163–75. doi: 10.1016/S0048-9697(02)00006-2

McDonnell, M.J. & Pickett, S.T.A. (1990). Ecosystem structure and function along urban-rural gradients: an exploited opportunity for ecology. *Ecology, 71(4)*: 1232-1237. doi: 10.2307/1938259

Neuman, M. and S. Smith, 2010. City planning and infrastructure: Once and future partners. Journal of Planning History 9: 21-42. doi: 10.1177/1538513209355373

Nisbet, M.C., Hixon, M.A., Moore, K.D., & Nelson, M. (2010). Four cultures: New synergies for engaging society on climate change. *Frontiers in Ecology and the Environment, 8(6),* 329–331. doi: 10.1890/1540-9295-8.6.329

Pickett, S.T.A., Cadenasso, M.L., Childers, D., McDonnell, M., & Zhou, W. (2016). Evolution and future of urban ecological science: Ecology in, of, and for the city. *Ecosystem Health and Sustainability, 2(7).* doi: 10.1002/ehs2.1229

Sanchez, C.A., Childers, D.L., Turnbull, L., Upham, R., & Weller, N.A. (2016). Aridland constructed treatment wetlands II: Plant mediation of surface hydrology enhances nitrogen removal. *Ecological Engineering, 97*, 658–665. doi: 10.1016/j.ecoleng.2016.01.002

Steiner, F., Simmons, M., Gallagher, M., Ranganathan, J., & Robertson, C. (2013). The ecological imperative for environmental design and planning. *Frontiers in Ecology and the Environment, 11(7),* 355-361. doi: 10.1890/130052

Underwood, A. J., 1991. Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Marine and Freshwater Research, 42(5),* 569-587. doi: 10.1016/0006-3207(93)90741-I

US Bureau of Reclamation. (2001). Water Measurement Manual. Available from: https://www.usbr.gov/tsc/techreferences/mands/wmm/chap07_11.html

Voorberg, W., Bekkers, V., & Tummers, L. (2014). Co-creation and Co-production in Social Innovation: A Systematic Review and Future Research Agenda. *Lipse.Org*, *320090* (320090).

Walsh, C. J., Fletcher, T. D., Bos, D. G., & Imberger, S. J. (2015). Restoring a stream through retention of urban stormwater runoff: a catchment-scale experiment in a social–ecological system. *Freshwater Science, 34(3)*, 161-168.

Weller, N.A., Childers, D.L., Turnbull, L., & Upham, R.F. (2016). Aridland constructed treatment wetlands I: macrophyte productivity, community composition, and nitrogen uptake. *Ecological Engineering, 97,* 649–657. doi: 10.1016/j.ecoleng.2015.05.044

APPENDIX A

ASU INSTITUTIONAL REVIEW BOARD (IRB) APPROVAL FOR RESEARCH INVOLVING HUMAN SUBJECTS

ASU Knowledge Enterprise Development

APPROVAL: MODIFICATION

Paul Coseo
The Design School
-
Paul.Coseo@asu.edu

Dear Paul Coseo:

On 10/2/2018 the ASU IRB reviewed the following protocol:

Type of Review:	Modification
Title:	Experiences and Preferences related to Central Arizona-Phoenix Long-Term Ecological Research Group Collaborative Projects
Investigator:	Paul Coseo
IRB ID:	STUDY00006718
Funding:	Name: National Science Foundation (NSF), Grant Office ID: FP00006797, Funding Source ID: DEB Award number 1637590
Grant Title:	None
Grant ID:	None
Documents Reviewed:	• 03 - CAP LTER Practitioner Survey 081717.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • 02 - CAP LTER Researcher Survey 081717.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Collaborative Project_HRP-502c - TEMPLATE CONSENT DOCUMENT -SHORT FORM.pdf, Category: Consent Form; • CAPLTER Design Research Protocol Revised100218.docx, Category: IRB Protocol; • CAP LTER orange mall & NFAC Music consent form 20180906.pdf, Category: Consent Form; • 01 - CAP LTER Interview Quesitons 081717.pdf, Category: Measures (Survey questions/Interview

	questions /interview guides/focus group questions); • 01 - CAP LTER Student Survey 081717.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • CAP IV renewal proposal.pdf, Category: Sponsor Attachment; • CAP LTER orange mall & NFAC Music Interview Questions 20181002.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • 01 - CAP LTER Focus Group Schedule 081717.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions);

The IRB approved the modification.

When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc:

Avalon Leavens
Christopher Sanchez
Veronica Horvath
Catherine Kent
Sara Aly El Sayed
Ishan Garg
Chingwen Cheng

APPENDIX B

IN-DEPTH INTERVIEW INSTRUMENT

Study title: CAP LTER Urban Ecological Design: Exploring co-production in the collaborative design processes: ASU Orange Mall Redevelopment & NFAC Music Drainage Improvements

Semi-structured interview administration time: 45-60 minutes

Semi-structured interview: *Researcher, Practitioner*

Interview Schedule: Fall 2018

Intended target group CAP LTER collaborative design project participants: 10 participants, drawing from researchers and practitioners associated with the Orange Mall Redevelopment Project & NFAC Music Drainage Improvements

Meta-data:

Interview number: ____

Date: ____

General Probes

Can you tell me more about that?

- Can you give me an example?
- What did you think?
- How did you feel?
- Repeat the last few words as an invitation for more
- Reference key findings from previous interviews ("In the past ____ has been raised as a concern
- What was that like?

In-Depth Interview Instrument

Overview: As discussed in the informed consent and introductory letter, one of the main purposes of this research is to understand the co-production process from experience and perspectives of participants related to CAP LTER urban ecological design projects. We are conducting this research to try to understand the collaborative design process and how collaborative design projects unfold. We know that your time is valuable and hope to keep the interview to no more than 45 minutes.

Informed consent: Before we can begin the interview, there is a process for informed consent to ensure there are clear expectations and understandings of this interview process. Here is a copy of the consent form to review and complete (participant to sign consent form before beginning the interview). To reiterate what is on the consent form, I would like to record this interview for review at a later date. Is it be okay to tape record the interview? You can ask me to turn off the device at any time and for any reason during the interview (start recording).

Terminology: Throughout this interview, I will be asking about your participation in collaborative design experiences. Specifically, we are interested in your experiences in this project and others as it relates to *urban ecological infrastructure*. To clarify, this refers to infrastructure which uses ecological or ecosystem-based approaches (such as vegetation) to provide desired services (such as water retention or quality improvement). Other common terms for this include green infrastructure and nature-based solutions, among others.

Questions/Probes:

1. <u>*Background:*</u> To get a sense of how your story fits into this project, we are interested in understanding your educational and professional background.

   a) What is your educational history?
   b) What is your professional history?
   c) Could you tell me a little about how long you have been working in your field on work related to urban ecological design projects? (probe: months or years) In the Phoenix Metropolitan Area (PMA)? (probe: months or years)
   d) What aspects of this work do you enjoy most? The least?
   e) What are your responsibilities? (probe: what do you do at work)
   f) How often do you work on collaborative projects related to urban ecological design in the PMA? (probe: the majority of our work, about 50 %, less than 50%, very seldom).
   g) Do you have any accreditations? If so, what are they? (probe: RLA, LEED AP, etc)

2. <u>*Project Narrative:*</u> To better understand how collaborative urban ecological design projects unfold more broadly, we are very interested in learning how this project came to be, and

a) How did you come to work on this project? Did you choose it, or was it chosen for you?
b) Have you or your employer/organization worked with any of the other project partners in the past? If so, which ones?
c) What is your understanding of Green Infrastructure? How does your field define it and how you approach it?
d) Why was a GI-oriented approach chosen for the redevelopment?

3. Monitoring: Another key goal for this project was to develop a monitoring plan to provide data to support the SITES accreditation effort that the project team is working towards. We are very interested in understanding how collaboration shapes the development of these monitoring plans.

a) Was data collection, analysis, or presentation a component of any of your previous professional experiences related to green infrastructure? If so, how?
b) Which components of this project do you think are most important to monitor and analyze? Examples include water quality, quantity etc. Why?
c) Did your interaction with the other researchers and practitioners shape your attitudes towards the monitoring protocol? If so, how?

4. *Learning:* I am going to ask you some questions about what you **learned** /took away during the collaborative design process related to your experience working on a collaborative design process, and how this might impact your future involvement in these projects.

a) How did this experience differ from other collaborative experiences for other types (e.g. non-urban ecological) design work?
b) Has your participation in this project impacted the likelihood of future collaboration with the project partners? How so?
c) Has your participation in this project impacted the way you will approach collaborative design projects around urban ecological infrastructure in the future? How so?
d) Has your participation in this project impacted your attitudes towards research and data collection as part of urban ecological design? How so?
e) If you were to go through the process again, is there anything you would do differently?

5. *Motives/opportunities/barriers:* I am going to ask some questions related to **opportunities** and **barriers** for this kind of collaboration related to urban ecological design projects.

a) What motives you to participate in this kind of collaboration (probe: work requirement, personal interest, and advancing certain programs)?
b) From your perspective as a [researcher, practitioner], what are the big opportunities associated with using other types of knowledge [scholarly, practitioner, pragmatic] in your work related to urban ecological design of green infrastructure?

c) On the flip side, what are the barriers to using other types of knowledge in your work related to urban ecological design of green infrastructure? How might these be overcome?
d) In your opinion, what is the biggest institutional barrier to implementing more urban ecological design projects?

6. *CAP LTER follow up:* Would you be willing to participate in future CAP LTER urban ecological design workshops that are relevant to your interests?
a) if no, what are the barriers to participation?
b) If no, what would increase the likelihood of your participation?
c) Please let us more about how we can improve the effectiveness of future CAP LTER group collaborations and/or make the project more useful or helpful for achieving your needs or your organization's goals.

Wrap up: If there's anything else you'd like to add related to your experience with this project, please feel free. Are there any questions or topics you feel have been left out? Additionally, are there any additional key individuals you think we should speak with? Otherwise, thank you so much for your participation in this study.