Impacts of Grade Control Structure Installations on Hydrology and Sediment Transport as an Adaptive Management Strategy

Science and Technology Program
Research and Development Office
Final Report No. ST-2017-1751-01

Photo: Grade Control Structure #10 looking downstream, March 11, 2020 (Photo credit: Boy Scouts of America, Heard Scout Pueblo, Cameron Thomas)

Photo: Grade Control Structure #2 looking upstream, March 13, 2020 (Photo credit: Bureau of Reclamation, Phoenix Area Office, Deborah Tosline)

U.S. Department of the Interior **September 30, 2020**

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE 30-09-2020	2. REPORT TYPE Research	3. DATES COVERED *(From - To)* 03-10-2016 – 30-09-2020

4. TITLE AND SUBTITLE Impacts of Grade Control Structure Installations on Hydrology and Sediment Transport as an Adaptive Management Strategy	5a. CONTRACT NUMBER WBS/WOID 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER S&T 1751
6. AUTHOR(S) name and title Deborah J. Tosline, Hydrologist / Project Manager Laura M. Norman PhD, Supervisory Research Physical Scientist Blair P. Greimann, Hydraulic Engineer Jay Cederberg, Supervisory Hydrologist Victor Huang, Hydraulic Engineer Benjamin L. Ruddell PhD, Professor in and Director of School of Informatics, Computing, and Cyber Systems	5d. PROJECT NUMBER Final Report ST-2020-1751 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bureau of Reclamation, Phoenix Area Office 6150 W. Thunderbird Rd. Glendale, AZ 85306	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation 11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2020-1751

12. DISTRIBUTION/AVAILABILITY STATEMENT Final Report available at https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT This research examines the impacts of Grade Control Structure (GCS) installations at the Heard Scout Pueblo study site in the City of Phoenix, Arizona, USA. The site is comprised of eroded channels that convey storm flows and sediments into a downstream residential neighborhood. Baseline rainfall/runoff response conditions were established before structures were installed. Innovative monitoring equipment, including video cameras/pressure transducers; digital terrain models; sediment samplers/sediment chains; soil moisture sensors/monitoring wells; and weather stations were established, and a small Unmanned Aircraft System survey was completed during June/July 2017. A novel layout of 30 GCS installations was designed to reinstate a historic channel - 20 structures were built in the main channel in November 2018 and 10 were built in adjacent locations in January 2019. A surface-water model was applied to track the flow of water and potential infiltration before and after GCS installations to simulate their impacts. The model predicted a slight reduction and delay in peak flows for small events and simulated an increase in channel infiltration of ~15% over time. Weather data indicate that the HSP GCS installations created roughly a three-degree microclimate cooling effect for at least two days following rainfall events, as compared with the untreated channel.

15. SUBJECT TERMS
Low Impact Development; Stormwater; Erosion, Grade Control Structures, Sediment transport, Ecoclimate, Non-structural stormwater management, Urban heat, One rock dam, Ecohydrology, Check dams, Erosion Control Structures, Green Infrastructure

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT U	b. ABSTRACT U	THIS PAGE U			19b. TELEPHONE NUMBER *(Include area code)*

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Acknowledgements

The study was conducted under the Bureau of Reclamation's (Reclamation) Science and Technology Program (S&T). The S&T Program is a Reclamation-wide competitive, merit-based applied research and development program that focuses on innovative solutions for water and power challenges in the Western United States. This research is authorized under the Reclamation Act of 1902 and the Reclamation Project Act of 1939. This research was conducted with support from the Land Change Science (LCS) Program under the Land Resources Mission Area of the U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2020-Project ID 1751 - Report Number 1

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Acronyms and Abbreviations

ACE	American Conservation Experience
ADWR	Arizona Department of Water Resources
ASU	Arizona State University
AZWSC	Arizona Water Science Center
BSA	Boy Scouts of America, Grand Canyon Council
CEC	Categorical Exclusion Checklist
CME	Central Mine Equipment
COP	City of Phoenix
COVID-19	Coronavirus (COVID-19) pandemic
DTM	Digital Terrain Model
DTW	Depth to Water
EROS	Earth Resources Observation and Science
ESRI	Environmental Systems Research Institute
FCDMC	Flood Control District of Maricopa County
fps	frame per second
GCS	Grade Control Structures
GI	Green Infrastructure
HSP	Heard Scout Pueblo
IPDS	Information Product Data System
K(h)	Hydraulic Conductivity
Ksat	Saturated Hydraulic Conductivity
LIDAR	Light Detection and Ranging
LSPIV	Large Scale Particle Image Velocimetry
MCPRD	Maricopa County Parks and Recreation Department
NAD 83	North American Datum 1983
NAU	Northern Arizona University
NCD	Natural Channel Design, Inc.
NEPA	National Environmental Policy Act

NWIS	National Water Information System
ORD	One Rock Dam
PSD	Particle Size Distribution
PVC	Polyvinyl Chloride
PXAO	Bureau of Reclamation Phoenix Area Office
Q	discharge
Qal	Quaternary Alluvium
QR	Quick Response
Qp	peak discharge
Reclamation	Bureau of Reclamation
SD	Security Digital
SMS	Soil Moisture Sensor
Aquaveo’s SMS	Aquaveo’s Surface Water Modeling System
SRP	Salt River Project
S&T	Science & Technology
sUAS	small Unmanned Aircraft Survey
TCP	Traditional Cultural Property
TDR	Trusted Digital Repository
TLS	Terrestrial Lidar Survey
TSC	Bureau of Reclamation, Denver Technical Services Center
URL	Universal Resource Locator
USA	United States of America
USACE	United States Army Corps of Engineers
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
USGS WGSC	USGS Western Geographic Science Center

Measurements

%	percent
°C	degree Celsius
°F	degree Fahrenheit
cfs	cubic feet per second
cm/s	centimeter per second
cmc	centimeter
dV/dt	change in water level per time
ft, als	feet, above land surface
ft, bls	feet, below land surface
ft^3/s	cubic feet per second
hr	hour
in/hr	inches per hour
m	meter
m/hr	meters per hour
psi	per square inch
µg/L	microgram per liter

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Executive Summary

The goal of this research was to examine the impacts of Grade Control Structure (GCS) installations at the Heard Scout Pueblo (HSP) study site in the City of Phoenix, Arizona, USA. The study site is around a high-use trail system and is comprised of eroded and incised channels that conduct high flows and associated sediments into a residential neighborhood downstream, a noted stormwater control problem. We established baseline conditions associated with rainfall/runoff response before structures were installed so we could have some data for comparison afterwards.

Innovative monitoring equipment, including video cameras and pressure transducers (to calculate discharge); digital terrain models, sediment samplers and sediment chains (to measure erosion and deposition); soil moisture sensors in monitoring wells (to document infiltration and potential recharge); and weather stations (to track temperature and relative humidity) were established and a small Unmanned Aircraft System (sUAS) survey was completed by July, 11, 2017, in time for the typical summer monsoon season which officially runs from June 15th to September 30th. Only one pre-GCS installation rain event incurred a significant flow event (October 13, 2018).

Natural Channel Design (NCD), a landscape restoration company with decades of experience, was hired through a competitive bid process to develop a novel layout of ~30 GCS installations (sills, modified one-rock dams (ORD), and plugs, as well as a modified Zuni-bowl). The American Conservation Experience (ACE) hand-built the structures based on these designs in the main channel from November 13, 2018 through December 1, 2018. ACE built another ten structures in locations adjacent to the channel from January 15 through January 18, 2019. NCD worked with the landscape forensics to identify a historic channel and reinstate it using GCS.

A surface-water model was also applied, using some of the baseline measurements (terrain and hydraulic conductivity) to track the flows of water and potential infiltration associated with rainfall events before GCS installation, to assist NCD in their design. The same model was applied using the installed GCS locations to simulate impacts of the structures on flow and infiltration. Our model was able to predict the slight reduction and delay in peak flows for small events and simulate infiltration, which was measured and occurred in the channel. Results demonstrated that structures could increase infiltration by ~15% over time. More data describing geomorphology and hydrology after repeated rainfall events will allow for increased analyses.

Innovative monitoring, including the large-scale particle image velocimetry (LSPIV) were invaluable to this research. Given the arid-land location and added drought conditions, the water levels were not high enough to compute, even using the continuous slope-area method, so discharge was calculated solely using the LSPIV. The careful redundancy of data acquisition is extremely important when studying dryland hydrology.

Weather data indicated that the HSP GCS installations created roughly a three-degree microclimate cooling effect for at least two days following rainfall events, as compared with the untreated channel. The cooling was attributed to increased moisture, evaporation, and latent heat expulsion from the evaporation.

1 Introduction

1.1 Background

Installation of GCSs across a landscape is an ancient practice that is increasingly used by landowners, land managers, and municipalities for restoration, ecosystem support, and stormwater management. GCSs of varying sizes and materials, commonly rocks, are regularly installed within drainages to slow storm flows, while allowing water to pass through them, to reduce channel cutting, promote river and habitat restoration, increase and extend surface water flows, recharge groundwater systems, and reduce flood-flow sediment loads prior to storm flows discharging from a watershed. Anecdotal evidence and limited research show that GCS installations reduce storm peak flows, decrease sediment transport, and increase base flows in arid lands (Norman, Ecosystem Services of Riparian Restoration: A Review of Rock Detention Structures in the Madrean Archipelago Ecoregion, 2020).

The Study was designed to assess hydrologic conditions pre- and post-GCS installations at the Boy Scouts of America (BSA) Heard Scout Pueblo (HSP) located at the base of South Mountain Park/Preserve in Phoenix, Arizona, USA. Phoenix is located in a hot desert climate and is the largest U.S. city in this climate zone. There can be extreme precipitation variability in Arizona's arid to semi-arid climate, where drought may consist of several drier than normal years that are likewise interrupted by some wetter than normal years (https://azclimate.asu.edu/drought/). The study area and region are in a 21-year drought that began in 2000 (and continues in 2020). In addition to this, Arizona's 2018, 2019, and 2020 monsoon seasons were relatively dry throughout most of the state (https://new.azwater.gov/drought/drought-status). Average annual precipitation in Phoenix is 8.03 inches (20.4 cm) (https://www.usclimatedata.com/climate/phoenix/arizona/united-states/usaz0166). From September 2016 to October 2019, the average annual precipitation recorded at Flood Control District of Maricopa County gage 68900 – Dobbins Rd @ 19th Ave was 6.08 inches (15.4 cm).

We established monitoring to assess the impacts of GCS installations on storm flows, local hydrology, soil moisture, and sediment transport. Our hypothesis was that, even in this extremely arid environment, GCS installations would enhance local water resources, reduce stream velocities, optimize watershed function, support ecosystems, and reduce sediment transport. Although GCSs are currently being installed for land and ecosystem restoration, these installations typically do not include hydrologic monitoring and there is some uncertainty as to their impacts (Norman, Ecosystem Services of Riparian Restoration: A Review of Rock Detention Structures in the Madrean Archipelago Ecoregion, 2020).

Surface water rights holders question the use of GCS installations and whether GCS installations "capture flood flows" (ARS 45-141) and infringe on downstream surface-water rights appropriations. Hydrologic and sediment transport monitoring is required to accurately document the impact of GCS installations and to inform this policy.

There is a growing interest in using GCS installations and associated urban Green Infrastructure (GI), that use natural materials in landscaping to slow, store, infiltrate, or evapotranspirate stormwater and more actively manage rainfall runoff (Section 502 of the Clean Water Act). Our goal is to capture and share hydrologic and sediment transport data to support development of integrative storm water management systems for optimum water resource utilization.

Data generated from the Study will help derive results useful to land and water resource managers, flood control districts, reservoir managers, and agencies that manage stormwater, surface water rights and water quality, to inform policy and to assess using GCS installations as an adaptive management alternative to optimize watershed function.

The Study collected surface water flow, soil moisture, precipitation, and sediment transport data pre- and post-GCS installations and assessed their impacts on local water resources, and sediment transport. Despite the drought conditions, there were two storm flow events that provided enough data to model and analyze surface water conditions pre- and post-GCS installations. The three-year Study was extended one year to end on September 30, 2020 due to below average precipitation.

On March 13, 2020 the United States declared a National Emergency due to the Coronavirus (COVID-19) pandemic which impacted some data collection at the HSP from mid-March through September 30, 2020. The Flood Control District of Maricopa County (FCDMC) is planning to assume monitoring at the site pending Board of Supervisor approval in October 2020.

1.1.1 Study Area

The South Mountain Park/Preserve in Phoenix, Arizona is managed by the City of Phoenix (COP) and is the largest urban park in North America (Figure 1). The Civilian Conservation Corps built trails, dams, and other features in the area in the 1940s. South Mountain is sacred to Native Americans. The BSA HSP property is nestled on the north face at the base of South Mountain. The study site drains into the Salt River Watershed, part of the larger Colorado River Watershed. HSP consists of approximately 145 acres, bounded by COP residential land use to the north and South Mountain Park/Preserve to the south (Figure 1).

South Mountain peaks at ~2,700 ft (823 m) elevation and is a substantial source of runoff and associated sediment during heavy rainfalls. This can negatively impact the surrounding neighborhoods with sediment-laden floodwaters. The Bureau of Reclamation (Reclamation) is working with Flood Control District of Maricopa County (FCDMC) who is interested in addressing these issues. Reclamation was able to partner with BSA to conduct the Study in a small drainage at the HSP. The site may be used for further research and restoration projects in the area. A larger drainage west of the study area has historically flooded and transported sediments into a downstream residential area.

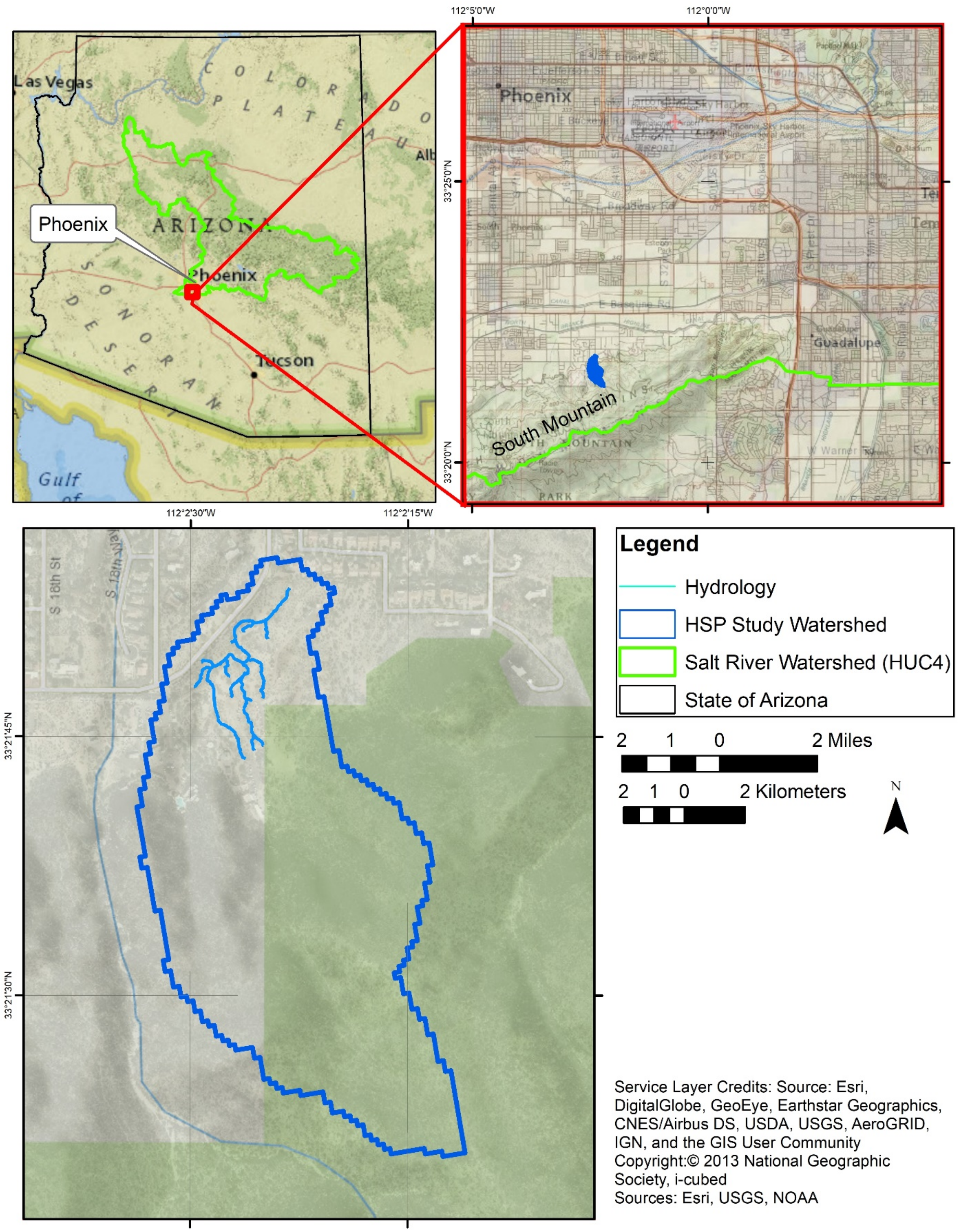


Figure 1. Study area watershed and hydrology in relationship to the State of Arizona, the Salt River (HUC 4) Watershed, the City of Phoenix and South Mountain Park/Preserve.

Using the StreamStats Web application developed by the U.S. Geological Survey (USGS) (available at https://streamstats.usgs.gov), we delineated our study site drainage area (Figure 1) and retrieved up-to-date flood frequency and basin characteristic data (Paretti, Kennedy, Turney, & Veilleux, 2014). The resulting HSP study area watershed is ~ 0.14 square miles (36 hectares; Figure 1), of which 11% of the surface area contains high permeability sediments. Mean annual precipitation is ~8.7 in (22 cm) and the average annual temperature is 71.06°F (21.7°C). The mean basin slope is ~33.62 %, where more than half of the basin is >30% slope. Magnitude and frequency of floods were estimated with regional regression equations in StreamStats for the study area (Table 1).

Table 1. Peak flow statistics calculated using StreamStats (Paretti, Kennedy, Turney, & Veilleux, 2014).

StreamStats

PIl: Prediction Interval-Lower, PIu: Prediction Interval-Upper, SEp: Standard Error of Prediction, SE: Standard Error (other -- see report)

Statistic	Value	Unit	PIl	PIu	SEp
2 Year Peak Flood	40.3	ft^3/s	9.11	179	109
5 Year Peak Flood	96.9	ft^3/s	42.2	223	52.4
10 Year Peak Flood	150	ft^3/s	86.4	259	33.3
25 Year Peak Flood	207	ft^3/s	123	346	30.2
50 Year Peak Flood	288	ft^3/s	170	490	31.1
100 Year Peak Flood	384	ft^3/s	198	746	39.7
200 Year Peak Flood	501	ft^3/s	213	1180	52.9
500 Year Peak Flood	686	ft^3/s	226	2080	72.2

Site features are shown on Figure 2 and described below (modified from Wilson 2019). The study drainage begins in the steep and rocky slopes of South Mountain Park/Preserve. The base of this steep section was excavated, and several BSA facilities were constructed. The drainage flows downstream through a shooting / archery range and amphitheater from the base of the mountain. Just above the amphitheater, a trench was dug to divert water to the east of the main drainage. This trench is of unknown age and may have contributed to head cut problems above the staging area for the shooting range. A culvert conveys the water under the amphitheater to a concrete-lined moat that separates the amphitheater stage from the audience. Flow continues under a pedestrian bridge and through a campground, across a road, and through several additional campgrounds. There are remnants of a pre-existing earthen berm located along the channel edges but the center of the berm has been erased from the channel upstream of a small amphitheater. There is a small area located west of the channel that contributes minor flow to the main drainage that historically flowed into a pool facility. The flows are now conveyed around the pool. Previously, this small contributing drainage was contained via an earthen berm which was breached prior to the start of the Study. The breach is narrow and there is a higher abundance of annual grasses and fine sediments above the berm. Overall, the area to be restored is small and contains multiple recreational structures (roads, ramadas, tables). The vegetation in the area of restoration consists of riparian woodland including palo verde, mesquite, and ironwood trees, and creosote–brittlebush shrubland, consistent with the low Sonoran Desert.

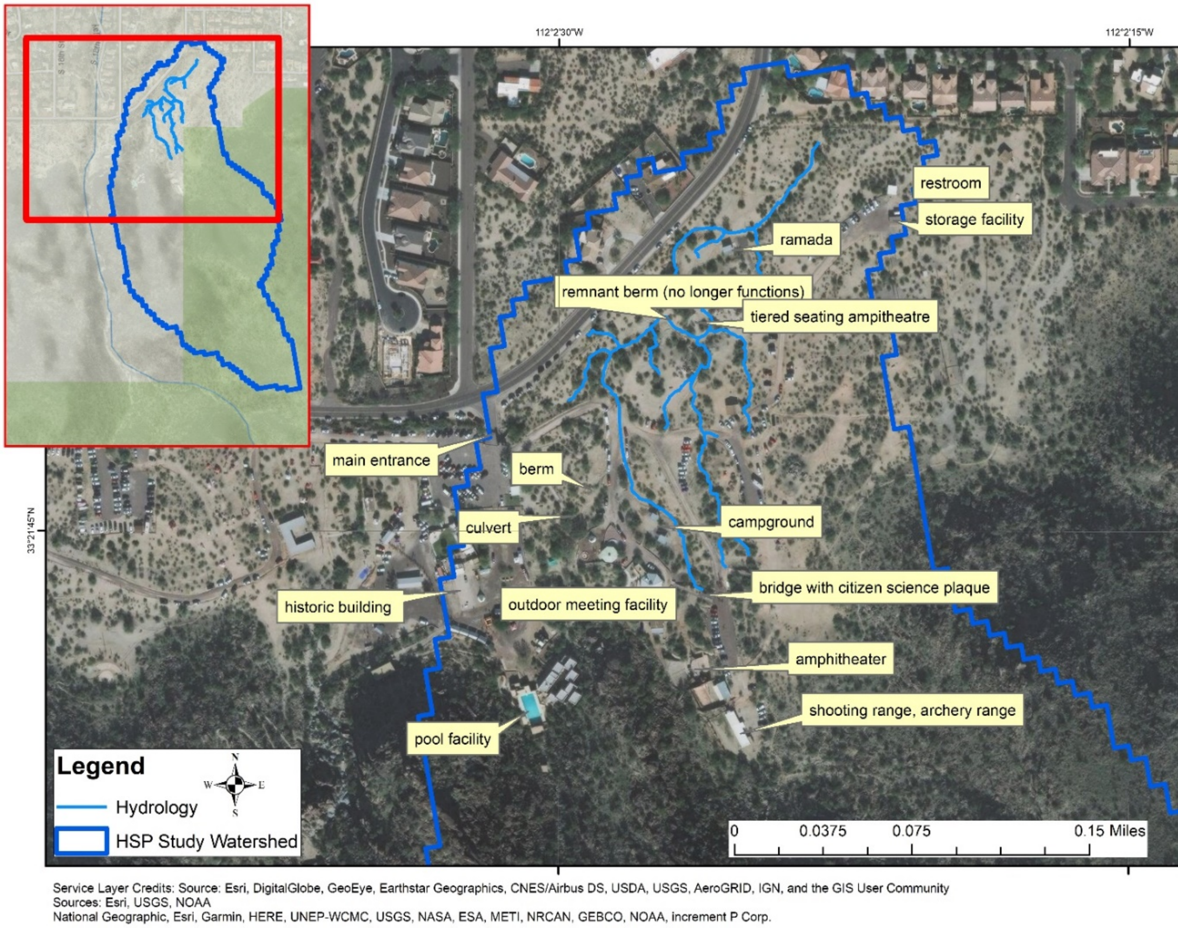


Figure 2. Boy Scouts of America, Heard Scout Pueblo study site and facilities.

The HSP site is open to the public and the study area provides a good venue to promote public education about local water resources. At the conclusion of the Study, the GCS installations will remain in place at the HSP. Originally, the monitoring equipment was scheduled to be removed from the HSP at the end of the Study on September 30, 2020; however, the FCDMC is establishing agreements with the BSA and the USGS to assume responsibility for continued monitoring at the site pending Board of Supervisors approval in October 2020.

1.1.2 Timeline

In 2017, Reclamation's Science & Technology (S&T) program approved a proposal (Appendix 1) for a three-year study for hydrologic research pre- and post-GCS installations. In 2019, the Study received a one-year extension due to drought conditions, expanding the study duration to four-years. Study tasks included: develop outreach, coordinate with partners and stakeholders, identify research locations, develop and execute agreements, conduct environmental and cultural surveys, obtain necessary permits, install monitoring equipment, survey drainage, conduct pre-GCS installation monitoring, install GCSs, conduct post-GCS installation monitoring, analyze data, interpret results and prepare report. Site activities are portrayed in the timeline (Figure 3).

During the first year, the Study Team initiated and planned the study. Agreements were completed between Reclamation and the BSA and between Reclamation and USGS. Site visits were conducted with team members to identify suitable locations for monitoring equipment. Site conditions were assessed, and potential GCS installation locations and staging areas were located. Reclamation staff completed National Environmental Policy Act (NEPA) requirements including U.S. Army Corps of Engineers (USACE) 404 permitting, and Endangered Species Act (ESA) and Historic Preservation Act (HPA) surveys. After receiving all required approvals, monitoring equipment was installed and data collection began. A sUAS survey was completed. See Appendix 2 for additional details of the 2017 field activities.

During the second year, monitoring at the site continued. In October 2018, the first significant pre-GCS installation stream flow event was recorded. USGS completed a sUAS survey to document the post-storm channel changes. Reclamation's contractor Natural Channel Designs (NCD) completed GCS installations in the channel in November and December 2018. USGS completed another sUAS survey to document the GCS installations. Additional rock plugs and simple rock structures were installed in eroded areas at the site in January 2019.

During the third and fourth year of the study, monitoring and data collection continued. A post-GCS installation storm flow event occurred on November 29, 2019. FCDMC staff completed a sUAS survey in March 2020. Terrestrial Laser Scanning (TLS) was completed on March 2 and 3, 2020 by the USGS to assist with channel delineation where the ground was obscured by vegetation. The USGS completed channel infiltration testing on June 18, 2020 to provide infiltration data for the surface water model.

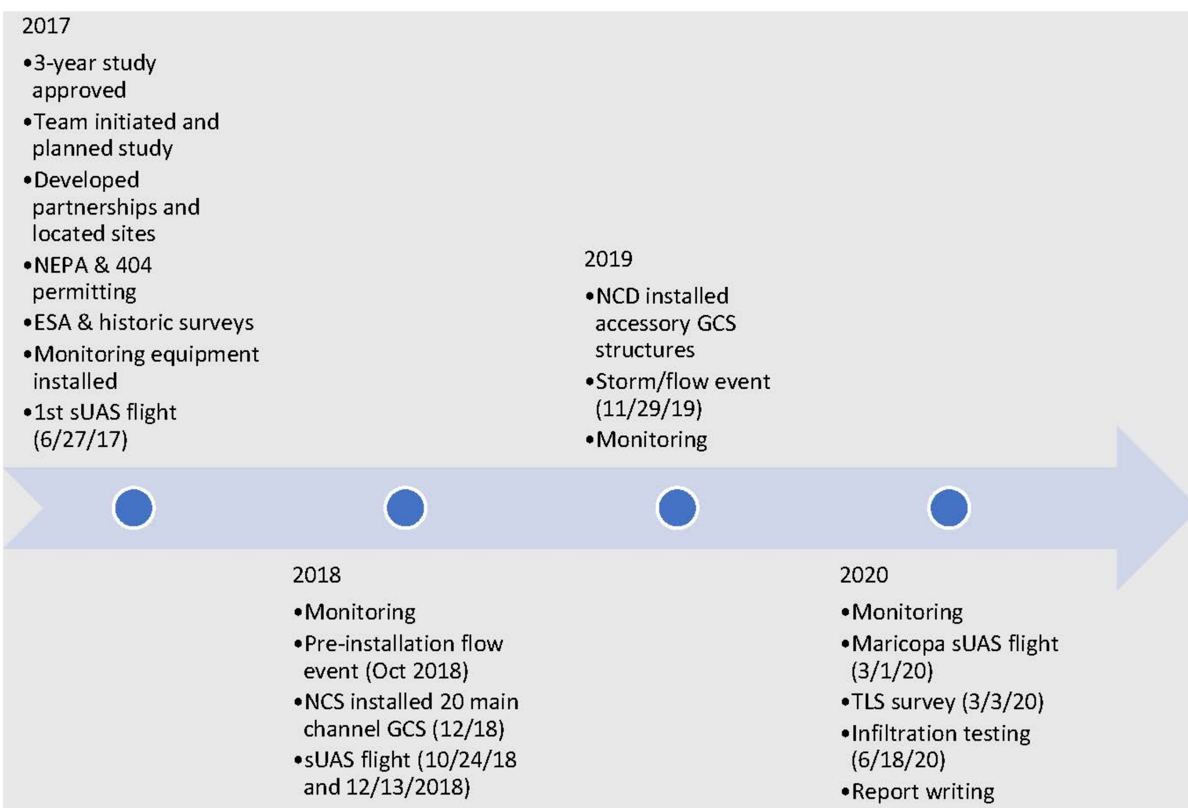


Figure 3. Timeline of Study research actions.

1.1.3 Partners

Active Study partners include: Boy Scouts of America (BSA) Grand Canyon Council, Reclamation's Denver Technical Service Center (TSC), USGS Western Geographic Science Center (WGSC), Arizona Water Science Center (AZWSC), Northern Arizona University (NAU), and Flood Control District of Maricopa County (FCDMC).

1.1.4 Stakeholders

Stakeholders who supported the S&T proposal submission and other interested stakeholders who attended the kickoff meeting include:

- Arizona Geological Survey
- Arizona State University
- Bat Conservation International
- Borderlands Restoration L3C
- Cuenca Los Ojos
- Hopi Tribe
- Maricopa County Parks and Recreation Department
- private citizens
- Reclamation's Albuquerque Area Office
- Sky Island Alliance
- Sky Island Restoration Cooperative
- Southern Rockies and Desert Landscape Conservation Cooperative
- Stream Dynamics, Inc.
- The Nature Conservancy
- Tucson Audubon
- U.S. Department of Agriculture – Agricultural Research Station
- U.S. Fish and Wildlife Service
- U.S. Forest Service
- WaterRock L3C

1.2 Research on GCSs

Reclamation's S&T Program approved S&T #720, a scoping study titled *Installing Erosion Control Structures across a Landscape as a Restoration Treatment and Adaptive Watershed Management Alternative,* that began on October 1, 2016 and concluded on September 30, 2017. The scoping study preceded the current Study. Work included a literature review, identification of potential partners and stakeholders and potential study locations, public outreach via an all-day meeting, and a final report. The scoping study resulted in identifying potential research locations, an email notification list of 90 members, and multiple Study partners. Subsequently, a proposal for an S&T study was submitted to request approval to conduct a three-year study for hydrologic research pre- and post-GCS installations.

In recent years, recommendations for alternative stormwater management to slow stormflows, reduce flooding and increase infiltration have been promoted. For example, in September 2015, the Environmental Protection Agency provided funding for a three-year study titled *Assessment of Stormwater Harvesting via Managed Aquifer Recharge to Develop New Water supplies in the Arid West: The Salt Lake Valley Example* (https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/10497/report/0). In December 2015, the National Academies of Sciences, Committee on the On-Site Reuse of Graywater and Stormwater, released a pre-publication report titled *Using Graywater and Stormwater to Enhance Local Water Supplies: An Assessment of Risks, Costs, and Benefits* (https://www.nap.edu/catalog/21866/using-graywater-and-stormwater-to-enhance-local-water-supplies-an).

Reclamation's Climate Change and Water 2016 Report to Congress included stormwater capture as an adaptation strategy and identified the need to take action to build ecosystem resiliency. Information from the Study may be applicable to assess the potential to use GCS installations. There is a need to identify methods that may be used for restoration to improve water quality and increase water resources. GCS installations may be applied in any environment, for example, to enhance groundwater recharge and support wetland, meadow, and stream corridor restoration in the Truckee River Basin; improve resource stewardship for forest health in the Sacramento and San Joaquin Basins; and increase groundwater storage capacity and improve soils and watershed resiliency in the Rio Grande Basin.

The Arizona Department of Water Resources (ADWR) provides technical support to the Arizona Water Protection Fund (AWPF) Commission which awards grants for projects that include GCS installations for restoration, conservation, and protection of water resources. In southeastern Arizona, over a period of 30 years, private landowners affiliated with Cuenca Los Ojos property have installed thousands of GCSs in the drainages on their property. This resulted in remarkable and notable quantifiable changes in the watershed, including reduced storm flow peaks; reduction in stormflow bedload; a spatial and temporal increase in post precipitation stormflow; increased availability of local water resources; habitat establishment with improved inter-connectivity; and increased environmental awareness, education, and economic opportunities (Norman, Ecosystem Services of Riparian Restoration: A Review of Rock Detention Structures in the Madrean Archipelago Ecoregion, 2020).

In 2014, land managers, restoration practitioners, and scientists toured the Cuenca Los Ojos property and installations in southeastern Arizona and joined together to form the Sky Island Restoration Cooperative (SIRC) to promote GCS installations for land management (Norman, et al., 2020 In Press). SIRC combined two million dollars' worth of in-kind resources from 35 contributing organizations on 16 inter-disciplinary and cross-jurisdictional GCS installation projects in its first year.

The USGS studied and published the impacts of GCS at various sites, for which a literature review follows. Results from the USGS Aridland Water Harvesting Study are compared to these findings in the discussion of this report. At Ambos Nogales, GCS were installed to prevent flooding using a watershed model and varied future urban scenarios. Results depict a reduction in peak flow for the 10-year, 1-hour event based on current land use in tributaries with GCS, but demonstrate that larger storm events and increasing urbanization limit their effectiveness (Norman, et al., 2010a; Norman, et al., 2010b). Norman et al. (2015) conducted hydrological investigations in the Chiricahua Mountains of southeast Arizona, comparing stormflow measurements from a mature drainage treated with GCS to measurements from an untreated drainage (control). They found that stormflows in the treated drainage were less flashy; had fewer transmission losses; extended summer base-flow; showed a reduction in average rate of flow by more than one half, and sustained about 28% increased flow volume than the untreated watershed (per unit area). The hydrological discharge measurements from the field were used to calibrate a soil and water assessment model to predict soil volumes at the same study area, with estimates of ~800 tons per year eroded in the treated drainage and 200 tons per year captured in the GCS system (Norman & Niraula, Model analysis of check dam impacts on long-term sediment and water budgets in Southeast Arizona, USA, 2016).

The USGS employed runoff, sediment transport, and geomorphic modelling, and repeat TLS surveys to map landscape changes at the same Chiricahua system and in gullies being studied in the Patagonia Mountains, Southeast Arizona (Norman, et al., 2017). Where discharge data were not available, event-based runoff was modeled and estimated for use as input to a two-dimensional unsteady flow-and-sedimentation model that combined a gridded flow, transport, and bed and bank simulation with geomorphic change. In addition, consecutive digital elevation models were compared, and identified the potential to substitute uncalibrated models to analyze stream restoration and assess hydraulics and associated patterns of aggradation and degradation resulting from the construction of GCS. Norman et al. (2019) investigated coupling field experiments with surface and groundwater modeling to investigate rangelands by the Huachuca Mountains, Southeast Arizona, using GCS to augment shallow and deep aquifer recharge. A watershed model was applied and calibrated using long-term discharge data and 3D terrain measurements, to simulate flow volumes. The average increase in infiltration measured in the field (~10%) at gabions was used in the model to quantify long-term impacts of riparian restoration on the larger annual water budget. Results support the potential of watershed-wide gabion installation to increase total aquifer recharge, with models portraying increased subsurface connectivity and accentuated lateral flow contributions.

Preliminary research using a remote-sensing analysis coupled with field data quantified the effects of GCS on vegetation in the Cienega San Bernardino, in the Arizona and Sonora portion of the U.S.-Mexico border (Norman, et al., 2014). The Normalized Difference Vegetation Index (NDVI) was used as a proxy for plant biomass and compared at gabion and control sites over a 27-year period, finding that green-up occurred at most sites where there were gabions and at a few control sites where gabions had not been constructed, despite long-term drought conditions. Wilson and Norman (2018) further analyzed spatial and temporal trends of GCS at San Bernardino to increase vegetation greenness and soil moisture areas up to 5 km downstream of restoration sites over time and to affect 1 km upstream of the structures themselves. All these USGS studies are summarized in a recent publication and translated into ecosystem services (Norman, Ecosystem Services of Riparian Restoration: A Review of Rock Detention Structures in the Madrean Archipelago Ecoregion, 2020).

GCS research conducted by the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) includes pre- and post-installation monitoring which provides a great foundation to build on; however, the USDA reports that "Ongoing research is needed to quantify the long-term … impacts of low-tech (GCS)" (Nichols, McReynolds, & Reed, 2012). Further studies are necessary to collect data to assess safety, potential impact on downstream water rights holders, and impacts to the environment and society. Reclamation research of GCS installations builds on the work of others to conduct further research to inform policy.

1.3 Problem the Study Addresses

In one of the first studies to assess long-term changes in monsoon activity, University of Arizona researchers compared precipitation records for Arizona from 1950-1970 to precipitation records from 1991-2010. The UA analysis showed that there were fewer storms and that large monsoon thunderstorms brought heavier rain than monsoon storms that occurred 60 years ago (Luong, et al., 2017). People living in arid lands are particularly vulnerable to climatic changes related to temperature and decreased precipitation. Land and resource managers are seeking solutions to adapt to change and increase resilience. Phoenix, Arizona, has the hottest average high temperatures in summer of any major city in the United States and provides a perfect study site to investigate how GCS installations might sustain water supplies and potentially impact the effects of climate change.

Limited hydrologic research has shown that GCS installations reduce stormflow peaks, reduce sediment transport, improve water quality, provide soil moisture for ecosystems, and increase local water resources (Norman, Ecosystem Services of Riparian Restoration: A Review of Rock Detention Structures in the Madrean Archipelago Ecoregion, 2020). Additional research to collect hydrologic data around structures is necessary to assess safety, potential impact on downstream surface water-rights holders, and impacts to the environment and society. This Study builds on the work of others and provides insight into how GCS installations impact hydrologic conditions and sediment transport as an adaptive management strategy to inform policy.

Measuring stream flow in ephemeral channels is challenging. The funds required to instrument remote surface water monitoring locations and hire staff to collect, analyze, interpret and report hydrologic data are often not available. As a result, hydrologic data associated with GCS installations is lacking. This research provides information to address significant legal and institutional barriers to the use of GCS installations as an adaptive management strategy.

1.4 Study Objectives and Approach

The objectives of the Study were to address the following research questions:

1. What are the impacts of GCSs installed in ephemeral drainages of extremely arid environments?
2. How do GCSs impact storm flows, local hydrology, soil moisture, microclimates, and sediment transport?
3. Can GCSs increase water quality by reducing sediment, a nonpoint source pollutant, deposition downstream (i.e. in reservoirs)?
4. Do GCSs support ecosystems and optimize watershed function in varied climates?
5. Can GCSs “capture flood flows” (ARS 45-141) without infringing upon surface water appropriations?

Our approach is outlined in the Conceptual diagram below (Figure 4), with specific timelines addressed previously (Figure 3).

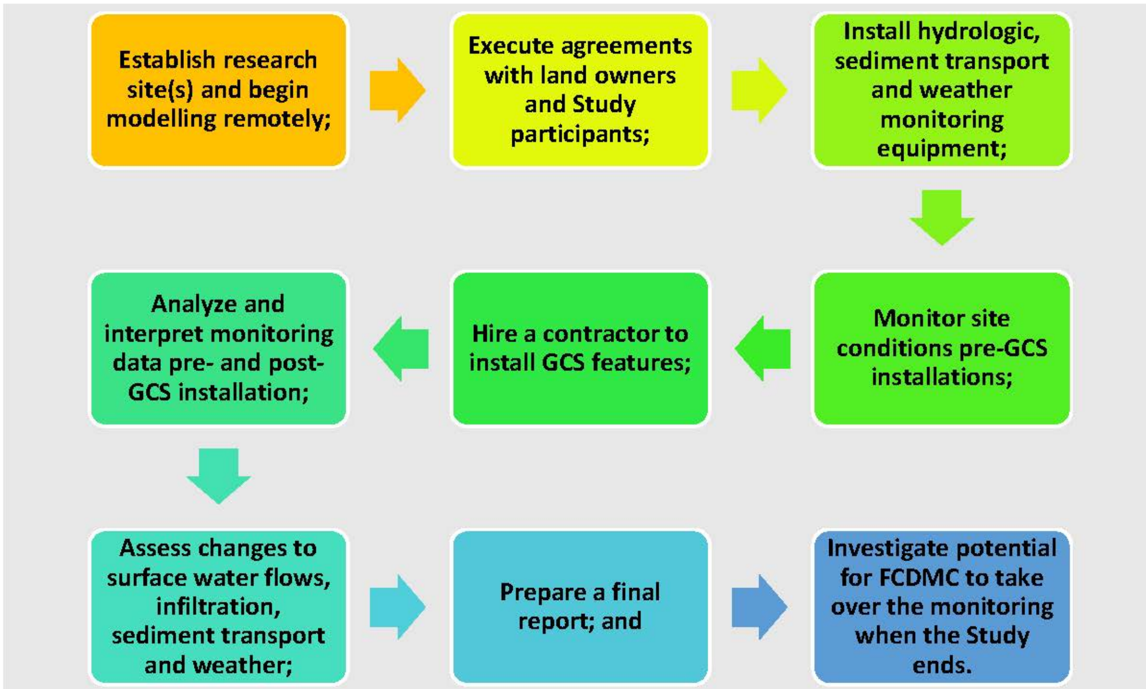


Figure 4. Conceptual diagram outlining Study approach.

1.5 Study Participants

A diverse group of people assisted throughout and on all aspects of the Study including site selection, preparation of agreements, environmental surveys, site visits, monitoring installations and data collection, analyses, and reporting. The many people who assisted on this Study are shown in Table 2.

Table 2. Study partners and agencies, and their contributions

Entity	Office	Personnel Name	Title	Contributions
Arizona State University	School of Life Sciences, Julie Ann Wrigley Global Institute of Sustainability	Nancy Grimm, Ph.D.	Professor, Senior Sustainability Scientist	Visited the site and promoted the site for student research projects.
Boy Scouts of America (BSA)	Grand Canyon Council	Gregory Harmon	Director	Partnered with Reclamation under MOU 17-MOU-32-0003 to use the Heard Scout Pueblo as a research site.

Entity	Office	Personnel Name	Title	Contributions
	Grand Canyon Council	Cameron Thomas	Ranger	All site visits were coordinated through Thomas.
City of Phoenix	Demand Research and Infrastructure Planning - Water Services Dept	Darin Lisonbee	Water Quantitative Analyst	Processed Light Detection and Ranging (LIDAR) data flown by the USGS in 2014. COP provided original files and processed files for the HSP area.
	Environmental Programs	Tricia Balluf	Environmental Programs Coordinator	Coordinated with COP staff to provide LIDAR data.
Flood Control District of Maricopa County (FCDMC)	Director's Office	Michael Fulton	Director	Assessed the potential for FCDMC to take over monitoring at the HSP site when the Reclamation Study ends on September 30, 2020. FCDMC staff are developing agreements with the BSA and the USGS to continue monitoring pending Board of Supervisor approval in October 2020.
	Landscape Architect and Water Conservation Branch	Harry Cooper	Manager	Introduced Reclamation to the BSA staff which led to use of the HSP as a research site.
	Mapping, Surveying, and CAD	Joe Wagner	Manager	Personally conducted a UAS flight at the Heard Scout Pueblo in March 2020 after USGS UAS program was temporarily halted due to software issues.
Maricopa County	Parks and Recreation Department	R.J. Cardin	Director	Provided the opportunity to use Spur Cross Ranch or the Hassayampa River Preserve as research sites. Meetings with Mr. Cardin and Kenneth Vonderscher indicated that it may take up to a year to establish an MOU between Reclamation and Maricopa County Parks and Recreation Department (MCPRD). Based on the limited timeframe of the Study it was mutually agreed that the MCPRD proposed research sites would not be pursued.

Entity	Office	Personnel Name	Title	Contributions
Northern Arizona University (NAU)	Computing, and Cyber Systems	Benjamin L. Ruddell Ph.D.	Professor in and Director of School of Informatics	Provided a pair of WeatherHawk Signature weather stations, freshly calibrated and analyzed and interpreted the data.
Bureau of Reclamation	Denver Technical Services Center (TSC)	Blair Greimann	Hydraulic Engineer	Oversaw all TSC technical work and developed and ran the surface water model
	Denver TSC	Victor Huang	Hydraulic Engineer	Assisted with modeling used to analyze hydrologic and sediment transport data pre- and post-GCS installations.
	Yuma Area Office	Jordan Mogdolino	Drill Crew	Assisted with operation of a drilling auger rig to drill and install two monitoring wells.
	Lower Colorado Regional Office	Michael Miller	Regional Geologist	Geologist on site, logged well cuttings and core, prepared and submitted samples for laboratory analysis, oversaw well installation.
	Yuma Area Office	Robert Firasek	Drill Rig Operator	Oversaw and operated a drilling auger rig to drill and install two monitoring wells.
	Yuma Area Office	Willie Nelson	Drill Crew	Assisted with operation of a drilling auger rig to drill and install two monitoring wells.
	Engineering Service Office (ESO) - Water Resource/ Hydrological Analysis Group	Colleen Dwyer	Technical Writer	Completed technical edits and ensured that the report format meets 508 compliance requirements.
	Phoenix Area Office (PXAO)	Johnida Dockens	Environmental Protection Specialist	Completed research and surveys and prepared Categorical Exclusions Checklist.
	PXAO	David Giffords	Archaeologist	Completed research and surveys and prepared HPA report.
	PXAO	Dennis Van Ryckeghem	Land Surveyor	Surveyed all monitoring installations and assisted with installation of two WeatherHawk stations.
	PXAO	Helena Yomomata	Student Intern	Assisted with installation of two WeatherHawk stations.

Entity	Office	Personnel Name	Title	Contributions
	PXAO	Lisa Rivera	Natural Resource Specialist	Assisted with processing weather data and preparing precipitation graphs.
	PXAO	Ryan Revells	Cartographer (GIS)	Oversaw and assisted with installation of two WeatherHawk stations. Maintained and monitored the WeatherHawk stations and pressure transducers that were installed in monitor well HSP-2.
	PXAO	Linda Howell	Agreements Specialist	Prepared Intergovernmental Agreements between Reclamation and USGS.
	ESO, Water Resource/ Hydrological Analysis Group	Chad Vellinga	Supervisory Engineer	Provided a Technical Peer Review for the Study.
Salt River Project	Water-measurement group	Jamie Ashby	Engineer	Collaborated to identify a potential research site in the Verde River watershed and planning.
	Water-measurement group	Lee Ester	Manager	Collaborated to identify a potential research site in the Verde River watershed. A site location was selected. SRP operates a previously installed long-term continuous surface water monitoring site. Existing monitoring would potentially extend the pre-GCS installation monitoring from one to four years and post monitoring from two years to a decade. Despite the interest, we were unable to execute agreements based on timing, funding, and agency priorities.
South Mountain Environmental Education Center (SMEEC)	Community Learning, Phoenix Zoo, Arizona Center for Nature Conservation	Carrie Flood	Community Learning Manager	Made opportunities available to provide public presentations, site visits and training for SMEEC staff and docents.

Entity	Office	Personnel Name	Title	Contributions
U.S. Forest Service (USFS)	Region 3, Kaibab National Forest	Kit MacDonald	Forest Ecologist	Collaborated to identify a potential research site in the Verde River watershed, USFS, Region 3, Kaibab National Forest in northern Arizona. A site location was selected. USFS completed NEPA surveys. Despite the interest, we were unable to execute agreements based on timing, funding, and agency priorities.
	Region 3, Kaibab National Forest	Micah Kiesow	Soil Scientist	Collaborated to identify a potential research site in the Verde River watershed, USFS, Region 3, Kaibab National Forest in northern Arizona. A site location was selected. USFS completed NEPA surveys. Despite the interest, we were unable to execute agreements based on timing, funding, and agency priorities.
	Region 3, Kaibab National Forest	Victoria Payne	NEPA Planner	Collaborated to conduct NEPA requirements for the selected site. USFS completed NEPA surveys and completed Public Notice requirements. Despite the interest, we were unable to execute agreements based on timing, funding, and agency priorities.
U.S. Geological Survey (USGS)	Arizona Water Science Center (AZWSC)	Jay Cederberg	Hydrologist	Oversaw and participated in most USGS monitoring activities including installations, monitoring, and reporting. The work was completed under Intergovernmental Agreement (IA) R17PG00037.
	AZWSC	Brandon Forbes	Hydrologist	Conducted one Terrestrial LIDAR Survey
	AZWSC	Bruce Gungle	Hydrologist	Assisted with equipment installation to monitor hydrologic conditions and sediment transport.
	AZWSC	Geoff DeBenedetto	Geographer	Conducted three sUAS surveys
	AZWSC	James Callegary	Hydrologist	Conducted infiltration testing.

Entity	Office	Personnel Name	Title	Contributions
	AZWSC	Nicholas Peretti	Hydrologist	Assisted with equipment installation to monitor hydrologic conditions and sediment transport.
	Western Geographic Science Center (WGSC)	Laura Norman, Ph.D.	Supervisory Research Physical Scientist	Provided data analysis, interpretation and support for report preparation under IA R20PG00023.
	WGSC	Natalie Wilson	Physical Scientist	Conducted a site visit and preliminary plant survey. Natalie also met with Reclamation and ASU students to assist with identifying potential plant research at the site.

2 Methods

2.1 Permitting

NEPA requires federal agencies to consider the environmental impacts of federal actions prior to making decisions on permit applications. Using the NEPA process, Reclamation evaluated the environmental and related social and economic effects of the proposed actions. Reclamation completed all required surveys to meet environmental requirements for the installation of monitoring equipment and GCSs in ephemeral drainages at the HSP.

Reclamation's Environmental Resource Management Division conducted site surveys and prepared a Categorical Exclusion Checklist (CEC). Environmental surveys were completed for 3,800 linear feet of ephemeral washes within about 14 acres at the HSP. Following approval of the CEC, site visits were completed, monitoring equipment was installed and all installations and some site features were surveyed.

NEPA Ecology

- The project is in a previously developed landscape. No federally listed or candidate species, or suitable habitat for those species, are known to occur within the action area. It was determined that Reclamation's proposed action would not affect federally listed species.

NEPA Cultural Resources

- South Mountain is a Traditional Cultural Property (TCP) and Sacred Landscape to the Tohono O'odham people. HSP is a historic facility managed by the BSA as a campground and retreat since 1925.
- Reclamation staff completed a Class I records search and Class III field survey of the HSP site on May 5, 2017 prior to ground-disturbing actions. Survey results were determined to be No Effect to Historic Properties. On June 7, 2017, the Arizona State Historic Preservation Office and interested Native American Tribes concurred with Reclamation's determination.
- <u>Environmental Stipulation</u>: It was determined that Reclamation's GCS installation contractor was required to source rock materials for the GCS installations from an environmentally approved commercial source. Alternatively, the Contractor was required to provide environmental clearance documentation to Reclamation's Environmental Resources Management Division if other material sources were to be used.

U.S. Army Corps of Engineers

- On May 4, 2017 the USACE determined that washes within the project area are non-jurisdictional, and therefore the project is not subject to authorization by the USACE.

Categorical Exclusion Checklist

- On June 23, 2017 Reclamation completed a CEC for monitoring equipment and GCS installations at the HSP under Exclusion Category 516 DM 14.5 B(l) – Routine planning investigation activities where the impacts are expected to be localized, such as land classification surveys, topographic surveys, archeological surveys, wildlife studies, economic studies, social studies, and other study activity during any planning, preconstruction, construction, or operation and maintenance phase. The CEC is provided in Appendix 3.

2.2 Monitoring

Reclamation PXAO and Denver TSC worked with USGS to identify locations for the monitoring equipment installations. Site visits were conducted at the HSP to verify site conditions and locations for monitoring equipment installations. Photographs of monitoring activities are shown in Appendix 4.

Monitoring equipment installations began on June 26, 2017 and were completed by July 11, 2017 in anticipation of the 2017 monsoon season. Figure 5 shows the monitoring equipment locations in relationship to hydrology and watershed boundary.

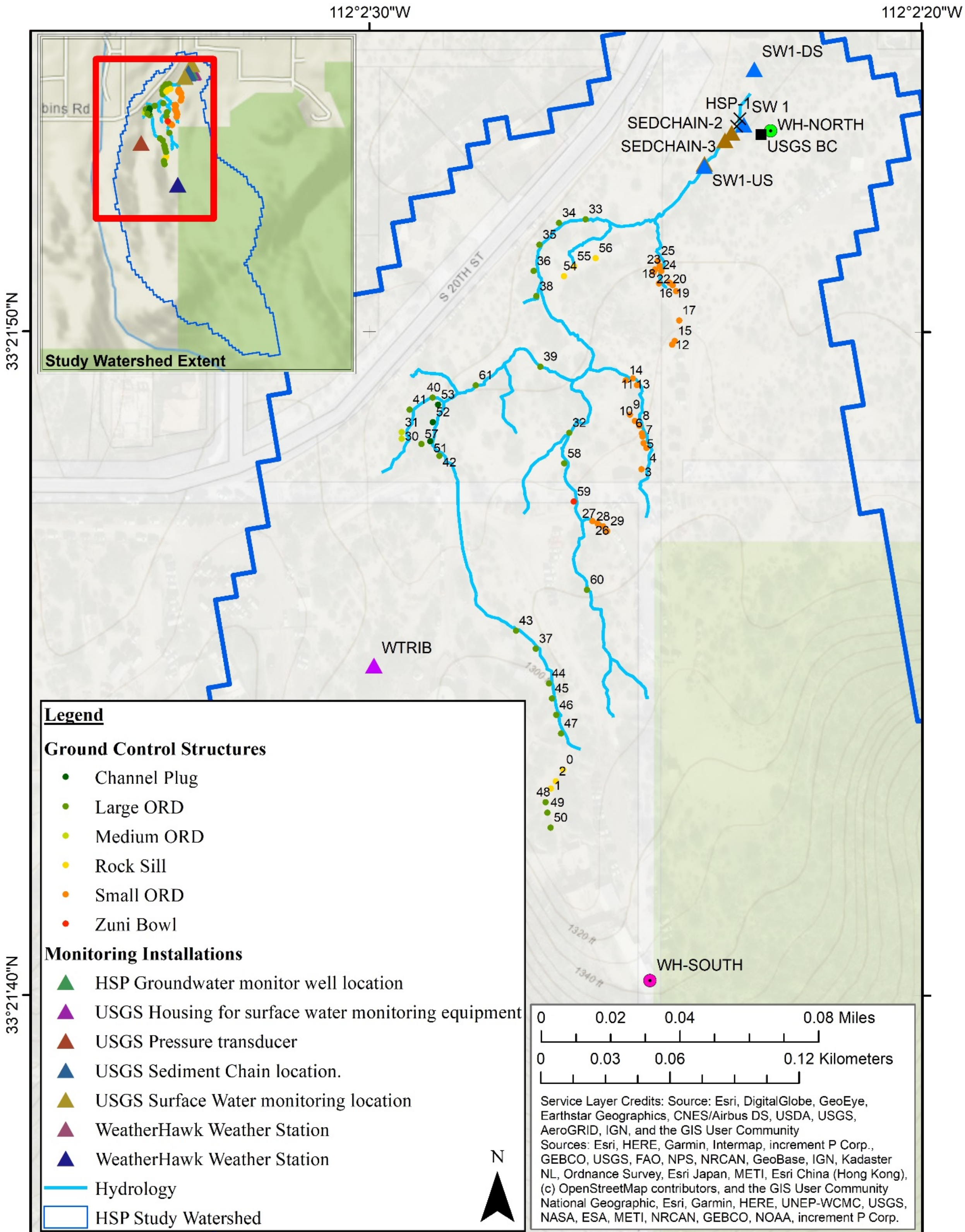


Figure 5. Locations of monitoring equipment for the Study.

The USGS installed one surface water flow monitoring station, a video camera, three sediment scour chains, and sediment samplers at the HSP (Figure 5). Site surveys were collected of the ephemeral drainage and study area by the USGS who piloted three sUAS and one TLS. In addition, Joe Wagner with the FCDMC piloted one sUAS survey.

Reclamation staff installed two weather stations at the HSP that were donated by NAU. To monitor channel infiltration, Reclamation drilled two groundwater monitoring wells within the ephemeral drainage near the USGS surface water monitoring station. Reclamation collected standard survey measurements for all monitoring equipment installations and some site features.

2.2.1 Surface water

The USGS began surface water streamflow data collection activities at an unnamed wash at HSP (USGS station number - 32153112022300) on June 26, 2017. A streamflow monitoring station was installed at the lower reach of the unnamed wash near the northeastern property boundary of the HSP. Streamflow was computed using standard USGS methods as outlined in Rantz and others (1982). Estimates of streamflow were obtained utilizing video of streamflow events collected on site in conjunction with large scale particle image velocimetry (LSPIV) techniques.

2.2.1.1 Equipment and Installation

The streamflow monitoring station is located at latitude 33.36475278, longitude -112.03979720 (NAD 83) (Figure 5; SW-1). The monitoring station consists of a 24 in x 24 in x 48 in a metal shelter located on the east stream bank terrace which houses the electronic recording equipment. A primary pressure transducer was installed in the channel using a metal U channel driven into the streambed as an attaching point. The transducer is used to monitor the water stage in the channel and is connected to the recording device in the shelter via a buried wire. Initially, the primary transducer was a non-vented Solinst Levelogger (model 5001) with barometric compensation computed at the time of measurement. The accuracy of this equipment did not meet specifications; as a result it was replaced with a vented In-Situ Troll (model 700 H) on August 8, 2017. The recording device was a Design Analysis H-522+ with GOES satellite telemetry. Stage data were collected at a 5-minute interval and transmitted via satellite to USGS and published to NWISweb hourly. Equipment was powered using 12-volt batteries with power levels maintained by solar panels.

A Hikvision video camera (model DS-2CD2T42WD-I5) was mounted on top of a 10 ft mast at the shelter. The video camera was programmed to record a 1-minute video of the stream at the pressure transducer every 5 minutes when water was detected in the stream channel. Collected video was stored on an internal SD card and manually downloaded during site visits.

Two additional non-vented pressure transducers (Solinst Levelogger model 5001) were installed in the stream reach, one upstream and one downstream, to verify stage measurements and aid in streamflow computations. Because the transducers were non-vented, stage readings were corrected for barometric pressure using an on-site auxiliary barometer. Under the proper conditions, computation of streamflow using indirect methods of a slope-area computation could be used as documented in Dalrymple and Benson (1967) and Smith, Cordova & Wiele (2010). The upstream transducer (Figure 5; SW1-US) is located at latitude 33.364581, longitude -112.039968 which is about 87 ft upstream of the primary transducer. The downstream transducer (Figure 5; SW1-DS) is located at latitude 33.364993, longitude -112.039744 which is about 90 ft downstream of the primary transducer.

2.2.1.2 Monitoring record

A nearly complete record of streamflow was collected for the period July 7, 2017 to July 28, 2020. Data for this station are accessible though the USGS NWISweb database at https://waterdata.usgs.gov/usa/nwis/uv?332153112022300. Streamflow at this site during the period of record was extremely rare and the channel was typically dry. Streamflow events that did occur were short in duration and flashy in nature.

The on-site video camera was programmed to collect and record video when the stream stage was greater than or equal to 0.10 ft above the stage sensor. Video was collected at a resolution of 1,920 x 1,088 pixels with a frame rate of 30 frames per second (fps). Video was only collected during daylight hours.

Collected video was subsequently processed and analyzed using Large Scale Particle-Image Velocimetry (LSPIV) techniques (Patalano, Garcia, & Rodriguez, 2017; Jodeau, Hauet, Paquier, LeCoz, & Dramais, 2008; Fujita, Muste, & Kruger, 1998) to determine velocity fields at the stream surface (Figure 6). The RiVER toolbox (Patalano, Garcia, & Rodriguez, 2017) and PIVlab (Thielicke & Stamhuis, PIVLab - Towards User-Friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB, 2014b; Thielicke & Stamhuis, PIVlab - Time-Resolved Digital Particle Image Velocimetry Tool for MATLAB (version 2.31), 2014a) open-source software packages were used to process and analyze video segments, and estimate streamflow. In the most general terms, LSPIV compares patterns of surface disturbance (particles) between sequential images to determine movement between the images. Computing the difference in pixel placement of the patterns in conjunction with the frame rate results in a velocity vector relative to pixel space. Control points with known geometry are identified within the images allowing for orthorectification of the images into geographic space allowing for translation of velocity vectors in real space.

For video collected at HSP, specific periods of interest in the stream hydrograph, including peak flow, were identified and a 10- to 20-second segment of the video was processed for each interval. The clipped segment was subsampled at a lower frame rate; typically, the subsampled frame rate was between 2 and 6 fps depending on the surface velocity. Depending on the segment length and subsampled frame rate, between 100 and 150 image pairs in a 10 to 20 second segment of video are analyzed. A mean velocity field is then computed for the analyzed pairs. Othorectification of the images was done using the known geometry between HSP-1, HSP-2, the gage orifice, and a reference mark on the right bank adjacent to HSP-1.

Bathymetry and cross-section information was extracted from high resolution digital elevation models computed from surveys conducted during the project. Utilizing the cross-section data and the computed velocity vectors, we were able to compute an estimated streamflow for the time period included in the video segment (Figures 6 and 7). Videos were processed for three time periods for video collected on October 2, 2018. Video was collected during the event on October 13, 2018, but the SD card became corrupted and the videos were not usable.

Figure 6. Surface water velocity vectors computed from video collected during a flow event on October 2, 2018 at an unnamed wash at Heard Scout Pueblo near Phoenix, AZ. (USGS image)

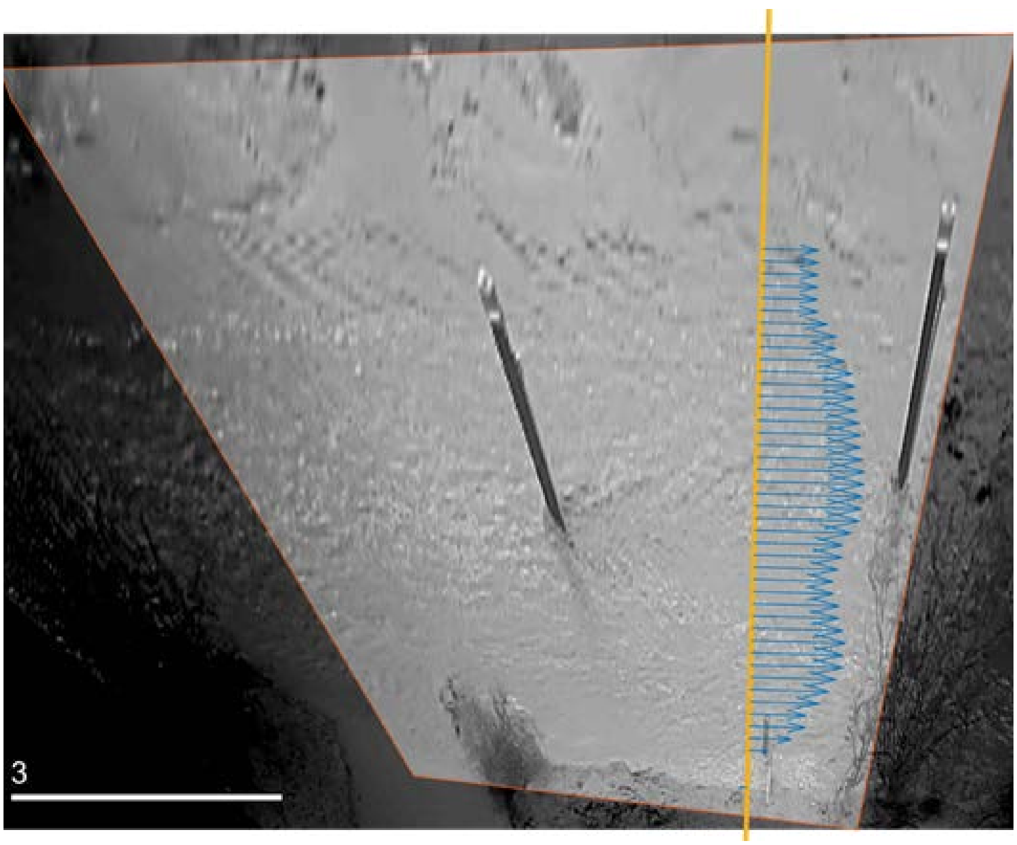


Figure 7. Orthorectified image with channel, a channel cross section, and interpolated velocity vectors for streamflow at an unnamed wash at Heard Scout Pueblo near Phoenix, AZ on October 2, 2018. (USGS image)

2.2.2 Sediment transport monitoring

USGS began monitoring aspects of sediment transport at HSP on July 7, 2017. Monitoring included sampling for suspended sediment concentration using an automated sampler and monitoring channel scour using sediment chains.

2.2.2.1 Equipment and Installation

An ISCO brand automated water sampler (model 6700) was installed at HSP in the metal streamflow gage structure on June 26, 2017. A 0.5 in diameter plastic tubing was installed between the gage structure and the stream channel to allow for sample collection. The tubing was mounted to the pressure transducer mount approximately 0.1 feet above the pressure transducer to limit the amount of bed sediment collected by the autosampler. The autosampler was programed to collect a sample every 15 minutes when flow was detected at the site.

Scour chains were installed at three locations (Table 3) in the gage reach to identify if scour and/or fill of the stream channel was occurring during events (Nawa & Frissel, 1993). The scour chain consists of about 3 ft of 0.25 in steel chain driven vertically into the streambed. The sediment matrix supports the chain and keeps it oriented vertically. During a flow event, if the streambed is scoured out, the vertical chain will drop to the depth of the scour. Following an event, the scour chain is located and the distance from the bed surface to the top of the disturbed chain is measured. This measurement gives the amount of fill, if any, that occurred. The chain is then evaluated to see if the top of the chain dropped in elevation. If it had, then a measurement of the disturbed part of the chain is measured to estimate the amount of scour that occurred during the event. The chain is re-set vertically following the measurements.

2.2.2.2 Monitoring record

The autosampler was initiated four times throughout the period of record. Samples were collected through the hydrograph during two events (October 2, 2018 and October 13, 2018). For the other two events where the autosampler was triggered, the water level in the channel was not high enough to reach the sampling line intake or the intake line was clogged and no samples were collected. Suspended sediment data for this station are accessible through the USGS NWISweb database at: https://nwis.waterdata.usgs.gov/usa/nwis/qwdata/?site_no=332153112022300&agency_cd=USGS&inventory_output=0&rdb_inventory_output=file&TZoutput=0&pm_cd_compare=Greater%20than&radio_parm_cds=all_parm_cds&format=html_table&qw_attributes=0&qw_sample_wide=wide&rdb_qw_attributes=0&date_format=YYYY-MM-DD&rdb_compression=file&submitted_form=brief_list

The scour chains were measured, evaluated, and reset following each of the flow events that occurred during the study. For the period of record, no scour was detected at any of the chain locations. Sediment accumulating above the chains was measurable at all three locations following two events occurring on October 13, 2018 and November 21, 2019.

Table 3. Location of sediment chains installed at Heard Scout Pueblo and associated field measurements of depth of scour and depth to chain as measured following streamflow events.

				Event date	Event date	Event date	Event date	Event date
Scour chain name	**Latitude (NAD 83)**	**Longitude (NAD 83)**	**Measurement**	**10/2/18**	**10/13/18**	**11/21/19**	**11/29/19**	**3/13/20**
SEDCHAIN-1 (downstream)	33.364709	-112.03985	Depth of scour (ft)	0.0	0.0	0.0	0.0	0.0
			Depth to chain after event (ft)	0.00	0.05	0.1	0.0	0.00
SEDCHAIN-2 (midstream)	33.364672	-112.039901	Depth of scour (ft)	0.0	0.0	0.0	0.0	0.0
			Depth to chain after event (ft)	0.00	0.05	0.05	0.00	0.00
SEDCHAIN-3 (upstream)	33.364592	-112.039963	Depth of scour (ft)	0.0	0.0	0.0	0.0	0.0
			Depth to chain after event (ft)	0.00	0.05	0.05	0.00	0.00

2.2.3 Infiltration

Infiltration rate data, represented as saturated hydraulic conductivity, were collected at two sites in the HSP study area. These data provide estimates of the potential of the channel sediments to uptake and store water. These data support the hydraulic computer models to assess the efficacy of GCS on the respective hydrologic system.

2.2.3.1 Methods

A tension infiltrometer (Soil Measurement Systems, LLC) was used to measure infiltration flow rates at different matric potentials for a variety of channel conditions at HSP. Two sites at the lower end of the study area were assessed. Site 1 (INFIL-1) was located at 33.364001, -112.040759, just below the most downstream GCS. Site 2 (INFIL-2) was located at 33.364701, -112.039854, just upstream of the streamflow gage. At each site, three complete measurement sets were collected at three different locations, each separated by about 2 meters. At each location, the tension infiltrometer was set up (Figure 8) and a variety of matric potentials, e.g., the height of water in the reservoir, was measured, which ranged from a minimum of -11.6 cm to a maximum of -4.4 cm. Although the instrument is capable of measuring over the range of -30 to 0 cm, given the sandy nature of the soils and goals of the Study, the focus was on obtaining measurements in the higher portion of the range. It was impractical to measure at tensions greater than about -4 cm given the turbulence and rapidity of the water level drop in the reservoir. Changes in reservoir volume over time were then converted to estimates of saturated and unsaturated hydraulic conductivity using steady-state solutions to the unsaturated flow equation (Gardner, 1958).

Figure 8. Tension Infiltrometer, Soil Measurement Systems, LLC. (Bureau of Reclamation photo, Phoenix Area Office, Deborah Tosline)

2.2.3.2 Results

A measurement was considered complete when change in water level per time (dh/dt) was relatively constant. However, at higher matric potential values, after a minimum dh/dt was reached, dh/dt almost always began to rise slowly. One possibility is that at higher values of dh/dt, smaller particles were gradually cleared from pores with a consequent increase in matric potential K(h).

Calculated values of unsaturated hydraulic conductivity as a function of matric potential (K(h)) were in the range typical of sands and fine gravels. Values ranged from 0.5 cm/hr at Site 1.1 (h = -11 cm) to about 338 cm/hr at Site 2.2 (Table 4; Figure 9). Saturated hydraulic conductivity (Ksat) values ranged from 0.01 cm/sec at Site 1.1 to 9.85 cm/sec at Site 2.2. Median values of Ksat were 0.13 cm/sec at Site 1.1 and 0.41 cm/sec at Site 2.2.

Table 4. Computed hydraulic conductivity from tension infiltrometer tests for two sites at Heard Scout Pueblo, AZ (-- no data, bold indicates median value)

Sample location	Ksat(α$_1$)	Ksat(α$_2$)	Ksat(α$_3$)	Ksat(α$_4$)	Ksat(α$_{median}$)
Site 1.1	0.01	0.22	0.13	--	**0.13**
Site 1.2	0.01	0.07	0.04	--	**0.04**
Site 1.3	0.23	0.50	0.08	--	**0.23**
Site 2.1	2.73	--	--	--	**2.73**
Site 2.2	9.85	0.52	0.23	0.30	**0.41**
Site 2.3	0.14	0.43	0.17	0.09	**0.15**

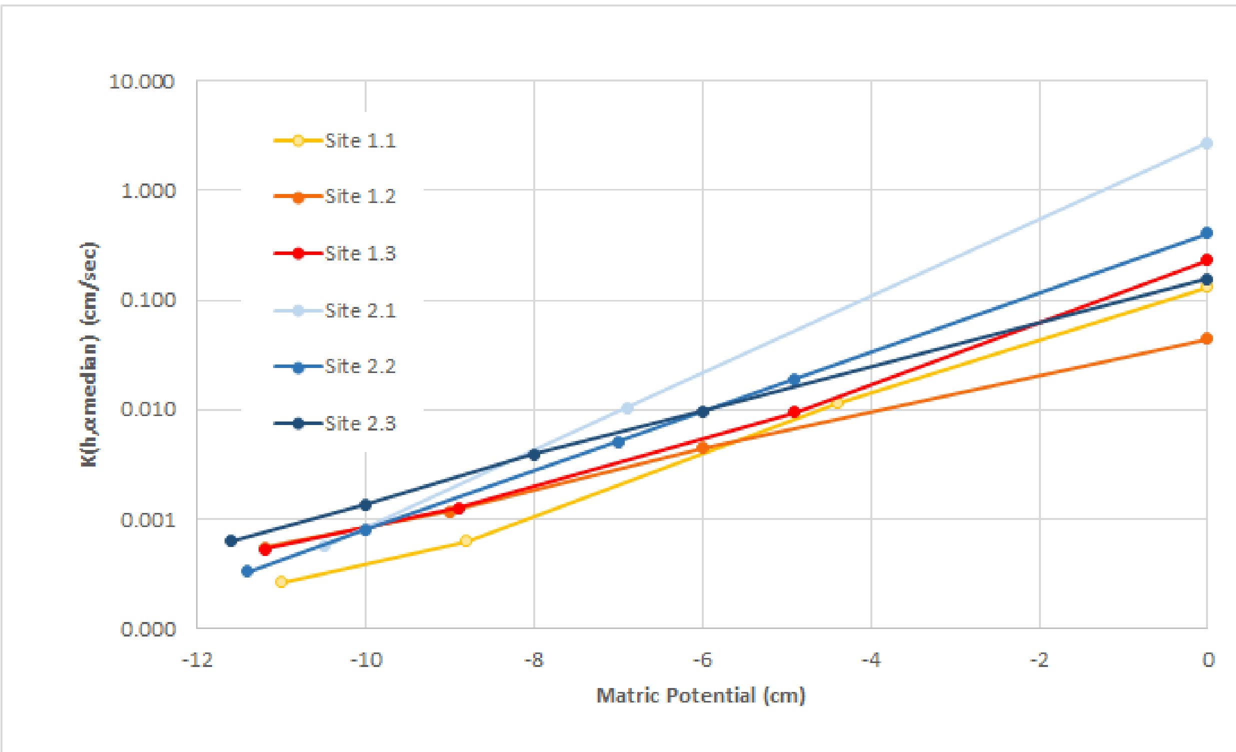


Figure 9. Relation between matric potential and hydraulic conductivity for two sites at Heard Scout Pueblo, AZ.

2.2.4 Groundwater Well Installation

Reclamation drilled and installed two wells, HSP-1 and HSP-2, near the USGS surface water monitoring equipment installations. Each well was drilled on natural ground within a small ephemeral drainage. Reclamation's Lower Colorado Regional Geologist logged the drill cuttings and submitted drill samples for laboratory analyses.

On June 29, 2017 Reclamation Yuma Area Office staff arrived on site with an AMS 9500 rig to drill a groundwater monitor well. The drilling attempt was abandoned when drilling hit refusal. It was determined that the drill crew would obtain a different drill rig and try to drill the well at a later date.

On July 7, 2017 Reclamation staff returned to the site with a truck-mounted rotary drill rig using a 5-foot-long, 3-1/4 inch Inside Diameter (I.D.), 6-1/2 inch Outside Diameter (O.D.) hollow stem auger rig to drill two groundwater monitor wells. See Appendix 5 for monitor well details and schematic diagrams.

2.2.4.1 HSP-1

HSP-1, ADWR well registration number 55-227363, was drilled and completed on July 7, 2017. HSP-1 was drilled from 0.0 to 50.0 feet, below land surface (ft, bls). The well was dry. The auger reached refusal at 50.0 ft, bls, when it would no longer proceed and the rig was jumping. It was assumed that the auger hit bedrock or a large cobble or boulder.

The well was completed with 2-inch diameter blank Polyvinyl Chloride (PVC) casing from 0 to 40 ft, bls and screened casing from 40 to 50 ft, bls. The casing was installed by inserting it into the hollow stem auger. The auger was then pulled back to backfill the drill hole with native material. A concrete plug was placed from 0.0-3.0 ft, bls to prevent preferential flow around the casing. A PVC stickup of 3.0 feet, above land surface (ft, als) was housed within a steel protective casing with a padlocked lid.

Subsurface geologic conditions at HSP-1 are classified as Quaternary Alluvium (Qal) from 0.0 to 50.0 ft, bls, that consists of poorly graded sand with silt from 0.0 to 10.0 ft, bls; poorly graded sand with silt and gravel from 10.0 to 20.0 ft, bls; silty sand with gravel from 20.0 to 30.0 ft, bls; poorly graded sand with gravel from 30.0 to 35.0 ft, bls; and silty sand from 35.0 to 50.0 ft, bls.

Campbell Scientific pressure transducer SDI-12 1200 bps; RS-232 9600 bps, was installed at 49.7 ft, bls to monitor channel infiltration during storm flow events. The transducer was connected to the onsite Design Analysis H-522+ datalogger via a buried cable from the well to the streamflow gage metal structure. Data were logged at 5-minute intervals and stored electronically on the datalogger. Data were downloaded periodically and provided to Reclamation with no quality assurance or quality control provided by USGS.

2.2.4.2 HSP-2

HSP-2, ADWR well registration number 55-227500, was drilled and completed on July 7, 2017. HSP-2 was drilled from 0.0 to 20.5 ft, bls. The well was dry.

The well was completed at a pre-determined depth of 20.5 ft, bls. PVC, 2-inch diameter blank casing was installed from 0.0 to 19.0 ft, bls and screened casing was installed from 19.0 to 20.0 ft, bls with a 6-inch end cap. A PVC stickup of 2.82 ft, als was housed within a steel protective casing with a padlocked lid. Six soil moisture sensors were attached to the outside of HSP-2 PVC casing during installation at the depths shown in Table 5.

Table 5. Sensor depths

Sensor Number	Sensor Depth (Ft, Bls)
S1	19
S2	16
S3	13
S4	10
S5	7
S6	4

Bentonite plugs were placed from 0.0 to 3.0, 5.0 to 6.0, 8.0 to 9.0, 11.1 to 12.1, 14.0 to 15.1 and 17.0 to 18.2 ft, bls in between the soil moisture sensors to prevent preferential flow down the casing. Native material was backfilled into the areas of the soil moisture sensor installations in between the bentonite plugs.

Subsurface geologic conditions at HSP-2 are classified as Quaternary Alluvium (Qal) from 0.0 to 20.5 ft, bls, that consist of poorly graded sand with silt from 0.0 to 10.0 ft, bls and poorly graded sand with gravel from 10.0 to 20.5 ft, bls.

2.2.5 Soil Moisture Sensors

2.2.5.1 Equipment

5TM sensors measure the dielectic constant of the soil using capacitance/frequency domain to determine volumetric water content (VWC). The 5TM filtering process minimizes salinity and textural influences to provide accurate measurements. Metrics for the 5TM sensors are provided in Table 6.

Table 6. Metrics describing the 5TM sensors

Apparent dielectric permittivity (Ea)	Volumetric Water Content (VWC): Using Topp equation	Using medium specific calibration, in any porous medium	Temperature	Resolution - Ea	VWC	Temperature
± Ea (unitless) from 1-40 (soil range), ±15% from 40-80	±0.03m3/m3 (±3% VWC) typical in mineral soils that have solution electrical conductivity <10dS/m	±0.01 - 0.02m3/m3 (±1-2% VWC)	±1°C	0.1Ea (unitless) from 1-20, <0.75Ea (unitless) from 20-80	0.0008m3/m3 (0.08% VWC) from 0to 50% VWC 0.25% VWC (rockwool)	0.1°C

Six Decagon 5TM Soil Moisture Sensors (SMS) were attached to the exterior of the HSP-2 PVC casing at 3-foot intervals from 4 ft, bls to 19 ft, bls using electrical tape. The SMSs were installed to monitor ephemeral channel infiltration during storm events.

The six 5TM SMSs were connected to the Design Analysis H-522+ datalogger via a buried cable from the well to the streamflow gage metal structure. Data were logged at 5-minute intervals and stored electronically on the datalogger. Data were downloaded periodically and provided to Reclamation with no quality assurance or quality control provided by USGS. Multiple 5TM sensors failed after a period of time. Multiple attempts to troubleshoot and reconnect to the sensors were completed, but ultimately no communication could be established with the down sensors.

The soil moisture sensor monitoring data indicated that the sensors may not be functioning properly. After installation, it was determined that the soil moisture sensor probe covers were not removed as recommended by the manufacturer. Loose probe covers may have been dislodged from some sensors during well installation and may have read as intended, but sensors that did not lose their covers may not have been reading correctly.

Sensors may be used to identify the start time and associated depth of potential in-channel infiltration during a storm flow event. Six SMSs installed on HSP-2 were monitored from July 11, 2017 through May 22, 2020. When monitoring began, all six SMSs appeared to function as expected. Over time, SM1, SM5 and SM6 continued to function as expected. However by December 2018, SM2, SM3, and SM4 no longer functioned and, despite attempts to troubleshoot the issue, ultimately no data were collected from these sensors. There were three time periods where the USGS datalogger did not record data. Table 7 shows the monitoring record for each of the HSP-2 SMSs. The soil moisture sensor data is provided in Appendix 6.

Table 7. HSP-2 Soil Moisture Sensor Monitoring Record

Period of Record	Soil Moisture Sensors						
	SM1	SM2	SM3	SM4	SM5	SM6	Note
07/11/2017 to 07/20/2017	Y	Y	Y	Y	Y	Y	
07/20/2017 to 08/18/2017	N	N	N	N	N	N	no record
08/08/2017 to 08/22/2017	Y	Y	Y	N	Y	Y	
08/22/2017 to 12/04/2017	Y	Y	Y	N	Y	Y	
12/04/2017 to 12/10/2018	N	N	N	N	Y	Y	
12/10/2018 to 02/12/2018	N	N	N	N	N	N	no record
02/12/2018 to 09/15/2019	Y	N	N	N	Y	Y	
09/15/2019 to 09/26/2019	N	N	N	N	N	N	no record
09/26/2019 to 05/22/2020	Y	N	N	N	Y	Y	
Explanation: Y = Recording, N = Not recording							

2.2.6 Monitor Well Pressure Transducers

Pressure transducers were installed in the HSP-1 and HSP-2 groundwater wells to monitor potential channel infiltration during storm flow events. Pressure transducer data for HSP-1 is in Appendix 6 and data for HSP-2 is in Appendix 7. Field notes for HSP-2 site visits and downloads are provided in Appendix 8.

2.2.6.1 HSP-1

Campbell Scientific pressure transducer SDI-12 1200 bps; RS-232 9600 bps, was installed at 49.7 ft, bls to monitor channel infiltration during storm flow events.

The transducer was connected to the onsite Design Analysis H-522+ datalogger via a buried cable from the well to the streamflow gage metal structure. Data were logged at 5-minute intervals and stored electronically on the datalogger. Data were downloaded periodically and provided to Reclamation with no quality assurance or quality control provided by USGS.

2.2.6.2 HSP-2

On July 7, 2017, two pressure transducers were installed in HSP-2. HOBO U20-001-04 S/N: 9811769 transducer was installed to monitor barometric pressure and HOBO U20-001-04 S/N 9811768 was installed to monitor the presence of water in the dry well.

Two new pressure transducers were installed on January 10, 2020. HOBO water level sensor U20L-04 S/N: 20741796, 0-13 ft, bls was installed to monitor barometric pressure and HOBO U20L-02 and water level sensor S/N 20698037, 0-100 ft, bls was installed at 20 ft, bls to monitor the presence of water in the dry well.

During the site visit on November 22, 2019, it was discovered that both the depth to water (DTW) and barometric pressure transducers had stopped functioning on October 29, 2019. The battery condition was reported as "good" for each and the transducers were relaunched and reinstalled. During a site visit on December 18, 2019, both transducers had failed and reported 33% battery remaining which should have been enough for continued logging. Two new transducers were installed and launched on January 10, 2020. Due to the Coronavirus (COVID-19) pandemic, restrictions were placed on Reclamation field work and site visits were not allowed after March 13, 2020.

2.2.7 Weather

2.2.7.1 Weather Stations

NAU provided a pair of WeatherHawk weather stations, freshly calibrated, to assess potential differences in precipitation across the HSP site. These weather stations employ a tipping-bucket rain gauge and an integral air temperature plus relative humidity sensor (shaded, shielded), which were used in this Study. The sensors are mounted on a steel mast at a height of two meters above ground level. The package also records wind speed and direction and shortwave incoming solar radiation, which were not used in this Study. The stations log data in programmable increments; this Study used 10-minute increments.

2.2.7.2 Weather Station Installations and Data Downloads

On June 28 and 29, 2017, Reclamation installed two weather stations at the HSP. One station was installed in the upgradient portion of the watershed and the second station was installed in the downgradient portion of the watershed near the USGS surface water monitoring equipment.

Reclamation installed concrete pads for the weather stations to provide a stable, level installation surface. Wire mesh fencing was installed on the perimeter of the concrete pads for protection. The upgradient weather station battery malfunctioned; the battery was replaced and data collection began on July 20, 2017.

Reclamation conducted site visits to observe conditions and to download data from the upgradient and downgradient weather stations about every 4 to 6 weeks.

2.2.7.3 Weather Station Monitoring Record

The upgradient and downgradient weather stations were monitored from June 28, 2017 through March 13, 2020, when the United States declared a National Emergency due to the COVID-19 pandemic. At that time, Reclamation's PXAO deemed the HSP field work to be non-essential and further site visits were not approved. Processed weather station data is provided in Appendix 9.

2.3 Surveys

At the start of the Study, Reclamation was only beginning to implement their sUAS program. In May 2017, the Study obtained required Reclamation approvals for USGS to control and operate sUAS surveys at the HSP site.

On July 29, 2017 Reclamation conducted land surveys of monitoring equipment and unique features at the HSP site using United States/State Plane 1983, NAD 1983 (Conus) datum, Arizona Central 0202 zone, GEOID12B (Conus). The survey results are provided in Appendix 10.

The USGS completed three sUAS surveys at the site. The first sUAS survey was completed on June 27, 2017 after the monitoring equipment had been installed at the HSP. The second sUAS survey was completed on October 24, 2018, following a large storm event that resulted in a pre-GCS installation flow event. The third sUAS survey was completed on December 13, 2018 after NCD completed GCS installations within the channel at the HSP. The team was scheduled to obtain one more sUAS flight when the United States blocked the use of the Huawei software used in the USGS sUAS technology. Reclamation and USGS determined that it would be best to conduct a TLS to collect channel and vegetation information to document baseline vegetation conditions and to assist with interpreting channel conditions in thickly vegetated areas. The TLS was completed March 2 and 3, 2020 using a Leica MS60 LiDAR system with ground control data collected using a Leica GS14 RTK. All TLS data are OPUS corrected. Four separate reaches, each about 50 meters in length, were surveyed and high-density point clouds generated. The georeferenced sites can be reoccupied in the future to assess changes in channel morphology. While the TLS data helped refine analyses for the existing sUAS surveys, no aerial surveys were conducted following the post-GCS installation, November 2019 flow event. Following discussions with FCDMC, it was determined that a final sUAS flight would be conducted at the site on March 1, 2020 by Joe Wagner (FCDMC).

2.4 Modelling

The choice of a model is often governed by time and budget constraints, project needs, access to and knowledge of existing models, and the availability of appropriate data to develop the model. It is important to understand the formulation of the selected model, recognize the model limitations, and apply the model in a manner that takes advantage of its strengths. Numerical model predictions will always include some uncertainty because the physical processes being modeled are not completely represented within the governing equations applied in a numerical model.

The numerical model utilized for this study was SRH-2D (v 3.0). SRH-2D is a two-dimensional (2D) mobile-bed hydraulics and sediment transport model for river systems developed by Reclamation at the TSC (Lai, SRH-2D version 2: Theory and User's Manual., 2008). SRH-2D solves the depth-averaged dynamic wave equations with a depth-averaged parabolic turbulence model using a finite-volume numerical scheme. The model adopts a zonal approach for coupled modeling of channels and floodplains; a river system is broken down into modeling zones (delineated based on natural features such as topography, vegetation, and bed roughness), each with unique parameters such as flow resistance. One of the major features of SRH-2D is the adoption of an unstructured hybrid mixed element mesh, which is based on the arbitrarily shaped element method of Lai (2000) for geometric representation. This meshing strategy is flexible enough to facilitate the implementation of the zonal modeling concept, allowing for greater modeling detail in areas of interest that ultimately leads to increased modeling efficiency through a compromise between solution accuracy and computing demand. SRH-2D also includes the capability to model infiltration using the Green-Ampt infiltration model.

The survey information used for the modelling is described in Section 2.3. Three sets of surveys were collected. The results in this report all use the October 2018 survey as the base terrain. This was prior to the installation of the grade control features. The post-installation terrain was developed by digitizing the aerial extent of each structure and then altering the elevation of those areas according to the grade control design. This was done because the structures are relatively small features of approximately 0.5 ft to 1 ft high (0.15 to 0.3 m), which is of similar magnitude of the expected error of the survey, approximately 0.5 ft (0.15 m).

ESRI ArcGIS rasters were used to represent the topographic surface for the October 2018 conditions. The existing conditions surface was then edited directly in Aquaveo's Surface-Water Modeling System (SMS) to develop surfaces for as-built conditions.

A 2D mesh is what defines the SRH-2D model topography and solution spacing. The mesh (nodes) stores ground elevation information from the model surface and consists of quadrilateral and triangular shaped elements. The mesh was developed using Aquaveo's SMS v 13.0. All material data was assigned within the SMS platform. The topography data without the grade control structures was assigned directly within ESRI's ArcGIS. A special tool was developed to modify the node elevations and cell roughness to represent the GCS. The tool takes in the SMS created mesh file and an Arc-Map polygon shapefile, which delineates the GCS and stores the structure height in its attribute table. The grid spacing was relatively fine with an approximate average grid cell size of 1 ft to adequately resolve the GCS. The mesh had approximately 500,000 cells. The model domain is shown in Figure 10, showing the depth at an example flow of 5 cfs.

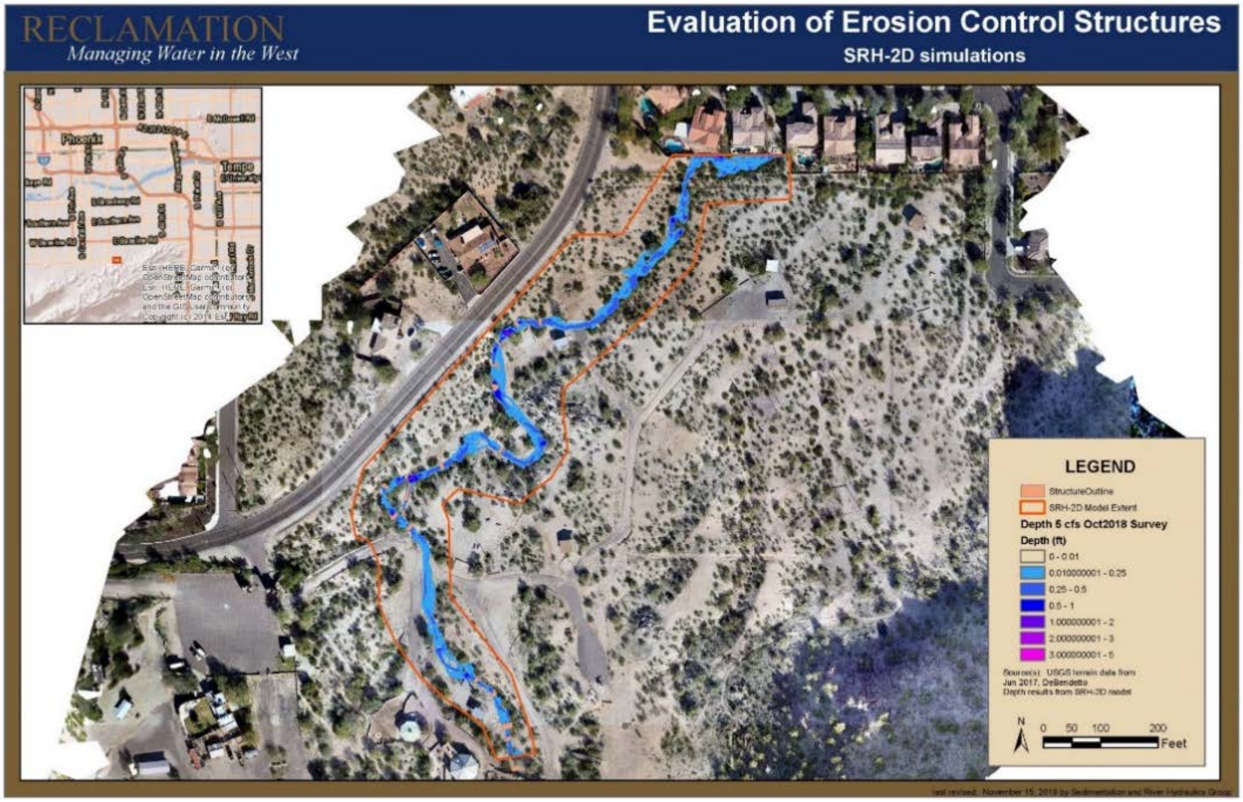


Figure 10. Overview of model extent, showing depth of flow at a flow of 5 cfs and location of GCS.

The model requires hydraulic roughness estimates. A roughness of 0.06 was assumed for the GCS and 0.03 for all the other cells. A roughness of 0.03 is a typical value for sand/gravel bed channels (Coon, 1998). The model also requires an upstream boundary condition of stream flow. These were taken from measured stream flows as described in Section 2.2.

Based upon the results from Table 1, the 95% confidence interval of the 2-year flood ranged from 9 to 179 cfs. This large range of values indicates that there is large variability in discharge between watersheds of the same size in this region. The flood that occurred on October 13, 2018 is within the range of potential estimates of a flood with a return period of 2 years (approximately an average annual flood). The total rainfall for the October 13, 2018 event was 3.2 inches over a period of approximately 6 hrs, which is expected to be much higher than a 2-year precipitation event, but because of the dry antecedent conditions it is likely that much of the precipitation infiltrated into the watershed.

Tension infiltrometer measurements were used to estimate hydraulic conditivity as described in Section 2.2.3., where the median value at Site 1 was 184 in/hr (0.13 cm/s) and the median value at Site 2 was 580 in/hr (0.41 cm/s). The estimated values have a large range from 63 in/hr to 3800 in/hr (0.04 cm/s to 2.7 cm/s). Initially, the median hydraulic conditivity of 0.27 cm/s was used to predict the run off of the October 13, 2018 flow rates. This estimated hydraulic conditivity is too high considering the estimated flow in October 2018. If applied to the channel, it would cause the entire October 2018 flood to infiltrate into the channel bed. If applied to the watershed, it would show that no water would make it to the channel. Even though there is large uncertainty in the estimation of hydraulic conditivity, it is expected that the ratio between infiltration with and without GCS would remain similar. In this numerical model the hydraulic conditivity was adjusted to 1.4 in/hr (1.0 x 10^{-3} cm/s) to better represent the infiltration rate. The hydraulic conditivity can be a calibration parameter if flow rate measurements were made both upstream and downstream of the study area.

2.5 GCS Installation

On September 18, 2018 Reclamation contracted with NCD, a civil engineering, habitat restoration and natural resource planning company based in Flagstaff, Arizona to design and install twenty rock GCSs at the HSP. A subsequent contract modification added five GCSs, three-rock plugs and six-rock sill installations at the site. NCD is an engineering consulting firm with an interdisciplinary team of engineers, scientists and specialists providing planning services to restore and enhance stream channels, waterways, and natural resources. NCD subcontracted with the American Conservation Experience (ACE) to provide materials and labor for installation of the structures.

Reclamation provided NCD high resolution USGS sUAS imagery collected at the HSP in July 2017 and October 2018. NCD used the imagery to determine channel conditions, GCS designs and spacing to estimate the rock quantities required for the installations.

NCD divided the study area into reaches based on the average bed slope and/or the presence of significant incoming tributaries. GCS structure spacing was based on the calculated length needed to reduce the channel bed slope between structures by at least 50% of the overall reach slope. Each GCS installation location was field located based on the presence of headcuts, scour or vegetation.

Bankfull discharge is defined as the flow associated with the elevation of the geomorphic floodplain. NCD estimated that the HSP channel bankfull flows were between 12 and 15 cubic feet per second (cfs), which is typically near the 2-year flood for alluvial channels. This magnitude of the 2-year flood is within the range of possibility based upon the results from Table 1.

The HSP channel is shallow and the GCSs were designed to encourage water detention, sediment deposition, and protect channel banks while maintaining a 2-year flow channel capacity minimum. HSP channel cross sections were analyzed using a cross-section hydraulic analyzer spreadsheet to ensure the modified channel would still have the capacity to hold at a minimum a 2-year flow. To reduce the potential for bed scour due to sandy soils, the structures were installed at about 0.5 ft above the existing channel bed.

NCD used a 25-year return interval (about 90 cfs) to size the rock used to construct the GCSs. The largest slope measured in the HSP channel was 5.7% and was used to calculate the shear stress. Based on this information, NCD determined that the top rock weir portion of all structures would require 12-inch diameter rocks to withstand a 25-year flow event. The source rock was sized between 12 and 16 inches with a Particle Size Distribution (D50) of 14-inches.

Source rock purchased for the GCS installations met cultural resource requirements. NCD provided environmental clearance documentation, validating that the source rock materials for the GCS installations were obtained from an environmentally approved commercial source.
NCD completed all GCS installations during three work periods:

- The first work period was from November 13 to 19, 2018 with a 5-person crew and an equipment operator for three days.
- The second work period was November 28 to December 1, 2018 with a 7-person crew and equipment operator for three days.
- The third and final work period was January 15 to 18, 2019 with an 8-9 person crew and an equipment operator for three days.

The GCS structures installed at the HSP were based on the One Rock Dam (ORD) design developed by Zeedyk Ecological Consulting LLC; the ORD design was modified to increase channel stability. The design also included components of a cross-vane weir design developed by Dave Rosgen as the main structure; the weir arms (sometimes labeled as vane arms), are shorter than a typical rock weir design and an additional downstream rock pad was added to prevent bed scour. The cross-vane weir design requires less source rock than a standard ORD and helps to reduce bank scour by focusing stream energy towards the center of the channel.

Details for and photographs of the GCS installations are provided in the NCD construction and monitoring report included as Appendix 11.

Reclamation took photos of the GCS installations with downstream, upstream, left bank and right bank views of each structure on March 13, 2020. The images are shown in Appendix 12.

When the Reclamation Study ends, all GCS installations will remain at the HSP site, in perpetuity.

3 Results

All the monitoring data were collected and reported below.

Reclamation prepared signage to describe monitoring activities and research at the HSP, as shown in Figure 11. There is heavy public traffic at and around the HSP and users who are curious about the monitoring equipment and GCS installations may learn more about GCS research at the site. BSA members utilize the HSP for camping and other outdoor activities and for public access to the South Mountain Park/Preserve hiking trails on the perimeter and from within the HSP. (Note: The signage won First Place - People's Choice Award at the 2019 EPA Region 6 Stormwater Conference!).

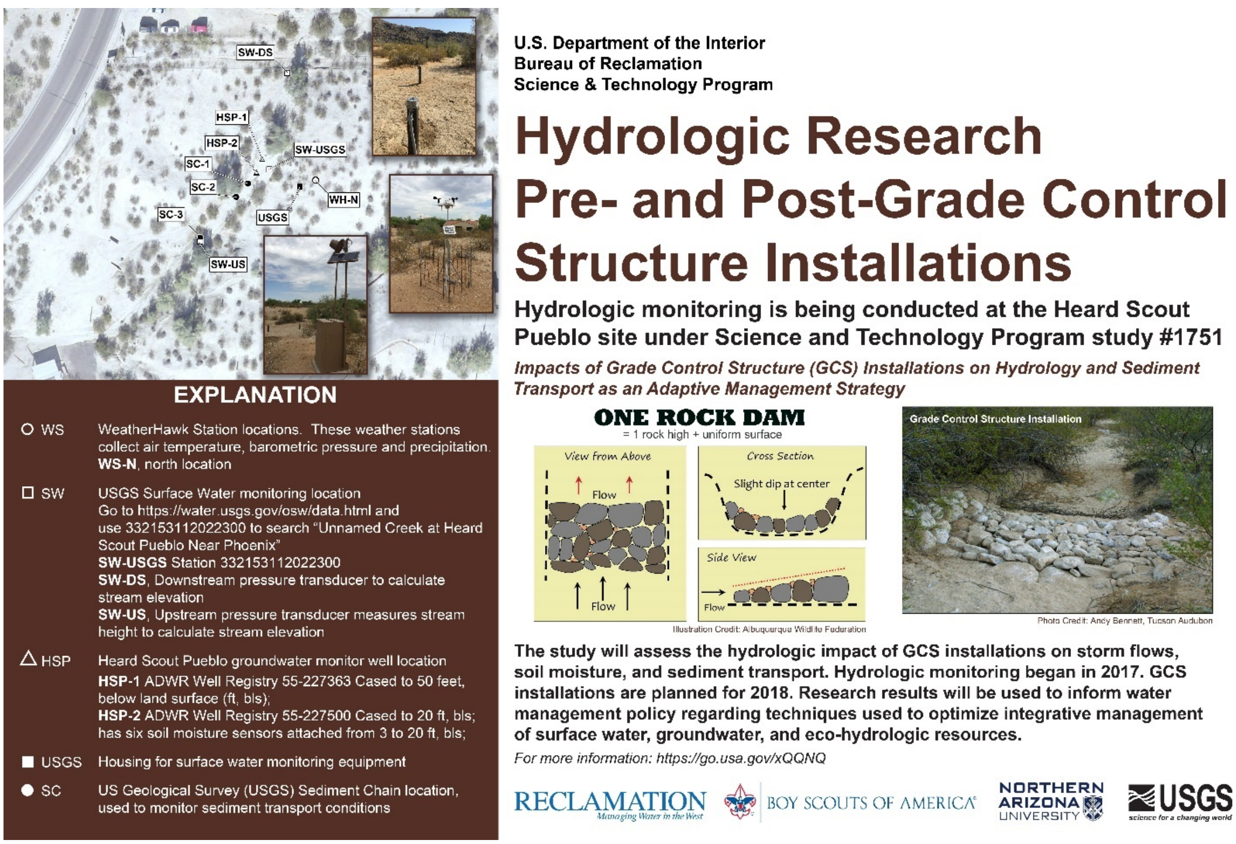


Figure 11. Interpretive sign describing the monitoring locations and research at the HSP.

3.1 Rainfall–Runoff Response

The sUAS, TLS and LIDAR data were used to extract cross-sections of the channel topography for use in calculating stage-discharge relationships. Any disturbance can alter the geomorphology of the channel, including GCSs installation activities, people traversing the channel, or rainfall/runoff impact erosion and sediment dispersion. Each dataset portrays a snapshot in time and the associated changes in the channel geomorphology. As the structures continue to alter the channel profile with subsequent deposition, these baseline datasets will offer the potential to document that change.

Results for data collected by the USGS will be published in ScienceBase (https://www.sciencebase.gov/catalog/), a Trusted Digital Repository (TDR), as digital datasets and accessible via web browser, meant to be publicly available in perpetuity. These datasets are published in USGS "data release" format with metadata after undergoing peer-review in the USGS Information Product Data System (IPDS). All data products from this effort collected, reviewed and released are cited in their respective section below, including surface-water discharge, infiltration, and sediment results. Imagery results collected by USGS for this project likewise will go to the USGS repository at the Earth Resources Observation and Science (EROS) Center and be served through the USGS EarthExplorer website (the raw geotagged photos, and the products).

A short table was created to highlight 88 precipitation events that occurred during the study timeframe, for which only 12 incurred a runoff response (Table 8).

Table 8. Daily rainfall and runoff captured during study

DATE	Weather Station South (in)	Average Q (cfs)	Qp (Maximum flow)
8/1/2017	0.37		
8/3/2017	0.04	0.69	1.01
8/10/2017	0.61		
8/11/2017	0.33		
8/23/2017	0.16		
12/17/2017	0.08		
1/9/2018	0.12		
1/10/2018	0.08		
2/14/2018	0.31		
2/15/2018	0.04		
2/27/2018	0.20		
3/11/2018	0.04		
7/9/2018	0.47	13.56	4.87
7/10/2018	0.28		
7/11/2018	0.04		
8/10/2018	0.79		
8/11/2018	0.04		
8/12/2018	0.04		
9/3/2018	0.20		
9/19/2018	0.28		
9/30/2018	0.16		
10/1/2018	0.43		
10/2/2018	2.99	3.31	8.20

DATE	Weather Station South (in)	Average Q (cfs)	Qp (Maximum flow)
10/7/2018	0.39		
10/13/2018	3.23	5.31	15.10
11/29/2018	0.20		
11/30/2018	0.20		
12/31/2018	0.24		
1/5/2019	0.04		
1/6/2019	0.47		
1/13/2019	0.04		
1/14/2019	0.00		
1/15/2019	0.16		
2/3/2019	0.31		
2/6/2019	0.16		
2/14/2019	0.08		
2/18/2019	0.04		
2/21/2019	1.22		
2/22/2019	0.35		
3/11/2019	0.00		
3/12/2019	0.43		
3/13/2019	0.04		
9/14/2019	0.08	0.00	0.00
10/23/2019	1.69		
11/19/2019	0.31	0.40	0.40
11/20/2019	0.43	0.47	0.98
11/21/2019	0.59	1.69	3.49
11/29/2019	0.87	3.28	4.23
12/7/2019	0.16		
12/7/2019	0.04		
12/9/2019	0.16		
12/24/2019	0.16		
12/25/2019	0.29		
12/26/2019	0.16		
12/27/2019	0.12		
1/21/2020	0.29		
2/22/2020	1.28	0.40	0.40
3/13/2020	0.30	0.71	1.00
5/10/2020	0.06	0.40	0.40

3.2 Surface Water Model

SRH-2D was used to model the hydraulics and infiltration with and without GCS in the ephemeral channel study site (Figure 10). The without-GCS geometry was based on the October 2018 survey prior to the installation of the structures. The with-GCS geometry was developed by increasing the elevation of the existing conditions mesh by the observed as-built height of the GCS (during photo documentation on March 13, 2020). The as-built height was predominantly 6-inches from the channel bottom, although several structures ranged between a height of 6- and 12-inches.

We simulated the velocity at a steady flow of 18 cfs, which is within the range of potential values for a 2-year flood based upon the estimates from Table 1, for existing (without structures) conditions. The velocity magnitudes are typically 4 to 5.6 ft/s (1.3 to 1.7 m/s) in the main channel of the upper portion of the domain, while the channel velocities are 1.6 to 3.3 ft/s (0.5 to 1 m/s) in the lower portion of the domain.

Three varied storms documented in the Study (Table 8) were used to simulate flows: (i.) October 13, 2018, (ii.) November 21, 2019, and (iii.) November 29, 2019. The measured flows were collected from the stream gage, as described previously, and used as the upstream flow boundary for the SRH-2D model domain shown in Figure 10. The SRH-2D model is used to calculate the infiltration into the stream bed with and without structures.

The simulated inflow and outflow for the HSP during the October 13, 2018 event with and without structures is shown in Figure 12. This storm was a ~3 hour, 1000-year event, and the largest in our study (Bonnin, et al., 2006). The peak was slightly less and slightly delayed for the with-structure case relative to the without-structure case. The cumulative infiltration is shown in Figure 13, and the model estimates that the structures could increase the infiltration approximately 15% for the October 13, 2018 event. A sensitivity study of the infiltration rate was also conducted by increasing and decreasing the infiltration rate by a factor of 10. The increase in infiltration for the with-structures conditions relative to without-structures only varied between 15 and 16%. Therefore, the total infiltration is of course sensitive to the hydraulic conductivity, but the relative difference in infiltration is not sensitive to the absolute values of the hydraulic conductivity.

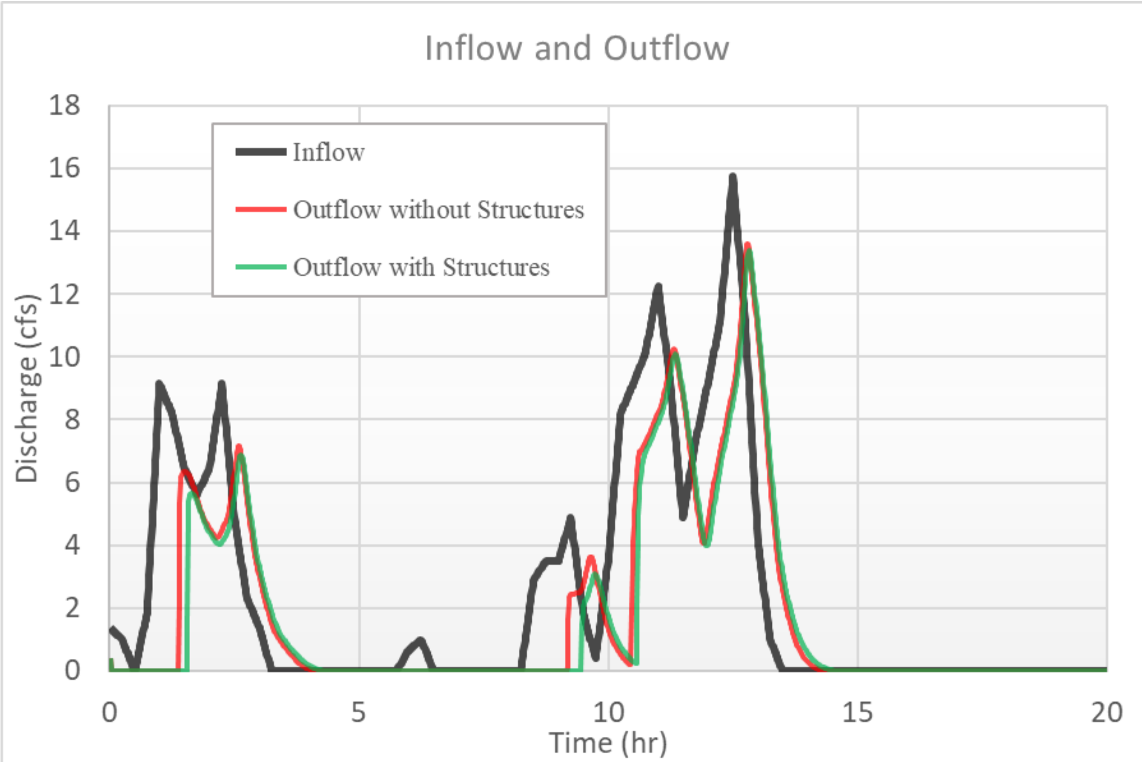


Figure 12. Simulated inflow and outflows for the HSP with and without GCS for October 13, 2018 event.

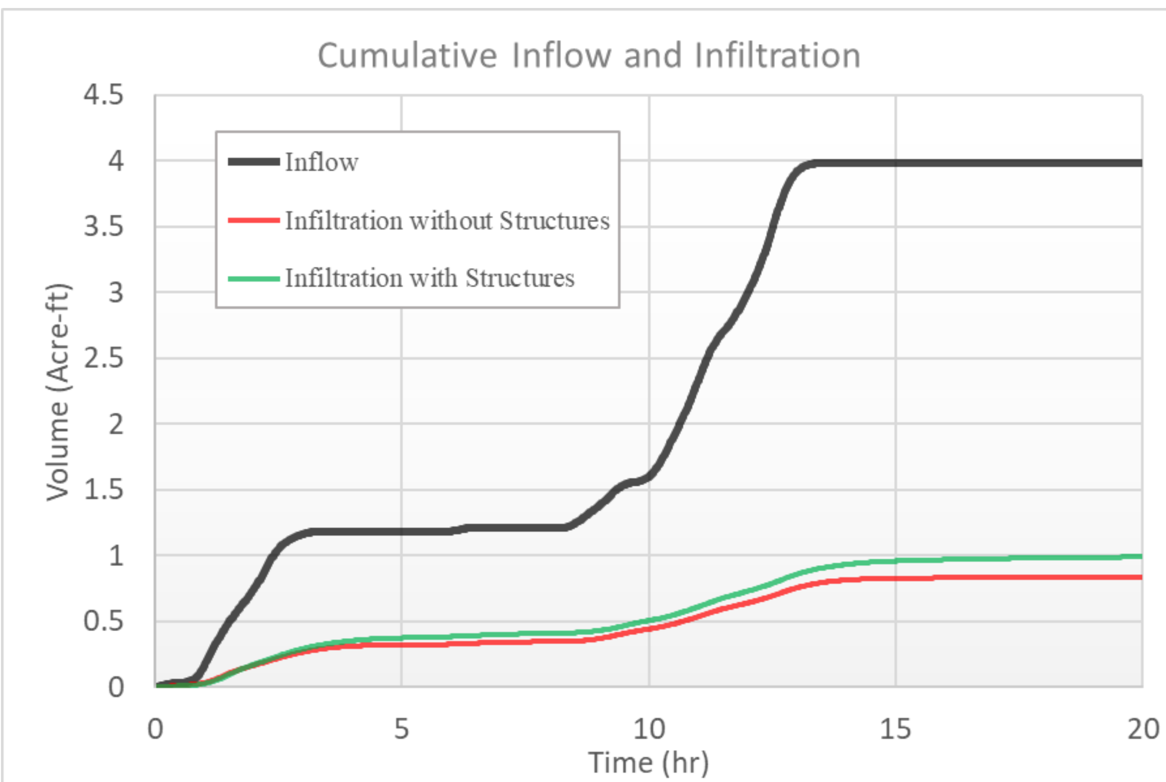


Figure 13. Simulated cumulative infiltration in acre-ft for the HSP with and without GCS for the October 13, 2018 storm.

The map of the total infiltrated depth is shown in Figure 14 for the October 13, 2018 event. The infiltration depth is noticeably increased upstream of many of the structures. Not all the structures have the same effect as some structures are slightly larger than other structures.

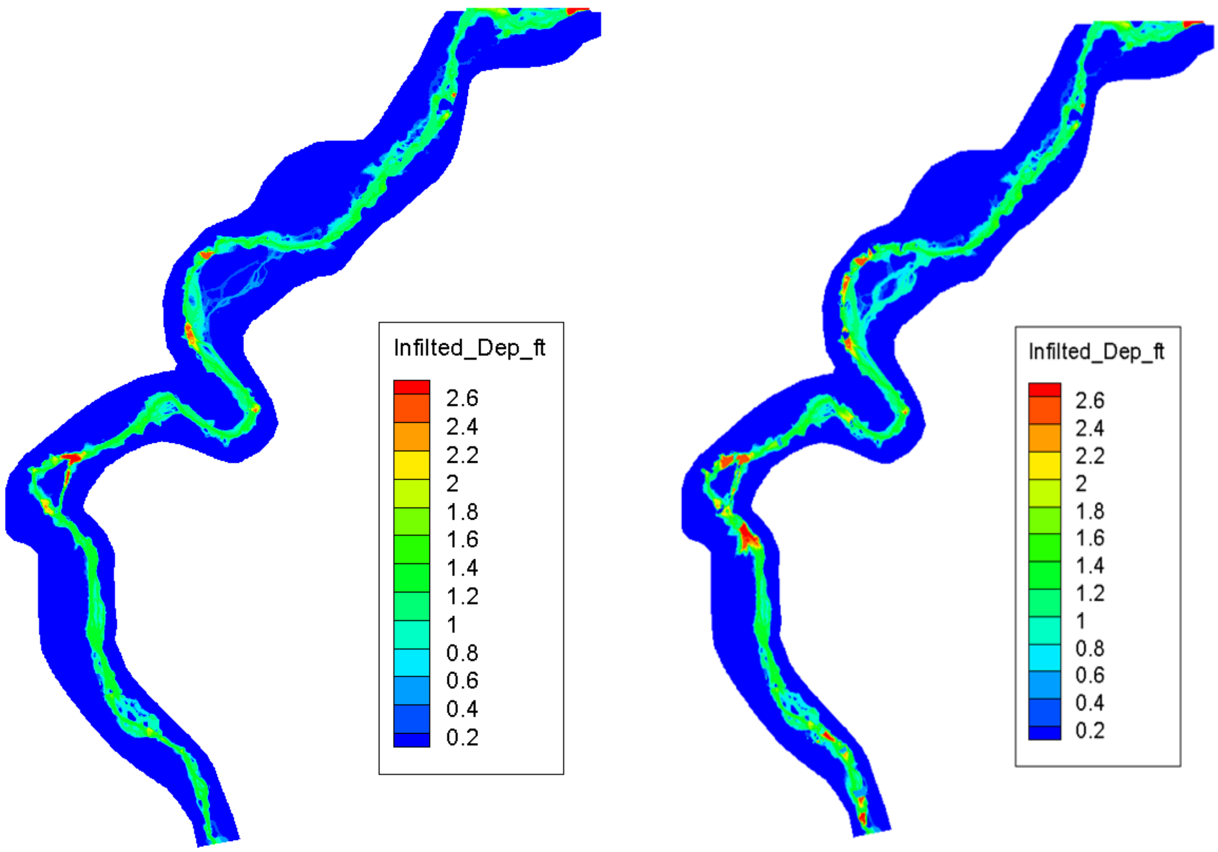


Figure 14. Simulated infiltration for the HSP with and without GCS for October 13, 2018 event.

The simulated flows for the November 29, 2019 event (~30 min., 2-year event (Bonnin, et al., 2006)) are shown in Figure 15 and the cumulative infiltration in Figure 16. The relative difference in cumulative infiltration between with- and without-structures is approximately the same for the October 13, 2018 event, but the amount of infiltration relative to the storm size is much higher because the storm was significantly smaller.

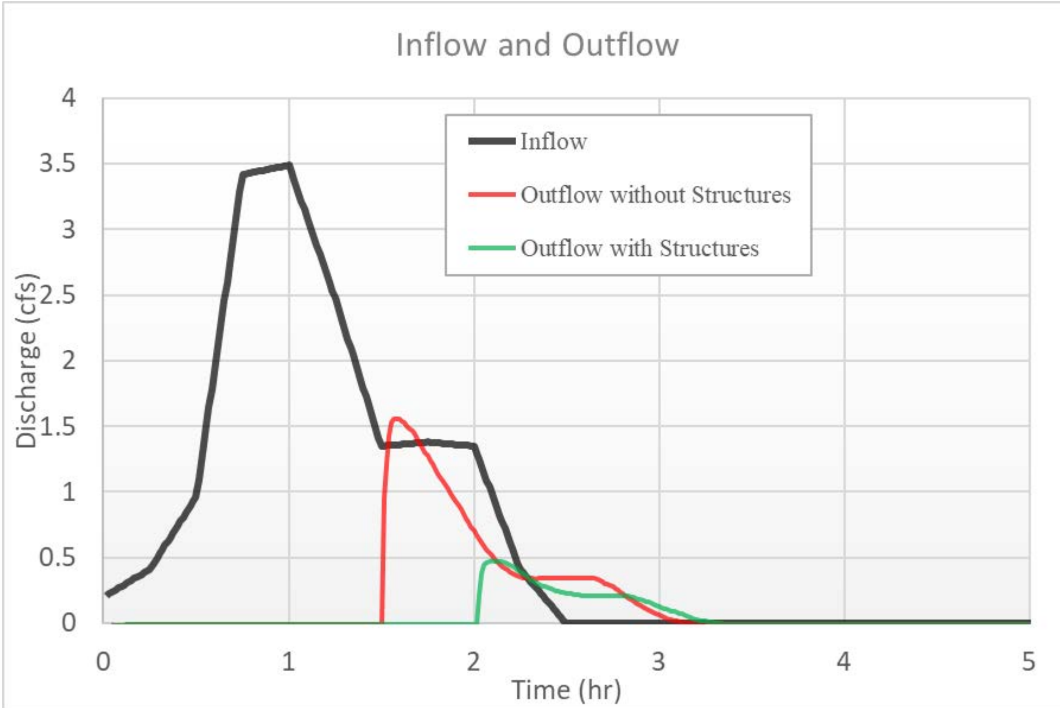


Figure 15. Simulated inflow and outflows for the HSP with and without GCS for November 29, 2019 storm event.

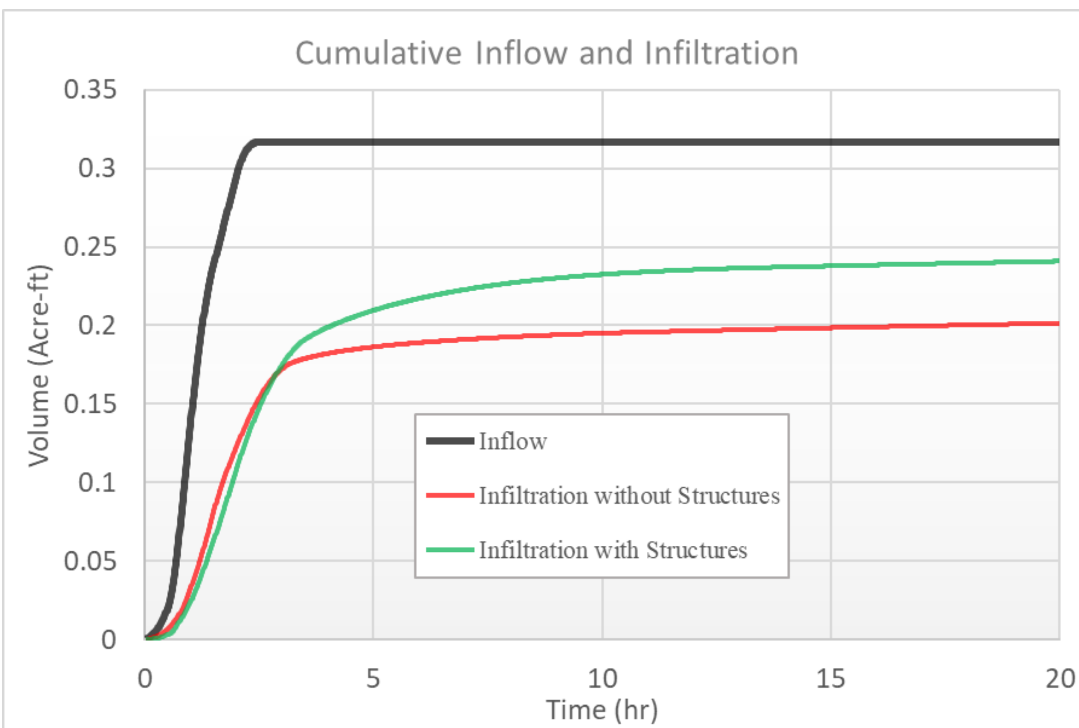


Figure 16. Simulated cumulative infiltration in acre-ft for the HSP with and without GCS for the November 29, 2019 storm event.

The simulated flows for the November 29, 2019 event (1 hour, 5-year event (Bonnin, et al., 2006)) are shown in Figure 17 and the cumulative infiltration is provided in Figure 18. The relative difference in cumulative infiltration between with- and without-structures is again approximately the same as for the October 13, 2018 event.

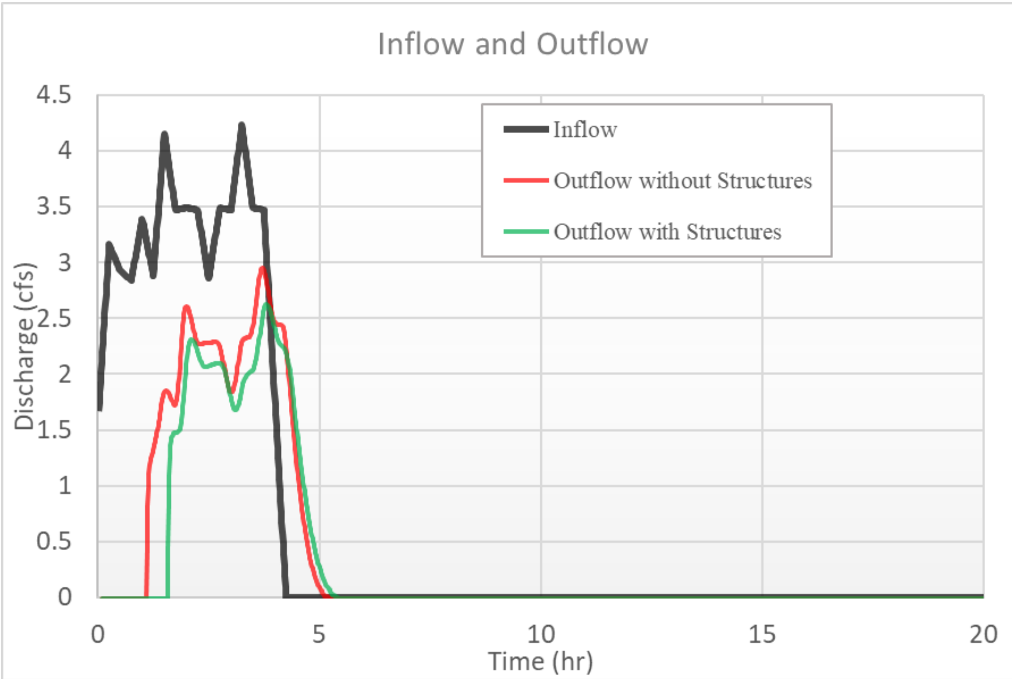


Figure 17. Simulated inflow and outflows for the HSP with and without GCS for November 29, 2019 storm event.

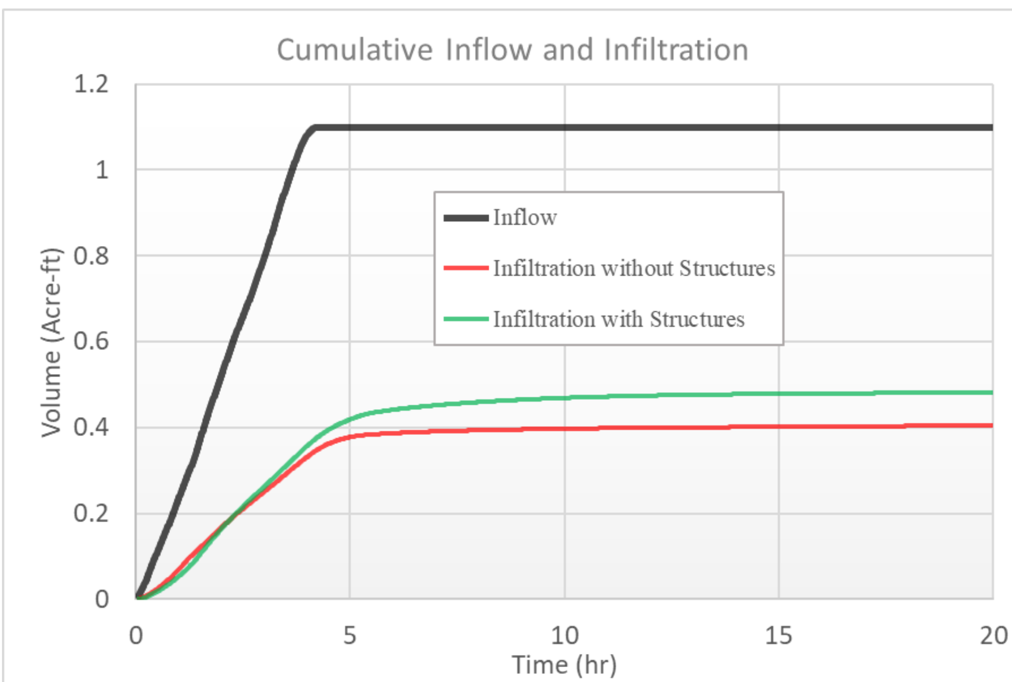


Figure 18. Simulated cumulative infiltration in acre-ft for the HSP with and without GCS for the November 29, 2019 storm.

The measured stream flow, suspended sediment concentrations, and soil moisture from the October 13, 2018 storm are provided in Figure 19.

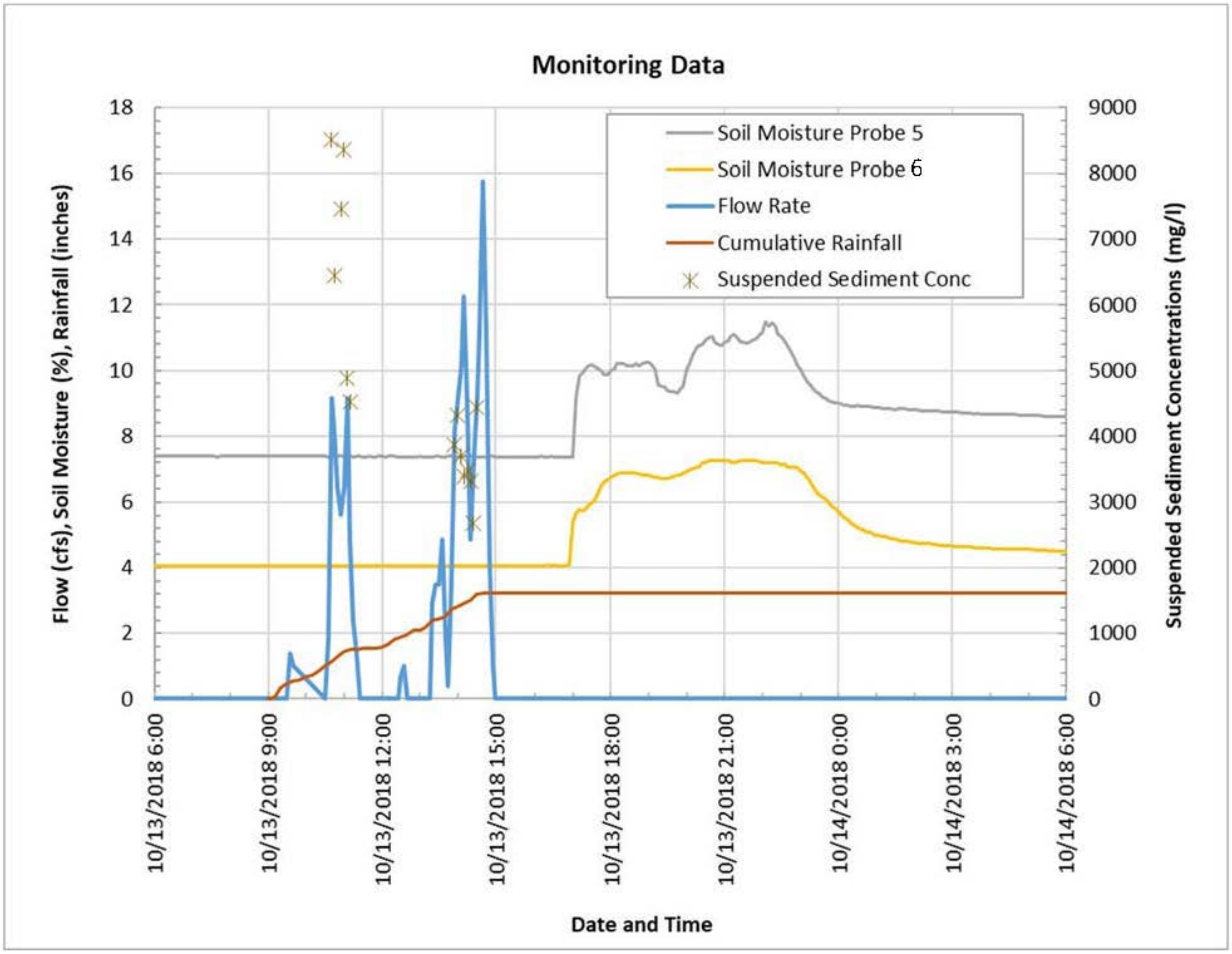


Figure 19. Measured stream flow, suspended sediment concentrations, and soil moisture from the October 13, 2018 storm event.

3.3 Groundwater Monitoring

3.3.1 HSP-1

A pressure transducer was installed in HSP-1 at 50 ft, bls to monitor potential channel infiltration following a storm flow event. The transducer is connected to the USGS datalogger. The transducer data (uncorrected for barometric pressure) indicate that zero infiltration was detected in HSP-1 during or after the October 13, 2018 or the November 29, 2019 storm flow events. Figure 20 shows HSP-1 water level and borehole temperature monitoring results from July 2017 through April 2020. HSP-1 transducer data are provided in Appendix 6.

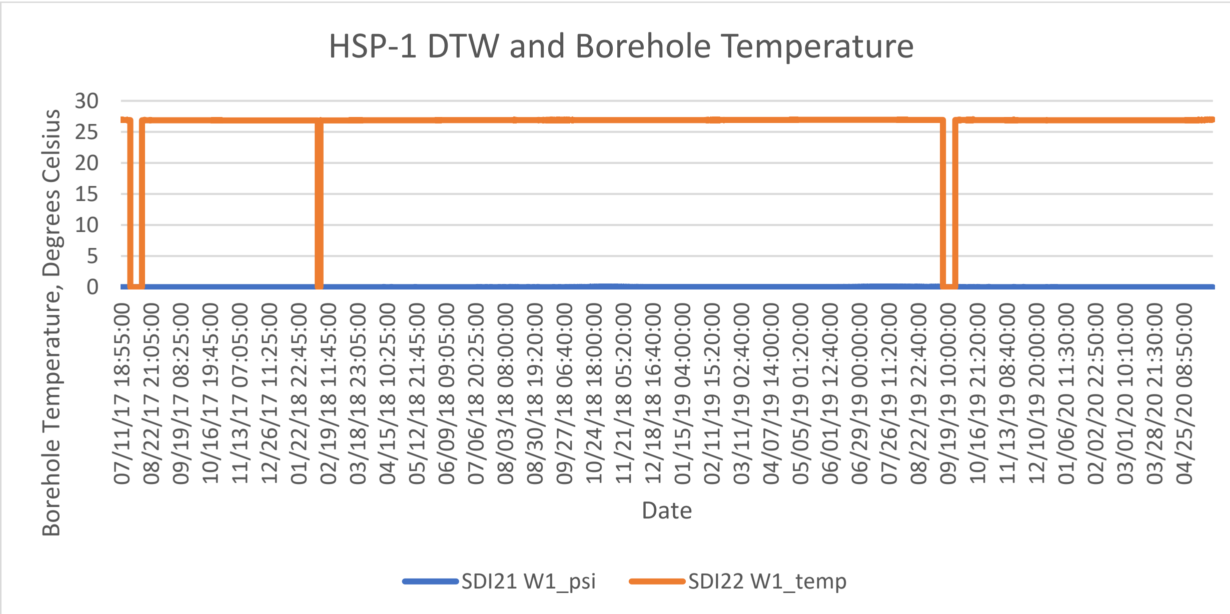


Figure 20. HSP-1 Depth to water and borehole temperature from July 2017 to April 2020.

3.3.2 HSP-2

HOBOware software was used to download the DTW and barometric pressure transducers installed in HSP-2. The DTW transducer is set at the bottom of the 20-foot monitor well. The HOBOware software was used to correct the depth to water measurements for barometric pressure influences, although some diurnal fluctuations from zero to 0.01 feet are present in the processed water level data. Data collected before, during and following the October 13, 2018 storm event are shown in Figures 21 and 22. It appears that no infiltration entered the well at a depth of 20 ft, bls during or after the October 13, 2018 flow event.

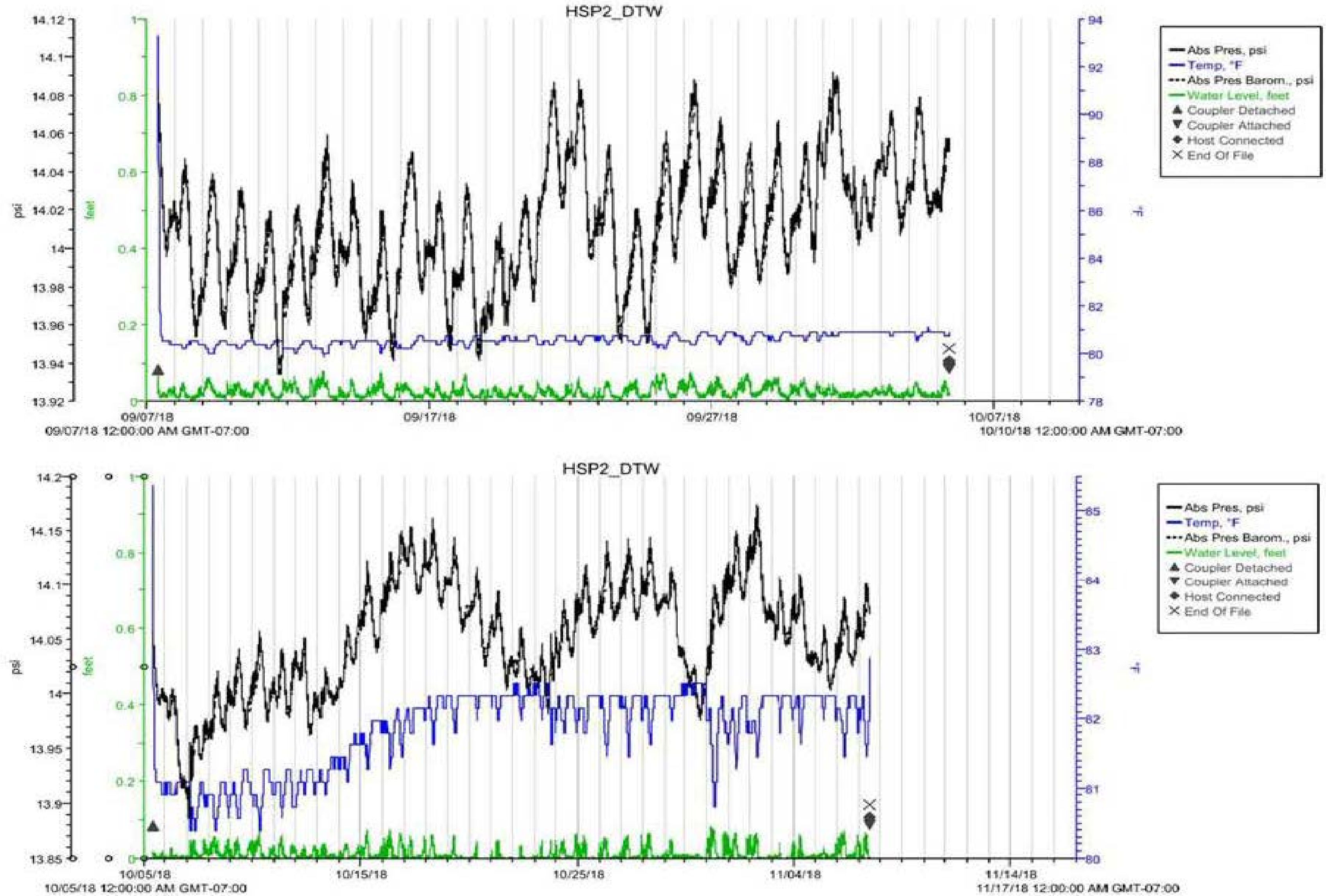


Figure 21. HSP-2 depth to water September 7, 2018 to November 7, 2018

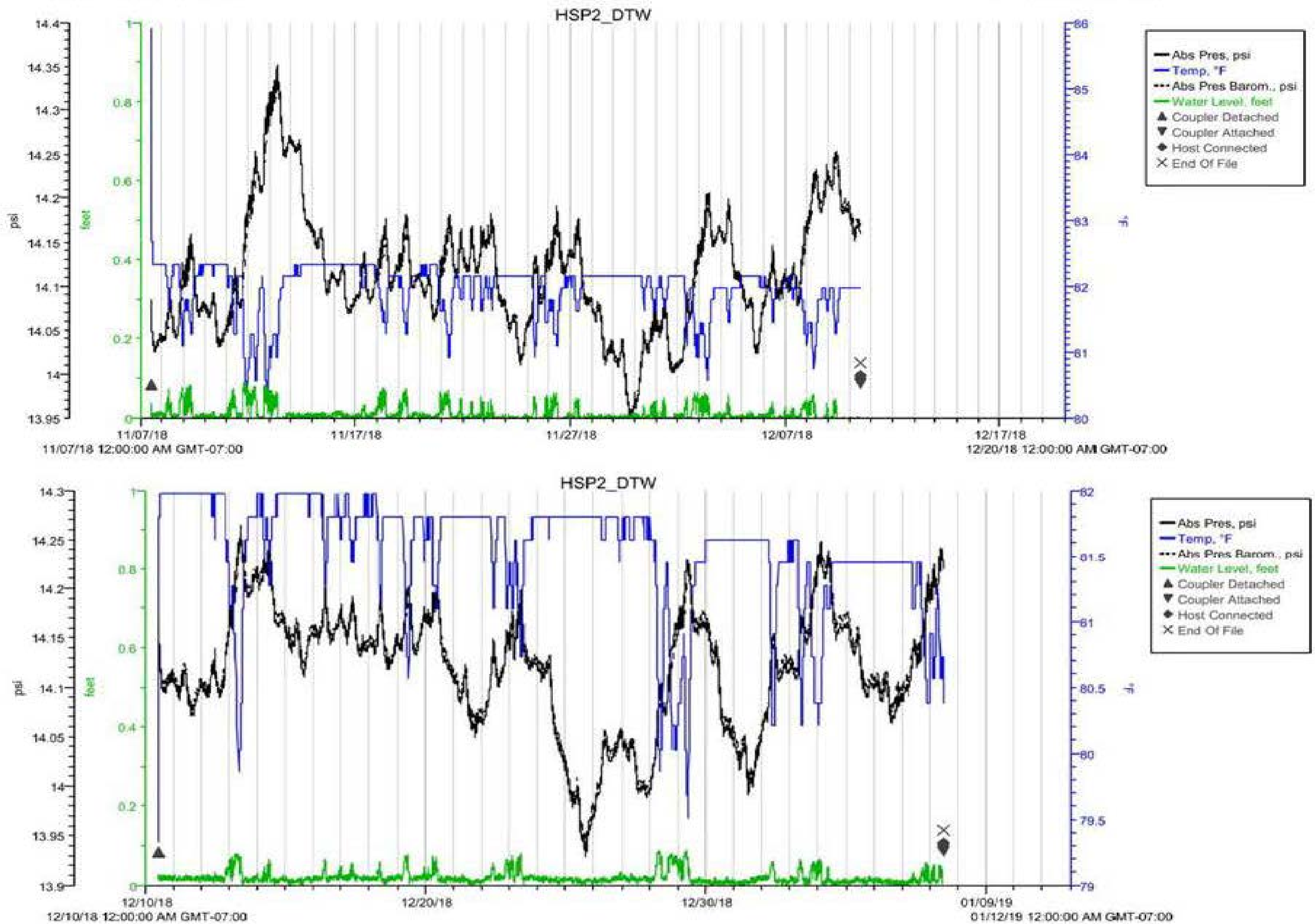


Figure 22. HSP-2 depth to water November 7, 2018 to January 7, 2019.

Due to transducer malfunctions, in November and December 2019, no HSP-2 DTW data were collected during or after the November 29, 2019 storm flow event.

3.4 Soil Moisture Sensor

Soil moisture sensor data were qualitatively assessed because the sensors were installed incorrectly. Of the six soil moisture sensors that were installed, SM1, SM5 and SM6 continue to provide readings. A pre-GCS installation precipitation event occurred on October 13, 2018 that began at 09:20 and ended at 14:20. The HSP soil moisture sensor responses indicate that moisture was detected at SM6 (4 ft, bls) on 10/13/18 at 21:35:00 at SM5 (7 ft, bls) on 10/13/18 at 22:05:00 and finally at SM1 (19 ft, bls) on 10/14/18 at 15:35:00. The maximum amount of soil moisture was detected: at SM6, located at 4 ft, bls at about 12 hours after the precipitation began; at SM5, located at 7 ft, bls at about 12 hours and 30 minutes after precipitation began; and at SM1, located at 19 ft, bls at about 30 hours and 15 minutes after precipitation began (Table 9).

The well installation was designed to prevent cross-circuiting of water flow along the well casing.

Infiltration rates were calculated for each functioning sensor using the distance from land surface to each sensor and the distance between sensors. The average infiltration rate associated with the October 13, 2018 precipitation event is 0.13 inches per minute or 7.8 inches per hour.

Table 9. S&T 1751 HSP-2 Soil Moisture Sensor Readings during October 2018 Precipitation Event

Soil Moisture Sensor (SMS) Number	Depth (feet, below land surface)	Infiltration Analyses	Distance (inches)	Date/Time of Largest SMS Moisture Content	Hours from Surface Water Flow to Largest SMS Moisture Content	Minutes from Surface Water Flow to Largest SMS Moisture Content	Infiltration Rates (inches / minute)
Precipitation Start	NA	---	---	10/13/2018 9:10	---	---	---
Precipitation End	NA	---	---	10/13/2018 14:40	---	---	---
Surface Water Gage	NA	---	---	10/13/2018 9:35	---	0	---
SM1	19	between Land Surface / SM1	228	10/14/2018 15:35	30:00:00	1800	0.13

Soil Moisture Sensor (SMS) Number	Depth (feet, below land surface)	Infiltration Analyses	Distance (inches)	Date/Time of Largest SMS Moisture Content	Hours from Surface Water Flow to Largest SMS Moisture Content	Minutes from Surface Water Flow to Largest SMS Moisture Content	Infiltration Rates (inches / minute)
SM5	7	between Land Surface / SM5	84	10/13/2018 22:05	12:30:00	750	0.11
SM6	4	between Land Surface / SM6	48	10/13/2018 21:35	12:00:00	720	0.07
SM5	7	between SM1/SM5	144	10/13/2018 22:05	12:30:00	750	0.19
SM6	4	between SM1/SM6	180	10/13/2018 21:35	12:00:00	720	0.25
SM6	4	Between SM5/SM6	36	10/13/2018 21:35	12:00:00	720	0.05
						Average	**0.13**

The soil moisture sensor readings indicate that channel infiltration occurred following the October 13, 2018 flow event. Figure 23 shows monitoring results for SM1, SM5, and SM6.

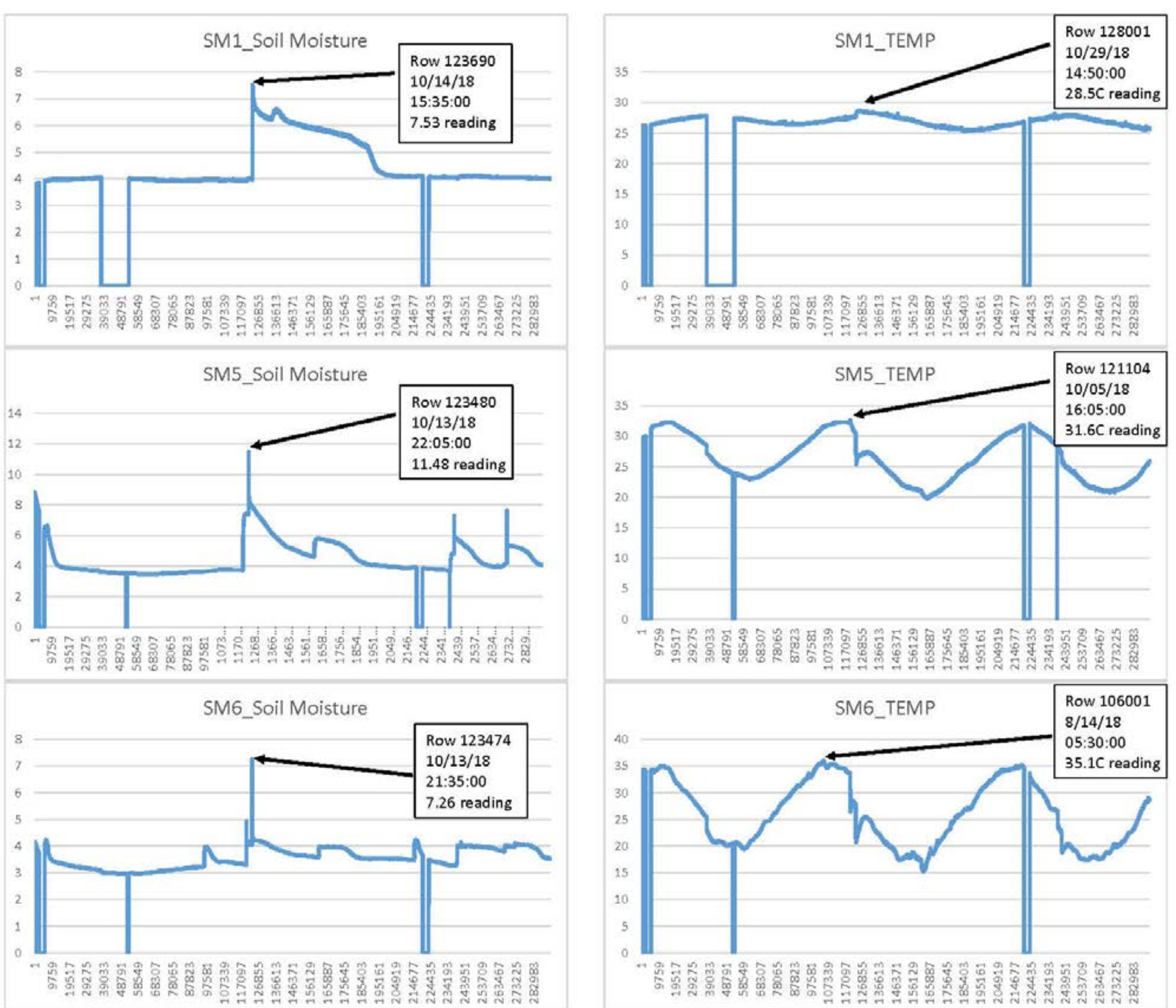


Figure 23. HSP-2 Soil Moisture Sensor readings for SM1, SM5, and SM6.

3.5 Weather and Microclimate

3.5.1 Weather and Precipitation Events

The HSP site is in the low Sonoran Desert and experiences relatively low humidity and relatively high maximum temperatures, especially during summer (Figure 24). Only a handful of significant rainfall events occurred at the sites during the study period; most notably, the October 2018 tropical depression and the November/December 2019 storms delivered significant rainfall total.

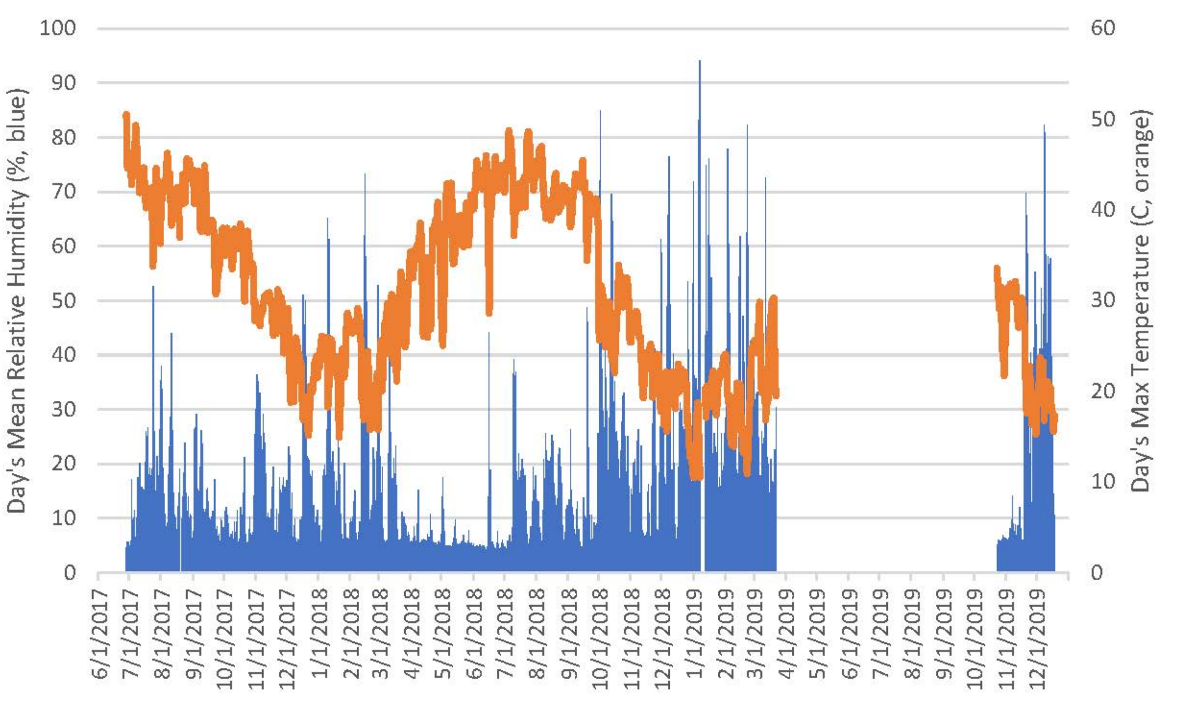


Figure 24. Daily mean relative humidity (blue) and maximum air temperature (orange) (2m AGL) for the upgradient weather station.

Monitoring data from the upgradient and downgradient weather station installations show that precipitation events correlate between the upgradient and downgradient stations. The downgradient station (Figure 25) typically shows less precipitation than the upgradient station (Figure 26) during precipitation events. During the October 13, 2018 precipitation event the upgradient weather station recorded 3.23 inches of precipitation and the downgradient weather station recorded 2.28 inches of precipitation. The instruments were calibrated before they were installed and may need to be recalibrated to verify the readings. The upgradient station is located on colluvium at the base of South Mountain and is 1,327 feet, measured as a straight line, from the downgradient station, located northeast on alluvium near the boundary of the HSP and residential development. Processed weather station data is provided in Appendix 9.

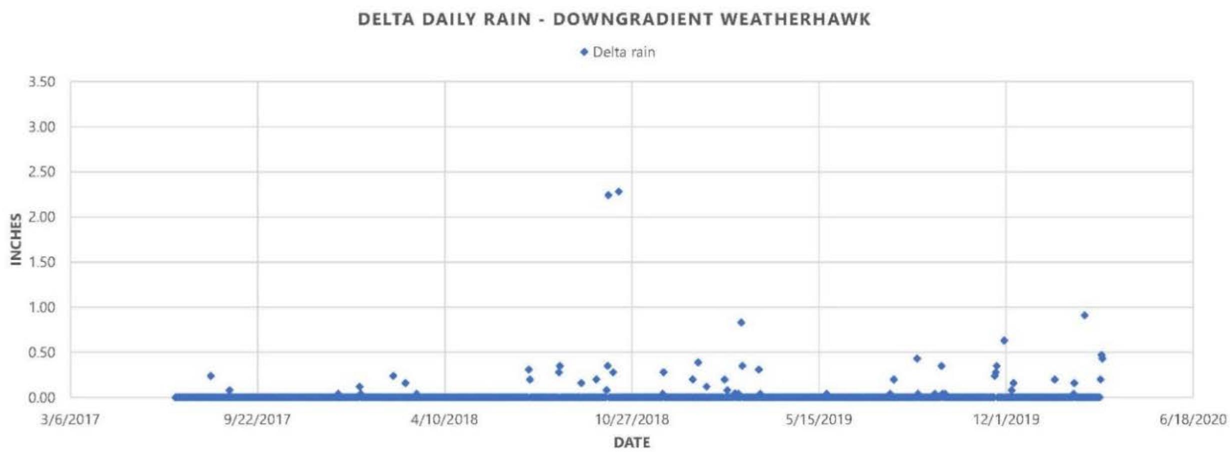


Figure 25. Downgradient weather station precipitation graph July 2017 to March 2020.

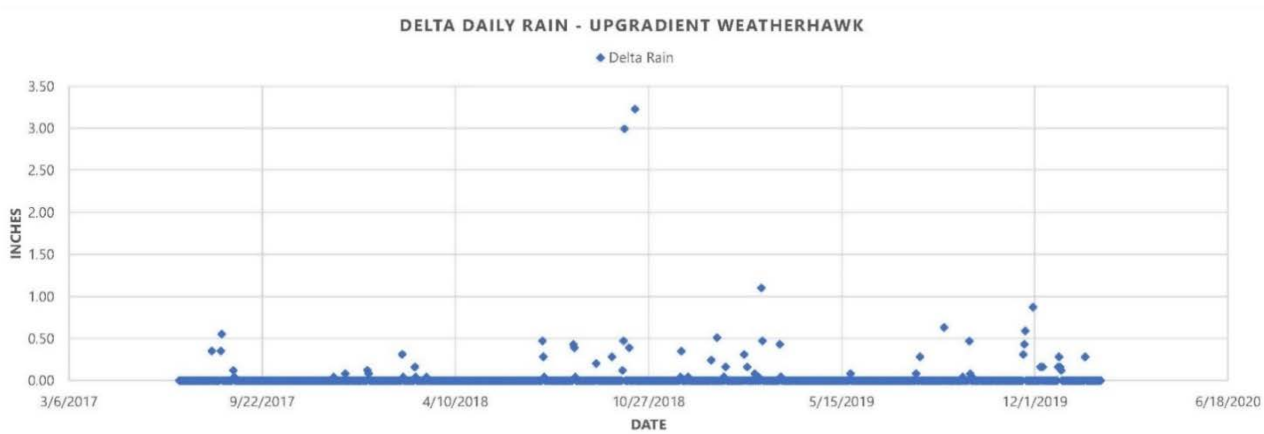


Figure 26. Upgradient weather station precipitation graph July 2017 to February 2020.

3.5.2 Microclimate Effects Analysis

The two microclimate stations are placed upgradient (south) and downgradient (north) along a single wash in the treatment location. Because the treatment alters the hydrology and increases detention of water and soil moisture at the site, we expect to see lower surface temperatures and higher relative humidities after rainfall events, or lasting for longer after rainfall events, post-treatment as compared with pre-treatment.

Due to the limited number of rainfall events it is not possible to compute statistically significant difference results for the pre/post analysis. However, we can calculate the difference between the pre- and post-treatment microclimates following rainfall events, and we can observe the maximum and minimum range of differences. This provides some degree of confidence regarding the range of possible results. In this analysis (Figures 27 and 28) we plot the pre- and post-treatment values of the anomaly of the average hourly air temperature (degrees Celsius) and of the 15-minute relative humidity (%), including the average across all precipitation events of the mean, minimum, and maximum values, for post-rainfall time lags ranging from zero to five days. An anomaly in this case is the difference of the observed value in that hourly period from the average value at that same time of day and site during all days in the month of the observation. The anomaly is a difference from normal conditions. In these results the mean, minimum, and maximum values are simply weighted by the depth of rainfall, so events with more rain figure more prominently in the results. The shaded areas of the graphs represent the range of values observed after all storms, while the lines represent the average value of all storms.

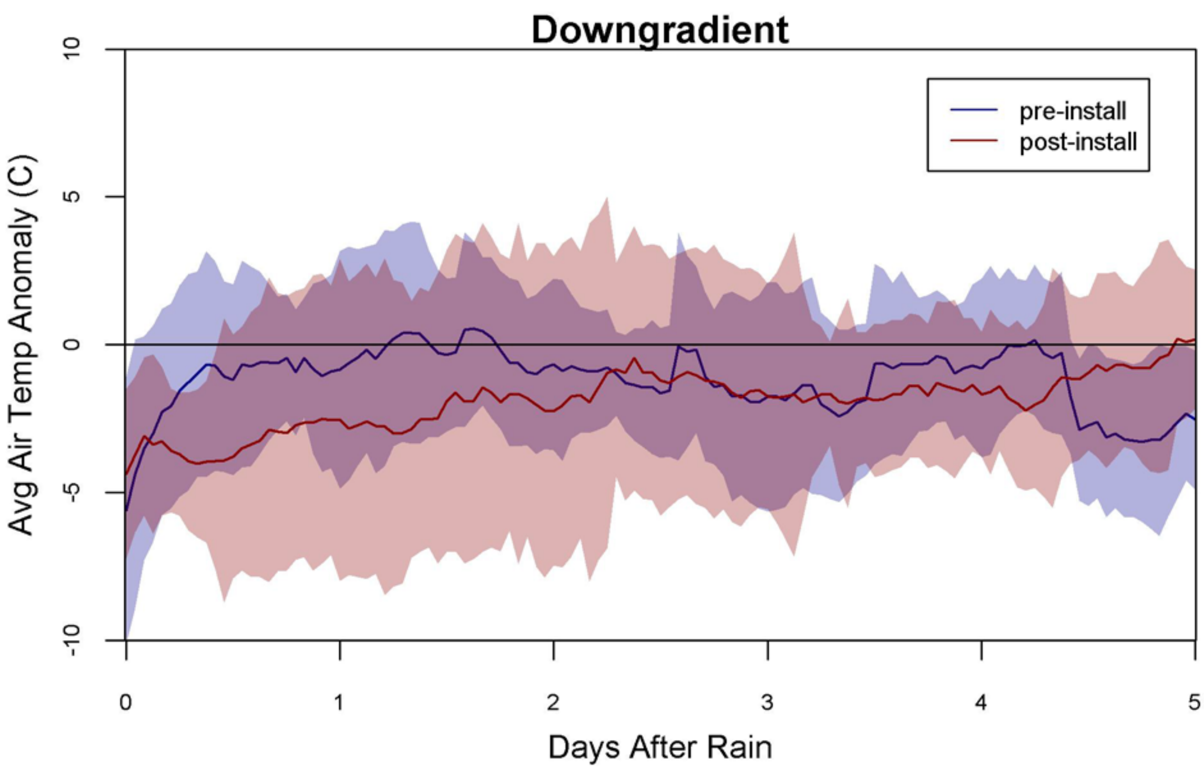


Figure 27. Downgradient/south site, pre- (blue) and post- (red) treatment/installation air temperature anomalies occurring after rainfall events.

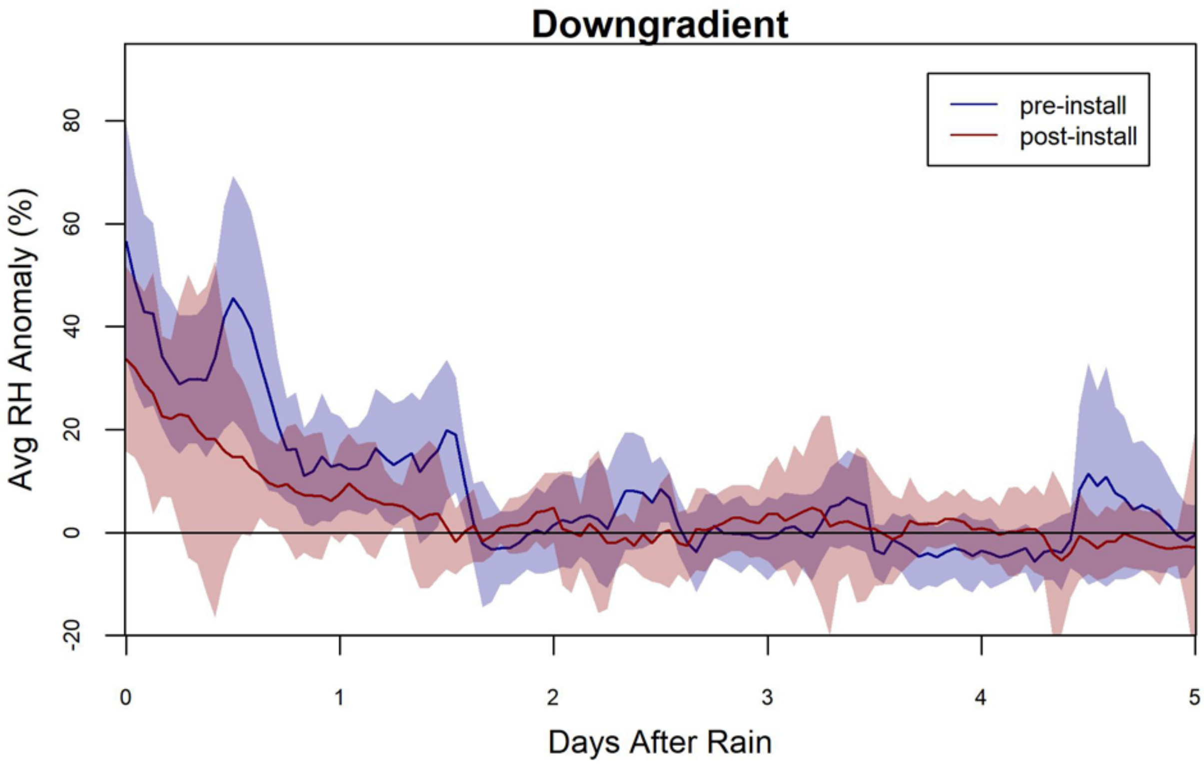


Figure 28. Downgradient/south site, pre- (blue) and post- (red) treatment/installation relative humidity anomalies occurring after rainfall events.

Microclimate air temperatures are roughly 3ºC below normal, and relative humidities are roughly 40% above normal after rainfall events. These anomalies decay quickly and disappear within roughly 1-2 days after the rainfall event pre-treatment/install. Post-treatment/install, the air temperature remains depressed by roughly three degrees until the end of the second day after the rainfall, whereas the pre-treatment/install site's air temperature returns to near-normal within roughly eight hours after the rainfall, and the minimum air temperature anomaly pre-install is similar to the average air temperature anomaly post-install. 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.

4 Discussion

4.1 Limitations

Our research experienced some delays, due to the development of necessary Interagency Agreements and Memorandums of Understanding, postponing work for 6 months. Further delays were incurred associated with permitting and clearances needed to work at the site (NEPA, USACE, CEC, etc.). These approvals stalled instrumentation because the study site is an origination site and culturally important to three local Tribes, so extra clearances were necessary to access the landscape.

Our project overcame many obstacles along the way (aside from the initial delays). On June 10, 2019, Presidential Determination No. 2019-13, pursuant to the Defense Production Act, determined that the "domestic production capability for sUAS is essential to the national defense." Pending further guidance, the fleet was grounded with the exception of emergency operations, and our sUAS campaign was terminated. Fortunately, Maricopa County flew the site for us and developed a Digital Terrain Model (DTM) of the study area on March 1, 2020. All the DTMs collected for the study were processed to remove vegetation to attempt a 'bare earth surface', though this was sometimes difficult and differencing between the pre- and post-GCS DTMs proved very difficult. The datasets are currently available and should be useful when more rainfall, runoff, and sediment transport or capture occurs in the study site.

The Coronavirus Disease 2019 (COVID-19) was identified in Wuhan, China, at the end of 2019 and spread throughout the world. On March 13, 2020, the President of the United States proclaimed the COVID-19 outbreak a national emergency and citizens and employees of the U.S. Government were asked or ordered to stay home. Our field access effectively ended at this time due to the global pandemic.

The recent climate conditions over the Southwest have not been conducive for monsoon moisture to reach the study area. Instead they have led to a prolonged period of dangerous heat. As of July 21, 2020, Phoenix had not received any measurable precipitation (at least 0.01 inches) in more than 90 days. The prolonged mega drought greatly limited our rainfall/runoff analyses. Fortunately, the data has been collected, documented, and published and impacts of future precipitation can be more readily compared. Drought conditions prevented a rigorous analysis of storm flow conditions pre- and post-GCS installations. The existing comprehensive monitoring program provides a good opportunity to continue stormwater monitoring and potentially collect data under wetter climatic conditions. It would be interesting to monitor the HSP for a period of time long enough to allow the flow system to equilibrate following the GCS installations.

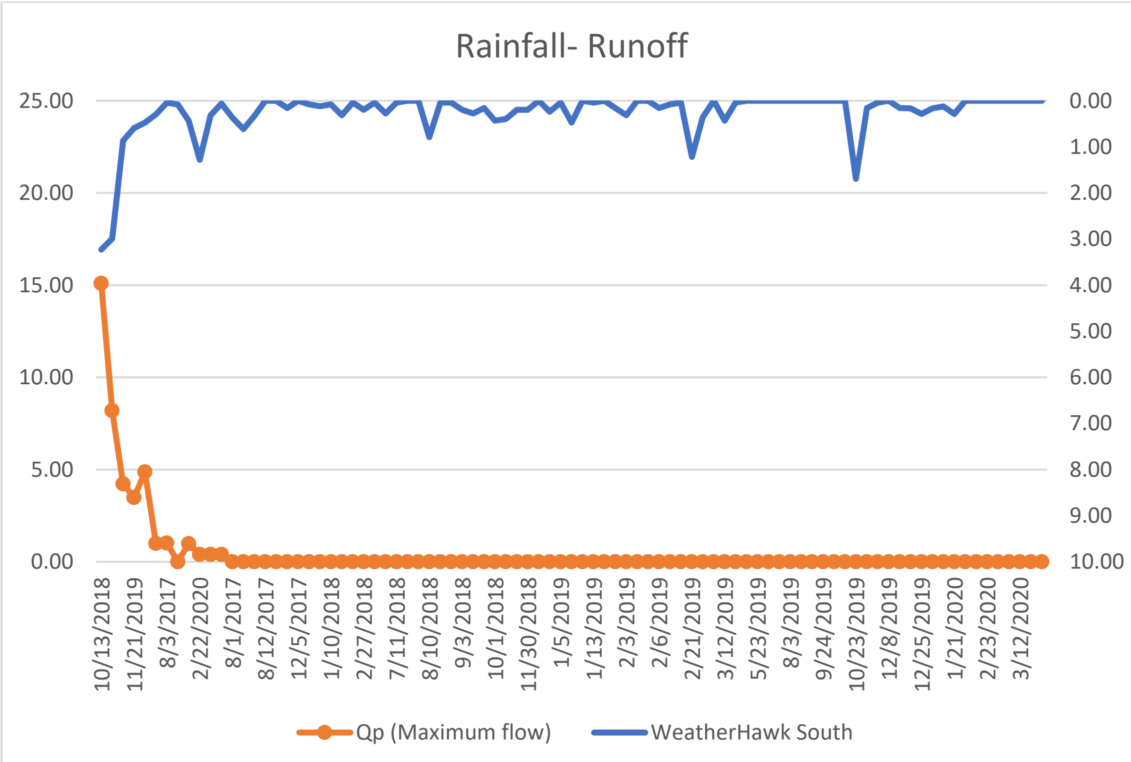
Because we did not have measured inflows at the upstream boundary of the model, we were unable to directly calculate the infiltration in the channel for use in the surface water model and so, the relative change in infiltration between the pre- and post-structures conditions for various flow events is not large. In the future, watershed model estimates could be used as an upstream flow condition, which would likely generate more accurate and likely, greater impacts.

4.2 Education

We were excited at the success of the interpretive sign that was developed for our study site. Over the years, a variety of field trips and training sessions were held to share the research. Observations made during field trips and normal site visits indicate that participants, hikers and campers use the signage to identify and describe the monitoring system and GCS installations. Similar outreach was developed associated with the weather stations. In addition, NAU, in collaboration with Michigan Technical University, installed a Mobile Hydrology Citizen Science monitoring location in the HSP channel upstream from the walking bridge, downstream from GCS # 3 and upstream from GCS #4. A placard installed on the bridge provides instructions for citizens to use a smart phone to scan the Quick Response (QR) code box or navigate to https://cshci.cs.mtu.edu/water/gauges/view/11 to use the web application to collect surface water data during a storm event. A citizen may stand by the placard, take a photo of the red and white stream gage installed in the channel below, and send the photo to the QR code to collect and record a surface water measurement. This citizen science opportunity received little response. There would be more opportunities to participate under normal precipitation conditions. We feel this is a great location for continued outreach and environmental education, even beyond our interpretive signage. Some examples include incorporating help from the nearby Boy Scout and Girl Scout camps in future installations and maintenance. Also, Scouts could become involved in vegetation monitoring at sites. In the long term, it would be wonderful if the research could be used to warrant new badges or other accolades in areas such as land stewardship, watershed stewardship, restoration, science, and ecology. Weather and hydrology data collected from the Study could be made available to campers or local hikers. The location within an urban park makes all these outreach ideas potentially available to non-Scouts too.

4.3 Watershed Response to GCS

The GCSs were installed at the end of 2018 (after the referenced storm on October 13, 2018) and were completed by January 2019. The rainfall-runoff response time appears to be muted, delayed, and shows reduced peak flows after GCSs were installed (Figure 29).



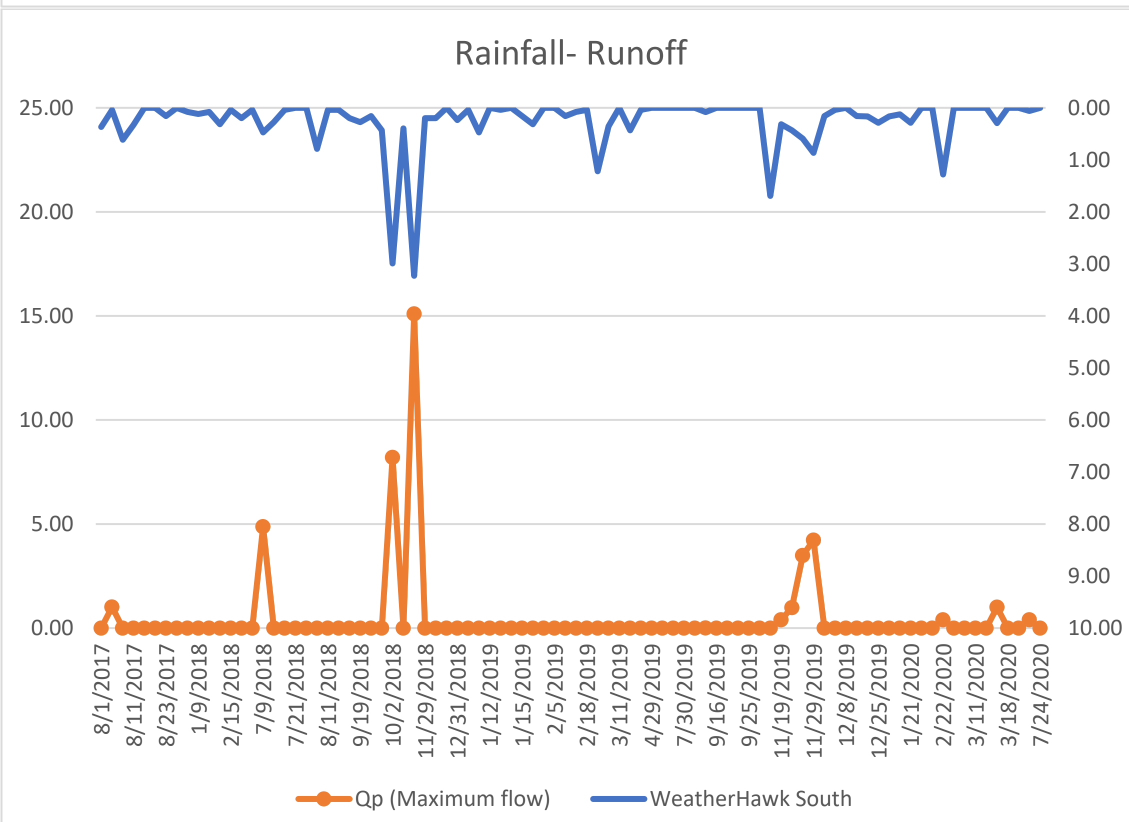


Figure 29. Hyeto-hydrograph portraying southerly weather station data (upgradient) precipitation over the study period (top graph) in relation to the peak discharge measured downstream (bottom graph).

In the Chiricahua study (Norman, et al., 2015) as the soil profile becomes saturated and rainfall exceeds infiltration capacity, the volumes of water discharged from a treated watershed are greater than an untreated watershed. In Phoenix, the soils do not get saturated with very infrequent events and therefore, the discharge rate does not seem to be impacted by GCS. Table 10 shows the ratio (percent of rainfall accounted for by runoff), normalized for differences in area, which appear to vary between 0-6.35% with little difference before or after GCSs are installed.

Table 10. Percent rainfall discharged over time during the Study

Date	Precipitation (Event Total * Watershed Size, In Cubic Feet)	Q Volume (Total Cubic Feet)/Event	Runoff (%)
8/3/2017	13,009.92	826.30	6.35
7/9/2018	153,660.56	4,066.57	2.65
10/2/2018	973,183.52	16,894.36	1.74
10/13/2018	1,050,013.80	57,802.84	5.50
9/14/2019	26,019.84	0.08	0.00
11/19/2019	102,440.37	120.00	0.12
11/20/2019	140,855.51	0.47	0.00
11/21/2019	192,075.69	4,574.12	2.38
11/29/2019	281,711.02	15,749.31	5.59
2/22/2020	416,317.44	240.00	0.06
3/13/2020	95,948.16	1,281.04	1.34
5/10/2020	19,514.88	120.00	0.61

4.4 Future Research

Discharge and associated flooding are dependent on the size of the rainfall event as well as the site's antecedent soil moisture, prior stream flow or stage, urbanization, and basin characteristics. While the connection between rainfall-return period and flood-return period is obvious, their relationship is not direct nor well understood. NCD built GCSs in the study area to withstand a 25-year return interval (about 90 cfs). The precipitation on August 10, 2018, was equivalent to a 15-min., 25-year storm event (Bonnin, et al., 2006) but incurred no flow. And likewise, the largest storm during this 3-year study was on October 13, 2018, which was a 1000-year event (Bonnin, et al., 2006), but incurred a maximum flow of only ~15 cfs. More research relating these two regularly used indices and their relationship would benefit planning for floods.

This Reclamation study ended on September 30, 2020. At the start of the Study, arrangements were made for the BSA to take ownership of the GCS installations in perpetuity. All other monitoring equipment, including the two weather stations and the USGS equipment, were planned for removal at the end of the Study. Additionally, there is an opportunity for FCDMC to include the HSP site in their regional monitoring network and continue to collect data to assess how GCS installations may be used in regional stormwater management. FCDMC has coordinated with and is establishing agreements with USGS and the BSA to continue hydrologic and climatic monitoring at the site pending approval from the Maricopa County Board of Supervisors in October 2020.

5 Conclusions

Our model analyses predicted the slight reduction and delay in peak flows for small events. This is consistent with the literature for gabions (Norman, et al., 2010a; Norman, et al., 2010b) and check dams (Norman, et al., 2015). The data collected for this Study agreed with model predictions and documented these effects, giving confidence for future modelling efforts. Our data collection did not portray impacts on rainfall-runoff response (quantity) from the installation of GCS. We attribute this to the dry antecedent conditions of the study area and lack of previous flow. The structures did reduce flashiness of peak flows though (which should limit erosion). The model estimates that the structures could increase the infiltration approximately 15% over time – slightly larger than average infiltration increases (~10%) measured at the Babacomari Ranch in southeast Arizona, where gabions had been constructed (Norman, et al., 2019).

It was found that the GCS installations increased the infiltration occurring in the stream channels by approximately 15% for a variety of storms. A sensitivity study was conducted to vary the hydraulic conductivity from 10 times less than to 10 times greater than the base hydraulic conductivity values (0.14 in/hr to 14 in/hr, or 1E-2 cm/s to 1E-4 cm/s). The relative infiltration between the with- and without-GCS installations did not vary significantly. The range of the values used in the sensitivity study encompassed the average infiltration rate of 7.8 inches per hour, calculated from the SMS data. While the relative amount of infiltration with and without grade control structures did not vary significantly with changes to the hydraulic conductivity, the total amount of infiltration is directly related to the hydraulic conductivity, and continued model testing and monitoring is necessary to reduce the uncertainty in the hydraulic conductivity value.

We recommend further research, extended over time, to examine rainfall-runoff response in wetter timeframes, even in this very dry setting, and to better investigate how that might impact the geomorphology. We visually identified increased sedimentation behind GCS, decreased erosion evidenced at scour chains, and decreased suspended sediments following GCS installations, but were unable to quantify these results due to the very low amounts, impacts from construction, and lack of runoff-induced sediment movement. The potential to decrease downstream sediment loads, especially in reservoirs, is important because so much time and money is spent removing and dredging sediment. Innovative monitoring, including large-scale particle image velocimetry (LSPIV) were invaluable to this research. Given the arid-land location and added drought conditions, the water levels were not high enough to compute, even using the continuous slope-area method, so discharge was calculated solely using the LSPIV. The careful redundancy of data acquisition is extremely important when studying dryland hydrology.

Microclimate at the site was monitored pre- and post-GCS installations, providing an excellent control for analyzing the monitoring results. The sample size (number of storms) is small and future microclimate results will build statistical confidence. However, the results of the analyses are strong and potentially important because they demonstrate that this kind of green infrastructure treatment creates roughly a three-degree microclimate cooling effect for at least two days following rainfall events, as compared with the untreated channel. We attribute this to the increased moisture, evaporation, and latent heat expulsion from the evaporation on the treated site and recommend further investigation to better document these effects. Because microclimate cooling is an important objective of urban green infrastructure in hot/dry cities like Phoenix, this finding establishes an important microclimate cooling benefit for GCS and other green infrastructure treatments that retain stormwater.

6 References

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7 Appendices

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