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DESIGNING AND IMPLEMENTING A NETWORK FOR SENSING WATER QUALITY AND HYDROLOGY ACROSS MOUNTAIN TO URBAN TRANSITIONS[1]

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ABSTRACT: Water resources are increasingly impacted by growing human populations, land use, and climate changes, and complex interactions among biophysical processes. In an effort to better understand these factors in semiarid northern Utah, United States, we created a real-time observatory consisting of sensors deployed at aquatic and terrestrial stations to monitor water quality, water inputs, and outputs along mountain to urban gradients. The Gradients Along Mountain to Urban Transitions (GAMUT) monitoring network spans three watersheds with similar climates and streams fed by mountain winter-derived precipitation, but that differ in urbanization level, land use, and biophysical characteristics. The aquatic monitoring stations in the GAMUT network include sensors to measure chemical (dissolved oxygen, specific conductance, pH, nitrate, and dissolved organic matter), physical (stage, temperature, and turbidity), and biological components (chlorophyll-*a* and phycocyanin). We present the logistics of designing, implementing, and maintaining the network; quality assurance and control of numerous, large datasets; and data acquisition, dissemination, and visualization. Data from GAMUT reveal spatial differences in water quality due to urbanization and built infrastructure; capture rapid temporal changes in water quality due to anthropogenic activity; and identify changes in biological structure, each of which are demonstrated via case study datasets.

(KEY TERMS: monitoring; instrumentation; urbanization; sensor network; environmental observatory; quality assurance/quality control.)

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INTRODUCTION

Monitoring water systems with high temporal and spatial resolution for an extended duration provides important insight into aquatic ecosystem processes (Parr *et al.*, 2002; Kirchner *et al.*, 2004; Rundel *et al.*, 2009; Halliday *et al.*, 2012; Rode *et al.*, 2016). In the past decade, the use of *in situ* sensors in environmental monitoring has increased (Hart and Martinez,

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2006; Porter *et al.*, 2012; Laney *et al.*, 2015; Blaen *et al.*, 2016; Pellerin *et al.*, 2016); however, data gaps still exist at scales ranging from watersheds to the globe (Montgomery *et al.*, 2007; Harding *et al.*, 2014; Peters *et al.*, 2014; Goodman *et al.*, 2015), and guidance on sensor deployment, use, and data management remains limited (Rundel *et al.*, 2009; Laney *et al.*, 2015; Lundquist *et al.*, 2015; Pellerin *et al.*, 2016). As Lundquist *et al.* (2015) observe, there is a paucity of literature regarding "... how instruments are actually installed, maintained, and quality-controlled, likely because technicians are paid to fix problems rather than write about them." Furthermore, there is a lack of documentation and standardization of quality control (QC) in environmental sensor networks (Strachan *et al.*, 2016), casting doubt on the reliability and comparability of resulting data (Campbell *et al.*, 2013), even though quality-controlled and annotated datasets are of high value for reuse (Porter *et al.*, 2012). Despite these concerns, high-frequency water quantity and water quality monitoring are essential to capture hydrologic and chemical patterns in aquatic systems, test hypotheses (Horsburgh *et al.*, 2011; Rode *et al.*, 2016), and facilitate water resource management (Parr *et al.*, 2002; Pellerin *et al.*, 2016).

Globally, mountains play an important role in providing water resources from snow and ice to downstream urban population centers (*e.g.*, Viviroli *et al.*, 2007; Immerzeel *et al.*, 2010; Buytaert and De Bièvre, 2012), but are underrepresented in environmental data collection networks (Strachan *et al.*, 2016). The Intermountain West of the United States (U.S.) encompasses high elevation landscapes from the Sierra Nevada east to the Rocky Mountains, is characterized by arid to semiarid climate (Wise, 2012), and provides water resources to well over 30 million people in urban centers in the U.S. and Mexico (Vano *et al.*, 2014). In Utah, nearly 86% of the state's population resides in the rapidly growing urban corridor along the Wasatch Front (Hale *et al.*, 2015), a population that is highly dependent on mountain water resources. Monitoring of water storage and water quality fluxes is increasingly important in this region because of high rates of population growth (Kotkin, 2013), long-term droughts (Cook *et al.*, 2004), and reduced snowpack (Gillies *et al.*, 2012; Luce *et al.*, 2013; Scalzitti *et al.*, 2016). There is growing concern that current water supplies will be inadequate for increased water demand (Montgomery *et al.*, 2007; Bardsley *et al.*, 2013), and dwindling water supplies increase the significance of water quality.

Within the urban context, flows in natural conveyances are abstracted into drainage pipes, canals, and other man-made infrastructure that provide water supply, flood control, and stormwater management (Kaushal and Belt, 2012). Return flows from these systems significantly affect water quantity and quality in urban streams (Groffman *et al.*, 2003), hence tracking water as it passes through Utah's urban areas requires monitoring not only the streams, but also significant inflows such as stormwater outfalls. Water quality in urban streams can be highly dynamic both spatially and temporally, driven not only by signals from upstream watersheds (*e.g.*, spring snowmelt) but also by diversions, local stormwater inputs, and urban groundwater (Bhaskar and Welty, 2012; Kaushal *et al.*, 2014; Hall *et al.*, 2016c; Gabor *et al.*, 2017). Quantifying the varying hydrologic response from land uses that differ in urban infrastructure is challenging (Ryan *et al.*, 2010), but it can be critically important for understanding the function of urban streams, predicting potential flooding, and assessing water quality impacts on urban streams and downstream receiving waters (Paul and Meyer, 2001; Walsh *et al.*, 2005, 2016).

In this article, we describe a water quality sensor network for a mountain to urban environmental observatory that is part of the innovative Urban Transitions and Aridregion Hydro-sustainability project (iUTAH: http://iutahepscor.org). This statewide, multi-university effort seeks to understand the impacts of population increase, changing land use, and climate change on Utah's water resources to provide better information in planning for the sustainability of natural and urban systems. The seminal infrastructure of iUTAH is a real-time observatory network of terrestrial climate and aquatic stations called GAMUT (Gradients Along Mountain to Urban Transitions) that collectively captures changes in water resources along a gradient from Utah's high elevation mountains through the state's most densely populated urban areas. GAMUT is a cooperative effort between Utah's three major research universities (Utah State University, University of Utah, and Brigham Young University).

Our study combines the expertise of technicians and scientists to describe the design, deployment, and operation of the GAMUT network. We provide specifics on station selection and sensor deployment, maintenance considerations, data integration and management, and post-processing. We describe important lessons learned in network implementation and operation, information that we wish we had *a priori* and that we believe will be useful for a wide community of scientists who are now developing sensor networks for monitoring aquatic and terrestrial systems (*e.g.*, McDowell, 2015; Hinckley *et al.*, 2016). We present our findings as follows: Gradients along Mountain to Urban Transitions Network outlines the requirements that drove our work; Network Design details the methods used in designing a network to meet those requirements; Network Implementation provides the results of our specific implementation of the principles laid out in the design, including solutions to challenges we encountered, resources required to implement the network, and how GAMUT has catalyzed further research; and Case Studies presents three brief data vignettes to illustrate the utility of GAMUT data for assessing the effects of urbanization and anthropogenic activity on water quality.

GRADIENTS ALONG MOUNTAIN TO URBAN TRANSITIONS NETWORK

GAMUT was conceptualized as an *in situ* water research facility to provide insights into biophysical processes that impact water resources, facilitate new projects by institutional researchers and educators, and improve existing monitoring and data infrastructure to catalyze Utah's competitiveness for research funding — as Hinckley *et al.* (2016) observe, monitoring networks have potential to engage the scientific community to synergize scientific discovery. The overarching objective of GAMUT was to capture how water quantity and quality change in multiple watersheds along the gradient from the high mountains of Utah to the state's population centers in the valleys. In our selection of watersheds to instrument, we also wanted to represent gradients in the rate and types of urbanization and land-use change. These gradients are not specific to Utah, but are common in the Intermountain West region where water begins as mountain snowpack, flows through rivers and streams, is stored in reservoirs, and is eventually used by populations living in the mountain valleys (Brown *et al.*, 2005; Grimm *et al.*, 2008). The following design requirements and principles emerged from our original conceptualization of the network:

1. Multiple watersheds were required to capture different patterns of urbanization, different stream sizes, and different mountain water sources.
2. Each watershed needed to be monitored along an elevation gradient and through urban areas.
3. Both aquatic and terrestrial climate stations were required to capture water fluxes and instream water processes.
4. An advanced suite of water quality observations for aquatic sites was necessary to capture biological and chemical parameters of interest.
5. The sensor network needed to be standardized so that it could be managed and operated by multiple collaborating institutions and to ensure comparability of data across sites and watersheds.
6. The network needed to capture the effects of human water management infrastructure common to urban Utah watersheds (*e.g.*, dams and reservoirs, diversions, and stormwater return flows).
7. The network needed to observe variables at high frequencies and for extended durations to capture seasonal variation (*e.g.*, spring snowmelt runoff, summer agricultural diversions) and discrete natural and anthropogenic events (*e.g.*, precipitation, agricultural returns, stormwater flows).
8. The resulting data needed to be accessible to a broad audience (*i.e.*, scientists across domains, educators and students, and stakeholders) per iUTAH's data policy (Horsburgh and Jones, 2016).
9. Data generated by GAMUT needed to be published in standardized formats to be discoverable on a broader scale and to facilitate integration with other monitoring networks.

NETWORK DESIGN

Designing the GAMUT network required specification of monitoring hardware (*e.g.*, sensors, dataloggers, communication peripherals) as well as a plan for operating and maintaining the network and its resulting datasets. In the following subsections, we describe the methods we used to design these aspects of GAMUT. We follow with a section to describe in more detail the specific implementation of these designs.

Monitoring Station Design and Siting

To meet the requirements for the GAMUT network, we established standard designs for both aquatic and climate stations. Station design included variables to be measured, sensors to be used, and how stations would be standardized in equipment and programming, a crucial component to optimize usability of monitoring network data (Thorpe *et al.*, 2015; Hinckley *et al.*, 2016). Based on our experience (*e.g.*, Bowling *et al.*, 2010; Horsburgh *et al.*, 2010; Eiriksson *et al.*, 2013), we needed sensors to be easily serviceable, consistent across sites, and replaceable.

We sought robust and documented equipment from established manufacturers to minimize time spent troubleshooting and to ensure that technicians could access support from vendors. Where possible, we sought to use sensor technology implemented by agencies and other observatories (*e.g.*, U.S. Geological Survey [USGS], National Ecological Observatory Network) to facilitate data comparability.

We designed all stations to include onsite data recording and storage with real-time connectivity via active telemetry connections. We selected reliable and standardized equipment for supplying power and providing communications to ensure that the stations could operate autonomously, that data were consistently collected across all sites, and that data were dependably streamed to a centralized base station (ESIP EnviroSensing Cluster, 2014). The power and communication equipments installed at each GAMUT station are detailed in Table 1. We used manufacturer estimates of sensor power consumption to develop power budgets for the GAMUT stations and selected battery and solar panel sizes that exceeded the power needs of the sensor suite with the goal of keeping stations fully functional for 7-10 days on battery power without a charge (Campbell Scientific, 2011; Balam, 2013).

We developed a plan for locating stations within each watershed. In designing watershed observatories, placement of monitoring sites is dependent on the scientific goals of the study, the topographic and land-use characteristics of the watershed(s), as well as logistical aspects such as access, telemetry options, and physical infrastructure for installation (Strobl and Robillard, 2008; ESIP EnviroSensing Cluster, 2014). In order to span elevations and mountain to urban environments in each watershed, we decided to place aquatic monitoring stations: (1) in a high elevation first- or second-order stream; (2) in a mid-elevation second- or third-order stream, which may correspond to immediately below a significant impoundment to capture the effects of a dam and reservoir; (3) at a low elevation valley site; and (4) near the terminus of each stream within or below the urban area of interest. For climate and terrestrial monitoring, we attempted to locate stations in: (1) high elevation mountain headwater areas; (2) mid-elevation areas near reservoirs; and (3) low elevation in the valley/urban areas. Where possible, we planned to co-locate aquatic stations with existing discharge gaging stations to take advantage of historic and ongoing data collection efforts by federal agencies and local water districts. Furthermore, we attempted to approximately co-locate climate and aquatic stations where possible. Ideally, the location of each station provides measurements that are representative of a relatively large area (valley scale for climate sites, reach scale for aquatic sites). To this end, climate stations were positioned in open areas and aquatic stations were sited within the main channel flow. This enables more accurate interpolation between sites and minimizes bias caused by localized climatic and aquatic features (World Meteorological Organization, 2008).

TABLE 1. Power, Communications, and Peripheral Components at Gradients Along Mountain to Urban Transitions Network Sites. The battery, radio or modem, and datalogger are housed in an enclosure attached to a mast or tower along with the solar panel and antenna.

Component	Manufacturer and Model
Battery	Powersonic
Charge controller	Morningstar SunSaver
Spread-spectrum radio	Campbell Scientific RF450
Cell phone modem	RAVEN
Datalogger	Campbell Scientific CR3000-RC (climate), CR800 (aquatic)
Solar panel	Solartech
Antenna	Campbell Scientific 14201 Yagi
Enclosure	Campbell Scientific ENC16/18
Mast	Campbell Scientific UT20
Tower	ROHN 25SS020

Fundamental and Enhanced Water Quality Stations. We designed aquatic monitoring stations to collect data for a set of "fundamental" water quality variables. These include dissolved oxygen (DO), specific conductance (SC), pH, water temperature, turbidity, and stream stage. We determined that observations for these sensors could help in answering many, but not all of our driving research questions, particularly in urban areas. Therefore, we added a set of "enhanced" variables to measure at aquatic stations bracketing sites up- and downstream of urban areas. Enhanced variables included biological constituents (*i.e.*, chlorophyll-*a* and phycocyanin pigments), nutrients (*i.e.*, nitrate), and fluorescent dissolved organic matter (fDOM). Many of the aquatic variables are measured by sensors attached to a multiparameter sonde. Table 2 lists the variables measured at GAMUT sites and provides a justification and basis for why we chose to measure each variable. Specific sensors used to measure these variables are also included in Table 2, and details of their deployment are described in more detail in the Network Implementation section.

Climate Stations. Climate stations were designed to complement aquatic stations and provide infrastructure for research activities related to water supply, soil moisture, evapotranspiration, and biogeochemistry. The core suite of sensors acquired for climate

TABLE 2. Site Type, Variables Measured, Rationale for Inclusion, and Sensor Manufacturer and Model.

Site Type	Variables	Rationale	Sensor Model
Fundamental and enhanced aquatic	Dissolved oxygen	Important for aquatic organisms and the health of aquatic ecosystems. Used by State of Utah as an overall indicator of water quality	YSI EXO2 599100-01
	Specific conductance, water temperature	Temperature influences biological activity and growth. Specific conductance measures the concentration of dissolved constituents. Both are used by the State of Utah as water quality indicators	YSI EXO2 599870-01
	pH	Determines the solubility and biological availability of chemical constituents in water	YSI EXO2 599795-02
	Stage	Measure of stream water level needed to calculate discharge	Campbell Scientific CS451
	Turbidity	Optical measure of water clarity that is related to concentrations of total suspended solids (*e.g.*, Jones *et al.*, 2011)	Forest Technology Systems DTS-12
Enhanced aquatic	Fluorescent dissolved organic matter (fDOM)	DOM includes important components of the carbon cycle, is important in aquatic food webs, and can indicate aquatic-terrestrial linkages (*e.g.*, Gabor *et al.*, 2015)	YSI EXO2 599101-01
	Phycocyanin, chlorophyll-*a*	Indicators for the concentration of photosynthetic pigments present in cyanobacteria and algae	YSI EXO2 599102-01
	Nitrate	Important biological macro-nutrient	Satlantic SUNA V.2
Terrestrial climate	Air temperature, relative humidity	Air temperature can control rates of biological growth, chemical reactions, and affects nearly all other weather parameters. Relative humidity is a measure of the water vapor content of air	Campbell Scientific HC2S3
	Air temperature	Redundant measure of air temperature	Apogee T110
	Barometric pressure	The weight of the atmosphere. Indicates changes in weather patterns	Campbell Scientific CS106
	Wind speed, wind direction	Important for monitoring and predicting weather patterns. Affects rates of evaporation, aeration, and mixing in surface waters	RM Young 5303
	Precipitation	Measure of the delivery of atmospheric water to the surface of the earth. Amount and duration of precipitation affects water availability for humans and ecosystems	Geonor T-200B
	Snow depth	Indicator of the amount of water stored in solid form on the surface of the earth relating to water availability	Judd Communications Ultrasonic Depth Sensor
	Incoming and outgoing shortwave and longwave radiation	Indicators of the amount of energy from the sun reaching the earth's surface and the amount of radiation emitted by the earth's surface and lower atmosphere. Important in estimating an energy budget	Hukseflux NR01
	Incoming shortwave radiation	Redundant measure of incoming shortwave radiation	Apogee SP-230
	Incoming and outgoing photosynthetically active radiation	Indicators of the amount of light available for photosynthesis	Apogee SQ-110
	Infrared surface temperature	Influences physical, chemical, and biological processes at the soil surface	Apogee SI-111
	Soil moisture, soil temperature, soil conductivity	Important in estimating the exchange of water and heat between the atmosphere and soil	Acclima ACC-SEN-SDI
	Enclosure humidity	Quality assurance/control variable indicating moisture intrusion into the datalogger enclosure	Campbell Scientific CS210
	Enclosure open door sensor	Quality assurance/control variable indicating when maintenance actions were performed at a station	Campbell Scientific 18166

stations measures air temperature, relative humidity, barometric pressure, wind speed and direction, radiation, precipitation, snow depth, soil moisture, and soil temperature. See Table 2 for the complete list of variables, sensors, and rationale.

Operational Design

The operational design for GAMUT includes the plans and procedures for how the network would be operated across multiple watersheds. Settling on a design for the operational aspects of GAMUT was important up front given that we planned to deploy sites in three watersheds managed by different technicians employed by separate organizations. GAMUT's operational design needed to include the following: plans for quality assurance (QA) and QC, site and sensor maintenance, rating curve development for aquatic stations, and data collection and management.

Quality Assurance/Quality Control Plan. To ensure procedural consistency across the watersheds, we developed and implemented standard protocols for data QA and QC. Campbell *et al.* (2013) differentiate between QA and QC of sensor data: *quality assurance* refers to a "set of processes or steps taken to ensure that the sensor network and protocols are developed and adhered to in a way that minimizes inaccuracies in the data produced," whereas *quality control* "occurs after the data are generated and tests whether they meet the necessary requirements for quality outlined by the end users."

Protocols to ensure that the data are reliable are important given the geographic scope of the GAMUT network, the distribution of technicians across institutions, the potential turnover of personnel, and the broad audience for which the data are intended. Regular maintenance of stations and sensors, including cleaning and calibration, is essential to QA (Parr *et al.*, 2002; Campbell *et al.*, 2013). Manufacturers provide guidelines for sensor maintenance; however, the recommended periodicity is typically unspecified. Our plan was to implement a minimum frequency of monthly site visits and to increase the frequency if the monitoring of data or site conditions revealed issues (Wagner *et al.*, 2006). An aquatic site visit involves cleaning sensors to minimize the effects of fouling and performing calibration for sensors that are subject to drift. We initially adopted calibration criteria from the USGS (Wagner *et al.*, 2006) and from sensor manufacturers (*e.g.*, Xylem, 2012).

A detailed record of field activities is essential to document environmental conditions and site and station maintenance actions such as calibrations, sensor deployments, and retrievals (World Meteorological Organization, 2008; ESIP EnviroSensing Cluster, 2014) and is important for post-processing as data corrections should not be made unless the source of error can be explained by field notes or data from other stations or other variables (Wagner *et al.*, 2006). We planned an online equipment management system, currently under development, to ensure that important information about what activities were performed where, when, and by whom would be recorded in standardized formats and be accessible digitally.

Post-processing of raw environmental sensor data, which consists of adjustments to data along with the application of flags, or data qualifiers, to annotate data points, is usually required before those data can be reliably used in scientific analyses (Mourad and Bertrand-Krajewski, 2002; Horsburgh *et al.*, 2011; Campbell *et al.*, 2013). To perform these functions, GAMUT technicians use Observations Data Model (ODM) Tools (Horsburgh *et al.*, 2015), a software program designed for post-processing of time series data. Our project data policy gave GAMUT a goal of performing QC post-processing within six months of original data collection.

We adopted a series of standardized post-processing steps for all variables across GAMUT sites, consistent with practices and recommendations described in the literature (Campbell *et al.*, 2013; Horsburgh *et al.*, 2015). These steps are designed to advance the raw time series data from GAMUT sensors to a quality-controlled product suitable for scientific analysis (subject to any limitations of the data noted in data qualifiers) and include addressing out of range values and erroneous data due to sensor malfunction or environmental conditions, correction for sensor drift and calibration, filling data gaps, conducting a final data review, and applying data flags. More details are provided on the implementation of these QC steps in the Supplemental Materials (File S1) for this article.

Discharge Rating Curve Development. Stream discharge is an essential quantity for aquatic monitoring, allowing the comparison of flow rate between sites and time periods as well as the quantification of constituent transport. For GAMUT aquatic sites, operation of the station and development of a continuous record of discharge required establishing rating curves to translate stream stage measurements to discharge (Kennedy, 1982; Schmadel *et al.*, 2010). Our design was to use standard methods to manually measure discharge (Rantz, 1982; Turnipseed and Sauer, 2010; Mueller *et al.*, 2013), associate those measurements with concurrent stage readings, and fit relationships to resulting data to develop a rating curve (Herschy, 2009). The rating curve can then be used with high-frequency water level data to derive discharge (Horsburgh *et al.*, 2010).

For GAMUT sites co-located with existing gaging stations, we adopted the discharge measurements from those gages. For all other aquatic sites, periodic discharge measurements were made using several flow gaging methods to capture the wide range of flows observed at GAMUT sites. Instead of including these techniques in the NETWORK IMPLEMENTATION section, details are in the Supplemental Materials (File S2), along with the steps we undertook to develop stage-discharge rating curves and generate high-frequency estimates of discharge. Although these methods are understood to be standard, they are typically documented in disparate sources.

Design for Data Collection and Dissemination

Early on, participants in the iUTAH project committed to openly publish data to a broad audience. This was codified in a data policy (Horsburgh and Jones, 2016) that outlines timelines and procedures for data sharing designed to maximize the impact and use of datasets collected within iUTAH facilities and by iUTAH research teams. For GAMUT, Jones *et al.* (2015) provide a complete description of the data management cyberinfrastructure that supports the network. In short, raw data are streamed directly into operational databases and made available online in near real time. We designed the GAMUT cyberinfrastructure so that time series data are stored using the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) ODM (Horsburgh *et al.*, 2008) and published in Water Markup Language (WaterML) format using WaterOneFlow web services (Zaslavsky *et al.*, 2007). This makes the GAMUT data available in a national context, permitting discovery and download along with data from any other networks registered with the CUAHSI Water Data Center. Using standardized formats also permitted us to integrate visualization of agency data (*e.g.*, USGS) with GAMUT data (http://data.iutahepscor.org/tsa).

NETWORK IMPLEMENTATION

At the time of writing, GAMUT includes 40 instrumented climate, aquatic, or storm drain monitoring sites, each collecting a subset of 141 variables, depending on the site type, resulting in the generation of 2,012 individual time series, consisting of all of the observations for a variable measured using a specific method at a particular site. Currently, the GAMUT time series comprise over 174 million individual data values after approximately 3.5 years of network operation. In the following subsections, we illustrate how we applied the design procedures and principles described in the previous section to create a monitoring network that met our requirements. We also address our specific findings and discuss considerations for network implementation.

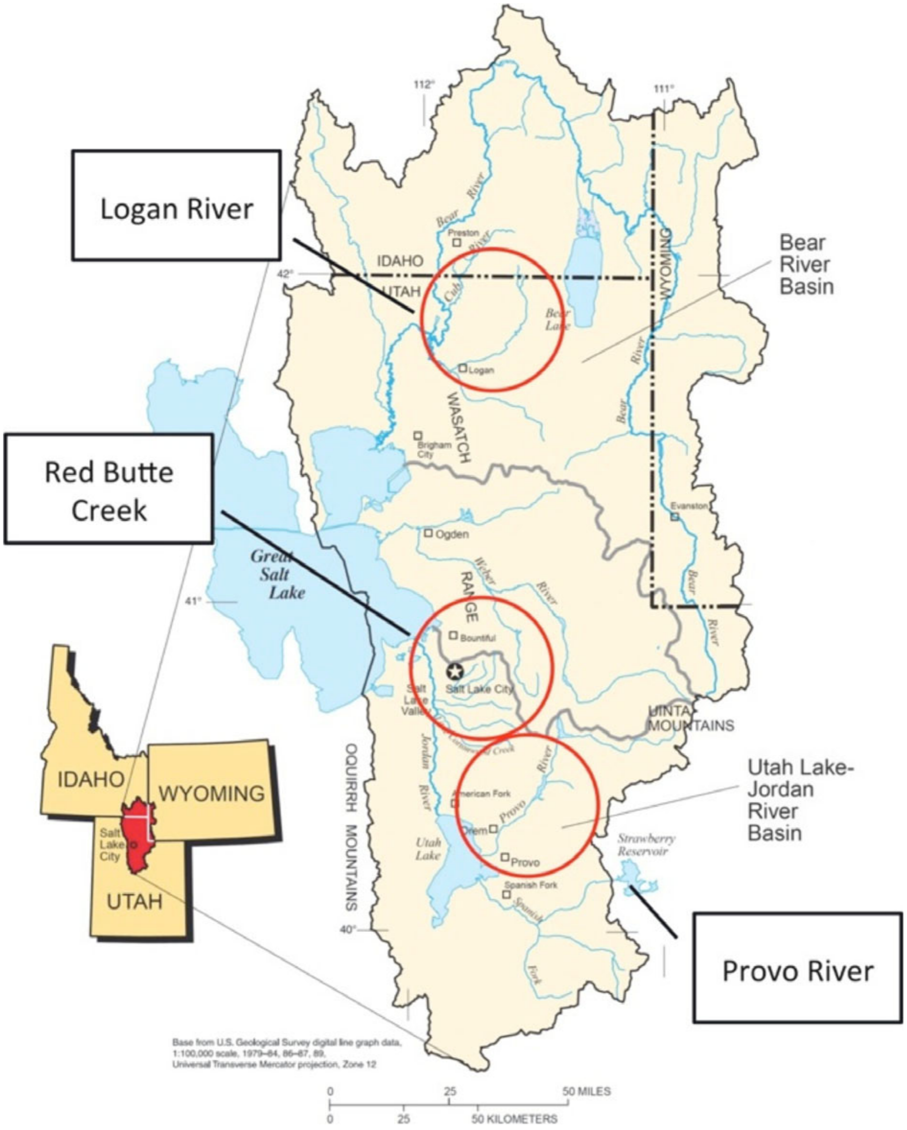
Watershed Selection

We selected the Logan River, Red Butte Creek, and the Provo River watersheds as the bases for GAMUT (Figure 1). These watersheds met our criteria of mountain snow water sources in different ranges, varying levels and patterns of urbanization, and water bodies of differing sizes. The three watersheds were also strategically viable given their proximity to the three participating institutions.

The Logan River originates high in the Bear River Mountains with headwaters near the Utah-Idaho border (2,900 m), flows through forest and rangeland, is impounded to create several small reservoirs in Logan Canyon, and then flows through lower elevations in Cache Valley (1,380 m), which is slowly transitioning from agricultural to urban land use, before terminating at Cutler Reservoir on the Bear River. The average daily discharge (1971-2015) at the USGS gage near the outlet of Logan Canyon (USGS 10109000 Logan River Above State Dam, near Logan, Utah) is 6.51 m^3/s from a catchment area of 554 km^2, and the mean elevation is 2,300 m (U.S. Geological Survey, Surface Water Data for U.S.: USGS Annual Statistics. Accessed September 23, 2016, http://waterdata.usgs.gov/nwis/; all streamflow and catchment areas are derived from this source). Deployment and maintenance of GAMUT in the Logan River watershed are managed by personnel at Utah State University.

Red Butte Creek originates in the Wasatch Mountains in Salt Lake County (2,300 m) in a forested, protected research natural area (Ehleringer *et al.*, 1992), is impounded by a dam in Red Butte Canyon, and then flows through the University of Utah campus and highly urbanized portions of Salt Lake City (1,300 m) where the creek joins the subsurface and storm drain system and eventually terminates in the Jordan River. Red Butte Creek has a catchment area of 20.8 km^2, mean elevation of 2,012 m, and an average daily discharge (1964-2015) near the mouth of the canyon (USGS 10172200 Red Butte Creek at Fort Douglas, near SLC, Utah) of 0.114 m^3/s. Scientists and technicians from the University of Utah manage GAMUT installations in Red Butte Creek.

The Provo River originates high in the Uinta Mountains in Summit County (3,600 m), flows through relatively remote mountains and forest before being impounded to create a large reservoir (Jordanelle), and then flows through the mid-elevation Heber Valley, which is currently transitioning from agriculture to ex-urban land use with rapid population growth (25% for Heber City in the past five years) (U.S. Census, 2015 Quick Facts. Accessed



Base from U.S. Geological Survey digital line graph data, 1:100,000 scale, 1979–84, 86–87, 89, Universal Transverse Mercator projection, Zone 12

FIGURE 1. Location of Watersheds Selected for the Gradients Along Mountain to Urban Transitions Network. Adapted from Baskin *et al.* (2002).

October 12, 2016, http://www.census.gov/quickfacts/table/PST045215/4934200,49043). After leaving the Heber Valley (1,660 m), the Provo River flows through a second large reservoir (Deer Creek), down Provo Canyon and into the city of Provo, Utah, and ultimately discharges to Utah Lake. A gage before the river enters Jordanelle Reservoir (USGS 10155000 Provo River near Hailstone, Utah) records an average daily discharge (1950-2015) of 7.76 m^3/s from a catchment area of approximately 596 km^2, and a gage in the Heber Valley (USGS 10155500 Provo River near Charleston, Utah) records an average daily discharge (1992-2015) of 7.22 m^3/s from a catchment area of approximately 930 km^2. The mean elevation of the watershed is 2,450 m. GAMUT in the Provo River is managed and maintained by staff from Brigham Young University.

Monitoring Site Selection

We sited aquatic water quality stations at five locations and terrestrial climate stations at four locations in each watershed. Stations and locations are detailed in Table 3, and Figure 2 provides a representation of each site within the watershed. All monitoring sites, regardless of type, were subject to several siting considerations. First, reliably communicating data in near real time were a challenge given remote monitoring sites and mountainous topography. We created a mixed telemetry system using both cellular and spread-spectrum radio technologies to overcome these challenges. Second, we considered the likelihood of vandalism and theft at potential monitoring locations (also described by Campbell *et al.*, 2013; ESIP EnviroSensing Cluster, 2014). Third, since the

TABLE 3. Gradients Along Mountain to Urban Transitions Network Station Locations and Land-Use Types Organized by Watershed and Ordered by Elevation. Elevations are in meters. Site classifications are determined in part by Woods *et al.* (2001).

Watershed	Site Name	Site Type	Elevations	Land Use	Latitude	Longitude
Red Butte	Knowlton Fork Climate	Climate	2,010	Wasatch montane	40.810122	−111.76695
	Knowlton Fork Aquatic	Fundamental aquatic	1,990	Wasatch montane	40.809522	−111.765472
	Todd's Meadow	Climate	1,763	Semiarid foothills	40.789054	−111.796416
	Above Red Butte Reservoir Aquatic	Enhanced aquatic	1,674	Semiarid foothills	40.779602	−111.806669
	Above Red Butte Reservoir Climate	Climate	1,655	Semiarid foothills	40.780567	−111.807222
	Red Butte Gate	Fundamental aquatic	1,579	Urban transition	40.774228	−111.817025
	Cottam's Grove	Fundamental aquatic	1,505	Urban transition	40.763958	−111.828286
	Conner Road	Storm drain	1,499	Urban	40.762522	−111.828439
	Green Infrastructure Research Facility Climate	Climate	1,488	Urban	40.7608	−111.830474
	Green Infrastructure Research Facility Storm Drain	Storm drain	1,486	Urban	40.760912	−111.829696
	Fort Douglas	Storm drain	1,473	Urban	40.759012	−111.831446
	Dentistry Building	Storm drain	1,463	Urban	40.757989	−111.832084
	Foothill Drive	Enhanced aquatic	1,459	Urban	40.757225	−111.833722
	1300 East	Enhanced aquatic	1,353	Urban	40.744995	−111.854441
	900 West	Fundamental aquatic	1,291	Urban	40.7416	−111.9176
Provo River	Trial Lake	Climate	3,040	Uinta subalpine forest	40.678111	−110.948339
	Beaver Divide	Climate	2,508	Uinta subalpine forest	40.612508	−111.098289
	Soapstone Climate	Climate	2,388	Uinta subalpine forest	40.573928	−111.043503
	Soapstone Aquatic	Fundamental aquatic	2,367	Uinta subalpine forest	40.579503	−111.047669
	Woodland	Fundamental aquatic	2,136	Exurban	40.5578613	−111.168625
	Below Jordanelle Reservoir	Enhanced aquatic	1,790	Exurban	40.59507	−111.42864
	Sage Creek	Canal	1,690	Exurban	40.488245	−111.440195
	Sage Creek Flood	Canal	1,690	Exurban	40.488245	−111.440195
	Lower Midway	Fundamental aquatic	1,676	Exurban	40.50707	−111.44991
	Charleston Climate	Climate	1,659	Exurban	40.484717	−111.462558
	Charleston Aquatic	Enhanced aquatic	1,658	Exurban	40.48498	−111.46245
Logan River	TW Daniels Experimental Forest	Climate	2,629	Wasatch montane	41.864805	−111.507494
	Franklin Basin Climate	Climate	2,109.52	Semiarid foothills	41.949815	−111.581352
	Franklin Basin Aquatic	Fundamental aquatic	2,110.3	Semiarid foothills	41.9502	−111.580553
	Tony Grove Climate	Climate	1,927.86	Semiarid foothills	41.885493	−111.568767
	Tony Grove Aquatic	Fundamental aquatic	1,886.1	Semiarid foothills	41.875846	−111.564533
	Utah Water Research Laboratory west bridge	Enhanced aquatic	1,414	Urban transition	41.739034	−111.795742
	Spring Creek	Storm drain	1,386	Urban	41.710961	−111.833736
	Main Street (Highway 89/91)	Fundamental aquatic	1,377	Urban	41.721091	−111.835096
	River Heights Bridge	Storm drain	1,373	Urban	41.725147	−111.825917
	Blacksmith Fork above confluence with Logan River	Fundamental aquatic	1,366	Urban	41.704431	−111.8508
	Logan River Golf Course	Climate	1,364	Urban	41.705643	−111.854268
	Mendon Road (600 South)	Enhanced aquatic	1,353	Agricultural	41.720533	−111.886928

iUTAH project has a strong education and outreach component, we considered sites that were visible to the public and accessible by student and other groups. Furthermore, for all GAMUT sites, partnerships with landowners (the U.S. Forest Service for many GAMUT sites), local city and county governments, conservation districts, and universities were critical during the initial permitting phase, and many sites required legal access agreements between the university and the landowner.

Ultimately, we worked to balance scientific needs with physical site constraints, communication constraints, public engagement goals, site security, and partnership potential. Our planning and site selection process was iterative and took well over a year to complete. Iteratively revising network design allows for practitioners to incorporate important lessons learned through their experience (Strobl and Robillard, 2008). Some legal access agreements took months to negotiate, which was a limiting step and can be a major constraint and timing consideration for implementing new networks. In addition, despite our best efforts to secure stations and sensors, we have experienced damage, including theft of cable

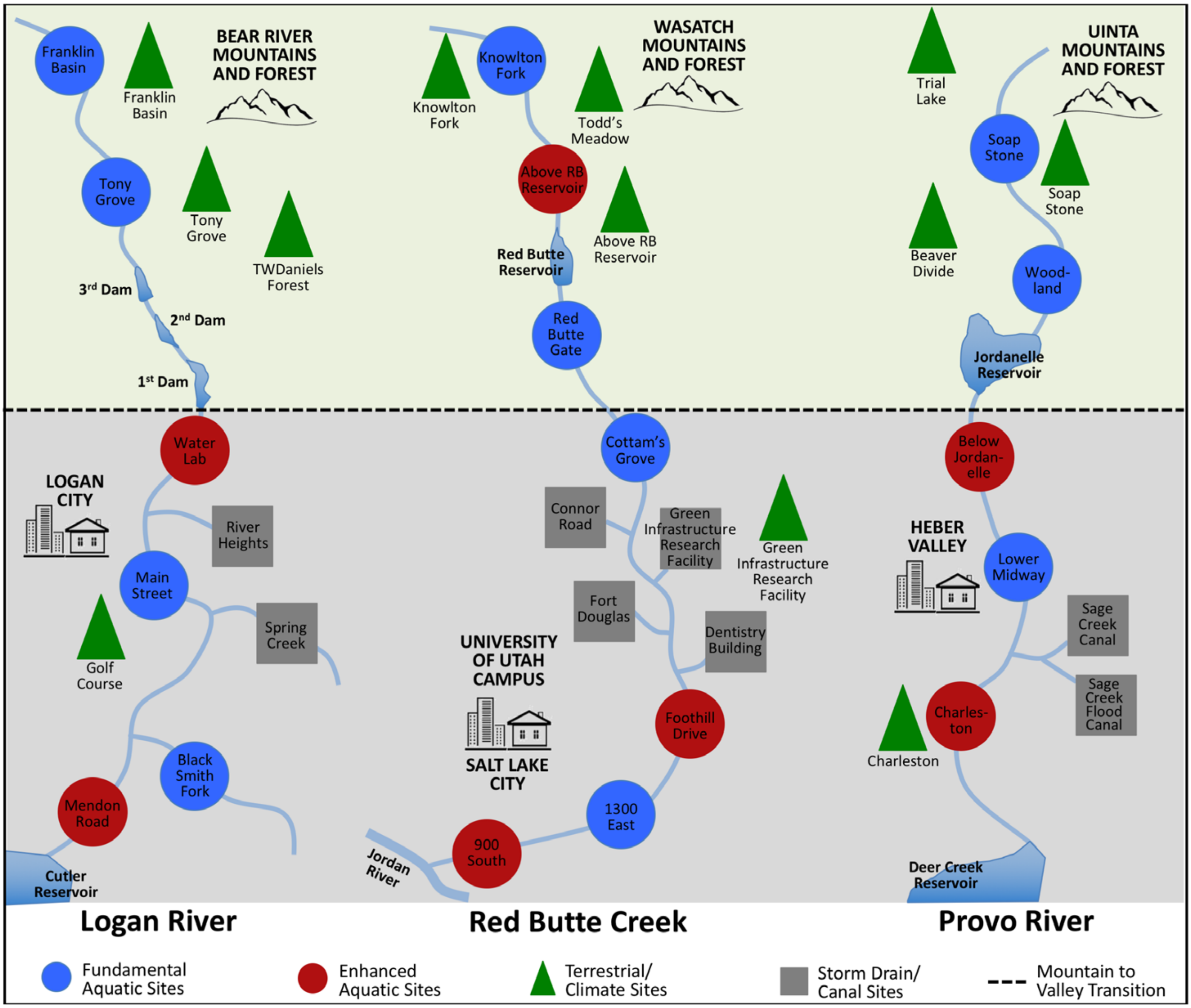


FIGURE 2. Conceptual Diagram of Gradients Along Mountain to Urban Transitions Network Site Locations Relative to Each Other and Major Features within Each Watershed. Not to scale.

and solar panels and cable damage by wildlife. Suggestions of best practices for avoiding site damage are included in the Supplemental Materials (File S1). In particular, purchasing an extra set of all equipment permits quick replacement of sensors or other components to minimize potential data loss.

Factors we considered for locating aquatic stations include anchoring the sensors and datalogger enclosure, accessing the sensors for maintenance at high and low water levels, ensuring that the sensors remain submerged at low water levels, protecting the sensors from debris and shear stress at high flow levels, preventing sedimentation in the sensor housings, and assessing the likelihood for water freezing and resulting sensor damage. Despite our attention to these considerations, flows in Utah's rivers are highly variable, and we have had cases of sensors exposed to air due to low water levels as well as sensor housings shearing at high flow levels. Some of our aquatic sites are also prone to sedimentation in sensor housings during snowmelt or significant storm events. We have yet to experience sensor damage due to freezing, likely because we made efforts to ensure that even when the surface of the water is frozen, the sensors remain submerged in flowing water below the ice. Our experience has been that varying environmental conditions require that we adopt an adaptive strategy for managing stations, adjust site visit frequency as necessary, and utilize housings that enable modifying sensor positions in response to flow conditions.

We also considered the development of rating curves when selecting locations for aquatic stations. Important factors include a suitable stream gaging cross section (*i.e.*, straight river reach and uniform flows across stream) nearby and a natural hydrologic control and streambed that are not prone to shifting. These qualities minimize the likelihood that rating curves will need to be re-created after high flow events (Rantz, 1982).

For climate stations, we made similar considerations in determining locations. We consistently deployed stations in open areas with low vegetation to prevent obstruction of radiation sensors, provide a level area for valid snow depth readings, and avoid potential interference with wind and precipitation meters from nearby trees, buildings, or other tall objects. Furthermore, we sought un-irrigated locations with natural vegetation, even in urban areas, to prevent interference with precipitation gaging and to provide representative radiation readings. We acknowledge that siting climate monitoring in mountain topography requires a balance for selecting ideal settings for sensing different variables. For example, precipitation is most accurately gaged in protected zones, whereas air temperature, humidity, and wind should be measured in open areas to be generally representative (Strachan *et al.*, 2016).

Another factor for site selection was co-location with existing monitoring sites to augment data collection by other entities, reduce redundancy, and facilitate integration. All three watersheds include USGS gages with long discharge records, and we deployed our water quality monitoring equipment adjacent to these gages where possible. In the Provo River, we co-located GAMUT aquatic sites with additional gages maintained by the Central Utah Water Conservancy District, and two GAMUT climate sites were co-located with existing Snow Telemetry (SNOTEL) sites operated by the U.S. Department of Agriculture's National Resources Conservation Service (NRCS). The Logan River watershed contains an experimental forest with a long record of meteorological and soil observations (Mahat and Tarboton, 2014), and we integrated our monitoring with existing infrastructure at that site. In Red Butte Creek, climate stations were located to complement and/or replace a previous sensor network maintained by the University of Utah (Ehleringer *et al.*, 1992).

Sensor Deployment and Station Installation

Our network design specified the sensors that we would use for monitoring (Table 1), but we needed to implement the physical installation of the stations and the deployment of sensors. In general, implementations were standardized to each site type, although in some cases, effective installations involved addressing site-specific challenges.

Aquatic Station Implementation. Across all aquatic sites, sensors are housed in acrylonitrile butadiene styrene (ABS) pipes extending into the river with a mast to which the instrumentation enclosure and solar panel are attached (Figure 3). Sondes and turbidity sensors are housed in 10.16 cm (4 in) ABS pipe, pressure transducers are housed in 5.08 cm (2 in) ABS pipe, and nitrate sensors are housed in 15.24 cm (6 in) polyvinyl chloride pipe. Sensor housings terminate in pump screens or pipe caps with holes drilled into the bottom to allow adequate water flow for accurate measurements while protecting the sensors from debris during high flows. At some sites, existing structures (*e.g.*, bridges, concrete walls) were used to mount these housings. At sites with no structures present, a sensor mounting frame was designed, fabricated, and deployed (Figure 3b) consisting of two vertical fence posts cemented into the ground with horizontal sensor mounting posts affixed to the vertical posts using structural fittings. This platform allows for flexibility of installation in a variety of streambank situations. Each aquatic site was also equipped with a graduated stage plate, with locations surveyed to local benchmarks to provide a permanent reference for observations of water surface elevations.

Climate Station Implementation. All climate stations were deployed by erecting a ~6 m tower based in concrete to which cross arms were connected for mounting sensors (Figure 3a). Manufacturer guidelines were generally followed in sensor installation. Sensor arms were typically mounted 2 m above the ground, although deep snowpack required that sensors be mounted higher at some high elevation sites. This was an important consideration as sensors can be buried by deep snow, and any snow "creep" can shear cross arms, instrument enclosures, and sensors from their mountings. Radiation sensors were mounted to a mast arm on the south side of the tower to eliminate the risk of shading from the tower and solar panel, though reflection from the solar panel may occur. We found that at high elevation sites, precipitation gages needed to be mounted to 2.5 m pedestals to reduce the possibility of snow interference with gage orifices, whereas lower elevation precipitation gages could be mounted to 1 m pedestals. To minimize variability in wind data caused by local micro terrain and vegetation, anemometers were mounted near the top of towers (World Meteorological

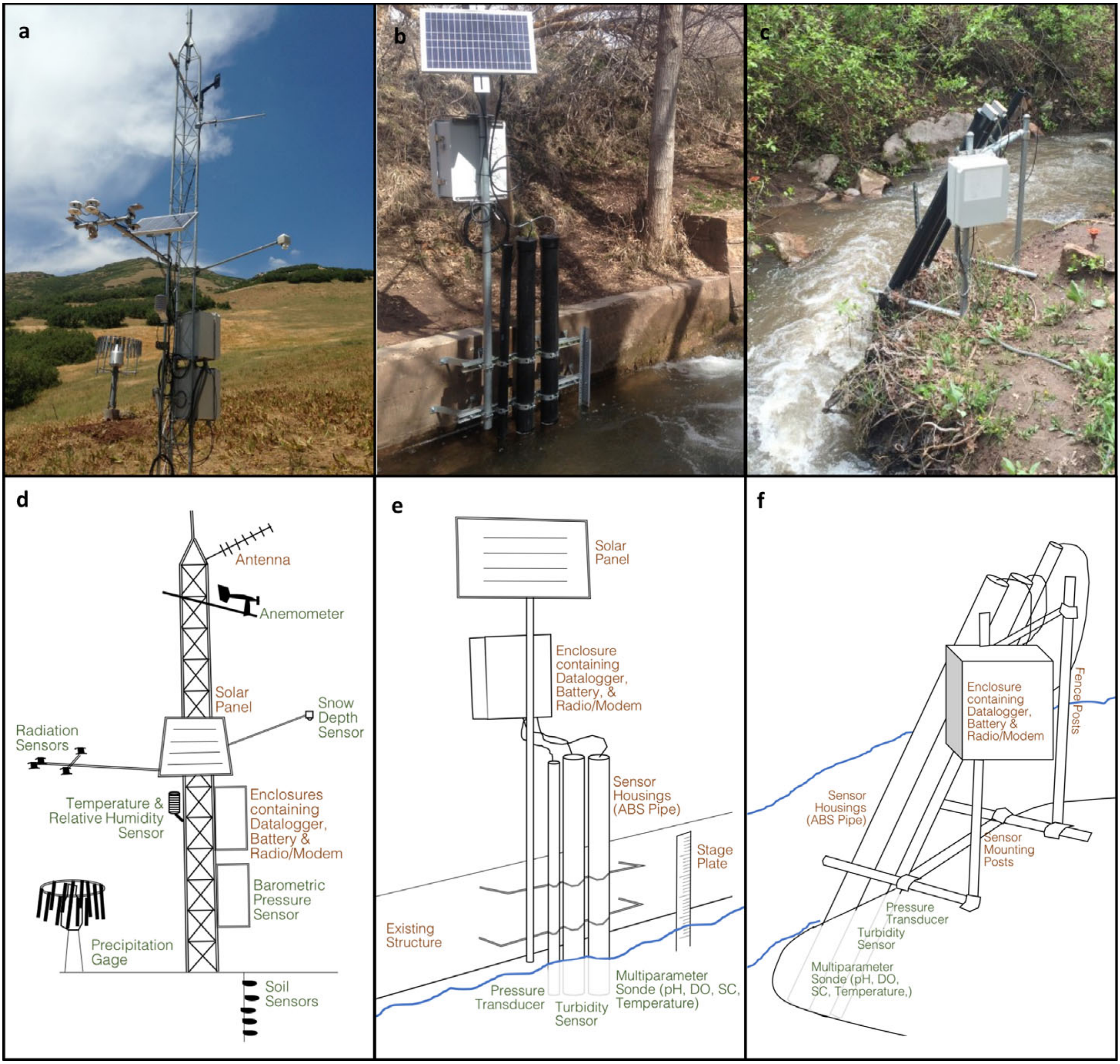


FIGURE 3. Examples of Gradients Along Mountain to Urban Transitions Network Station Installations with Schematics: (a, d) typical climate site, (b, e) aquatic site mounted to a bridge, (c, f) aquatic site with custom sensor mounting framework. Green text indicates sensors while brown text signifies infrastructure and peripherals. DO, dissolved oxygen; SC, specific conductance; ABS, acrylonitrile butadiene styrene.

Organization, 2008). Soil moisture/temperature sensors were installed in pits adjacent to the sensor tower, and cables were protected from rodents with flexible conduit.

Storm Drain Station Implementation. For storm drain sites, acoustic Doppler velocity meters (ADVM: Teledyne ISCO 2150 flow module) were mounted to adjustable scissor rings that expand to fit pipe diameters ranging between 40.64 and 203.2 cm. The ADVM sensors were positioned in the bottom of storm drain pipes and measure both water depth and velocity to instantaneously determine discharge using the pipe geometry. In some storm drains, hydraulic conditions (*e.g.*, pipes with slopes great enough to cause "rooster tail" flows from low depth, high velocity water impacting the face of the flow module) invalidated the methods used by the ADVM to measure discharge. In these cases, we mounted downward-facing sonic sensors, designed for measuring snow depth, to the top of the scissor ring to generate an additional water depth measurement for flow calculations. We use the depth measurements with site-specific constants to generate discharge estimates using Manning's equation.

Datalogging, Telemetry, Power, and Data Publication

Our initial design included industry standard dataloggers and power and communications peripherals, but we needed to program measurement intervals and averaging procedures as well as determine the frequency of communication and mechanisms for eventual data publication. We selected 15 min as the frequency for recording data in an attempt to observe actual temporal fluctuations in variables of interest and estimate process rates while avoiding capturing sensor noise, generating unnecessarily large datasets, and straining power resources. Several sensors include internal processing for value reporting, and we incorporated averaging in the datalogger programs to minimize spurious data points, reduce sensor noise, and capture conditions over the measurement recording interval. At aquatic stations, factory settings were used for variables reported by the sondes. Given a single measurement command from the datalogger, the sonde's onboard processing performs burst sampling, outlier exclusion, and averaging algorithms with stabilization criteria specific to each variable, returning processed results. For the turbidity sensor, a single measurement command triggers a burst of 100 instantaneous measurements made over five seconds, and a suite of statistics are returned. For the pressure transducer, we implemented burst sampling by calling for the sensor to make 25 instantaneous measurements (requiring about 20 s) and report the mean. For most climate variables, we programmed the datalogger to scan at 10-second intervals and average values over 15 min. For sensors that measure variables that are prone to noise (*i.e.*, snow depth, soil moisture, and precipitation), we implemented burst sampling to better capture instantaneous values. For these variables, measurements are made every 10 s during the final minute of the 15-min interval and the average is reported. Generic datalogger programs implemented for GAMUT aquatic and climate sites are provided as Supplemental Materials (File S3 — aquatic, File S4 — climate).

Station dataloggers store data in local memory, and GAMUT uses a variety of telemetry connections to transmit data, including spread-spectrum radios where line-of-sight is available and commercial cellular band modems where spread-spectrum radios are impractical. One or more base stations in each watershed retrieves the data from all sites and is connected to the Internet, permitting data to be transmitted to a centralized location, uploaded to operational databases, and made accessible. Our initial design was to communicate with sites hourly to provide data in near real time; however, in some cases, this frequency contributed to power losses. The power budgets we developed for GAMUT suggest that stations should be fully functional for 7-10 days on battery power alone; however, this assumes new batteries and the original suite of sensors. At some sites, sensors have been added, which, along with aging batteries, reduce the longevity of the battery's effective charge. At the time of writing, we have experienced a number of cases of battery failure, particularly at high elevation climate sites in the winter where cold temperature, snow accumulation, and rime on solar panels are common and where additional peripheral sensors have been deployed, all of which may strain power resources. Based on our estimates for GAMUT sites, communications can account for 20-30% of the power budget, and one strategy for reducing power consumption is to reduce the frequency of communications, which we have done for select sites. Battery failure may also be prevented by establishing a voltage threshold for cutting power to the system, but we have not yet implemented this practice.

The workflow for data streaming from field sensors to operational databases to dissemination via the Internet is described by Jones *et al.* (2015). We also use HydroShare, a community repository for heterogeneous resource types (http://www.hydroshare.org), to provide long-term archival, publication, and simplified access for the following GAMUT data resources: (1) raw data in a flat CSV file for each monitoring site; (2) quality-controlled data for each variable at each site with the script of editing steps; and (3) stage-discharge relationships as a package consisting of individual discharge measurements, the resulting relationship, and pertinent metadata (*e.g.*, iUTAH GAMUT Working Group 2016, 2017a, b). Raw data are updated in HydroShare on a daily basis. There is some lag in the publication of quality-controlled and derived data products due to the time needed for technicians to review and generate these datasets, but quality-controlled data are generally published within six months. Resources containing stage-discharge relationships are updated as needed.

Quality Assurance Implementation

We implemented QA in GAMUT by employing consistent procedures for cleaning, calibration, and maintenance of sensors, by recording those activities, and by regularly monitoring data. The following subsections describe sensor maintenance, including cases that prompted us to modify our maintenance protocol when our experience revealed deficiencies in our practices. In general, technicians record field and maintenance activities on uniform field sheets as well as digitally while we develop an online equipment management system (Jones *et al.*, 2015).

To monitor data, a technician in each watershed performs regular visual inspections (2-3 times per week) of raw data to identify and document potential problems and to prioritize field activities. We also implemented automated alerts to identify possible issues in data streams occurring between regular visual checks of the data and to reduce the required frequency of visual checks. The alerts are programmed as stored procedures in our operational databases, which run daily and send email notifications when data screening criteria are not met. The rules currently implemented for GAMUT include checks of battery voltage range, checks for "no data" values, checks for data persistence (*e.g.*, flat line), and checks to ensure data are current (Jones *et al.*, 2015) and are consistent with community recommendations for sensor data QA/QC (Campbell *et al.*, 2013; ESIP EnviroSensing Cluster, 2014; Integrated Ocean Observing System, 2015).

Sensor Maintenance at Aquatic Stations. Our original QA plan called for monthly site visits for cleaning, calibration, and other maintenance. After observing large shifts in the fDOM, phycocyanin, and chlorophyll-*a* data associated with calibration events, we discovered that calibration coefficients varied more than expected. We determined that the preparation of calibration solutions and field calibration procedures were introducing more error than if the original calibrations had been retained. We changed our protocols to only calibrate these sensors in the laboratory under constant temperature, with sufficient time for equilibration, and under controlled conditions for calibration solution preparation and storage. We concluded that optical sensors (*i.e.*, fDOM, DO, phycocyanin, chlorophyll-*a*, and nitrate) are generally stable enough to require calibration checks only every three to four months or more and should only be calibrated if needed. Our experience is similar to that of other users of these instruments and informal guidance provided by sensor manufacturers (YSI). For DO, calibrations should still be performed in the field at the elevation at which the sensor is measuring. We have continued monthly calibration checks for pH and SC sensors, which are more prone to drift.

After observing large diurnal fluctuations in stage data that were not independently corroborated and were correlated with water temperature, we determined that the pressure transducer temperature compensation was invalidated at some sites. Communication with the manufacturer (Campbell Scientific) verified that this is due to scale buildup that may occur in systems with significant calcium carbonate content, which is all of the aquatic sites in the Logan River and Red Butte Creek. The one pressure transducer deployed in the upper Provo River has not exhibited this behavior, which we conclude is because the upper Provo River is more pH-neutral than Logan and Red Butte Creek. To prevent scale buildup, we now regularly (every two to three months) rinse the pressure transducers in a vinegar solution for 5-10 min, depending on the visible condition of the sensor.

While automated wipers that clean sensor faces minimize the effects of fouling on the aquatic sensors, we needed to clean sensors at least monthly to remove sediment from the sonde measurement cup, to ensure that wipers on all sensors are functioning, and to remove biofilms and scale from sensor bodies with a cloth or soft-bristled brush. For some sites during some seasons, more frequent cleaning is necessary (*e.g.*, sediment accumulation during spring snowmelt runoff necessitates weekly visits at some aquatic sites). Several times each year, the probe housings and pump screens need to be removed and cleaned of biological growth. Additional procedures for aquatic site maintenance include checking sensor wipers, which may need periodic replacement, and checking the pressure transducer desiccant and replacing when expired. The technicians' regular visual monitoring of data and automated alerts also help identify environmental conditions that may require additional attention. Manufacturer recommendations for regular maintenance of sensors and equipment are outlined in the Supplemental Materials (File S1).

Sensor Maintenance at Climate Stations. The GAMUT climate stations are mostly autonomous and require relatively little maintenance, as problems with sensors are typically identifiable with data monitoring procedures. Regular maintenance includes monthly inspections to check that sensors are not contaminated by dirt, insect activity, *etc.*; adjustment to verify that sensors remain level; and general cleaning to ensure optimal operation. A few seasonal circumstances necessitate additional maintenance. During the winter, solar panels and radiometers must periodically be cleared of snow, as solar radiation data can be impacted by snow accumulation on the sensors, and snow, ice, or rime on solar panels can prevent station batteries from recharging. We detect snow accumulation by monitoring precipitation, station power, and incoming shortwave radiation measurements. The precipitation gages installed in GAMUT also require routine (at least twice per year) replacement of antifreeze and oil to the measurement bucket. Manufacturer recommended maintenance for sensors deployed at climate sites is included in the Supplemental Materials (File S1).

As climate sensors are not easily calibrated, we sought other methods to verify sensor readings. Some variables (*i.e.*, incoming shortwave radiation and air temperature) are measured by two independent sensors at each climate station, which facilitates data comparison and validation. For variables that are not measured in pairs, we verify by comparing readings between sites. As of this writing, we have plans to maintain a spare set of equipment to be used as roving reference sensors (Campbell *et al.*, 2013) to spot check readings of deployed sensors.

Quality Control Implementation

Within GAMUT, QC consists of regular review of data series and post-processing to apply flags and adjust data to generate an approved, reviewed data series, which is performed by technicians in each of the three GAMUT watersheds using the ODM Tools software. ODM semantics use QC levels to designate the level of post-processing associated with a dataset. For GAMUT, we determined to use QC level 0 (QC0) for raw data streaming from sensors, and QC level 1 (QC1) to designate data series that have been reviewed, have corrections applied, and are approved by technicians. GAMUT also uses QC level 2 to represent derived products (*e.g.*, discharge derived from stage). These levels are consistent with those described by Porter *et al.* (2012).

As they performed QC, GAMUT technicians observed that, although we collectively set up a framework to guide post-processing, application of edits and corrections was often subjective. For example, two technicians performing QC post-processing on the same raw dataset could arrive at two separate results. To promote consistency in the transformation from QC0 to QC1 in GAMUT, we developed and implemented more specific guidelines for QC, described below, including a general QC workflow, priorities for QC (*e.g.*, which time series would be processed), and variable-specific post-processing steps. We also discovered several unusual cases requiring innovative QC solutions. This was particularly important as the number of personnel conducting post-processing grew beyond the three watershed technicians.

Quality Control Workflow. To perform QC, a technician reviews the QC0 data, performs the necessary edits using ODM Tools, and saves the resulting Python script wherein each edit is captured as a line of code in a text file. The data and script are then reviewed by a supervising technician, revised if needed, and the processed data are committed to the operational database as QC1. The script serves as the record of the transfer from QC0 to QC1, and technicians make comments in the script to annotate the rationale for corrections. For GAMUT, the process for creating new QC1 data series or updating existing series with ODM Tools is used as described by Horsburgh *et al.* (2015).

We made several decisions to specifically implement the QA/QC framework for GAMUT. First, we needed to determine how to handle data gaps, anomalies, and periods of erroneous data. Figure 4 shows examples from GAMUT of these common QC cases. We concluded that for periods of two hours or less, linear interpolation could reasonably be used to fill gaps or periods of verified erroneous data. For longer periods, or if the technician judges that linear interpolation is inappropriate, we assign data to values of −9,999 to represent “No Data.” Including a “No Data” value (rather than leaving the period blank) indicates proper data collection did not occur and permits the assignment of a qualifier to provide an explanation. We settled on a standard set of flags from which all technicians could select the appropriate qualifier to explain periods of questionable data (*e.g.*, sediment, ice, snow) (Table 4). In all cases of interpolation or assignment to −9,999, a flag is applied to alert data users and provide relevant details.

We determined that linear drift correction should be used for all cases of aquatic sensor calibration and cleaning (Figure 4c) unless there is no perceptible shift in the data. The value by which to shift data for drift corrections is determined by visual estimation, by calculation based on the slope of the data at the time of calibration, or by the difference in the pre- and post-calibration readings reported by the sensor. We use ODM Tools to apply filters to identify anomalies and data gaps, interpolate, fill data gaps, assign values as −9,999, apply qualifiers, and perform linear drift correction (Horsburgh *et al.*, 2015).

Variable-Specific Quality Control. We developed specific recommendations for data review and post-processing for each of the GAMUT variables that undergo QC, and these details are included in the Supplemental Materials for this article (File S2). Several variables exhibited behavior that was outside of our (and the sensor manufacturers’) expectations, requiring unconventional QC solutions. Figure 5 illustrates six of these conditions, which are documented in detail as technical notes in the Supplemental Materials (File S4).

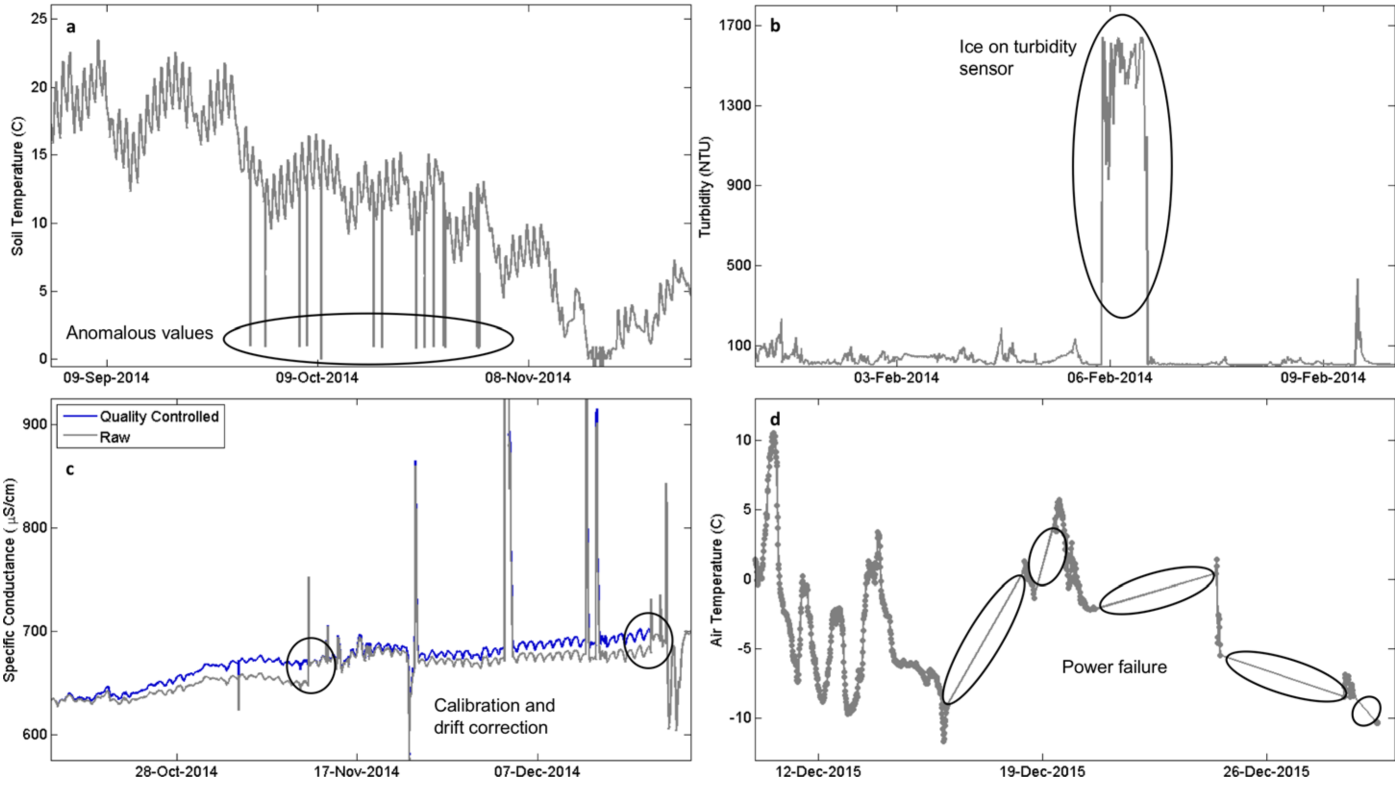


FIGURE 4. Examples of Raw Data Requiring Quality Control Post-Processing: (a) data outliers in soil temperature (degrees Celsius), (b) period of sensor malfunction in turbidity (nephelometric turbidity units [NTU]) data, (c) for specific conductance (microSiemens per centimeter), sensor calibration in raw data and drift correction in quality-controlled data, (d) gaps in air temperature (degrees Celsius) measurements.

TABLE 4. Standardized Qualifiers/Flags Used in Gradients Along Mountain to Urban Transitions Network.

Code	Description
LI	Linear interpolation
SM	Sensor malfunction
PF	Power failure
S	Suspicious values
ICE	Ice interference with sensor
SNOW	Snow interference with sensor
MNT	Erroneous or missing data due to maintenance
SED	Sediment interference with sensor
LWT	Data suspicious due to low water. Sensor likely dry
CAL	Improper or erroneous calibration
COR_PT	Pressure transducer data corrected to remove erroneous data signal
ZERO	Value set to zero

Our solutions might be applicable to other monitoring networks using similar sensors, but more broadly, observatory developers should expect to face similar QC issues that may require unfamiliar or unique solutions. Sensors are tools for which the proper use may depend on the particular situation to which they are applied. Although we are inclined to rely on the results of sensors from trusted manufacturers, these cases show that scientists and researchers should be skeptical of sensor outputs and seek independent methods of data verification.

Resources to Create and Maintain GAMUT

The initial proposal for GAMUT anticipated that operating the network would require the support of several personnel at each institution and some funds for sensor servicing and repair. The original plan called for three full-time field leads/technicians, each employed by one of the supporting institutions and assigned to the associated GAMUT watershed; one part-time data manager; and several university faculty as project leads, all of which are roles outlined in Sutter *et al.* (2015).

The installation and maintenance of GAMUT sites was labor intensive. While the time required varied depending on ease of access and technician experience, generally speaking, after preparation and planning, the physical installation of each aquatic site took approximately one day for two to three individuals to complete and each climate site took approximately two to three days for three to five individuals to complete. Significant time was also invested in siting and installing repeater telemetry stations. As the

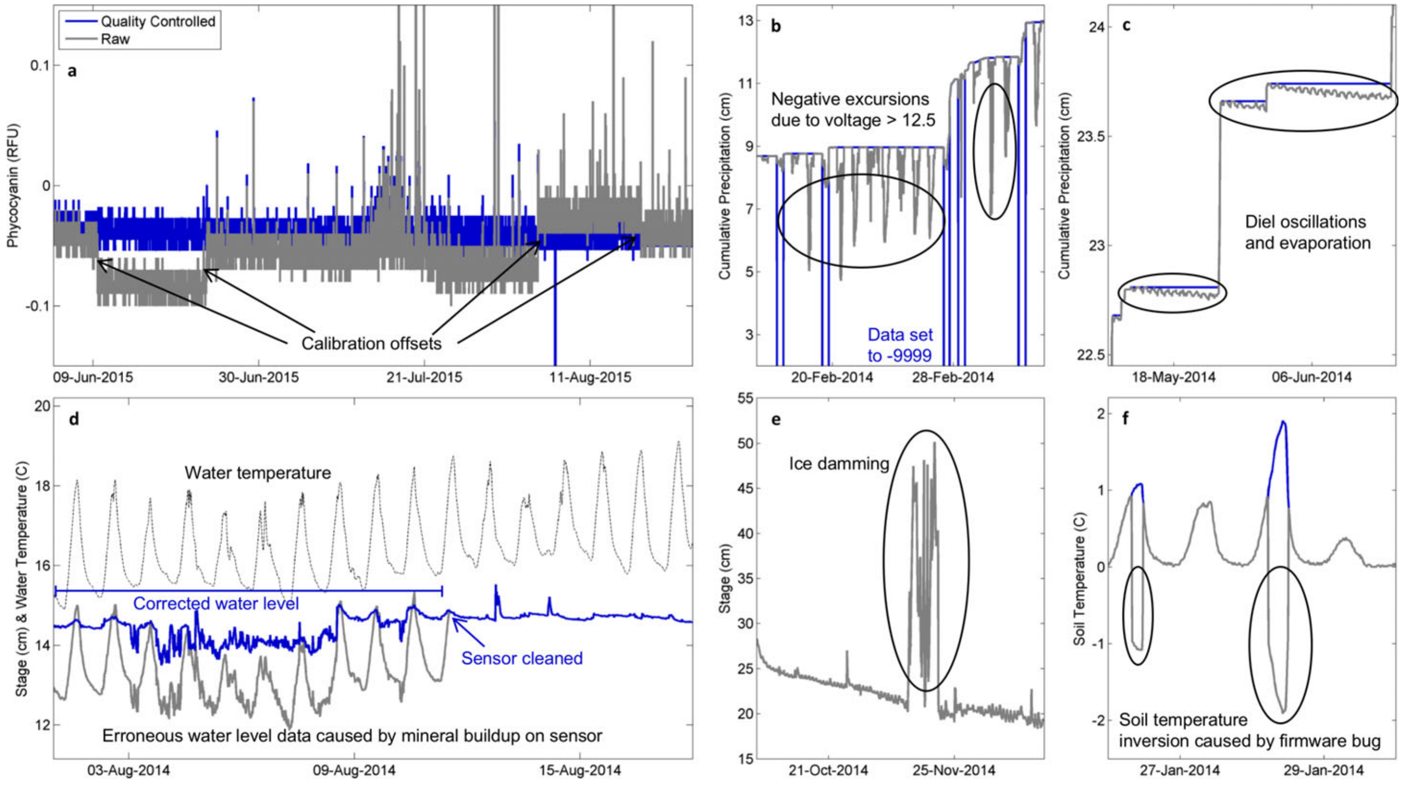


FIGURE 5. Variable-Specific Cases of Data Requiring Quality Control Post-Processing Showing Raw Data and the Quality-Controlled Data. (a) Phycocyanin (relative fluorescence units [RFU]) with calibration events for which calibration coefficients shifted. Data were corrected by retroactively applying corrected calibration coefficients. (b) Negative precipitation (centimeters) resulting from high power voltages corrected by either interpolation or reassignment to −9,999 to represent "No Data." (c) Negative precipitation (centimeters) caused by sensor noise and evaporation of accumulated precipitation. Data were corrected using an algorithm that compares each point to the previous to eliminate decreases. (d) Water level (centimeters) prior to and after sensor cleaning. Diurnal fluctuations in level are erroneously associated with water temperature (degrees Celsius), so the slope of the temperature-level relationship was used to remove the incorrect water temperature compensation. (e) Elevated water level (centimeters) due to stream ice damming. Data were corrected by interpolation or reassignment to −9,999. (f) Inverted soil temperature (degrees Celsius) due to a sensor firmware issue. Data were corrected by reversing the sign during these periods.

technicians and data manager developed and implemented the GAMUT QA/QC Plan, it became apparent that the regular site visits and post-processing required support from additional personnel. For GAMUT, we have found the ideal arrangement to be a technician in each watershed with two to three well-trained assistants, along with a data manager with one assistant. A more mature network may require fewer personnel.

Significant monetary resources were required to initially purchase sensors and infrastructure. At the time of acquisition, the sensors for a GAMUT climate station cost ~$25,000, a fundamental aquatic station cost ~$14,000, and an enhanced aquatic station cost ~$41,000. Each station required ~$1,700 in power and communications equipment, and each telecommunications repeater station cost ~$2,800. In addition to the obvious upfront costs, funds must be allocated to support network longevity. Many manufacturers recommend sensor replacement, factory recalibration, and/or cable replacement after one to five years (see Table S2 in Supplementary Materials). Damage caused by vandalism, wildlife, and environmental events may require more frequent equipment replacement.

After the initial hiring of technicians and procurement of sensors, it was six months before the first GAMUT stations were deployed and nine months before the first GAMUT data were available online. After 15 months, the majority of the existing GAMUT stations were operational. Documenting and beginning full implementation of the QA/QC Plan occurred after 18 months. To acquire enough data to derive sufficiently robust stage-discharge relationships and to catch up on the backlog of post-processing data took approximately three years. It was also only after multiple years of data collection that variable-specific QC issues became apparent. Finally, to document this process and present the results in a scientific journal took four years. Although we are aware that individual circumstances will vary, we present these time frames as a point of reference for others who may be considering building observatories similar to GAMUT, and we anticipate that the findings we present in this article may help expedite the establishment of other monitoring networks.

Extensibility and Synergy

As mentioned, an intended outcome of GAMUT was its capacity to catalyze further science, which Hinckley *et al.* (2016) assert to be the greatest information contribution of long-term monitoring. We anticipated that research efforts would benefit from the foundation provided by GAMUT watersheds and sites, the GAMUT physical infrastructure and cyberinfrastructure, and the GAMUT data. Indeed, we wanted the GAMUT network to serve as a "backbone" onto which researchers could add complementary monitoring infrastructure. Furthermore, we anticipated that we would need to address situations such as additional or revised monitoring locations as we learned more about important processes in the three watersheds. The design of GAMUT is scalable and modular, permitting the addition and removal of sensors at stations, the transferring of entire stations to new locations, and the addition of new stations to the network. Our upfront decisions to standardize equipment across watersheds and stations facilitates flexibility and expansion.

After deploying the first set of GAMUT stations and the initial phase of monitoring, we recognized that we were not capturing important components of the hydrologic system in urban and urbanizing areas. As a result, we deployed additional sites to better capture stormwater inputs and downstream urban areas in Red Butte Creek, stormwater outfalls, and important tributaries to the Logan River, and an agricultural canal on the Provo River. We also relocated aquatic sites downstream to better capture water quality conditions of the Provo River before reaching its terminus at Utah Lake, an impaired water body (UDWQ, 2016). These changes were made without major modifications to our telemetry network or underlying data management cyberinfrastructure.

Climate stations were envisioned as data collection platforms that could be added to for studies beyond initial iUTAH funding. To accomplish this, we acquired dataloggers and multiplexors with capacity for expansion beyond the initial sensor suite described in our design. Most stations have been upgraded to include sensors that measure soil oxygen, soil carbon dioxide, and soil heat flux. At several higher elevation sites, monitoring rates of sapflux for particular tree species have been undertaken in conjunction with GAMUT (Chan and Bowling, 2016a, b, c, 2017).

Furthermore, because of the scale of GAMUT data and the other available resources, researchers are choosing to build on GAMUT by using GAMUT data and working in GAMUT watersheds. Examples include efforts to better understand nitrogen dynamics in snow, soil, and water in Red Butte Creek (Hall, 2016a, b; Hall *et al.*, 2016a, b); analyses for trace elements and isotopes in precipitation, snowpack, surface water and groundwater, and plants, algae, and moss in all three GAMUT watersheds (Carling *et al.*, 2015, 2016; Hall, 2016c; Hall *et al.*, 2016b); and experiments to study effects of nutrients and pharmaceuticals and the structure of bacterial communities at GAMUT aquatic sites (Ogata and Baker, 2016). Researchers have conducted intensive synoptic sampling in each of the watersheds to help validate sensor readings, to understand relationships with unmeasured variables, and in an attempt to better capture groundwater interactions.

Other facilities have used GAMUT as a springboard. In the Logan River watershed, a sister network monitoring urban stormwater has been deployed in an adjacent canal (Melcher and Horsburgh, 2017), which adopts components of GAMUT's design and implementation, including the GAMUT telemetry network. In the Provo River watershed, a recent toxic algal bloom on Utah Lake prompted the deployment of buoyed monitoring platforms by the State of Utah. For this effort, the State has used the expertise of GAMUT technicians and the GAMUT cyberinfrastructure.

In addition to biophysical studies, GAMUT is a hub for education and outreach efforts and social science research. The GAMUT watersheds and aquatic stations are the central venue for summer institutes that train K-12 teachers, undergraduates, and high school students. Several faculty members are incorporating GAMUT station visits and data into their university courses, and an outreach effort at a local museum features GAMUT data in an interactive display. Social science researchers have broadened the idea of environmental monitoring into a socio-ecological observatory as they collect social water science data (Flint *et al.*, 2017) within and adjacent to GAMUT watersheds.

All of these additional efforts have built from GAMUT's base infrastructure and baseline datasets, and all were facilitated by forethought in planning, locating, and instrumenting the GAMUT network stations. This is an important consideration in building networks like GAMUT, as the original funding under which the infrastructure is built rarely extends beyond the three- to five-year period of the original research grant (Thorpe *et al.*, 2015). Designing extensibility into the network from the beginning was important in catalyzing these types of new efforts that can bring new sources of funding to support longer term sustainability.

DATA CASE STUDIES

We have described in detail the practices that we followed and our insights and findings in the installation and operation of GAMUT. Aside from the focus on the logistics of the network, data from GAMUT reveal insights into water quality, especially as it is impacted along the mountain to urban gradient. In this section, we provide three brief examples of applications of GAMUT data. We use GAMUT data to show simply how urbanization affects fDOM pulses and availability as well as the frequency of algal blooms indicated by peaks in chlorophyll-*a* and phycocyanin. We also use GAMUT data to provide insight on the effects of built infrastructure on aquatic systems and to provide evidence for a specific anthropogenic activity.

Urbanization Increases Pulses of Organic Matter and Algae Blooms

Runoff events in urbanized areas carry pulses of nutrients and organic matter to streams, which heterotrophic bacteria may exploit. We compared fDOM between the three most downstream sites in each watershed and identified cases of “pulses,” which we defined as an increase in fDOM of at least 100% within an hour. In Red Butte Creek, the most urbanized of the GAMUT watersheds, fDOM pulses occurred 22 times over a three-month period, sometimes lasting up to three days (Figure 6b). By comparison, levels of fDOM remained relatively constant in the Provo River (~30 quinine sulfate units [QSU]) and Logan River (1.5 QSU) over the same time period. The pulses of fDOM in Red Butte Creek mostly coincide with weather driven episodes that transport sediment and other materials to streams (Wilson *et al.*, 2013), a process that is expedited by urbanization. The transport of fDOM with sediment is corroborated by concurrent spikes in turbidity measured at the same site in Red Butte Creek and the general paucity of turbidity spikes in the Logan and Provo watersheds (Figure 6c). High percentages of impervious surfaces and multiple storm drain outfalls lead to flashy flow regimes characteristic of urban streams (Hong *et al.*, 2012), which, for Red Butte Creek, also correspond to higher frequency of fDOM pulses.

We also compared the patterns of photosynthetic pigments chlorophyll-*a* and phycocyanin between the three watersheds to give an indication of the frequency of potential algae blooms. If either of these variables increased over 100% within an hour, we identified that period as a bloom. Generally, these spikes were more common in Red Butte Creek than the other two less-urbanized rivers. Phycocyanin peaks, which may represent cyanobacteria blooms (Figure 6e) were more frequent than chlorophyll-*a* peaks, which may represent green algal blooms (Figure 6d). In Red Butte Creek, 236 cyanobacteria blooms occurred over three months. On days with pigment spikes, the average increase of phycocyanin concentrations was 200% compared to days without elevated levels. Over the same time period, 75 green algal blooms occurred, which increased chlorophyll-*a* concentrations an average of 313% per day compared to days without elevated levels. We also observed photosynthetic pigment spikes in the Provo River from mid-November to the end of December (33 algal and 11 cyanobacterial). In both cases, we cannot demonstrate whether these elevated photosynthetic pigments resulted from blooms in the river or reservoirs upstream of the monitoring station and/or were generated from sloughing of benthic periphyton closer to the sensor locations. Regardless, these patterns are similar to those observed by Reed *et al.* (2016), who found algal biomass and growth rates and harmful cyanobacterial blooms more common in urbanized creeks and stormwater ponds compared to forested and agricultural tidal creeks. Our findings support claims that developed lands may aggravate water quality issues (Paul and Meyer, 2001; Walsh *et al.*, 2005, 2016; Kaushal *et al.*, 2014). Because these peaks appeared and disappeared within single days, high-frequency data were essential in capturing the flashiness of algal pigments in these systems.

Reservoir Size Structures Water Quality

Built infrastructure, specifically the size and characteristics of a reservoir system, impacts water chemistry (Ward and Stanford, 1983; Stanford and Ward, 2001). As mentioned, all of the GAMUT watersheds include reservoirs for water resource management, but the size of the catchments and reservoir systems vary. Jordanelle Reservoir on the Provo River is large (maximum surface area of ~13.5 km^2), while the reservoirs on the Logan River (1st, 2nd, and 3rd dams, combined total surface area of 0.088 km^2) and Red Butte Creek (Red Butte Reservoir, surface area of 0.038 km^2) are relatively small (Figure 2). We examined the effects of these reservoirs on water quality by comparing data from the aquatic sites above and below the reservoirs in each watershed.

The longer retention times associated with the larger reservoir on the Provo River translated into the

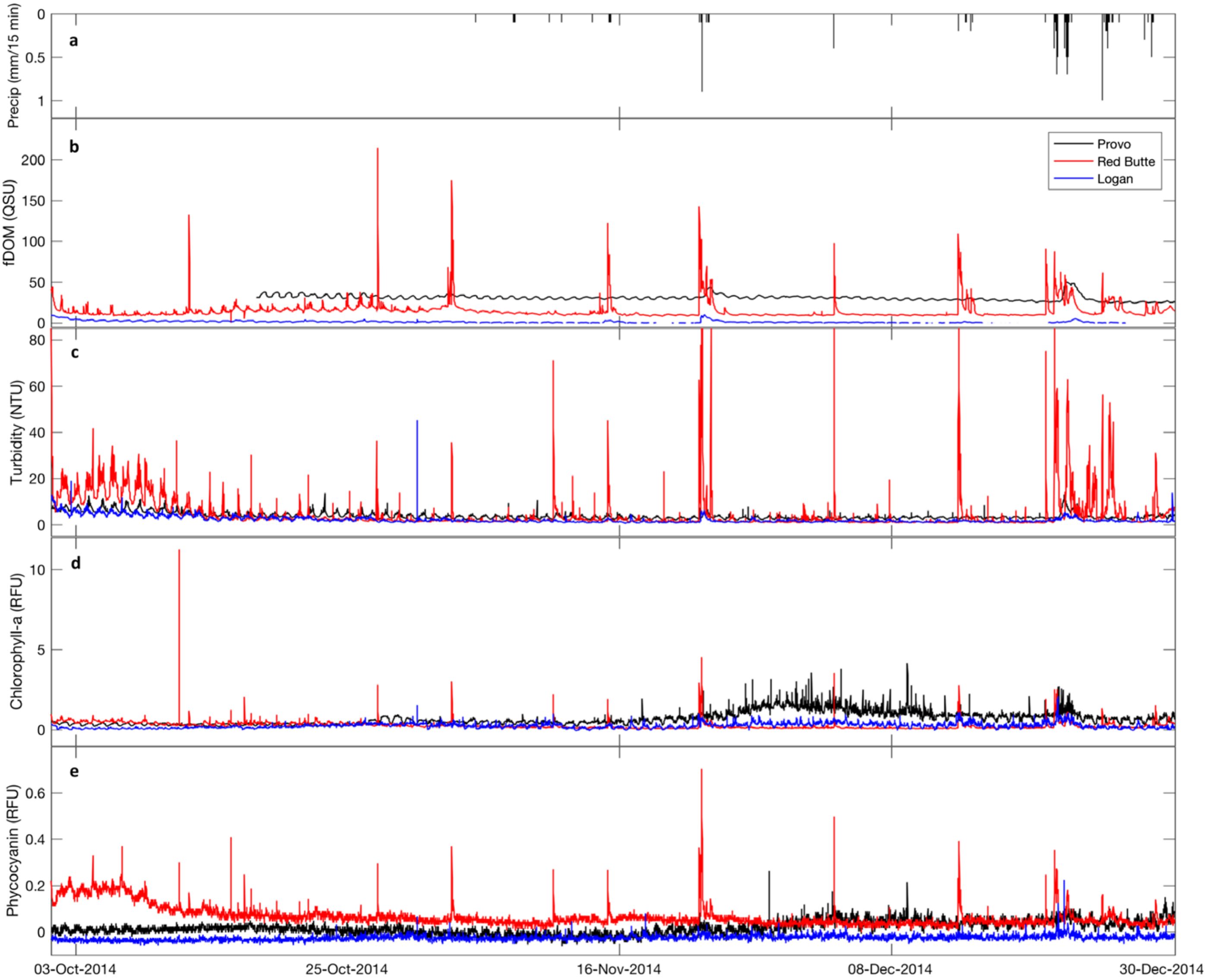


FIGURE 6. Data Are Water Chemistry and Biology Variables from Urban Aquatic Sites in Three Watersheds Showing: (a) precipitation intensity (millimeters per 15 min) and pulses of (b) fDOM (quinine sulfide units), (c) turbidity (nephelometric turbidity units), (d) chlorophyll-*a* (relative fluorescence units), and (e) phycocyanin (relative fluorescence units).

most dramatic changes in water quality. For example, DO is 80-90% of saturation directly below the dam in contrast to the site 29 km above the dam, which is consistently near saturation (Figure 7a). This observation could be due to oxygen consumption in reservoir sediments and reservoir stratification (Friedl and Wüest, 2002), or caused by differences in stream geomorphology above and below the reservoir that influence physical reaeration and the capacity for benthic algae to influence the diurnal DO signal (*e.g.*, Erwin *et al.*, 2016; Hall, 2016d). In Red Butte Creek and the Logan River, the overall DO levels are similar above and below the dams. Below Jordanelle Reservoir on the Provo River, the pH was substantially higher than above the reservoir, with greater diurnal variability and divergent seasonal patterns (Figure 7b). In the Logan River and Red Butte Creek, pH stayed relatively constant through this time period, and the values above and below the reservoirs did not deviate from each other to the degree occurring in the Provo. SC provides an indicator of the level of dissolved constituents and can be used to distinguish surface runoff from groundwater or baseflow. In the Provo River, SC (Figure 7c) below Jordanelle Reservoir was consistently higher than above the reservoir by 300%, primarily due to changes in lithology between the sample sites, but also potentially reflecting greater evaporative water losses that concentrate dissolved solutes. Carling *et al.* (2015) also found greater temporal variability in trace element and ion concentrations above Jordanelle Reservoir than below. However, SC between

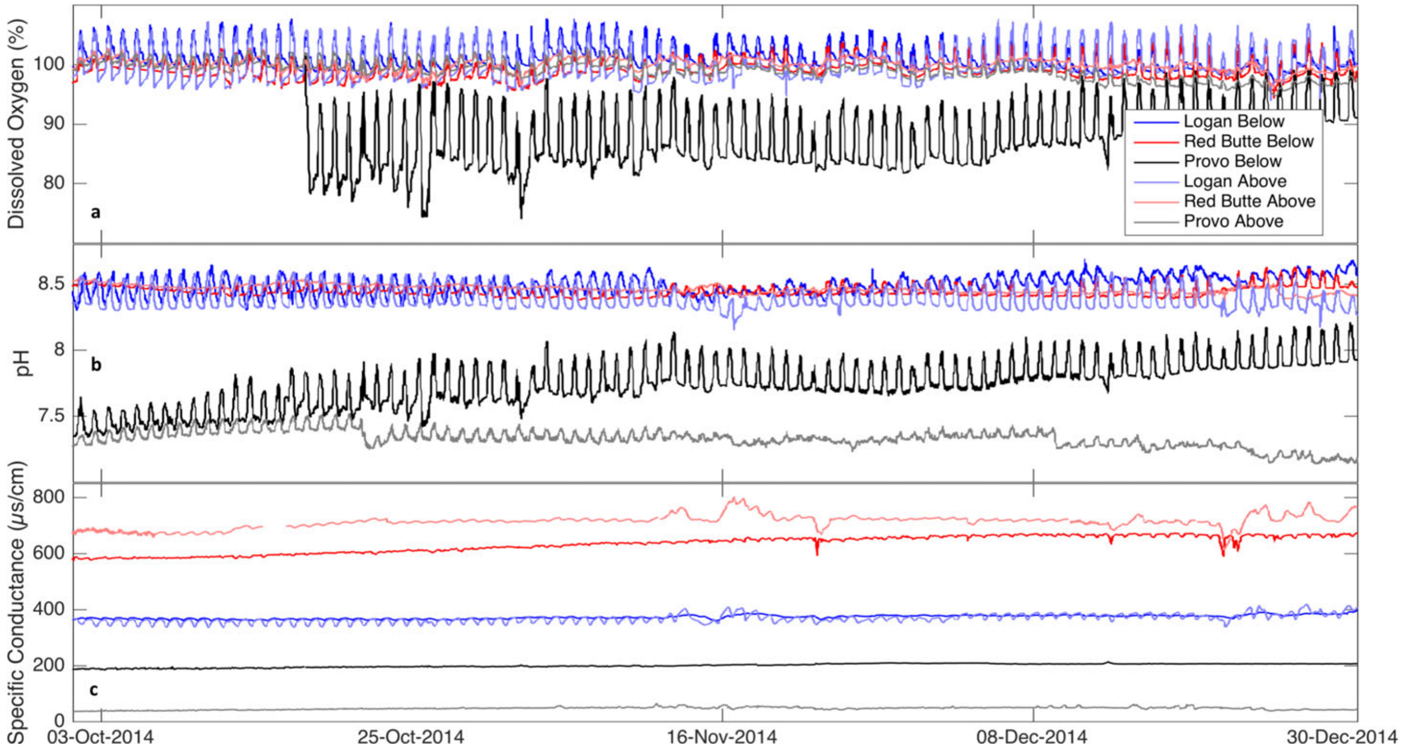


FIGURE 7. Water Chemistry Variables from Aquatic Stations above and below Reservoirs in Each of the Gradients Along Mountain to Urban Transitions Watersheds: (a) dissolved oxygen as percent saturation, (b) pH, (c) and specific conductance (microSiemens per centimeter).

the sites above and below Red Butte Reservoir was lower by 17%, which may reflect groundwater inputs to lower monitoring sites (Hall *et al.*, 2016c). There was no notable difference above and below the dams on the Logan River.

Signs of Construction Are Visible as Turbidity

The late winter/spring of 2011 was wet with deep snowpack and an extended melt period that resulted in high river flows throughout the Intermountain West (Alexander *et al.*, 2015). During this time, the Logan River experienced extended flooding that resulted in damage to city infrastructure on the order of $100,000, with county-wide per capita impact of $4.04 (FEMA, 2011). In response to this flooding, the NRCS, Cache County, and City of Logan applied for federal funding through the Emergency Watershed Protection Program. Those funds were used in part to implement a plan for optimal flood hazard protection. City and county engineers chose a hard engineering approach to increase hydraulic efficiency of the river. Construction began in late winter/early spring of 2014, wherein the channel was deepened through excavation, and the banks were stabilized. Channel roughness was also reduced by removing coarse woody debris and installing a liner topped with native and imported cobbles and boulders (McMillen LLC, 2012a, b).

These weekday construction activities within the channel created tractable increases in turbidity along the Logan River. On Monday to Friday during working hours (08:00 AM-17:00 PM), excavation and bank stabilization efforts caused daily turbidity increases of almost 67-fold at the Logan Main Street aquatic station (Figure 8). Conversely, during the weekends, turbidity held relatively constant. Elevated turbidity is an established indicator of soil and land disturbance (*i.e.*, construction work) with higher potential for erosion near or within waterways in both mountain and urban areas (Wolman and Schick, 1967; Anderson and Potts, 1987). The high-resolution data measured by GAMUT allowed the rapid assessment of water quality and the potential to more precisely identify and quantify human-induced changes along a river's reach.

CONCLUSIONS

GAMUT is the product of a community effort of scientists to create an environmental observatory to monitor fluxes of water quantity and quality along

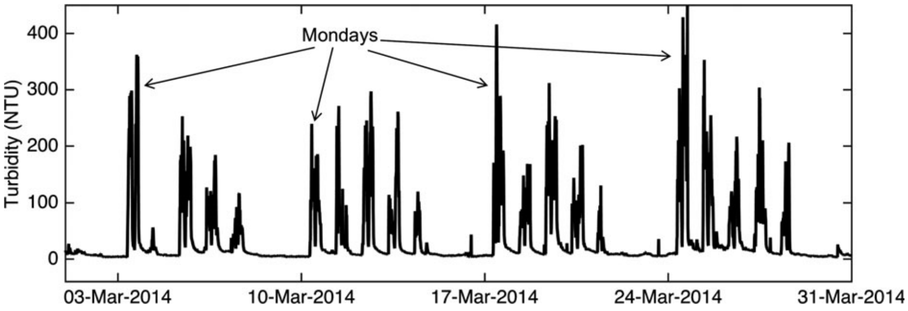


FIGURE 8. Turbidity (nephelometric turbidity units) Measured in the Logan River in March 2014 Showing Spikes Corresponding to Instream Construction and Bank Stabilization.

mountain to urban gradients in three watersheds in northern Utah, U.S. The contrasts in watershed characteristics, including degrees and patterns of urbanization, can be effectively compared using GAMUT data given standard practices for station design, installation, operation, and data management. Though the network was designed and planned by experienced scientists with what we consider to be adequate time and funds, we encountered unexpected setbacks. Overall, network design required an iterative approach to overcome these challenges.

For effective QA/QC for GAMUT, documented standard practices and coordination between personnel were essential. Cleaning and calibration of sensors must be performed consistently and regularly and must also be well documented to enable post-processing. We found that actively monitoring data was essential for identifying and addressing problems to minimize potential data loss. Although subjectivity in performing post-processing may not be completely overcome, we implemented a standard QC workflow that includes recording post-processing steps, made decisions about consistently handling inaccurate data, and developed variable-specific guidelines to address this challenge.

GAMUT revealed nuances with data that have resulted in changes in field procedures, novel solutions for post-processing data, and even adjustments to hardware by sensor manufacturers. We emphasize the importance of experience in these cases and conclude that scientists should remain skeptical and seek independent verification of sensor data, even for sensors from trusted manufacturers. We suggest that there is room for manufacturers to further clarify recommended procedures and frequencies for maintenance as well as documentation of algorithms and data processing.

Our three case studies demonstrate the utility of the high-frequency data generated by GAMUT to initially assess impacts of urbanization, built infrastructure, and anthropogenic activity. The water quality dynamics were only evident with high-frequency data over the spatial extent of GAMUT. Some of these research questions were conceptualized at GAMUT's outset as we developed hypotheses to deductively test via water quality monitoring, but others have only been revealed through the analysis of GAMUT data.

GAMUT is underlying infrastructure that serves as a vehicle for other research endeavors. Researchers have confidence in the GAMUT network and data given its consistency of data collection and commitment to standardized operation, maintenance, and post-processing. Although we attempted to collect a broad suite of variables at representative sites in the study watersheds and apply standardized QA/QC to address data consistency and usability, ultimately secondary users of the data should be familiar with the provenance of the GAMUT data so that they can make their own assessment of potential bias and assumptions in determining whether the data meet their specific needs.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: (S1) Supplemental Guidelines for GAMUT Quality Assurance and Quality Control; (S2) Generation of Rating Curves and Discharge Data for GAMUT; (S3) Generic Datalogger Programs for GAMUT Aquatic Sites; (S4) Generic Datalogger Programs for GAMUT Climate Sites; and (S5) Post-Processing Solutions to Unexpected Sensor and Data Issues for GAMUT.

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