DETERMINING EPHEMERAL SPRING FLOW TIMING WITH LABORATORY AND FIELD TECHNIQUES: APPLICATIONS TO GRAND CANYON, ARIZONA

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ABSTRACT

DETERMINING EPHEMERAL SPRING FLOW TIMING WITH LABORATORY AND FIELD TECHNIQUES: APPLICATIONS TO GRAND CANYON, ARIZONA

ERIC A. ADAMS

Springs along the South Rim of the Grand Canyon, Arizona, are an important resource supporting riparian habitat vital to terrestrial and aquatic wildlife, and to recreational users within the Grand Canyon National Park. Increasing population and development of regional and localized groundwater aquifers on the Coconino Plateau has raised concerns about potential impacts to the park's spring resources. A recent drought showed the influence of climate variability on these resources. Springs along the South Rim are discharge points for regional and local aquifers and could be at risk of diminishing flow. There is a lack of data describing intermittent and ephemeral flow in the spring-fed tributaries of the South Rim due to the difficulty of measuring spring-flow timing in the steep, rocky terrain where diffuse flow with depths less than 1 cm exist.

Electrical resistance sensors were used to conduct a baseline survey of spring-flow timing along three stream reaches. Sensors were installed in alluvial channels and were attached to nearly vertical rock walls at spring outlets. Spring-flow timing data inferred by the electrical resistance sensors were consistent with observations during site visits, flow events recorded with collocated streamflow-gaging stations, and with local precipitation gages. Electrical resistance sensors were able to distinguish the presence of flow along nearly vertical rock surfaces with flow depths between 0.3 cm and 1.0 cm. A comparison of flow patterns along the stream reaches and at springs identified the timing and location of gaining, losing, perennial, and intermittent flow, and periods of increased evapotranspiration. Sensors were also tested in a controlled laboratory environment to study the sources of variability affecting measured resistance data. The laboratory study concluded that saturated sediment and the height of the sensor above the substrate surface were factors affecting measured resistance by causing a delay in the detection of drying.

ACKNOWLEDGMENTS

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Many friends and colleagues have contributed to the completion of this thesis. Dr. Abe Springer was instrumental in obtaining funding for this project and provided endless support and guidance with the project and text editing processes. Abe also spent many days assisting me in the field. I would also like to thank Dr. Diana Anderson, Dr. Ronald Blakey, and Dr. Dave Best for editing the text and serving on my committee. Dr. Best also helped me with the statistical analysis for the study. I wish to thank my collaborators on this project at the USGS in Flagstaff, Stephen Monroe and Donald Bills who also provided support and guidance during the study as well as helping me with the installation of the field equipment. Stephen Monroe also assisted me in the canyon on several occasions. Others who assisted me in the field were Jeremy Kobor and Cubbie Miller; thanks for all your help.

Tiffany Adams provided support and inspiration through frustrating times throughout the thesis process. Being able to spend more time with my daughter Alyssa provided the motivation for the timely completion of this thesis.

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PREFACE

Chapter 2 of this thesis was written as a manuscript for publication in a journal. The remaining chapters provide additional details of the study which may be duplicated in Chapter 2. Chapter 1 discusses the geology and hydrology of the study area and summarizes previous relevant research. Chapter 3 discusses the sourcs of variabilty of the ER sensors and the methods used to test those factors. Chapter 4 summarizes the findings of the study.

CHAPTER ONE

INTRODUCTION

Purpose

Springs along the South Rim of the Grand Canyon are an important resource for Grand Canyon National Park (GRCA). The numerous springs that discharge from the Redwall-Muav aquifer of the Coconino Plateau Sub-Basin along the South Rim support the riparian habitat vital to terrestrial and aquatic wildlife, and to hikers within the park. Increase in population and development on the Coconino Plateau led to the initial development of the Redwall-Muav aquifer as a water supply in 1989. This development of the groundwater aquifer combined with a prolonged drought led to concerns about potential impacts to the park's spring resources. Errol L. Montgomery & Associates, Inc. (1998), Kessler (2002), and Kobor (2004) have suggested that springs along the South Rim of the canyon could be at risk of diminishing flow and in the worst case could go dry over relatively short time scales (years). A decrease in spring discharge will alter the timing and magnitude of water availability causing damage to associated riparian habitats, which in turn could lead to negative impacts on the aquatic wildlife and leave hikers without a water source.

To accurately describe the hydrologic connectivity between regional aquifers and local springs along the South Rim, baseline data on water quantity, timing of flow, and chemistry from South Rim springs are needed. This study examines spring-flow timing and discharge at three South Rim springs. The USGS and NPS operated three streamflow-gaging stations at spring-fed tributaries along the South Rim in GRCA since

1994 to monitor discharge for the evaluation of seasonal and long-term variability. These three gaging stations are at Cottonwood Spring (09402450), Pumphouse Wash Spring (09403013), and Hermit Creek (09403043) (Fig. 1). However, these gages only provide spring-flow timing information at the location of the gages and do not provide information the NPS needs to address sustainability issues for the source springs and the many other springs along the South Rim. In particular, data describing the intermittent and ephemeral flow in spring-fed tributaries are generally absent.

Except for the three springs along the South Rim with gages, the rest of the springs do not have continuous monitoring. A low-cost method to monitor spring flow is needed to monitor these remote spring-fed tributaries. These sites have challenging conditions to monitor, which include intermittent and ephemeral alluvial channels and sites where diffuse flow with depths less than 1 cm exists on near vertical hard rock walls. Traditional streamflow-gaging and monitoring techniques such as stream gages, crest-stage gages, temperature methods, and water-content methods are not suitable for the conditions found along the spring-fed tributaries of the South Rim. Most stream channels that contain spring flow also carry high-magnitude runoff events; thus, flow and depth can range over several orders of magnitude. Furthermore, due to the sensitive nature of the environmental conditions, the use of low-impact and low-visibility instruments is required.

This study uses electrical resistance (ER) sensors to monitor spring-flow timing of South Rim springs. The recent development of ER sensors provides a new method for collecting spring-flow and timing data from previously immeasurable sites. These sensors have been used successfully in alluvial ephemeral-stream channels in southern Arizona

(Blasch et al. 2002), and have been shown to be advantageous owing to their low cost, accuracy, and minimal data-interpretation and analysis requirements. The ER sensors, however, have not been evaluated in spring settings or bedrock channels.

Objectives

The primary objectives of this study were (1) to demonstrate applicability of ER sensors in a variety of field and laboratory applications and (2) to determine the suitability of the ER sensors for use in monitoring timing of spring flow near spring sources, sensitive riparian areas, and intermittent- or perennial-stream reaches important to popular hiking trails. Other specific objectives of this study were to compare flow patterns along the stream reaches and at springs to identify the timing and location of gaining, losing, perennial, and intermittent flow, and periods of increased evapotranspiration. This study also provides additional verification of the utility of the ER sensor method in unconsolidated stream channels and extends the method to the occurrence and timing of flow in bedrock channels.

Study Area

Structure

The study area is on the northern edge of the Coconino Plateau at the South Rim of the Grand Canyon between Horseshoe Mesa and Horn Creek (Figs. 1B and 1C). The Cenozoic aged, upland, physiographic province of the Coconino Plateau Sub-Basin consists of relatively horizontal layers of Paleozoic strata underlain by Precambrian basement (Beus and Morales, 2003). The 9,500-km^2 Coconino Plateau Sub-Basin (Errol

L. Montgomery & Associates, Inc., 1998) is the catchment area for recharge to the Redwall-Muav Limestone aquifer (Fig. 1A). The recharge area is bounded to the west and southwest by the Toroweap and Aubrey fault systems and monoclines; to the east and northeast by the Grandview-Phantom Monocline, East Kaibab Monocline, and the Mesa Butte Fault; and to the south and southeast by the Mogollon Escarpment (Errol L. Montgomery & Associates, Inc., 1998). The Toroweep, Aubrey, and Mesa Butte Faults act as likely groundwater barriers because they offset permeable units against non-permeable units or direct groundwater flow away from the fault either into or out of the aquifer.

Structural geology along the South Rim plays a vital role in the direction of flow and distribution of groundwater and spring discharge. Groundwater flow is controlled primarily by the numerous structural features on the plateau. Primary porosity is low in the aquifer and secondary porosity occurs primarily as a result of dissolution enhancement along faults and fractures. Surface fractures are abundant on the exposed surface of the Kaibab Formation and along the flexures of monoclines. The fracturing of the Kaibab Formation is probably due to ongoing Basin and Range extension processes to the south that are stretching the Coconino Plateau (Billingsley et al. written communication, 2003). These fractures provide pathways for infiltration of precipitation. Extension of rocks along the flexures of monoclines provides additional pathways for downward migration of water. Nonfractured areas away from the monoclines are relatively impermeable. Solution channels and cavities that have developed along faults and fractures in the Redwall and Muav Limestones are another important control on the occurrence, movement, and flow of water along the South Rim of the Grand Canyon.

These infiltration pathways are the primary source of recharge to the aquifer, occurring primarily several tens of kilometers south of the Grand Canyon or along the South Rim of the Grand Canyon (Metzger, 1961).

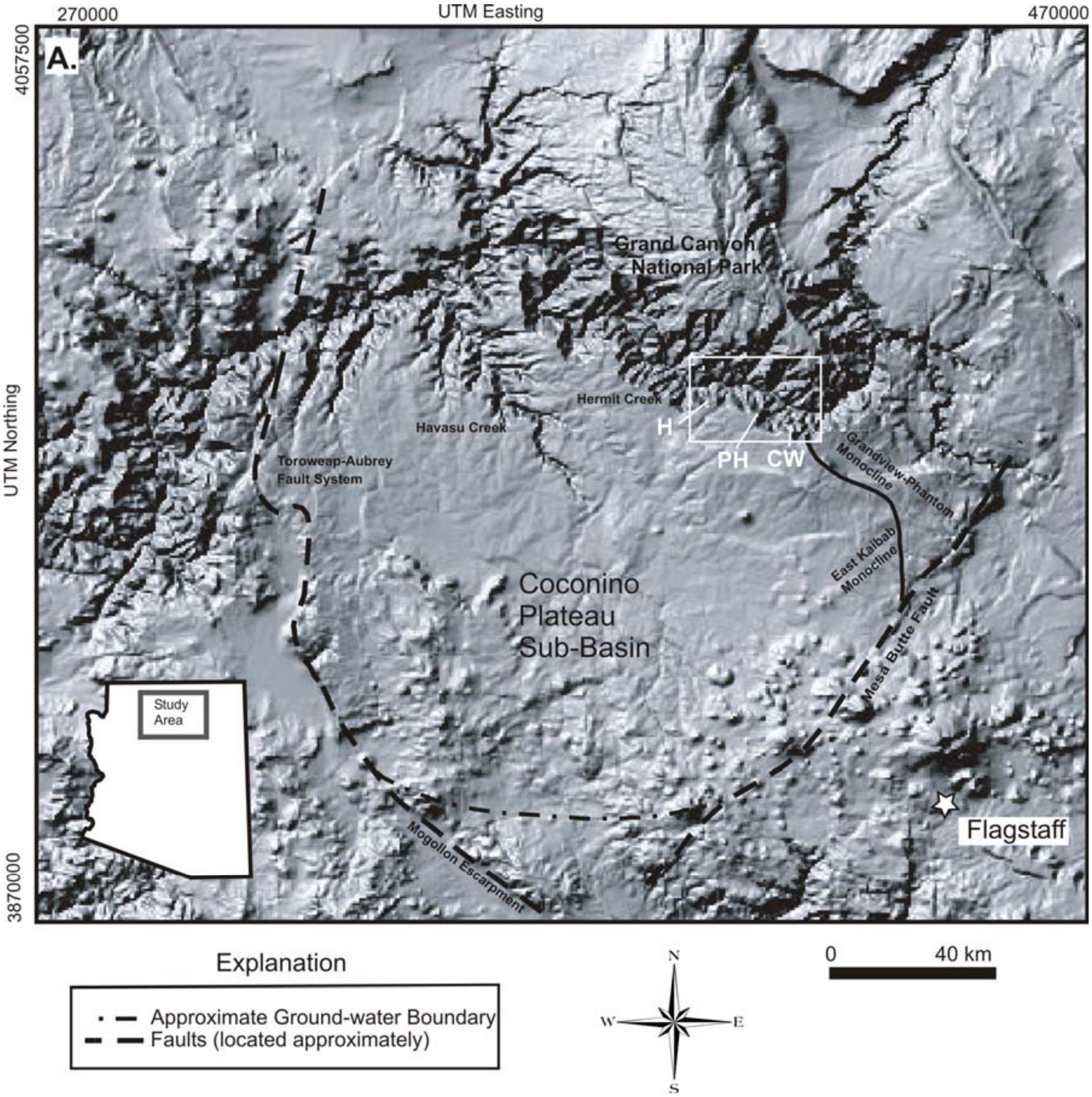


Figure 1. Location of study area, physiographic features, and electrical resistance sensor locations, Grand Canyon National Park, Arizona; (A) Study area showing physiographic features. The area in the white rectangle shows the location of Cottonwood Creek (CW), Pumphouse Spring (PH) and Horn Creek (H), and is shown in detail in Fig. 1B and 1C (Modified from Kessler, 2002).

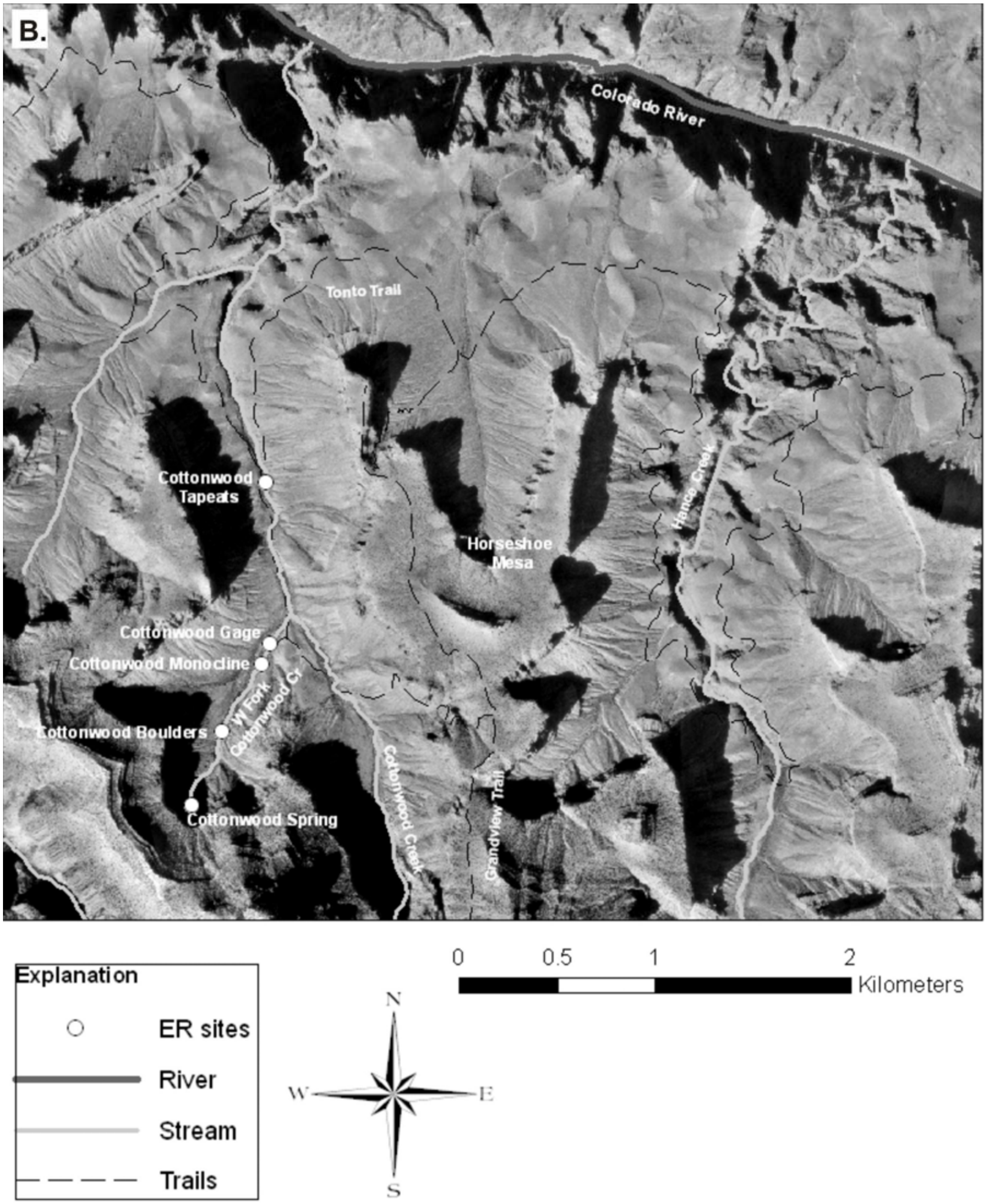


Figure 1B. Location of electrical resistance sensor study sites at Cottonwood Creek.

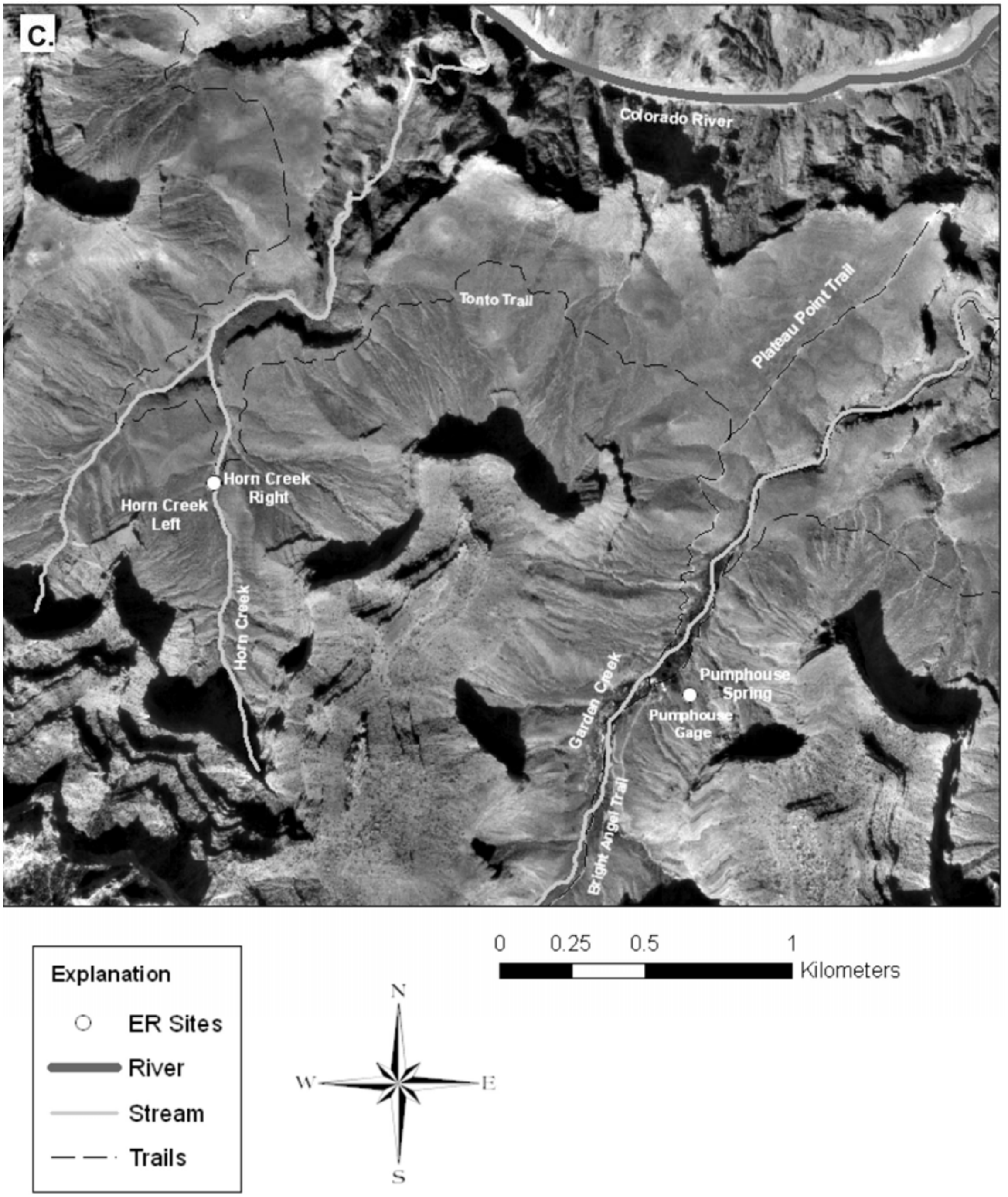


Figure 1C. Location of electrical resistance sensor study sites at Pumphouse Spring and Horn Creek.

Stratigraphy

The Redwall-Muav Limestone aquifer is the major water-bearing unit in the Paleozoic stratigraphy of the Grand Canyon and Coconino Plateau (Metzger, 1961; Errol L. Montgomery & Associates, Inc., 1998). The Middle to Upper Cambrian Muav Limestone and Lower Mississippian Redwall Limestone are hydraulically connected, behaving as a single, confined, hydrostratigraphic unit forming the Redwall-Muav Limestone aquifer (Fig. 2). For this study, the Temple Butte and Surprise Canyon Formations are included in the Redwall-Muav Limestone hydrostratigraphic unit as they are assumed to be discontinuous and hydrogeologically insignificant units. The aquifer is confined below by fine-grained mudstones and claystones in the Bright Angel Shale and above by mudstones in the lower Supai Group (Metzger, 1961).

The Cambrian Bright Angel Shale is a slope-forming, interbedded, fine-grained sandstone, siltstone and shale. The coarse-grained sandstones and conglomerates of the Bright Angel Shale contain quartz, minor feldspar and sedimentary rock fragments, and glauconite (Middleton and Elliot, 2003). Thickness of the Bright Angel Shale ranges from 82 – 137 m, which is due to the complex intertonguing relationships with the underlying Muav Limestone.

The Middle Cambrian Muav Limestone is ~50 m thick and consists predominantly of thin-bedded, nodular, and mottled limestone and dolostone (Rose, 2003). The formation overlies the Bright Angel Shale and forms resistant cliffs. Additional lithologies include pebble conglomerates, fine-grained sandstone, silty limestone, and bioturbated siltstone (Middleton and Elliott, 2003; Rose, 2003). The

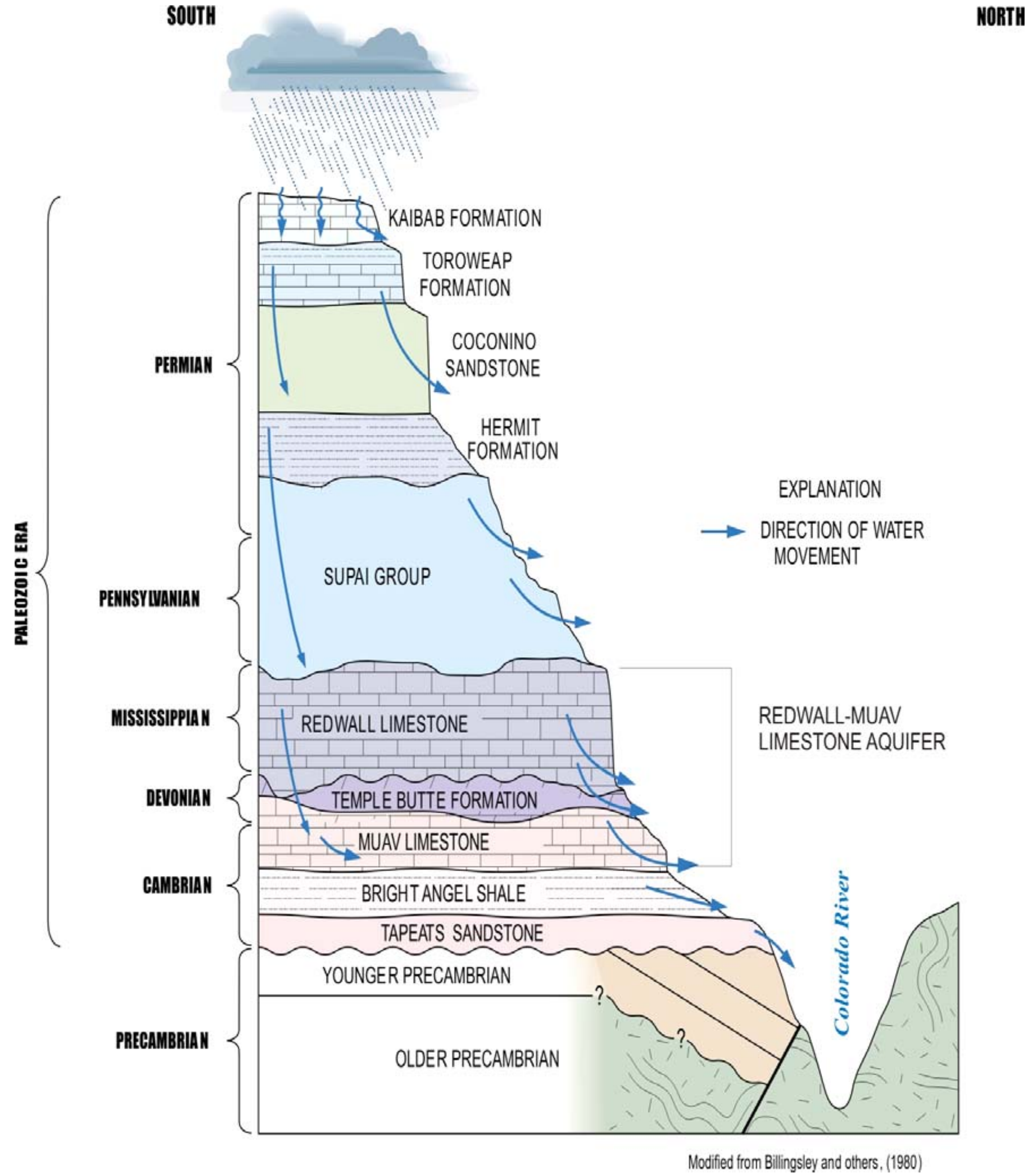


Figure 2. Generalized stratigraphic section showing rock units and groundwater flow of the South Rim Grand Canyon, Arizona (Billingsley and others, 1980).

contact with the overerlying Bright Angel Shale is gradational and complex intertonguing of the two formations occurs (Middleton and Elliot, 2003).

The Early to Late Mississippian Redwall Limestone is ~ 150 m thick forming massive, vertical cliffs overlying the Muav Limestone. The formation consists of four distinct stratigraphic members (Beus, 2003). The lowest member is the Whitmore Wash Member, which consists of thickly bedded, fine-grained dolomite (Beus, 2003). Overlying this member is the Thunder Springs Member, which consists of thinly bedded limestone and dolomite alternating with thinly bedded chert. The overlying Mooney Falls Member consists of limestone with minor chert lenses. The upper most member is the Horseshoe Mesa Member which consists of thinly-bedded limestone with a mudstone to wackestone texture and minor chert lenses (Beus, 2003).

The Lower Pennsylvanian Watahomigi Formation is the oldest formation of the Supai Group consisting of red mudstone and siltstone and gray limestone and dolomite. The unit forms a broad, slightly westward-thickening sheet that ranges in thickness from 30 m to 90 m in the canyon (Blakey, 2003). The lower contact of the Watahomigi Formation is sharp and unconformable with the underlying Redwall Limestone.

Hydrology

There are three types of streams in the tributary drainages of the South Rim of the Grand Canyon; ephemeral, intermittent and perennial. Many of these drainages contain small perennial springs either at the base of the vertical to near-vertical Redwall-Muav Limestone cliffs or as discharge from talus slopes, colluvium, or streambed alluvium. Perennial streams that flow from spring sources to the Colorado River are uncommon along the South Rim. Most of the streams along the South Rim are ephemeral streams and are dry most of the year, only flowing for short durations during and (or) after precipitation and snowmelt events. Intermittent streams are also common along the South Rim, in which flow may occur more frequently in response to smaller precipitation events that may saturate the ground long enough to temporarily raise the water table to the streambed.

Groundwater resources consist of perched water-bearing zones, a regional aquifer, and the regionally extensive Redwall-Muav aquifer (Bills and Flynn, 2002). The water-bearing zones supporting seeps and springs include the Cambrian Tapeats Sandstone, the Pennsylvanian and Permian Supai Group, and the Permian Coconino Sandstone. The aquifer discharges the vast majority of groundwater from the Coconino Plateau northward to the Grand Canyon due to the slight regional dip to the north. Most springs along the South Rim of the Grand Canyon flow from the Redwall and Muav Limestones under confined conditions by the underlying, low-pearmability Bright Angel Shale

The semiarid climate of the South Rim of the Grand Canyon has an average annual precipitation of 480 mm per year at the rim to less than 230 mm per year in the inner canyon (Sellers et al. 1986). Most of the precipitation occurs in two seasons, late winter and early spring when large Pacific storms move across Arizona depositing rain at lower elevations and snow at higher elevations, and mid- to late summer when tropical moisture moving into the State from the Gulf of California or the Gulf of Mexico results in locally intense but brief thunderstorms (Sellers et al. 1986). Evaporation rates are high throughout the study area. The potential evaporation rate on the South Rim ranges from 1524 to 1651 mm per year and is higher in the inner canyon (Sellers and Hill, 1974).

Snowpack evapo-sublimation rates during the winter are high as well (Avery and Dexter, 2000).

Previous Investigations

There have been many studies of the history and geology of the Grand Canyon. A complete listing of these references is beyond the scope of this thesis. However, references by McKee (1937, 1939, 1963, 1974, 1975, 1976, and 1982), McKee and Gutschick (1969), and by Beus and Morales (2003) provide the necessary description of Paleozoic rock stratigraphy and lithology to develop a better understanding of the occurrence and flow of South Rim springs. In contrast, comparatively little has been written on the spring resources of the Grand Canyon. Powell (1874) and LaRue (1925) collected some of the earliest information on springs in the canyons of the Colorado River. Metzger (1961) provided an assessment of the availability of water along the South Rim of the Grand Canyon in relation to the canyon geology. Johnson and Sanderson (1968) provided information describing spring flow into the Colorado River of the Grand Canyon on the basis of data collected in the 1950s and 1960s. All of these earlier studies included only the most easily accessible sites in the canyon. Recent commercial growth and development on the Coconino Plateau south of the Grand Canyon have resulted in renewed interest in spring resources of the canyon. Monroe et al. (2003) collected flow and water-chemistry data from 46 sites along the South Rim from Blue Spring in the east to Mohawk Spring in the west. NPS and USGS databases have documented most of the South Rim spring resources and locations, flow and water-chemistry data, as well as gaging data at a few perennial springs.

Several groundwater flow models have been constructed to describe flow in the Coconino Plateau subbasin to springs of the Grand Canyon. Errol L. Montgomery & Associates, Inc. (1998) constructed a two-dimensional ground-water flow model as part of the Tusayan Growth Environmental Impact Statement (EIS), which evaluates land exchange alternatives for development south of GRCA. The model indicated that withdrawals of water from the water-bearing zones in the Redwall and Muav Limestones could significantly impact seeps and springs below the South Rim of the canyon over long (100 year) time scales. The model addressed spring flow in only three drainages: Havasu Creek, Hermit Creek, and Garden Creek (Fig. 1). Wilson (2000) constructed a digital, three-dimensional, geologic framework model and a three-dimensional flow model to simulate discharge and delineate capture zones from the same three springs modeled by Errol L. Montgomery & Associates, Inc. Kessler (2002) expanded Wilson's model with the addition of 17 minor South Rim springs to better define the capture zones and flow paths to each spring. Kobor (2004) constructed a coupled local groundwater and surface-water flow model for the riparian aquifer associated with Cottonwood Springs. The model indicated a potential for alteration to South Rim spring-fed ecosystems over relatively short timescales (less than 10 years) due to trends of decreasing discharge coupled with ongoing groundwater pumping and climate predictions of continuing drought.

While these reports and data are valuable sources of information for the characterization of South Rim springs, they contain little useful information for determining temporal spring-flow quantity and timing. All data describing spring flow are based on measurements with limited time-series information, and the models are based on limited subsurface information.

Several strategies have been used to record the presence and the timing of stream flow, including streamflow-gaging stations, crest-stage gages, temperature methods, and water-content sensors (Constantz et al. 2001; Blasch et al. 2002; and Blasch et al. 2004). Blasch at al. (2002) used modified temperature sensors to monitor channel flow and streambed saturation to infer ephemeral stream flow and timing near Tucson, Arizona. The sensors were modified by removing the thermistor and stripping the insulation enclosing the electrodes according to the methodology described by Blasch et al. (2002) (Fig 3). The sensors were evaluated in an alluvial channel through comparison with temperature-based methods, a streamflow-gaging station, and soil-water content sensors (Blasch et al. 2002). The study demonstrated that ER sensors were an accurate method for estimating stream-flow timing and that the resultant data required less interpretation than data from temperature-based methods. The accuracy of the ER sensors was

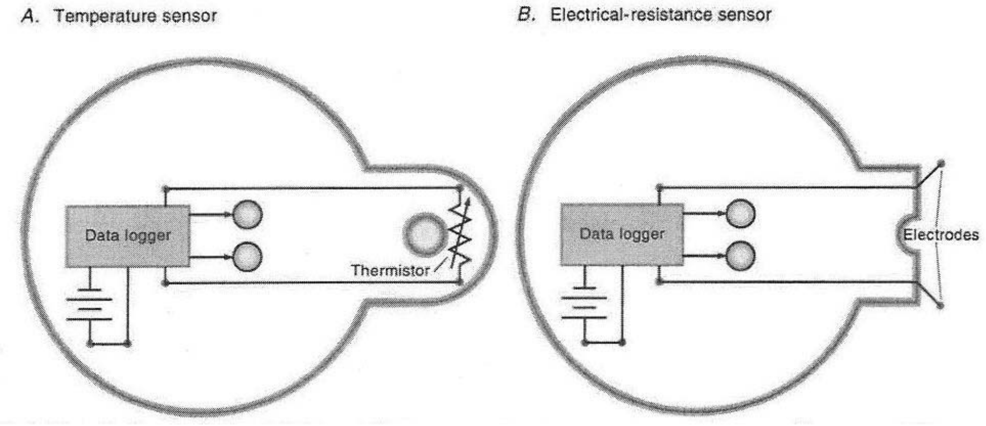


Figure 3. Schematic diagram of a temperature sensor (A) before modification, and (B) after conversion to an electrical resistance sensor through removal of the thermistor.

equivalent to timing methods using streamflow-gaging station and soil-water content measurements (Blasch et al. 2002). The ER sensors were advantageous for use in ephemeral stream channels because they are inexpensive, deployable above or below sediment surface, insensitive to depth, and do not require an external datalogger or power source.

Site Description

This study focuses on three streams along the South Rim to provide a range of intermittent and perennial flow conditions as well as a variety of terrain conditions. They include Cottonwood Creek (Fig. 1B), Pumphouse Spring near Garden Creek, and Horn Creek (Fig. 1C). Cottonwood Springs is located near the eastern margin of the basin, between Grapevine and Hance Springs. Cottonwood Creek consists of a series of small springs rather than a single source, some of which are buried beneath recent colluvial material. No springs occur at the headwaters of the main stem of Cottonwood Creek. They instead are located at the headwaters of a small tributary to Cottonwood Creek referred as West Fork Cottonwood Creek by Kobor (2004). Pumphouse Spring is on the hillslope about 75 m east of Indian Gardens. Horn Creek is located west of Indian Gardens.

Cottonwood Creek was selected for its rockwall springs and variety of unconsolidated channel settings with gaining and losing reaches. Additionally, Cottonwood Creek is the location of numerous complementary and simultaneous studies of channel morphology, riparian habitat, geochemistry, and groundwater flow patterns by other researchers (John Rihs, hydrologist, Grand Canyon National Park, oral communication, 2004; Kobor, 2004). Pumphouse Spring was selected because the source of the spring is from unconsolidated colluvial deposits. Pumphouse Spring is associated with the Bright Angel Fault, which is a major structure extending northeast from the South Rim across the canyon to the north rim (Billingsley and Huntoon, 1983; Huntoon and Billingsley, 1996). This fault acts as an effective collection gallery for groundwater in the vicinity and discharges at Pumphouse Spring. Cottonwood Creek and Pumphouse Spring both have streamflow-gaging stations available to provide data for ER sensor confirmation. Horn Creek was selected because it is near a trail crossing, has a bedrock setting, and is of particular interest to the NPS because of an abandoned uranium mine within the drainage. The physical characteristics of each field site were described with a spring classification system (Springer et al. in press).

CHAPTER TWO

JOURNAL MANUSCRIPT

ABSTRACT

Springs along the South Rim of the Grand Canyon, Arizona, are an important resource supporting riparian habitat vital to terrestrial and aquatic wildlife, and to recreationalists within Grand Canyon National Park. Development of regional and localized ground-water aquifers along the rim has raised concerns about potential impacts to the park's spring resources. A recent drought has pointed out the influence of climate variability on these resources. Springs along the South Rim are discharge points for regional and local aquifers and are at risk of diminishing flow. Owing to the difficulty of measuring spring-flow timing due to the steep, rocky terrain, there is a lack of data describing intermittent and ephemeral flow in the spring-fed tributaries of the South Rim. Electrical resistance sensors were used in this study to conduct a baseline survey of spring-flow timing along three stream reaches. Sensors were installed in alluvial channels and were attached to nearly vertical rock walls at spring outlets. Spring-flow timing data inferred by the electrical resistance sensors were consistent with observations during site visits, flow events recorded with collocated streamflow-gaging stations, and with local precipitation gages. Electrical resistance sensors were able to distinguish the presence of flow along nearly vertical rock surfaces with flow depths between 0.3 cm and 1.0 cm. A comparison of flow patterns along the stream reaches and at springs identified the timing and location of gaining, losing, perennial, and intermittent flow, and periods of increased evapotranspiration.

Background

Spring flow from the South Rim of the Grand Canyon is an important resource for Grand Canyon National Park (GRCA). The National Park Service (NPS) has identified four issues that need to be addressed related to South Rim spring resources: the quality and quantity of water from springs can limit recreational use of the water; changes in the quality, quantity, and sustainability of flow from springs can affect the long-term health of biological communities and riparian habitats associated with these areas; climate variability can affect spring flow and thus the riparian habitat; and ground-water withdrawal from the Redwall and Muav Limestones south of the Grand Canyon may affect the quantity of spring flow (John Rihs, Hydrologist, GRCA, written communication, 2003). Errol L. Montgomery & Associates, Inc. (1998), Kessler (2002), and Kobor (2004) have suggested that springs along the South Rim of the canyon could be at risk of diminishing flow, and in the worst case, could go dry.

Baseline data on water quantity, timing of flow, and chemistry from South Rim springs are needed to more accurately describe the hydrologic connectivity between the regional aquifer and springs along the South Rim. The USGS operated three streamflow-gaging stations at spring-fed tributaries along the South Rim in GRCA from 1994 to 2002. These gaging stations are at Cottonwood Spring (09402450), Pumphouse Wash Spring (09403013), and Hermit Creek (09403043) (Fig. 4). The NPS has continued operation of these gaging stations since 2002. The purpose of the gaging stations is to monitor flows for the evaluation of seasonal and long-term variability. However, these gages only provide spring-flow timing information at the location of the gages and do not provide information the NPS needs to address the sustainability issues for the source

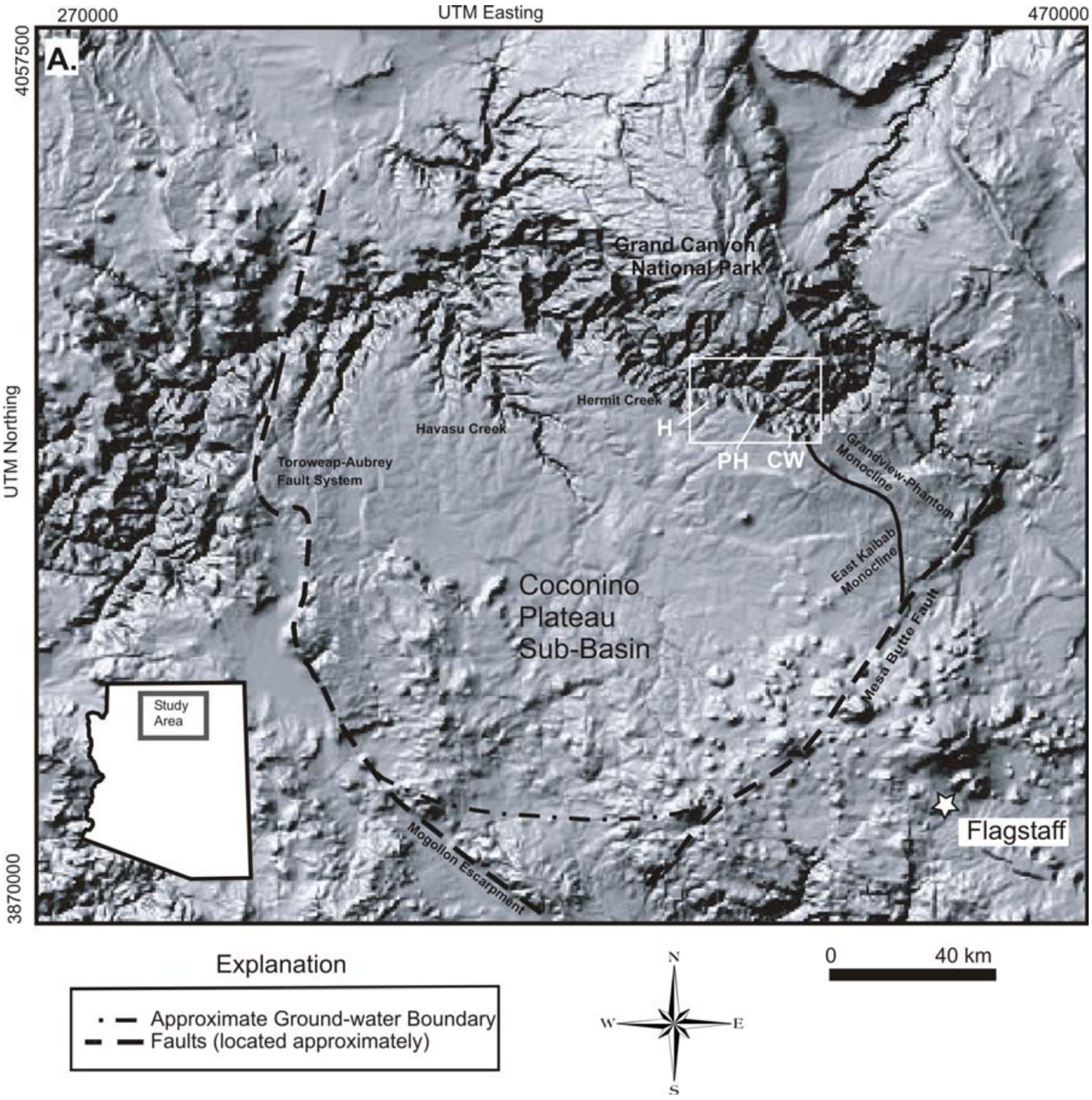


Figure 4A. Location of study area, physiographic features, and electrical resistance sensor locations, Grand Canyon National Park, Arizona; (A) Study area showing physiographic features. The area in the white rectangle shows the location of Cottonwood Creek (CW), Pumphouse Spring (PH) and Horn Creek (H), and is shown in detail in Fig. 1B and 1C (Modified from Kessler, 2002).

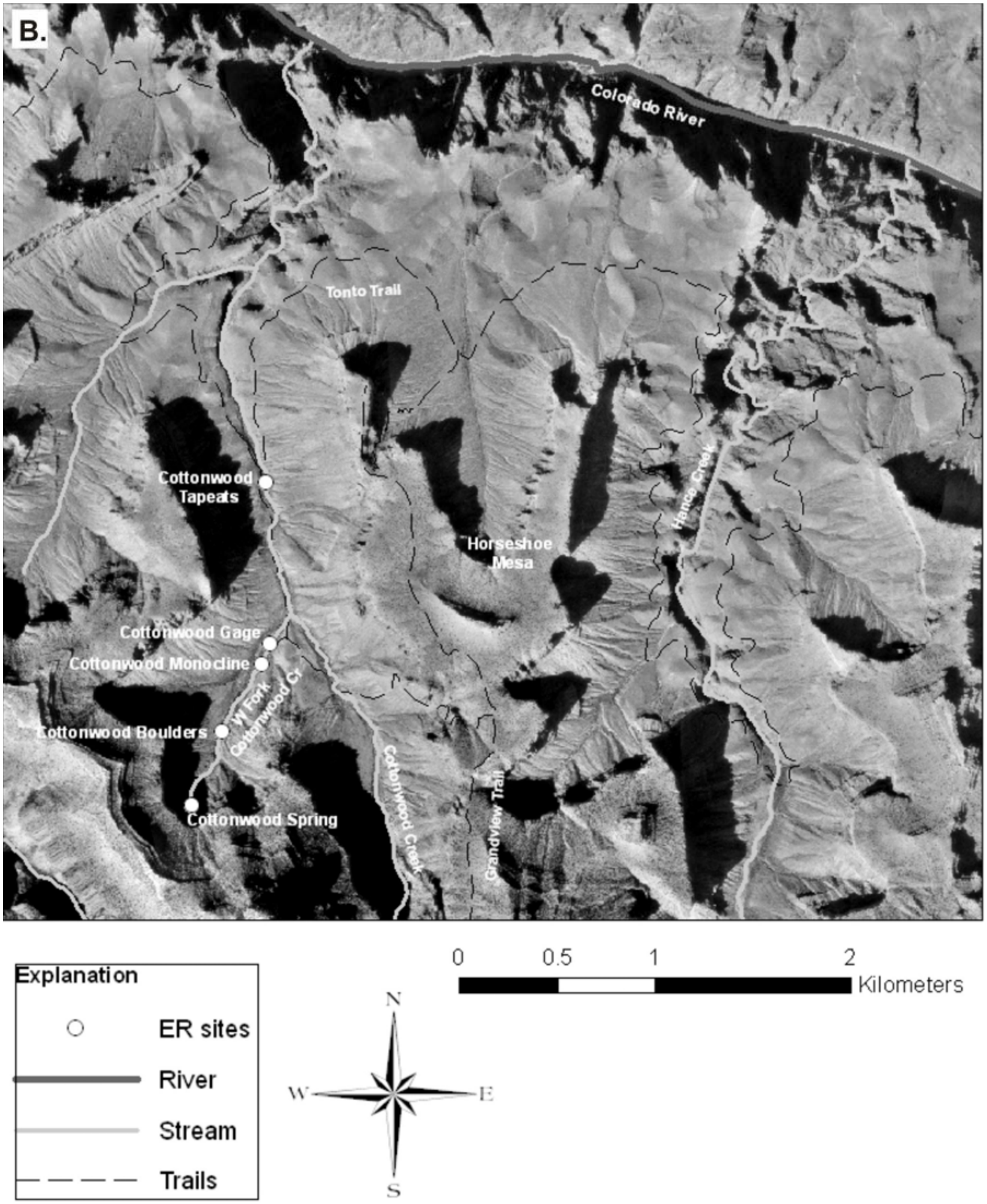


Figure 4B. Location of electrical resistance sensor study sites at Cottonwood Creek.

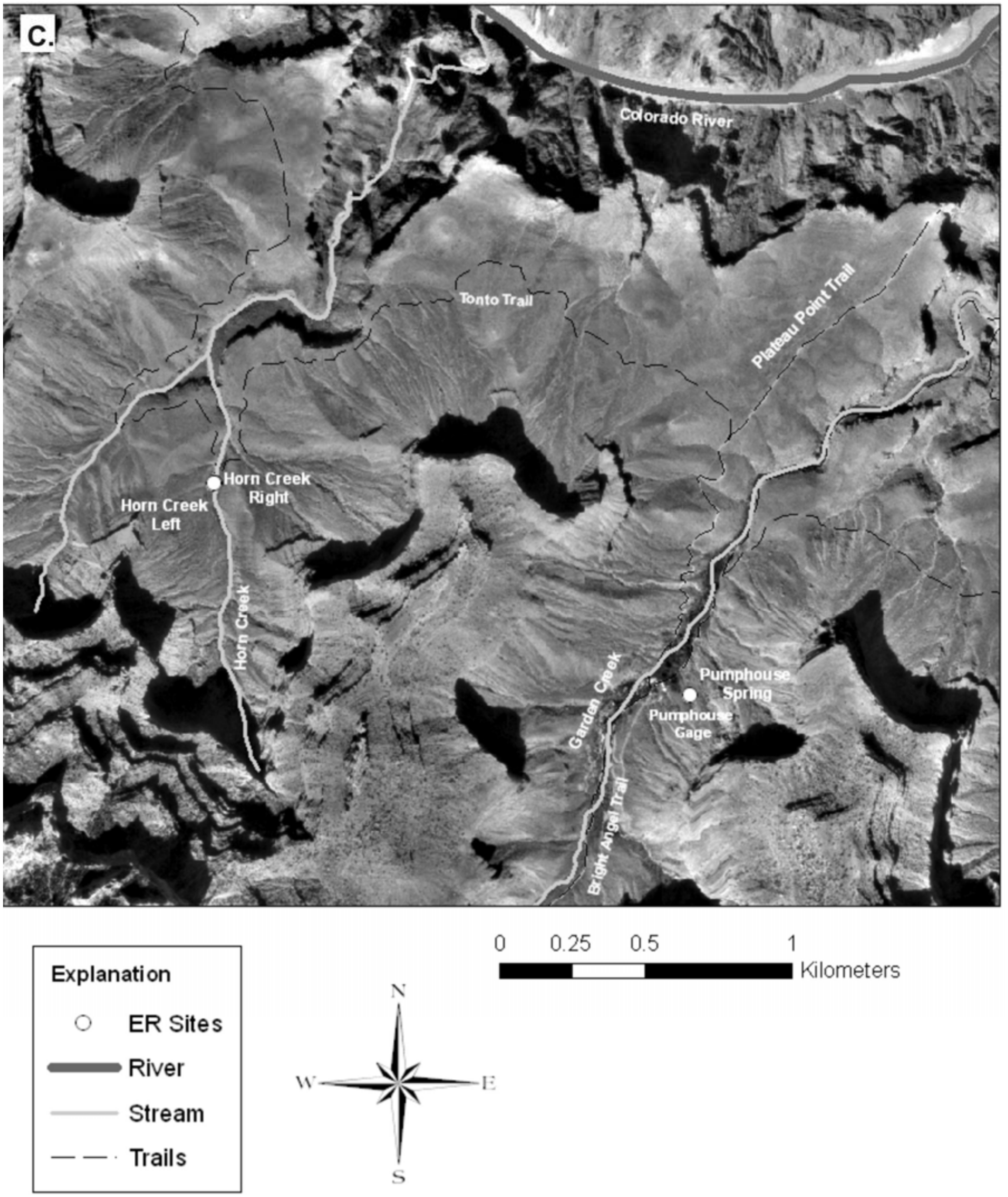


Figure 4C. Location of electrical resistance sensor study sites at Pumphouse Spring and Horn Creek.

springs and the many other springs along the South Rim. In particular, data describing the intermittent and ephemeral flow in spring-fed tributaries are generally absent.

Traditional streamflow-gaging and monitoring techniques such as stream gages, crest-stage gages, temperature methods, and water-content methods are not suitable for the conditions found along the spring-fed tributaries of the South Rim. Conditions occurring in these tributaries include intermittent and ephemeral alluvial channels and sites where diffuse flow with depths less than 1 cm exists on near vertical hard rock walls. Moreover, due to the sensitive nature of the environmental conditions, the use of low-impact and low-visibility instruments is required. Most stream channels that contain spring flow also route high-magnitude runoff events; thus, flow and depth can range over several orders of magnitude. Electrical resistance (ER) sensors have been used successfully in alluvial ephemeral-stream channels in southern Arizona (Blasch et al. 2002), but have not been evaluated in spring settings or bedrock channels. The ER sensors have been shown to be advantageous for use in the intermittent and ephemeral stream channels owing to their low cost, accuracy, and minimal data-interpretation and analysis requirements.

The primary objective of this study was to demonstrate applicability of ER sensors in a variety of field and laboratory applications and to determine the suitability of the ER sensors for use in monitoring timing of spring flow near spring sources, sensitive riparian areas, and intermittent- or perennial-stream reaches important to popular hiking trails. This study also provides additional verification of the utility of the ER sensor method in unconsolidated stream channels and extends the method to the occurrence and timing of flow in bedrock channels.

Previous investigations

There have been many studies of the history and geology of the Grand Canyon. A complete listing of these references is beyond the scope of this report. However, references by McKee (1937, 1939, 1963, 1974, 1975, 1976, and 1982), McKee and Gutschick (1969), and Beus and Morales (2003) provide the necessary description of Paleozoic rock stratigraphy and lithology to develop a better understanding of the occurrence and flow of South Rim springs. In contrast, comparatively little has been written on the spring resources of the Grand Canyon. Some of the earliest information on springs in the canyons of the Colorado River was collected by Powell (1874) and LaRue (1925). Metzger (1961) provided an assessment of the availability of water along the South Rim of the Grand Canyon in relation to the canyon geology. Johnson and Sanderson (1968) provided information describing spring flow into the Colorado River of the Grand Canyon on the basis of data collected in the 1950s and 1960s. All of these earlier studies included only the most easily accessible sites in the canyon. Recent growth and development on the Coconino Plateau south of the Grand Canyon have resulted in renewed interest in spring resources of the canyon. Most South Rim spring resources have been located and documented in NPS or USGS databases. Monroe et al. (in press) collected flow and water-chemistry data for most of the springs along the South Rim. A few perennial springs along the South Rim have been gaged by the USGS and GRCA since 1994 (see USGS Annual Water Data reports, for example, Smith et al. 1995). Additional miscellaneous flow and water-chemistry data are included in USGS and GRCA databases.

Three ground-water flow models have been constructed that describe flow in the Coconino Plateau Sub-Basin to springs of the Grand Canyon. Errol L. Montgomery & Associates, Inc. (1998) constructed a two-dimensional ground-water flow model as part of the Tusayan Growth Environmental Impact Statement (EIS), which evaluated land exchange alternatives for development south of GRCA. The model indicated that withdrawals of water from the water-bearing zones in the Redwall and Muav Limestones could cause up to a 30% decrease in discharge that may occur after 100 yrs of pumping at current abstraction rates, which could significantly impact seeps and springs along the South Rim of the canyon. The model addressed spring flow in only three drainages: Havasu Creek, Hermit Creek, and Garden Creek (Fig. 4). Wilson (2000) constructed a digital, three-dimensional, geologic framework model and a three-dimensional groundwater flow model to simulate discharge and delineate capture zones from the same three springs modeled by Errol L. Montgomery & Associates, Inc. Kessler (2002) expanded Wilson’s model with the addition of 17 minor South Rim springs to better define the capture zones and flow paths to each spring.

While these reports and data are valuable sources of information for the characterization of South Rim springs, they contain little useful information for determining temporal spring-flow quantity and timing. All data describing spring flow are based on measurements with limited time-series information, and the models are based on limited subsurface information.

Several strategies have been used to record the presence and the timing of stream flow, including streamflow-gaging stations, crest-stage gages, temperature methods, and water-content sensors (Constantz et al. 2001; Blasch et al. 2002; and Blasch et al. 2004).

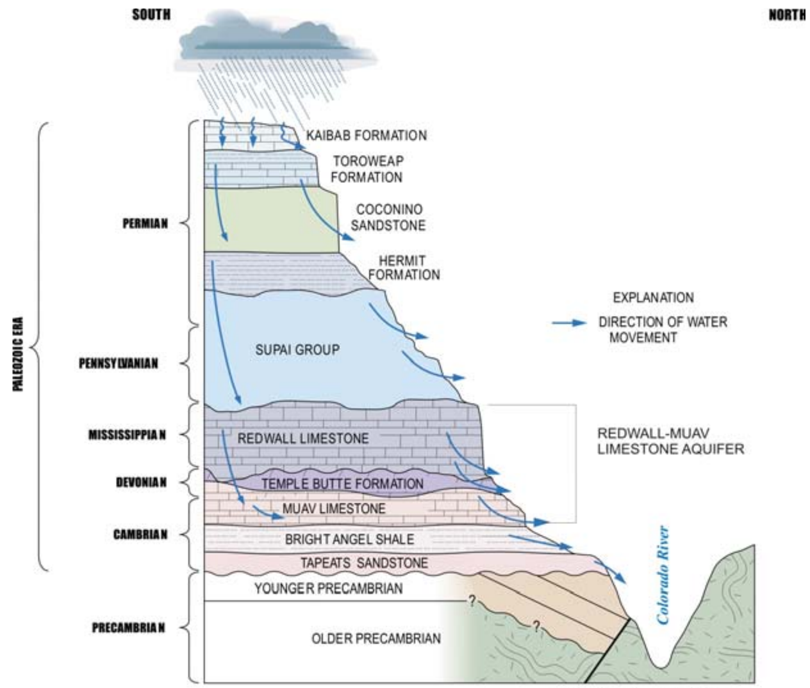
Blasch et al. (2002) used modified temperature sensors to monitor channel flow and streambed saturation to infer ephemeral stream flow and timing near Tucson, Arizona. The sensors were evaluated in an alluvial channel through comparison with temperature-based methods, a streamflow-gaging station, and soil-water content sensors (Blasch et al. 2002). The study demonstrated that ER sensors were an accurate method for estimating stream-flow timing and that the resultant data required less interpretation than data from temperature-based methods. The accuracy of the ER sensors was equivalent to timing methods using streamflow-gaging station and soil-water content measurements (Blasch et al. 2002). The ER sensors were advantageous for use in ephemeral stream channels because they are inexpensive, deployable above or below sediment surface, insensitive to depth, and do not require an external datalogger or power source.

Description of study area

The study area is on the northern edge of the Coconino Plateau at the South Rim of the Grand Canyon between Horseshoe Mesa and Horn Creek (Figs. 4B and 4C). The 9,500-km^2 Coconino Plateau subbasin is the catchment area for recharge to the Redwall-Muav Limestone aquifer (Fig. 4A). The recharge area is bounded to the west and southwest by the Toroweap and Aubrey fault systems and monoclines; to the east and northeast by the Grandview-Phantom Monocline, East Kaibab Monocline, and the Mesa Butte Fault; and to the south and southeast by the Mogollon Escarpment (Errol L. Montgomery & Associates, Inc. 1998).

Tributary drainages of the South Rim of the Grand Canyon are characterized by three types of streams: ephemeral, intermittent and perennial. Small perennial springs are found in most of these drainages either at the base of the vertical to near-vertical Redwall-Muav Limestone cliffs or as discharge from talus slopes, colluvium, or streambed alluvium. Most of the streams along the South Rim are ephemeral streams and are dry most of the year, only flowing for short durations during and (or) after precipitation and snowmelt events. Intermittent streams are also common along the South Rim. Flow may occur more frequently in these streams in response to smaller precipitation events that may saturate the ground long enough to temporarily raise the water table to the streambed. Perennial streams that flow from spring sources to the Colorado River are uncommon along the South Rim.

The Redwall-Muav Limestone aquifer is the major water-bearing unit in the Paleozoic stratigraphy of the Grand Canyon and Coconino Plateau (Metzger 1961; Errol L. Montgomery & Associates, Inc. 1998; and Monroe et al. in press). The Middle to Upper Cambrian Muav Limestone and Lower Mississippian Redwall Limestone are hydraulically connected, behaving as a single hydrostratigraphic unit forming the Redwall-Muav Limestone aquifer (Fig. 5). The aquifer is confined below by fine-grained mudstones and claystones in the Bright Angel Shale and above by mudstones in the lower Supai Group (Metzger 1961). The aquifer discharges the vast majority of ground water from the Coconino Plateau northward to the Grand Canyon. Most springs along the South Rim of the Grand Canyon flow from the lower Redwall and upper Muav Limestones under water-table conditions that are caused by the erosional removal of the upper confining layer proximal to the canyon rim. Other springs flow under water-table conditions near the Bright Angel Shale and Muav Limestone contact.



Modified from Billingsley and others, (1980)

Figure 5. Generalized stratigraphic section showing rock units and ground-water flow of the South Rim Grand Canyon, Arizona (Billingsley and others, 1980).

Surface fractures are abundant on the exposed surface of the Kaibab Formation and along the flexures of monoclines. The fracturing of the Kaibab Formation is probably due to ongoing Basin and Range extension processes to the south that are stretching the Coconino Plateau (Billingsley et al. written communication, 2003). These fractures provide pathways for infiltration of precipitation. Stretching of rocks along the flexures of monoclines provides additional pathways for downward migration of water. Nonfractured areas away from the monoclines are relatively impermeable. Solution channels and cavities that have developed along faults and fractures in the Redwall and Muav Limestones are another important control on the occurrence, movement, and flow of water along the South Rim of the Grand Canyon. These infiltration pathways are the primary source of recharge to the aquifer, occurring primarily several tens of kilometers south of the Grand Canyon or along the South Rim of the Grand Canyon (Metzger 1961).

The semiarid climate of the South Rim of the Grand Canyon has an average annual precipitation of 480 mm per year at the rim to less than 230 mm per year in the inner canyon (Sellers et al. 1986). Most of the precipitation occurs in two seasons, late winter and early spring when large Pacific storms move across Arizona depositing rain at lower elevations and snow at higher elevations, and mid- to late summer when tropical moisture moving into the State from the Gulf of California or the Gulf of Mexico results in locally intense but brief thunderstorms (Sellers et al. 1986). Evaporation rates are high throughout the study area. The potential evaporation rate on the South Rim ranges from 1524 to 1651 mm per year and is higher in the inner canyon (Sellers and Hill 1974). Snowpack evapo-sublimation rates during the winter are high as well (Avery and Dexter 2000).

LABORATORY METHODS

Stowaway Tidbit[1] temperature sensors manufactured by Onset Corporation of Bourne, Maine, were modified to measure electrical resistance for this study[2]. These sensors contain a thermistor, onboard datalogger, and battery encapsulated in a 10-cm^3 plastic housing. The sensors were modified by removing the thermistor and stripping the insulation enclosing the electrodes according to the methodology described by Blasch et al. (2002). The cessation of stream flow is accompanied by drying of the sediments and a reduction in saturation, causing an increase in the total electrical resistance. An ER sensor detects an increase in electrical resistance during drying until the contact resistance

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[1] The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or Northern Arizona University.

[2] The Tidbit configuration used in this analysis and described by Blasch et al. (2002) is no longer available by the manufacturer; however, substitute instruments are available which can be more easily modified.

threshold of the medium surrounding the electrodes (air or sediment) is reached, which is recorded as a rapid increase in the measured total electrical resistance. Data collected from both the field and laboratory ER sensor studies were converted from temperature data to resistance in ohms using an inverse polynomial equation.

A bench-top laboratory experiment was conducted to test the ER sensors in a controlled environment, simulating diffuse seep or spring flow along bedding planes or fractures. The bench-top test was conducted to determine if there were any significant differences among instruments in detecting the inception of drying. The bench-top study allowed direct observation of instrument variability for a specific physical setting, such as a bedrock surface, and for high resolution analysis of the wetting and drying period. These experiments examined resistance range versus wetness and sensor saturation. The bench-top was established in a container with three cinder blocks positioned on bricks with a recirculating pump passing water through the inside of each block, simulating a spring emerging from fractured bedrock (Fig. 6). Three ER sensors collected data at 30-

Figure 6. Photograph showing view of artificial springs and electrical resistance sensors in a laboratory setting. Electrical resistance sensors are located at the base of the cinder blocks. Water flows out of the base of the cinder block reservoirs though a narrow crack past the sensors.

second intervals. The sensors were allowed to equilibrate in dry conditions for 5 minutes prior to initiation of flow for 20 minutes. The ER sensors were allowed to collect resistance data for another 15 minutes after flow ceased to detect the drying period. Twenty replicates were conducted for each of the three sensors. Flow depth was measured to be less than 0.3 cm during all trials.

FIELD METHODS

In the field ER sensors were attached to a plastic T-bracket or placed in perforated capsules. The T-bracket or capsules were attached to rebar driven into stream channels, and the ER sensors were oriented so that the electrodes were close to the channel surface (Fig. 7). Stream flow detection can be minimized by proper installation of the ER sensors. For example, deposited sediments can bury sensors placed too low or sensors may fail to detect flow at low depths if placed too high.

Stage data collected at 15-minute intervals from the Cottonwood Spring and Pumphouse Wash Spring streamflow-gaging stations were obtained from the NPS for the study period. Presence or absence of flow was determined by observations at the time of each site visit, and discharge was measured volumetrically when flow was present (Rantz et al. 1982). In addition to the ER sensors, unmodified Stowaway Tidbit temperature sensors were installed at each study site to monitor air and water temperatures. Air and water temperature were measured during each site visit with calibrated thermometers. Precipitation data were collected by Onset rain gages located near Cottonwood Creek and near Indian Gardens. Geographic position of each study site was determined by Differential Global Positioning System (DGPS) methods or topographic maps (Table 1, Fig. 4).

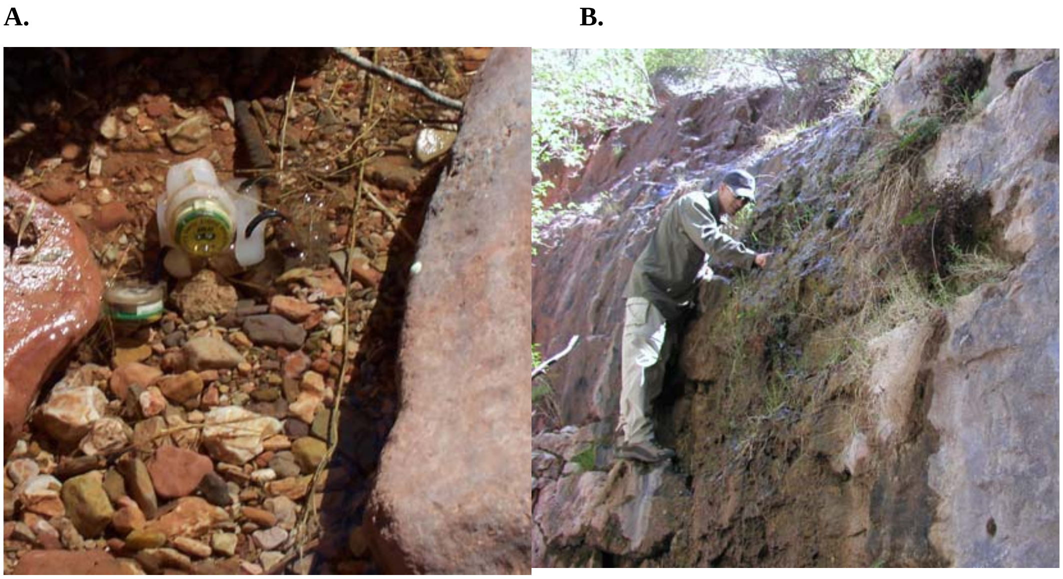

Figure 7. Photographs showing typical electrical resistance sensor installations; (A) Alluvial channel; (B) Rock wall.

DATA COLLECTION AND SITE DESCRIPTION

Three streams were selected for this investigation to provide a range of intermittent and perennial flow conditions as well as a variety of terrain conditions. They include Cottonwood Creek (Fig. 4B), Pumphouse Spring near Indian Garden Creek, and Horn Creek (Fig. 4C). Cottonwood Creek was selected for its rockwall springs and variety of unconsolidated channel settings with gaining and losing reaches. Additionally, Cottonwood Creek is the location of numerous complementary and simultaneous studies of channel morphology, riparian habitat, geochemistry, and ground-water flow patterns by other researchers (John Rihs, hydrologist, Grand Canyon National Park, oral communication, 2004; Kobor 2004). Pumphouse Spring was selected because the source of the spring is from unconsolidated colluvial deposits. Cottonwood Creek and Pumphouse Spring both have streamflow-gaging stations available to provide data for ER sensor confirmation. Horn Creek was selected because it is near a trail crossing, has a bedrock setting, and is of particular interest to the NPS because of an abandoned uranium mine within the drainage. The physical characteristics of each field site were described with a spring classification system (Springer et al. in press).

The ER sensors were installed at eight sites within the three stream drainages (Table 1). Five of the sites were in the Cottonwood Creek drainage, one site was near Pumphouse Spring in the Garden Creek drainage, and two sites were in the Horn Creek drainage (Fig. 4C). Two ER sensors were installed at spring sources (Cottonwood Creek and Pumphouse Spring). Three ER sensors were installed in alluvial channels with associated riparian areas to determine periods of intermittent flow that could be related to evapotranspiration (Cottonwood Boulders, Cottonwood Monocline, and Cottonwood Tapeats). Three ER sensors were placed near the intersection of hiking trails and flowing streams to evaluate the intermittent or ephemeral nature of these sites (Cottonwood Tapeats, Horn Creek Right, and Horn Creek Left).

The data were collected from April 2003 through October 2004. For each site, the electrical resistance was measured at hourly intervals and stored in the datalogger. The dataloggers can store up to one year of hourly data before the data are overwritten. Site visits were made every other month to collect field data, download ER sensor data, ensure proper instrument operation, and visually monitor site conditions. Some sites had periodic gaps in data due to sensor loss from local storm events, failure to launch sensors after downloading data, or battery failure. ER sensors that failed or were washed out by runoff were replaced during site visits. Field data collected during each site visit included discharge, air temperature, and water temperature. During each site visit data were downloaded from ER, air-temperature, and water-temperature sensors. Precipitation data were downloaded from the rain gage near Cottonwood Creek (Fig. 4B). Data from the rain gage near Pumphouse Spring at Indian Gardens were collected by NPS (Fig. 4C).

Table 1. List of electrical resistance sensor data collection sites showing site name, latitude, longitude, altitude of site above sea level, and the range of flow measured during the study.

Site name	Latitude north (dd-mm-ss)	Longitude West (dd-mm-ss)	Altitude, (meters above sea level)	Data collection period	Range of measured flow, (L/min)
Cottonwood Spring	36 00 57	111 59 31	1,402	April 25, 2003 to October 3, 2004	0.29 to 0.59
Cottonwood Boulders	36 01 11	111 59 27	1,248.7	April 25, 2003 to October 3, 2004	0.23 to 2.80
Cottonwood Monocline	36 01 21	111 59 19	1,185.1	April 25, 2003 to October 3, 2004	0.00 to 18.93
Cottonwood Gage	36 01 25	111 59 18	1,172.1	April 25, 2003 to October 3, 2004	0.00 to 9.84
Cottonwood Tapeats	36 01 51	111 59 19	1,102.4	April 25, 2003 to October 3, 2004	0.00 to 45.20
Pumphouse Spring	36 04 39	112 07 31	1,194.8	April 19, 2003 to October 9, 2004	1.59 to 4.59
Horn Creek Right	36 05 03	112 08 35	1,084	April 19, 2003 to October 9, 2004	0.00 to 5.27
Horn Creek Left	36 05 03	112 08 36	1,084	April 19, 2003 to October 9, 2004	---

The Cottonwood Spring ER sensor was installed on a near vertical rock wall at the main spring near the head of the Cottonwood Creek drainage (Fig. 4B). Flow on the rock wall is diffuse and approximately less than 1 cm of depth. Water emerges from bedrock near the Redwall Limestone-Temple Butte Formation contact. This is a bedrock site, channel form is not affected by runoff events, and flow is spring dominated. The flow forcing mechanisms for this spring are gravity driven through fractures and bedding planes. Flow was perennial during this study.

The Cottonwood Boulders site was about 500 m downstream from Cottonwood Spring (Fig. 4B). The sensor was installed in a riparian area on the right edge of the stream channel, which is composed of thick unconsolidated sediments of cobble, boulder, and organic debris overlying the Bright Angel Shale. The spring at Cottonwood Boulders is a seepage or filtration spring, and water emerges from alluvium under a large boulder about two meters upstream from the ER sensor. Gravity is the flow forcing mechanism, driving water through unconsolidated sediments and possibly bedrock to the spring source. Base flow in Cottonwood Creek is spring dominated and was perennial during this study. The morphology of Cottonwood Creek is controlled by infrequent, high-magnitude runoff events. Air and water temperature data for Cottonwood Boulders (Fig. 8A) were representative of air- and water-temperature data collected for other perennial sites in this drainage during the study.

The Cottonwood Monocline site was about 200 m downstream from Cottonwood Boulders and about 100 m upstream from the USGS-NPS Cottonwood Spring streamflow-gaging station (Fig. 4B). The ER sensor was installed in a willow dominated reach of Cottonwood Creek near the rising limb of the Grandview-Phantom Monocline (Fig. 4A). Stream channel morphology in this reach is runoff dominated, and the bed material is composed of unconsolidated sediments of organic material and clay overlying Bright Angel Shale. Stream flow is spring dominated and was intermittent during this study.

The Cottonwood Gage ER sensor was at the USGS-NPS Cottonwood Spring streamflow gaging station (Fig. 4B). The sensor was installed close to the gage structure, in a cottonwood-willow riparian area. The bed material is unconsolidated sediments of organic material and clay overlying Bright Angel Shale. Channel morphology here is runoff dominated, and base flow is spring dominated and was intermittent during this study.

The Cottonwood Tapeats site was at the Tonto Trail crossing of Cottonwood Creek and about 1 km downstream from the USGS-NPS Cottonwood Spring streamflow-gaging station (Fig. 4B). The stream channel here is composed of a gravel veneer (less than approximately 0.5 m) overlying the Tapeats Sandstone. During the study, water intermittently emerged from channel alluvium about 10 m upstream from the ER sensor. The riparian habitat is sparse, and the channel morphology is runoff dominated. Flow is gravity driven and base flow is spring dominated and was intermittent during this study. Air- and water-temperature data for Cottonwood Tapeats (Fig. 8B) are representative of the air- and water-temperature data collected at other intermittent-stream and spring sites in this drainage.

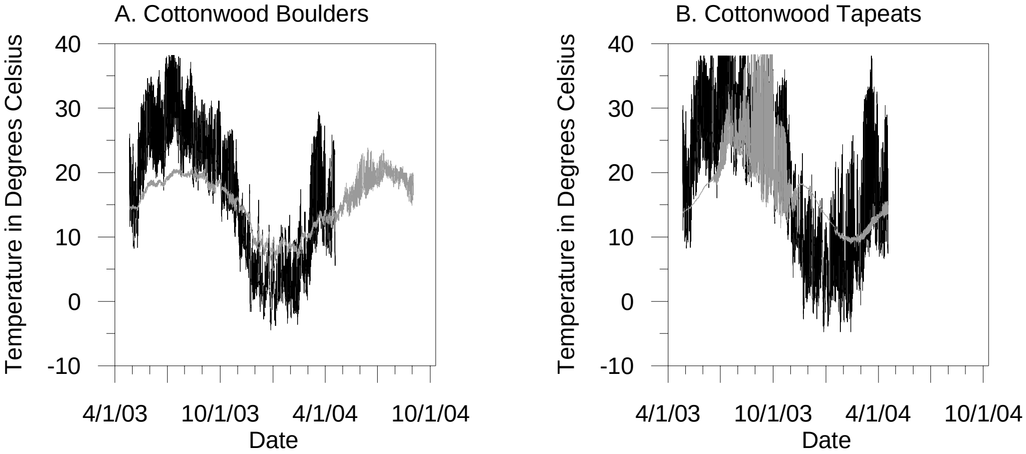

Figure 8. Air (black line) and water temperature (grey line) data: (A) Cottonwood Boulders; (B) Cottonwood Tapeats**.**

Pumphouse Spring is on the hillslope about 75 m east of Indian Gardens (Fig. 4C). The ER sensor was installed near the Bright Angel Fault about 1 m downstream from where water emerges from unconsolidated sediments of silty clay and fine sand near the base of two large cottonwood trees. Channel morphology and base flow are spring dominated at this site. Spring flow at this site is gravity driven and was perennial during this study.

Two ER sensors (Horn Creek Right and Horn Creek Left) were installed in Horn Creek about 20 m upstream from the Tonto Trail crossing where the stream splits around an island of unconsolidated sediments composed of gravel and sand (Fig. 4C). ER sensors were placed in the stream channels on both sides of the island. The stream channel in this reach is exposed bedrock of Bright Angel Shale. The morphology of Horn Creek is controlled by infrequent, high-magnitude runoff events. Base flow in this reach is spring dominated and was intermittent during this study.

ANALYSIS METHODS

Field data were evaluated using field observations, streamflow-gaging station data, local precipitation data, and air and water temperature data. Statistical analyses were performed on data from the drying period of the laboratory bench-top test by taking the mean and standard deviation of resistance.

ER sensor data from the three stream reaches were compared to climate and other hydrologic data to determine the timing of flow, locations of intermittent flow, and periods of increased evapotranspiration. Comparison of flow timing data between the different sites was used to define spatial trends and duration of spring flow. Precipitation and temperature data from local weather stations and data collection sites were compared with ER sensor data to determine if trends observed by ER sensors were due to runoff generated by local rainfall or to spring flow. Discharge data collected during this investigation were used to establish spring-flow responses to short-term climate fluctuations. Historical spring-flow measurements were used to augment these trend analyses.

RESULTS

Laboratory Study

In the controlled laboratory study of resistance, the ER sensors delineated the wetting period with an initial, instantaneous change in resistance from an air resistance value to a water resistance value (Fig. 9). Change in resistance was similar for each of the three sensors for each of the 20 trials for the wetting period. All three sensors recorded the maximum (dry) and minimum (wet) resistance between the dry and wet readings during the wetting period for each trial. There was minimal variability among the minimum resistances for each trial.

The ER sensors recorded varying patterns during periods immediately following cessation of flow (Fig. 9). The drying periods consisted of a sequence of instantaneous and delayed responses. The delayed response was frequently of a greater magnitude than the instantaneous response. Each sensor recorded an instantaneous change between 8,106.94 and 124,269.64 ohms after flow ceased (Figs. 9A, 9B, and 9C). This change in resistance was approximately two standard deviations less than the mean of the resistance for the drying period. The instantaneous drying response was the full range of recorded resistance for 17 percent of the trials, frequently occurring as long as 10 to 15 minutes after flow ceased.

Differences between the initiation of the wetting and drying periods seen in the laboratory study data were due to human error resulting from difficulties synchronizing flow timing precisely. For all laboratory study trials the ER sensors recorded distinct wet and dry periods. The differences in the drying period may be explained by factors that influence the ER sensors, such as the electrodes being moved during flow or disturbance that occurred when ER sensors were moved during data download.

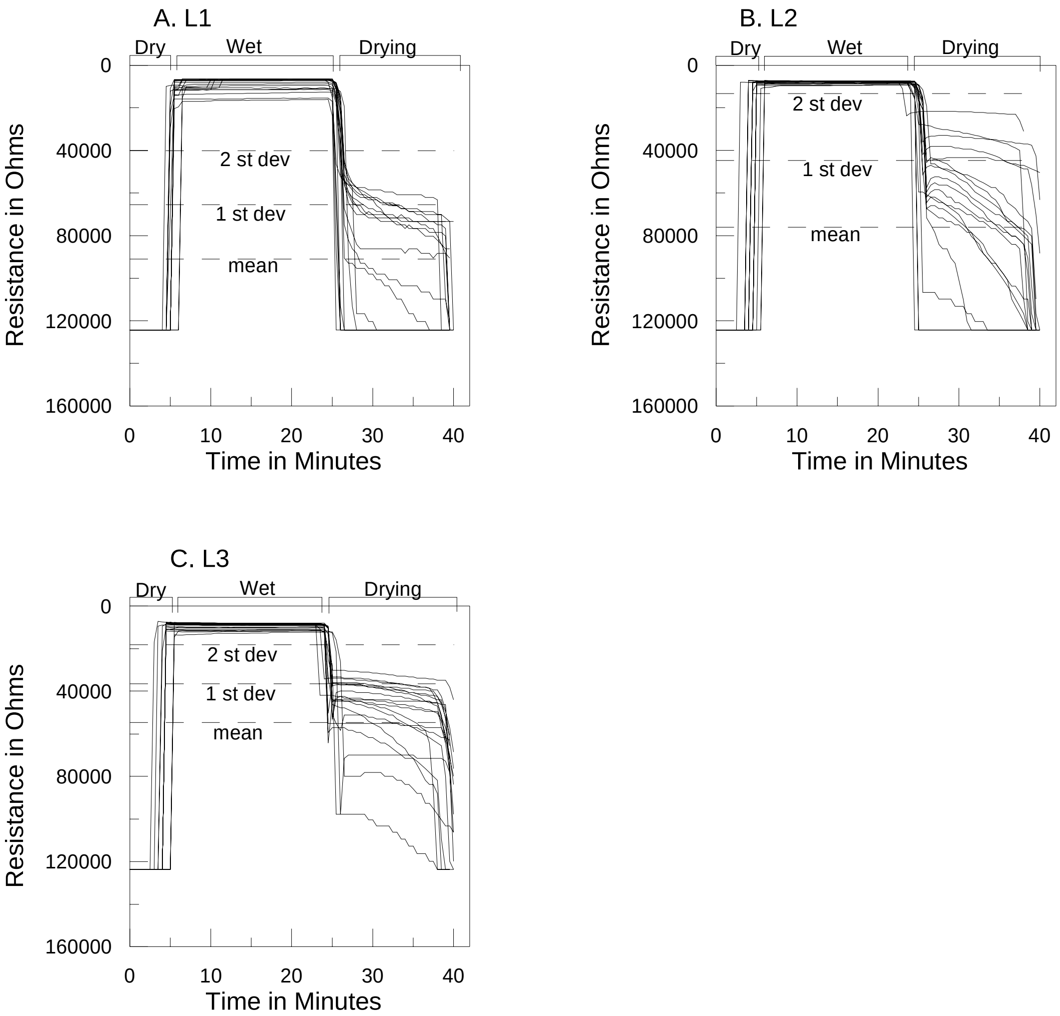

Figure 9. Electrical resistance sensor data for laboratory study: (A) L1; (B) L2; (C) L3. Dashed lines show mean and standard deviations for drying period.

Field Study

The accuracy of the ER sensors used in this study to document presence of flow was confirmed by other hydrologic data. During the study, Cottonwood Creek flowed intermittently with the exception of the Cottonwood Spring and Cottonwood Boulders sites, which were perennial (Figs. 10A and 10B). There was a dry period from late May to October 2003 in the lower stream reach at Cottonwood Monocline, Cottonwood Gage, and Cottonwood Tapeats (Figs. 10C - E) with short periods of flow due to precipitation (Fig. 11A). Constant flow occurred from October 2003 to April 2004 at all these sites. This was followed with a dry period from the beginning of May to July 2004 and constant flow from August to October 2004. Short periods of flow observed at some sites during the summers months coincided with local precipitation data (Fig. 11A) and were confirmed by stream-gage and water-temperature data (Figs. 8 and 11A). The perennial sites, Cottonwood Spring and Cottonwood Boulders, had decreased flow during the summer dry period (Figs. 10A and 10B).

The streamflow-gaging station at Pumphouse Wash Spring recorded perennial flow for the duration of the study; however, there were variations in electrical resistance at this site (Figs. 10F and 11B). Horn Creek ER sensor data indicated a dry period from May to September 2003 with a few short duration wet periods due to precipitation (Figs. 10G and 11B). Additionally, Horn Creek was dry for a brief period in November 2003.

In the Cottonwood Creek drainage, ER sensor data for all sites consistently corresponded with data from field observations, a streamflow-gaging station, and temperature sensors (Fig. 10). At Pumphouse Spring the ER sensor data also agreed with these traditional methods of determining presence or absence of flow. At Horn Creek, data from ER sensors in both the left and right channels were confirmed by field observations and complementary air- and water-temperature data (Figs. 19 and 20).

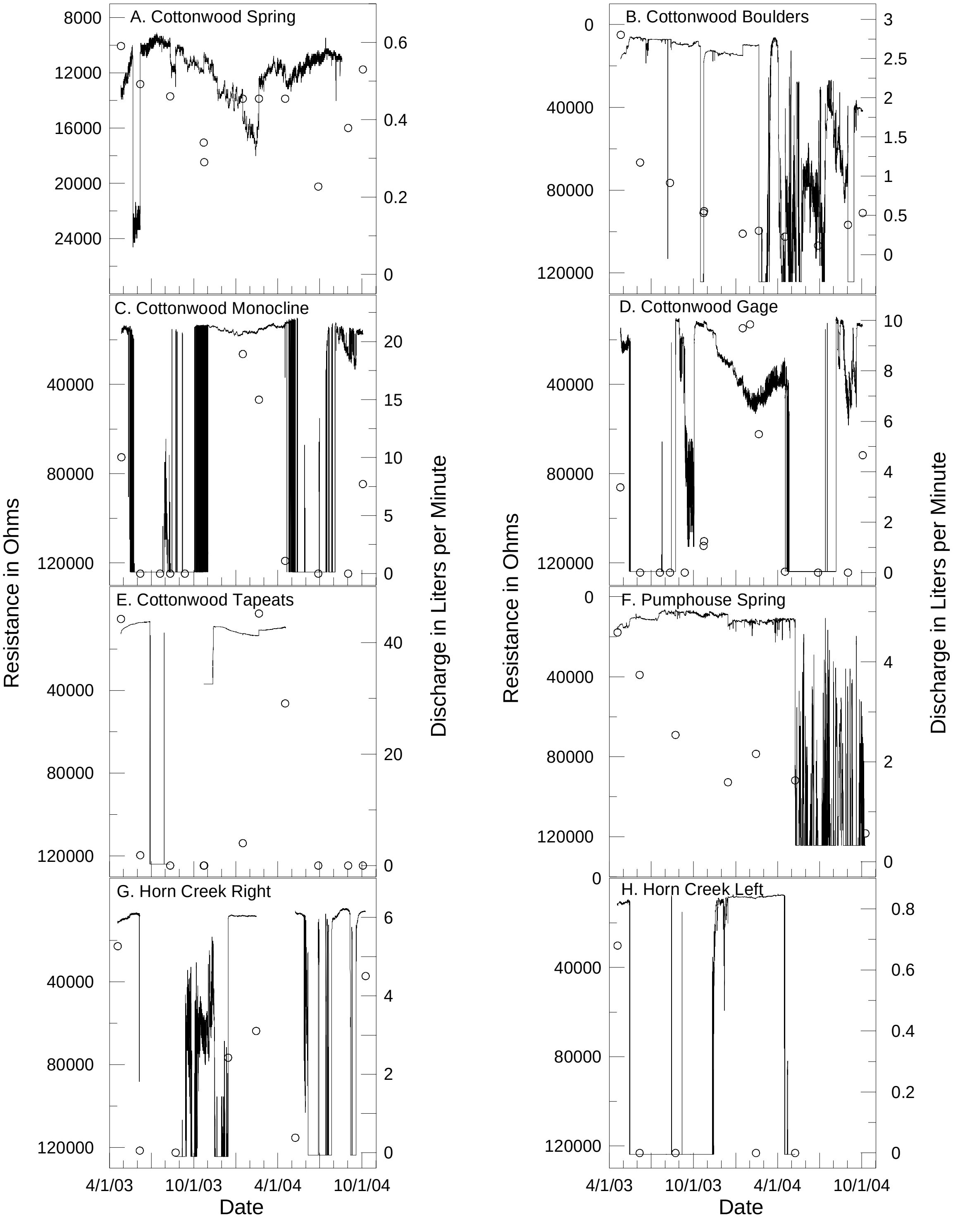

Figure 10. Electrical resistance and discharge data: (A) Cottonwood Spring; (B) Cottonwood Boulders; (C) Cottonwood Monocline; (D) Cottonwood Gage; (E) Cottonwood Tapeats; (F) Pumphouse Spring; (G) Horn Creek Right; (H) Horn Creek Left. Discharge measurements are shown by circles representing the flow at the time of measurement.

Field observations and ER sensor data indicated that sites in the lower reach of Cottonwood Creek were dry for periods during the study. The Cottonwood Monocline site had a dry period from May 24, 2003, to October 3, 2003 (Fig. 10C), with peaks in the ER sensor data coinciding with precipitation events recorded by the Cottonwood Creek rain gage (Fig. 11A). ER sensor data indicate that periods of diurnal flow occurred immediately before and after the dry period. Flow occurred every morning and ceased during the daylight hours as air temperatures rose. Periods of no flow were recorded every afternoon and evening when air temperatures and evapotranspiration rates were highest. Cottonwood Gage had a dry period from May 17 to August 23, 2003 (Fig. 10D), with the peaks attributed to precipitation.

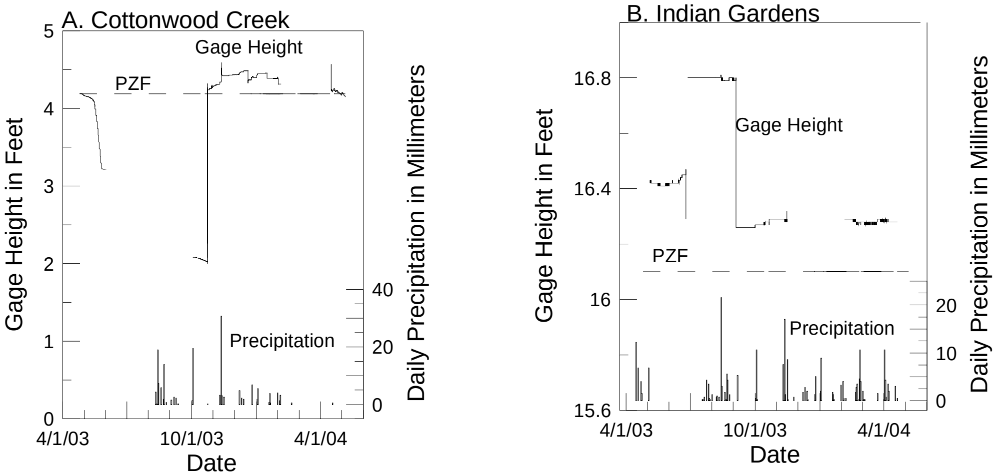

Figure 11. Streamflow-gaging station and precipitation data: (A) Cottonwood Creek; (B) Indian Gardens. Dashed line represents point of zero flow at the gages.

Electrical resistance sensor data, streamflow-gaging station data, and field observations indicate that the Pumphouse Spring site had perennial flow during the study (Fig. 10F). Although data were missing for part of the study period at Horn Creek, available data from both sensors document wet and dry periods that were confirmed by field observations during site visits. Interestingly, the ER sensor data at Horn Creek indicate periods when all the flow is in one channel and the other channel is dry (Fig. 10G).

DISCUSSION

The ER sensors clearly measured dry and wet periods at each study location; however, the individual response of ER sensors to site conditions varied. Periodic field observations and streamflow–gaging station data indicated that Cottonwood Spring, Cottonwood Boulders, and Pumphouse Spring had perennial flow during this study. These sites discharge water from the Redwall-Muav Limestone aquifer and are associated with the Grandview-Phantom Monocline and the Bright Angel Fault, which are major structural features that influence ground-water flow in the South Rim region (Fig. 4). The ER sensor data for these sites show a resistance response suggesting periods when these springs were dry (Figs. 10A, 10B, and 10F). This likely occurred during periods when the sensor became isolated from flow either during low-flow conditions or channel migration away from the sensor. Blasch et al. (2002) noted the advantage of installing the sensors below the sediment surface to use saturated conditions as a surrogate for surface flow; however, the limited thickness of alluvium or the coarse nature of the bed material (i.e. boulders) at many of the sites in this study precluded this methodology. Thus, site selection is important under these conditions.

At the bedrock wall of Cottonwood Spring, the maximum observed resistance values were a result of a broken wire on the ER sensor (Fig. 10A). After the sensor was replaced, the resistance data indicated perennial flow, in agreement with field observations during site visits. The ability of ER sensors to be installed in any orientation as long as the electrodes were in contact with the flow of water allowed the successful detection of flow at this site. Aerated conditions could preclude a continuous circuit, but at this site the conductivity of the water was sufficient for the sensor to record timing of flow. It is possible that the saturated surface of the rocks could have been sufficient to close an electrical circuit; however, this condition was not observed. The ER sensor electrodes were submerged by an estimated minimum of 0.3 cm of water on the bedrock surface at the time of all field observations. The laboratory experiment confirmed the abilities of the sensors to repeatedly record the presence of flow under low depth conditions. The diameter of the wire electrodes is less than 1 mm, leading to the hypothesize that detection of flow at depths lower than 0.3 cm is possible; however, this was not determined during this study.

Streamflow-timing data from the ER sensors were consistent with other hydrological data collected during this study. The ER sensors recorded similar dry periods to the streamflow–gaging stations (Fig. 11), although a complete comparison was not possible owing to missing gage data. Observations of flow or no flow at time of site visits confirmed the ER sensor data. ER sensor data were confirmed by both air- and water-temperature data. Recorded water temperatures increased and had greater daily fluctuations during periods of no flow than when flow was present, agreeing with ER sensor data for comparable periods. Air temperatures rose during dry periods detected by the ER sensors (Fig. 8). At some sites (Cottonwood Monocline, Cottonwood Gage, and Horn Creek) the absence of flow was probably due to high evapotranspiration rates during the summer. The channel in Cottonwood Creek flows over thick alluvium, and evapotranspiration rates are high during the summer (Michael Scott, Ecologist, USGS, oral commun., 2004). ER sensors at Horn Creek are far from the spring source, which makes this site more susceptible to evapotranspiration or infiltration. Water-temperature data collected simultaneously with ER data were useful for inferring flow during periods when resistance data were missing or not available (Fig. 12).

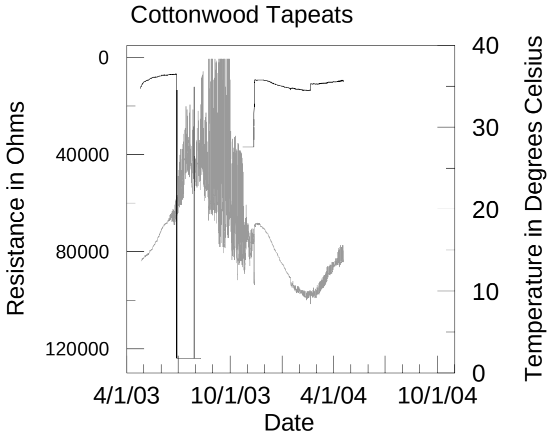

Figure 12. Electric resistance (black line) and water temperature (grey line) data at Cottonwood Tapeats.

The ER sensor data were used in combination with the stream- and rain-gage data to identify gaining, losing, perennial, and intermittent reaches along Cottonwood Creek (Fig. 4B). The timing information was used to create stream-reach hydrograph inputs that could be used as input for ground-water models. The combined influences of evapotranspiration from riparian areas, inflow from discharge points along the channel, losing reaches, and runoff tributaries resulted in a complex spring-flow timing hydrograph.

Sources of variability in the measured resistance due to electrical resistance sensors and field conditions existed for almost every site (Table 2). Variability due to site conditions occurred at 25 percent of the sites. Sources of variability included whether the wires were in air, water, or sediment, and what type of sediment was present. Different combinations of these factors occurred at each site. Cottonwood Spring was a rock wall and therefore did not have the variability source of sediment. The other sites had variable amounts of clay, sand, gravel, etc., depending on channel morphology and slope. Pumphouse Spring had continuous flow and was never exposed to air. It did, however, have variability introduced by sediment deposition.

Table 2. Sources of variability in electrical resistance sensor data and field conditions observed at each electrical resistance sensor location in the Grand Canyon. Site locations are shown on Figure 1.

Site	Sensor[1]	Site condition[2]
Cottonwood Spring	A,B,C	D,E
Cottonwood Boulders	A,B,C	D,E,F,G,H
Cottonwood Monocline	A,B,C	D,E,F,G,H
Cottonwood Gage	A,B,C	D,E,F,G,H
Cottonwood Tapeats	A,B,C	D,E,F,G,H
Pumphouse Spring	A,B,C	D,E,F,H
Horn Creek Right	A,B,C	D,E,F,G,H
Horn Creek Left	A,B,C	D,E,F,G,H

[1] Sensor variability identifier: (A) wire length, (B) separation distance of wires, (C) wire corrosion.

[2] Site condition variability identifier: (D) range of flow, (E) depth of flow, (F) sediment type, (G) wires in air or water, (H) wires in air or sediment.

The laboratory study indicated that response to wetting and drying in a system with only air and water occurred in less than 15 minutes, despite variability within the 15-minute interval of drying. If the field ER sensors had collected data on hourly intervals instead of 15-minute intervals, they might not have recorded the variability within the drying period. If a resistance sensor is located in sediments, or if it has corrosion or chemical precipitation on the wires from repeated wetting/drying, then the delay in recording an air resistance value may be longer than 15 minutes and may be observed over hourly or daily recording intervals of a drying period.

Although ER sensors were successful at determining the timing and locations of spring flow, technical modifications would improve the application tested in this study. Problems associated with equipment — frail wires, wire fouling, and unique individual sensor response — are well documented by Blasch et al. (2002) and were all encountered in this study. Newer sensor types that may solve many of these problems are now available. Development of an ER sensor with longer leads would allow installations that extend the width of a small stream channel or of a bedrock wall.

CONCLUSIONS

Electrical resistance sensors were installed at eight sites in three spring-fed tributaries along the South Rim of the Grand Canyon. Comparison of the ER sensor data with other hydrologic data confirmed the usefulness and versatility of the sensors for determining spring-flow timing in the dynamic hydrologic conditions of the Grand Canyon. Near perennial spring orifices, the sensors provided immense flexibility to record spring-flow timing in almost any orientation, location, or flow level. Field installed ER sensors and the laboratory experiment demonstrated that this technology is capable of monitoring timing of diffuse shallow flow on impervious surfaces. In the channels downstream of spring orifices, ER sensors identified changes of flow in multiple types of hydrological settings, including intermittent, gaining, and losing reaches. The ER sensors are appropriate for use as long as the users are aware of limitations such as the fragility of the exposed wires and detection errors due to low flow and debris build up.

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CHAPTER THREE

SENSOR VARIABILITY STUDY

Introduction

ER sensors were used during this study in a variety of field and laboratory settings to determine if the technology was appropriate to monitor spring flow timing in the conditions of the Grand Canyon. Field observations determined that the ER sensors experience many sources of variability in measured resistance due to the ER sensors and field conditions. Laboratory experiments were conducted to study the many sources of variability discussed in Chapter 2.

The bench-top laboratory experiment discussed in Chapter 2 examined resistance range versus wetness and sensor saturation. This previous laboratory study determined that the ER sensors recorded distinct wet and dry periods and that the drying periods consisted of a sequence of instantaneous and delayed responses. Differences in the drying period were also observed; however, the factors that influenced those differences were not determined. The sources of variability in electrical resistance sensor data and field conditions observed at each sensor location in the Grand Canyon were also discussed in Chapter 2 (Table 2). The sensor variability study discussed in this chapter further examined the sources of variability that affect the measured resistance during drying periods. The objective of the sensor variability study was to determine if sources of variability observed in the field were factors affecting the measured resistance data.

Laboratory methods

A bench-top laboratory experiment was conducted to test the ER sensors in a controlled environment, simulating diffuse spring flow along bedding planes or fractures. The bench-top experiment was conducted to determine if the sources of variability in the measured resistance were factors detected by the ER sensors during the inception of drying. The bench-top setting was the same as discussed in Chapter 2 (Fig. 6). Three ER sensors, named L1, L2, and L3, collected data at 30-second intervals. The sensors were allowed to equilibrate in dry conditions for 5 minutes prior to initiation of flow for 20 minutes. The ER sensors were allowed to collect resistance data for another 30 minutes after flow ceased to detect the drying period, which is a longer period of ER sensor observation than used during the laboratory study in Chapter 2. The purpose of the longer drying period was to determine if resistance would return to the maximum (air resistance) value. Base conditions include separation distance of wires, height of wires above datum, flow rate, and flow depth. Separation distance of wires was 7 mm for all trials except for the wire separation distance study. Heights of wires were 1 mm above the surface unless otherwise stated. Flow rate was consistent and flow depth was measured to be less than 0.3 cm during all trials.

Table 3. Sources of variability in electrical resistance sensor data and field conditions and the experiments used to test those sources in the controlled laboratory environment.

Sources of Variability	Experiment
Wire separation distance	Separation distances of 2 mm and 9 mm
Wire height above datum	Wires touching surface of datum and 1 mm above surface
Multiple drying periods	Water turned off and on at 5 minute intervals
Substrate	Wires exposed within sand

Many sources of variability have been hypothesized to be factors affecting measured resistance of the ER sensors (Table 2). Possible factors of sensor variability that were studied included separation distance of wires, height of wires, multiple drying periods, and sediment type (Table 3).

Wire Separation

One variable for consideration was the wire separation distance within the sensors. It was assumed that the sensors would not properly detect measured resistance if the wires were too close or too far apart. Wires of the ER sensors during this study were in contact with the datum surface. Wire separation distances of 2 mm and 9 mm were studied to determine if the separation distance of the wires affects measured resistance data (Fig. 13). The wire separation distance was also measured before and after each trial to determine if wire separation distance varied during flow.

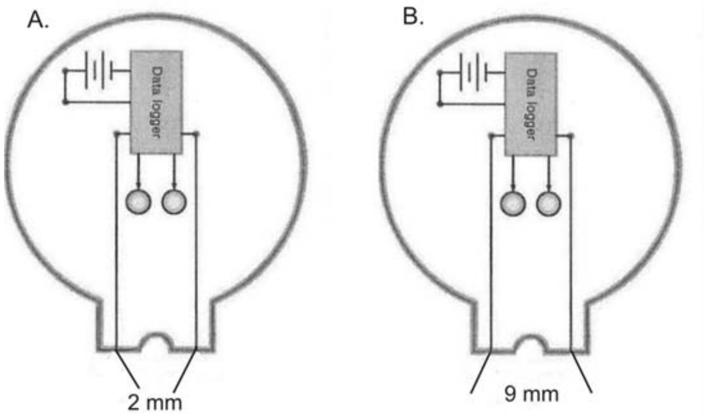

Figure 13. Schematic diagram of wire separation distance of ER sensors (A) 2 mm and (B) 9 mm.

Height of sensor above substrate surface

The height of the wires above the datum was studied with the wires touching the surface and with a height of 1 mm above the datum to determine which height resulted in less detection of surface saturation and better drying results (Fig. 14). Stage during the experiment was measured at ~ 1 mm, and therefore a wire height above 1 mm would result in the sensors not detecting the presence of flow due to the wires not having contact with the water.

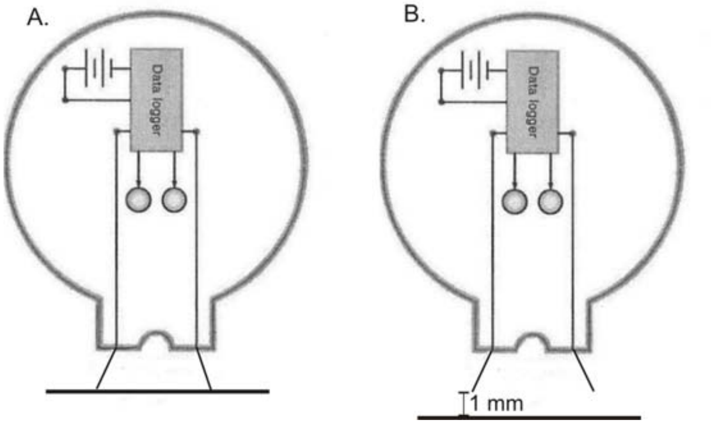

Figure 14. Schematic diagram of height of ER sensors above datum (A) wires touching surface and (B) wires 1 mm above surface (datum).

Multiple drying periods

Because previous field and laboratory experiments indicated that the sensors might have difficulty detecting multiple drying periods over short time scales, additional experiments were conducted. The flow of the water was turned off and on at five-minute intervals for 35 minutes to study the influence of multiple drying periods on the sensors.

Substrate

To determine if the substrate surrounding the sensors affected resistance, sand was used as a substrate to determine the affect on sensors. The sensor wires were completely buried in sand within a perforated container to allow flowing water. The sand was well-sorted, coarse-grained, quartz sand with a mean grain size of 2 mm.

Laboratory results

The controlled laboratory study of sensor variability determined that many of the variability sources were factors affecting the measured resistance data. Laboratory and field observations verified that the variability of the wires of the ER sensors exposed to air, water, or sediment were factors affecting measured resistance data. Sensors with wires exposed to air recorded the maximum resistance value of the sensor, indicating dry or drying periods. The detection of flow was indicated by the minimum resistance value. The same was true for wires exposed to sediment with the presence of flow. Sensors with wires in saturated sediment, however, may have a delayed response and not record a maximum resistance value during the drying period, which depends on the type and drying time of sediment.

Wire Separation

Separation distance of wires was determined to be a small factor of the ER sensors. The ER sensors recorded varying patterns during periods immediately following cessation of flow for all trials except for ER sensor L1. Wire separation distances of 2 mm and 9 mm produced minimal differences in drying results for L1 (Fig. 15). For ER sensor L2 and L3, the delayed response was frequently of greater magnitude for a wire separation distance of 9 mm than 2 mm. Wires with a separation distance of 2 mm resulted in a delayed response with a mean of 10 minutes after the cessation of flow to reach full resistance value. A wire separation distance of 9 mm resulted in a mean of 15 minutes delayed response to the full range of recorded resistance after flow ceased. Although the delayed responses were partly due to detection of surface saturation with the wires being in contact with the substrate surface, a wire separation distance of 9 mm had a longer response to the drying period. A wire separation distance of ~7 mm was used for the other laboratory studies, which produced similar results as a wire separation distance of 2 mm.

Measuring the wire separation distance before and after each trial determined that the wires separation distance did not vary during flow. This might, however, be affected by sediment and debris during a high flow event in a natural channel.

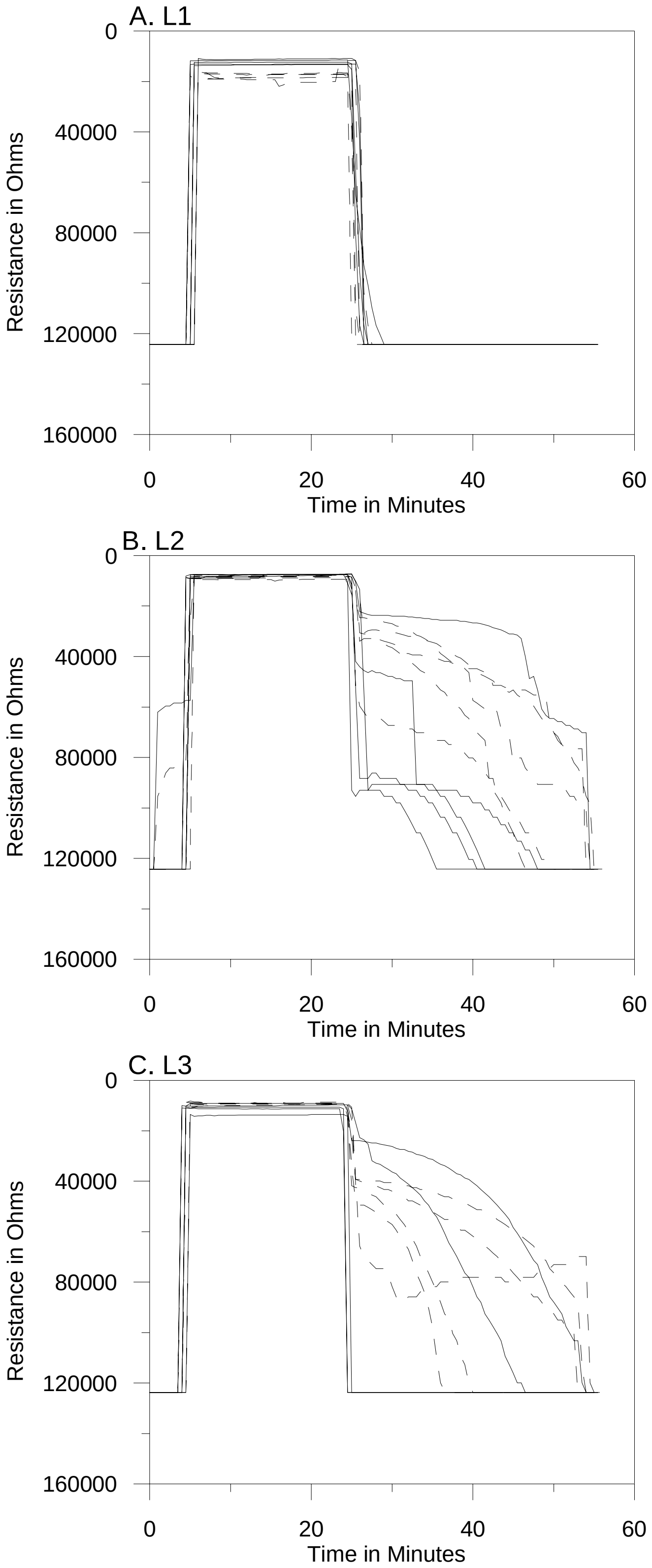

Figure 15. Laboratory study of electrical resistance sensor sensitivity for wire separation distances of 2 mm (solid lines) and 9 mm (dashed lines) for sensors (A) L1 (B) L2 and (C) L3.

Height of sensor above substrate surface

The height of the wires above a datum was determined to be a factor of variability of the ER sensors. Wires with a height of 1 mm above the substrate surface resulted in the instantaneous drying response to the full range of recorded resistance immediately following the cessation of flow (Fig. 16). Sensors with wires touching the substrate surface had drying periods consisting of a sequence of instantaneous and delayed responses following the cessation of flow. The delayed response was frequently of greater magnitude than the instantaneous response with a mean of 15 minutes to reach the full range of recorded resistance value. These delayed responses were likely due to the detection of surface saturation. Delayed responses were eliminated by using a wire height of 1 mm above the surface, which prevented the detection of surface saturation.

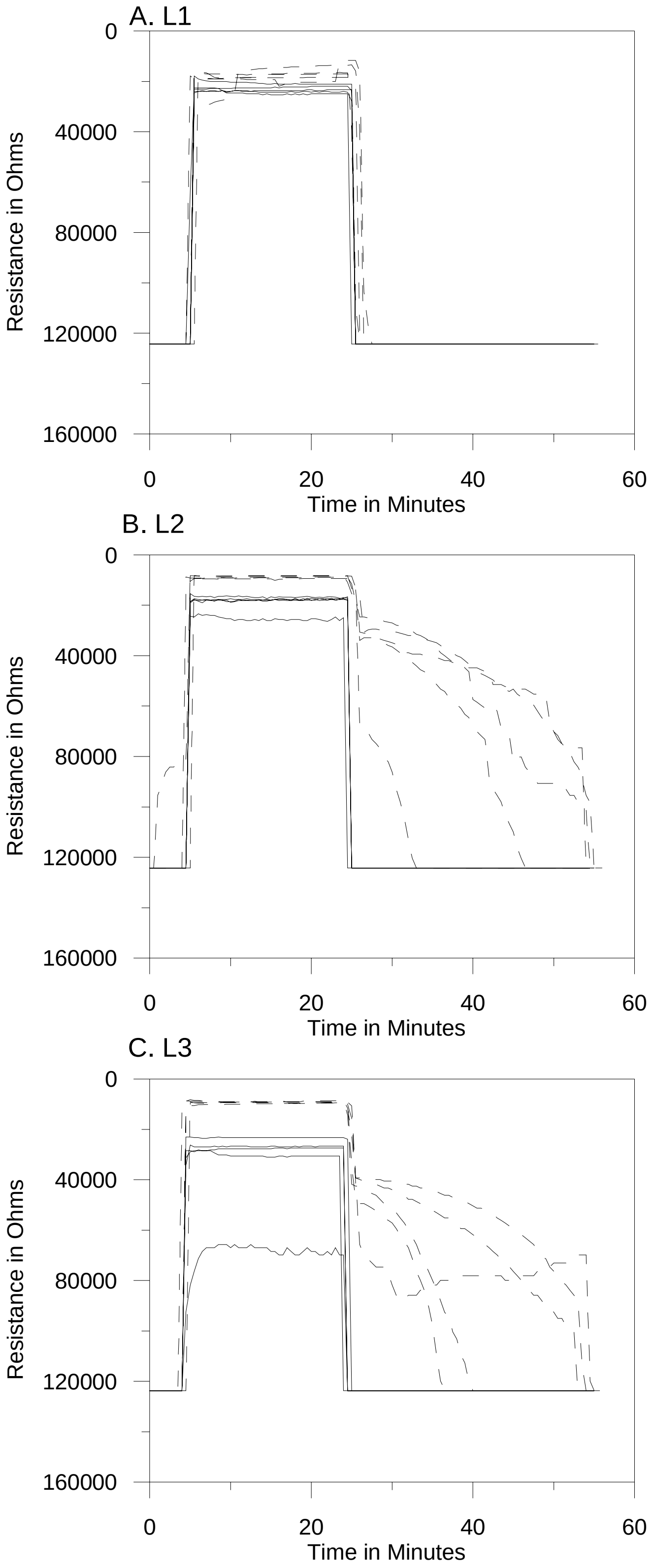

Figure 16. Laboratory study of electrical resistance sensor sensitivity for wire height of 1 mm above substrate surface (solid lines) and touching substrate surface (dashed lines) for sensors (A) L1 (B) L2 and (C) L3.

Multiple drying periods

Turning the water off and on during the experiment demonstrated that the sensors are capable of detecting multiple drying periods during a short time scale. The ER sensors delineated the wetting and drying periods with an initial instantaneous change in resistance (Fig. 17). The drying periods consistently changed from a water resistance value to an air resistance value. The wetting period however, had variability in resistance change and often did not record a minimum resistance value.

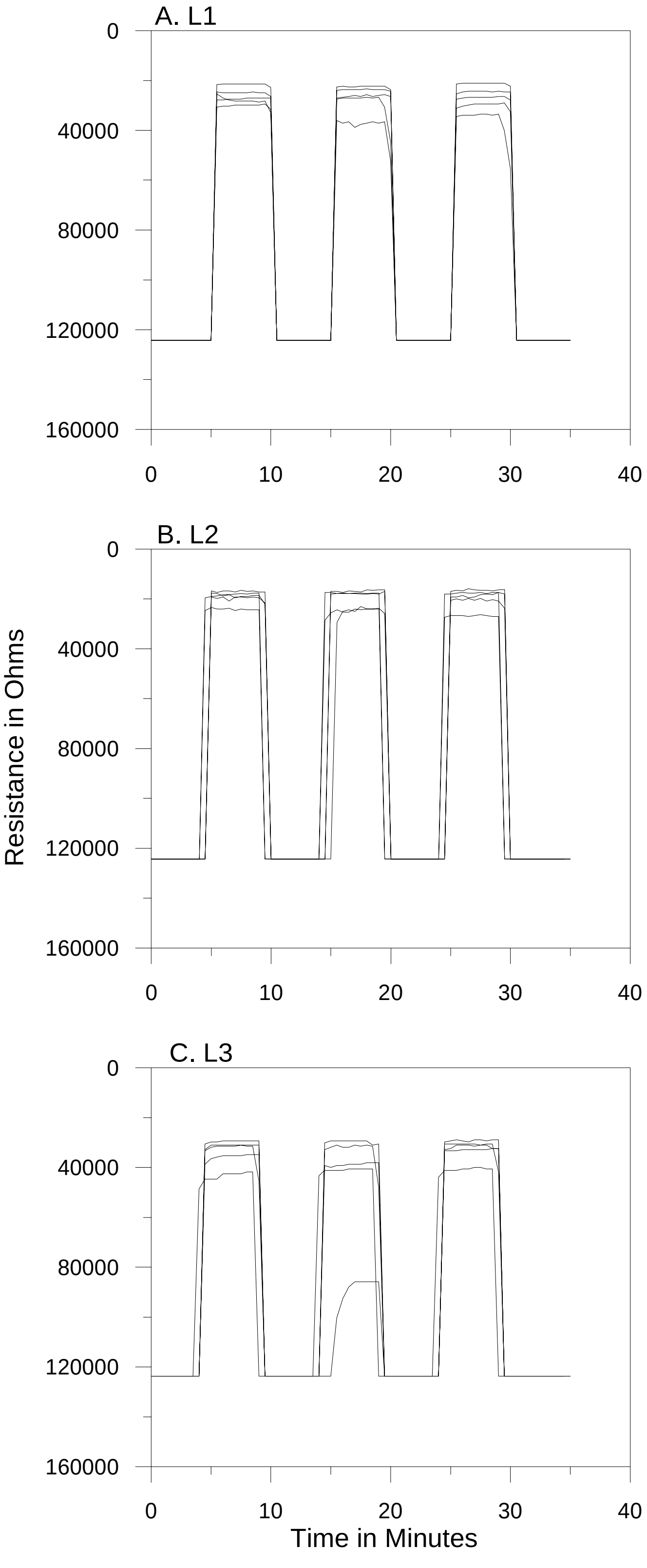

Figure 17. Laboratory study of electrical resistance sensor sensitivity for multiple drying periods for sensors (A) L1 (B) L2 and (C) L3.

Substrate

The type of substrate and its saturation was determined to be a major sensitivity factor of the ER sensors. It was determined that wires in saturated sand greatly affected the measured resistance data during the drying period and in some trials the detection of a drying period was absent (Fig. 18). Most of the laboratory experiments indicated that response to wetting and drying in a system with only air and water occurred in less than 15 minutes. This, however, was not observed in the field due to the ER sensors collecting data on hourly intervals. A delay occurs in recording an air resistance value if the wires are in sediment, which causes a drying period longer than 15 minutes and may be observed over hourly or daily intervals. Although sensors in saturated conditions result in delayed detection of cessation of flow, sensors in saturated conditions can be used as a surrogate for surface flow. Although not tested in the laboratory study, the presence of clay would cause a longer delay to reach the maximum resistance value after the cessation of flow due to longer dewatering conditions of clay.

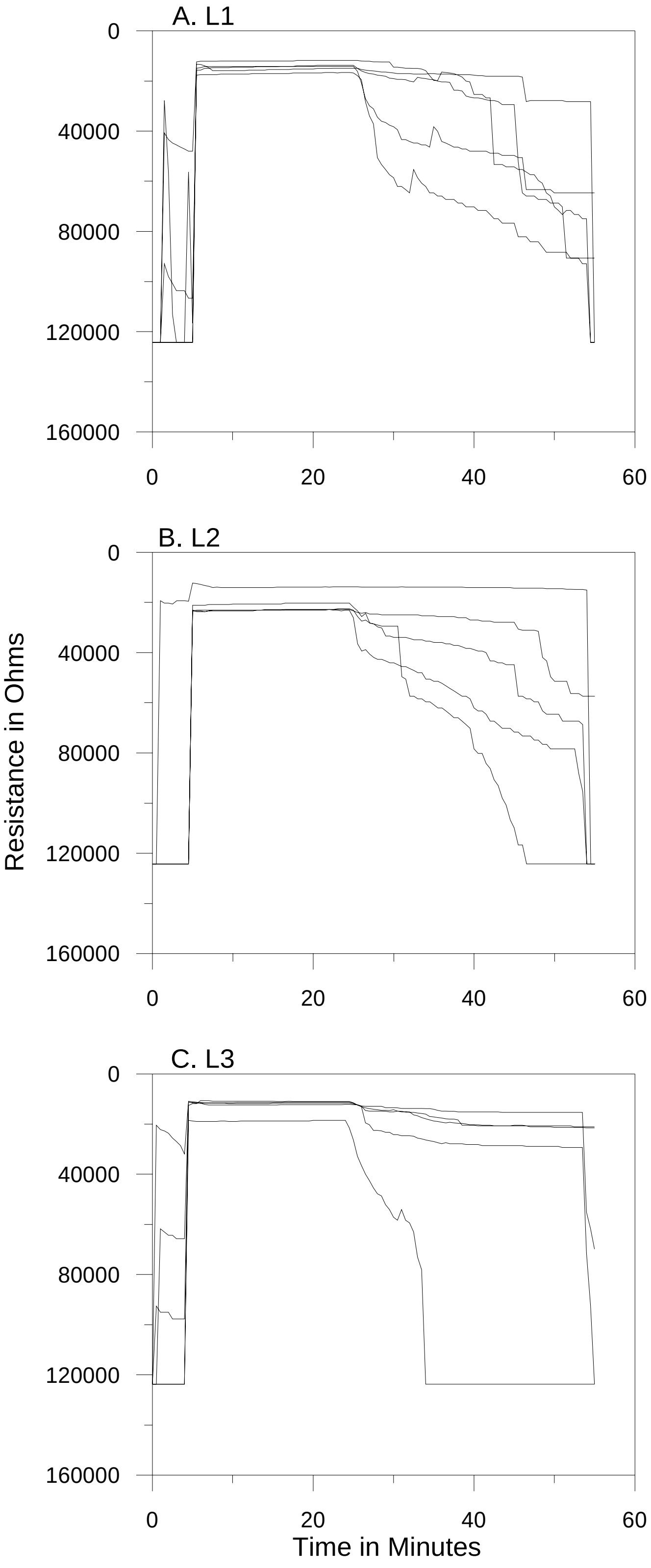

Figure 18. Laboratory study of electrical resistance sensor sensitivity for sediment with sand as the substrate for sensors (A) L1 (B) L2 and (C) L3.

Summary

It was observed that different combinations of sensor variability occurred at each site in the Grand Canyon during this study (Table 2). The controlled laboratory study helped determine which of those sources of variability were factors affecting measured resistance (Table 4). Each site experienced different combinations of the variability of wires exposed to air, water, or sediment. Cottonwood Spring, Cottonwood Boulders, and Pumphouse Spring were perennial and did not have the variability of the wires exposed to air.

Table 4. Sources of variability in electrical resistance sensor data and field conditions determined to be factors at each electrical resistance sensor location in the Grand Canyon. Site locations are shown on Figure 1.

Site	Sources of Variability[1]
Cottonwood Spring	A,B,E,F
Cottonwood Boulders	A,B,C,D,E,F,H
Cottonwood Monocline	A,B,C,D,E,F,G,H
Cottonwood Gage	A,B,C,D,E,F,G,H
Cottonwood Tapeats	A,B,C,D,E,F,G,H
Pumphouse Spring	A,B,D,E,F,H
Horn Creek Right	A,B,C,D,E,F,G,H
Horn Creek Left	A,B,C,D,E,F,G,H

[1] Sensor variability identifier: (A) separation distance of wires, (B) height of wires, (C) multiple drying periods, (D) substrate, (E) range of flow, (F) depth of flow, (G) wires in air or water, (H) wires in air or sediment.

The separation distances of wires were determined to have minimal affect on measured resistance data. The laboratory study determined that wires placed 9 mm apart had a greater delay to drying than a wire separation distance of 2 mm. Wire separation distance of field ER sensors was not measured during the study, however, was estimated to be about 7 mm, eliminating it as a source of variability in the field.

The height of the sensor above the substrate surface was a factor for every site in the Grand Canyon. The height of the wires, however, was not a consideration during installation of the sensors. Wire height was determined to be a factor during the laboratory study and explains some of the variability of the measured resistance data from the field sites. Many of the sites experienced a delayed response to drying after the cessation of flow due to the detection of surface saturation.

Many of the sites experienced multiple periods of wetting and drying due to seasonal and diurnal variations in evapotranspiration rates. Multiple periods of wetting and drying during a short time scale may have not been detected in the field due to the ER sensors collecting data at hourly intervals. The exceptions to this source of variability were the Cottonwood Springs, Cottonwood Boulders, and Pumphouse Spring ER sensors that were in reaches of stream, which had continuous (perennial) flow during the study (Fig. 1).

Substrate sediment type was determined to be a source of variability experienced at every ER sensor site with the exception of Cottonwood Spring. Cottonwood Spring had perennial flow on a vertical rock wall and therefore did not have variability due to sediment. ER sensors exposed to substrate may have delayed the detection of the drying periods until the sediment dried out exposing the wires to air. This time lag is a function of hydraulic conductivity of the sediments, pore-water redistribution at depth, and ET demands.

Pumphouse Spring consisted of unconsolidated substrate sediments of silty clay and fine sand. This type of substrate sediment caused high-saturated conditions, which may have affected the measured resistance data by causing a time lag to reach the air resistance value. Cottonwood Boulders substrate sediments were cobble, boulder, and organic debris overlying the Bright Angel Shale. The sensors, therefore, experienced moderate saturated conditions and better flow detection. The buildup of substrate sediment and debris around the sensor may have caused the flow of water to be diverted away from the sensor. However, saturated conditions of substrate sediment caused the sensor to continue detecting the presence of flow.

Cottonwood Monocline and Cottonwood Gage sites had unconsolidated substrate sediments of organic material and clay. The accumulation of clay around the sensor during the study may have resulted in high-saturated conditions causing poor drying results. The channel substrate sediment type at Cottonwood Tapeats had gravel veneer (less than approximately 0.5 m). This gravel veneer combined with very little sand or clay resulted in less saturated conditions and a good detection of drying periods. The two sites at Horn Creek had unconsolidated substrate sediments of gravel and sand. As the lab experiment determined, sand causes high-saturated conditions and poor drying results. The sites at Horn Creek, therefore, most likely did not accurately detect drying periods by having delayed responses due to saturated sediment.

Variable depth and range of flow were sources of variability experienced at each site. Quantity of discharge and depth of flow can range over several orders of magnitude consisting of high magnitude runoff events and diffuse flow with depths less than 1 cm. Laboratory results determined that the ER sensors were successfully able to detect a stage of 1 mm as well as detect the presence of small and large ranges of flow.

CHAPTER FOUR

CONCLUSIONS

Summary

It has been established from previous studies that the springs along the South Rim of the Grand Canyon are threatened due to being susceptible to drought and groundwater pumping south of the park (Errol L. Montgomery & Associates Inc., 1998; Kessler, 2002; Kobor, 2004). Electrical resistance sensors were installed at eight sites in three spring-fed tributaries along the South Rim of the Grand Canyon to determine timing of flow. Repeated field observations of stream discharge, air and water temperature, and flow timing data allowed for the characterization of the seasonal range of spring flow timing. Due to the hydrogeological and topographical similarity of the three spring-fed tributaries from this investigation to many of the other South Rim springs, the results of this study are likely applicable to many other springs within the Grand Canyon.

Electrical resistance data were compared with other hydrologic data to confirm the usefulness and versatility of the sensors for determining spring-flow timing in the dynamic hydrologic conditions of the Grand Canyon. The ER sensors are advantageous over traditional streamflow-gaging and monitoring techniques, which are not suitable for the conditions found in the spring-fed tributaries along the South Rim, and require less interpretation than temperature based methods. ER sensors installed in the field and laboratory experiments demonstrated that this technology is capable of monitoring timing of diffuse shallow flow on impervious surfaces. The ER sensors identified changes in flow in multiple types of hydrological settings, including intermittent, gaining, and losing reaches. Data indicated that the timing of low at intermittent sites had a dry period from late May to October 2003 with short periods of flow due to precipitation. The peaks in the resistance data coincided with precipitation events recorded by rain gages. Continuous flow occurred from late October 2003 to April 2004. This was followed by a dry period beginning of May to July 2004 and constant flow August to October 2004. The perennial sites had decreased flow during the summer dry period. The ER sensors also detected periods of diurnal flow that occurred before and after the dry periods, where flow occurred in the morning and ceased during the afternoon and evening when air temperatures and evapotranspiration rates were highest.

Knowledge of which reaches are losing flow upstream of those that are gaining is important for accurately recording where riparian areas are most at risk due to limited water availability. One measurement station in a channel, such as a gaging station, is not sufficient to determine the water availability for the entire length of channel. It cannot be assumed that a downstream reach is dry just because an upstream reach is dry. If wireless technology were coupled with these sensors, it would be possible for the National Park to be able to accurately advise backcountry hikers of the availability of drinking water where hiking trails cross these spring-fed tributaries.

A bench-top laboratory experiment was conducted to study the many sources of ER sensor variability observed in the field. It was determined that many factors influence the measured resistance data. Saturated sediment was determined to be the most sensitive factor of the ER sensors, causing a delay in the detection of the drying period. It was determined that a wire height of 1 mm above the substrate surface allows better drying results due to less surface saturation. The ER sensors are appropriate for use as long as the users are aware of the limitations and sources of variability involved. The ER sensors provide a new method for continuous monitoring of spring-flow timing from previously immeasurable sites.

Many previous studies show trends of decreasing discharge at gaging stations in the Grand Canyon since at least 1994. The discharge trends may be the result of groundwater abstraction or the result of decreases in precipitation associated with current drought conditions leading to changes in recharge to the regional aquifer. Further monitoring of springs in the Grand Canyon is needed to determine the cause of these decreases. Continuous monitoring of springs, precipitation rates, and groundwater abstraction rates is vital to properly manage the spring-aquifer system so that these important resources may be preserved for future generations.

Recommendations for Future Deployment

Site-specific conditions that should be considered for future sensor monitoring sites include bedrock substrate and any other kinds of substrates as long as the sensor is installed properly above the substrate surface to determine timing of flow. The sensors are more accurate when placed above the substrate surface to avoid the influence of sediments and to reduce analysis requirements. The sensors can also be used to identify the occurrence of saturated soil conditions if installed below the substrate surface. The sensors have been proven to work in any type of spring or channel setting. Another possible use of the ER sensors is to detect overland runoff.

Sites within the Grand Canyon with high magnitudes of flow (Cottonwood Monocline, Cottonwood Gage, Cottonwood Tapeats, and Horn Creek) due to local storms resulted in loss of sensors and the build up of sediment and debris, causing delays in the detection of drying periods due to saturated conditions. The installation method should be modified to secure sensors in areas with high magnitudes of flow to prevent loss of sensors and valuable data and reduce the amount of build up.

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APPENDIX A

Stream discharge measurements at Cottonwood Springs, Pumphouse Spring, and Horn Creek.

Table 5: Stream discharge measurements at Cottonwood Springs ER sensor sites. Measurements are in L/min. See figure 1 for locations.

Site Name	Cottonwood Spring	Cottonwood Boulders	Cottonwood Monocline	Cottonwood Gage	Cottonwood Tapeats
4/26/2003	0.59	2.80	10.03	3.38	44.23
6/7/2003	0.49	1.17	-	0.00	1.85
8/11/2003	0.46	0.91	0.00	0.00	0.00
10/23/2003	0.34	0.53	-	1.06	0.00
10/24/2003	0.29	0.55	1.78	1.25	0.00
1/16/2004	0.45	0.26	18.93	9.69	4.01
2/20/2004	0.45	0.30	14.99	5.49	40.28
4/17/2004	0.45	0.23	1.10	0.04	29.07
6/28/2004	0.23	0.11	0.00	0.00	0.00
9/1/2004	0.38	0.38	0.00	0.00	0.00
10/3/2004	0.53	0.53	7.72	4.66	0.00

Table 6: Stream discharge measurements at Pumphouse Spring and Horn Creek ER sensor sites. Measurements are in L/min. See figure 1 for locations.

Site Name	Pumphouse Spring	Horn Creek Right	Horn Creek Left
4/19/2003	4.59	5.27	0.68
6/6/2003	3.74	0.05	0.00
8/23/2003	2.54	0.00	0.00
12/15/2003	1.59	2.42	-
2/14/2004	2.16	3.10	-
5/9/2004	1.63	0.38	0.00
10/9/2004	0.57	4.50	0.00

APPENDIX B

Air and water temperature data at Cottonwood Springs, Pumphouse Spring, and Horn Creek ER sensor sites.

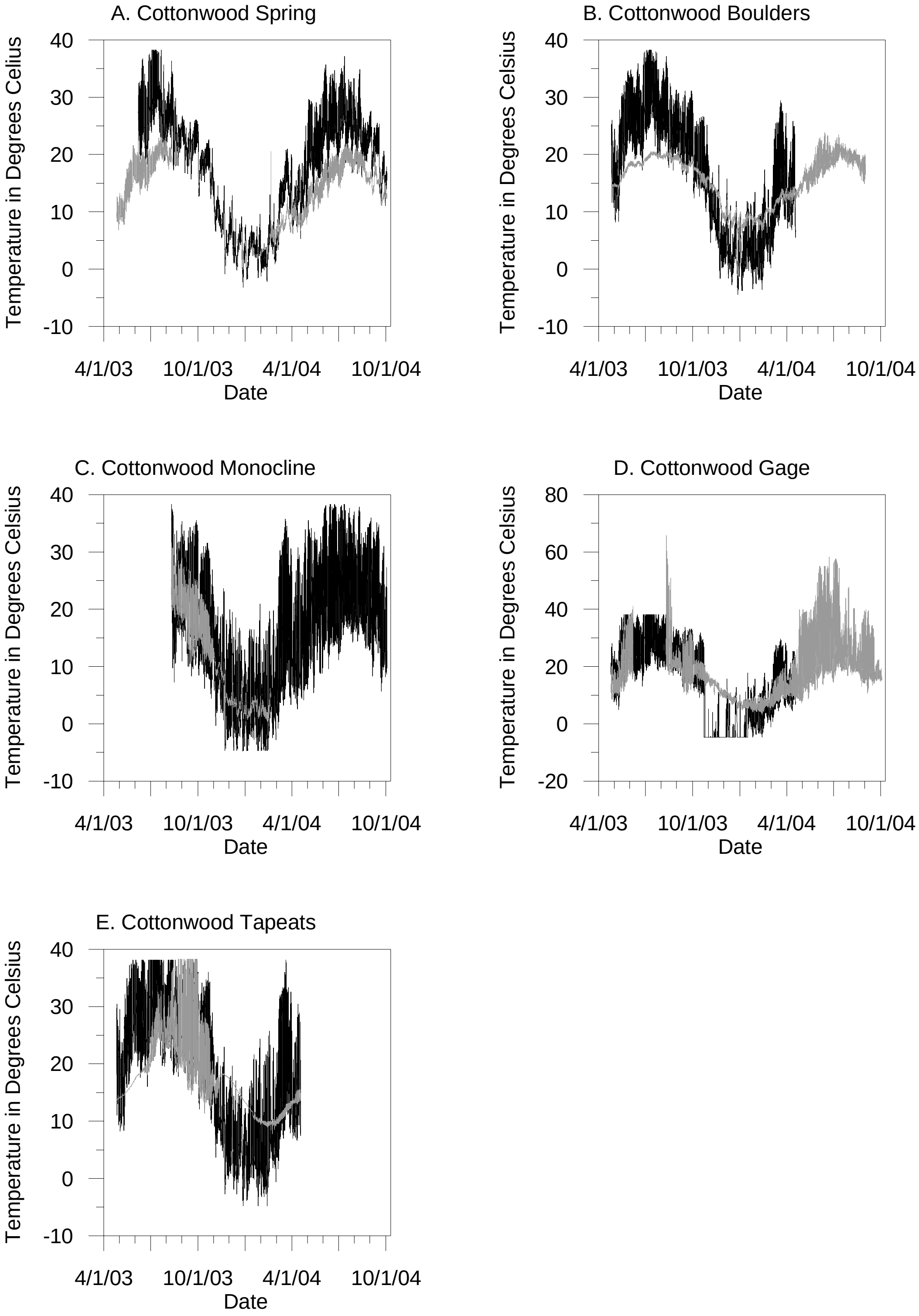

Figure 19. Air (black line) and water temperature (grey line) data for Cottonwood (A) Cottonwood Spring (B) Cottonwood Boulders (C) Cottonwood Monocline (D) Cottonwood Gage and (E) Cottonwood Tapeats.

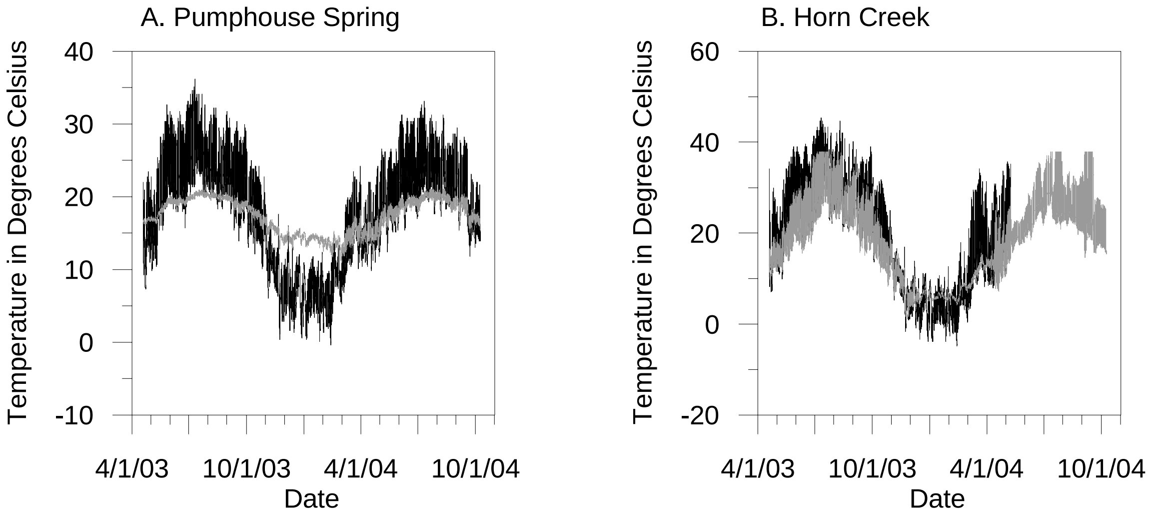

Figure 20. Air (black line) and water temperature (grey line) data for (A) Pumphouse Spring and (B) Horn Creek.