SHORT COMMUNICATION

ELECTRICAL RESISTANCE SENSOR ARRAYS AS A MEANS TO QUANTIFY LONGITUDINAL CONNECTIVITY OF RIVERS

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ABSTRACT

Electrical resistance sensors are used as a novel approach to quantify streamflow continuity (continuous through time) and longitudinal connectivity (continuous through space) across watersheds in south-eastern Arizona, USA. We demonstrate this approach by reporting on a spatial array of 21 sensors installed in streams supporting naturally perennial, intermittent and ephemeral flow on the US Army Garrison, Fort Huachuca. Continuity and connectivity were quantified based on a strict interpretation of continuous flow at an individual sensor (strict continuity) or simultaneous streamflow at multiple sensors (strict connectivity). In addition, we evaluated continuity and connectivity to include periods (<48 h) when in-channel refuges may exist between streamflow events (refuge-maintained continuity and connectivity). Continuous streamflow in intermittent reaches accounted for 34% of the 121-day monitoring period (15 April–13 August 2010) and 28% of the summer monsoon period (1 July–13 August 2010). Streamflow in ephemeral reaches accounted for 1.5% and 2.3% of the entire monitoring and monsoon period, respectively. Canyon-wide longitudinal connectivity was rare (<1%); however, substantial longitudinal connection occurred along extensive portions of individual canyons. The refuge-maintained criteria increased continuity 2–8%, with less influence on connectivity (e.g. <3% increase in only some portions of canyons). Despite this result, the refuge-maintained concept remains important because of its broad applicability to refuge persistence across aquatic species and hydro-climatic regimes. The approach presented in this study supports the growing scientific research on the influence of longitudinal hydrologic connectivity on population dynamics and ecological processes in dendritic river networks. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: riverscape; hydrological connectivity; streamflow timing; streamflow regime; desert streams; dams; fragmentation

Received 18 March 2011; Revised 29 April 2011; Accepted 1 June 2011

INTRODUCTION

Hydrological connectivity refers to the water-mediated transfer of matter, energy and/or organisms within or between elements of the hydrologic cycle (Pringle, 2003). Operating in longitudinal, lateral and vertical dimensions, connectivity is a fundamental property of aquatic ecosystems (Ward and Stanford, 1989; Tockner and Stanford, 2002; Ward et al., 2002; Freeman et al., 2007). In intermittent and ephemeral streams, hydrological connectivity exerts particular control because drying and wetting events shape the spatiotemporal patchwork and linkages of habitats over time (Bunn et al., 2006). Drought conditions can interrupt longitudinal connectivity (e.g. surface water connections in the upstream and downstream direction), resulting in periods of temporary habitat loss and limiting dispersal of obligatory aquatic species and downstream transport of matter and energy (Dodds et al., 2004; Sponseller and Fisher, 2006; Doering et al., 2007; Nadeau and Rains, 2007). Consequently, longitudinal connectivity, notably the shifting spatiotemporal character between the flow presence and absence, can define the ecological structure and function of lotic ecosystems (Nilsson et al., 1989; Larned et al., 2009; Arscott et al., 2010).

Artificial interruption of longitudinal connectivity from the burial of headwater streams (Freeman et al., 2007), physical barriers such as dams and diversions (Nilsson et al., 2005) or dewatering associated with groundwater pumping (Falke et al., 2010) can result in temporary or permanent fragmentation of aquatic habitats (Fullerton et al., 2010). For already naturally fragmented dryland streams in arid and semi-arid systems, there is concern of further decreases in connectivity, particularly as a result of more frequent and severe droughts associated with forecasted changes in climate (Seager et al., 2007; Cayan et al., 2010) and greater human appropriation of freshwater resources (Sabo et al., 2010). Increasing temperatures and changes in precipitation patterns could alter flow timing, potentially increasing streamflow intermittency, with subsequent impacts to aquatic biota (Levick et al., 2008; Sheldon et al., 2010).

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Quantifying the considerable spatial and temporal variability of streamflow patterns that determines connectivity remains an ongoing challenge despite its established importance on ecological processes in river systems (Fullerton et al., 2010; Larned et al., 2010). The need to develop metrics describing longitudinal connectivity at broad spatial scales has become more pressing with increased research that focuses on riverscape patterns and processes (Fausch et al., 2002). Currently, metrics are limited and hindered by the substantial effort and monetary cost required to implement monitoring programmes across a channel network. Some methods such as field mapping the contraction and expansion of surface water in streams can effectively quantify longitudinal connectivity (e.g. Hunter et al., 2005; Larned et al., 2010; Turner and Richter, 2011). However, their accuracy is limited by the frequency of field visits, which can be time consuming, requiring the work of many individuals or dedicated work of a few, depending on the spatial extent of the area of interest. Repeat satellite imagery is applicable to areas of large spatial extent such as floodplain rivers (e.g. Puckridge et al., 2000, 2010), but may not be useful in smaller streams as a result of spatial resolution constraints. Other methods, including thermograph interpretation of field-deployed temperature sensors throughout a channel network, may not have a temporal resolution sufficient to capture shorter duration (<24 h) streamflow events typical of intermittent and ephemeral stream reaches (Constantz et al., 2001; Blasch et al., 2004; Gungle, 2006). Consequently, current models (hydrologic, hydraulic and statistical) would benefit from near-continuous, fine-scale measurements of flow timing and longitudinal connectivity at riverscape scales.

A technique using electrical resistance (ER) sensors provides a novel opportunity for quantifying network-scale longitudinal connectivity that requires substantially less effort than field mapping while exceeding the spatial and temporal resolution of the thermograph interpretation and modelling methods. Temperature loggers (TidBit v2, Onset Computer Corporation, Bourne, MA, USA) are customized to measure relative conductivity (the inverse to resistance) as a proxy for streamflow presence (Blasch et al., 2002; Goulsbra et al., 2009). Electrical conductivity increases in wet sediments relative to dry sediments, and abrupt increases in relative conductivity values indicate the onset of streamflow (Figure 1). The changes in relative conductivity values are more marked and therefore easier to confidently interpret compared to temperature fluctuations in the thermograph-based approaches with no time delay between the signal of the surface water sensor and the true timing of streamflow. We demonstrate the ER sensors’ utility to measure flow timing and hence, longitudinal connectivity across a riversine network characterized by clear transitions between perennial, intermittent and ephemeral reaches. This research is part of a larger project investigating the role of longitudinal connectivity on population landscape genetics of amphibian and aquatic macroinvertebrate species in desert systems.

**STUDY SITE**

Our study site is the US Army Garrison, Fort Huachuca and surrounding areas along the eastern flank of the Huachuca Mountain Range within the Upper San Pedro River Basin, south-eastern Arizona, USA (Figure 2). The Huachuca Mountains are part of the Madrean Sky Island Region, a term illustrating the region’s distinct biogeography, which is supported by the complex topography of isolated mountain ranges (maximum elevations of 1830 to 3350 m) that are separated by arid valleys. The climate in the Huachuca Mountains is semi-arid; mean annual precipitation is approximately 40 cm with 50–60% occurring as high-intensity, local convective thunderstorms associated with the North American monsoon season. Winter precipitation typically resulting from North Pacific frontal storms accounts for 21–35% of the annual precipitation. Frontal storms tend to be of broader spatial extent producing rain events of longer duration and less intensity (Ely et al., 1993), which turns to snow at higher elevations.

The region’s climate and topographic complexity sustains a sharp geomorphic and hydrologic gradient. The canyons that comprise the Huachuca Mountains are composed of granite, limestone and other sedimentary geologic units.
Stream channel morphology is characterized by cascade and bedrock reaches in the upper canyons draining the mountain front, which give way to step-pool, plane bed and pool-riffle channel forms downstream. Channel bed substrates range from large cobble and boulder in the upper reaches fining downstream to primarily sand and gravel. Calcium carbonate deposition has armoured the channel bed or contributed to a travertine step-pool morphology in some reaches both within and downstream of where the streams flow through the limestone unit. Wetlands located along streams in some of the canyons contribute silt, clay and fine organic debris, which deposit in low-gradient reaches that are interspersed among steeper reaches. Extending beyond the mountain front onto the valley floor, channels are primarily sand-bedded and ephemeral.

**APPROACH**

We installed 44 ER sensors at approximately 2-km intervals throughout eight canyons primarily on Fort Huachuca (Figure 2). The relatively systematic spatial array provides broad representation of perennial, intermittent and ephemeral reaches, which we define following Levick *et al.* (2008). Perennial reaches are reaches with streamflow during all times of the year. Ephemeral reaches are characterized by short duration streamflow events occurring in direct response to local precipitation, most of which takes place during the late summer North American monsoon season. Intermittent reaches flow continuously for only certain times of the year and are supported by sources such as bedrock springs, melting snow or repeated monsoon events. These water sources locally recharge the water table to produce sustained streamflow with durations that extend beyond the ephemeral runoff response.

The specific sensor modifications consist of replacing the thermistor with two polyvinyl chloride (PVC)-insulated copper wires soldered to the sensor circuit board and protruding from the encased water-proof datalogger. Insulation from approximately 4 mm of the end of each wire was stripped and the exposed wires were secured approximately 20 mm apart from each other at the top of the sensor. Following the methods described by Blasch *et al.* (2002) and Gungle (2006), the sensors were housed in a perforated ~5 by 15-cm PVC piece, shallowly buried (<10 cm) in the streambed and secured. The sensor housing was then leashed with wire cable to a nearby tree or rock in the event...
that it scoured during high streamflow conditions. Sensors were deployed in mid-April 2010 at a 15-min logging interval and are expected to have a battery life of approximately 4 years. Data were retrieved from a subset of 21 sensors in mid-August 2010 to validate their operation and confirm the stability of their location. The remaining 23 sensors were left untouched to continue to log data until the next retrieval period scheduled for July 2011. The 121-day monitoring period from April to August represents the cessation of the spring snowmelt period to approximately the middle of the North American monsoon period. We report on these 21 sensors, which comprise complete sensor representation along the mainstem of Huachuca, Ramsey and Garden Canyons and adequately support this study’s objective of demonstrating the sensors’ utility to quantify longitudinal connectivity. Two sensors (H5 and G5) had been excavated during the summer monsoon season, therefore only data recorded prior to the excavations, which are clearly evident in the individual streamflow records, were included in streamflow analyses.

Streamflow continuity and connectivity

Longitudinal connectivity consists of both a structural component describing the shape, size and location of habitat patches and their physical linkage via hydrological corridors and a functional component describing the linkage of habitat patches by organism dispersal and gene flow. This distinction was originally made in the field of landscape ecology (Taylor et al., 1993). In the case of structural longitudinal connectivity (the focus of our paper and hereafter called connectivity), periods of stream drying and wetting events that link ephemeral, intermittent and perennial reaches create a patchwork of habitats at different locations and times during the year. In order to quantify connectivity in terms of relevance to various aquatic biotas, it is necessary to first provide some definitions for conceptual ideas of streamflow in time and space.

It is important to make the distinction between streamflow that is continuous in time at an individual sensor location (i.e. continuity) versus continuous in space across multiple

Figure 3. Schematic of streamflow continuity (continuous in time) and connectivity (continuous in space) for three hypothetical sensors recording surface flow presence (blue) or absence (white) over seven time periods (boxes). Each box represents a 24-h time period. Boxes with blue shapes represent time periods that support refuges. Consecutive time periods of flow at an individual sensor location is considered strict continuity (A). Refuge-maintained continuity refers to time periods where continuous streamflow is interspersed with short time periods (<48 h) of no flow conditions, which may support refuges (B). Strict connectivity refers to time periods when multiple sensor locations within a canyon simultaneously exhibit strict continuity (C, Time 7). Refuge-maintained connectivity refers to time periods when multiple sensor locations within a canyon simultaneously exhibit refuge-maintained continuity (C, Times 2 and 7). This figure is available in colour online at wileyonlinelibrary.com/journal/tra.
sensor locations (i.e. connectivity). At an individual sensor location, the presence of surface water during consecutive time steps (15 min in our study) is considered to be continuous through time; a time period defined as ‘strict continuity’ (Figure 3). However, in the time following strict continuity when stream drying is occurring, contraction of surface water to discrete locations in the vicinity of the sensor can provide refuge for aquatic organisms (e.g. Labbe and Fausch, 2000; Magoulick and Kobza, 2003; Larned et al., 2009; Sheldon et al., 2010). If streamflow resumes before the remaining refuges dry out, the likelihood of local extirpation decreases. Thus, we consider this time period as ‘refuge-maintained continuity’, the criteria being that a sensor must have a signal of streamflow within a particular length of the last streamflow signal (Figure 3). We recognize that this time period will vary according to the particular species or ecological process of interest and across river systems characterized by differing geomorphologies and climate conditions. For our purposes, we chose 48 h as a reasonable time period when water can be expected to remain in the channel following strictly continuous streamflow. This 48-h time period is based on field observations of stream drying dynamics in the Huachuca Mountains, notably the anecdotal identification of sizes and frequency of pools that serve as refuges in intermittent and ephemeral reaches.

Following with this line of reasoning, under the same strict interpretation, ‘strict connectivity’ is considered the condition when multiple sensors within a canyon simultaneously signal continuous surface flow. In this condition, we must assume continuous streamflow between sensors. During this time, aquatic species movement along a channel network is theoretically maximized (although this will vary across species, thus defining functional longitudinal connectivity). We quantify strict connectivity by summing time intervals of strict continuity that are simultaneous among sensors within a canyon. ‘Refuge-maintained connectivity’ consequently is composed of time periods that have streamflow

Figure 4. Bottom panel: Time series record of streamflow presence/absence of Garden Canyon during 15 April–13 August 2010 monitoring period. Individual sensors numbered sequentially in the downstream direction (left axis). Solid symbols indicate the surface flow presence at sensor location. Geology of sensor location is noted along the right axis. Top panel: Precipitation measured at two climate stations (31.461°N; 110.371°W and 31.49°N; 110.308°W) in Garden Canyon is presented as grey and black bars.
under the ‘refuge-maintained continuity’ criteria (Figure 3). Connectivity is represented as the total number of days and the percent of the total monitoring period (15 April–13 August 2010) and the monsoon monitoring period (1 July–13 August 2010; not shown); notably the day time unit was selected for illustrative purposes and could be defined according to the study objectives (e.g. ecological requirements of a specific organism). We recognize that continuity and thus connectivity values are dependent on sensor placement. Consequently, locations different from the sites we chose may result in different values of streamflow timing. However, we expect that the systematic spatial array of the sensors produces a reasonably accurate representation of spatiotemporal streamflow variation at the landscape scale.

RESULTS AND DISCUSSION

The ER sensors provide a record of streamflow continuity and longitudinal connectivity in hydrologically complex streams in the Huachuca Mountains, information relevant to both reach-scale and riverscape-scale aquatic investigations. Sustained declines in relative conductivity values for sensors in intermittent and some ephemeral reaches beginning in April and continuing through May indicate a distinct stream drying that corresponds to cessation of spring runoff (Figure 4); mean time for surface flow cessation was 11 May 2010. Intermittent and ephemeral reaches remained dry throughout June and the early part of July 2010. Short duration (<24 h) surface flow occurred in ephemeral and...
intermittent reaches in response to individual monsoonal rain events, which are recorded in 15-min time increments at Army Base-operated climate stations located throughout Fort Huachuca. Continuous flow in some intermittent reaches resumed in late July and early August as the monsoon season developed. Streamflow type (e.g. perennial, intermittent, ephemeral) only moderately corresponded to the underlying geologic unit, suggesting that the influence of geology on streamflow type may vary in relation to the particular positioning in the channel network (e.g. headwaters versus lower in the network).

**Continuity and connectivity metrics**

Intermittent reaches, on average, experienced ~42 days of flow (~12 of which occurred during the monsoon monitoring season), accounting for 34% of the whole monitoring period or 28% of the monsoon period (Figure 5). Ephemeral reaches, on average, experienced 1.8 days of flow (1.0 of which occurred during the monsoon season), accounting for 1.5% of the whole monitoring period or 2.3% of the monsoon period. Flow at a particular sensor during an individual monsoon event had an average duration of 5.2 h in intermittent reaches and 3.5 h in ephemeral reaches. Total number of monsoon events for the monitoring period averaged eight in intermittent and seven in ephemeral reaches. Refuge-maintained continuity calculations increased flow days an average of 3–4 days during the monsoon period in both intermittent and ephemeral reaches, resulting in a 2–8% increase in the duration of continuous flow for both the entire monitoring period and the monsoon period. This was likely caused by the above average precipitation during the 2010 monsoon period that contributed to elevated water tables and produced sustained flows in some reaches.

Canyon-wide connectivity (even under the more relaxed refuge-maintained criteria) was rare to non-existent (i.e. a fraction of 1% of the monitoring period) during the 121-day monitoring period (Figure 6). Canyon-wide connectivity refers to the full spatial extent of all ER sensors within an individual canyon from headwaters to downstream of the mountain front. Despite the absence of total connectivity, however, extensive reaches within a canyon experienced longitudinal connectivity for substantial periods of time. Perennial and intermittent reaches along the mountain front in Garden and Ramsey Canyons remained connected for 22% and 41% of the monitoring period, respectively. Although we assume continuous flow between adjacent sensors that are simultaneously activated, hydrologic models can serve to interpolate the flow presence between sensor locations.

The refuge-maintained criteria increased streamflow continuity values, but quantifying connectivity by the same criteria had little effect on canyon-wide connectivity, and only increased connectivity by 1–2% in portions of some canyons. Regardless of the lack of influence in our study, refuge-maintained connectivity remains an important concept to longitudinal connectivity because of its applicability to a broad spectrum of time periods relevant to aquatic biota of choice (i.e. aspects that define functional connectivity) that vary widely according to the persistence of particular refuges in different hydro-climatic landscapes. Refuge persistence can range on the order of a few hours in dryland streams (Lytle et al., 2008), weeks to months in small streams in midwestern USA (Capone and Kushlan, 1991; Labbe and Fausch, 2000) or 1–2 years in larger floodplain river systems in Australia (Bunn et al., 2006; Sheldon et al., 2010). Notably, our study demonstrated just one approach to quantifying longitudinal connectivity: data collected by sensor arrays could readily inform other measures of connectivity (e.g. Cote et al., 2009).

**CONCLUSION**

Using ER sensors, we have demonstrated a riverscape approach to quantify streamflow continuity through time and longitudinal connectivity through space. We accomplished this for several semi-arid watersheds that are characterized by hydrologically complex flow patterns, but the proposed methodology is broadly applicable. A burgeoning area of research is focusing on the influence of longitudinal connectivity on population dynamics and ecological processes in dendritic river networks (e.g. Grant et al., 2007; Brown and Swan, 2010; Erös et al., 2011). Data generated from spatial arrays of surface flow sensors could contribute significantly to this effort by yielding information on streamflow timing and duration at a higher spatial and temporal resolution compared to previous methods and requiring substantially less effort and monetary cost compared to implementing field mapping programmes.

**ACKNOWLEDGEMENTS**

This project was funded by the Department of Defense—SERDP (RC-1724). The authors would like to thank Meryl Mims for field assistance, Brooke Gebow (The Nature Conservancy Ramsey Canyon Nature Preserve) for additional field support, Sheridan Stone and Kyle Molloy (Department of Defense) and Bruce Gungle, Kyle Blasch and Onset Computer Corporation for technical assistance with the ER sensors. This manuscript was improved by the helpful comments of Angela Strecker, David Lytle, Martin Schlaepfer, Aimee Fullerton and one anonymous reviewer.
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