Evaluation of a Runoff Monitoring Methodology for Rangelands: UBe Tubes

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ABSTRACT

Rangeland degradation is a global concern that is exacerbated by soil loss through water erosion. A deeper understanding of rainfall and runoff dynamics can assist in the development of sustainable management strategies. Current methods to measure surface runoff (i.e., natural runoff plots, rainfall simulation and overland flow experiments, modeling approaches) have many advantages but can be prohibitively expensive, may require considerable maintenance, and/or result in significant disturbance during installation. To address these limitations, we assessed a relatively new and underused method for monitoring runoff, the Upwelling Bernoulli Tube (UBe Tube). The UBe Tube is a low-cost, passive runoff monitoring method that estimates runoff from the height of water flowing out of a slot machined in the side of a vertical tube. In this study, we evaluated the UBe Tube across a range of flow rates with three specific objectives: 1) calibrate the UBe Tube measurements using clean water, 2) assess the impacts from varying sediment loads on UBe Tube measurement accuracy, and 3) evaluate accuracy under conditions similar to those on undisturbed and disturbed rangelands. We found that properly calibrated UBe Tubes could be a relatively accurate runoff monitoring method on rangelands (mean percent error = 7.7% clean water calibration, 34.1% sediment loading, 35.2% undisturbed overland flow, 17.7% disturbed overland flow). UBe Tubes provide an alternative method to monitor runoff on rangelands that can augment current methods by providing near-real-time measurements of runoff generated during natural precipitation events. Easily and rapidly deployed across the landscape, UBe Tubes could allow for the relative measurement of spatially variable hydrologic dynamics and serve as another source of information for management decision-making processes and the creation of sustainable strategies for rangeland development.

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Introduction

Rangeland degradation, including that due to accelerated water-borne erosion, is a global concern negatively impacting the livelihoods of 3.2 billion people reliant on the ecosystem services provisioned by these landscapes (Herrick et al. 2019). The associated reduction in ecosystem services can diminish quality of life for communities dependent on rangelands and decrease sustainability of rangeland production enterprises. Understanding the root causes of degradation and creating effective approaches to restoration have been identified as key factors in creating sustainable development strategies for the future of rangelands globally (Herrick et al. 2019). Since accelerated erosion may occur with the loss of infiltration capacity and increased runoff, development of tools and methods to monitor changes in these hydrologic processes can serve as a basis for informing and assessing rangeland management (Williams et al. 2016).

Numerous methods are available to quantify runoff across spatial and temporal scales of interest. Weirs, flumes, and streamgaging methods are commonly used to quantify watershed-scale event, seasonal, and annual runoff or streamflow within channels (Stone et al. 2008). Natural runoff plots of various scales are used to quantify surface runoff during natural rainfall events (Wilcox 1994; Reid et al. 1999). These plots typically incorporate nearby rain gauges with a system for capture and storage of surface runoff and/or a datalogger/sensor pair for direct runoff measurement. Runoff amounts, directly measured or quantified through subse-

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quent laboratory analyses of runoff samples, are used to determine event, seasonal, and annual responses to precipitation inputs. Rainfall simulation and overland flow experiments apply water to field plots as precipitation and/or overland flow in known amounts, and the resulting event infiltration and runoff are directly measured or derived through capture and subsequent analyses of runoff samples (Pierson et al. 2002; Polyakov et al. 2018). These experiments are conducted at various plot sizes of interest to quantify hydrologic processes over point to hillslope scales (Williams et al. 2020). Data obtained from the methods noted earlier have been extensively used to develop, evaluate, and improve runoff models (e.g., Robichaud et al. 2007; Hernandez et al. 2017). Such models usually simulate runoff processes at the soil surface and provide predictions of runoff for ranges of precipitation inputs based on site-specific parameters.

Although the aforementioned techniques effectively quantify (measured or simulated) hydrologic processes, each approach has advantages and disadvantages. Weirs and flumes necessitate well-selected, semipermanent locations, construction and installation costs, and frequent maintenance and calibration along with data retrieval and data management concerns. Installation of natural runoff plots can cause site disturbance, and these plots typically require frequent on-site maintenance and laboratory processing of runoff samples. Rainfall simulation and overland flow methods likewise can cause temporary disturbance, require substantial investments of time and resources (e.g., water transport, equipment, field support, runoff sample processing), and provide runoff estimates for select rainfall or overland flow application rates. Model-based approaches can be valuable, but with numerous options available for use, determining the proper model with corresponding model parametrization for each specific inquiry can be challenging.

This study evaluated an existing, but minimally applied, passive method to measure surface runoff, the Upwelling Bernoulli Tube (UBETube). The UBETube is a relatively low-cost monitoring system recently developed to measure surface runoff (Stewart et al. 2015). As originally designed, UBE Tubes use hydrologic flow relationships to allow for the calculation of surface flow (i.e., runoff) from water height measurements within the device. When coupled with a precipitation gauge, researchers can produce near-real-time estimates of plot-scale runoff. Field installations across a site could provide unique insight into the variability of runoff for naturally occurring precipitation and site-level hydrologic function more generally.

To assess whether UBE Tubes can accurately measure plot-scale runoff on rangelands, testing was needed to evaluate measurement performance under conditions typical of rangeland systems (e.g., variable flows and sediment loading). In this study, we evaluated the UBETube across a range of flow rates with three specific objectives: 1) calibrate the UBETube measurements using clean water, 2) assess the impacts from varying sediment loads on UBE Tube measurement accuracy, and 3) evaluate accuracy under conditions similar to those on undisturbed and disturbed rangelands.

Methods

We constructed an UBE Tube following methods of Stewart et al. (2015) using schedule-40 polyvinylchloride (PVC) pipe for the main body of the device and suggested slot geometry, with \( h_0 = 0 \) cm, \( h_1 = 9.8 \) cm, \( h_2 = 15.8 \) cm, \( w_0 = 0.1 \) cm, \( w_1 = 1.0 \) cm, and \( w_2 = 6 \) cm (Fig. 1A). A METER Group, Inc. HYDROS 21 (www.metergroup.com) electrical conductivity, temperature, and depth sensor was installed within the UBE Tube at the bottom of the PVC tube (see Fig. 1B) to measure water height, and the instantaneous measurements during experiments were recorded using a METER Group, Inc. EM50 datalogger. The HYDROS 21 sensor uses a vented differential pressure transducer to measure pressure from the water column to determine water depth with a resolution of 0.2 cm. Calculations of flow rate through the slot are made using measurements relative to a baseline \( h_0 \) measurement that will vary with each UBE Tube device (in our experiments this baseline \( h_0 \approx 36.0 \) cm). All testing took place at the US Department of Agriculture–Agricultural Research Service, Southwest Watershed Research Center, Walnut Gulch Experimental Watershed facilities in Tombstone, Arizona.

Our initial calibration assessed the effectiveness of the UBE Tube to accurately quantify runoff with no sediment (clean water calibration; Table 1). Water was pumped through an 80-micron filter and inline flow meter (FLOMÉC TM series, FLOMÉC, Inc., North Chesterfield, VA) into a 10.2-cm (4-inch) PVC inlet to the lower section of the UBE Tube housing (see Fig. 1). We conducted trials with target steady-state flow rates ranging from 5 L·min\(^{-1}\) to 40 L·min\(^{-1}\) in increasing increments of 5 L·min\(^{-1}\). Flow rates were manually adjusted until reaching target steady-state flow rates as confirmed by the flow meter. Water height within the UBE Tube was monitored by the HYDROS 21 sensor and datalogger system and then converted to observed flow rate exiting the device and paired with timed bucket samples (15-30 sec per sample) taken at the UBE Tube outlet. Bucket samples were weighed and converted to volumes and then divided by the sampling time to determine the actual flow rate (L·min\(^{-1}\)). The UBE Tube height measurements were taken at the midpoint of each timed bucket sample with five paired measurements taken per target steady-state flow rate. UBE Tube height measurement variations observed during the experiment fell within the sensor’s measurement resolution of ± 0.2 cm.

In a second experiment (sediment loading; see Table 1), we assessed the capability of the UBE Tube to accurately quantify runoff under a broad range of sediment loads. Sediment derived from local soil (52% sand, 26% silt, 22% clay) and sieved (< 2 mm) was manually added to clean water inflow. Our target sediment concentration was 10 g·L\(^{-1}\), although actual sediment concentrations varied as sediment was added in pulses. We conducted trials with target steady-state flow rates ranging from 5 L·min\(^{-1}\) to 35 L·min\(^{-1}\) in increasing increments of 5 L·min\(^{-1}\) for 5 min per trial. Sediment pulses were loaded into a small metal box through which water was routed before emptying into the same UBE Tube inlet used in the clean water calibration. Five timed bucket samples were taken per trial, and UBE Tube height measurements were taken at the midpoint of each timed bucket sample. Immediately before each timed bucket sample, a grab-sample of the UBE Tube discharge was collected in a 1-L bottle to quantify the associate bucket sample sediment load. Each grab sample was processed in a lab by weighing the sample before and after drying in an oven at 95°C to determine the respective runoff and sediment masses and flow sediment concentration.

In a third experiment, we assessed the capability of the UBE Tube to accurately quantify runoff on conditions like those found on undisturbed (undisturbed overland flow; see Table 1) and disturbed rangelands (disturbed overland flow; see Table 1). Overland flow simulations were conducted on a sloped soil box (6 m long × 2 m wide × 0.3 m deep; 3.5% slope; see Fig. 1C) described by Nearing et al. (2017). Before the runoff measurements, the soil box was gently wetted to increase soil moisture to conditions more similar to those expected under natural overland flow. In order to dissipate the energy from the pumped water, flow was routed through a small metal box filled with polystyrene foam pellets and a 10 × 10 cm outlet (Williams et al. 2020). The metal box was placed 5 m upslope from the base of the soil box. During the undisturbed overland flow simulations, flow was released onto the soil box at flow rates of 10, 18, 26, and 35 L·min\(^{-1}\) for approximately 15 min per flow rate. A metal tray at the base of the plot routed water as described in the sediment loading tests. Ten timed bucket samples were collected per flow rate, and UBE Tube measurements were taken at the midpoint of each timed bucket.
Figure 1. A, UBeTube slot design used during evaluation (h₀ = 0 cm, h₁ = 9.8 cm, h₂ = 15.8 cm, w₀ = 0.1 cm, w₁ = 1.0 cm, and w₂ = 6 cm). B, UBeTube schematic showing the full device design and relative positions of the slot and sensor. C, UBeTube during the overland flow experiment.

Table 1

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<tr>
<th>Experiment</th>
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<th>n</th>
<th>Flow range (L·min⁻¹)</th>
<th>Mean sediment concentration (g·L⁻¹)</th>
<th>Sediment concentration range (g·L⁻¹)</th>
<th>Mean percent error (%)</th>
<th>Percent error range (%)</th>
<th>Root mean squared error (L·min⁻¹)</th>
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<td></td>
<td>17.9</td>
<td>0.8-34.5</td>
<td>4.7</td>
</tr>
</tbody>
</table>

¹ Flow rate estimated from UBeTube water height measurements using Bernoulli’s equation (Stewart et al. 2015) without calibration factor equation.
² Flow rate estimated from UBeTube water height measurements using Bernoulli’s equation and calibration factor equation from Stewart et al. (2015).
³ Flow rate estimated from UBeTube water height measurements using optimized calibration factor equation from Stewart et al. (2015). Only data from clean water calibrations were used for optimization.
⁴ Flow rate estimated from power-law relationship between UBeTube water height measurements and bucket samples during clean water calibration.

sample. Immediately before each timed bucket sample, a sediment concentration grab-sample was taken as described in the sediment loading tests. A second set of overland flow simulations were completed on disturbed soils (disturbed overland flow). Before these simulations, the soil box was raked, disturbing approximately the top 5 cm of the soil surface. Flow rates of 10, 20, and 30 L·min⁻¹ were released onto the soil box for approximately 15 min per flow rate, and runoff and sediment concentrations were sampled consistent with methods described for the undisturbed simulations. UBeTube water height (cm) measurements were converted to flow rates (L·min⁻¹) using methods described by Stewart et al. (2015). To improve accuracy, we compared three calibration methods (standard [Stewart et al. 2015], optimized, and rating curve) to uncalibrated measurements (see Table 1). Stewart et al. (2015) rec-
ommended a calibration factor (c) that is a function of the water height (h). We modified their proposed calibration factor equation by allowing for the optimization of the introduced variable β:

\[ c = 1 - \frac{\beta h}{100}, \quad h < 32 \text{ cm} \]  

(1)

As per Stewart et al. (2015), we set β equal to 1.4 for one set of calibrations (standard method). We then allowed β to be optimized (optimized method) to 2.8 by minimizing the sum of squared errors (i.e., difference between calculated UBeTube flow rate and paired bucket sample measurement). A final set of calibrations (rating curve method) were completed by forgoing the use of Bernoulli’s equation and establishing a direct power-law relationship between h and flow rates determined via bucket samples (i.e., rating curve). All calibrations used only data from clean water calibration trials. Detailed descriptions of rating curve calibration and flow calculation are provided in the supplemental materials (available online at doi.org/10.5281/zenodo.4056774). All analyses were completed using R (version 3.6.3; R Core Team 2019).

Results

In our clean water calibration, we found differences between flow rate estimates derived from the UBeTube and those from bucket samples (i.e., error) can be substantially reduced via calibration (see Table 1, Fig. 2A). The root mean squared error (RMSE) was reduced from 10.8 L·min\(^{-1}\) (no calibration) to 1.6 L·min\(^{-1}\) via the rating curve calibration method. Consistent with findings from Stewart et al. (2015), flow rate estimates derived from methods based solely on Bernoulli’s equation showed increasing error as water height increased within the UBeTube (see Fig. 2A). Although the correction factor suggested by Stewart et al. (2015) moderately reduced this error, optimizing the calibration equation considerably improved accuracy (see Table 1, Fig. 2A).

The sediment loading experiment indicated the accuracy of the UBeTube is sensitive to large pulses of sediment. Even using the most effective calibration method (rating curve), RMSE remained over 10 L·min\(^{-1}\) (see Table 1). During this experiment, we subjected the UBeTube to sediment concentrations much greater than those observed during both the undisturbed and disturbed concentrated flow experiments (see Table 1).

The undisturbed flow experiments on undisturbed and disturbed conditions also show that calibration substantially reduces error (from 16 to 20 L·min\(^{-1}\) to 4 to 7 L·min\(^{-1}\), on average) between the UBeTube flow rate measurements and the bucket sample flow rate measurements (see Table 1, Figs. 2B and 2C). Error during these experiments was negatively associated with flow rates with less error at lower flow rates typical of rangelands. Across all experiments, each calibration method improved measurement accuracy with the greatest reductions in error coming from the optimized calibration equation and the rating curve based on empirical relationships from our calibration trials (see Table 1, Fig. 2A–C).

Discussion

With sufficient calibration, UBeTubes can be used effectively for runoff monitoring on rangelands. We found that calibration of the device is a crucial component to improve accuracy of runoff measurements. Although each calibration method used in our experiment reduced error, we suggest developing a rating curve specific to each UBeTube to achieve the greatest accuracy of runoff measurements. Results of our undisturbed and disturbed overland flow experiments show potential for using UBeTubes to monitor runoff in typical rangeland conditions, which could provide an effective method for capturing spatially variable rainfall and runoff dynamics across the landscape.

Because of the high error rates found during the sediment loading experiment, we caution against using UBeTubes, as originally designed, in settings where high flow rates may be coupled with high sediment loads (e.g., after fire or in steep terrain). One source of this error was larger sediment particles becoming lodged in the outflow slot, artificially inflating flow rate estimates. Redesign of the outflow slot (e.g., widening the slot to allow for passage of larger particles) could potentially lead to increased applicability under those conditions but reduce the capability of the device to measure low flow rates due to the relationships between slot geometry and flow rates as shown in Stewart et al. (2015). Although sediment becoming trapped in the outflow slot increased the error observed during our sediment loading experiment, we observed no apparent impact to measurements from sediment accumulations within the UBeTube device itself. A consistent baseline \( h_0 \) measurement (range = 35.9–36.5 cm) was maintained throughout our experiments. We did not observe a trend in those measurements as sediment accumulated, even though no sediment was removed from the UBeTube during the entirety of the study. Although we found no trend in baseline \( h_0 \) in our experiments, longer-term applications should include assessing ramifications of prolonged sediment accumulation within the tube.

In addition, changing the slot geometry from two superimposed trapezoids (see Fig. 1) to a single trapezoid would sim-
ply flow calculation and calibration. To increase accuracy across all settings, automating device construction and slot machining would increase precision. With a precise manufacturing process, calibration across multiple devices may become possible, substantially reducing time spent on calibration before installation. Absent further testing, calibration is still recommended for each device, even with the same slot geometry.

Overall, the results of our experiments show that UBETubes provide an alternative method to monitor runoff on rangelands and that could augment existing runoff monitoring techniques by providing passive, time series measurements of natural rainfall-runoff events with limited investment. UBETubes are relatively quick and easy to install and move, which could allow widespread implementation increasing replication of monitoring plots in many rangeland settings. UBETube installations would be most similar to natural runoff plots (Wilcox 1994; Reid et al. 1999) in that they passively measure runoff amounts, but they also have the advantages of limited maintenance, minimal initial disturbance, and time-specific measurements that aid understanding of rainfall and runoff dynamics. They could also be used in concert with rainfall simulation and overland flow approaches to limit site disturbance, extend collection of data beyond the simulation time window, and assess runoff processes under natural and simulated precipitation. Combining UBETube measurements with modeling outputs could also provide insights into hydrologic dynamics across spatial scales.

Implications

UBETubes used alone or in association with other current methods for evaluating relative rangeland runoff rates would provide more in-depth assessments of hydrologic function. This low-cost runoff monitoring method could be employed for a variety of specific objectives tied to land management concerns. For example, if brush control with an objective to limit runoff and water-driven erosion was implemented, UBETubes could be installed across treatment and reference sites to assess progress toward that goal. This knowledge of hydrologic relationships can then add to improvements in sustainable rangeland development strategies focused on reducing accelerations in runoff on a landscape. When used to capture rainfall and runoff dynamics from natural events, this information could be incorporated into management decision support tools, such as ecological site descriptions (Williams et al. 2016). Further enhancement of knowledge relative to runoff rates from natural rainfall events will offer another source of information for development of sustainable rangeland management strategies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2021.05.003.

References


