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ORIGINAL PAPER

Environmental controls on drainage behavior of an ephemeral stream

Kyle W. Blasch · Ty P. A. Ferré · Jasper A. Vrugt

Abstract Streambed drainage was measured at the cessation of 26 ephemeral streamflow events in Rillito Creek, Tucson, Arizona from August 2000 to June 2002 using buried time domain reflectometry (TDR) probes. An unusual drainage response was identified, which was characterized by sharp drainage from saturation to near field capacity at each depth with an increased delay between depths. We simulated the drainage response using a variably saturated numerical flow model representing a two-layer system with a high permeability layer overlying a lower permeability layer. Both the observed data and the numerical simulation show a strong correlation between the drainage velocity and the temperature of the stream water. A linear combination of temperature and the no-flow period preceding flow explained about 90% of the measured variations in drainage velocity. Evaluation of this correlative relationship with the one-dimensional numerical flow model showed that the observed temperature fluctuations could not reproduce the magnitude of variation in the observed drainage velocity. Instead, the model results indicated that flow duration exerts the most control on drainage velocity, with the drainage velocity decreasing nonlinearly with increasing flow duration. These findings suggest flow duration is a primary control of water availability for plant uptake in near surface sediments of an ephemeral stream, an important finding for estimating the ecological risk of natural or engineered changes to streamflow patterns. Correlative analyses of soil moisture data, although easy and widely used, can result in erroneous conclusions of hydrologic cause—effect relationships, and demonstrating the need for joint physically-based numerical modeling and data synthesis for hypothesis testing to support quantitative risk analysis.

Keywords Ephemeral stream · Redistribution · Drainage · Rhizosphere · Restoration

1 Introduction

Many ephemeral stream channels in arid and semi-arid climates are characterized by relatively short periods of flow followed by longer no-flow periods (Stonestrom et al. 2007). The magnitude, frequency, duration, and fluvial geomorphic processes associated with these periods of flow have been used to describe the suitability of ephemeral stream channels to support riparian vegetation (Hupp and Osterkamp 1996; Bendix and Hupp 2000; Lytle and Poff 2004; Shaw and Cooper 2008). Additionally, the importance of streambed sediments to retain and redistribute water within the rhizosphere during periods of no-flow has been identified (Shaw and Cooper 2008). However, the emphasis has been placed on the cumulative infiltration prior to cessation of streamflow and evapotranspiration during cessation (Loik et al. 2001).

To date, there have been no published studies describing environmental controls on the rate of vertical drainage

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through streambed sediments after the cessation of an ephemeral streamflow event. Maximum potential evapotranspiration only occurs when the surface and rooting zone are wet. Therefore, streambed drainage rates directly influence both cumulative evaporative loss and groundwater recharge beneath channels.

This investigation considered the following environmental controls on drainage rates: temperature; stage; duration; no-flow duration; and antecedent bed sediment water content. The impact of temperature variability on hydraulic conductivity and streambed infiltration has been well studied (Constantz 1998; Blasch 2003). Higher sediment and water temperatures produce higher hydraulic conductivities, which were hypothesized to increase drainage rates. The influence of temperature, however, decreases with depth as heat is exchanged with the sediments as water is transported downward. Stage is directly proportional to infiltration rate and depth of infiltration during an event. The depth of water infiltration into the sediments was considered a possible factor controlling succeeding drainage. Specifically, higher infiltration rates would result in a larger volume of water transported into the soil profile and a smaller capillary gradient from the ground surface across the wetting front. Likewise, flow duration was thought to increase the depth of infiltration, and decrease capillary gradients. The decreased gradients would reduce drainage rates. No-flow duration defined as the time period between the cessation of one event and the onset of a succeeding event was considered important as a surrogate measurement for antecedent conditions of the channel sediments. The longer the period of no-flow the drier the sediment profile becomes caused by evapotranspiration at the surface and drainage/dewatering at depth. Lower antecedent water content at the surface with higher sorptiviy was hypothesized to increase the wetting front depth. While sediment texture is an important factor to consider for drainage behavior (coarse sediments have higher conductivities than fine sediments), it was constant during the study and was thus not considered as a factor for the changes in observed drainage rates.

We present a study of the drainage response of an alluvial stream channel, Rillito Creek, located in Tucson, Arizona (Fig. 1). The study is supported by a large data set including soil moisture and temperature measurements at seven depths within the upper 2.5 m collected every 2 min during 26 flow events from August 2000 to June 2002 (Blasch 2003). From these soil moisture data, we could also infer the duration of flow events, the duration of no-flow periods, and the antecedent soil moisture in the shallow subsurface at the onset of flow.

In addition to examining drainage responses of ephemeral streams and their importance for management of riparian areas, the present work demonstrates a clear need for combining the strengths of quantitative, physically-based modeling and data synthesis to better test scientific hypotheses, by directly comparing correlative and physically-based model analyses.

1.1 Field methods

1.1.1 Site description

Rillito Creek is an ephemeral stream in southern Arizona that has a drainage area of approximately 2,256 km^2 (Fig. 1). The channel cross-sectional width at the study site is about 75 m. Sediments at the Dodge Boulevard study site consist of an upper layer of recent alluvial stream-channel deposits and a second deeper layer of Pleistocene or older basin-fill deposits (Davidson 1973). Cores collected near the site indicate that the alluvial deposits are about 7 m thick and consist predominantly of loose to moderately compacted sands and gravels, with less than 10 percent clay and silt (Hoffmann et al. 2002). The underlying basin-fill deposits, which extend to depths of several hundred meters, consist of unconsolidated to poorly consolidated interbedded gravel, sand, and silt (Davidson 1973; Hoffmann et al. 2002). The hydraulic properties of these layers, estimated on the basis of core data, are listed in Table 1. The water table depth is approximately 40 m at the study site.

Rillito Creek has two primary seasons of streamflow in response to two precipitation periods: North American Monsoon (July–September) and winter (December–March). Summer flows typically result from localized, short-duration convective storms, whereas longer-duration frontal storms and snowmelt produce winter flows. During the months of October and November, precipitation from tropical storms or changes in weather patterns caused by periodic climate fluctuations can cause periods of streamflow. These events, however, are less common than summer and winter events. A U.S. Geological Survey (USGS) streamflow-gaging station, 09485700, is 45 m downstream from the study site. Discharge events rarely (<5%) exceed 28 m^3/s; the maximum discharge recorded at the site was about 680 m^3/s during the 1993 El Niño season (Tadayon et al. 2001).

1.1.2 Field measurements

A 1.5-m wide by 10-m long by 2.5-m deep trench was excavated perpendicular to the longitudinal axis of the channel. Seven nested pairs of thermocouples and time-domain reflectometry (TDR) probes were installed in four profiles along the upstream wall of the trench (Fig. 1). Once instrumentation was installed, the trench was backfilled. The shallowest sensor depth was 0.5 m; but three

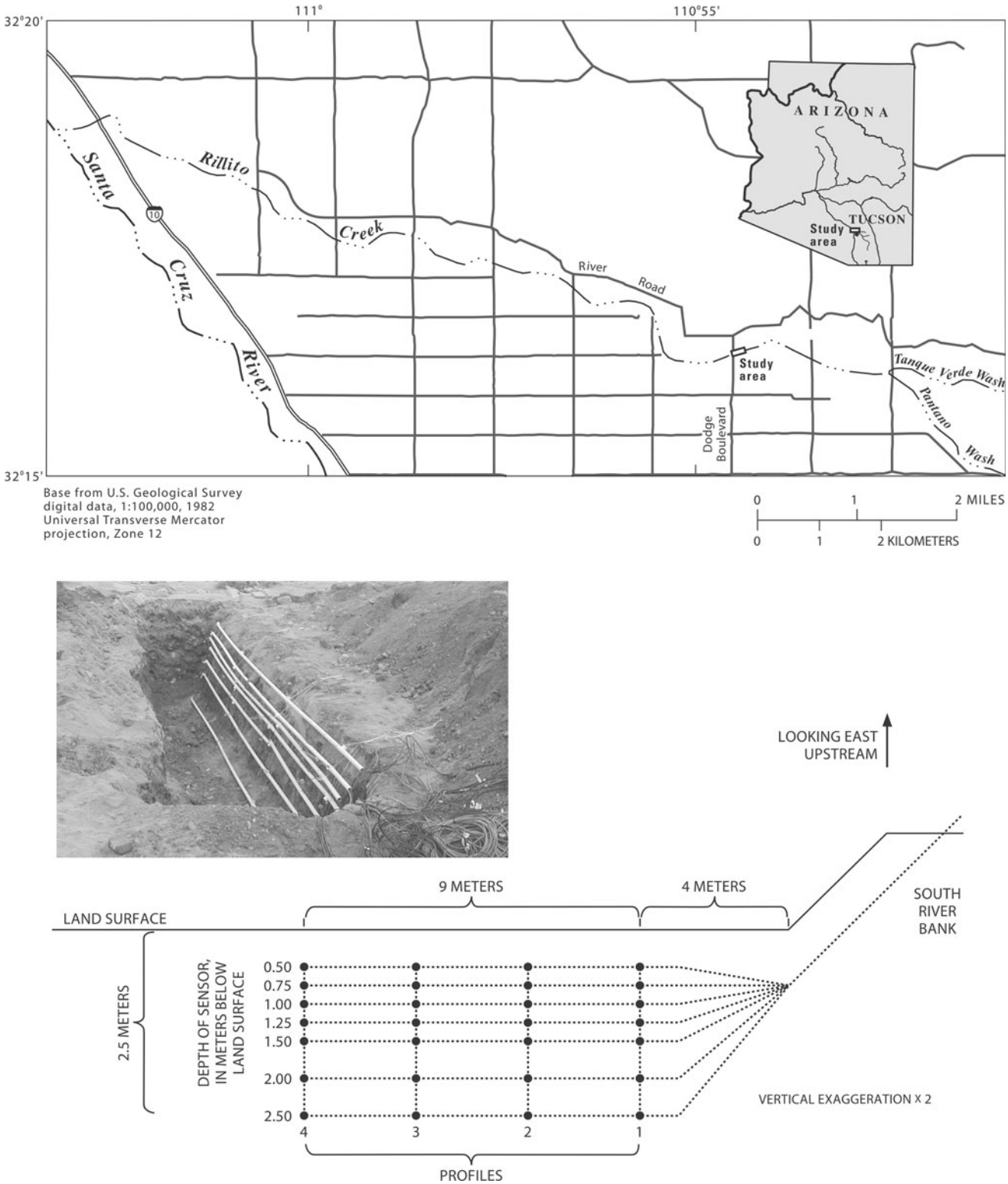

Fig. 1 Location of Rillito Creek study area and view of Rillito Creek within the Tucson Basin, Tucson, Arizona. Photograph and schematic of the two-dimensional array of sensors within the stream channel deposits. Each *solid circle* represents a temperature and soil-water content sensor

flow events before monitoring began scoured 0.25 m from the streambed surface. Subsequent scour and deposition resulted in streambed elevation changes of less than 0.1 m. Therefore, the measurement depths during the monitoring period were 0.25, 0.50, 0.75, 1.0, 1.25, 1.75, and 2.25 m below the streambed.

Table 1 Soil hydraulic properties (mean and ranges) and top depths of the upper layer stream channel deposits and lower layer basin-fill deposits based on laboratory analyses of core samples and calibration of a variably saturated numerical model to observed drainage responses

Layer	Number of samples	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (1/cm)	n	K_s (cm/d)	Top depth (m)
Upper layer: core	5	0.055	0.33	0.071	1.27	220	0
		0.028–0.124	0.23–0.47	0.004–0.012	1.21–1.34	208–242	
Lower layer: core	8	0.047	0.32	0.042	1.34	40	7
		0.027–0.060	0.24–0.39	0.019–0.066	1.30–1.38	7–70	
Upper layer: simulated		0.06	0.33	0.07	1.5	600	0
Lower layer: simulated		0.05	0.32	0.04	1.56	5	7

Residual soil moisture, θ_r, and saturated soil moisture, θ_s van Genuchten parameters, α (approximate of inverse of air entry) and n (slope of the retention function), and saturated hydraulic conductivity, K_s

Soil moisture was measured with time domain reflectometry (TDR) every 2 min at each measurement depth. Two-rod TDR probes were constructed using 0.32-cm-diameter stainless steel wave-guides, 0.2 m long and, spaced 0.03 m apart. To minimize signal transmission losses, RG-8 coaxial cable in lengths that ranged from 11 to 26 m was used to connect the probes to the TDR instrument. A Campbell Scientific TDR100[1] (Campbell Scientific, Inc., Logan, UT) was used to transmit, receive, and convert waveforms into volumetric water content. TDR assemblies were calibrated using Win TDR to determine the effective length of the cable and probe components. The effective lengths of the probe and cable assemblies ascertained through laboratory calibration were used to infer volumetric water content from the TDR100 responses. In addition, stream water temperature was measured using a TidbiT thermistor (Onset Computer Corp., Bourne, MA) with a precision of 0.1°C, positioned at the bed sediment surface, and located about 45 m downstream of the profiles. This thermistor was installed beneath a bridge and approximately 4 cm above the streambed surface.

2 Results and discussion

Data were collected from July 2000 through December 2001: 26 different streamflow events were recorded (Fig. 2). These events varied in duration from 2 h to 11.6 days—16 events were less than 1 day in duration, and only 3 events were longer than 7 days. The median event lasted about 12 h. Peak discharge for events ranged from 0.03 to 180 m^3/s; the median discharge was 3 m^3/s. The no-flow period between flow events ranged from 6 h to 67 days. Water level measurements from nested piezometers within the study area show that the wetting front did not connect with the regional water table during any of the flow events. Of the 26 events, only 12 events exhibited drainage at the 1.75 or 2.25 m depths before the onset of succeeding events. These 12 events were used in the succeeding analysis. Multiple sensor profiles were used for each of the events to provide 26 estimates of one-dimensional vertical flow during and after streamflow.

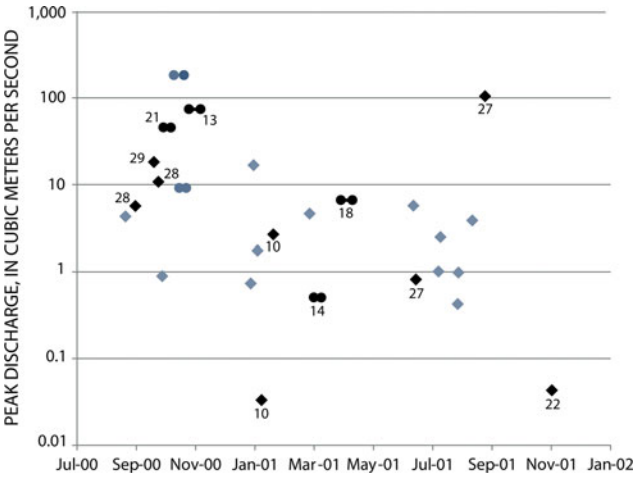

Fig. 2 Hydrograph for Rillito Creek at Dodge Boulevard. Diamonds represent events that are less than 24 h in duration. Events are shown with their peak discharge value. Black symbols represent events that were used for the analysis. Numbers beside the black symbols represent the average temperature of the trench at the onset of the ephemeral event in degrees Celsius

2.1 Characteristic redistribution response

All of the drainage events showed similar characteristic water content changes with time. As an example, one representative event (September 10, 2000) is shown in Fig. 3a. The saturated water content varied with depth between 0.35 and 0.42 cm^3/cm^3. After approximately 2 days of drainage, the water content (θ) reached a near constant value at each depth. We refer to this as the field capacity, and it ranged from $\theta = 0.19$ to 0.27 cm^3/cm^3. Drainage from full saturation to field capacity occurred very rapidly at each depth, but there was a delay in the time of onset of drainage with increasing depth.

[1] Does not constitute endorsement by the U.S. Geological Survey.

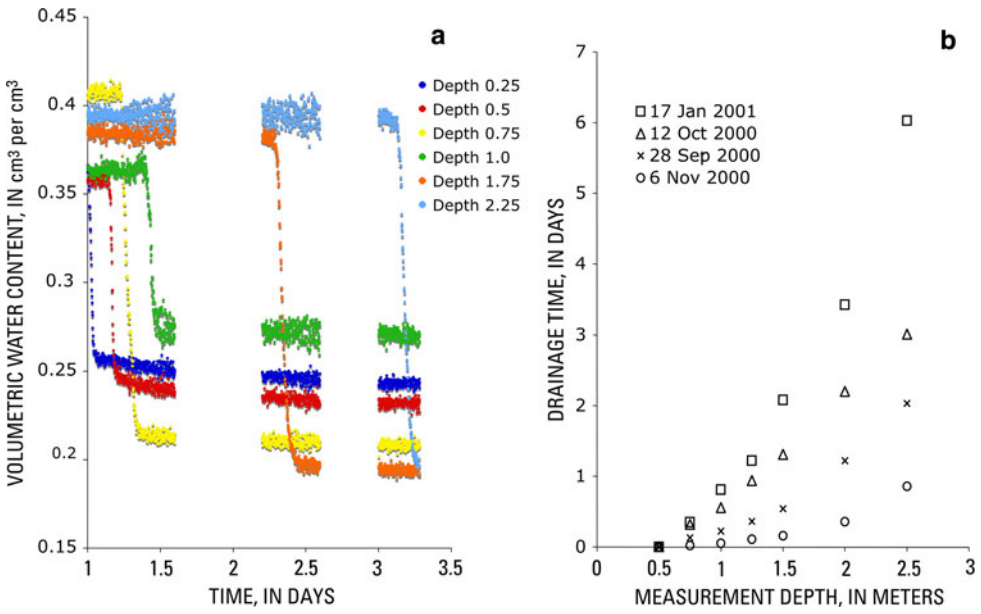

Fig. 3 **a** Volumetric water content measurements (cm^3/cm^3) at 6 depths (m) during drainage and **b** elapsed time (days) for the drainage front (defined as a volumetric water content of 0.30 cm^3/cm^3) to travel from 0.25 m to each measurement depth for four flow events. Data gaps in Fig. 3a are a result of equipment malfunctions

For the observed soil moisture time series, the timing of the onset of drainage at each measurement depth can be described simply by the time that the water content decreases below some water content threshold at that particular depth. We chose a water content value of 0.30 m^3/m^3 as the threshold. Thus drainage for each depth began when the soil moisture sensor measured 0.30 m^3/m^3 and drainage ended when the sensor measured field capacity. Given the very rapid drainage response at each depth, the results presented herein are not very sensitive to the specific value of the threshold water content. Furthermore, because the water content typically decreases from full saturation to this threshold value within a few measurements, the results will be insensitive to "smearing" due to the distributed spatial sensitivity of the TDR probes (Ferré et al. 2002). Similarly, errors in the specific calibration of dielectric permittivity to water content relationship are not important for our analysis given the rapid and large change in water content at the onset of drainage.

Our shallowest measurement depth was 0.25 m, so we have no information regarding the time required for the drainage front to reach 0.25 m from the streambed surface. We therefore calculated the elapsed time for drainage after flow cessation at each depth as the difference between the time that the threshold (0.30 m^3/m^3) was crossed for each depth and the time that threshold was crossed at the shallowest measurement depth, 0.25 m. Despite the similarity of the drainage patterns among flow events, there were significant variations in the absolute timing of drainage among events (Fig. 3b). Additionally, there is some nonlinearity in the velocity with depth (Fig. 3b). For this study, we considered the elapsed time to 1.75 m depth.

Owing to the extensive data set available, we first conducted a systematic search for correlations between drainage velocity and all other measured data. Specifically, drainage velocity was plotted as a function of duration of streamflow (period of event), no-flow period (period of time between events), streambed temperature, maximum stage, and normalized antecedent water content. To allow for comparison of the simulation results with the measurements in the field, the observed soil moisture data were normalized such that each layer had normalized saturated soil moisture, θ_s, and residual soil moisture, θ_r, values of 0.33 and 0.05, respectively:

$$\theta = 0.05 + \frac{\theta_{meas} - 0.05}{0.33 - 0.05}(\theta_{max} - 0.05)$$

where θ is the normalized water content, θ_{meas} is the measured water content at each observation depth, and θ_{max} is the maximum measured soil moisture value at that same depth.

Temperature shows a strong linear correlation with the measured drainage velocity (Fig. 4a). Linear regression to temperature explains 87% of the observed variation in elapsed drainage time to 1.75 m depth (Table 2). To see whether this correlation can be further enhanced, we performed partial least squares regression of all combinations of the five measured variables to the elapsed time for drainage. A linear combination of temperature and no-flow period was shown to explain approximately 92% of the measured variation in drainage velocity (Fig. 4f). No other combination of two variables existed that exhibited such a high correlation with the measured drainage velocities. We initially concluded, based on the correlative analysis, that

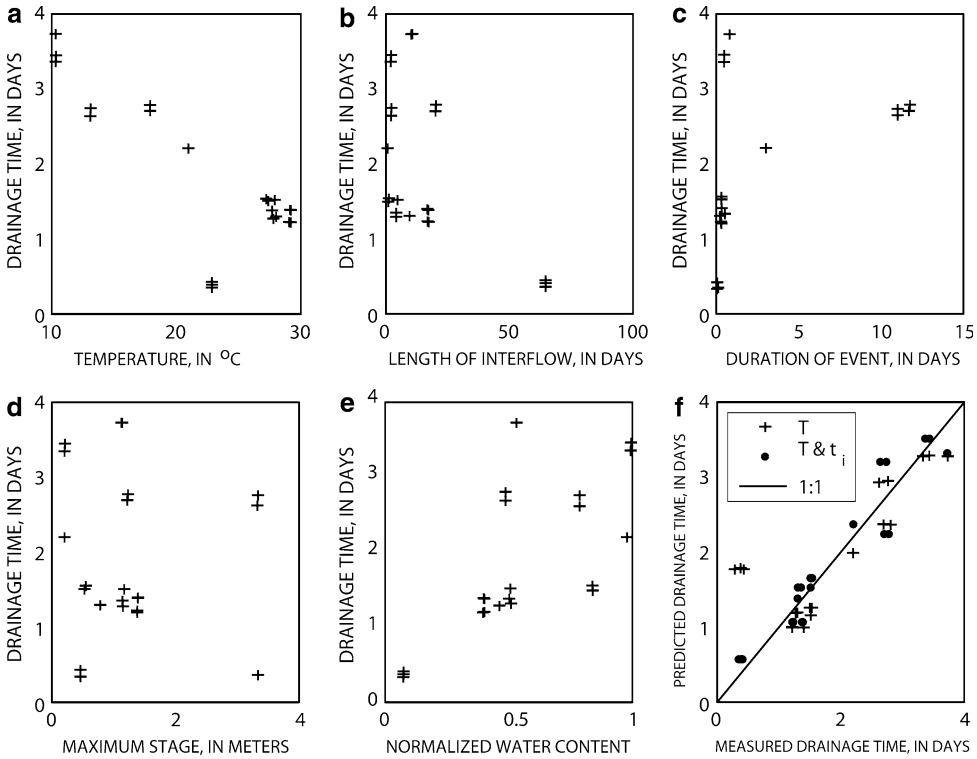

Fig. 4 Drainage time in days from 0.25 to 1.75 m as a function of **a** temperature, **b** length of no-flow, **c** duration of event, **d** maximum stage, and **e** normalized antecedent water content. **f** Predicted drainage times based on linear regression compared to measured drainage times as a function of T (temperature) and T and t_i (length of no-flow) combined

Table 2 Correlative relationship between drainage velocity (m/days) and environmental controls for ephemeral streamflow drainage in Rillito Creek

	Drainage velocity (m/days)	Temperature (°C)	No-flow period (days)	Event duration (days)	Maximum stage (m)
Drainage velocity (m/days)	1.00				
Temperature (°C)	−0.87	1.00			
No-flow period (days)	−0.49	0.14	1.00		
Event duration (days)	0.51	−0.39	−0.12	1.00	
Maximum stage (m)	0.26	−0.22	−0.17	0.65	1.00
Normalized water content	0.56	−0.38	−0.81	0.15	−0.05

water temperature exerts a primary control on drainage rate in Rillito Creek and that the duration of the no-flow period has a smaller, secondary impact, probably through its impact on the initial water content throughout the profile. This is evidenced through the strong correlative relationship between antecedent normalized water content and the no-flow period (Table 2). These results seemed appropriate as higher temperatures produce larger hydraulic conductivities and higher drainage velocities. This is consistent with, for instance, the Jury and Horton (2004) rectangular drainage model, which would show faster drainage with higher K_{sat}.

2.2 Parameter estimation for a base case flow event

Correlative models are used widely in hydrologic sciences due to their computational efficiency and their ability to assimilate data continuously (e.g. Modarres 2007; Ramos 2006). Some of these models are based purely on correlation, while others make an explicit effort to link the correlative relationships to more complex and computationally intensive physical models (e.g. Gau et al. 2006). One clear danger of correlation-based approaches is that observations may be correlated with other, unmeasured states, leading to incorrect assumptions regarding causation. In contrast, while physical models are better able to identify sensitivities to and interactions among parameters, and therefore to identify causation, they are susceptible to errors due to the exclusion of important processes during model conceptualization. This has led to recent efforts to formalize the process of model conceptualization (e.g. Sivakumar 2008). In the context of this study, a colleague (Shlomo Neuman, personal communication) pointed out that correlation-based

findings need to be supported by a physical model to ensure the purported interactions among environmental controls on drainage are reasonable. So, we decided to test our initial conclusions with a physically-based variably saturated numerical flow model.

Given the similarity in responses among the four laterally separated columns of sensors, water flow was assumed to be vertical during drainage. HYDRUS-1D (Simunek et al. 1999) was used to simulate infiltration and drainage. On the basis of core data, the subsurface was comprised of two layers (Table 1): a shallow streambed layer and an underlying basin fill layer. Therefore, although all of our measurements are located in the upper layer, we modeled the system using two layers, with a contact below our deepest measurement point.

One flow event was chosen as a base case: 12 October, 2000. This event was selected because it had intermediate values of temperature (21°C), flow duration (3 days), and elapsed time to 1.75 m (2.2 days) of the drainage front from 0.25 to 1.75 m depth. This allowed us to do single parameter sensitivity analyses, both increasing and decreasing each parameter, and then to compare the predicted and observed drainage velocities over the observed range of environmental conditions. The measured water content before the base case flow event began was about 0.29 cm^3/cm^3. The normalized antecedent water content for the base case event was 0.26 cm^3/cm^3 throughout the entire profile.

The first step was to adopt the soil hydraulic properties measured on core samples collected near the site (Table 1) together with the measured flow duration, antecedent water content, and antecedent water temperatures measured in the stream and within the soil matrix at each depth. Initially, the upper boundary was represented as a zero pressure head during flow and with a temperature equal to that of the stream water. Drainage was modeled with a zero flux top boundary and temperatures within the model domain equal to the antecedent temperatures. The upper boundary temperatures did not vary. To facilitate convergence of HYDRUS-1D with the recommended settings of the Picard numerical solution scheme, the van Genuchten n values were increased for both layers from their core-derived values (Table 1). All other soil hydraulic parameter values and environmental conditions were kept to their measured values. The model-predicted drainage behavior (Fig. 5a) was quite different from that observed in the field (Fig. 3a). Specifically, the simulated response did not show the characteristic rapid drainage at each depth with delays among depths seen in the field data. The model-predicted elapsed time to each measurement depth did not agree with the observations, either (Fig. 5b). The core-derived parameters were obtained from a well drilled in a small bench next to the stream channel. The bench appeared to have a higher content of fines than the coarse alluvium of the stream channel. Thus we considered that the upper layer hydraulic conductivity values from the bench may be lower than those in the stream channel. Hydraulic conductivities of the lower layer were assumed to be the similar between the well cores and layers underlying the trench.

Because the independently measured soil hydraulic properties did not predict the observed drainage behavior, we attempted to estimate the parameter values based on drainage velocity observations. For simplicity, hydraulic parameter values were varied manually to improve the fit to the observed elapsed times for the representative base case. During this manual parameter estimation, we kept as many of the measured core-based parameter values and environmental conditions equal to their measured value as possible. Indeed, we could fit the soil moisture observations reasonably well (Fig. 5c) by changing only the hydraulic conductivities of the two soil layers (Table 1). Specifically, we had to reduce the hydraulic conductivity of the lower layer to 5 cm/day to match the delay in drainage among the different measurement depths. This inferred value is similar to the lowest core-measured value of 7 cm/day. The hydraulic conductivity of the upper layer was increased to three times the highest core measurement to produce the rapid drainage observed at each measurement depth. The fit between the simulated and measured elapsed time to 1.75-m depth can also be considered reasonable (Fig. 5d). No formal estimation of parameter uncertainty was conducted for this analysis because our objective was to test the validity of our conceptual model of temperature dependent drainage, rather than to determine the soil hydraulic parameter values for predictive modeling.

2.3 Hypothesis testing: dependence of drainage velocity on temperature

Having matched the base case response, the manually calibrated HYDRUS-1D model was used to examine the dependence of drainage velocity on temperature, flow duration, and normalized antecedent water content. With our event-based modeling approach, we could not examine the impacts of changes in the no-flow period. For the remaining four variables (temperature, duration of event, maximum stage, and normalized antecedent water content), each parameter value was varied over its observed range while maintaining the values of all other base case parameters and environmental conditions.

Results from the single parameter manual sensitivity analysis indicate that the observed temperature variations cannot explain the observed range of variation of the drainage velocity (Fig. 6a). Specifically, despite the strong correlation between drainage velocity and temperature observed in the field data (Fig. 4) the numerical model

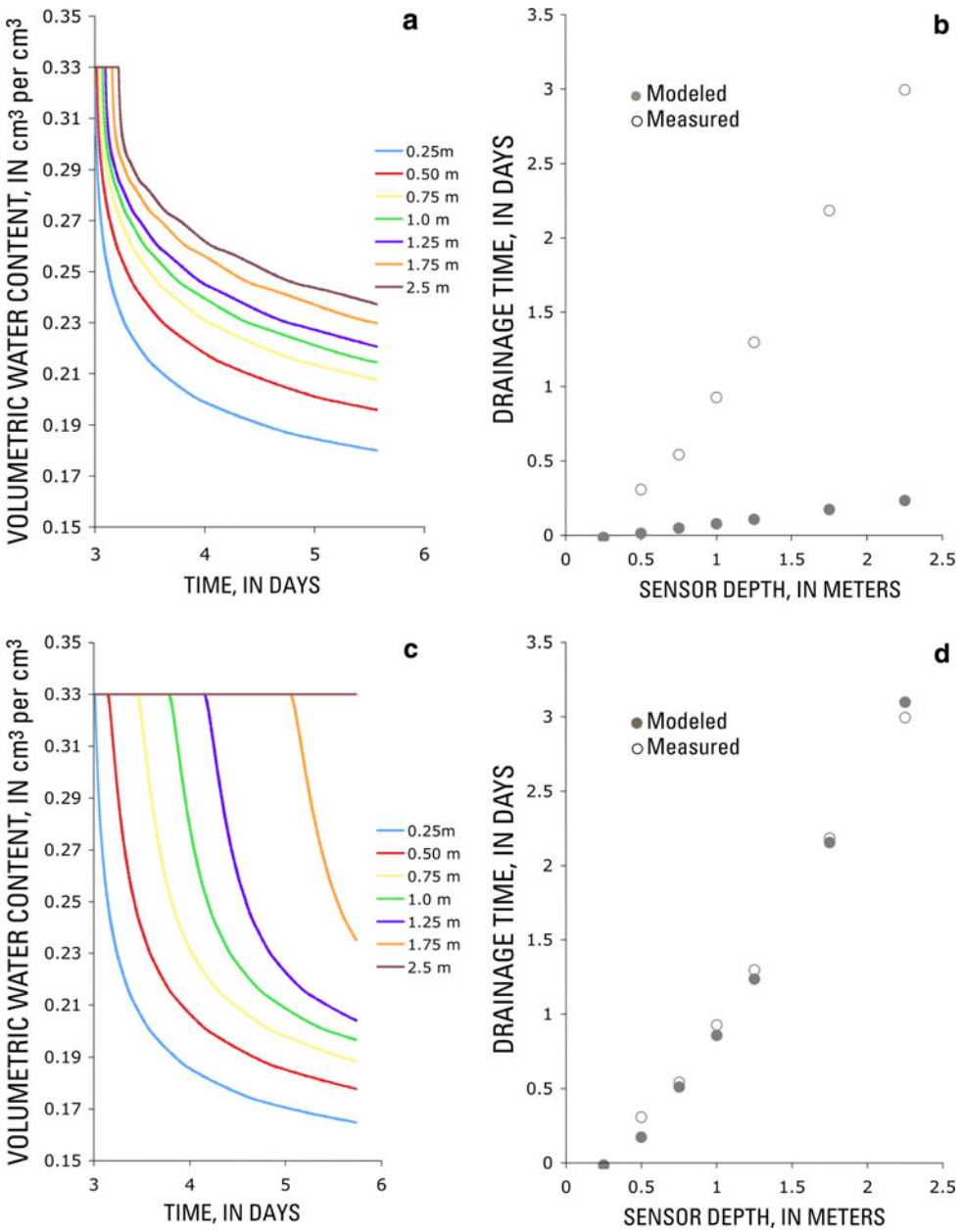

Fig. 5 **a** Simulated water content (cm^3/cm^3) at each measurement depth based on core-derived parameters; **b** measured and simulated elapsed time (days) for the drainage front (defined as a volumetric water content of 0.30 cm^3/cm^3) to reach each measurement depth based on core-derived parameters; **c** simulated water content (cm^3/cm^3) at each measurement depth using calibrated parameters; and **d** measured and simulated elapsed time (days) for the wetting front to reach each measurement depth based on calibrated parameters

contradicted our initial conclusion that water temperature is a primary control on drainage velocity.

Having disproven our initial, data-driven primary hypothesis, other possible physical causes for the changes in drainage velocity were considered. Antecedent water content was evaluated because it can control the capillary gradient at the wetting front during drainage. Specifically, higher initial water contents would result in decreased capillary gradients across the wetting front, thereby slowing drainage. This assumes that increases in unsaturated hydraulic conductivity from higher initial water contents are small compared to the range in conductivities caused by capillary gradients. However, similar to the results for water temperature, variations in antecedent water content within the numerical model could not explain the observed variations in drainage velocity (not shown). Next, the duration of flow was evaluated. Flow duration contributes to wetting front depth at the end of the flow event and, thereby, the contribution of capillarity to the drainage response. Specifically, shorter flow duration would result in a larger capillary gradient from the ground surface across the wetting front, leading to faster drainage. In fact, the modeling results support this interpretation: the observed range of variations in flow duration explains most of the observed variation in drainage velocity (Fig. 6b). Only two flow events with short flood durations and long drainage times

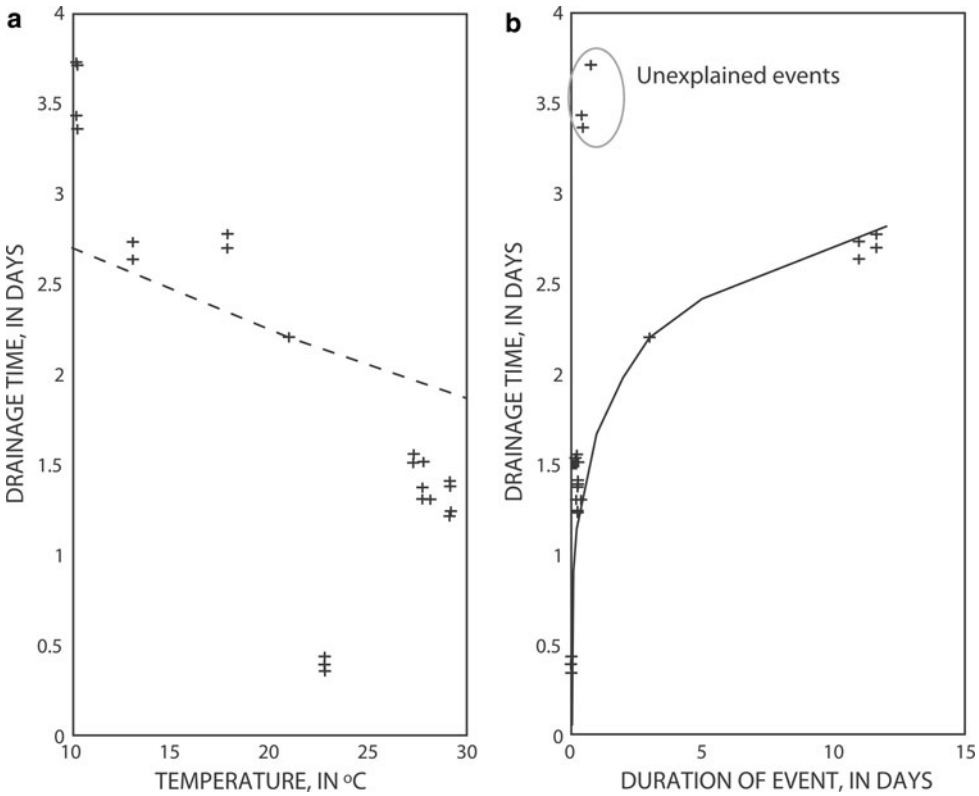

Fig. 6 Simulated drainage time from 0.25 to 1.75 m as a function of **a** temperature and **b** length of event. Drainage was simulate using a two-layer, one-dimensional flow model, HYDRUS 2-D (Simunek et al. 1999). The model was calibrated to the flow event with a temperature of 21°C and a duration of 3.3 days. The temperature and then the duration of event were varied while all other parameters were held constant to produce the results shown by the *dashed* (temperature) and *solid* (duration of event) shown. *Crosses* represent the observed data

could not be explained using the calibrated model. This suggests that there is at least one other process that is not considered in our conceptual model.

2.4 Comparing correlation-based and physically-based data analysis approaches

The correlation-based approach to data analysis suggested that the drainage response was primarily controlled by temperature, with a secondary dependence on no-flow period. In this case, the rapid drainage events that are not explained by a linear dependence on temperature are associated with the longest no-flow periods (Fig. 4e and b). This could suggest that something related to long no-flow periods has a strong influence on the drainage responses. But, closer inspection suggests that the result may be an artifact of the partial least squares regression approach and the assumption of a linear relationship. Specifically, the drainage times that are not explained by temperature have no-flow periods that are far longer than the other flow events (Fig. 4b). Therefore, including no-flow period in a multiple linear regression can change the predicted response for the outlying events (where no-flow period has large leverage) while having very little impact on the predictions for the events that are explained by a linear temperature dependence (where no-flow period has very small leverage).

More critically, HYDRUS-1D showed that the slope of the dependence of drainage velocity on temperature that is evident in the data is not consistent with the physical dependence of drainage on temperature. In fact, in Tucson, winter flows are characterized by cold water temperatures and longer durations; whereas summer flows have warm water temperatures and shorter durations. Therefore, much of the apparent dependence of drainage velocity on temperature may actually be due to correlation of temperature with flow duration. This points out a critical limitation to correlation-based analysis: unrecognized relationships, primarily nonlinear in nature, between variables can result in misinterpretation of causative relationships.

Sensitivity analysis using HYDRUS-1D suggests strongly that flow duration controls the drainage response for all but a few events (Fig. 6b). Longer duration flow events resulted in a decreased drainage rate. In general, capillary gradients in the subsurface profile exhibit the greatest influence on drainage at the cessation of flow. Thus a longer duration event with a large infiltration of water into the subsurface reduces the capillary gradients. The larger infiltration of water can result from ephemeral events characterized by low antecedent water contents, high stage, high temperatures, and longer duration. However, the greatest volumes of water transmitted to the sediment profile occur with duration. While temperatures from infiltrating water can persist in the subsurface after the cessation

of streamflow the depth of influence is limited to the upper sediments and magnitude of impact decreases with time.

This physically-based analysis leads to more convincing explanations of drainage behavior for most of the flow events, and only two events (Jan 16, 2001; Jan 27, 2001) are not explained using this analysis. These two unexplained events had a confounding impact on the results of the correlative analysis. The two unexplained events had the lowest water temperatures (10.3°C, 10.3°C), relatively short no-flow (2.6 days, 10.6 days) and flow durations (0.49 days, 0.82 days), relatively low stage (6.7 cm, 34.4 cm) and intermediate antecedent water contents (0.29 cm^3/cm^3, 0.22 cm^3/cm^3). These drainage events occurred during and after five consecutive flow events from January 8 through 27, 2001. The two outlying events (each with two profiles) are labeled on Fig. 5b. It is suggested that the consecutive events prior to these two events could be acting as a single long duration event and thus antecedent conditions in the water profile are not accurately represented. Even considering the multiple short duration events as a single event does not account for the drainage rate. Future research should focus especially on drainage following successive cold flow events or, perhaps, on identifying other properties that were not measured that could explain these two responses.

Our initial conceptual model was based on standard treatments of one-dimensional infiltration and drainage in a homogeneous porous medium. Solutions such as those presented by Philip (1957) suggest that infiltration will be high at early stage of wetting and will reduce with time as the contribution of sorptivity decreases. Similarly, simple drainage models, such as the rectangular drainage model presented by Jury and Horton (2004) suggest that the wetting front velocity will decrease with time as the profile drains. For the flow events observed during this investigation, we expected infiltration would be dominated by gravity and that drainage would be dominated by the hydraulic properties of the medium that control the hydraulic conductivity. Our initial conceptual model was further influenced by the data we had available. As is commonly the case with correlative approaches, we sought explanations of our observed behavior (drainage velocity) based on our available data (water temperature and water content in the shallow sediments with time). In retrospect, it is clear that the correlative approach was misleading because flow duration and water temperature were highly correlated. But, neither our initial conceptual model nor our available data and linear correlative analysis suggested flow duration as a primary control on drainage velocity. Thus, an additional, although basic point, is that the independency of relationships between interrogated variables is important to consider when investigating regressions of variables no matter how minor the relationship determined by the preconceived conceptual model.

2.5 Implications of correlation- and physically-based analyses for water management

In a managed stream reach, optimal water availability in the rhizosphere can be adjusted to match the requirements of the local riparian vegetation (Leenhouts et al. 2006; Stromberg et al. 2007). Results of our physically-based analysis suggest that for Rillito Creek and other similar environments the length of flow should be adjusted to control the length of time that water will be available to plants after a flow event. In contrast, the correlation-based analysis suggested that water temperature is the primary control variable. The inconsistency is related to the correlation between temperature and event durations as well as the use of a tool that may not discern nonlinear relationships. These differing interpretations between numerical modeling and correlative analysis could have significantly different implications for water resources management practices, especially for assessing the relative risks of different approaches for controlled release of water into ephemeral channels, construction of detention facilities, or other channel adjustment features (restorative or artificial).

3 Conclusions

As is the case for many ephemeral channels in alluvial aquifer systems, the hydrogeology of Rillito Creek consists of a coarse-grained highly permeable alluvial layer overlying a finer-grained and less permeable basin-fill layer. We observed a distinctive drainage response following many flow events, with a sharp drainage front advancing downward with time. This response has significant impacts on the availability of water to near- and in-channel vegetation. A physically based one-dimensional numerical flow model replicated this response for all but two events. The hydraulic parameters inferred from the model fits and from cores are similar to those measured in other ephemeral streams (Coes and Pool 2005), suggesting that the observed drainage pattern is not specific to the Rillito Creek, but may occur in many ephemeral channels.

The observed drainage front velocity showed a clear linear correlation with water temperature. Partial least squares regression analysis suggested that temperature and the duration of the no-flow period preceding the monitored drainage event could explain more than 90% of the variability in observed drainage velocity. However, numerical water flow simulations showed that the measured variations in soil temperature cannot explain the observed variations in drainage velocity. Rather, the physically-based model

indicated that the duration of the flow event preceding the monitored drainage event is most important in determining drainage velocity. Capillary gradients in the subsurface profile exhibit the greatest influence on drainage at the cessation of flow. Thus a longer duration event with a large infiltration of water into the subsurface reduces capillary gradients.

In summary, this work provides two important conclusions. First, this study presents a simple, yet powerful example of the potential pitfalls of depending solely upon correlative data analyses to understand or predict hydrologic processes. Second, the dependence of drainage velocity on event duration has direct implications for the time that water is available for use by plants in ephemeral channels and for the assessment of alternative approaches for stream restoration.

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