Infiltration on alluvial fans in arid environments: Influence of fan morphology

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[1] Mountain-front recharge through highly permeable alluvial fans can be an important source of groundwater recharge in arid climates. To better understand the geomorphic factors (e.g., fan slope, fan area, active channel proportion of fan area, sediment permeability, and entrenchment of the active channel) that control flow and infiltration on alluvial fans, we developed a coupled numerical model of steady surface water flow and Green-Ampt-type infiltration. The model was applied to synthetic alluvial fans using random walkers to create connected distributary networks. The purpose of this approach is to predict where and how recharge occurs on fans as a function of fan morphology. Using the numerical model, we examined how the fan shape and the sequence of fan surfaces influenced where infiltration occurred on the fan. We also investigated how fan morphology influenced the partitioning of infiltration between the fan and the valley floor. Finally, we examined how infiltration influenced the spatial distribution of flooding. The greatest amount of infiltration occurred on low gradient fans where water spread laterally with shallower ponded water depths, although the large inundation area often included less permeable sediments outside of the active channel. The ratio of the incision depth to the input flow depth was an important predictor of the amount of infiltration. The greatest amount of infiltration occurred on fans with incision depths slightly smaller than the input flow depth. These results have implications for groundwater resource assessment and for development of monitoring networks on fans in arid environments.


1. Introduction

[2] Flooding on alluvial fans, where highly permeable fan deposits surround a basin, can be an important source of groundwater recharge in arid environments [Bull, 1977; Hendricks et al., 1991; Houston, 2002]. Surface flows from upland catchments are focused at the fan apex where channels distribute flow toward the valley floor over gently sloping fan deposits. Prediction of the amount and location of infiltration on fans is difficult due to complex flood behavior and the heterogeneous and poorly constrained permeability structure of fan sediments. Flooding on fans is typically characterized by deep channel flow in several large channels with a complex distributary channel network [National Research Council, Committee on Alluvial Fan Flooding, 1996]. Infiltration is controlled by the spatial distribution of paleosols [Weissmann and Fogg, 1999; Bennett et al., 2006] that can lower permeability values locally by up to two orders of magnitude relative to the parent material [McFadden et al., 1987, 1992; McDonald et al., 1996]. Often only limited hydrologic information is available to constrain predictions of distributed infiltration on fans. Typically, only sparse streamflow data or flood stage information has been collected due to infrequent flows of short duration coupled with the uncertainty of where these flows will occur.

[3] Mountain-front recharge through alluvial fans, an intermittent recharge mechanism, is not easily quantified for groundwater resource evaluation [Houston, 2002; Weissmann et al., 2002b] due to complex responses to climate change, climate variability, and changes in land use. Quantifying infiltration over large areas is complex because of the large spatial and temporal variability of infiltration observed whether using point-scale measurements (direct physical methods, indirect physical methods, environmental tracers) alone or in combination with larger-scale geophysical methods used to interpolate and extrapolate between point measurements [Liu et al., 1995; Scanlon et al., 1999; Massuel et al., 2006]. On highly permeable alluvial fans, a combination of water level, soil texture, and hydrochemical data have been used in event-based distributed models to estimate water fluxes and traveltimes to the water table in arid environments [Houston, 2002; Massuel et al., 2006]. For example, for a flash flood event that occurred during...
January 2000 on a fan in arid northern Chile, about 70% of the flow percolated to the underlying aquifer producing groundwater rises at the distal portion of the fan that persisted for 5 to 9 months [Houston, 2002].

Mountain-front recharge through alluvial fans is a function of morphology (topography, soil texture, vegetation) as well as channel and flow characteristics [Houston, 2002; Izibicki et al., 2002]. Geomorphology provides an alternative approach to point-scale field measurements of infiltration to characterize infiltration over large areas in arid environments [Scanlon et al., 1999]. Previous field studies in arid settings have shown that the spatial variability in infiltration is related to the geomorphic setting as distinguished by interdrainage area, topographic depression, and drainage area [Scanlon et al., 1999] or by distance from the mountain front [Izibicki et al., 2002]. The objective of this study is to examine the influence of fan morphology on infiltration on fans using simple observables. Specifically, we considered how the shape of the fan and the sequence of fan surfaces influence where infiltration occurs using a two-dimensional (2-D) distributed numerical model of synthetic fans with coupled surface flow and infiltration. Another characteristic of fan morphology with significance for infiltration is the permeability of fan sediments, which is related to the depositional environment, fan age, soil development, and geology of the source basin [Weissmann et al., 2002a; Young et al., 2004; Winfield et al., 2006]. Using the numerical model, we also examined how fan morphology, including sediment permeability, influences the partitioning of flow between on-fan flows and those that extend downslope of the fan environment. Finally, we examined how infiltration affected the spatial distribution of flooding during flow events. The purpose of this approach is to predict where and how recharge occurs on fans as a function of fan morphology. These results can be used to guide the development of monitoring networks on fans, guide geomorphic mapping for flood hazard prediction, and characterize the infiltration to runoff ratio at the basin scale which is important for groundwater resource assessment.

2. Conceptual Model of Alluvial Fans

Alluvial fans are sedimentary landforms that form at the base of mountain fronts where confined feeder streams emerge onto valley floors and deposit the sediment load of the streams. Alluvial fans develop where there is sufficient sediment supply, sediment accumulation, and adequate relief for vertical fan growth. Alluvial fans comprise greater than 30% of the landscape of the southwestern U.S. [Antsey, 1965]. The planform morphology of an alluvial fan is generally semicircular whereas the three-dimensional morphology is conic; the fan apex is located at the point where the feeder stream emerges from the base of the mountain front. Deposition occurs as a feeder stream emerges from a steep channel near the mountain front due to a decrease in stream competence associated with the unconfined nature of flow on fans and, secondarily, due to a decrease in channel slope [Bull, 1977]. If a fan is unrestricted by adjacent fans, distributary channels form a radial pattern emanating from the fan apex. Overall, radial topographic profiles are concave-upward or of almost constant slope and cross-fan profiles are concave-downward [Bull, 1977; National Research Council, Committee on Alluvial Fan Flooding, 1996]. Typical fan radii range from 5 to 15 km and vary in slope between 0.5 and 10 degrees [Rust and Koster, 1984].

In the basin and range physiographic province of the western U.S., many alluvial fans are composed of a suite of terraces that rise from the active channel as a sequence of steps. Fans in Death Valley, California exemplify this classic form which is created by temporal changes in the sediment composition and sediment concentration in the channels draining the mountain front [Bull, 1977, 1991]. During aggradational periods, the ratio of sediment to water flux is high and sediment is deposited across the fan, or in the available area adjacent to an older abandoned terrace, to form a low-relief deposit via repeated episodes of channel avulsion [Bull, 1979]. In contrast, entrenchment occurs during periods with a lower ratio of sediment to water flux. Conditions that result in a reduced ratio of sediment to water flux are numerous and include cooler and wetter climate conditions that revegetate hillslopes and anchor the regolith [McDowell et al., 2003].

On stream-dominated alluvial fans, incision at the fan apex produces a fan-head trench in which the longitudinal stream profile is at a lower elevation and lower gradient than the surrounding fan surface. The trench is deepest at the apex and becomes shallower with distance downfan. In general, the greatest difference in elevation between the active channel and older surface deposits occurs near the fan apex and may range over tens of meters. Near the toe of the fan, however, the difference between the oldest and youngest deposits may be less than 1 m. Shifts in the location of the intersection point, both upfan and downfan, over time create sequences on the alluvial fan.

Fan sediments are complex and heterogeneous [Weissmann and Fogg, 1999; Weissmann et al., 2002a] because deposition occurs by numerous surges of sediment-laden water and backfilling of channels. For example, fan sediments may be debris flow dominated at the apex while the distal portion of the fan may be dominated by fluvial sands. Many fans have near-surface sediments that progressively fines with distance away from the fan apex [Bull, 1964; Waters and Field, 1986] while other fans are poorly sorted and have planar bedding [Blair and McPherson, 1994]. Previous studies of fans of the Mojave Desert found significant correlation between surface age and surface sediment texture [McFadden et al., 1987, 1992]. For example, Young et al. [2004] found significant correlation between the surface age and texture of Quaternary soils from five sampling sites located on a broad alluvial fan in the Mojave National Preserve in California. More than 90% of the variability in the saturated hydraulic conductivity of these samples was explained by the age of the soil [Young et al., 2004]. Younger soils had higher sand contents and high hydraulic conductivities. As the surface age increased there was a reduction in the sand content and a corresponding increase in the content of silt and clay [Young et al., 2004]. Young et al. [2004] concluded that a single-soil modeling approach for soil water retention was appropriate for both younger soils, which had no significant soil horizon development, and for older soils in which the wetting front remained in a fine-grained, gravel-poor vesicular A (Av) horizon.

The Av horizon, or any horizon that produces a larger permeability contrast with surrounding deposits, has impor-
tant implications for infiltration and ecological processes at both intradrainage and interdrainage scales. The fine-grained Av horizon is a widespread surficial horizon of desert soils that almost consistently occurs below a desert stone pavement [e.g., McFadden et al., 1987, 1992] and is associated with soils forming in hot and arid climates. Fines entrained by the wind and dispersed over the landscape accumulate over long timescales to form this horizon. Entrapment of fine material is augmented by desert pavement due to the surface roughness which creates local airflow turbulence and results in deposition of eolian material [Wells et al., 1985]. The rough surface of the desert pavement also protects the dust from raindrop impact [McFadden et al., 1998]. The source of the dust is often playa basins in both modern times [Reheis and Kihl, 1995] and during the Pleistocene-to-Holocene transition which may have resulted in an increase in dust accumulation and soil development as the climate become more arid, with a reduction in vegetation, and the playas expanded [e.g., Wells et al., 1985; McFadden et al., 1992; Reheis et al., 1995].

[10] Beneath the Av horizon of Late Pleistocene soils, at depths of 3 to 4 cm, there is often a Bt argillic horizon that has developed from the downward movement of soluble or suspended material of high clay content from the A horizon into the B horizon. In such soils the Bt horizon extends to a depth of about 50 cm. Also, below the Bt horizon there is frequently a Bk or calcic horizon that develops from the accumulation of calcium carbonate in the soils which extends to a depth of 75 or 150 cm [McFadden et al., 1998].

[11] More recently, Winfield et al. [2006] examined alluvial fan sediments from Oro Grande Wash and Sheep Creek Wash in the western Mojave Desert and noted the impact of textural and structural characteristics on the relation of water content to water potential and unsaturated hydraulic conductivity. Structure was defined as the arrangement of soils resulting from aggregate formation, depositional sorting, shrink-swell processes, and macropores from animal burrows and root channels. Texture was determined to have a greater influence than structure on the water retention properties of the water-laid and debris-laid sediments [Winfield et al., 2006].

[12] In addition to sediment texture, infiltration on fans is also strongly dependent on the morphology of the fan drainage network which can be grossly characterized by the intersection point. Upfan of the intersection point the stream is incised into the fan surface and is part of a tributary drainage network while downfan of the intersection point the drainage network spreads across the fan and deposition can occur [Hooke, 1967]. The drainage network on alluvial fans is not static on human timescales [e.g., National Research Council, Committee on Alluvial Fan Flooding, 1996; Klawon and Pearthree, 2000; Field, 2001]. When floods deposit large quantities of sediment the conveyance capacity of the channel is reduced which can result in forcing flows overbank into adjacent channels. Conversely, the drainage network can also be modified by channel erosion from overbank flooding.

[13] Fans with deeply entrenched main stem channels and a narrow active channel area in planform are generally associated, along with other factors, with low sediment supplies from upland drainages. Examples of such fans are the fans of the Tortolita piedmont [Pearthree et al., 1992; Demsey et al., 1993; Vincent et al., 2004] near Tucson, Arizona and the Harquahala piedmont near Phoenix, Arizona [Klawon and Pearthree, 2000; Pearthree et al., 2004]. Fans of the opposite end-member type have shallow entrenchment (less than 1 m) at the apex and active channels with rapid lateral expansion with downfan distance. These types of fans are typical of depositional environments with sufficient sediment supplies to maintain the backfilling of channels. In the Little Rainbow Valley near Phoenix, Arizona, both types of fan morphologies occur juxtaposed on either side of a valley (Figure 1). To the northeast of Little Rainbow Valley are the Sierra Estrella Mountains (Figure 1) which exemplify fans with shallow entrenchment and a wide active channel area. The Maricopa Mountains, located to the southwest of Rainbow Valley (Figure 1), exemplify the deeply entrenched and narrow active channel area morphology.

[14] Numerous numerical models of alluvial fans [e.g., Price, 1974; De Chant et al., 1999] have been developed. Many of these simulate the evolution of alluvial fans and morphological feedbacks of both external forcings (changes in base level, changes in flood magnitude and frequency associated with climate change, and changes in water and sediment inputs to the fan) and autogenic mechanisms [e.g., Coulthard et al., 2002; Nicholas and Quine, 2007]. In this alluvial fan model we focus on the relationship between fan morphology and the hydrologic response with consideration of the dynamic nature of the drainage network.

3. Numerical Model

[15] The numerical model consists of the equations used to define the geometry of a fan and its distributary channel system, routing of surface flow, and infiltration of surface flow. A random network of distributary channels was created using a random walk technique as described below in section 3.1. Flow events were characterized by the duration of the flow event and a time-invariant discharge in the feeder channel applied at the fan apex. Steady-surface flow was routed based on the continuity equation and Manning’s equation [Chow, 1959] using an iterative finite difference approach [e.g., Pelletier et al., 2005] as described in section 3.2. Green-Ampt infiltration was applied as a sink for surface flows as described in section 3.3.

[16] The driving input to the model is water depth in the active channel at the fan apex. In the application portion of the paper, we considered a range of flow depths between 0.5 and 1.0 m. On the basis of streamgage data from piedmonts in Maricopa County [Flood Control District of Maricopa County (FCDMC), 2006] and on paleoflood reconstructions for five canyons supplying flows to the Tortolita fan complex [House, 1991], we noted small variations in flow depth for a two order of magnitude range in drainage area (4.7 km² to 390 km²) (Figure 2). For each gaging station, the three largest peak flows on record were plotted as was any available historical flood information. The period of record for these stations ranged from 4 to 16 years. The error bars on flood depths determined from paleoflood reconstructions represent variations due to assumptions about subcritical or supercritical flows, and the range in
elevations of the slack water deposits or other paleostage indicators [House, 1991] at the study site. Most flows, 28 out of 33, have depths between 0.5 and 1.75 m (Figure 2). This small variation in flow depth is a result of channel adjustment to maintain critical flow which is highly efficient for routing water through channels [Bull, 1979; Grant, 1997]. This range of flow depth for Maricopa County is similar to alluvial fan bankfull depths of 0.5 to 1.5 m observed at fan heads in the western U.S. [Stock and Schmidt, 2005].

3.1. Alluvial Fan Geometry

[17] The radially symmetric fan has a constant slope along the longitudinal axis (Figure 3) and the cross-fan topographic profile is concave-downward (Figure 4). In our study, the suite of fan terraces frequently found in the Basin and Range was simplified in the numerical model and only two surfaces were simulated. While most fans have a sequence of several older terraces, we represented this sequence as a single integrated unit in this model. The entrenchment depth diminishes from a maximum at the fan apex to a minimum value of zero at the toe of the fan. The

![Figure 2.](image)

Figure 2. Drainage area versus flow depth for 7 gaging stations on piedmonts in Maricopa County [FCDMC, 2006] and paleoflood reconstructions for 5 canyons supplying flows to the Tortolita fan complex. For each gaging station, the three largest peak discharge events during the period of record plus any available historical flood events were plotted. For the paleoflood data, the error bars on the flow depth represents a range in the discharge estimates.

![Figure 1.](image)

Figure 1. (a) Image of Little Rainbow Valley which is located to the southwest of Phoenix, Arizona. Waterman Wash runs through the center of Little Rainbow Valley (3× vertical exaggeration). Image from NASA World Wind, LandSat7. (b) Image of the Maricopa Mountains from Google Earth, 2.75× vertical exaggeration. (c) Image of the Sierra Estella Mountains from Google Earth, 2.75× vertical exaggeration.

![Figure 3.](image)

Figure 3. Schematic of alluvial fan model with fan geometry input variables identified (I is the incision depth at the fan apex, L is the relief of the fan, R is the radius of the fan, $x_j$ is the horizontal distance to grid cell $j$, and $w_0$ is the channel half-width at the fan apex).
The model domain is a square that encompasses the fan radius at the toe of the fan. The topographic elevation at each node of the inactive surface is calculated as:

\[ z_{ij} = \frac{L}{R} \left( \frac{R - x_{ij}}{R} \right) \]  

where \( L \) is the total relief of the fan, \( x_{ij} \) is the distance between the fan apex and location \((i, j)\) in a horizontal plane, and \( R \) is the fan radius.

The most prominent topographic feature is the entrenchment of the active portion of the fan. The alluvial fan consists of an entrenched or active channel area, and an overbank flow area, or inactive area which is the highest topographic surface and represents the oldest geomorphic surface (Figure 3). The term inactive surface is a bit of a misnomer as this surface is inundated in the model and is hence more appropriate thought of as a less-active surface. For the active portion of the fan the maximum incision depth at the fan apex, \( I \), is used to calculate the topographic elevation at each node as:

\[ z_{ij} = \left( L - I \right) \left( \frac{R - x_{ij}}{R} \right) \]  

where \( x_{i} \) is distance down fan in the \( i \) direction, \( \ln \) is the natural logarithm, \( w_{0} \) is the half-width of the active channel at the apex, and \( R \) is the fan radius, and the variable \( w \) is the half-width of the active channel at a downfan distance of \( i \). For a fan with a channel half-width at the apex equal to 2.3% of the fan radius (3.0 km), a \( c \) value of 5 results in downfan expansion of the active channel such that the radius of the active channel is 23% of the total fan radius at the toe of the fan, a downfan distance of 100% (Figure 5).

In the numerical model the elevation of the two fan surfaces above the active channel is determined by the fan gradient and the entrenchment depth of the active channel. Consequently, the value of these parameters affects the geomorphic interpretation of these surfaces as does the sediment permeability. Real-world fans have dissected early to mid-Pleistocene surfaces that will not be inundated even during the largest floods except perhaps at the distal portion of the fan where the depth of dissection is small. Mid-Holocene deposits, however, are expected to be inundated on occasion near the proximal portion of the fan and to have undergone some soil development processes. Consequently, the highest topographic surfaces in the model represent modern to mid-Holocene deposits while the active channel deposits are conceived of as modern.

\[ w = w_{0}\left(1 + \frac{x_{i}}{R}\right)^{\frac{w_{0}}{R}} \]  

Figure 4. Fan geometry for the case-study of Tiger Wash, Maricopa County, Arizona. (a) longitudinal profile down the fan (vertical exaggeration 8), (b) radial cross-section middistance down the fan (vertical exaggeration 1600).

Figure 5. Plan view of the widening of the active channel with distance along the longitudinal axis as specified by the variable \( c \) for a feeder channel half width that is 2.3% of the radial distance of the total fan radius. \( c \) values of 7, 20, and 40 correspond to configurations where the active channel area is 15%, 34%, and 49% of the total fan area (9 km²).
Within the entrenched portion of the fan a network of distributary channels were created using a random walk method [Price, 1974]. Random numbers were used to determine the location of channels in the active portion of the fan based on specified probabilities. A set of random walkers (one for every pixel in the input channel cross section) was initiated at the top of the fan. If a grid node is located in the entrenched channel at the top of the fan, and a randomly drawn number is less than 0.5, then a set of \( N \) nodes located one node downfan and toward the right bank is specified as a channel if it is also located within the entrenched portion of the fan. If another independent random number is less than 0.5 and another independent random number is less than \( p \), then a set of \( N \) nodes located one node downfan and toward the left bank is specified as a channel if it is also located in the entrenched portion of the fan. The value of \( N \) increased downfan following equation (3). In this way, a connected distributed network was created that expands geometrically downfan (Figure 6d). This application of the random walk method resulted in three distinct topographic surfaces which represent the smoother and higher topographic surface of the unentrenched portion of the fan, a lower topographic surface that represents the active portion of the entrenched channel, and a topographic surface consisting of islands of higher topography within the entrenched channel (Figure 6) which have the same height as the unentrenched portion of the fan. Consequently, differences in altitude between the islands and the surrounding terrain diminish downfan such that near the toe of the fan, several shallow distributary channels may merge into a broad sheet of flow.

Figure 6. Examples of \( p \) values used to define topographic surfaces in plan view. Black areas correspond to the oldest unincised surface, white areas correspond to the topographic islands in the active channel, and the gray areas correspond to the lowest topographic surface in the active channel for a single random realization of topography. (a) \( p = 0.15 \) (b) \( p = 0.5 \). (c) Surface flow depth for a flow of a 1 h duration and an input flow depth of 1.5 m \((p = 0.3)\). (d) Inset of flow depth near fan apex.
The continuity equation is the basis for all flow routing models and states that the imbalance in the rate of mass leaving the system equals the rate of change in mass in the system or

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v})$$  \hspace{1cm} (4)

where $\rho$ is the density of the fluid, and $\mathbf{v}$ is the velocity vector. With the assumption of steady flow the rate of change of mass in the system is zero. Furthermore, if the fluid is assumed to be incompressible (of constant density), the continuity equation reduces to

$$\nabla \cdot \mathbf{v} = 0.$$  \hspace{1cm} (5)

Expressed over a control volume in finite difference form in two-dimensions, equation (5) yields:

$$\frac{Q_{ix,i} - Q_{ix,i+1} + Q_{iy,i+1} - Q_{iy,i}}{\Delta x \Delta y} = 0$$  \hspace{1cm} (6)

where $Q_{ix,i}$ and $Q_{iy,i}$ are the volumetric discharge rates in the $x$ and $y$ direction and $\Delta x$ and $\Delta y$ are the pixel dimensions.

Discharge in the entrenched channel at the fan apex, specified as a flow depth which depends on the fan slope and roughness, was the input forcing to the model. With the exception of this constant-head boundary at the apex of the fan, the model boundary conditions are head-dependent flux (or a Cauchy-type boundary condition) thus the flux at the model boundary is determined by the depth of surface water. A bifurcation method was used to route flow to multiple downslope directions, with a maximum of 8 possible directions (4 cardinal and 4 intercardinal), weighted by bed slope [Freeman, 1991]. The routing algorithm was initiated by ranking all grid nodes in the model domain from high to low elevation. Beginning with the highest elevation node, surface flow was distributed to all of the neighboring downslope nodes, weighted by slope. Specifically, the outflow from a cell is shared between all of the adjacent cells of lower elevation. The fraction of flow passed on to the adjacent cell $i$ is the maximum of 0 and the surface water slope of cell $i$ divided by the sum over each of the 8 adjacent cells of the maximum of 0 and the slope of each adjacent cell. Next, routing was performed for the second-highest elevation node in the basin, and then proceeding by rank order to the lowest elevation node, This method ensures that incoming flows have been accounted for prior to the distribution of flows downstream. The bifurcation method with multiple downslope directions affords an advantage for modeling distributed flow across low-relief surfaces [Clevis et al., 2003]. Steady state flow depths were determined by applying the Manning’s equation to the routed discharge at each node. The bed roughness coefficient, or Manning’s $n$, was set to 0.035 (Table 1).

To route flow down the fan, the downstream ranked order must be determined a priori. Because the downstream rank order of the bed topography and the down stream rank order of the water surface profile may differ, the flow routing algorithm was implemented iteratively. For each of $n$ iterations, flow in the feeder channel was routed downfan based with bifurcation routing determined by the rank order of the water or ground-surface elevation. For the first iteration, ranking was based on the ground-surface elevation or bed topography. For each subsequent iteration, a small fraction of the calculated water depth was added to the topography of the bed to create a new topographic surface at each node. This new topographic surface was used to rank and route flow downstream to determine a new surface water profile. This process was repeated until convergence was achieved when the total...
mass of water on the fan did not increase with additional iterations.

For this paper, the assumption of steady flow (depth and velocity do not vary with time at a given location) oversimplifies the hydrologic system considering flow events in arid climates are often of short duration and have hydrographs with steeply sloped rising and falling limbs. However, steady flow was an appropriate level of complexity for examining a variety of synthetic fans geometries with inputs based on arguments about critical flow depth. In other applications such as an investigation of a particular real-world fan, steady flow is not likely an appropriate assumption if flood attenuation is important particularly if hydrograph data is available.

### 3.3. Infiltration

At each node surface water was lost to infiltration based primarily on the sediment permeability, the depth of surface water, and the flow event duration. We used the explicit Green-Ampt model to simulate infiltration because vertical infiltration models, and more specifically, infiltration approximated by the Green-Ampt solution have been successfully fit to measured profiles of infiltration in alluvial deposits including alluvial deposits with significant lateral flow [Martin et al., 1993]. The Green-Ampt model assumes piston flow through an unsaturated soil driven by the difference in the water surface potential and a constant wetting front capillary potential; water is assumed to infiltrate into a homogeneous soil as a saturated rectangular pulse at a uniform volumetric water content. For the Green-Ampt solution, the infiltration rate diminishes exponentially with time until approaching the saturated vertical hydraulic conductivity (Figure 7). The expression for the infiltration rate of the explicit Green Ampt solution consists of four terms that approximate an infinite series which results in less than 2% error when compared to the implicit Green-Ampt solution [Salvucci and Entekhabi, 1994]. The four term explicit solution for the infiltration rate is

\[
f(t) = f_s(1 - \frac{1}{3} + \frac{2}{3} \sqrt{\frac{t}{t + \chi}})
\]

where \(K_s\) is the saturated hydraulic conductivity, \(t\) is time, and \(\chi\), which has units of time, is defined as

\[
\chi = \frac{1}{K_s} \left( \theta_s - \theta_i \right) (-\psi_r + \psi_s)
\]

Table 2. Hydraulic Properties (Saturated Hydraulic Conductivity, Initial Water Content, Saturated Water Content, and Bubbling Pressure) for the Explicit Green-Ampt Solution Were Assigned on the Basis of the Geometric Mean Soil Texture [Rawls et al., 1992]

<table>
<thead>
<tr>
<th>Soil Texture</th>
<th>(K_s), cm/h</th>
<th>(\theta_i), cm³/cm³</th>
<th>(\theta_s), cm³/cm³</th>
<th>Bubbling Pressure, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>20.00</td>
<td>0.020</td>
<td>0.417</td>
<td>-7.26</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>5.98</td>
<td>0.035</td>
<td>0.401</td>
<td>-8.69</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>2.18</td>
<td>0.041</td>
<td>0.412</td>
<td>-14.66</td>
</tr>
<tr>
<td>Loam</td>
<td>1.32</td>
<td>0.027</td>
<td>0.463</td>
<td>-11.15</td>
</tr>
<tr>
<td>Silt loam</td>
<td>0.68</td>
<td>0.015</td>
<td>0.501</td>
<td>-20.76</td>
</tr>
<tr>
<td>Clay loam</td>
<td>0.23</td>
<td>0.075</td>
<td>0.390</td>
<td>-25.89</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>0.15</td>
<td>0.040</td>
<td>0.471</td>
<td>-32.56</td>
</tr>
</tbody>
</table>
Within the active portion of the fan, frequent flows deposit sand and gravel and consequently, the active channel was conservatively characterized by sediments of coarse sand. Islands of higher topography within the active channel area are inundated less frequently and some eolian accumulation of finer material may occur resulting in an increased proportion of silt and clay in the surface sediments. The undissected portions of the fan, which represents the oldest geomorphic surface, have the largest proportion of silt and clay. The active channel sediments, portions of the fan consisting of islands in the active channel, and the undissected portion of the fan are characterized by homogenous deposits of coarse sand, loamy sand, and sandy loam respectively.

At each node with a surface flow depth greater than zero, the explicit Green-Ampt solution, a time dependent solution, was applied to the steady state numerical model by calculating cumulative infiltration as a function of time. The applied infiltration rate corresponds to the median cumulative infiltration (Figure 7) for each soil texture. Thus cumulative infiltration determined from the explicit Green-Ampt solution at the duration of the flow event was applied as a constant infiltration rate in the steady state model. To implement this solution in the numerical model with minimal computation time, second order polynomials were fit to the time-dependent infiltration rate as a function of the surface water flow depth for each soil texture. Infiltration, a sink in the mass balance, was incorporated in the mass balance as:

$$d_o = d_i - \Delta x f / v,$$

where $d_i$ is the depth of surface water into a grid cell, $d_o$ is the depth of water out of the cell, and $v$ is the absolute magnitude of the velocity of the surface flow at the cell node, $\Delta x^2$ is the area of a square grid cell, and $f$ is the infiltration rate from equation (7). Since $d_i$ and $d_o$ were nearly identical, a single value of velocity was used for flow in and out of the grid cell (Figure 8).

4. Application

As an illustration of the model for a real-world example, we applied the numerical model to Tiger Wash near Phoenix, Arizona using existing geologic maps, streamflow data, a channel cross-section, and precipitation gage data. We compared surface flow depths and infiltration resulting from a low-recurrence interval monsoon event and a low-recurrence interval winter event. Monsoon storms which are primarily generated during July and August in the Sonoran Desert produce small-scale convective thunderstorms of short duration and high intensity. A second wet season occurs during the winter. During winter larger-scale frontal systems can persist for days creating storm events of much longer duration but typically of lower intensity than monsoon storms. On the basis of streamflow and precipitation gage data at Tiger Wash [FCDMC, 2006], we simulated storm events on 29 December 2004 and 25 August 2003 (Figure 9). The storm on 29 December 2004 was a typical winter flow event. Several precipitation events of increasing magnitude were recorded at the gage before any streamflow was detected due to the large drainage area of the watershed (221 km²). This storm produced 10 h of flow at the gage and a peak discharge of 105 m³/s. The monsoon event on 25 August 2003 produced flow at the gage for about 1 h,
peaking at a discharge of 23 m$^3$/s. Both flows are estimated to have recurrence intervals on the order of 2 to 5 years based on the gaged precipitation [FCDMC, 2006] and on the National Oceanic and Atmospheric Administration’s point precipitation frequency estimates [Bonnin et al., 2006].

4.1. Tiger Wash Case-Study

We applied water volumes in the observed hydrographs as a steady input discharge for the duration of the storm by integrating the hydrograph over the duration of the flow event and calculating time-invariant flow depth inputs (0.38 m and 0.23 m for the winter and monsoon flows, respectively) to the numerical model (Figure 9). Additional input variables were determined from a cross-section at the stream gage (channel entrenchment = 3 m; channel width = 37 m) and from digital terrain model data (channel slope = 0.0085) [FCDMC, 2000] with a reported positional accuracy of ±1.5 m. A surficial geologic map of the Tiger Wash distributary system [Klawon and Pearthree, 2000] was used to define the geometry of the active portion of the fan for the numerical model. Late Holocene active channel, sheetflood, and overbank deposits (Qy) and early to late Holocene relict alluvial fan and terrace deposits (Qy1), Early to late Holocene active channel, sheetflood, and overbank deposits; Qy1, Early to late Holocene relict alluvial fan and terrace deposits; Ql, late Pleistocene alluvium; Qm, Middle Pleistocene alluvial fan deposits). The black line denotes the active channel area used in the numerical model. The hatched area denotes inactive channel sediments within the active channel area used in the numerical model. (b) Lateral expansion of the active channel area with distance from the fan apex along transect a–a’. The width of the active channel is plotted as a half-width for direction comparison with the parameter $w_0$ used in the numerical model.

Figure 10. (a) Surficial geologic map of Tiger Wash (modified from Klawon and Pearthree [2000] provide courtesy of the Arizona Geological Survey) (Qy, Late Holocene active channel, sheetflood, and overbank deposits; Qy1, Early to late Holocene relict alluvial fan and terrace deposits; Ql, late Pleistocene alluvium; Qm, Middle Pleistocene alluvial fan deposits). The black line denotes the active channel area used in the numerical model. The hatched area denotes inactive channel sediments within the active channel area used in the numerical model. (b) Lateral expansion of the active channel area with distance from the fan apex along transect a–a’. The width of the active channel is plotted as a half-width for direction comparison with the parameter $w_0$ used in the numerical model.

The winter flow event persisted long enough to approach the saturated hydraulic conductivity which resulted in significantly lower infiltration rates relative to the monsoon event. For example, for a flow depth of 0.3 m, the infiltration rate for the winter event was 61% that of the monsoon event (0.2357 m/h and 0.3851 m/h, respectively) for the sandy active channel sediments. On the basis of the output of the numerical model, both the winter and summer flows were confined to the active portion of the fan (Figure 11). Surface flow depths were at a maximum near the fan apex and rapidly
decreased with distance down fan. In contrast, infiltration was less variable across the fan.

[32] It was difficult to separate the effects of storm duration from discharge magnitude on the infiltration responses because the winter and monsoon discharges were not equal. To this end, flow duration was varied with a constant input discharge (flow depth = 0.5 m) and the infiltration responses were examined. Because the event-average infiltration rate applied in the numerical model is much lower when events last longer, the infiltration rate of the active channel sediments decreased rapidly with increasing event duration. For example, for a ponded water depth of 0.5 m applied to sandy active channel sediments, infiltration rates decreased from 43.2 cm/h for a flow event 1 h in duration to 22.4 cm/h for a flow event 24 h in duration (Figure 12). For these conditions, infiltration rates did not decrease much for flow durations greater than 6 h due to the dominance of the large, early time infiltration rates (Figure 12). The infiltration rate had a strong effect on the proportion of the active channel area inundated by surface flows. As the applied infiltration rates decreased, the area of inundation of the active channel sediments increased because modeled infiltration was a sink for surface flows. For example, the inundation area approximately doubled, from 4% to 8% of the active channel area, as the infiltration rate varied from a maximum of 43.2 cm/h for a 1 h flow event to a minimum of 22.4 cm/h for a 24 h flow event (Figure 12).

[33] The applied infiltration rate and the area of inundation had a complex effect on the fan-wide infiltration volume (infiltration accumulated during the flow event in each grid cell times the area of the grid cell summed over all grid cells (m³)). To compare fan-wide infiltration volumes for events of varying duration, the fan-wide volumetric infiltration rate was also examined as a function of the event duration. For 1 to 4 h events, an increase in the event duration resulted in a slight decrease in the fan-wide volumetric infiltration rate (m³/s) which reflected the large decrease in the applied infiltration rate which dominated the infiltration responses (Figure 12). However, for events 8 to 24 h in duration, the fan-wide volumetric infiltration rate (m³/s) increased reflecting the dominance of the inundation area. The 24-h flow duration resulted in the largest fan-wide volumetric infiltration rate, however, this value was only 10% larger than that of the 1 h flow event. The decrease in fan-wide volumetric infiltration rate which occurs at the 8 h duration reflects a change in the balance of the impact of the applied infiltration rate and the inundation area.

![Figure 11. Surface flow depth (m) (top row) and infiltrated water (m) (bottom row) accumulated over the duration of the storm for a 1 h monsoon flow event (left column) and a 10 h winter flow event (right column).](image)
infiltration as a percent of the distance down fan, \( x_m' \), which was calculated as:

\[
x_m' = \frac{100 \sum m_i x_i}{\sum m_i},
\]

where \( m_i \) is the mass of infiltrated water in grid cell \( i \) and \( x_i \) is the longitudinal distance to the node of grid cell \( i \). For example, if the mass of infiltrated water was uniformly distributed along the longitudinal axis \( x_m' \) would be equal to 50%. Also, as the center of mass of the infiltrating water shifts toward the apex \( x_m' \) approaches 100%.

[36] An open question in fluvial geomorphology is how fan geometry affects the partitioning of flow between on-fan infiltration and surface flow leaving the fan system. Flows leaving the fan system may eventually reach the valley floor depending on evapotranspiration rates and transmission losses. With sufficient connection to the groundwater system these flows can become an axial river which either exits the watershed or drains internally to a playa.

[37] We investigated the ratio of fan-wide volumetric infiltration rate to input discharge to determine what fraction of the input flow infiltrated on the fan and what fraction of the flow exited the fan system (Figure 13). In the first experiment we examined the partitioning of flow as a function of fan size and fan slope. We independently varied fan area and slope to consider a full spectrum of fan morphologies; however, correlations have been noted, based primarily on fans of the southwestern U.S., between fan size and drainage area [Denny, 1965; Blair and McPherson, 1994], and between fan slope and drainage area [Denny, 1965; Harvey, 1987]. Fan area was varied between 1 km² and 100 km² and, simultaneously, fan slope was varied between 0.0175 and 0.0875 at the base case parameter values (Table 1) with the exception of the active channel expansion factor, \( c \), which was varied with fan area to maintain a constant active channel proportion (25%) of the total fan area.

[38] Ponded surface flow depths were greater on the more gently sloped fans due to reduced surface water velocities. Consequently, the greatest amount of infiltration occurred on fans with shallower slopes where water also tended to spread out laterally (Figure 13). In contrast, shallower, more laterally confined flow occurred on the steeper fans. Most of the water ran off the smaller fans, and at a minimum, 4% of the input flow infiltrated on the fan. For the largest and lowest gradient fans, no water ran off and, at a maximum, 100% of the flow infiltrated on the fan. As fan area increased there was a corresponding linear response in the proportion of infiltrated water for fan areas up to 20 km²; this response was largely independent of slope. About 20% of the incoming flow exited to the valley floor at the threshold of 20 km². Fan slope was a minor influence on the partitioning of flow between the fan and the valley floor for fans greater than 30 km². For fans greater than 30 km², the variability in the partitioning of flow between the fan and the valley floor was small (0% to 30%) of the incoming flow exited the fan system. Infiltration volume per input discharge depended only on channel slope and was independent of fan area for the largest fans (greater than 50 km²).

[39] The deepest surface flows occurred on fans with the shallowest slopes as indicated by the center of mass of the

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**Figure 12.** (a) Active channel area inundated with surface flow (%) and the infiltration rate into sandy active channel sediments for a ponded water depth of 0.5 m. (b) Fan-wide infiltration volume (m³) and fan-wide volumetric infiltration rate (m³/s) as a function of event duration.

### 4.2. Numerical Experiments

[34] A series of numerical experiments was carried out on synthetic fans to analyze the relationships between fan morphology (fan area, depth of active channel entrance, active channel area, sediment permeability, and fan slope) and the associated runoff and infiltration. The numerical experiments were performed in a Monte Carlo framework and averaged over different realizations of channel topography created by the stochastic distributary channel network. Output metrics for ten independent realizations of the random-walk process were averaged in order to isolate the controlling effects of the deterministic fan geometry. For each realization a constant input flow depth of 1 m was distributed across the fan during a 1 h flow event with the assumption of an initially fully drained soil profile.

[35] Key model outputs of greatest interest to fluvial geomorphologists and hydrologists are how much infiltration occurs and where it occurs. To determine how much infiltration occurs we employed an infiltration to runoff ratio metric. The infiltration to runoff ratio was calculated as the fan-wide volumetric infiltration rate (m³/s) divided by the sum of the fan-wide volumetric infiltration rate and discharge off the fan at the model boundaries or \( \frac{(\Delta x^2)}{(Q_x + (\Delta x^2) f)} \). The infiltration to runoff ratio is a unitless metric that scales between 0 and 1. To determine where on the fan infiltration occurs, we used two additional metrics: the ratio of infiltration on unincised surfaces to infiltration on active surfaces, \( I/I_m \), and the longitudinal distance to the center of mass of the
surface flow ($x_m$) which shifted toward the fan apex with decreasing fan slope (Figure 13). In general, the center of mass of the surface flow was affected more by fan area than by channel slope. For the largest fans $x_m$ approached 10% of the fan radius. As fan area approached zero, $x_m$ approached 45% of the fan radius and was independent of fan slope.

The magnitude and frequency of flooding on alluvial fans as a percentage of the fan surface is controlled by the ratio of the flow depth to the entrenchment depth at the fan apex. This ratio largely determines whether flows are confined within the active channel, or whether flows fill the active channel and also inundate older surfaces. In this case, the surface water flow regime consists of deeper flow in the active channel and shallow sheetflow on the unincised surfaces.

In the second experiment, we examined the influence of the ratio of the input flow depth to the entrenchment depth on infiltration responses as a function of the active channel area. To examine the threshold between these two flow regimes we considered the morphologic end-members:

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**Figure 13.** Channel slope versus fan area with an input flow depth of 1.0 m and an incision depth of 2.0 m. (a) Fan-wide volumetric infiltration rate divided by the input discharge. (b) Longitudinal distance of the center of mass of the surface flow as a percent of the distance downfan, $x_m^s$.

**Figure 14.** Ratio of input flow depth to incision depth versus active channel area (%) with an input flow depth of 1.25 m for (a) Fan-wide volumetric infiltration rate [m$^3$/s] on the fan divided by the sum of the fan-wide volumetric infiltration rate and discharge off the fan [m$^3$/s], $(\Delta x^c) f/(Q_e + (\Delta x^c) f)$, and (b) fraction of the older surface area inundated with flow (%).
fans with narrow, deeply entrenched channels and fans with shallowly entrenched active channel areas that rapidly widens with distance down fan. In the second experiment, we simultaneously varied the depth of active channel entrenchment (from 0 to 4 m) at the apex and the active channel area (from 15% to 55% of the total fan area) for an input flow depth of 1.25 m. The remaining parameters used to specify the fan geometry were set at the base case parameter values (Table 1).

[42] Surface flow was radial and unconfined for fans with small incision depths. In addition, overbank flooding occurred near the apex and a maximum of 94% of the unincised surface area was inundated by surface flow (Figure 14). As the active channel area increased, the area of inundation slightly decreased indicating that the point of outburst onto the unincised surface moved toward the toe of the fan. Flow was contained within the entrenched portion of the fan and almost no inundation of the unincised surface occurred on the most deeply entrenched fans.

[43] The active channel proportion of the fan strongly influenced the infiltration regime. In the second experiment, the amount of infiltration was as quantified as an infiltration to runoff ratio. The largest infiltration to runoff ratio occurred on fans with incision depths slightly smaller than the input flow depth, or at an incision depth of 1 m (Figure 14); a maximum of 93% of outflow exited the fan system as infiltration. Flow was largely confined to the active channel for incision depths much greater than the input flow depth and, consequently, almost no infiltration occurred on the unincised surfaces. The least amount of infiltration, only 40% of the outflow exited the system as infiltration, occurred on fans with the largest incision depth and the smallest active channel area. For incision depths much smaller than the input flow depth, large portions of the unincised surface were inundated with sheetflow resulting in infiltration on the unincised surfaces; however, shallower incision depths resulted in shallower ponded water depths in the active channel area. Because the active channel had the highest permeability sediments, this resulted in reduced infiltration volume. Overall, the results of the second experiment showed that infiltration volume was primarily dependent on the fan area inundated with surface flow and, secondarily, on the depth of surface flow. It is important to consider that for fans with a deep fanhead trench it may not be appropriate to compute area inundation metrics based on total fan area but rather only on the area distal from the intersection point. For these deeply dissected fans, even the largest floods will not inundate the inactive surface and thus referencing the total fan area is ambiguous when comparing inundation areas among different fan morphologies.

[44] Although the geomorphic factors considered thus far (fan area, fan slope, active area proportion of fan, incision depth) significantly affect infiltration responses, hydraulic conductivity is the primary parameter used to determine the infiltration rate. In the third and final experiment we considered the impact of sediment permeability on distributed infiltration responses. As discussed in the conceptual model section, sediment permeability varies between basins due to differences in geology, depositional environment, slope, history of the sediment to water flux, tectonics, and soil development. The permeability of the sediments, and the permeability contrast between different geomorphic surfaces, has a primary impact on the infiltration rate and a secondary influence on the surface water flow regime by influencing the area of inundation and the depth of surface flows. We varied the permeability contrast between two surfaces and examined where on the fan infiltration occurred. In particular, we investigated permeability contrasts between the unincised and active channel deposits which can be can be attributed to surface age [Young et al., 2004] or depositional environment. For example, older surfaces on fans adjacent to playas may accumulate eolian material resulting in reduced permeability given sufficient time and prevailing winds from the playa toward the fan. For fans adjacent to playas, the older surfaces (the undissected surface and islands in the active channel) can be characterized by a texture of clay loam [Young et al., 2004]. In the active portion of the fan, frequent flow events transport fine particles as suspended load and no significant eolian accumulation of fine particles would occur. Consequently, the active channel sediments were assigned hydraulic properties based on a texture of coarse sand. In the third experiment, the input discharge divided by drainage area (from 2 to 16 (m²/s)/km²) and the permeability contrast between the sediments of the active channel and the older surfaces were simultaneously varied for a 1 h flow event. The permeability contrast, ΔK, was calculated as:

$$\Delta K = K_a/K_u,$$

where $K_i$ and $K_u$ are the hydraulic conductivities of the unincised channel sediments and the active channel sediments, respectively. The permeability contrast was varied by more than 2 orders of magnitude, from 0.0095 to 0.14, by changing only the permeability of the unincised sediments ($K_u$) when $K_a$ was set equal to 20.0 cm/h. Values of $\Delta K$ of about 0.01 are representative of fans with an influx of eolian sediment [Young et al., 2004]. The remaining parameters used to specify fan geometry were set at the base parameter values (Table 1) with the exception of the active channel expansion factor, c, which was set to 15, or equivalently, the active channel area comprised 27% of the total fan area.

[45] We also employed the metric $I_a/I_u$ (the ratio of infiltration on unincised surfaces to infiltration on active surfaces) to determine where on the fan infiltration occurred as the input discharge and the permeability contrast were varied. In general, most of the infiltration occurred in the active channel. More infiltration occurred on older surfaces due to increased overbank flow as the input discharge was increased. For fans with a significant influx of eolian material, the metric $I_a/I_u$ ranged from 0.1 to 0.2 m³/m³ indicating that, at most, infiltration on the unincised surfaces was one-fifth that of the active surfaces. In contrast, for fans without a significant influx of eolian material, the metric $I_a/I_u$ ranged from 0.2 to 0.65 m³/m³ indicating that, at most, infiltration on the unincised surfaces was one-half that of the active surfaces although the unincised surfaces represented 73% of the total fan area. The partitioning of infiltration between the unincised and active surfaces became more sensitive to the value of the permeability contrast than to the input discharge for the unincised surfaces with low permeabilities ($\Delta K = 0.03$). This behavior represents a threshold value of hydraulic conductivity at
which little infiltration occurs on the highest topographic surfaces.

Because most of the infiltration occurred in the active channel, altering the permeability contrast of the sediments had no influence on where infiltration occurred on the fan as quantified by the center of mass of the infiltration \((x_m)\). The center of mass of the infiltration increased in a nearly linear manner as the input discharge per drainage area increased from 0 to 4 \(\text{m}^3/\text{s}\)/km\(^2\). The center of mass of the infiltration approached a maximum value of 51% for values of input discharge per drainage area between 4 and 16 \(\text{m}^3/\text{s}\)/km\(^2\) (Figure 15). The center of mass of the infiltrated water was much greater and less variable than the center of mass of the surface water which varied between 26.5 and 36.5% (not shown) due to much greater water depths near the fan apex than at the toe of the fan for the range of parameter values considered.

### 5. Conclusions

We simulated a variety of fan morphologies and quantified the amount and location of infiltration on fans using numerical experiments of synthetic alluvial fans. On the basis of the model results most of the infiltration occurred in the active channel which had the deepest surface flow and highly permeable sediments. We also found that the amount of infiltration on fans was most sensitive to the geomorphic factors that influenced the area of inundation rather than the depth of surface flow. The greatest amount of infiltration occurred on fans with low gradients which resulted in greater surface flow depths and more lateral spreading of flow across the fan. The dominance of the area of inundation over the depth of ponded surface water was also illustrated with the Tiger Wash application in which the fan-wide volumetric infiltration rate was shown to be 6% larger for the 24 h flow event than for the 1 h flow event due to an increased area of inundation although the infiltration rate of the 24 h flow event was considerably smaller than the infiltration rate of the 1 h flow event. The magnitude and frequency of flooding on the inactive fan surfaces is largely controlled by the ratio of the flow depth to the entrenchment depth of the active channel at the fan apex. This ratio partitions flow between the active channel and the unincised surfaces. As such, this ratio largely determines whether the surface flow regime consists of deeper flow confined within the active channel, or whether flow also inundates unincised surfaces with shallow sheetflow. The greatest amount of infiltration occurred on fans with incision depths slightly smaller than the input flow depth. Investigation of the ratio of the flow depth to the entrenchment depth at the fan apex also illustrated that the fan-wide volumetric infiltration rate \((L^3/T)\) was found to be primarily dependent on the fan area inundated with surface flow and, secondarily, on the depth of surface flow.

With regard to where infiltration occurs on fans, significant differences were found between the mass distribution of surface flows and the mass distribution of infiltrated water. The location of the center of mass of the surface flows in the down fan direction was closer to the fan apex and also more variable than the location of the center of mass of the infiltrated water. The water depth, generally deeper at the proximal portion of the fan than at the toe, has a stronger influence on the center of mass of the surface flow than on the center of mass of the infiltrated water which tends to be controlled by highly permeable sediments in the active channel rather than the depth of ponded surface water. Although the geomorphic factors considered (fan area, fan slope, active area proportion of fan area, incision depth) significantly affect infiltration responses, the hydra-
lic conductivity is the primary parameter used to determine the infiltration rate. We considered the impact of contrasts in permeability between the active channel and the unincised surfaces on how much infiltration occurred on the unincised surfaces. The permeability contrast between different geomorphic surfaces has a primary impact on the infiltration rate and a secondary influence on the surface water flow regime by influencing the inundation area and the depth of surface flows. For fans with a one order of magnitude permeability contrast, infiltration on the unincised surfaces was, at most, one-half that of the active surfaces although the unincised surfaces comprised 73% of the fan area. In contrast, for fans with a two order of magnitude contrast between the permeability of active and unincised sediments, infiltration on the unincised surfaces was, at most, one-fifth that of the active surfaces.

[40] We have shown that fan morphology exerts a first-order control on the recharge potential. Therefore at the basin scale, this method could be used to compare the recharge potential of different arid and semi-arid basins using limited hydrologic information. Frequently, when an estimate of recharge potential is needed at the basin scale, simple precipitation-recharge or precipitation-elevation-recharge empirical relations such as the Maxey-Eakin method [Maxey and Eakin, 1949; Eakin, 1960] are employed. Using a modification of this fan model, discharge-drainage area and discharge-frequency relations could be used to estimate recharge-runoff ratios for a collection of alluvial fans and their adjacent drainage basins. Given detailed recharge measurements for one basin, the model results could be used to scale the recharge estimates of an instrumented fan to adjacent fans based on fan morphology.

[50] We also illustrated that fan morphology strongly influenced the area of flow inundation which has implications for flood hazard assessment. If the model was applied to a particular fan, the stochastic distributary channel network would likely be replaced with real topography. In this case, if geomorphic site information was available, the hydrologic-geomorphic portion of the model could be applied to the fan to predict where flows are likely to occur and how deep infiltration is likely to be. These model predictions could be used to guide monitoring efforts to determine the appropriate distance down fan and the depth at which to place monitoring instruments. Careful selection of monitoring sites is essential when flows are infrequent and of short duration and both monitoring budgets and monitoring periods are typically limited. Later on, these data would typically be used to calibrate a flow model that incorporated the dynamic momentum equation. However, the modified version of the fan model could be used to explore the feasible parameter space efficiently before moving to the more computationally intensive dynamic momentum equation approach common for flood hazard assessment.

[51] Additionally, at the scale of a single fan, the hydrologic-geomorphic portion of the model could be used to spatially interpolate existing hydrologic data. For example, if limited infiltration point-data was collected on a fan, this model could be used to develop a first-order approximation of fan-wide infiltration responses based on fan morphology. Similarly, if flow was gaged or estimated from high-water marks at a single cross-section, this model could be used to estimate the fan-wide hydrologic response. Moreover, the model could be used to develop scaling relationships between flow magnitude and inundation area for different magnitude storm events.

[52] We have shown that the surface permeability of the fan sediments has a primary influence on the hydrologic response. This underscores the importance of understanding the history of sediment deposition on alluvial fans particularly how climate variation has affected the prograding and retrograding of fan sediments over time. These processes produce spatial variability in sediment permeability in the vertical direction and a temporal variability in recharge rates that are important to characterize for assessing water supplies and for predicting the migration of chemical constituents.

**Notation**

- $c$: active channel expansion factor
- $d_0$: depth of surface water in to a grid cell, m$^3$/s
- $d_1$: depth of surface water out of a grid cell, m$^3$/s
- $f$: infiltration rate, m/s
- $I$: incision depth at the fan apex, m
- $I_a$: total infiltration on active surface, m$^3$
- $I_i$: total infiltration on unincised surfaces, m$^3$
- $K_a$: saturated vertical hydraulic conductivity of the active surface sediments, m/s
- $K_i$: saturated vertical hydraulic conductivity of the unincised surface sediments, m/s
- $K_s$: saturated hydraulic conductivity, m/h
- $L$: relief of fan, m
- $m_i$: mass of water in grid cell $I$, kg/m$^3$
- $n$: Manning’s channel bed roughness coefficient
- $N$: number of iterations
- $p$: random walk probability parameter
- $Q_e$: total discharge off the fan at the model boundaries, m$^3$/s
- $Q_i$: net volumetric flow rate in to a grid cell, m$^3$/s
- $Q_o$: net volumetric flow rate out of a grid cell, m$^3$/s
- $R$: radius of the fan, m
- $v$: velocity of surface flow, m/s
- $w$: channel half-width, m
- $w_0$: channel half-width at the fan apex, m
- $x_{ij}$: horizontal distance from the fan apex to grid cell $i,j$, m
- $x_m$: center of mass of the infiltrated water along the longitudinal axis of the fan, %
- $x_s$: center of mass of the surface flow along the longitudinal axis of the fan, %
- $z_{ij}$: relative topographic elevation at grid cell $i,j$, m
- $\Delta x$: grid cell length, m
- $\theta_1$: initial water content, m$^3$/m$^3$
- $\theta_s$: saturated water content, m$^3$/m$^3$
- $\rho$: density of water, kg/m$^3$
- $\psi_{cr}$: potential at the soil surface, m
- $\psi_s$: potential at the wetting front, m

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