Channel avulsion on alluvial fans in southern Arizona

John Field *

Green Mountain College, One College Circle, Poultney, VT 05764, USA

Received 6 January 1999; received in revised form 1 September 2000; accepted 4 September 2000

Abstract

Historical aerial photographs and field observations on five fluvially dominated alluvial fans in southern Arizona demonstrate that channel avulsion invariably occurs where bank heights are low and often at channel bends. Channel abandonment occurs through stream capture when overland flow from the main channel accelerates and directs headward erosion of smaller channels heading on the fan surface. Five distinct channel morphologies observed on the fans are related to different stages of the avulsion process and can be used to identify areas on a fan surface that are prone to avulsion. A descriptive model of channel avulsion illustrates how the morphology of a single channel reach will evolve through time as it captures the main flow path and is itself eventually abandoned. Immediately following avulsions, small preexisting channels that capture flow from the main channel will typically experience three fold or greater increases in channel width. Subsequent large floods can be stably conveyed through these high-capacity reaches. An uninterrupted sequence of sediment-charged small flows, however, will eventually begin to back-fill the wide channels as vegetation growth stabilizes the banks. The stabilized and back-filled channels are now prone to abandonment during large floods because the decrease in the channel’s capacity leads to the generation of overland flow beyond the margins of the shallowed channels. The action of the small aggrading floods is critical in the avulsion process since the greatest amount of overland flow is generated where bank heights are lowest. As a result, both small and large floods are effective agents of landscape change on the fans. Channel avulsions on the five fans are not completely random events in space and time because their occurrence is controlled by the relative positioning of low banks along the main channel and smaller channels draining the fan surface. Consequently, the location and timing of future channel avulsions can potentially be anticipated in an effort to improve flood hazard assessment on fluvial fans in the rapidly urbanizing southwestern United States. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: avulsion; alluvial fan; Arizona; geomorphic effectiveness

1. Introduction

The importance of channel migration on alluvial-fan development has long been recognized (Drew, 1873). Over long time periods (10^3 to 10^5 years), channels must migrate over the entire surface to ensure the establishment and maintenance of fan form. When considering the long-term aggradation of alluvial fans, the exact location of channels through time is indeterminate and channel migration can be modeled as a stochastic process (Price, 1974; Hooke and Rohrer, 1979). However, short-term processes of channel migration on alluvial fans are of greater
interest to engineers and geologists studying flood hazards and the effect of individual floods on fan morphology. Mathematical models used by the Federal Emergency Management Agency to establish flood hazard zones on alluvial fans assume randomness in the location of channel avulsions during a single flood. However, a recent report by the National Research Council calls into question whether the position of alluvial-fan channels during a single event should be considered indeterminate. Previous studies have examined short-term channel avulsion processes on debris-flow fans (Beaty, 1963; Whipple and Dunne, 1992) and fluvial fans alike (Kesel and Lowe, 1987; Wells and Dorr, 1987), but many questions related to the National Research Council report (NRC, 1996) remain unanswered. What role do floods of different magnitude play in the process of channel avulsion? How do pre-existing fan morphology and drainage patterns control the avulsion process? In addition, should the locations of future channels on shorter time scales (10s to 100s of years) be considered indeterminate as they are on longer time scales? This paper addresses these questions by examining the influence of both large- and small-scale floods on channel morphology and channel avulsion processes on five fluvial fans in southern Arizona (Fig. 1; Table 1). Documentation of recent channel changes on the five fans is used to construct a model of channel avulsion that links channel morphology to different stages of channel development and the avulsion process. Channel morphology can thus be used to identify areas on a fan surface prone to avulsion and target areas for more quantitative hydraulic analysis of flood hazards.

2. Site description

The five alluvial fans are located in a tectonically inactive portion of the Basin-and-Range province in southern Arizona with source areas largely composed of felsic intrusive rocks (Table 1). The climate is semi-arid with mean annual rainfall ranging from 15 to 28 cm, increasing to the southeast. The five fans are active secondary fans (Blissenbach, 1954) forming at the downstream termini of fanhead trenches passing through abandoned Pleistocene surfaces higher on the respective piedmonts. Fan de-

Table 1
Selected drainage-basin characteristics for the five southern Arizona study fans

<table>
<thead>
<tr>
<th>Alluvial fan</th>
<th>Location of fan apex</th>
<th>Total drainage area (km²)</th>
<th>Distance fan apex to mtn front (km)</th>
<th>Dominant lithology</th>
<th>Average annual rainfall (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruelas Fan</td>
<td>Ruelas Canyon</td>
<td>91.200, (89.200)</td>
<td>9.3</td>
<td>(36.200)</td>
<td>granite, granodiorite</td>
</tr>
<tr>
<td>Wild Burro Fan</td>
<td>Ruelas Canyon</td>
<td>91.250, (89.500)</td>
<td>18.5</td>
<td>(36.200)</td>
<td>granite, granodiorite</td>
</tr>
<tr>
<td>Cottonwood Fan</td>
<td>Marana</td>
<td>92.600, (82.700)</td>
<td>34.5</td>
<td>(36.200)</td>
<td>granite, granodiorite</td>
</tr>
<tr>
<td>White Tank Fan</td>
<td>White Tank Mts.</td>
<td>97.750, (85.400)</td>
<td>14.6</td>
<td>(36.200)</td>
<td>granite, gneiss</td>
</tr>
<tr>
<td>Tiger Wash Fan</td>
<td>Weldon Hill</td>
<td>97.000, (85.050)</td>
<td>249.6</td>
<td>(36.200)</td>
<td>Mix</td>
</tr>
</tbody>
</table>
posits are predominately fine grained (sand through clay fraction) and boulders are uncommon.

Detailed studies of surficial processes have been completed on all five fans (House et al., 1991, 1992; Maricopa County, 1992; Field, 1994). Secondary fans throughout southern Arizona are dominated by fluvial processes associated with discontinuous ephemeral streams, a distinctive stream pattern characterized by alternating erosional and depositional reaches (Fig. 2; Schumm and Hadley, 1957; Bull, 1997). Overland flow, a critical component of the channel avulsion process described below, emanates from the margins of the sheetflood zones and aggrading downstream ends of channels (Fig. 2). Channel backfilling caused by the headward migration of aggradational reaches can transform a deep channel into an area of sheetflooding over periods of tens to hundreds of years (Bull, 1997). The five alluvial fans studied in this report show no evidence of debris-flow activity; modern rates of weathering in the mountain ranges of southern Arizona are insufficient to produce debris flows with enough sediment to reach distant fan apices (Table 1; Melton, 1965; Bull, 1991).

3. Evidence of past channel avulsions on the alluvial fans

Historical aerial photographs extending over 60 years were used to establish the timing of recent channel avulsions on the five alluvial fans by noting changes in flow paths between pairs of aerial photographs taken on different years (Fig. 3). In addition, aerial photographs and field reconnaissance were used to document changes in channel morphology associated with each avulsion and to identify channel reaches abandoned prior to the earliest photographs. Avulsion is defined here as the diversion of a majority of flow from one channel into another, leading to a total or partial abandonment of the previous flow path. Avulsions that occurred at or near the fan apex and which appeared to have diverted more than 50% of the fan’s total discharge.
Fig. 3. Aerial photographs of Ruelas Fan: (a) 1936 and (b) 1988 showing the avulsion that occurred between 1949 and 1956. The arrow, in the same position on both photos, highlights the channel reach into which flow was diverted. The letter "a", indicating the fan apex, is in the same position on both photos. Note the bend created in the main channel when flow was diverted into the narrow preexisting channel.
were termed major avulsions; all others were considered minor avulsions. All five fans show evidence of at least one minor avulsion with evidence of a major avulsion on four of the fans (Table 2). Channels abandoned by major avulsions prior to the photographic record are identified by vegetation growth in and minor incision of the former channel bottoms. The following observations are critical for understanding the avulsion mechanisms on the five alluvial fans.

(i) All of the avulsions, major or minor, happened along aggrading channel reaches or sheetflood zones (Fig. 2; Table 2). The location of the avulsions along these discontinuous ephemeral stream systems corresponds to areas where channel banks were low or nonexistent (Table 2).

(ii) Channel avulsions preferentially occurred on the outside bends of channels (Fig. 4; Table 2), but some avulsions actually resulted in the creation of bends along previously straight reaches (Fig. 3).

(iii) Following an avulsion, the new flow paths, in all cases, followed the preexisting course of a small tributary channel draining only a small portion of the fan surface itself (Figs. 3 and 4; Table 2).

(iv) The increases in discharge, as the channels receiving the diverted flow were incorporated into the main flow path, resulted in greater than three-fold increases in channel width along some channel reaches (Figs. 3 and 5).

(v) The bed elevation of the new flow path following the avulsion was generally lower than, but in a few cases the same as, the bed elevation of the abandoned reach (Table 2).

(vi) Wide channel reaches abandoned by avulsions sometimes experienced minor incision with a narrower channel inset into the old channel bed.

Table 2
Characteristics of past avulsions on the five alluvial fans

<table>
<thead>
<tr>
<th>Avulsion</th>
<th>Year</th>
<th>Avulsion type</th>
<th>Preexisting channel?</th>
<th>Avulsion at bend?</th>
<th>Bank height at avulsion (cm)</th>
<th>Max. on fan (cm)</th>
<th>Change in bed elevation (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruelas fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF-1</td>
<td>1949–1956</td>
<td>X</td>
<td>Yes</td>
<td>Yes</td>
<td>8</td>
<td>123</td>
<td>6</td>
</tr>
<tr>
<td>RF-2</td>
<td>Before 1936</td>
<td>X</td>
<td>Unknown</td>
<td>Yes</td>
<td>21</td>
<td>123</td>
<td>12</td>
</tr>
<tr>
<td>RF-3</td>
<td>Before 1936</td>
<td>X</td>
<td>Unknown</td>
<td>No</td>
<td>0</td>
<td>123</td>
<td>5</td>
</tr>
<tr>
<td>Wild Burro fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WB-1</td>
<td>Before 1936</td>
<td>X</td>
<td>Unknown</td>
<td>No</td>
<td>19</td>
<td>136</td>
<td>70</td>
</tr>
<tr>
<td>Cottonwood fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF-1</td>
<td>1962</td>
<td>X</td>
<td>Yes</td>
<td>No</td>
<td>32</td>
<td>194</td>
<td>70</td>
</tr>
<tr>
<td>CF-2</td>
<td>1949–1956</td>
<td>X</td>
<td>Yes</td>
<td>No</td>
<td>0</td>
<td>194</td>
<td>4</td>
</tr>
<tr>
<td>CF-3</td>
<td>1936–1949</td>
<td>X</td>
<td>Yes</td>
<td>Yes</td>
<td>24</td>
<td>194</td>
<td>40</td>
</tr>
<tr>
<td>CF-4</td>
<td>1936–1949</td>
<td>X</td>
<td>Yes</td>
<td>Yes</td>
<td>0</td>
<td>194</td>
<td>0</td>
</tr>
<tr>
<td>CF-5</td>
<td>Before 1936</td>
<td>X</td>
<td>Yes</td>
<td>No</td>
<td>0</td>
<td>194</td>
<td>36</td>
</tr>
<tr>
<td>White Tank fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WT-1</td>
<td>1951</td>
<td>X</td>
<td>Yes</td>
<td>Yes</td>
<td>9</td>
<td>54</td>
<td>10</td>
</tr>
<tr>
<td>Tiger Wash fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TF-1</td>
<td>1900(?)–1953</td>
<td>X</td>
<td>Unknown</td>
<td>No</td>
<td>0</td>
<td>142</td>
<td>4</td>
</tr>
<tr>
<td>TF-2</td>
<td>Before 1953</td>
<td>X</td>
<td>Unknown</td>
<td>No</td>
<td>12</td>
<td>142</td>
<td>91</td>
</tr>
</tbody>
</table>

*a* Indicates whether flow was diverted into an already existing channel. For diversions prior to photographic record, this can be determined by continuity of new channel with a tributary channel upstream of avulsion site.

*b* Indicates whether diversion occurred on the outside of a channel bend.

*c* Comparison of bank height at point of avulsion to maximum bank height on fan to illustrate how avulsions occur where bank heights are low.

*d* Taken as the difference in bed elevation between the new channel and abandoned channel at the point of avulsion.

*e* Tin cans circa 1900 transported in now abandoned channel.
Fig. 4. Channel network on White Tank Fan in (a) 1942 and (b) 1992. Channel patterns were traced from aerial photographs and the designation of channel types (e.g., active channels) based on geomorphic maps constructed in the field. Note that the major avulsion at the fan apex in 1951 occurred on the outside bend of the channel and activated large portions of the western half of the fan surface. Arrows point to small tributary channels heading on the fan surface that were incorporated into the main flow path following the 1951 avulsion.

Vegetation growing in the abandoned reaches gives rise to increasing gray tones on subsequent aerial photographs (Fig. 3).

(vii) Five distinctive channel morphologies are present on the alluvial fans and are associated with different stages of channel development preceding and following an avulsion (Fig. 6).

Except for a short gaging record of the Tiger Wash Fan drainage basin, no gaged records of discharges exist for the five alluvial fans. Consequently, the record of floods since the beginning of the photographic record is spotty and pieced together from field evidence, eyewitness accounts, and a few published reports (Table 3). Paleohydrologic analyses in the Wild Burro Fan and White Tank Mountain Fan drainages and the gaged record from Tiger Wash Fan provide estimated discharges and recurrence intervals for some of the known floods (Table 3). While significant floods likely precipitated all of the avulsions, this cannot be conclusively demonstrated because of the incomplete record. Of important note, however, is that no avulsions resulted from an extreme flood on Wild Burro Fan in 1988 or from moderate floods on Cottonwood Fan in 1990 and
Fig. 6. Five channel morphologies observed on the five fluvial fans. Note that a single channel reach can go through each phase of channel development through time, and each stage of development may be observed at different places on a fan at the same time. During the active channel phase, the channel reach is connected to the upper drainage basin. Aggrading channels are unstable and prone to avulsion while “new” channels and adjusted channels are more stable.

Tiger Wash Fan in 1970 (Table 3). The lack of change resulting from these floods is of particular interest since small to moderate floods on fluvial fans in other regions have caused major avulsions (Griffiths and McSaveney, 1986; Kesel and Lowe, 1987; Wells and Dorr, 1987).

4. Processes of channel avulsion

Based on the observations described above, a model has been developed to illustrate the processes preceding, accompanying, and following channel diversion on the five fans (Fig. 7). The active distributary channels conveying flow from the upper drainage basin occupy only a small portion of a fan surface at any one time, so numerous narrow “on-fan” channels are formed that drain small portions of the inactive fan surface (Fig. 6a); in places, an incipient dendritic drainage system develops (Fig. 4a). Portions of these “on-fan” channels occasionally approach the larger distributary channels (Fig. 7a) and can be incorporated into the main drainage net as the result of an avulsion (Figs. 3, 4, and 7b). The banks

Table 3

<table>
<thead>
<tr>
<th>Alluvial fan</th>
<th>Year of flood</th>
<th>Recurrence interval of flood (years)</th>
<th>Associated avulsion</th>
<th>Type of evidence for flood occurrence</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruelas</td>
<td>No record</td>
<td></td>
<td>none</td>
<td>flood debris/sand sheets</td>
<td>House (1991)</td>
</tr>
<tr>
<td>Wild Burro</td>
<td>1988</td>
<td>&gt; 100</td>
<td>none</td>
<td>written and oral accounts</td>
<td>Rostvedt (1968)</td>
</tr>
<tr>
<td>Cottonwood</td>
<td>1962</td>
<td>50–100</td>
<td>CF-1</td>
<td>written and oral accounts</td>
<td>Rostvedt (1968)</td>
</tr>
<tr>
<td></td>
<td>1991</td>
<td>&gt; 100</td>
<td>WT-1</td>
<td>aerial photos/written account</td>
<td>Kangeser (1969)</td>
</tr>
<tr>
<td>Tiger Wash</td>
<td>1970</td>
<td>&gt; 10</td>
<td>none</td>
<td>stream gage</td>
<td>Maricopa County (1992)</td>
</tr>
</tbody>
</table>
Fig. 7. Model of channel avulsion developed from observations on the five fluvial fans. See text for description. View is looking upstream. Note relationship with five channel morphologies illustrated in Fig. 6.

of the smaller channel that has captured the flow are widened and become vertical in response to the dramatic increase in discharge from the upper drainage basin (Figs. 5 and 6b). The old and new segments of the main channel, joined at the point of avulsion, have contrasting morphologies (Fig. 7b). The channel banks along the older upstream segment are low, rounded, and vegetated, while downstream of the diversion point the banks are vertical. Widening and perhaps deepening of the newer downstream channel reach will continue as floods larger than the diversion event pass through the reach (Figs. 6c and 7c). An avulsion is unlikely in reaches at this stage of channel development because the channel is adjusted to convey large flows.

As the frequency of floods large enough to continue channel enlargement decreases, smaller floods will begin to modify the channel’s morphology. In channels with high width:depth ratios (Fig. 6c), transmission losses are maximized and only the largest floods can transport the imposed sediment load through the channel. Ephemeral streams carrying fine-grained sediments characteristically aggrade during smaller flows because stream discharge infiltrates into the sandy channel bottoms before reaching the channel mouth (Bull, 1979, 1997). Channels with greater width:depth ratios also have a greater hydraulic roughness, further promoting channel aggradation. In the absence of a flood large enough to flush accumulating sediments through the channel reach, a succession of small floods will eventually reduce the height of the channel banks through a rise in the bed elevation (Figs. 6d and 7d). The carrying capacity of the channel is further reduced by the slumping, rounding, and revegetation of the increasingly stabilized channel banks. Floods at this stage of channel development begin to overtop the channel banks, generating overland flow. With continued aggradation, sheetflood zones may ultimately develop; and the magnitude of the smallest flood needed to produce overland flow decreases.

Overland flow is a critical component of the channel avulsion process on the five study fans. Streamflows overtopping the banks of a channel tap the upper portion of the water column and are thus relatively clear, devoid of bed load, and capable of erosion (Hooke and Rohrer, 1979; Slingerland and Smith, 1998). Any sediment carried by the overland flow is deposited rapidly at the channel and sheetflood zone margins in response to the flow expansion (Fig. 8). Although overland flow initially diverges and spreads out over the fan surface, it ultimately recollects into the existing network of small narrow channels draining the fan surface (Figs. 4b and 8). Consequently, overland flow enters and en-
larges these small channels and generates headward erosion directed towards the aggrading active channel (Fig. 7d). When the channel heading on the fan surface is eroded back to the aggrading reach, stream capture will occur because the bed of the headward eroding channel is generally lower than the backfilled channel (Fig. 7e; Table 2). The capturing channel is, in some respects, a passive partner with overland flow from the main channel dictating where and how rapidly headward erosion occurs. Since the bed of the previously abandoned channels remains lower than the surrounding fan surface, overland flow often enters these reaches and incises the old channel bed (Figs. 6e and 7d–e). Previously abandoned channels can, at times, become reactivated into the main flow path as at the apex of White Tank Fan (Fig. 4).

5. Rate of channel avulsion

The number of years required for a single channel reach to progress through the channel avulsion process illustrated in Fig. 7 is dependent on several factors: (i) the initial depth of the main channel; (ii) the magnitude of the largest flood occurring during the active channel phase (Figs. 7b–d); (iii) the sequencing of flood magnitudes; and (iv) the location of the “on-fan” channels draining the fan surface with respect to sheetflood zones and aggrading channels along the active channel.

First, the depth to which a new channel incorporated into the main flow path is eroded will determine in part the amount of aggradation and time required before overland flow is initiated. Second, an extremely large flood flowing down an “adjusted” channel (Fig. 6c) could conceivably overwhelm the channel’s capacity at any time and produce enough overland flow in a single event to precipitate a channel avulsion. However, an aggrading channel or sheetflood zone elsewhere on the fan (Figs. 2 and 6d) during the same flood would be the more likely site of a diversion since more overland flow would emanate from these areas.

Third, a series of moderate to large floods during the early stages of channel development (Fig. 6b–c)
may actually prolong the diversion process by periodically flushing sediment out of a channel reach and hindering the generation of overland flow. In contrast, considerable aggradation resulting from an uninterrupted sequence of small sediment-charged flows will eventually lead to overland flooding during even the smallest discharges. Diversions that have occurred during small floods on fluvial fans elsewhere (Griffiths and McSaveney, 1986; Kesel and Lowe, 1987; Wells and Dorr, 1987) fit within this context and should not be considered anomalous events. While extended periods of constant discharge can produce avulsions in experimental studies (Bryant et al., 1995), a similar uninterrupted sequence of small floods is unlikely in arid and semi-arid regions where record discharges can be hundreds of times larger than mean annual discharge (Graf, 1988). A series of small floods on fluvial fans in semi-arid regions likely hasten the diversion process and increase the effectiveness of extreme events by raising the channel bed through aggradation.

Finally, overland flow is more likely to result in a channel avulsion if a nearby channel is receiving the flow. Headward erosion towards the main channel will not occur if overland flow does not reconverge into a small channel draining the fan surface. As parts of discontinuous ephemeral systems (Fig. 2), aggrading depositional channels on the five alluvial fans migrate headward; and overland flow is generated at different points along the channel through time. Eventually the aggrading portion of the main channel will approach an area where a small channel draining the fan surface can capture overland flow. The headward migration of a sheetflood zone on Wild Burro Fan between 1936 and 1988 coincides with the widening of Reach A on Wild Burro Fan (Fig. 8). As the sheetflood zone migrated upstream and backfilled the main channel, more and more overland flow entered Reach A. The widening may not have occurred without the upstream shift in the location of the sheetflood zone.

6. Discussion

If geomorphic effectiveness is defined as the ability of an event to shape or form the landscape (Wolman and Gerson, 1978), then channel avulsions must be considered an effective process on alluvial fans. Large infrequent floods are widely regarded as the effective geomorphological agents of change in arid climates (Wolman and Miller, 1960; Baker, 1977; Wolman and Gerson, 1978; Kochel, 1988), but the fine-grained nature of the five study fans means that small to moderate events can transport sediment and play an active role in landscape modification. Although large flows appear to have directly caused all of the avulsions on the five fans, this should not imply that small events are ineffective agents of change. Channel aggradation resulting from small flows decreases bank heights and increases the amount of overland flow produced by subsequent flows, thereby setting the stage for and, to some extent, dictating the location of future avulsions. Without the action of small aggrading flows, the geomorphic effectiveness of large events would be greatly diminished on the five fans.

Alluvial-fan flooding is of increasing concern in the rapidly urbanizing southwestern United States, where over 30% of the landscape is composed of alluvial fans (Antsey, 1965). The present Federal Emergency Management Agency method of flood-hazard assessment on alluvial fans, based on a stochastic procedure proposed by Dawdy (1979), assumes that channel positions move across an alluvial fan surface at random during each flood without regard to preexisting flow paths (FEMA, 1995). However, channel avulsions on the five study fans are not completely random events over the short term, since avulsions invariably occur where channel banks are low and divert flow into preexisting channels (Table 2). The diversion of flow into preexisting channels following an avulsion appears to be typical of fluvial fans in other regions as well (Kesel, 1985; Griffiths and McSaveney, 1986; Richards et al., 1987; Wells and Dorr, 1987; McCarthy et al., 1992). The Federal Emergency Management Agency method also does not account for the fact that large floods on fluvial fans do not always produce avulsions or major channel adjustments (Table 3; Harvey, 1984; Ribble, 1988). While the assumption of randomness in the Federal Emergency Management Agency method for assessing flood risk on alluvial fans may appear safely conservative by assuming the whole fan surface is equally prone to avulsion, the method severely underestimates flow depth and velocity.
along existing channels where flow is most likely to occur (O’Brien and Fullerton, 1990; House et al., 1992; O’Brien and Fuller, 1993; Field, 1994).

Recognizing the deficiencies in the Federal Emergency Management Agency method, a recent report by the National Research Council (NRC, 1996) recommends site-specific assessment of alluvial-fan flood hazards. The use of detailed hydraulic modeling along channel reaches identified as probable avulsion sites on alluvial fans has been suggested previously (Gundlach, 1974; Richards et al., 1987), and recent advances in quantitative modeling of avulsions along meandering rivers (Slingerland and Smith, 1998) may also prove useful on alluvial fans. The model presented in Fig. 7 is useful for identifying those channel reaches most prone to an avulsion as the channel morphology of a given reach on a fluvial fan indicates the susceptibility of that reach to diversion and abandonment (Fig. 6). Site-specific maps of fluvial fans can focus the attention of land-use planners and hydraulic modelers on specific fan areas such as aggrading reaches with low banks and nearby small “on-fan” channels that might capture overland flow. Through time, a channel’s morphology will evolve as aggrading reaches and sheetflood zones in a discontinuous ephemeral stream system migrate headward in response to small sediment-charged flows (Fig. 8). As site-specific studies of flood hazards on fluvial fans are undertaken, periodic monitoring will be necessary in order to identify changes in flood hazards brought about not only by large floods but also seemingly ineffective small floods.

7. Conclusions

A descriptive model has been developed that elucidates the processes of channel avulsion on fluvially dominated alluvial fans in southern Arizona (Fig. 7). After a period of bank widening along a new channel reach, aggradation begins due to small floods that are unable to transport the imposed sediment load through the stream system. The resulting decrease in bank height leads to the generation of overland flow, which accelerates and directs the headward erosion of small channels heading on the fan surface. Stream capture ultimately occurs and the channel receiving the diverted flow is rapidly transformed as it is incorporated into the main channel network. The model is similar to avulsion and meander neck cutoff models developed for mega-fans (Wells and Dorr, 1987; McCarthy et al., 1992) and semi-arid river systems (Schumann, 1989; Gay et al., 1998), suggesting that the avulsion processes outlined here operate at different scales and in varied environmental settings.

The avulsion process described here demonstrates how small floods, under certain circumstances, can cause an avulsion while large floods often do not precipitate changes. Small floods on the southern Arizona fans have not directly caused an avulsion, but they do potentially accelerate the avulsion process culminated by large floods. The importance of both small and large floods on channel avulsion underscores the need for geomorphologists to focus on how different scales of geomorphological events work in concert to modify the landscape rather than on which scale of events is the most geomorphologically effective.

Although channel avulsions occur suddenly and are clearly a hazard on alluvial fans, the location of channel avulsions on fluvial fans should no longer be regarded as unpredictable, since new channels almost invariably follow preexisting flow paths. A careful analysis of all existing flow paths in relationship to potentially unstable reaches along the active channel (i.e., low channel banks) may help identify the location of future channel positions. The most likely paths of future channels on the five southern Arizona fans have been noted elsewhere (Field, 1994), and follow-up studies will establish the accuracy of these predictions. The results of this study suggest that understanding the interplay between large and small-scale geomorphic events is critical for anticipating the timing and location of future avulsions on some, if not most, fluvially dominated alluvial fans.

References