



A Review of Stream Processes and Forms in Dryland Watersheds

California Department of Fish and Game

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One of the most startling paradoxes of the world's drylands is that although they are lands of little rain, the details of their surfaces are mostly the products of the action of rivers. To understand the natural environments of drylands is to understand the process and forms of their rivers.

W.L. Graf (1988)

Cover: Oblique aerial photograph of Mission Creek, east of Palm Springs, California.
Photo by D. Finnegan, September 2003 in Lichvar and Wakeley 2004.

PREFACE

This document was prepared to provide California Department of Fish and Game (Department) staff a science based technical reference on dryland stream forms and processes.

The author of this document, Kris Vyverberg, Senior Engineering Geologist with the Department's Conservation Engineering Program, benefited from editorial and technical review provided by the following Department staff: Cathie Vouchilas, Senior Environmental Scientist, Habitat Conservation Planning Branch; Mark Smelser, Engineering Geologist, Northern Region; Jeff Brandt, Senior Environmental Scientist, Inland Deserts Region; Heather Pert, Environmental Scientist, Inland Deserts Region; Deborah Hillyard, Plant Ecologist, Central Region. This document was also independently reviewed by: Thomas Spittler, Senior Engineering Geologist, California Geological Survey; Jeremy Lancaster, Engineering Geologist, California Geological Survey; Dr. Roland Brady, Consulting Professional Geologist, and Dr. G. Mathias Kondolf, Geomorphologist, University of California, Berkeley.

Notes to the Reader

Terms in common use in the practice of stream ecology, geomorphology, and hydrology that are not defined in the narrative can be found in the Glossary at the end of this document. The first occurrence of such a term in the narrative is noted in **bold-faced** type.

Readers with comments or recommendations, or the desire for further information on the topic of dryland streams should contact:

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1 INTRODUCTION

“A Review of Stream Processes and Forms in Dryland Watersheds” provides a synthesis of the scientific literature of stream processes and forms in dryland watersheds. As such, it represents a science-based approach to identifying dryland streams. Although subject to the same basic controls, dryland stream processes occur with greater variability and produce characteristic adjustments in form distinct from their temperate-humid region counterparts. The hydrologic and morphologic character of these streams is the focus of this document.

Streams are described as having one or more channels (i.e., **single-thread** or **compound channel** form). These channels may all be active or, as is often the case, receive water only during some high flow event. A network of subordinate features, such as **low flow channels**, **active channels**, banks associated with secondary channels, floodplains, and stream-associated vegetation, may occur within the bounds of a single, larger channel. This larger channel is designated in this document as the **watercourse** to discriminate between it and the smaller, episodically active secondary features that may lie within its bounds. The watercourse is not defined by particular flow events, such as **bankfull** flow, but rather by the topography or elevations of land that confine a stream to a definite course when its waters rise to their highest level (Figure 1). For the purposes of this document, a watercourse is a stream, the boundaries of which define the maximal extent or expression of a stream on the landscape.

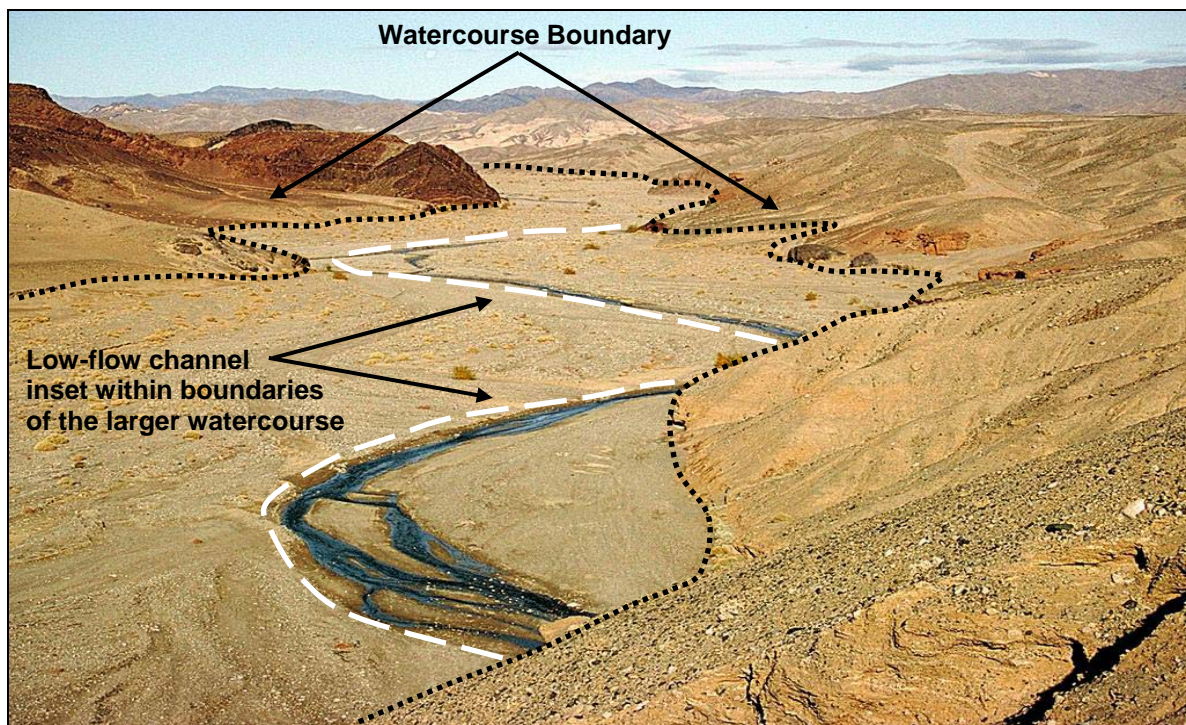


FIGURE 1. Watercourse boundary of a compound channel. As this photograph shows, the form typical of many dryland streams is characterized by a low-flow **meandering** channel nested within a larger watercourse defined by a frequently shifting, channel network. The larger watercourse may lack well defined banks and often lacks a classic “geomorphic floodplain.” The physical and biological evidence for the location of a stream’s waters at the highest level of confinement defines the watercourse channel. Amargosa River, Death Valley, California. *Photo courtesy of Marli Bryant Miller.*

A watercourse usually has a defined bed, and banks that rise vertically above and horizontally away from it. However, in **dryland** environments the stream banks can be slight or nearly imperceptible, and hence the degree of channel confinement can vary along the line of flow. However subtle the channel topography, whether a single-thread or compound channel form, if the physical and biological evidence for the location of a stream's waters at the highest level of confinement can reasonably be identified, then this line of flow defines the watercourse channel even though flow may otherwise be intermittent or ephemeral (Figure 1).

2 DRYLAND REGIONS AND STREAMS

The term **drylands** is used in this document as a collective noun for the arid and semi-arid regions of California, and is equivalent to those regions defined as the "arid west" by the Natural Resources Conservation Service (U.S. Department of Agriculture 2006). Dryland regions are characterized by low and highly variable precipitation, where mean annual evapotranspiration exceeds mean annual precipitation by 10 inches or more (Figure 2) (Bull and Kirby 2002; Levick et al. 2008; U.S. Fish and Wildlife Service 2009).

The direct and indirect effects of land use change on the physical and biological character of streams have been well documented, but the majority of studies have focused on impacts to **perennial** streams (Rhoads 1986; Chin and Gregory 2001; Coleman *et al.* 2005; Bledsoe *et al.* 2008). Few studies have considered or evaluated the impacts of urban, agricultural, and industrial development on streams in arid and semi-arid regions – herein collectively defined as **drylands** – where the majority of streams are **ephemeral** or **intermittent** (Bull and Kirby 2002; Coleman *et al.* 2005; Bledsoe *et al.* 2008).

Keeping in mind that in some dryland regions there may be many years without precipitation, average annual precipitation can be used as an indicator of the relationship between potential evapotranspiration and the subdivisions of aridity. Lands that receive less than 8 inches of precipitation are considered arid; lands that receive between 8 and 20 inches of precipitation are considered semi-arid (Figure 3) (Thomas 1997). Because the drylands of California are regionally more widespread than the commonly perceived extent of "arid" or "desert" lands, this document avoids these terms (Figure 3).

Climatically dryland regions are influenced by large-scale patterns in precipitation that either separately or in combination influence discharge patterns and stream **channel morphology** in the region. These precipitation patterns can seasonally generate intense rains over an entire **watershed**, or perhaps just a portion of a watershed, and a complete lack of flow in others (Lichvar and Wakeley 2004; Lichvar and McColley 2008). Precipitation produced by these weather patterns varies greatly on an annual and interannual basis for any given locality. This, combined with the cumulative effects of highly variable topography, interception of precipitation by vegetation, evaporation and transpiration, and seepage losses through the stream bed results in dryland stream systems with more rapid responses to rainfall, greater variations in flow between **runoff** events, and shorter duration flows than their temperate-region counterparts (Lichvar and Wakeley 2004).¹

Dryland streams are those streams that occur in the dryland regions of California. They may be ephemeral, intermittent, or perennial, but ephemeral streams dominate (Bull and Kirby 2002; Shaw and Cooper 2007). Ephemeral streams only flow during and shortly after rainfall events; intermittent streams flow continuously only in places where they receive water from a groundwater source. However modest the flows, both of these stream types perform the same critical hydrologic functions as perennial streams. They move water, sediment, debris, and nutrients through the stream network; recharge groundwater; provide physical and biological connectivity and habitat for many local species; and typically support most of the biodiversity in dryland regions (Gomi *et al.* 2002; Levick *et al.* 2008; Shaw and Cooper 2008).

The U.S. EPA estimates that ephemeral and intermittent streams comprise 66 percent of all streams in California – an estimate that is likely low given that it does not include stream segments less than 1 mile long, and is derived from a topographic map scale (1:100,000) too coarse to account for streams having small channels (Levick *et al.* 2008).

¹ An in-depth discussion of the meteorological processes in dryland regions is beyond the scope of this document. A more detailed discussion can be found in Lichvar and Wakeley 2004, or Thornes 2009.

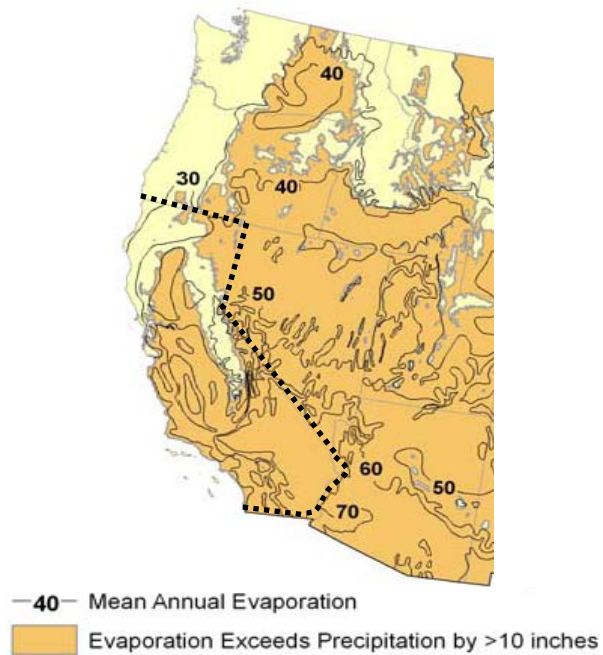


FIGURE 2. Geographic extent of dryland regions. The mean annual evaporation in dryland regions exceeds mean annual precipitation by 10 inches or more. *Graphic adapted from USFWS 2009.*

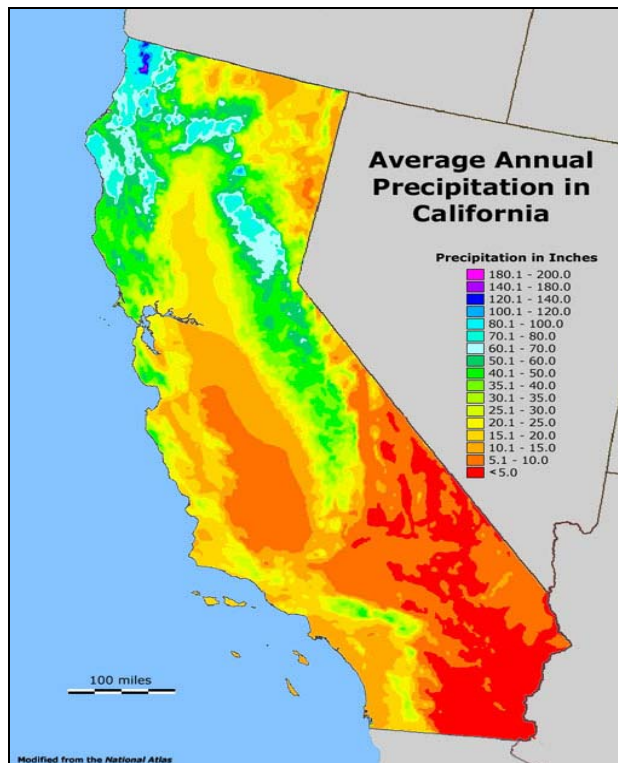


FIGURE 3. Average annual precipitation in California. Showing variability in rainfall across the state for 1961-1990. Drylands include arid and semi-arid regions that receive less than 8 inches and no more than 20 inches of rainfall per year. *Graphic from the US Geological Survey.*

3 HYDROLOGIC AND MORPHOLOGIC CHARACTERISTICS

The channel morphology of a stream is driven in large part by the discharge patterns associated with the local hydrologic regime and the characteristics of the geologic materials across which the stream flows. While the hydrologic controls are fundamentally the same in dryland regions as those of temperate and humid areas the pronounced distribution and temporal intensity and discontinuities in runoff volumes and durations for dryland streams lead to a much less ordered pattern of processes and stream forms (Thornes 2009). As a consequence, dryland streams are often outside the normal range of the hydrologic and morphologic characteristics of their temperate and humid region counterparts, and their hydrology, sediment transport characteristics, and resultant channel forms cannot be reliably predicted by extrapolation from temperate and humid region fluvial systems. Characteristics that distinguish dryland streams from temperate-regions streams are described below in Sections 4.1 through 4.3.

3.1 Water

- **Flow:** Dryland streams are dominated by short-lived, localized, and highly variable flow the result of discrete precipitation events and the dominance of **overland flow** in runoff generation (Reid and Frostick 1997). Often referred to as a **flashy discharge pattern**, runoff events are characterized by a rapid rise to the peak discharge quickly followed by declining flows. A **hydrograph** is a chart that shows change in flow over time. The hydrographs in Figure 4 compare the quick rise in flow, its rapid recession, and short time period characteristic of a dryland runoff event with that of a similar runoff event on a temperate regions stream.

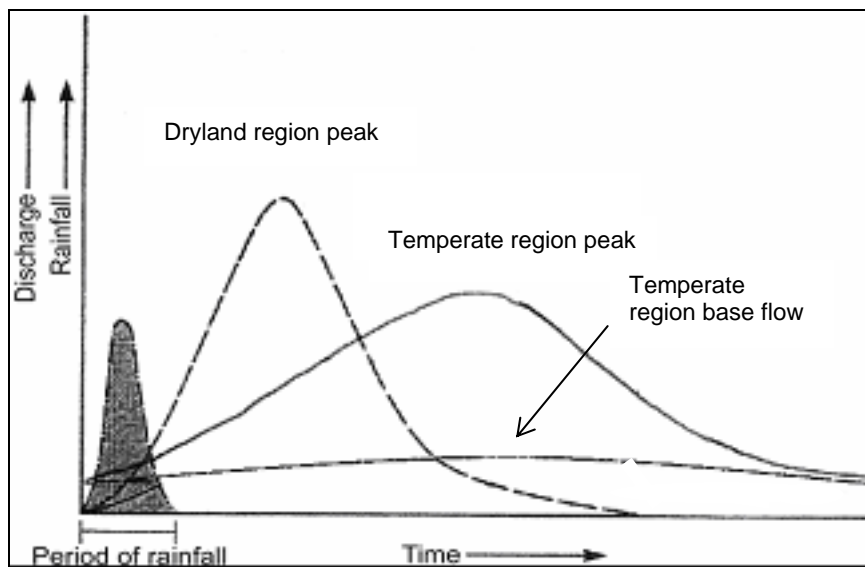


FIGURE 4. Comparison of idealized hydrographs. Dryland-region and temperate-region runoff hydrographs for the same rainfall event in watersheds of similar size and shape. *Graphic adapted from Lichvar and Wakeley, 2004.*

- **Flood magnitude:** The variability in flood magnitudes in dryland streams is much greater, and the discharge of their larger floods tends to be significantly greater than the mean annual flow (McMahon 1979). For example, in contrast to a humid region such as Pennsylvania, where the discharge of a 50-year return interval flood is about 2.5 times the mean annual flow (Wall and Englot 1985), the 50-year return interval flood discharge of the Gila River in Arizona is about 280 times the mean annual flow (Graf 1988). This is not only a function of high-intensity rainfall, but also for a given intensity, rains in dryland environments tend to produce more runoff per unit area because plant cover and surface organic matter is sparse, and poorly developed dryland soils are commonly more compacted (Knighton and Nanson 1997). Typical effects of these large events are significant channel widening, channel deepening, and high sediment concentrations in the flow (Scott 2006).
- **Downstream decreases in flow volume:** in temperate region streams discharge usually increases downstream. But in dryland streams considerable water is lost through evaporation or through seepage into the unconsolidated **alluvium** of channel boundaries (i.e., **transmission losses**). Transmission losses reduce discharge whether or not there is appreciable tributary inflow further downstream. They also decrease downstream flood peaks and total runoff volumes that strongly influence sediment transport and resulting channel forms. Although accounting for transmission losses makes hydraulic modeling of dryland streams difficult, they are a vital component of development-related **hydraulic analyses** (Kirkby and Bull 2002).
- **Asynchronous flow:** Localized rainfall patterns and rapid and highly variable runoff results in unequal flow in tributaries and main channels. This tendency can produce abrupt morphological changes at tributary confluences with **main stem** streams – such as tributary-junction fans – that can make the morphology and biological significance of dryland streams and their tributaries difficult to interpret (Figure 5).

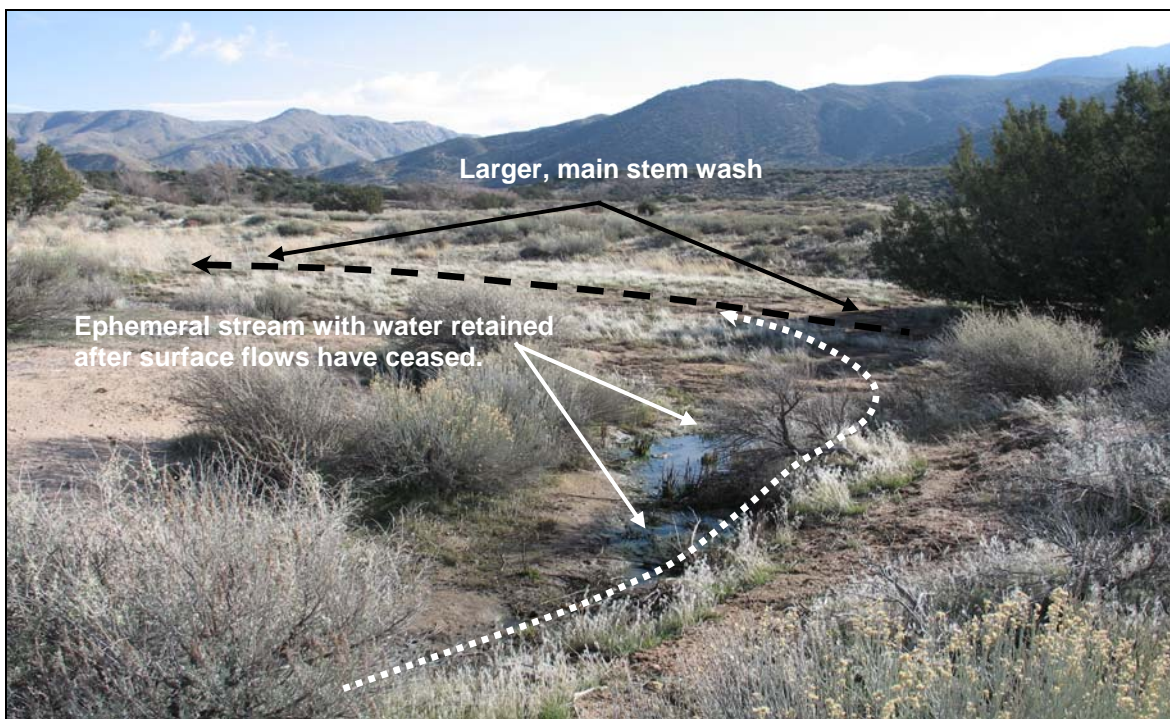


FIGURE 5. Asynchronous flow event. A small ephemeral stream tributary to a larger **wash**. The rainfall and runoff event resulted in surface flow in the ephemeral channel, but not in the larger wash (running from right to left). Given that small, frequent and highly local flow events dominate the fluvial landscape of dryland regions, the flow and brief retention of residual water on these small, ephemeral channels suggests that their biological significance may exceed their modest size – in this case, less than 200 feet long. East side of the San Bernardino Mountains, near the West Fork of the Mojave River. *Photo by K. Vyverberg, February 2010.*

- **Surface runoff:** Rainfall quickly becomes runoff because plant cover and surface organic matter is sparse, and poorly developed dryland soils are commonly more compacted (Knighton and Nanson 1997). Most runoff occurs as overland flow. Moreover, many dryland soils vary in erodibility and permeability over short distances. Models that assume, for example, that overland flow depths and surface erosion can be described using a single mean value, are likely to be in error when used to calculate erosion rates. Rainfall–runoff models developed specifically for dryland regions should be used to more accurately account for transmission losses, soil moisture storage, spatial distribution of rainfall, evaporation, and groundwater recharge (Field and Lichvar 2007).
- **Groundwater:** While groundwater obeys the same rules as in temperate environments, its contribution and influence on a dryland stream and associated ecosystem is generally minimal or absent because the water table is usually well below the stream bed. Conversely, the contribution of stream flow to groundwater from transmission losses through the bed of a stream or alluvial fan can be a very important source of recharge to valley bottom aquifers (Bull and Kirby 2002; Levick et al. 2008; AFTF 2010b). For example, transmission losses from ephemeral stream flow are estimated to account for 90 percent of the recharge to the groundwater reservoir in the Amargosa River basin above Shoshone, California (Osterkamp et al. 1994).

3.2 Sediment

- **Sediment transport:** The lack of cohesive clays in a stream and higher percentages of silt results in the high mobility of sediments during large flow events (clay-size particles require a higher energy to entrain them than silt and sand particles). This, combined with high-magnitude, low-frequency flow and downstream flow losses that result in rapid declines in **transport capacity** and abrupt, episodic deposition of sediment create a fabric of highly varied transient channel forms. When they flow, dryland streams are more efficient erosional agents – in part because sediment of all sizes is readily available for erosion on the sparsely vegetated slopes, as well as from the channel bed (Laronne and Reid 1993). As a result, **suspended sediment** concentrations and **bedload** transport rates are typically much higher in dryland streams. Even at low flows, sediment concentrations in dryland streams are often more than five times greater than during high flows in perennial streams (Reid and Frostick 2000). As with transmission losses, sediment volume and the tendency for its episodic transport must be considered a critical component of dryland stream hydraulic analyses.
- **Bed form:** In addition to their low sinuosity and greater width, the lower reaches of dryland streams tend to have particularly flat and **plane bed** topography (Reid and Frostick 2000). Bed flatness and channel width are likely related through flow depth in that wide, shallow flows tend to suppress the swirling currents (i.e., separations of flow) that would otherwise encourage the development of bars (Reid and Frostick 2000). Gravel bars, where present, tend to be flat-topped and with little to no elevation above the channel **thalweg** (Leopold et al. 1966; Frostick and Reid 1977), and rapidly receding flows tend to destroy or modify **bed forms** such as ripples and dunes that may have developed at greater flow depths. However, dryland channels can develop distinctive patterns of longitudinally-sorted sediment bars that are analogous to the pool-riffle or step-pool sequence of perennial streams (Powell 2009).

3.3 Channel Form

- **Transitory channel morphology:** In contrast to temperate region streams characterized by regular flow and continuous sediment transport, the high-magnitude, low-frequency flow events of episodic streams combine with downstream flow losses and declining sediment transport capabilities to create a fabric of highly varied, transient channel forms. These

transient forms – particularly those that occur along a single stream channel – can confound determinations of active versus **relict** stream processes and forms. Similarly, the transient nature of stream channels where change is the norm challenges conventional notions of **stable** and **unstable** channel form commonly applied to temperate region streams.

- **Low sinuosity and high width-to-depth channel ratios:** Dryland streams tend to have low **sinuosity** and higher **width-to-depth ratios** (Schumm 1961; Scott 2006). This is due in part to the sparseness of vegetation and a paucity of clay, both important for forming and stabilizing channel banks. Because dryland regions are dominated by mechanical rather than chemical weathering, clay production is inhibited, and stream beds, banks, and floodplains tend to contain more silt, sand, and gravel and less clay. This also explains in part why dryland channels tend to widen rather than deepen their cross-section during flood events.
- **Non-equilibrium channel form:** In contrast to the dominant influence of lower, more frequent intermediate flow events that tend to govern the **equilibrium** channel shape and size of alluvial stream channels in temperate regions, higher magnitude, less frequent flow events shape dryland streams (Wolman and Gerson 1978; Baker 1977; Graf 1983; 1988). Thus, equilibrium and related concepts such as bankfull or **channel-forming flow** may not be relevant in the dryland environment.
- **Floodplains:** Geomorphic floodplains are absent from many dryland channels because the extreme variability of discharges prevents the repetitive over-bank flows needed for the vertical accretion of this landform (Graf 1988). Where streams have intermittent or perennial flow they may behave more as streams in temperate areas and may have well-defined floodplain-like landforms that are episodically built and reshaped between sizable flood events. Where present, this less well-developed and less-persistent landform is herein defined as a **flood terrace**.
- **Physical habitat:** From an ecosystem perspective, one result of transient channel forms that expand and contract laterally and longitudinally is the creation of diverse and spatially variable physical habitat. Examples of these specialized physical habitats include the local retention of residual water on small, ephemeral channels noted above; the concentration of stream bed sediment that is often looser than the soils of surrounding uplands that can be exploited by specialized sand-burrowing species of wildlife, or the small caves and crevices in eroded dry wash banks that provide refuge from predators and from extreme heat and dryness (Levick et al. 2008).
- **Channel roughness:** in contrast to temperate region streams where vegetation grows mainly along the banks, vegetation in dryland streams grows in the channel bottoms because water remains here longest and can be retained within the near-surface sediment even when none remains at the surface (Graeme and Dunkerley 1993; Huang and Nanson 1997). This vegetation creates complex flow hydraulics due in part to variations in channel roughness during individual floods when flow depth exceeds that of the vegetation and between events as vegetation that has been scoured away regrows. Instead of the usual inverse relation between roughness and water depth, as discharge increases roughness may increase with increasing depth as the denser, upper portions of vegetation in the channel are encountered (Figure 6).
- **Drainage pattern:** The sparse vegetation, lack of soil, high erosion rates, localized runoff, and downstream decreases in stream flow lead to closely spaced channels and high drainage densities such that lower **stream order** channels that are tributaries to larger **washes** tend to be smaller and more numerous than their temperate region counterparts (Bull and Kirkby 2002).

- **Alluvial fans:** Alluvial fans form when **confined streams** flow out of the mountains and onto plains and sediment is deposited. As a stream leaves a mountain canyon, flow velocity decreases, channel confinement is lost, and water spreads out and sediment carried by the stream is deposited, often as **debris flows** (AFTF 2010a). Stream channels on all but the most inactive alluvial fans are subject to **flow path uncertainty** due to the rapid diversion of flow from one stream channel to another (i.e., **avulsions**) in response to channels blocked by sediment accumulations from previous debris flows. Channel avulsions produce the **divergent** flow channel pattern and dramatic temporal and spatial changes in channel morphology and position characteristic of alluvial fans (NRC 1996). These divergent **drainage networks** increase in channel density downstream in contrast to temperate environs where **confluent** networks tend to decrease in channel density (Reid and Frostick 1997; Bull and Kirkby 2002).

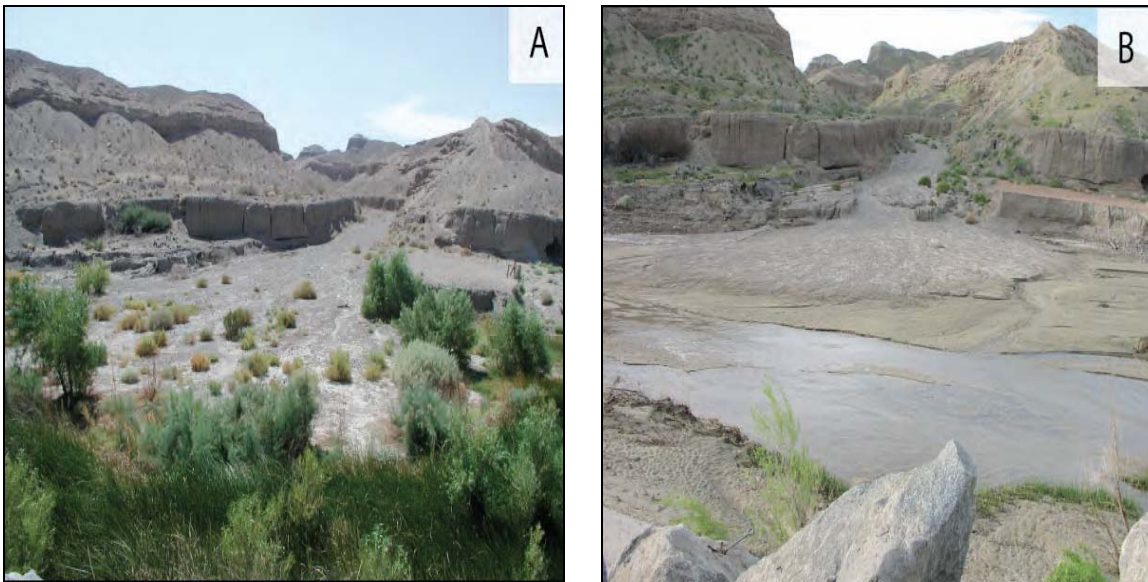


FIGURE 6. Change in channel roughness. Pre-flood vegetation (A) and post-flood removal of vegetation (B) from the Mojave River at Afton Canyon, January 2005. Largely concentrated in the channel, the vegetation creates complex flow hydraulics due in part to variations in channel roughness during individual flood events as flow depth exceeds that of the vegetation and between events as vegetation that has been scoured away re-grows. Instead of the usual inverse relation between roughness and water depth, as discharge increases roughness may increase with increasing depth as the denser, upper portions of vegetation in the channel are encountered. *Photos from Lichvar and McColley 2008.*

4 DRYLAND STREAM CHANNEL FORMS

Although stream morphology tends to exist on a continuum where the channel form varies along the length of any given stream (e.g., a narrow, single-thread channel form in bedrock dominated reaches; a wide and braided channel form where the same stream flows through sands and gravels), three major channel forms characterize the dryland streams of California: (1) single-thread channels, (2) compound channels, and (3) **discontinuous channels**.

4.1 Single-thread Channels

Single-thread channels tend to be shorter, more numerous, have a lower sinuosity than temperate region streams, and are generally **first-** or **second-order** tributaries that flow directly to larger, main stem channels (Figures 7 and 8) (Schumm 1961).

Single-thread channels generally lack a true floodplain, but where floodplains do occur they are generally limited to streams having origins in more humid upland regions, or on spring-fed streams (Figure 9). However, some sand and gravel bed streams do episodically build and reshape floodplain-like features between sizable flood events (Figure 10). Where present, this less well-developed and less-persistent landform is herein defined as a **flood terrace**. Flood terraces usually occur on the inside of meandering bends and along one or both banks of straight channel reaches.



FIGURE 7. Single-thread channel with sand and gravel bed. Tributary to El Paso Wash, Mojave Desert, Ridgecrest, California. *Photo by K. Vyverberg, January 2010.*



FIGURE 8. Single-thread channel with sand bed. Tributary to El Paso Wash, Mojave Desert, Ridgecrest, California. *Photo by K. Vyverberg, January 2010.*



FIGURE 9. Single-thread channel with floodplain. Spring-fed and meandering tributary to the West Fork Mojave River, east side of the San Bernardino Mountains. *Photo by K. Vyverberg, February 2010.*



FIGURE 10. Flood terrace on dryland channel. Note the break in slope, the textural change from a finer-grained matrix within the active channel to sand and cobble in the flood terrace floodplain, and the increase in vegetative cover and maturity on the terrace. *Photo from Lichvar and McColley 2008.*

4.2 Compound Channels

Generally considered the most common channel form for larger streams in dryland regions, compound channels are characterized by a single, low-flow meandering channel nested within a larger watercourse defined by a frequently shifting, **braided channel** network (Figure 11) (Graf 1988; Tooth 2000). The low-flow channels are susceptible to widening and avulsion during moderate to high discharges, re-establishing as smaller channels with declining flows or during subsequent low flow events.



FIGURE 11. Compound channel. Most recent and transient low flow channel nested within the larger watercourse, Mojave River, California. *Photo from Lichvar and McColley, 2008.*

4.3 Discontinuous Channels

Discontinuous streams form a distinctive pattern characterized by defined erosional channel segments that alternate with depositional reaches (**sheet flood zones**) that lack a defined channel form (Figure 12) (Thornwaite *et al.* 1942; Schumm and Hadley 1957; Bull 1997; Field 2001). The distinctive channel-pattern sequence is repeated down valley at intervals that reflect the size of the stream flow, and may vary in length from feet to miles (Bull 1997).

Fluvial processes active along the channel change from **aggradation** to **degradation**. A single channel conveys flow to the apex of an aggrading **channel fan**, and sediment is deposited as water infiltrates into the channel bed. The single thread channel transitions into a **distributary** network of channels, which lose confinement and dissolve into sheet flood areas that then drain to **headcuts**. The headcuts re-concentrate the flow into a single channel. The complete sequence of reaches between headcuts is termed a **discontinuity**.

While a discontinuous, dryland stream system as a whole might be considered to be in equilibrium if the channelized area relative to sheet flood area remains constant over time, a single point along the system will never reach an equilibrium state. Channel morphology is always in flux, even if headcuts and sheet flood zones are migrating headward at the same equilibrium rate. On discontinuous, dryland stream systems, dramatic changes in channel morphology are spatially abundant and frequent (Bull 1997; Field 2001; Field and Lichvar 2007).

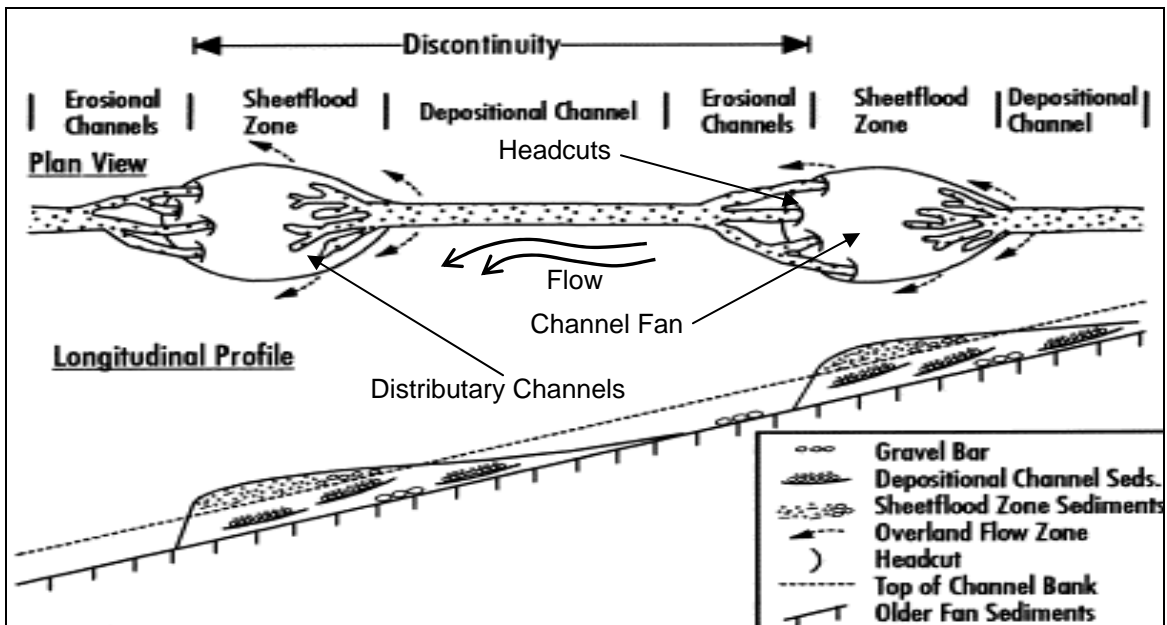


FIGURE 12. Discontinuous ephemeral stream. Schematic plan view and longitudinal profile. *Graphic adapted from Field and Lichvar 2007.*

5 ALLUVIAL FAN DISTRIBUTARY CHANNEL NETWORKS

Alluvial fans are estimated to comprise more than 30 percent of dryland landscape in the Colorado and Mojave deserts (House 2005). Alluvial fans are gently sloping, fan-shaped deposits of sediment that form where steep, confined mountain streams flow out onto a **piedmont plain**. Although often resembling extended fans when viewed on maps or aerial photographs, their morphology can be elongated and irregular if bounded laterally by adjacent fans (i.e., a **coalesced fan** or **bajada**), resistant rock, or **abandoned fan** or **relict fan surfaces** (Figure 13) (House 2005).

Alluvial fans are commonly formed by debris flow and **hyper-concentrated flood** deposits, producing a distributary system of channels and broad areas of unconfined flow below the **topographic apex** that convey flood waters and sediment onto the fan surface (Figure 14). Alluvial fans are dynamic depositional systems that differ with geographic location and are broadly categorized by the physical process that dominates their formation: **stream flow fans**, **debris flow fans**, and **composite fans** that contain features found on both streamflow and debris flow fans (Bull 1977; NRC 1996).

Compound, discontinuous and single-thread channels and combinations of these channel forms all occur on alluvial fans, but in a distinctive drainage pattern reflective of the depositional processes active on fans. From the fan downslope toward the valley floor, the stream channels tend to separate (i.e., have a distributary flow pattern). The channels – whether single-thread, compound, or discontinuous – diverge and diminish in width, depth, and discharge along their general flow path due to the rapid diversion of water by channel blockages of sediment and debris deposited abruptly during flow events.



FIGURE 13. Coalesced alluvial fans (or bajada). Where alluvial fans converge from multiple source valleys, the fan-shape may not be obvious. West side of Death Valley, California. *Photo courtesy of Marli Bryant Miller, www.marlimillerphoto.com.*

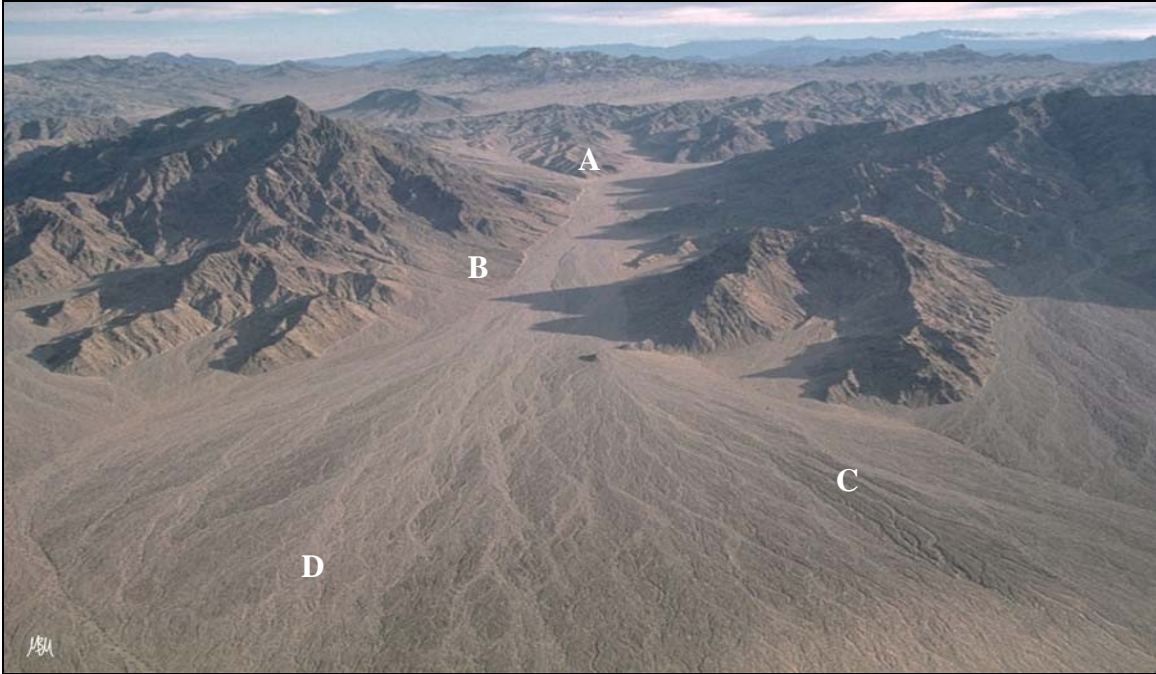


FIGURE 14. Alluvial fan morphology. Note that (A) the single compound stream channel emerges from the mountains (at the **topographic apex**, top center of the photograph) and (B) splits into a network of distributary watercourses (at the hydrographic apex). These distributary channels are separated by (C) drainage divides formed by older fan deposits, shown by their darkened desert varnish. As stream flow proceeds down the fan, channel form typically becomes less defined or lost altogether, and sheet flood process may dominate on the lower fan apron (D). In contrast to channels that typically decrease in number as they converge toward a single, larger channel, these distributary channels diverge from the single-source channel, as they increase in number and decrease in size toward the toe of the fan. Death Valley, California. *Photo courtesy of Marli Bryant Miller, www.marlimillerphoto.com.*

Despite transmission losses and the downstream decrease in flow, the reduced channel width, depth, and gradient can force water over the bank into a thin, relatively uniform expanse of unconfined water. This **shallow flooding** is superficially similar to overland (i.e., **sheet flow**) and sheet flood conditions but, as defined here, is a distinct flood phase that occurs when the capacity of a channel is exceeded. Although a classic “geomorphic floodplain” is generally absent from dryland streams, this shallow flood is analogous to unconfined out-of-bank flooding and inundation of the floodplain that occurs in temperate region streams.

On fans where the transport capacity of a stream exceeds sediment supply, the stream channels can incise and become better defined. In this case, small, well-defined diverging channels may convey the flows directly to the toe of the fan and onto the valley floor. But in general, distributary channels tend to become increasingly less defined as they flow down the fan. As channel form is lost the flood phase may transition to unconfined sheet flood conditions (Figure 15 (a)-(c)).

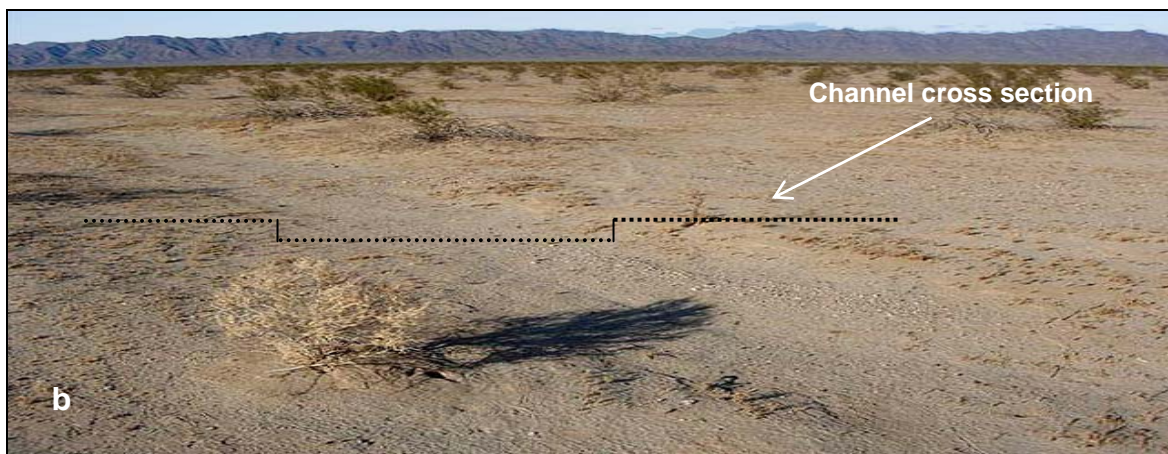
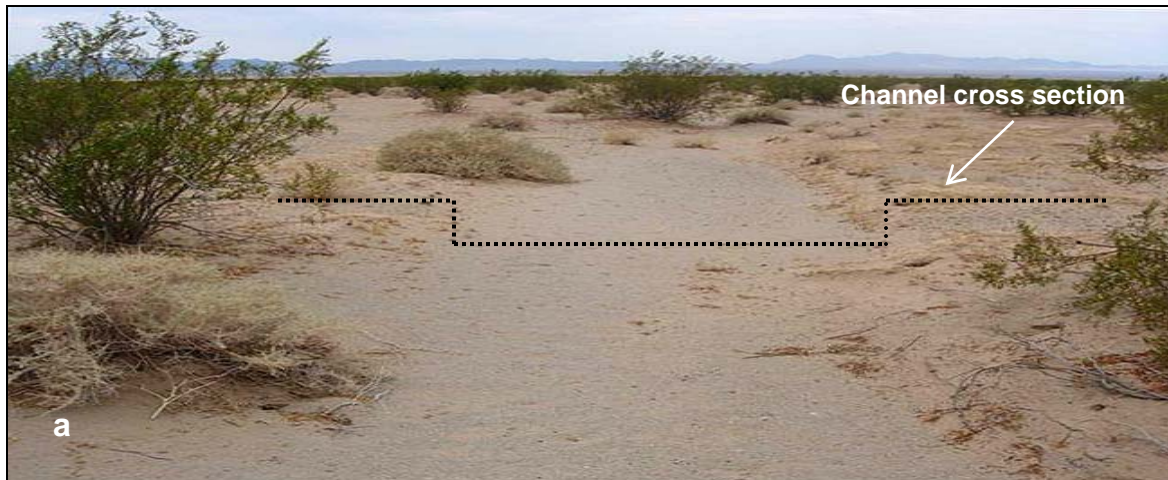


Figure 15 (a)-(c). Distributary channel upstream to downstream transition. As stream flow proceeds down the alluvial fan channel definition tends to decline. Figure 15 (a) a small single-thread channel with well-defined banks and a plane sand bed in a distributary drainage network near the toe of an alluvial fan. Figure 15 (b) increasing loss of a defined channel form where flows that exceed channel capacity can result in unconfined shallow flood conditions. Figure 15 (c) complete loss of channel form typical of an unconfined sheet flood area. Although they can occur elsewhere as well, these channel forms and sheet flood areas tend to occur on the distal or downstream-most edges of alluvial fans (between areas C and D and downstream of area D on Figure 14). Ford Dry Lake area, Blythe, Riverside County. *Photo by K. Vyverberg.*

In a landscape dominated by a network of active distributary channels, such as on alluvial fan and piedmont landforms, streams have definable beginnings where they leave the mountain areas or spill from shallow swales, and end where channel confinement is lost and flow dissipates. In between, the flow proceeds across a broad, definable zone within which is set a dense network of channels prone to rapid diversions of flow and channel avulsion. Given this, the watercourse boundary is defined not by individual channels, but rather by the larger flow zone bounding the channel network, and within which channel relocations are likely to occur (Figure 16).

In this example the boundary is broadly based on the presence of older fan deposits capped with **lag gravel pavements** darkened by **desert varnish** as an indicator of inactive fan surfaces and thus likely inactive stream channels.

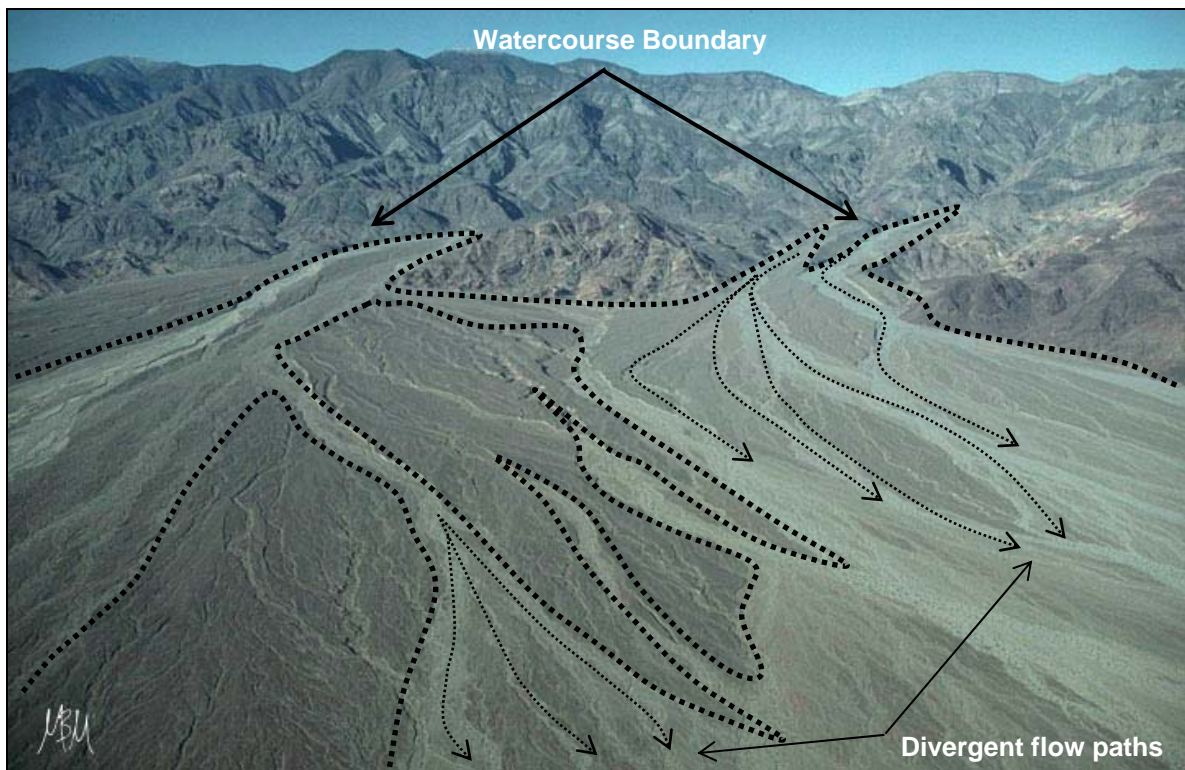


Figure 16. Watercourse boundary of a distributary channel network on coalesced alluvial fans. The distributary channel network within the watercourse may include single-thread, compound, and discontinuous channel types. Note that the streams have definable beginnings where they leave the mountain areas and end where channel confinement is lost and flow dissipates into the alluvial valley. In between, the flow proceeds in a broad definable zone within which is set a dense distributary network of channels prone to rapid diversions of flow. The watercourse boundary is defined not by individual channels, but rather by the larger flow zone bounding the channel network, and within which channel relocations are likely to occur. The scale limitations of the photograph prevent delineation of a more detailed watercourse boundary inclusive of all potentially active channels. West side of Death Valley, California. *Photo courtesy of Marli Bryant Miller.*

6 PROJECT CONSIDERATIONS IN DRYLAND WATERSHEDS

The net effect of the distinct hydrologic and geomorphic characteristics described above is that dryland stream processes and forms are less clear-cut, and stream behavior is more difficult to predict, than that of a temperate or humid region counterpart. In summary, some of the more problematic characteristics include:

- Flow dominated by short-lived, high magnitude-low frequency, highly variable runoff events often associated with significant channel widening, channel deepening, and high sediment concentrations;
- Rainfall-runoff processes, transmission losses, and sediment transport characteristics that make hydraulic modeling difficult;
- Asynchronous flows between tributary and main stem streams that make the morphology and biological significance of dryland streams difficult to interpret;
- Non-equilibrium, transitory channel forms confound conventional notions of stable versus unstable stream behavior, and complicate determinations of active versus relict or abandoned stream processes and forms.

Stream behavior and project-related impacts on dryland stream environments are difficult to evaluate because many of the concepts and tools developed in the larger field of fluvial studies were developed in more humid regions. The transfer of these commonly used concepts, theories and practices without consideration for the variations in processes active in dryland streams can be problematic (NRC 1996; AFTF 2010b; Bledsoe *et al.* 2008). Until these concepts and tools can be adapted for use in the dryland environment – a work in progress as of this writing – when reviewing projects in these watersheds, the characteristics that distinguish dryland streams from temperate-region streams outlined in Section 4 of this document, should be considered along with the information below:

6.1 Concepts

- **Equilibrium channel form:** In contrast to the influence of lower, more frequent intermediate flow events that tend to govern the equilibrium channel shape and size of alluvial stream channels in temperate regions, higher magnitude, less frequent flow events shape dryland streams. Equilibrium and related concepts such as bankfull or channel-forming flow are of questionable relevance on dryland streams, and the rationale for their use to predict project-related impacts on stream channel form and function should be explored.
- **Transitory channel morphology:** Episodic stream processes create a fabric of highly varied, transient channel forms. These transient forms can confound determinations of active versus relict stream processes and forms. Similarly, the transient nature of stream channels where change is the norm challenges conventional notions of stable and unstable channel form. Project-related assessments of whether a stream is active, stable or unstable, should be accompanied by the evidence used to make such determinations.

6.2 Tools

- **Hydraulic models:** Commonly used hydraulic models – such as HEC-Ras – are not designed to account for the extreme variability in sediment loading and flow regime inherent to dryland streams and therefore are of limited value as a predictive tool for the behavior of these streams or for evaluating the performance and sustainability of projects built within

this stream environment unless the model has been adapted for use on the episodic streams of dryland environments.

- **Alluvial fans:** The Alluvial Fan Task Force (AFTF 2010b) has developed an assessment tool available for use as a preliminary means of identifying the fluvial processes active on alluvial fans, and the potential distribution of floods, debris flows, and areas where anthropogenic activities may result in detrimental modification of stream flow patterns (AFTF 2010b, Chapters 2-8, and appendices). The AFTF reports are available online at <http://csusb.edu>.
- **Stream assessment tools:** Tools predicated on temperate and humid region **riparian** area processes and attributes – such as the California Rapid Assessment Method (Collins *et al.* 2008) – should be considered unsuitable for use in establishing the pre-project condition of streams unless the tool has been adapted for use on the episodic streams and associated plant communities of dryland environments.
- **Surface runoff:** Rainfall–runoff models developed specifically for dryland regions should be used to more accurately account for transmission losses, soil moisture storage, spatial distribution of rainfall, evaporation, and groundwater recharge (Field and Lichvar 2007).
- **Surface erosion:** Many dryland soils vary in erodibility and permeability over short distances. Models that assume that overland flow depths and surface erosion can be described using a single mean value, are likely to be in error when used to calculate erosion rates.

6.3 Water and Sediment

- **Transmission losses:** In dryland streams considerable water is lost through evaporation and through seepage into the unconsolidated sediment of channel boundaries. These transmission losses decrease downstream flood peaks and total runoff volumes that strongly influence sediment transport. Development-related hydraulic analyses should account for transmission losses to reliably predict project-related impacts on sediment transport or downstream flooding.
- **Groundwater:** The contribution of episodic stream flow to groundwater from transmission losses through the bed of a stream or alluvial fan can be a very important source of recharge to valley bottom aquifers (Bull and Kirby 2002; Levick *et al.* 2008; AFTF 2010b). Projects that propose large scale alterations to natural patterns of surface water movement should consider the potential impact of these alterations on groundwater recharge and demonstrate that detrimental impacts will not result from the project as proposed.
- **Sediment transport:** Sediment concentrations in dryland streams are often more than five times as high as at times of high flow on perennial streams (Reid and Frostick 2000). As with transmission losses, sediment volume and the tendency for its episodic transport should be considered in project-related hydraulic analyses.
- **Distributary flow paths:** Projects that propose to redirect the flows of distributary channel networks by concentrating flows to a few channels alter the naturally diffused flow and water distribution over a broader landscape that is typical of these streams. These hydrologic modifications can affect the variability and distribution of stream habitat; can result in decreased recharge to local groundwater aquifers; can result in increased channel bed and bank erosion and increased sediment transport in some areas and increased deposition in others, and can increase the likelihood of downstream flooding. Development-related hydraulic analyses should take into account the potential consequences of distributary channel modifications to reliably predict project-related impacts.

6.4 Ecology

- **Physical habitat:** Transient channel forms that expand and contract laterally and longitudinally tend to create diverse and spatially variable physical habitat that can provide refuge from predation and extreme heat and dryness for many species (Levick et al. 2008). Projects that propose to “stabilize” an otherwise dynamic environment – such as by the lining of a dryland wash with soil cement or concrete – should consider the potential impact of these alterations on habitat diversity and species survival.
- **Biological and hydrologic relevance of small ephemeral streams:** Smaller, more frequent and highly localized flow events dominate the fluvial landscape of the dryland regions. These seemingly minor augmentations of infrequent water flow produce detectable vegetation patterns (e.g., volume, height, or stem density compared to upland areas) and collect and disperse loose sediment subsequently utilized as habitat by many species. This suggests that in some landscapes the importance to the biological community of the more frequent flows of these small ephemeral streams may equal or exceed that of larger associated washes where surface flow is rare. Given this, the biological significance of these small streams should be assessed prior to any large scale alteration.

The above list is not intended to be all-inclusive, but rather a starting point for considering the types of analyses necessary to characterize the physical behavior and biological function of episodic streams and to protect the integrity of dryland ecosystems.

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GLOSSARY

The terms below were defined paraphrasing a variety of sources relevant to stream ecology, geomorphology, and hydrology. Citations are included in the Reference section of this document (Bates and Jackson, 1984; Blair and McPherson 1994; Wilson and Moore, 1998; Alluvial Fan Task Force, 2010a, 2010(b)).

Abandoned fan and abandoned fan surfaces: Holocene Epoch fan deposits that contain incised tributary drainage networks, may or may not have varnished surface clasts, and do not convey water, sediment, and debris from the upland drainage basin; they may also be subject to deposition and erosion due to avulsive processes during extreme events. See *relict fan* and *relict fan surfaces*.

Active channel: The portion of the channel receiving sufficient and frequent enough flows to leave evidence on the landscape, such as a cleanly scoured substrate, a line impressed on the bank, changes in soil characteristics, or changes in vegetation.

Aggradation: An increase in the channel bed or floodplain elevation by deposition of sediment in excess of that the stream is capable of transporting.

Alluvial fan: Gently sloping fan-shaped landforms that form where steep, confined mountain streams flow out onto a *piedmont* plain. They often resemble extended fans when viewed on maps or aerial photographs, but their morphology can be irregular forms bounded laterally by adjacent fans, bedrock outcrops, and relict fan surfaces, among other possibilities (House, 2005).

Alluvium: A general term for unconsolidated clay, silt, sand, gravel deposited as sorted or semi-sorted sediment in the bed of a stream or its floodplain or delta, or as a fan at the base of a mountain slope.

Avulsion: The rapid full or partial redirection of the course of a stream from one channel into another due to the blockage of the channel by sediment or debris.

Bajada: Coalesced alluvial fans; a broad, continuous, gently inclined depositional surface that extends from the base of mountain ranges out into and around an inland basin, formed by the lateral coalescence of a series of separate but confluent alluvial fans.

Bankfull: The discharge that fills the active channel to a stage above which any further increase in depth results in a rapid increase in width as flow spreads across the floodplain.

Base flow: That part of stream discharge sustained by groundwater discharge and not attributable to direct runoff or melting snow.

Bed forms: Bedding surface features that are individual elements of a mobile granular or cohesive bed.

Bedload: The part of the total sediment load that is moved on or immediately above the stream bed. Includes the larger or heavier particles (boulders, pebbles, gravel) transported by traction or saltation along the stream bed.

Braided channel: Interlacing or tangled network of several small, branching, and reuniting shallow channels separated from each other by islands or channel bars. Braided channels commonly appear to be part of a single channel, and in plan view appear to be strands of a complex braid.

Channel fan: A thin, narrow accumulation of alluvium deposited in a stream channel that results from the downstream loss of stream flow and decline in sediment transport capacity.

Channel-forming flow: The dominant discharge, defined as a theoretical discharge that, if maintained, would produce the same channel geometry as the natural long-term *hydrograph*. Channel-forming discharge concepts are applicable to stable alluvial streams (i.e., streams that have the ability to change their shape and are neither *aggrading* nor *degrading*). The channel-forming discharge concept is generally not applicable for channels in dryland environments because runoff is generated by localized high-intensity storms and the bank vegetation is sparse or absent so the channel adjusts to each major flood event.

Channel morphology: The form and physical characteristics of a stream channel.

Coalesced or coalescing alluvial fans: The lateral growth of adjacent alluvial fans until they finally combine to form a continuous, inclined deposit along a mountain front. See *Piedmont and piedmont plain*.

Compound channel: A channel form typical of many dryland intermittent and ephemeral streams characterized by a low-flow meandering channel nested within a larger watercourse defined by a frequently shifting, braided channel network. See *Braided channel*.

Composite fans: Alluvial fans built-up through both hyperconcentrated floods and debris flows and that contain features found on both streamflow fans and debris flow fans. Slopes on composite fans typically range from 4-8 degrees (AFTF 2010b).

Confined stream: The physical restriction of lateral movement by a stream channel because of the presence of bedrock or other geologic features.

Confluent drainage pattern or network: A network of individual streams that combine with one another to form one stream.

Debris flow: A mix of water and debris, which may include particles ranging in size from clay to boulders and may contain woody debris and other materials, that flows down a stream channel or steep slope, sometimes at great velocity, and contains more than 60 percent debris (less than 40 percent water) by volume.

Debris flow fan: Alluvial fans built-up through successive debris flow events. Slopes on debris flow fans may be as steep as 6 to 8 degrees, and may have terminal lobes, marginal levees and trapezoidal or U-shaped channels with relatively low width-to-depth ratios. Deposition is episodic, and rapid aggradation or plugging may occur in much deeper channels than is the case for stream flow fans. Even channels that appear to be stable during water flood events may be subject to avulsion during or after debris flow, and this contributes to the uncertainty in down-fan flow path typical for alluvial fans (AFTF, 2010b).

Degradation: The lowering of a stream bed due to such factors as changes in sediment supply or increased scouring that results in changes in channel cross-sectional area.

Desert varnish: A dark coating from 2 to 500 microns thick that forms on rocks at and near the Earth's surface largely the result of mineral precipitation. The chemical composition is dominated by clay minerals and iron and/or manganese oxides and hydroxides, forming red and black varnishes, respectively. The thickness of the coating increases with time if abrasion or burial of the rock surface do not occur. As a result, gravels and cobbles on alluvial fan surfaces that have been inactive for long periods of time have darker and thicker coatings of varnish than younger deposits.

Discontinuity: The complete sequence of reaches between headcuts along a *discontinuous channel*.

Discontinuous channel: A channel along which fluvial processes change from aggradation to degradation and a well-defined channel form is periodically lost along the stream length.

Distributary flow pattern, channel, or network: Channels flowing away from the main stream and not rejoining it. The number of channel forks commonly exceeds the number of channel confluences, creating a divergent distributary, rather than convergent tributary drainage pattern.

Divergent flow, channel or drainage network: See *Distributary flow pattern*.

Drainage network or system: The spatial and geometric relationship between individual streams in an area; may be dendritic, trellis, parallel, or distributary.

Dryland regions: Areas where potential evapotranspiration is greater than rainfall (Bull and Kirkby, 2002), and the term is used here as a collective noun for the arid and semi-arid regions of California.

Ephemeral stream: A stream that flows in direct response to and only during and shortly after precipitation events. Ephemeral streams may or may not have a well-defined channel. Their beds are always above the elevation of the water table, and stormwater runoff is their primary source of water. Ephemeral streams include normally dry arid or semi-arid region desert washes.

Equilibrium: A basic principle of fluvial geomorphology which holds that stream channel form – its cross sectional shape, planform, and gradient – is adjusted to the prevailing watershed conditions that control the amount of sediment and water delivered to the channel (Leopold et al., 1964, Dunne and Leopold, 1978).

First- or second-order streams: Relative to stream order. The smallest and second smallest headwater tributary to downstream watercourses. See *Stream order*,

Flashy flow or discharge pattern: Periods of no flow or low-magnitude flow, high- frequency events separated by short-duration, high-magnitude, low-frequency events.

Flood terrace: As defined here, a relatively ephemeral geomorphic surface formed by deposits where over bank flow has occurred and is oftentimes reworked and rebuilt by subsequent flood events. A similarly formed but less persistent landform superficially related to temperate region *floodplains* and *stream terraces*.

Floodplain: The surface or strip of relatively flat area adjacent to a river channel that is prone to flooding, and which has evolved through the deposition of alluvial materials. The floodplain is integral to stream function. Where one exists and is functionally connected to the stream, the floodplain lies within the bounds of the watercourse.

Flow path uncertainty: The perceived, historical channel or network of channels cannot be relied on to convey the base flood without the creation of new flow paths or the abandonment of existing flow paths (AFTF, 2010a).

Headcut: An abrupt vertical drop in the bed of a stream channel that is actively eroding upstream (or in a headward direction).

Headwater channel or stream: Headwater channels are typically considered to be first- and second-order streams (Gomi et al., 2002), meaning streams that have no upstream tributaries (i.e., “branches”) and those that have only first-order tributaries, respectively. See *Stream order*.

Hydraulic analyses: analytical methodologies for assessing the movement and behavior of stream flow and floodwaters and determining water surface elevations.

Hydrograph: A graph showing stage, flow, velocity, or other properties of water with respect to time.

Hydrographic apex: The highest point on an alluvial fan where the flow is last confined and at which flow-paths become *distributary*.

Hyper-concentrated flood: A moving mixture of sediment and water containing between 20 and 60 percent sediment by volume.

Intermittent stream: A stream that flows only at certain times of the year when it receives water from springs, groundwater, or rainfall, or from surface sources such as melting snow. Includes intermittently dry desert washes in arid or semi-arid regions.

Lag gravel pavement: A residual accumulation of coarse rock fragments remaining on a surface after the finer material has been removed by wind or water erosion.

Low flow channel: On ephemeral streams, the channel within a larger watercourse occupied by frequent flow events; on intermittent and perennial streams, the channel within a larger watercourse that is occupied and sustained by the lowest groundwater discharge. See *baseflow*.

Main stem: Relative to stream order. The largest and downstream-most watercourse.

Meandering: The curving or winding of a stream channel in its alluvial valley.

Overland flow: The down slope movement of water taking the form of a thin, continuous layer over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills (i.e., very small, steep-sided channels resulting from erosion and cut in unconsolidated materials by concentrated but intermittent flow of water). This flow typically is short lived with a limited travel distance; a relatively high-frequency, low-magnitude event.

Perennial stream: A stream that flows continuously during a year of normal rainfall.

Piedmont and piedmont plain: The descriptive term for a relatively broad, generally low relief area at the base of the mountain front that slopes down toward the center of the valley. Piedmonts are composed mostly of sediment (alluvium) shed from adjacent highlands by streamflows or debris flows, but they often include complex mixtures of eroded bedrock and various types of surficial geologic deposits and landforms (House, 2005).

Plane bed: A flat, almost featureless bedding surface.

Relict: A landform remnant that has survived after the processes responsible for its formation have ceased; a channel or remnant of a channel that is no longer part of an active fluvial process.

Relict fans and relict fan surfaces: alluvial fan deposits that occurred during the Pleistocene Epoch under a different climate regime, and contain deeply incised tributary drainage networks that do not convey water, sediment and debris from the upland drainage basin. See also *abandoned fans* and *abandoned fan surfaces*.

Riparian: Riparian areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine-marine shorelines (NRC 2002).

Runoff: That part of precipitation that appears in surface streams. Runoff in streams begins when depression storage in the watershed (e.g., ponds, small depressions) is full and the rate of rainfall exceeds the rate of infiltration (Dunne and Leopold, 1978).

Shallow Flooding: Unconfined flows that exceed the channel capacity of distributary channels and spread out over broad, relatively low relief areas, such as alluvial plains.

Sheet flood or sheet flood zones: Shallow, unconfined flow that occurs in channel fan areas of discontinuous channels, and on low relief areas of alluvial fans where channels no longer exist; a relatively low-frequency, high-magnitude event.

Sheet flow: See *Overland flow*.

Single-thread channel: a stream where flow is restricted to a discrete channel.

Sinuosity: A measure of a stream's "crookedness" measured as the total stream length along the stream *thalweg* divided by the valley length. Sinuosity is the result of the stream dissipating its flow forces. Intermittent streams have a varying flow regime, and so tend to be less sinuous downstream than perennial streams.

Stable: The relative state of the location, geometry and roughness of a channel, network of channels or landform where any changes of location, geometry and roughness can be ignored in assessing flood risk (AFTF, 2010a).

Streamflow fan: Alluvial fans built-up through successive *hyperconcentrated* floods. Slopes on stream flow fans are generally less than 3-4 degrees, which is considered to be the threshold between streamflow fan deposition and debris flow deposition. Channels on streamflow fans have large width-to-depth ratios and are typically braided. Erosion and deposition can alter channel flow during a single flood event where deposition occurs as bars along the margins or center of the channel (AFTF, 2010b; NRC, 1996).

Stream terrace: One of a series of level surfaces in a stream valley, flanking and more or less parallel to the stream channel, originally occurring at or below, but now above, the level of the stream, and representing the dissected remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

Stream order: A measure of the position of a stream (defined as the reach between successive tributaries) within the hierarchy of the *drainage network or system*. A commonly used approach allocates order '1' to unbranched tributaries, '2' to the stream after the junction of the first tributary, and so on. It is the basis for quantitative analysis of the network.

Suspended sediment: The part of the total sediment load that is carried for a considerable period of time in suspension above the bed. It consists of mainly of clay, silt, and sand.

Swale: Depression or hollow where runoff from the surrounding uplands accumulates. Swales that yield channel flow are important sources of water, sediment, nutrients, and other materials during runoff, and are considered source areas to and integral parts of streams.

Thalweg: The line connecting the lowest or deepest points along a stream channel.

Topographic apex: The point at which an alluvial fan is last confined within the mountain front.

Transmission losses: The water loss due to seepage of surface flow into the unconsolidated sediment of the channel bed and banks.

Transport capacity: The maximum amount of sediment that can be carried along by a stream.

Unstable: The relative state of the location, geometry, and roughness of a channel, network of channels or landform that cannot be ignored in assessments of flood risk (AFTF, 2010b).

Wash: A broad, shallow, sandy or gravelly, and normally dry bed of an intermittent or ephemeral stream.

Watercourse: The stream channel in which water currently flows, or has flowed over a given course as defined by the topography that confines the water to this course when the water rises to its highest level. A stream may have more than one active channel or, as is often the case, secondary channels that receive water only during higher flow events. Low flow channels,

active channels, banks associated with these channels, floodplains, and stream-associated vegetation, may all occur within a single larger channel, designated the watercourse channel to discriminate between it and similar but smaller subordinate features that lie within its bounds. For the purposes of this review of stream processes and forms in dryland watersheds, a watercourse is a stream, the boundaries of which define the maximal extent or expression of a stream on the landscape.

Watershed: An area of land that drains water, sediment, and dissolved materials to a common outlet.

Width-to-depth ratio: A relative index of channel shape. Width is the total distance across the channel and depth is the mean depth of the channel. Channels with high width-to-depth (w/d) ratios tend to be shallow and wide. Channels with low w/d ratios tend to be narrow and deep.