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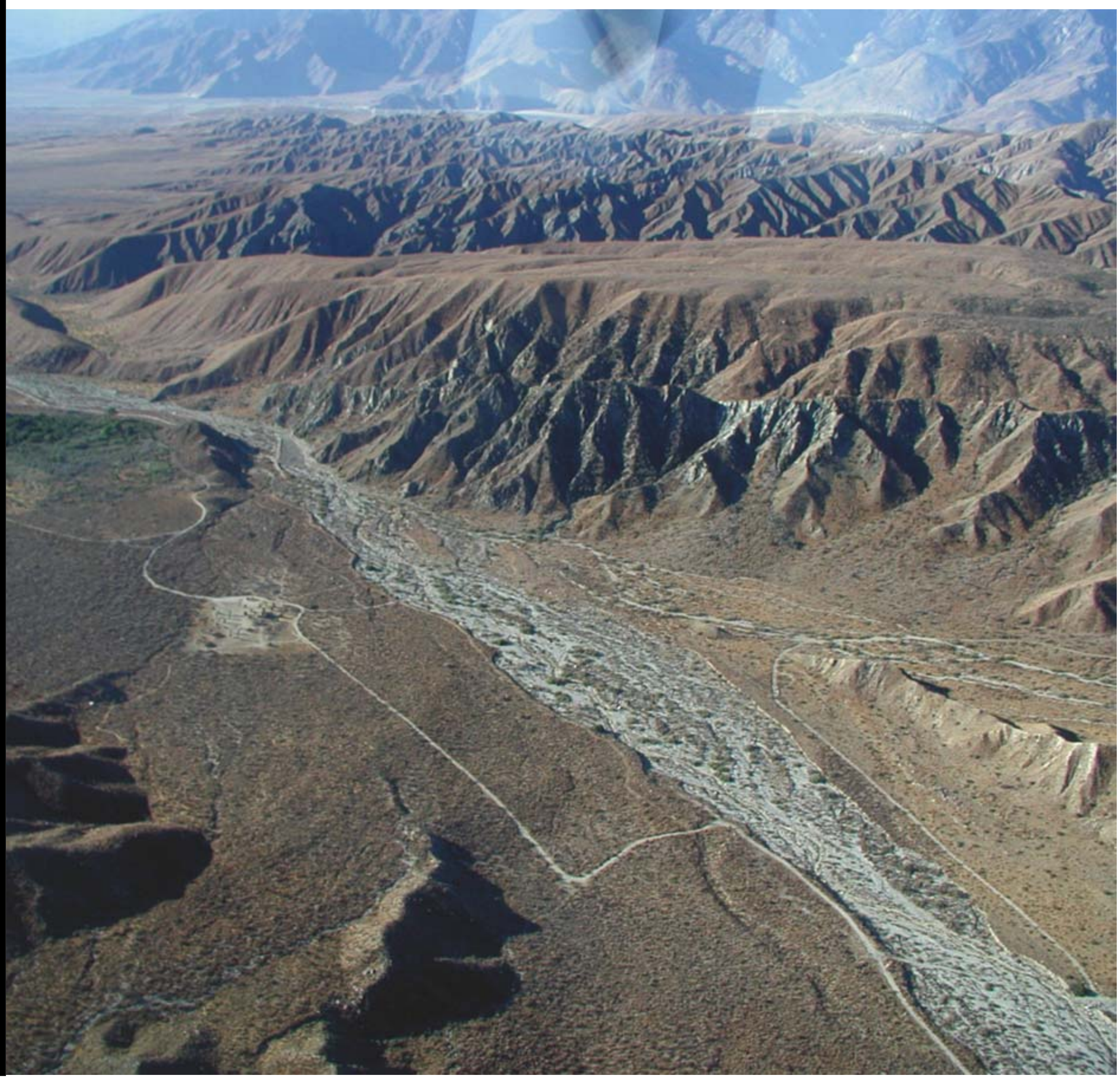
Edited by Robert W. Lichvar and James S. Wakeley

January 2004



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Front cover: Oblique aerial photograph of Mission Creek, east of Palm Spring, California, acquired during CRREL/NASA LIDAR research flights for indicators of "ordinary high water marks," September 2003. Photo by D. Finnegan, ERDC/CRREL.

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Review of Ordinary High Water Mark Indicators for Delineating Arid Streams in the Southwestern United States

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ENVIRONMENTAL PROTECTION AGENCY

ABSTRACT

The U.S. Army Corps of Engineers (Corps) delineates the jurisdictional extent of wetlands and other "Waters of the United States" (WoUS) under Corps and Environmental Protection Agency (EPA) regulations implementing Section 404 of the Clean Water Act (33 U.S.C. 1344). As part of this responsibility, Corps districts in the southwestern United States and elsewhere must delineate the extent of WoUS in arid areas, including arid-land stream channels. In non-tidal waters lacking adjacent wetlands, Corps jurisdiction extends to the ordinary high water mark (OHWM). Unlike wetlands, for which there are criteria for hydrology, soils, and vegetation specified in a national wetland delineation manual, there is no hydrologic definition of ordinary high water (OHW), and the identification of WoUS relies entirely on physical features of stream channels. This literature review investigates the climatic and regional conditions controlling hydrologic discharges in arid-land streams and the resulting physical features that develop within channels and floodplains. The review covers three main features associated with arid stream systems that might be useful for delineation purposes: hydrology, fluvial geomorphology, and vegetation. Based on the reviews, certain physical features were selected as potential OHWM indicators and were categorized by location above, at, or below the OHW line. To support the identification of OHW, these potential indicators are intended to be tested in selected locations across the Southwest to identify consistent and reliable indicators of the OHWM.

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PREFACE

This report was edited by Robert Lichvar, Ecologist, Remote Sensing/ Geographical Information Systems and Water Resources Branch (RS/GIS), Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Engineer Research and Development Center (ERDC), Hanover, New Hampshire; and James Wakeley, Research Wildlife Biologist, Wetlands and Coastal Ecology Branch, Environmental Laboratory, ERDC, Vicksburg, Mississippi. The chapters on hydrology and fluvial geomorphology were prepared by John Field, Geomorphologist, Field Geology Services, Farmington, Maine, and the chapter on vegetation was prepared by Gabrielle Katz, Department of Geography and Planning, Appalachian State University, Boone, North Carolina. Funding was provided by Headquarters, U.S. Army Corps of Engineers (HQUSACE) as part of the Wetlands Regulatory Assistance Program (WRAP) and by the U.S. Environmental Protection Agency (EPA), Region 9, San Francisco.

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The Commander and Executive Director of ERDC is COL James R. Rowan, EN. The Director is Dr. James R. Houston.

Chapter 1. Introduction and Summary of Ordinary High Water Mark Indicators

ROBERT W. LICHVAR AND JAMES S. WAKELEY

1.1 PROJECT BACKGROUND

Arid-land fluvial systems are critically important environments that provide valuable ecological benefits to the Nation. Small streams and rivers convey floodwaters and help ameliorate flood damage; maintain water quality and quantity; provide habitat for plants, aquatic organisms, and wildlife; and determine the physical characteristics and biological productivity of downstream environments (Brinson et al. 1981, Davis et al. 1996, Meyer et al. 2003). Ephemeral and intermittent streams dominant the stream types of the arid southwestern United States. For example, in Arizona most of the stream networks—96% by length—are classified as ephemeral or intermittent (Beven and Kirby 1993). Arid stream systems are located within montane, piedmont, or basin landscapes and have rough bed surfaces that are related to the stream gradient and watershed lithology, slowing the movement of water and allowing for water infiltration and recharge of groundwater (Knighton 1998). Fluvial morphology within these channels is frequently associated with extreme discharge events; streams and floodplains trap sediments and nutrients in addition to attenuating flood waters (Graf 1988, Leopold 1994). The accumulation of sediments and nutrients and the availability of water are also instrumental in maintaining the high levels of biological diversity associated with arid streams (Naiman et al. 1993). Some of the same fluvial features that maintain physical, chemical, and biological functions also may be useful for identifying Federal jurisdictional limits. This review is intended to help identify useful field indicators resulting from fluvial processes that can be used to locate the extent of Ordinary High Water (OHW) in arid-land streams.

Delineating the extent of Federal jurisdiction in wetlands and other “Waters of the United States” (WoUS) is fundamental to Corps of Engineers (COE) and Environmental Protection Agency (EPA) responsibilities under Section 404 of the Clean Water Act (33 U.S.C. 1344). As part of these responsibilities, COE Districts in the southwestern U.S. and elsewhere must be able to delineate the

extent of WoUS in arid areas. In 2001 the COE South Pacific Division published guidelines for use in determining jurisdictional limits for WoUS in the arid Southwest. These guidelines discussed pertinent literature regarding arid-land fluvial systems, types of flow regimes, general indicators of high water stages, and a matrix approach for establishing the presence of jurisdictional waters. The intent of the document was to describe physical features useful for identifying Ordinary High Water Marks (OHWM) and provide a method that would improve the accuracy and consistency of jurisdictional determinations. No effort was made to investigate all potential indicators, their relationship to storm or flood return intervals, or their reliability. In January 2003, representatives from the COE and EPA met in San Francisco and initiated a plan to refine OHWM indicators and methods for intermittent and ephemeral streams in the arid Southwest.

A number of objectives were identified at the San Francisco meeting to increase the accuracy and reliability of field indicators of OHWM. These were:

1. Undertake a literature review to assess existing information on fluvial hydrology, geomorphology, and vegetation;
2. From the literature, develop a list of potential indicators for testing and subsequent field use;
3. Survey the COE districts in the arid Southwest for further comment and input;
4. Develop a testing protocol to determine what flood return intervals were associated with the development of certain physical features of stream channels;
5. Test the field indicators across the arid Southwest to determine their reliability and subregionalize the indicators if necessary; and
6. Develop the protocols necessary for applying OHWM field indicators for jurisdictional purposes.

This report addresses items 1 and 2 above. One goal of this review was to discuss the climatic and hydrologic influences on potential OHWM indicators. The temporally and spatially variable streams of arid regions typically flow only during storm events and remain dry the remainder of the year. Therefore, indicators for field identification of OHWM may differ greatly from those used in wetland delineations. In Chapter 1 we provide the background and highlight key concepts influencing the development of OHWM indicators, propose a working definition of OHW, and summarize potential OHWM indicators identified from the literature. Chapters 2, 3, and 4 review and synthesize available literature on fluvial hydrology, geomorphology, and vegetation in the arid Southwest and provide support for our selection of potential OHWM indicators.

1.2 OVERVIEW OF THE CONCEPT OF "WATERS OF THE UNITED STATES"

Methods for delineating WoUS in arid stream systems are required for establishing jurisdictional responsibilities under the Clean Water Act (33 U.S.C. 1344). In non-tidal waters lacking adjacent wetlands, Corps jurisdiction extends to the "ordinary high water mark," which is defined in 33 CFR Part 328.3 as the line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation, or the presence of litter and debris. In practice the OHWM for a stream is usually determined by examining recent physical evidence of surface flow in the stream channel. In dryland fluvial systems typical of southwestern desert areas, the most common physical characteristics indicating the OHWM include, but are not limited to, a clear natural scour line impressed on the bank, recent bank erosion, destruction of native terrestrial vegetation, and the presence of litter and debris (COE South Pacific Division 2001). This approach to delineating WoUS is different from the approach used to identify and delineate wetlands. In the case of wetlands, there are criteria for hydrology, soils, and vegetation specified in a national wetland delineation manual (Environmental Laboratory 1987 and subsequent guidance from COE Headquarters). In contrast, there is no hydrologic definition of ordinary high water, and the identification of WoUS relies entirely on physical features of streams.

1.3 GENERAL APPROACH TO THE IDENTIFICATION OF OHWM INDICATORS

Methods for identifying and classifying wetlands for various purposes have generally taken a multi-factor approach based on two or more environmental features or kinds of evidence. Thus, wetland identification and classification rely heavily on hydrology, soil, and vegetative characteristics (Environmental Laboratory 1987, Cowardin et al. 1979, Mitsch and Gosselink 1993, Soil Conservation Service 1994, Tiner 1999, Wakeley 2002). In addition, recent efforts to develop functional assessment approaches have used hydrogeomorphic classifications to identify groups of wetlands that function similarly (Brinson 1993).

Likewise, in the arid Southwest, with its distinct climate and physiography, various landscape features lend themselves to identification of jurisdictional limits in arid fluvial systems. Unlike most wetlands, the soils in arid stream channels are typically Entisols (i.e., young soils with little horizon development) (Fanning and Fanning 1989), reflecting the dynamics of recent flood events and transport of sediments within the channel. Thus, the use of hydric soils (Natural Resources Conservation Service 2002) or their features for delineating arid streams is limited since these systems rarely develop redoximorphic features. The river flow regime, characterized by patterns of variation in surface flow magnitude, duration, frequency, and timing, has been termed the "master variable" shaping the associated aquatic and riparian environments (Poff et al. 1997). The size and shape of a river channel is controlled in large part by the dominant discharge in a particular region (Chapter 3). Riparian plant communities in the arid Southwest occur along streams as linear corridors and typically contrast sharply with upland deserts or grasslands (Chapter 4). These communities typically have a distinctive composition and structure that is influenced by the hydrodynamics of the channel. To meet the needs of the COE, field indicators of the OHWM must be specific responses to the hydrodynamics of the stream, and they must be readily observable to a field investigator throughout the year. Given these requirements, this review focuses on fluvial geomorphology and vegetation as the two major landscape features best representing antecedent hydrologic conditions in arid stream channels.

1.4 PROJECT AREA

The area broadly covered by this review includes all or portions of ten semi-arid western states: Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Texas, Utah, and Wyoming (Fig. 1). This region encompasses multiple physiographic provinces and is characterized by spatially and seasonally variable moisture sources that produce a highly variable rainfall pattern markedly different from that in the eastern U.S. (Chapter 2). The region generally falls within the Dry Domain and four Divisions—Tropical/Subtropical Steppes, Tropical/Subtropical Deserts, Temperate Steppes, Temperate Deserts, and their associated mountains—of the *Ecoregions of the United States* (Bailey 1995) and within the Western Range and Irrigated Region and California Subtropical Fruit, Truck, and Specialty Crop Region of the USDA Land Resource Regions (Soil Conservation Service 1981).

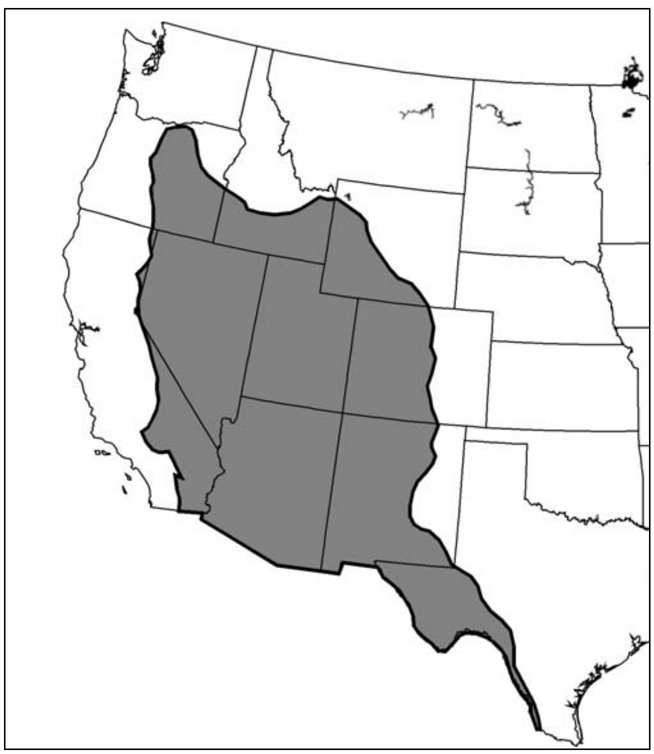

Figure 1. Area covered by this review.

1.5 LANDSCAPE FEATURES AND THEIR USEFULNESS AS OHWM INDICATORS

Hydrology

Physical features that develop within arid stream channels are a result of hydrometeorological events that produce flows in the stream channel. Therefore, understanding the nature of these events is critical to the development of OHWM field indicators. Climatically the region is influenced by three large-scale patterns in precipitation that influence channel morphology and OHWM field indicators. These are winter North Pacific frontal storms, summer convective thunderstorms, and late-summer eastern North Pacific tropical storms (Ely 1997). Either separately or in combination, these precipitation patterns influence channel discharges seasonally in the region. In general, winter North Pacific frontal storms make up an increasing proportion of the total rainfall as one proceeds toward the north in this region (Andrade and Sellers 1988). Convective thunderstorms, or the so-called "summer monsoons," typically are associated with Arizona and New Mexico. The North Pacific tropical storms occur across Arizona, New Mexico, southern California, and southern Utah. Changes in water temperature in the Pacific Ocean and subsequent El Niño patterns can cause increased precipitation in winters in California, shifts in monsoonal precipitation, and increased fall to spring precipitation throughout parts of the region. These patterns also cause shifts in decadal-scale precipitation and flood frequency. The region is well known for highly variable spatial and temporal rainfall (Reid and Frostick 1977, Graf 1988, Pilgrim et al. 1988), which can result in intense rains that can fall in one watershed or portions of a watershed while an adjacent watershed or portion remains dry (Chapter 2). Interannual variability in precipitation is also high in arid regions, with a high ratio of record peak to average annual discharge (Graf 1988).

In addition to a high ratio of peak to average annual discharges, there are other factors that make the occurrence of extreme discharges more common in the arid Southwest. The cumulative effects of interception of precipitation by vegetation, evaporation and transpiration, transmission losses, and topography play an important role in discharge rates. Rapid runoff rates are due in part to lower infiltration and interception rates combined with greater rainfall intensities in arid versus more humid climates (Pilgrim et al. 1988). Topography exerts a strong influence on the type, location, and amount of precipitation. Because of orographic effects, higher elevations experience more precipitation than low-lying areas. At higher elevations there also is an increase in vegetation cover and the possibility of snow. These factors result in more consistent runoff throughout

the growing season. More abundant vegetation at higher elevations tends to stretch the runoff over longer periods compared to low-lying areas (Chapter 2). The cumulative effects of all these factors on runoff causes arid stream systems to have greater flow magnitudes, more rapid responses to rainfall, and shorter-duration flows than their humid-region counterparts (Chapter 2). These factors, coupled with the highly variable climate and intense precipitation events, make selection of reliable OHWM field indicators challenging.

Geomorphology

Channel bed morphology and sediment arrangement in arid streams retain information about prior hydrologic events. Knowledge of these “fingerprints” has a basis in the principles of fluvial geomorphology. As in all graded streams, the river channel’s form—cross section, planform, and gradient—is a result of prevailing watershed conditions that control the amount of sediment and water delivered to the channel (Leopold et al. 1964, Leopold and Bull 1979). The dominant, or effective, discharge in a particular region generally controls the size and shape of the channel (Chapter 3). More frequent events, in concert with revegetation, tend to “heal” the impacts of larger flows and return the channel to a size that is in equilibrium with the dominant sediment and water discharge. OHW is sometimes interpreted as the bankfull position in an active channel (Rosgen 1996). Bankfull discharges are reported as having a recurrence interval of 1.5 years (Dunne and Leopold 1978, Rosgen 1996). Williams (1978) pointed out exceptions to this rule, so one should not assume that this average value holds for any given channel (Chapter 3).

Beyond the bankfull position in river channels are active floodplains and abandoned terraces. These abandoned terraces, typically at higher elevations, are a consequence of channel gradient changes resulting from either decreases or increases in sediment loads. These changes isolate previous channels and floodplains above the newly established channel (Chapter 3). In arid stream systems, abandoned terraces sometimes are easy to distinguish since they are high above the active channel; however, in systems with limited relief it is difficult to distinguish the active floodplain (Dunne and Leopold 1978). This constant striving to achieve equilibrium in arid regions with highly variable and intense discharges further confounds the selection of OHWM indicators.

Landscape setting, size of the watershed, location in the watershed, elevation, gradient, lithology, and hydrologic events all play an important role in developing different stream types in the arid Southwest. Stream types in this region are classified as discontinuous, ephemeral, compound, alluvial fan, anastomosing, and single-threaded channels. These various types are in part a response to

various gradients, sediment sizes, and volumes and rates of discharge. Field (Chapter 3) listed a suite of potential OHWM indicators below, at, and above OHW. No literature specifically discussed the relationship of landform types to these indicators, but these stream types are typically located within specific landform settings and they may sort along landform types. The distribution of OHWM field indicators by landform may play an important role in helping to increase the reliability of the indicators.

Vegetation

Riparian vegetation is one of the most dynamic plant communities within the arid landscape. Dramatic changes in vegetation patterns can occur over short time scales because of periodic cycles of destruction and regrowth from flooding events. As a result of these disturbances, the ability of riparian vegetation to have "pure stands" or "climax" vegetation is limited in these environments. Periodic flooding can quickly change the distribution and species composition and reset the disturbance–recovery cycle. It is within these natural cycles that patterns of species composition, age, succession, or physical characteristics develop that can be useful indicators of OHW.

Climatic patterns, elevation, and other influences operating at both regional and landscape scales strongly influence riparian plant assemblages (Bendix 1994, Minckley and Brown 1994). At the reach scale, effects of geology, floodplain soil chemistry, sediment particle size, disturbance, and land management are all superimposed on the primary hydrologic effects (Chapter 4). Vegetation pattern responses are also tied to lateral gradients in inundation duration and frequency, floodwater depth, velocity and unit stream power, and depth to groundwater that vary with distance from the stream channel (Stromberg 1993, Auble et al. 1994, Stromberg et al. 1996, Stromberg 1998, Bendix 1999).

Several major factors distinguish riparian plant community arrangements along arid streams. Elevation is associated with increases of precipitation, an increase in the abundance of vegetation, and the selection of certain assemblages of species. For example, Arctic-Boreal wetlands in subalpine environments and Interior Riparian Deciduous Forest at mid-elevations are dominated by species that are associated with more mesic conditions than those on lower slopes and valley floors (Minckley and Brown 1994). Another factor influencing the arrangement and distribution of riparian communities is local moisture availability. Johnson et al. (1984) recommend a classification scheme based on three distinct vegetation types associated with different hydrologic regimes—hydroriparian, mesoriparian, and xeroriparian. This scheme recognizes variation in available water within riparian corridors and the resulting vegetation

responses. Vegetation classes are differentiated in part based on the wetland indicator status of plant species (Reed 1988) but sensitized to riparian ecosystems. Other factors influencing vegetation patterns are reach-scale stream power or stream gradient, valley width, geomorphic setting, geologic substrate, human influence, and fire history (Szaro 1990, Bendix 1994, Minckley and Brown 1994, Evans 2001). Recognizing vegetation responses to patterns in hydrology and other factors influencing species assemblages will be useful in establishing the OHW boundary.

1.6 WORKING DEFINITION: OHW IN THE ARID SOUTHWEST

We need a working definition of OHW for the arid Southwest to allow the selection of OHWM indicators. The definition must recognize that stream channels in the arid Southwest have greater flow magnitudes, more rapid response to rainfall, and shorter-duration flows than those in the humid East, where precipitation is more evenly distributed both temporally and spatially. Channel morphology in arid regions is mostly a result of either recent "ordinary" events or the most recent extreme event, which cannot be generalized across a landscape because of frequent localized storms and diverse topography. The great variability in hydrologic conditions can be expected to result in an even more tenuous relationship between flow recurrence interval and channel characteristics (such as bankfull discharge) than exists in less arid areas. Consequently the working definition does not identify OHW as a function of a flood recurrence interval. Rather, it focuses on the dominant processes in a channel that result in the development of potential OHWM indicators.

We proposed the following definition of OHW in arid stream channels:

That part of the active channel where sediment transport is due to the most frequent or repeating hydrologic discharges, resulting in the development of bed and bank or other physical features, including vegetation, representing long-term trends in either storm or annual discharge events. This definition recognizes that, in some instances, extreme events may have developed the outermost physical features of the active channel and that the current "ordinary" limits may occur within these features.

1.7 SYNTHESIS OF OHWM FEATURES

The literature reviews on hydrology (Chapter 2), geomorphology (Chapter 3), and vegetation (Chapter 4) explore in detail the connections between the magnitude, duration, frequency, and timing of flows and the development of physical characteristics of arid-land stream channels. Table 1 summarizes the geomorphic and vegetation features associated with the OHWM in arid streams. The authors found little support from the literature for sub-regional distinctions in these indicators across the arid Southwest. Therefore, they are presented as a unified regional list, pending further discussion and testing.

Potential OHWM indicators are sorted into several categories. As pointed out by Field (Chapter 3), the attempt to identify useful OHWM indicators should include “test positive” and “test negative” sets of indicators. So Table 1 presents OHWM indicators located above, at, and below the OHW boundary. In addition, vegetation indicators are sorted into the riparian wetness classes mentioned earlier—hydroriparian, mesoriparian, and xeroriparian. Hydroriparian vegetation is present in areas that are perennially saturated or inundated; mesoriparian communities are in areas that are seasonally moist; and xeroriparian communities are in areas that are mostly dry with infrequent flood events. Based on the editor’s (RWL) experience, a few of the vegetation OHWM indicators in Table 1 are listed in vegetation categories beyond where they were described and referenced in Chapter 4.

Features listed in Table 1 serve to divide the riparian area into zones extending laterally from the deepest part of the main channel. The strongest evidence of OHW are those features found consistently below the OHWM, such as crested ripples, meander bars, and hydromesic ruderal herbs. Many of these features are associated with the bottom of the channel. In contrast, strong evidence of nonjurisdictional conditions is represented by those features that are consistently above the OHWM, such as desert pavement, developed soils, and upland plant species. Together these two zones bracket a central zone within which the OHWM is located. The challenge lies in identifying a consistent and reliable OHWM within this zone.

The relationship between physical features and “ordinary” hydrologic events is difficult to establish in arid stream channels because of the extreme climatic variability that is typical of the region. Variability is also the defining characteristic of stream flows in dry-land intermittent and ephemeral stream systems. Thus, the concept of ordinary in this region must include a range of flows from the average annual or biennial high flow to some more extreme event. The occurrence of physical features resulting from both types of events may

overlap at a site and not be easily distinguished. Occasionally very large discharges fill the entire floodplain beyond the area where the majority of channel-forming processes occur. Evidence of previous hydrologic events, such as drift material, may be removed and redeposited at higher elevations within the floodplain, altering one's perception of what is ordinary.

The indicators we identify in Table 1 contain a degree of variability as to the level of event they may represent. This makes relying on any one indicator for one point in time challenging. In addition, to avoid misinterpretation and increase consistency in applications, many of the indicators need to be refined and will require unambiguous definitions and descriptions. These will need to be developed after initial testing and evaluation in a number of watersheds. Additional study may suggest the necessity to combine certain indicators or to use them only in particular positions in the watershed or landscape.

We make the following observations and suggestions about the potential OHWM indicators identified in this literature review:

- The indicators in Table 1 should not yet be used for jurisdictional purposes pending further testing and verification;
- The use of those indicators found consistently above and below OHW may be helpful in determining the area within which the OHW boundary is located;
- If possible, gauge data and local hydrology models should be used as supporting evidence until OHWM indicators are further refined and tested; and
- Other indicators not reported here may also be useful in delineating the OHW boundary.

Table 1. Potential OHWM indicators for testing and evaluation, categorized by location below, at, and above ordinary high water.

	Geomorphic indicators	Vegetation Indicators		
		Hydroriparian	**Mesoriparian**	**Xeroriparian**
Below OHW	• In-stream dunes • Crested ripples • Flaser bedding • Harrow marks • Gravel sheets to rippled sands • Meander bars • Sand tongues • Muddy point bars • Long gravel bars • Cobble bars behind obstructions • Scour holes down-stream of obstructions • Obstacle marks • Stepped-bed morphology in gravel • Narrow berms and levees • Streaming lineations • Dessication/mud cracks • Armored mud balls	• Herbaceous marsh species • Pioneer tree seedlings • Sparse, low vegetation • Annual herbs, hydromesic ruderals • Perennial herbs, hydromesic clonals	• Pioneer tree seedlings • Sparse, low vegetation • Pioneer tree saplings • Xeroriparian species	• Sparse, low vegetation • Xeroriparian species • Annual herbs, xeric ruderals
OHW	• Valley flat • Active floodplain • Benches: low, mid, most prominent • Highest surface of channel bars • Top of point bars • Break in bank slope • Upper limit of sand-sized particles • Change in particle size distribution • Staining of rocks • Exposed root hairs below intact soil layer	• Annual herbs, hydromesic ruderals • Perennial herbs, hydromesic clonals • Pioneer tree seedlings • Pioneer tree saplings	• Sparse, low vegetation • Annual herbs, hydromesic ruderals • Perennial herbs, hydromesic clonals • Pioneer tree seedlings • Pioneer tree saplings • Xeroriparian species • Annual herbs, xeric ruderals	• Sparse, low vegetation • Xeroriparian species • Annual herbs, xeric ruderals
Above OHW	• Desert pavement • Rock varnish • Clast weathering • Salt splitting • Carbonate etching • Depositional topography • Caliche rubble • Soil development • Surface color/tone • Drainage development • Surface relief • Surface rounding	• Annual herbs, xeric ruderals • Perennial herbs, non-clonal • Perennial herbs, clonal and non-clonal co-dominant • Mature pioneer trees, no young trees • Mature pioneer trees w/ upland species • Late-successional species	• Xeroriparian species • Annual herbs, xeric ruderals • Perennial herbs, non-clonal • Perennial herbs, clonal and non-clonal co-dominant • Mature pioneer trees, no young trees • Mature pioneer trees, xeric understory • Mature pioneer trees w/ upland species • Late-successional species • Upland species	• Annual herbs, xeric ruderals • Mature pioneer trees w/ upland species • Upland species

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Chapter 2. Hydrology Literature Review for Ordinary High Water Mark Delineation in the Arid Southwest

JOHN J. FIELD

2.1 INTRODUCTION

Since the physical features representing Ordinary High Water (OHW) are ostensibly the result of hydrometeorological events and the resulting flows in the stream channel, a thorough examination of the hydrology and hydraulics of arid-region rivers may yield useful insights and techniques for delineating the Ordinary High Water Marks (OHWM) in the southwestern U.S.

This chapter provides a literature review of hydrology and hydraulics research, with an emphasis on the southwestern U.S. and other arid regions of the world, in order to:

- Outline the dominant climatologically and physiographic controls on rainfall–runoff processes in the Southwest;
- Discuss the strengths and weaknesses of hydrologic and hydraulics models for describing arid-region fluvial processes; and
- Identify the potential value of hydrology and hydraulic studies for delineating the OHWM in the arid Southwest.

For the purposes of this chapter, the "Southwest" is broadly defined to include all or portions of ten arid to semi-arid western states: Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Utah, Wyoming, and Texas.

2.2 HYDROLOGY

The multiple physiographic provinces in the western U.S. (Fig. 2) interact with spatially and seasonally variable moisture sources to produce a highly variable rainfall distribution pattern that is markedly different from the eastern U.S. (Fig. 3). Differing sources of moisture result in sharp seasonal differences in rainfall between climatic regions in the Southwest, while local differences in physiography and geology sometimes lead to dramatic differences in precipitation within a given climatic zone. A number of distinct ecological subregions, or ecosystem provinces, are present in the southwestern U.S., each resulting from a distinct assemblage of climate, physiography, and vegetation (Bailey 1983, 1995) (Fig. 4, Table 2).

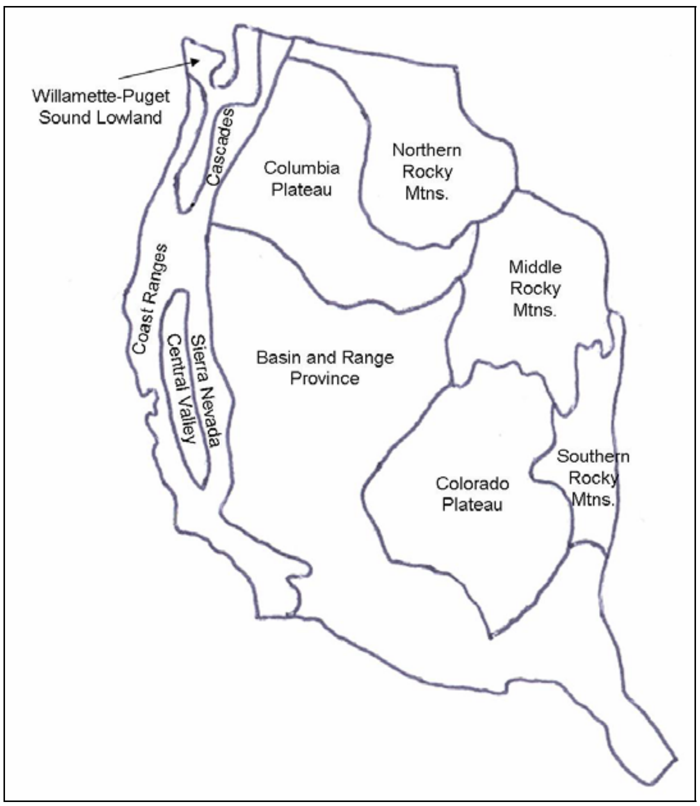


Figure 2. Physiographic provinces of the western United States, showing the major provinces found in the Southwest. (Modified from De Blij and Muller 1992, Figure 52-1, p. 518.)

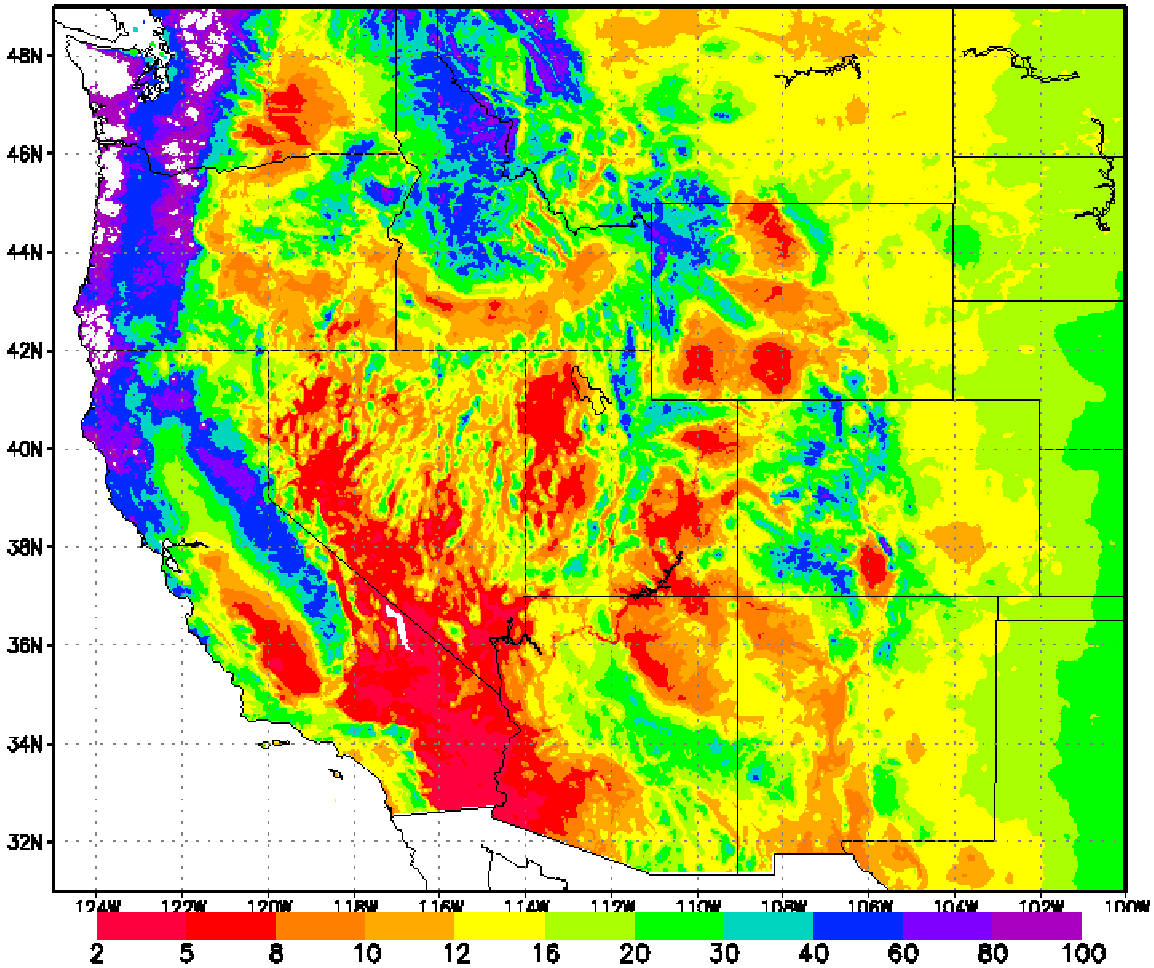


Figure 3. Average annual precipitation in the western U.S. for 1961–1990, showing the extreme variability in rainfall in the Southwest. The precipitation totals are in inches. (From http://www.wrcc.dri.edu/images/west.gif.)

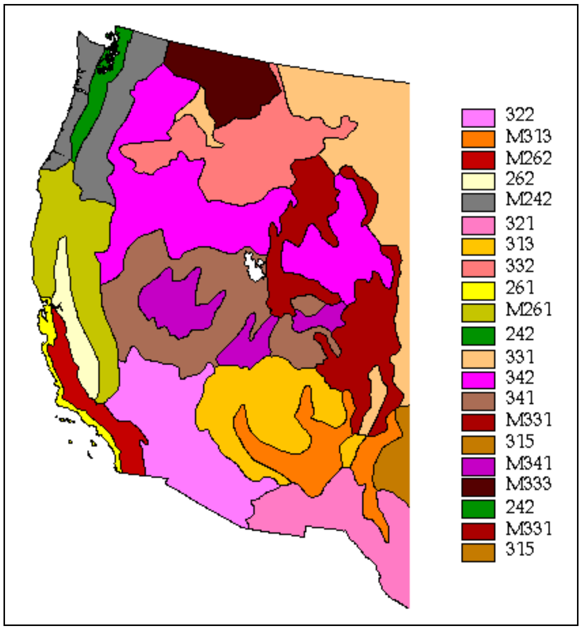


Figure 4. Ecosystem provinces of the western United States. See Table 2 for names of provinces and link to http://www.fs.fed.us/colorimagemap/ecoreg1_provinces.html for further description of each.

Meteorological Sources of Moisture

Three sources of moisture influence precipitation patterns in the Southwest: winter North Pacific frontal storms, summer convective thunderstorms, and late-summer eastern North Pacific tropical storms (Ely 1997). The relative importance of each storm type in different regions of the Southwest can be seen in the average monthly rainfall amounts for each state in the region (Table 3). Further information about rainfall in each state is available at www.wrcc.dri.edu.

North Pacific Frontal Storms

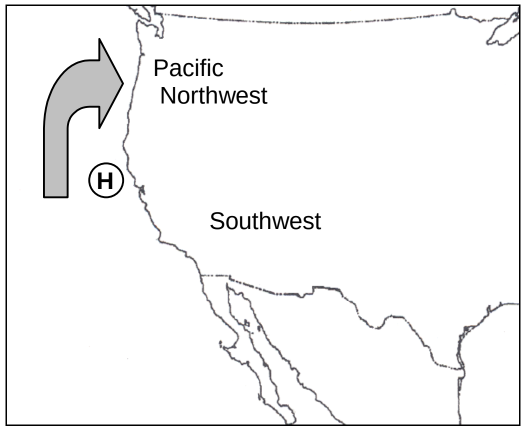
Winter North Pacific frontal storms that affect the southwestern U.S. result from low pressure systems traveling in the upper air westerly wind belt. During dry winters in the southern portions of the study area, the clockwise rotation around a high pressure ridge located just off the west coast of the U.S. tracks frontal storms to the north, impacting the Pacific Northwest (Fig. 5a). Wet winters occur when the high pressure center is displaced farther to the west, allowing the clockwise rotation to steer more frontal storms into Arizona and New Mexico (Fig. 5b).

Table 2. Ecosystem provinces of the western U.S. See Figure 3 for distribution of map units.

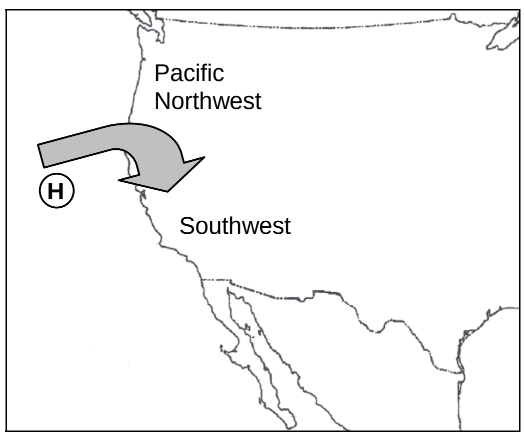
Map unit	Ecosystem province
242	Pacific Lowland Mixed Forest Province
M242	Cascade Mixed Forest—Coniferous Forest—Alpine Meadow Province
M261	Sierran Steppe—Mixed Forest—Coniferous Forest—Alpine Meadow Province
262	California Dry Steppe Province
261	California Coastal Chaparral Forest Shrub Province
M262	California Coastal Range Open Woodland—Shrub—Coniferous Forest—Meadow Province
322	American Semidesert and Desert Province
341	Intermountain Semidesert and Desert Province
M341	Nevada-Utah Mountains Semidesert—Coniferous Forest—Alpine Meadow Province
342	Intermountain Semidesert Province
332	Great Plains Steppe Province
331	Great Plains—Palouse Dry Steppe Province
M333	Northern Rocky Mountain Forest-Steppe—Coniferous Forest—Alpine Meadow Province
M331	Southern Rocky Mountain Steppe—Open Woodland—Coniferous Forest—Alpine Meadow Province
313	Colorado Plateau Semidesert Province
M313	Arizona-New Mexico Mountains Semidesert—Open Woodland—Coniferous Forest—Alpine Meadow Province
321	Chihuahuan Desert Province
315	Southwest Plateau and Plains Dry Steppe and Shrub Province

Table 3. Summary of annual and monthly average depths of precipitation, revealing the relative importance of different moisture sources throughout the study area (except Texas). The statewide averages represent a weighted mean of the average precipitation within each climate division located in a given state. (From www.wrcc.dri.edu.)

State	Average Depth of Precipitation (in.)												
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Ann
AZ	1.10	1.01	1.19	0.54	0.35	0.29	1.86	2.07	1.34	1.06	0.99	1.30	13.10
CA	3.77	3.28	3.13	1.52	0.61	0.27	0.18	0.35	0.58	1.25	3.14	3.35	21.43
CO	0.72	0.72	1.20	1.27	1.80	1.51	2.03	1.87	1.42	1.13	0.93	0.87	15.47
ID	2.22	1.68	1.69	1.50	1.77	1.64	0.82	0.96	1.19	1.29	2.07	2.19	19.02
NV	0.87	0.84	0.94	0.78	0.90	0.73	0.58	0.72	0.68	0.67	0.89	0.86	9.46
NM	0.59	0.60	0.63	0.57	0.92	1.17	2.27	2.58	1.87	1.17	0.73	0.75	13.85
OR	3.90	2.94	2.92	1.94	1.64	1.26	0.52	0.82	1.13	1.99	4.01	4.26	27.33
UT	0.90	0.89	1.15	1.07	1.04	0.71	0.91	1.06	1.07	1.12	1.00	0.91	11.88
WY	0.63	0.55	0.82	1.33	1.94	1.71	1.24	1.01	1.17	0.91	0.73	0.65	12.69



a. During wet winters in the Pacific Northwest and dry winters in the Southwest.



b. During dry winters in the Pacific Northwest and wet winters in the Southwest.

Figure 5. Positions of the North Pacific high pressure ridge and atmospheric circulation patterns.

In general, precipitation from winter frontal storms makes up an increasingly large portion of the total annual rainfall farther to the north in the study area (Table 3). Flooding due to areally extensive and long-duration winter frontal storms generally occurs in large drainage basins because all portions of the drainage basin contribute to runoff. Rainfall intensities are generally too low to impact smaller, steeper watersheds.

Convective Thunderstorms

Summer convective thunderstorms in the southwestern U.S. are the result of land surface heating and an influx of moist tropical air from the Gulf of Mexico, Gulf of California, and eastern tropical Pacific. This influx of tropical moisture is associated with the northwestward migration of the Bermuda high pressure ridge and the northward displacement of the Pacific high pressure cell (Bryson and Lowry 1955, Hales 1974, Carleton 1985, Douglas and Englehart 1990) (Fig. 6). This so-called “summer monsoon” is characterized by scattered convective thunderstorms that are triggered by intense surface heating and enhanced by orographic effects.

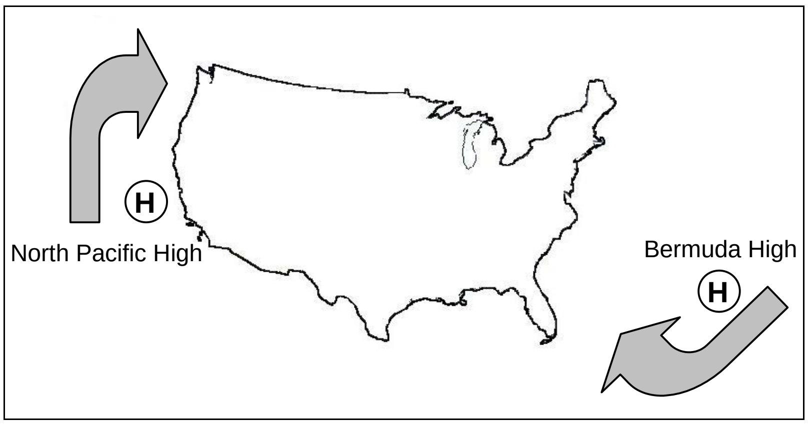
Summer precipitation totals associated with convective thunderstorms are greatest in Arizona and New Mexico, as these states are the closest to the tropical moisture sources. Uncertainty still exists as to the source of the tropical moisture fueling the monsoons, but it appears to be a combination of low-level moisture originating from the Gulf of California and eastern tropical Pacific and higher-level moisture from the Gulf of Mexico rising over the Sierra Madre mountains in Mexico (Adams and Comrie 1997). The amount of summer precipitation exhibits great interannual variability. Summer precipitation is highest in Arizona and New Mexico when a subtropical high pressure cell develops over the Four Corners region (Carleton et al. 1990). When this high pressure cell is depressed farther south, precipitation values are much lower. Small, steep watersheds are the most responsive to convective thunderstorms, as rainfall intensities are high and a single isolated storm cell can cover an entire small watershed. The isolated, short-lived nature of the thunderstorms means that runoff to larger rivers is being contributed from only a small portion of the total watershed area.

North Pacific Tropical Storms

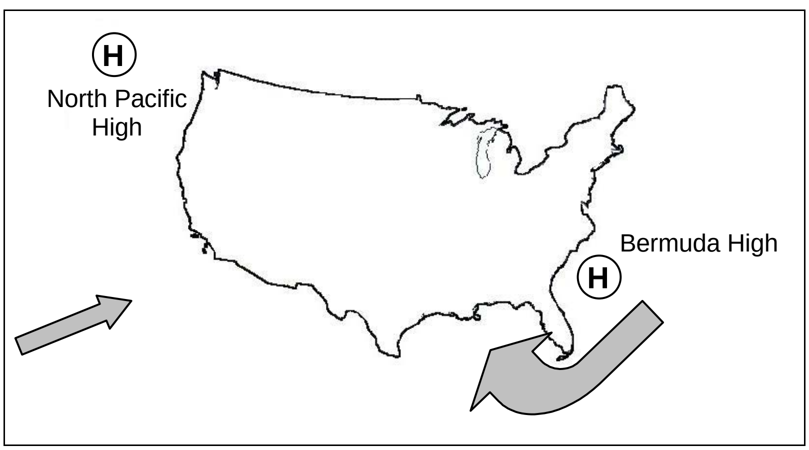
Tropical cyclones that form off the coast of southern Mexico normally migrate northwestward over the Pacific Ocean, but occasionally the cyclones recurve toward the northeast and make landfall, usually over Baja California or western mainland Mexico (Fig. 7). Moisture from tropical cyclones is, however, occasionally drawn into Arizona, New Mexico, southern California, and southern Utah, resulting in intense precipitation and floods (Ely 1997, Farfan and Zehnder 2001), with the Tucson Flood of 1983 being a prime example (Kresan 1988). Nearly every year the remnants of tropical cyclones move into a position where the upper-level winds transport moisture and then produce showers and thunderstorms in the Southwest (Farfan and Zehnder 2001). The frequency of tropical storm recurvature is greatest in the fall (September and October), when the

subtropical high pressure center begins to migrate southward and low pressure troughs begin to impact lower latitudes (Ely 1997).

The greatest climatic influence of North Pacific tropical storms is in Arizona, New Mexico, southern California, and southern Utah, as seen in the late summer/early fall average precipitation totals for these regions (Table 3). Tropical storms are areally extensive and have high rainfall intensities, so both large and small watersheds are prone to flooding from these events.



a. During the winter months when atmospheric circulation patterns inhibit the influx of tropical moisture into the Southwest.



b. During the summer months when atmospheric circulation patterns promote the influx of tropical moisture into the Southwest.

Figure 6. Positions of the North Pacific High and Bermuda High.

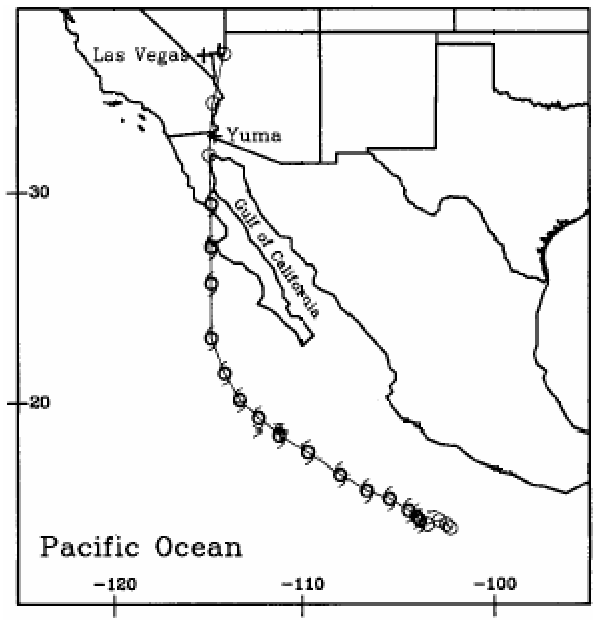


Figure 7. Track of Hurricane Nora in September 1997, showing recurvature towards the southwestern U.S. (From Farfan and Zehnder 2001.)

Influence of El Niño

The El Niño/Southern Oscillation (ENSO), an unusual warming of Pacific Ocean waters, has been directly linked to increased precipitation in California and decreased precipitation in the Pacific Northwest as the North Pacific frontal storm trek is depressed farther south (Schonher and Nicholson 1989, Piechota et al. 1997, Gershunov and Barnett 1998). However, no similar link is seen between ENSO and winter rainfall in New Mexico and Arizona (Andrade and Sellers 1988). A correlation between ENSO and summer monsoonal precipitation is uncertain (Adams and Comrie 1997); some studies suggest a positive correlation (Harrington et al. 1992, Hereford and Webb 1992), while others cite no such trend (Andrade and Sellers 1988, Carleton et al. 1990). Increased fall and spring precipitation is experienced in the southwestern U.S. (principally Arizona and New Mexico) during ENSO events (Andrade and Sellers 1988). ENSO appears to be related to decadal-scale changes in precipitation patterns and flood frequency in the Southwest (i.e., the southern part of the study area defined here)(Ely 1997). The influence of ENSO events on other portions of the study area is not well studied. Relationships between long-term patterns in streamflow

and ENSO events are similar to the precipitation patterns discussed above (Piechota et al. 1997).

Factors Controlling Runoff

Regardless of the source of precipitation, 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). Many factors control the ultimate timing and magnitude of runoff into streams, but only some of these factors are important for understanding differences in runoff characteristics between arid and humid climates: spatial and temporal variability of rainfall, interception, evaporation and transpiration, channel transmission losses, and time to the onset of runoff after rainfall begins (Pilgrim et al. 1988, Niemczynowicz 1990, Nouh 1990). In addition to these general comparisons between humid and arid regions, the highly varied topography and soils in the Southwest (Fig. 8) lead to locally variable precipitation (and streamflow) (Fig. 3).

Arid regions are well known for highly variable spatial and temporal rainfall (Graf 1988, Pilgrim et al. 1988, Reid and Frostick 1997). Intense rains can fall in one watershed or portion of a watershed while an adjacent watershed or portion remains dry. This extreme variability, especially characteristic of summer thunderstorms, can occur in all seasons because of the variable topography in the Southwest (Fig. 9). Attempts to predict runoff from a given rainfall event in arid climates are complicated by the fact that even in small watersheds the very spotty rain makes it difficult to know precisely how much of the watershed is receiving precipitation, especially given the low density of rain gauges in desert regions (Pilgrim et al. 1988). Interannual variability in precipitation is high in arid regions, with a high ratio of record peak to average annual peak discharge (Graf 1988). Along many very arid region river systems, as in southeastern California, no flow is experienced during some years. Runoff patterns are also variable on the decadal and century scale and appear related to ENSO events (Ely 1997). Recognition of a link between ENSO and annual and longer cycles in precipitation holds promise for improving long-term drought and flood forecasting (Schonher and Nicholson 1989).

Interception represents that portion of the rainfall that is held on the surface of leaves and branches of trees and other vegetation. Most of this moisture is later returned to the atmosphere through evaporation, so it does not contribute to runoff in streams. Interception is likely most important with low-intensity rainfall events (Pilgrim et al. 1988), which, in the Southwest, occur during winter frontal storms. Interception is unimportant (and therefore a greater percentage of rainfall

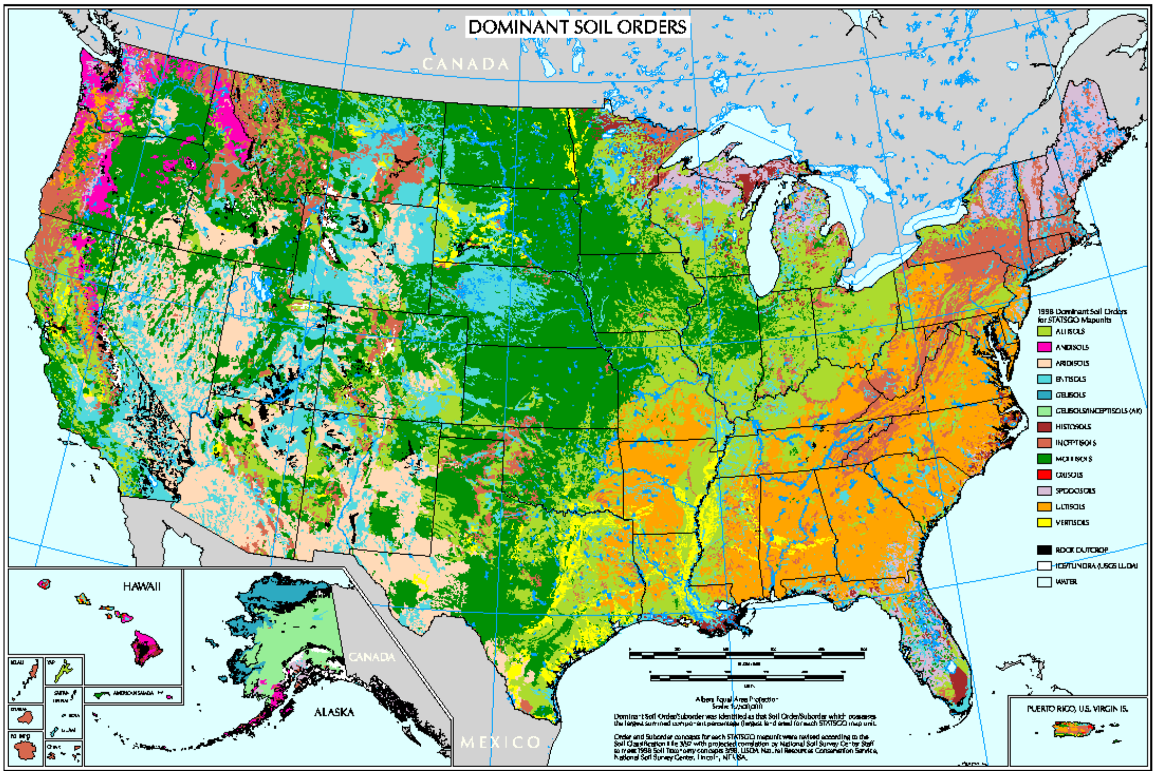


Figure 8. Soils map of the United States. (From http://www.nrcs.usda.gov/technical/land/lgif/m4025l.gif.)

is available for runoff) in extremely arid climates where little vegetation is present. When plants are present, interception is possibly more significant in arid climates for the same vegetation density, because many desert plants are adapted to maximize stemflow (i.e., they catch and focus rainfall towards the trunk or stem) (Pressland 1975). Forest fires, an important and recurring phenomenon in the Southwest, result in temporally variable interception rates in forested watersheds. Beyond these generalizations, little is known about interception in arid regions, and more data must be collected to improve modeling of rainfall–runoff relationships (Pilgrim et al. 1988).

Evapotranspiration accounts for 95% of precipitation in arid regions, with evaporation being far more significant than transpiration given the high percentage of bare ground (Pilgrim et al. 1988). The likelihood that soils will dry out between infrequent storm events precludes the need, in most cases, to consider antecedent moisture conditions when modeling rainfall–runoff processes.

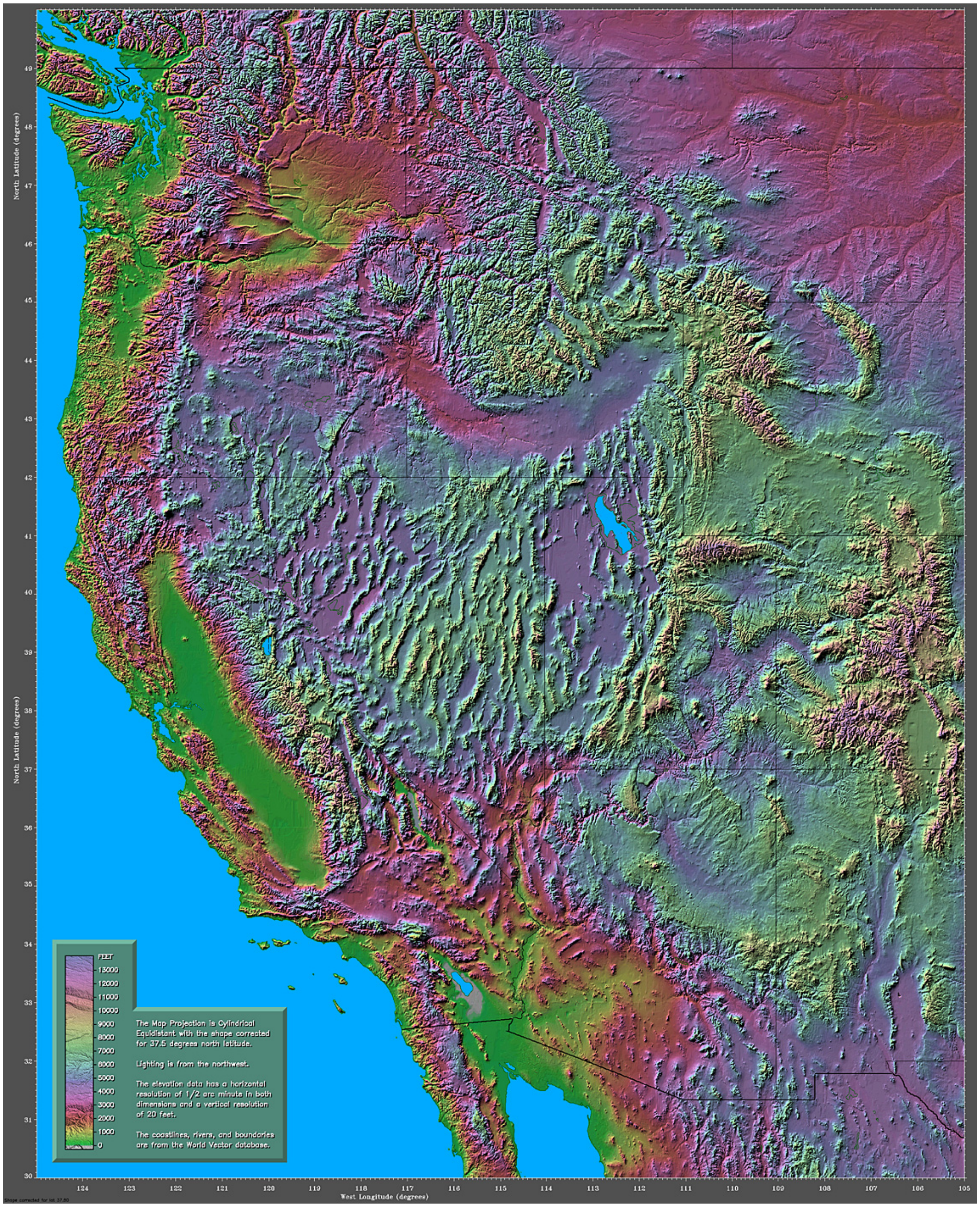


Figure 9. Topographic relief map of the western U.S. (Copyright Ray Sterner, Applied Physics Laboratory, The Johns Hopkins University, licensed by North Star Science and Technology, LLC, used by permission.)

Transmission losses (the loss of discharge due to infiltration of flow into the channel bed) are significant along ephemeral streams (Reid and Frostick 1997, Tooth 2000). As a result, runoff can actually decrease in a downstream direction despite the increase in drainage area. For headwater streams, especially where bedrock is near the surface, transmission loss is not an important factor. Rainfall–runoff modeling must account for transmission losses, but it is difficult to model because the rate of loss varies from point to point along a channel and with the degree of saturation of the channel bed from prior events (Pilgrim et al. 1988).

Arid regions have a characteristically rapid onset of runoff after the start of a rainfall event; consequently, only a small amount of rain is needed to initiate runoff (Pilgrim et al. 1988). This is in part due to lower infiltration and interception rates compared to humid climates and in part due to generally greater rainfall intensities in arid climates. These differences underscore the need to avoid applying to arid regions assumptions about runoff characteristics developed for humid climates (Pilgrim et al. 1988).

Topography exerts a strong influence on the type, location, and amount of precipitation throughout the Southwest. Higher elevations generally experience greater precipitation than low-lying areas because of orographic effects (e.g., Sierra Nevadas; Fig. 2 and 3). Snowfall in higher regions during the winter can prevent what would have been severe flooding if the precipitation had fallen as rain. Conversely, large floods often occur when warm heavy rain falls on a deep snowpack created during earlier colder frontal storms. The presence of a snowpack results in more consistent runoff through the spring, and even summer, along higher-elevation mountain streams while adjacent lower-elevation streams run dry. Greater vegetation at higher elevations also tends to stretch runoff over longer periods because of the increased infiltration rates. North–south-trending mountain ridges throughout the Southwest, especially in the Basin and Range Province, block moisture from eastward-moving frontal systems, creating rain shadows, or dry regions, on the east side of the mountain ridges (Fig. 2, 3, and 9). This phenomenon is manifested most dramatically by the Sierra Nevada Mountains, with some of the driest regions of the country found in eastern California (e.g., Death Valley) and western Nevada (Fig. 9).

The cumulative effect of all the factors controlling runoff described above is for arid-region river systems to have greater flow magnitudes, a more rapid response to rainfall, and shorter-duration flows than equivalent humid-region counterparts (Fig. 10). As a consequence, arid-region rivers are typically dry (i.e., they have no base flow) prior to a storm event. In many deserts, particularly where precipitation intensities are high, the runoff hydrograph characteristically rises very steeply as the result of limited infiltration capacity and then falls sharply in response to transmission losses (Fig. 10) (Cooke et al. 1993). The

lower infiltration capacities and higher rainfall intensities also result in higher runoff coefficients (which express the proportion of rainfall converted to runoff) in arid regions (Knighton and Nanson 1997). Given that soil types (Fig. 8) and topography (Fig. 9) vary dramatically throughout the Southwest, even within the same physiographic province (Fig. 2) or ecosystem province (Fig. 4), average annual precipitation (Fig. 3) is equally variable and generalizations about runoff patterns by province of limited value.

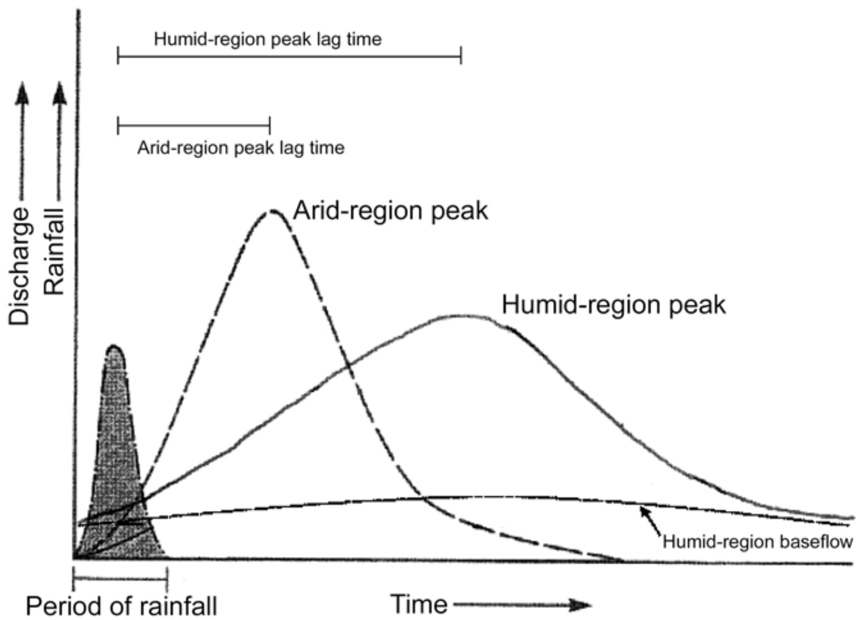


Figure 10. Comparison of idealized arid-region and humid-region runoff hydrographs for the same rainfall event in watersheds of similar size and shape.

Value and Limitations of Existing Maps for Understanding Runoff Patterns

Ecosystem province designations in the western U.S. (Bailey 1983, 1995) provide the best basis for establishing hydrology-based subregions in the Southwest because ecosystem provinces are delineated using those factors that exert the strongest influence on runoff patterns: vegetation, physiography, soils, and climate (Table 4). Soils maps themselves also reflect runoff characteristics and show variations within the same ecosystem province (Fig. 10).

In the Southwest, channel morphology and, as a consequence, the physical features associated with the OHWM are frequently the result of extreme floods (Graf 1988, Tooth 2000). Consequently, maps showing maximum rainfall

Table 4. Precipitation and runoff characteristics for ecosystem provinces in the western U.S.

Map unit*	Dominant moisture source	Importance of snowfall	Vegetation density	Physiographic province	Soil order	Character of runoff
242	winter	spring runoff	high	Puget Lowland	Andisol	perennial yet flashy
M242	winter	high	high except above tree level	Cascades	Andisol	perennial yet flashy
M261	winter	high	high except above tree level	Coast Ranges/ Sierras	Inceptisol/ Andisol	largely perennial yet flashy
262	winter	spring runoff	moderate	Central Valley	Entisol/ Alfisol	ephemeral to south; debris flows
261	winter	limited	moderate	Coast Ranges	Alfisol/ Mollisol	ephemeral to south
M262	winter	moderate	high	Coast Ranges	Entisol/ Alfisol	ephemeral to south
322	summer/ fall	low	low	Basin & Range	Aridisol/ Entisol	ephemeral
341	winter/ summer	moderate	low–moderate in mountains	Basin & Range/ Col. Plateau	Aridisol/ Entisol	ephemeral
M341	winter/ summer	moderate	moderate	Basin & Range/ Col. Plateau	Alfisol/ Mollisol	ephemeral w/ spring runoff
342	winter	moderate	low	Columbia Plateau	Aridisol/ Mollisol	ephemeral w/ spring runoff
332	winter	moderate	moderate	Rocky Mtn/ Great Plains	Mollisol	ephemeral w/ spring runoff
331	winter	moderate	moderate	Rocky Mtn/ Great Plains	Mollisol	ephemeral w/ spring runoff
M333	winter	high	high	Northern Rocky Mountain	Inceptisol	perennial yet flashy
M331	winter/ summer	high	moderate	Southern Rocky Mountain	Alfisol/ Mollisol	ephemeral w/ spring runoff
313	winter/ summer	moderate	low	Colorado Plateau	Aridisol/ Entisol	ephemeral
M313	winter/ summer	moderate	moderate	Basin and Range	Alfisol/ Inceptisol	ephemeral
321	winter/ summer	low	low	Great Plains/ Basin & Range	Aridisol/ Entisol	ephemeral
315	winter/ summer	low	low	Great Plains	Mollisol	ephemeral

* same as in Table 2

intensities in the recent past, not just statistically predicted intensities for a given time duration (e.g., 10-year 24-hour storm), would be useful for identifying those areas where the channel morphology is potentially the result of a recent extreme flood. Existing data on past rainfall and stream gauges are sparsely distributed throughout the Southwest, so rainfall intensity maps may be difficult to construct. Additionally, the accuracy of such maps would be difficult to determine, given the highly localized nature of rainfall events in the Southwest (Pilgrim et al. 1988). For larger drainages influenced by more regional storms, such maps may be of greater value.

Composite maps showing climate, physiography, and geology/soils would be particularly valuable for identifying watersheds with the highest potential for channel response to extreme events (e.g., areas that can experience intense rainfall, that have steep terrain, and where the rainfall flows through unconsolidated materials). Extreme events dominate the morphology of channels in arid climates because record peak flows are much greater than the average annual peak flow (Graf 1988). Maps developed to show variations in the ratio between record and average annual peak flows throughout the region have the potential to discriminate areas where the physical features associated with the OHWM are more likely the result of extreme events. This pronounced discrepancy between record and average peak flows is ameliorated at higher elevations, where snowfall runoff leads to lower winter peaks and greater flows in the generally dryer summer. The more consistent and persistent flow throughout the year leads to channel features that are the result of more “ordinary” flows. Intense rains from tropical storms are perhaps their strongest in the driest regions of the Southwest (southeastern California and southwestern Arizona), resulting in the greatest discrepancy between record and average peaks. Consequently, channel features in these areas are more likely the result of extreme events.

Rainfall–Runoff Models

Rainfall–runoff models account for both the meteorological and physiographic factors that control the amount of runoff that ultimately flows in the stream channel. Those models that consider the full hydrograph resulting from a runoff event, not just the peak discharge, are more valuable since the duration of a flow, not only the peak, is important in determining the impact of flows on channel morphology (Costa and O’Connor 1995). Peak discharges for a particular watershed can be estimated from regional regression equations or a statistical analysis of stream gauge data (Texas DOT 2002). Regional regression equations do not apply to watersheds with mixed-population floods, such as in the Southwest, where many watersheds are affected by three distinct storm types: winter frontal storms, summer convective thunderstorms, and fall tropical cyclones.

Stream gauge data are too sparsely distributed in the Southwest to provide widespread value in estimating peak discharges through statistical analysis.

A number of relatively simple techniques, such as the Rational Method and the Curve Number Approach, are used by the Natural Resources Conservation Service to establish crude runoff hydrographs. The Rational Method, originally designed for watersheds less than 200 acres in area, assumes uniform rainfall intensity over the whole watershed, a poor assumption in the Southwest, especially for larger watersheds, where thunderstorms are highly localized. The Curve Number Approach attempts to determine the ratio of rainfall converted to runoff by establishing a “curve number” that accounts for a number of controlling variables including soil type and land use. Once a curve number is established for a watershed, only the rainfall amount is needed to determine the depth of runoff distributed over the entire watershed. Modeling programs developed by the Natural Resources Conservation Service (e.g., TR-20) are available to convert the distributed rainfall amount into a hydrograph using a dimensionless hydrograph.

The most widely used rainfall–runoff model in the United States is HEC-1 (U.S. Army Corps 1998), which creates a synthetic flood hydrograph from user-specified information about the precipitation event (e.g., duration, intensity), existing conditions (e.g., antecedent moisture), and watershed characteristics (e.g., drainage area, time of concentration, curve number). Even in arid regions, accounting for deep groundwater and antecedent moisture conditions is critical in modeling stream yields (Ye et al. 1997). A depth–area option in HEC-1 allows a user to supply information on how precipitation depths vary within the drainage area, a critical component for modeling flood hydrographs in arid areas where precipitation totals are highly variable over small areas (Pilgrim et al. 1988). However, even a relatively dense rain gauge network (one gauge per 20 km^2) may be insufficient to detect convective rainfall in semi-arid regions and estimate its spatial coverage and depth (Michaud and Sorooshian 1994a). Transmission losses typical of arid regions can be modeled in the flood routing component of HEC-1 that accounts for channel and floodplain storage in various reaches along the stream. General assumptions in the model regarding the shape of the hydrograph that apply well in temperate regions may not work as well in arid regions, where a greater proportion of the flow is due to direct runoff (shorter time to peak). As a result, the separate analysis of single events with gauge or radar rainfall information is crucial for the accurate modeling of rainfall–runoff characteristics of high-magnitude floods in arid catchments (Lange et al. 2000a). While HEC-1 and other models are capable of simulating many of the conditions present in arid regions, many of the input parameters needed are difficult to

collect in arid regions, where rainfall data and data on physical watershed parameters (e.g., soils) are spread over wide areas.

The lack of hydrological data makes empirical methods of flood estimation in arid regions unsatisfactory, but physically based models that are calibrated in the field using measurements of soil hydrological properties offer a viable alternative modeling strategy (El-Hames and Richards 1994). These limitations of rainfall–runoff models can be overcome by using physically based input data that can be integrated within a GIS framework to help with the management of the large data sets required (Lange et al. 2000b). Parametric runoff models, while lacking complexity, require large amounts of historical rainfall–runoff data for calibration, data that are unavailable in ungauged watersheds. To overcome these difficulties, a physically based model of an ephemeral watershed can be used to generate synthetic calibration data (Truschel and Campana 1983). The processes most important to account for in the rainfall–runoff modeling in arid regions are infiltration, soil moisture storage, rainfall spatial distribution, evaporation, and groundwater recharge (Niemczynowicz 1990). Drainage size, followed by rate of infiltration and slope of land, are the most effective catchment characteristics affecting the accuracy of some arid-region rainfall–runoff models (Nouh 1990).

Distributed rainfall–runoff models that account for spatial variations in rainfall amounts and soil types do a better job of modeling flash floods in semi-arid regions than simple lumped methods (Michaud and Sorooshian 1994b). Other studies highlight the importance of accurately defining temporal variations in rainfall at a single point rather than establishing a dense network of rain gauges to understand spatial distributions (Nouh 1990, Krajewski et al. 1991). Rainfall–runoff models developed specifically for arid regions can more accurately account for transmission losses and other conditions characteristic of arid regions (Sharma and Murthy 1998) and overcome the limited data sets from arid regions, which inhibit the ability to calibrate such models.

A number of rainfall–runoff models, including HEC-1, have been accepted by FEMA for use in the National Flood Insurance Program (Table 5). Despite the limitations of modeling rainfall–runoff processes in arid regions, the accepted FEMA models may serve as a starting point for identifying the models most applicable for identifying the OHWM along ephemeral streams and for identifying the limitations that must be overcome to create reliable rainfall–runoff models for arid regions.

Table 5. Rainfall–runoff models accepted by FEMA for usage in the National Flood Insurance Program. (Modified from http://www.fema.gov/fhm/en_hydro.shtm.)

Modeling approach	Computer model	Available from
Single event	HEC-1 14.0.1 and up	U.S. Army Corps of Engineers
	HEC-HMS 1.1 and up	U.S. Army Corps of Engineers
	TR-20	Natural Resources Conservation Service
	TR-55	Natural Resources Conservation Service
	SWMM (RUNOFF)	U.S. Environmental Protection Agency
	MIKE 11 UHM	DHI, Inc.
	DBRM 3.0	University of Florida
	HYMO	U.S. Department of Commerce
	PondPack v. 8	Haestad Methods, Inc.
	XP-SWMM 8.52 and up	XP-Software
Continuous event	DR3M	U.S. Geological Survey
	HSPF 10.10 and up	U.S. Environmental Protection Agency
	Mike 11 RR	DHI, Inc.
	PRMS Version 2.1	U.S. Geological Survey
Interior drainage analysis	HEC-IFH 1.03 and up	U.S. Army Corps of Engineers

2.3 HYDRAULICS

The OHWM is delineated on the basis of physical features present along the stream channel. Rainfall–runoff models attempt to predict the hydrologic inputs (discharge, volume, and duration of flow) entering the stream system from the surrounding watershed but do not characterize the hydraulics of the flows (width, depth, and velocity) that ultimately create the physical features associated with the OHWM. Hydraulic models are therefore needed to characterize and predict flow conditions in the stream system.

Types of Flows

Flow conditions in arid-region stream systems vary between channelized flow, sheetfloods, and debris flows. Channelized flow, mostly ephemeral in the Southwest, occurs in all settings but predominates over other flow types in valley bottom settings. Perennial channelized flow occurs in very large watersheds that extend into more humid climates (e.g., Colorado River) and in high-elevation watersheds where snowmelt can extend flow into the hot, generally dryer summer months (e.g., Colorado Rockies). Channelized flow is confined to well-defined banks and, although potentially meandering or braided, is generally unidirectional in nature (i.e., rapid expansions in flow width generally do not occur).

Sheetfloods are defined as a sheet of unconfined flood water moving down a slope (Hogg 1982). They occur in piedmont settings (the gently sloping areas between the mountains and valley bottom) and in valleys during larger storm events. Sheetfloods are generally very shallow and, unlike channelized flow, experience rapid lateral flow expansion. Sheetflood zones and channelized reaches occur together in downstream alternating sequences along discontinuous ephemeral stream systems (Schumm and Hadley 1957, Bull 1997). Unique to arid regions, discontinuous ephemeral streams are quite common in the south-western U.S. and result from the inability of most storm events to transport sediment through the entire stream system. Over time the position of sheetfloods and channelized flow on discontinuous ephemeral streams will shift such that an area of channelized flow can be transformed into a sheetflood zone over a few years or decades. Such temporal and lateral variations in flow types complicate hydraulic modeling of single storms and the long-term management of flood hazards.

Debris flows, a viscous mixture of water, mud, and coarser particles (often including large boulders), are largely restricted to mountain canyons and alluvial

fans found at the mountain front. Mixed lithologies such as dolomite, quartzite, and shale produce the clay-to-boulder-sized range of particles necessary to produce debris flows during periods of high rainfall intensity in steep drainage basins. Debris flows are short-lived events (e.g., minutes to hours) that can plug deep channels (>7 m) during a single storm event, redirecting flow into new channels or over unchannelized surfaces. The viscous nature of debris flows can lead to the development of low berms along their flanks.

The occurrence of channelized flow, sheetfloods, and debris flows is spatially and temporally variable, with all three potentially occurring on the same stream system during the same flow event or at the same place through time. The characteristics and distribution of these flow types is further detailed in Chapter 3. In addition, these processes are active during only a small percentage of time, with no flow occurring in many watersheds in the Southwest more than 95% of the time. While sheetfloods and debris flows are infrequent, they exert a strong influence on the morphology of some fluvial landforms such as alluvial fans (Field 1994, Blair and McPherson 1992). On the other hand, the most frequent process, channelized flow, may have limited morphological impact. Attempts to define "ordinary" as it relates to identification of the Ordinary High Water Mark must recognize that commonly observed physical features are potentially the result of uncommon processes and that the effects of the most common condition (channelized flow or no flow at all) do not persist on the landscape.

Influence of Boundary Conditions

Runoff flowing through alluvial material (sediment deposited by the river itself) is capable of adjusting channel dimensions (width and depth) to accommodate the runoff, so the channel morphology along alluvial reaches reflects the flow conditions in the stream channel. Where the streambanks consist of easily erodible sand material, the channel adjusts its width more rapidly than depth, so shallow, braided channelized flows or sheetfloods are more likely than deeper channelized flows. Where banks are richer in clay and silt, channel depth adjusts more rapidly, so deeper channelized flows are more common.

Where runoff passes through nonalluvial material (i.e., bedrock or sediments that the river cannot move), the flow is not capable of adjusting channel dimensions, so the channel morphology is more reflective of the resisting forces of the bank material rather than the flow itself. For example, adjustments in channel width cannot occur in bedrock canyons, so the flow width of an extreme event may be very similar to that of a more-frequent (e.g., annual) event. Given that the extent of flow may be similar, regardless of flow magnitude, the delineation of

the OHWM may be easier in some nonalluvial settings compared to alluvial channels.

Hydraulic Models

The most widely used hydraulic model in the United States is HEC-RAS, which is an updated version of the once widely used HEC-2 model (U.S. Army Corps of Engineers 2002). HEC-RAS is a one-dimensional flow model that predicts flow velocity, width, and depth for a given discharge if the cross sectional area, gradient, and Manning's roughness value are known. Conversely, the HEC-RAS model can calculate the discharge necessary to reach a certain stage in the stream channel, which is especially useful for calculating the discharge of past flow events where the high water mark is preserved (O'Connor and Webb 1988). The high water mark for a given flow can be identified from hydrologic flow indicators such as the highest presence of silt, flotsam, or trim lines. Such hydrologic high water marks may be representative of the OHWM when found in conjunction with geomorphic or vegetation indicators, such as the height of the active floodplain or the lower level of perennial vegetation. As a one-dimensional model, HEC-RAS largely assumes that discharge is constant through time and space, conditions that rarely hold in nature, especially in arid climates. Sheetflood and debris flow conditions are especially difficult to model using HEC-RAS because of rapidly expanding flow and highly variable viscosity of flow, respectively.

Two-dimensional models are more capable of accounting for the spatial and temporal variations in flow conditions associated with arid-region river systems, but the increased analytical complexity associated with two-dimensional modeling has, to date, precluded its wide acceptance as a predictive tool in watershed management. Two-dimensional hydraulic models have been developed that are capable of characterizing several features and processes typical of arid-region rivers such as rapid width adjustments (Darby 1998), erodible banks (Mosselman 1998), multiple threaded braided channels (Lane and Richards 1998), debris flows (O'Brien et al. 1993), flow around obstructions such as boulders (Crowder and Diplas 2000), and transmission losses (El-Hames and Richards 1998). However, two-dimensional models are not yet capable of modeling all of these conditions and their complex interactions simultaneously, as occurs during natural flows in ephemeral channels. Two-dimensional models can accurately recreate conditions observed during known flows, but the extensive calibration necessary with actual conditions precludes their use for predictive purposes. With time and increasing computing power, these models hold promise to be of much greater value than at present.

Three-dimensional models are also becoming available and are useful for modeling secondary circulation associated with the confluence of tributaries (Bradbrook et al. 1998). While these conditions exist along ephemeral streams, they are more localized phenomenon and are not of great importance in understanding flow at the reach or watershed level. Three-dimensional models are important, however, for identifying the limitations of two-dimensional models and for identifying the needs of future model development (Bradbrook et al. 1998).

A number of hydraulic models, including HEC-RAS and several two-dimensional models, have been accepted by FEMA for use in the National Flood Insurance Program (Table 6). Despite the limitations of hydraulic modeling, the accepted FEMA models may serve as a starting point for identifying the models most applicable for identifying the OHWM along ephemeral streams and for identifying the limitations that must be overcome to create reliable hydraulic models for arid regions. Wide use of complex two- and three-dimensional models is unlikely in the near future because of the detailed data collection required and the difficulty in mastering the large-scale computer models (Leopardi et al. 2002). Additionally, it is unlikely that a single model will suffice for every situation, and it is important that model performance be evaluated with respect to specific field problems (e.g., delineation of the OHWM) as they are encountered (Lane 1998).

Usefulness of Hydrology and Hydraulics for Delineating the OHWM

Hydrological parameters such as precipitation inputs and watershed characteristics determine the amount of runoff entering a stream channel. The hydraulics of the flow in the stream exerts a force on the channel boundary, which in turn shapes the morphology of the channel. Although hydrology and hydraulics are extremely important in modeling and predicting flow in channels, they are unable to determine the ultimate channel morphology and physical features that develop along a stream in response to a flow event of a given size (e.g., ordinary or extreme flows). The development of channel morphology is not only dependent on the flow conditions but also on sediment inputs and boundary conditions along the channel, two aspects not adequately addressed in current hydrologic and hydraulic models.

While hydrologic and hydraulic models may be insufficient to predict the types and location of OHWM features, they can be extremely useful for reconstructing the flow conditions responsible for developing the physical features associated with the OHWM (see Chapter 3 for a list of these potential features). Channel cross sections and estimates of Manning’s roughness coefficient, along

Table 6. Hydraulic models accepted by FEMA for usage in the National Flood Insurance Program. (Modified from http://www.fema.gov/fhm/en_hydra.shtm.)

Modeling approach	Computer model	Available from
One-dimensional steady flow	HEC-RAS 3.0 and 3.1	U.S. Army Corps of Engineers
	HEC-2 4.6.2	U.S. Army Corps of Engineers
	WSPRO	Federal Highway Administration
	FLDWY	U.S. Department of Commerce
	QUICK-2 1.0 and up	Federal Emergency Management Agency
	HY8 4.1 and up	Federal Highway Administration
	WSPGW 12.96	Joseph E. Bonadiman & Associates, Inc.
	StormCAD v. 4 and v. 5	Haestad Methods, Inc.
	PondPack v. 8	Haestad Methods, Inc.
	Culvert Master v. 2.0	Haestad Methods, Inc.
	XP-SWMM 8.52 and up	XP-Software
One-dimensional unsteady flow	HEC-RAS 3.0 and 3.1	U.S. Army Corps of Engineers
	FEQ 8.92	U.S. Geological Survey
	FEQUTL 4.68	U.S. Geological Survey
	ICPR 2.20 and 3.02	Streamline Technologies, Inc.
	SWMM 4.30 and 4.31	U.S. Environmental Protection Agency
	UNET 4.0	U.S. Army Corps of Engineers
	FLDWAV	National Weather Service
	MIKE 11 HD	DHI, Inc.
	FLO-2D v. 2000.11	FLO-2D Software, Inc.
	XP-SWMM 8.52 and up	XP-Software
Two-dimensional steady/unsteady flow	TABS RMA2 v. 4.3	U.S. Army Corps of Engineers
	TABS RMA4 v. 4.5	U.S. Army Corps of Engineers
	FESWMS 2DH 1.1 and up	U.S. Geological Survey
	FLO-2D v. 2000.11	FLO-2D Software, Inc.
	MIKE Flood HD	DHI, Inc.
Floodway analysis	SFD	Federal Emergency Management Agency
	PSUPRO	Federal Emergency Management Agency

with the elevation of the identified OHWM, can be used to reconstruct the discharge necessary to emplace the given OHWM. This could be accomplished with one-dimensional or two-dimensional hydraulic models, depending on the degree of accuracy and computational effort desired. Once the discharge is estimated, the recurrence interval for that flow could be established to determine if the identified OHWM is the result of an extreme event or more frequently occurring flows. Conversely, if a recurrence interval is established that represents the "ordinary" flow, then the depth of flow associated with the OHWM along any given channel could be established. Such an approach, however, does not guarantee that the river stage associated with the chosen "ordinary" discharge will be consistent with the level at which the physical OHWM features are found. Once the flow conditions associated with the OHWM are established, various combinations of rainfall conditions (e.g., amount, intensity) and physical watershed parameters (e.g., drainage area, antecedent moisture conditions) necessary to create the given discharge could be modeled.

Comparisons of hydraulic model results from different watersheds and ecoregions could be used to determine if there is a general agreement in the recurrence interval of flows associated with identified OHWM features. Given the highly variable temporal and spatial distribution of rainfall in the Southwest and the slow channel recovery times after extreme events, congruence between recurrence intervals over wide areas seems unlikely. Hydrology and hydraulic studies will be extremely valuable, however, for identifying those physiographic, climatic, or ecological subregions where there is consistency in the recurrence interval of the "ordinary" flow (i.e., the flow responsible for creating the OHWM) from one watershed to the next.

2.4 CONCLUSIONS

Variable moisture sources and the complex physiography in the Southwestern U.S. results in a highly variable spatial and temporal distribution of precipitation and stream flow. Differences in watershed size and relief ensure that the stream response to a single precipitation event can vary between watersheds even within the same physiographic or ecological subregion. Consequently, regional generalizations about runoff patterns are difficult to make, and watershed-specific studies will be necessary to accurately delineate the OHWM.

Physical features associated with the OHWM are more readily identified using geomorphic methods, but hydraulic and hydrologic studies are potentially valuable for establishing the discharge recurrence intervals and runoff conditions, respectively, responsible for forming the OHWM features. Numerous hydrologic (Table 5) and hydraulic (Table 6) models are available for characterizing runoff and flow conditions associated with the OHWM, but no single model is likely to be superior in all situations. Comparing discharge recurrence intervals responsible for the development of the OHWM between watersheds holds the greatest promise for concluding whether OHWM features throughout the Southwest, or within specific subregions, are consistently formed by events of the same magnitude (i.e., frequent or extreme events) or whether such OHWM features are formed by events of varying magnitude because of the overriding influence of watershed characteristics, channel boundary conditions, and highly variable rainfall intensities.

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Chapter 3. Fluvial Geomorphology Literature Review for Ordinary High Water Mark Indicators in the Arid Southwest

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3.1 INTRODUCTION

The extent of riverine waters in temperate regions of the United States has generally been taken as those areas that are below the Ordinary High Water Mark (OHWM). How successfully these morphological features can be applied to rivers in the arid Southwest is unclear. To address uncertainties in delineating the OHWM along rivers in the Southwest, a fuller understanding of fluvial processes and forms that develop in arid climates is necessary. This chapter provides a literature review of fluvial geomorphology research in arid regions of the world with the purpose of:

- Outlining the dominant stream types and processes found in arid regions;
- Comparing arid-region fluvial processes and forms with humid-region counterparts;
- Identifying morphological features that might prove useful for delineating the OHWM in arid regions; and
- Revealing potential problems that may arise when attempting to delineate the OHWM in arid regions.

Five major stream system types are found in desert regions:

- Discontinuous ephemeral streams;
- Compound channels;
- Alluvial fans;
- Anastomosing rivers; and
- Single-thread channels with adjacent floodplains.

Many of the processes acting on arid-region river systems (e.g., channelized flow, sheetfloods) may be associated with more than one of these five stream types, but differences in the spatial and temporal distribution of processes give rise to the distinctive stream types.

After a brief summary of basic principles in fluvial geomorphology, this chapter will describe the processes associated with the five arid-region stream types and the resulting morphological features that develop. The reasons that the different stream types develop and the ways in which they differ from humid-region perennial rivers are provided, followed by methods that may prove useful in identifying the OHWM. The focus of this review is on alluvial channel forms in arid regions (i.e., channels formed in river-deposited sediment) and does not address bedrock channel forms in similar climates, recently described by Wohl (1993) and Wohl et al. (1994).

3.2 PRINCIPLES OF FLUVIAL GEOMORPHOLOGY

Equilibrium and Dominant Discharge

A basic principle of fluvial geomorphology is the concept of equilibrium, which holds that a river channel's 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, Leopold and Bull 1979). The concept of a graded stream was similarly defined by earlier workers but focused more on the river's gradient, with less attention to cross sectional shape and planform (e.g., Mackin 1948). Channels are self-adjusting and will change their morphology in response to changing watershed conditions (Dunne and Leopold 1978) but only if the threshold of critical power necessary to precipitate change is crossed (Bull 1979).

The dominant, or effective, discharge in a particular region generally controls the size and shape of the river channel. The effects of smaller flows that tend to decrease the size of the channel are reworked with subsequent larger flows. Conversely, larger flows that can increase the size of a channel generally occur too infrequently for the impact on the river channel to persist on the landscape. More frequent events, in concert with revegetation, tend to "heal" the impacts of larger flows and return the channel to a size in equilibrium with the dominant sediment and water discharge. The discharge at which channel maintenance is most effective often corresponds to the bankfull stage where water completely fills the channel and begins to spread out onto the floodplain (Dunne and Leopold 1978). In other words, the bankfull discharge governs the shape and size of the channel (Rosgen 1996). While the bankfull discharge has been shown to have, on average, a recurrence interval of 1.5 years (Dunne and Leopold 1978, Rosgen 1996), enough exceptions to this rule occur that one should not assume that this average value holds for any given channel (Williams 1978).

While many of these basic concepts in fluvial geomorphology evolved, in part, from early research in semi-arid climates (see, for example, Leopold et al. 1964), the general applicability of the equilibrium concept to desert regions has been called into question (Tooth 2000). The effects of extreme events persist in deserts for long periods because of the inability of the stream channel to recover or "heal" from large floods, in part due to the absence of sufficient revegetation (Baker 1977, Graf 1988a). A further discussion of equilibrium, dominant discharge, and their application to desert regions is provided later in this chapter.

Terrace Development

In response to significant long-term changes in watershed conditions, a river channel will alter its dimensions to accommodate changes in the delivery of sediment and water to the river channel. A typical response is for the channel gradient to change, which can lead to significant changes in the channel bed elevation. Watershed perturbations that result in a decrease in sediment supply will lead to bed lowering, leaving the previous channel and floodplain isolated above the newly established channel level. These abandoned floodplain and channel surfaces are referred to as terraces that formed under a previous hydrologic regime (Fig. 11).

Figure 11. River terraces along Wadi Mujib, Jordan. The river terraces are the flat surfaces high above the well-vegetated channel bottom.

The effects of repeated climate changes during the Quaternary are manifested along many rivers and piedmonts in the southwestern U.S. as a series of terraces, the youngest of which formed during the Holocene or at the Pleistocene-Holocene transition about 10,000 years ago (Basel and Royse 1972, Bull 1991, Reneau 2000). Tectonism can also create a succession of terraces with hundreds of feet of total relief (Schumm et al. 2000).

While many terraces are high above the active channel, others exhibit little relief above the current channel so are sometimes difficult to distinguish from the

active floodplain (Dunne and Leopold 1978), an important distinction to make if one delineates the OHWM based on the bankfull stage. Relief above the active channel is not a reliable measure, by itself, of whether a surface is isolated from flooding, but in conjunction with several weathering features (e.g., rock varnish, desert pavement) can provide strong evidence that a surface is a terrace, not an active floodplain (Field and Pearthree 1997). These weathering features, as discussed later, may prove to be reliable indicators of areas that are definitively above the OHWM. These distinctions are important because large superfloods, with the possibility of recurring under the current hydrologic regime, can create terraces along dryland rivers (Schick 1974, Schick and Magid 1978).

3.3 STREAM SYSTEM TYPES

Discontinuous Ephemeral Streams

Discontinuous ephemeral streams form a distinctive stream pattern characterized by alternating erosional and depositional reaches (Fig. 12) (Schumm and Hadley 1957, Patton and Schumm 1975, Bull 1997, Field 2001). The longitudinal distribution of processes and morphologies along one discontinuity can be repeated multiple times along a stream, with the length of individual discontinuities ranging from 15 m to over 10 km, depending on drainage area (Bull 1997).

Overland flow emanates from the unconfined sheetflood zones and aggrading downstream ends of channels. The reconcentration of the overland flow creates erosional knickpoints at the downstream end of sheetflood zones that migrate

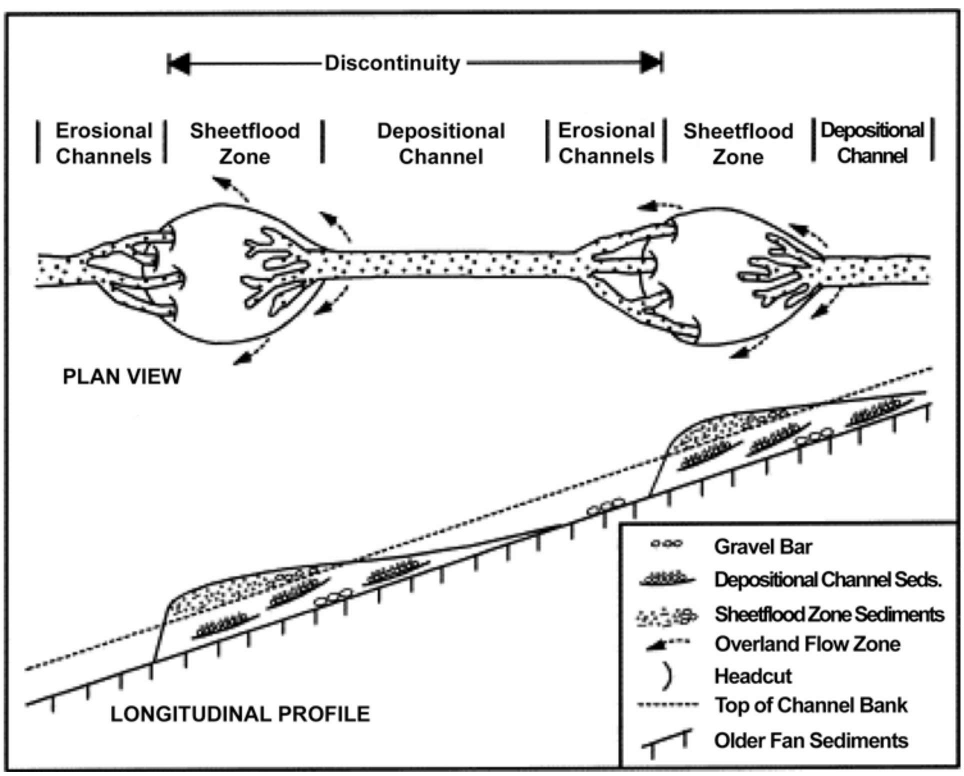

Figure 12. Schematic plan view and longitudinal profile of a discontinuous ephemeral stream system, showing the relationship between sheetflood zones, depositional and erosional channels, overland flow zones, and bank heights (not to scale). (Modified from Field 2001.)

Figure 13. Wide, shallow ephemeral stream channel with a nearly horizontal, planar bed on Wild Burro Wash near Marana, Arizona.

headward over time. Immediately downstream of the headcuts, the channels are narrow, with steep vertical banks and erosional beds. Discontinuous gravel lags are found on the bed of the erosional channels (Field 1994). Flows will rarely overtop the banks just downstream of the headcuts, as overland flow is more likely to be generated where bank heights are much lower or nonexistent. Incised reaches of washes in Arizona contain channels floored with coarse-grained sediments and flanked by berms of fine-grained sediment (Wells 1977).

Downstream of the erosional channels (Fig. 12), the channels widen, promoting deposition of the sediments supplied from the eroding reach upstream (Patton and Schumm 1981). The bed topography in these reaches is subdued, with braided flow possible. The beds of single-thread channels in arid climates are nearly horizontal and planar (Fig. 13), as opposed to the more-pronounced pool–riffle morphologies characteristic of more humid regions (Reid and Frostick 1997). Bar forms are flat-topped and rise only 10–20 cm above the channel thalweg (Leopold et al. 1966), because secondary flow cells that would encourage bar building are suppressed in the wider channels (Reid and Frostick 1997). The tail end of a flood will carve wide, shallow channels across the bars as the waning flows occupy the lowest portions of the channel bottom.

As water spreads out onto the sheetflood zones (Fig. 14), gravel trains can form behind obstructions (usually vegetation) and scour at the sides and downstream end of the obstruction (Blair 1987, Field 1994). Distributary channels

Figure 14. Unconfined sheetflood zone on Wild Burro Wash near Marana, Arizona. Note the organic debris in the foreground deposited by the most recent sheetflood.

form at the apex of the sheetflood zones and continue to branch out (becoming smaller and smaller and less distinct as they do) before terminating in elongated sand tongues of low positive relief. Particle sizes decrease rapidly downstream, from sand to silt and clay, as the sediment load drops out with the rapidly decelerating flow. Since flow is more easily diverted at lower velocities, the flood waters become reconcentrated into broad, gentle swales before ending at headcuts carved by the reconcentrated sediment-starved flow. Reconvergence of flow has been observed during natural sheetfloods (McGee 1897, Packard 1974) and at the toe of distributary areas on experimental fans (Schumm et al. 1987). Additionally, floodouts described from Australia appear similar to sheetflood zones and exhibit the reconcentration of flow at their downstream ends (Tooth 1999, 2000). [Floodouts are sedimentary basins formed at the endpoints of primary or distributary fluvial systems where channeled flow ceases and flood-waters spill across adjacent alluvial surfaces (Bourke and Zimbelman, 2001).] McGee's (1897) first description of sheetfloods in Sonora, Mexico, and southern Arizona is very similar to the processes described here for discontinuous ephemeral streams and fits Hogg's (1982) definition of sheetfloods as "a sheet of unconfined flood water moving down a slope."

The downstream decrease in discharge arising from transmission losses (i.e. water infiltrating into the channel bed) typical of ephemeral streams (Reid and Frostick 1997, Tooth 2000) means that the sediment load cannot be transported equally through each reach during a single flow (Bull 1997). This results in a buildup of the channel-floor elevation, especially during low- and intermediate-stage flows (Packard 1974), and gives rise to the distinctiveness of discontinuous ephemeral stream systems. The optimal hydrometeorological conditions for their formation appear to be 100–500 mm of annual rainfall (Bull 1997). The semi-arid climate maximizes sediment yield (Tooth 2000) while allowing for sufficient vegetation growth to trap sediment on sheetflood zones (Packard 1974). With transmission losses further inducing deposition, sheetflood zones and headcuts migrate upstream over time. Sediment has a tendency to move through dryland rivers episodically (Schumm and Hadley 1957), as a series of waves (Lekach and Schick 1983, Schick et al. 1987, Graf 1988b). Consequently, scour and fill are unlikely to be synchronized, with erosion occurring in one reach while another reach is simultaneously aggrading (Tooth 2000).

The morphological changes observed in a downstream direction along discontinuous ephemeral stream systems are the same changes that occur at a single point through time as the various reaches migrate headward. Consequently, temporal variations in morphology are extreme. 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 buildup of slope resulting from aggradation ultimately leads to retrenching of the same area once the threshold of critical power is crossed (Patton and Schumm 1975, Bull 1979). Numerous studies in the Southwest have documented the repeated cutting and filling of arroyos along discontinuous ephemeral stream systems during the Holocene (Antevs 1952, Patton and Schumm 1981, Waters and Haynes 2001).

Vertical-walled arroyos, entrenched ephemeral streams that form in desert environments (Fig. 15) (Waters and Haynes 2001), are best understood as erosional channels in discontinuous ephemeral stream systems (Fig. 11). Where rates of erosion exceed those of aggradation, continuous arroyos can form on valley floors because headcuts will advance headward faster than the aggrading sheetflood zones. This situation can arise when conditions result in a long-term increase in water:sediment ratios (Packard 1974) associated with climate change, destruction of vegetation cover, or artificial flow concentration (Cooke et al. 1993). Arroyos evolve and backfill over time, as has been the case for many arroyos in the 20th century (Emmett 1974). As the initial vertical walls and narrow channel of the arroyo begin to widen, stream power is lost, sediment:water ratios decrease, and vegetation takes hold in the channel,

Figure 15. Arroyo Chico in the Rio Puerco Watershed, New Mexico, showing entrenched vertical walls typical of arroyos. (From http://rockyweb.cr.usgs.gov/html/puerco/chico.html.)

resulting in aggradation. Aggradation can continue until the incised channel is completely backfilled and the valley floor has no well-defined channel, a condition that existed in the southwestern United States prior to 1850 (Leopold and Miller 1956). Exposures along existing arroyo walls contain evidence that arroyo cutting and subsequent filling has occurred several times throughout the Holocene (Waters and Haynes 2001). Incision of arroyos occurs relatively rapidly (a few years to decades), while subsequent backfilling is a much slower process (several decades to centuries). While some have linked arroyo formation to climate change (Bryan 1941, Balling and Wells 1990, Waters and Haynes 2001) and human land use (Antevs 1952, Graf 1983a, Bull 1997), arroyos can also occur endogenetically (Andres 1980) as localized oversteepening of aggradational reaches occurs during the natural evolution of a discontinuous ephemeral stream system under steady hydrological conditions (Patton and Schumm 1975).

While a discontinuous ephemeral stream system as a whole might be considered to be in equilibrium if the amount of channelized area relative to sheetflood zones remains constant over time, a single point along the system never reaches a steady state. Channel morphology will constantly be in flux, even if headcuts and sheetflood zones are migrating headward at the same rate to maintain equilibrium. Dramatic temporal and spatial changes in channel morphology should be considered the norm, rather than the exception, on discontinuous ephemeral stream systems.

Compound Channels

Compound channels consist of a single, low-flow meandering channel inset into a wider braided flood zone (Fig. 16) (Graf 1988a). Dramatic channel widening and activation of braided conditions accompany extreme flow events along dryland rivers, with a meandering form developing after a decades-long sequence of lower flows (Kondolf and Curry 1986, Pearthree and Baker 1987, Kresan 1988, Graf 1988a, Friedman and Lee 2002). Similar compound channels are found in more humid climates as well (Hickin and Sichingabula 1988). An anastomosing channel pattern forms as the low-flow channel under certain conditions (Nanson et al. 1986) instead of a meandering channel. Discontinuous ephemeral stream systems probably also occur within compound channels, but no published report of this exists to date. While the braided channel pattern is often considered the most common in drylands (Tooth 2000), single-thread, wide and shallow, planar-bed channels are also characteristic of drylands (Fig. 13) (Reid and Frostick 1997) and reflect the same discharge and bank conditions that produce braiding (Tooth 2000).

The transformation of the channel back to a narrower meandering pattern occurs by the attachment of midchannel braid bars to the channel banks by sediment accumulation and vegetation growth (Pearthree and Baker 1987). Vegetation plays a key role in the channel recovery process in drylands (Tooth 2000), with low flows enabling the establishment of vegetation on the channel bed (Friedman and Lee 2002), which, in turn, helps to trap fine sediment (Osterkamp and Costa 1987). The narrowing process is accelerated where a reliable moisture supply increases the density and growth rate of vegetation (Friedman and Lee 2002). Valley floor deposition by relatively frequent minor floods is interrupted at long intervals by large floods that clear out sediment (Schick 1974) and return the channel to a braided form.

The width:depth ratios of channels are directly related to bank composition (Schumm 1960). Channel widening and braiding are more pronounced where the sand content in the channel banks is higher. Silt and clay are less prevalent in the banks of desert streams compared to more humid regions, giving rise to wide, shallow channels with ill-defined banks and a braided pattern (Leopold et al. 1966, Baker 1977, Graf 1988a, Abdullatif 1989, Cooke et al. 1993). Vegetation lowers the width:depth ratio of channels and increases channel sinuosity (Graf 1981), so not surprisingly the removal of vegetation can lead to braiding (Kondolf and Curry 1986).

The geomorphic effectiveness of large floods in arid climates is well documented worldwide (Schick 1974, Baker 1977, Wolman and Gerson 1978, Graf 1988a, Cooke et al. 1993, Knighton and Nanson 1997, Tooth 2000, Kale 2002).

Figure 16. Compound channel showing a single-thread meandering channel inset into a wider braided pattern. [From Graf (1988a) Definition of floodplains along arid-region rivers. In *Flood Geomorphology* (V.R. Baker, R.C. Kochel, P.C. Patton, ed.). New York: John Wiley and Sons, p. 231–242. This material is used by permission of John Wiley and Sons, Inc.]

Arid-region river channels, especially those with sandy banks, are often very responsive to large flows and recover slowly from them because of the limited vegetation growth and the large interannual variability in peak discharges (Cooke et al. 1993, Tooth 2000). Nonexistent or poor armoring of ephemeral stream beds (Reid and Laronne 1995) increases the sensitivity of the river channel to a range of flow events and hinders the ability of the river to "hold" any one pattern. Consequently, desert rivers are often in a perpetual state of change—working to recover from a large flood but unable to "heal" completely before the next extreme event widens the channel and renews the process (Cooke et al. 1993, Tooth and Nanson 2000a). Unambiguous morphological features indicative of the OHWM are unlikely under these conditions since channel morphology is in a state of flux, with high water marks being constantly reworked. The faster the rate of revegetation and the longer the time interval between threshold-crossing extreme events, the greater the likelihood that the recovery process will result in the development of reliable OHWM indicators. Conversely, the slower the recovery process, the greater the likelihood that the high water mark indicators present along the channel are the result of extreme events. In certain instances, recovery is delayed even further because the effects of extreme events control the processes that occur during subsequent smaller events (Graf 1983b, Bourke and Pickup 1999). Regardless of the rate of recovery, dramatic temporal and spatial changes in channel morphology and position should be considered the norm, rather than the exception, along compound channels. A stable channel form is never really achieved because the rate of recovery is slower than the return interval of extreme events that alter the landscape.

Alluvial Fans

Alluvial fans are depositional landforms with a conical shape that develop where confined streams emerge from upland areas into zones of reduced stream power (Fig. 17) (Harvey 1997). While alluvial fans are found in almost all climates (Nilsen and Moore 1984, Rachocki and Church 1990), they are an especially important landscape element in the southwestern United States, where an estimated 31% of the land surface is covered by alluvial fan deposits (Antsey 1966). Alluvial fans are characterized by a distributary flow pattern (Bull 1977, Tooth 2000) with debris flow (Beaty 1963, Blair and McPherson 1992, Whipple and Dunne 1992), sheetflood (Blair 2000), and streamflow (Blissenbach 1954, Field 2001) processes predominating; all three processes are not necessarily active on all fans, however. Debris flows are intermediate between landslides and water flooding, with sediment concentrations ranging from 70 to 90% by weight; sediment and water move together as a slurry at the same velocity (Ritter et al. 1995). Poorly channelized braided flow is characteristic of streamflow processes

Figure 17. Conical shape and distributary flow pattern developed on an alluvial fan at the bottom of the Grand Canyon where Bright Angel Creek enters the Colorado River.

on alluvial fans in arid regions (Cazanacli et al. 2002). The type of process that predominates on a particular fan depends on several factors, including lithology (Blair 1999), climate (Hooke 1967, Bull 1977, Harvey 1992), and drainage area (Hooke and Rohrer 1979, Harvey 1984, Waters and Field 1986).

Channel avulsions—the rapid diversions of flow from one channel into another due to blockage of the channel by sediment or debris —are not unique to alluvial fans (Schumann 1989, Gay et al. 1998), but they are very important in the development and maintenance of the conical shape (Fig. 18) (Field 2001). Debris flow fans provide dramatic examples of avulsions caused by the blockage of deep (>7 m) channels and incision of new equally deep channels elsewhere on the fan surface (Chawner 1935, Kesseli and Beaty 1959, Morton and Cambell 1974, Whipple and Dunne 1992). While the location of new channels is more difficult to predict on debris flow fans, avulsions on streamflow-dominated fans typically occur where banks are low and always occupy a pre-existing flow path (Fig. 18) (Field 2001). Overland flow generated by discontinuous ephemeral stream systems active on many fan surfaces in southern Arizona leads to avulsions (Field 2001).

Five distinct channel morphologies are associated with different stages of the avulsion process on alluvial fans in southern Arizona (Fig. 19). The changes in morphology through time at a single point reflect the rapid channel enlargement

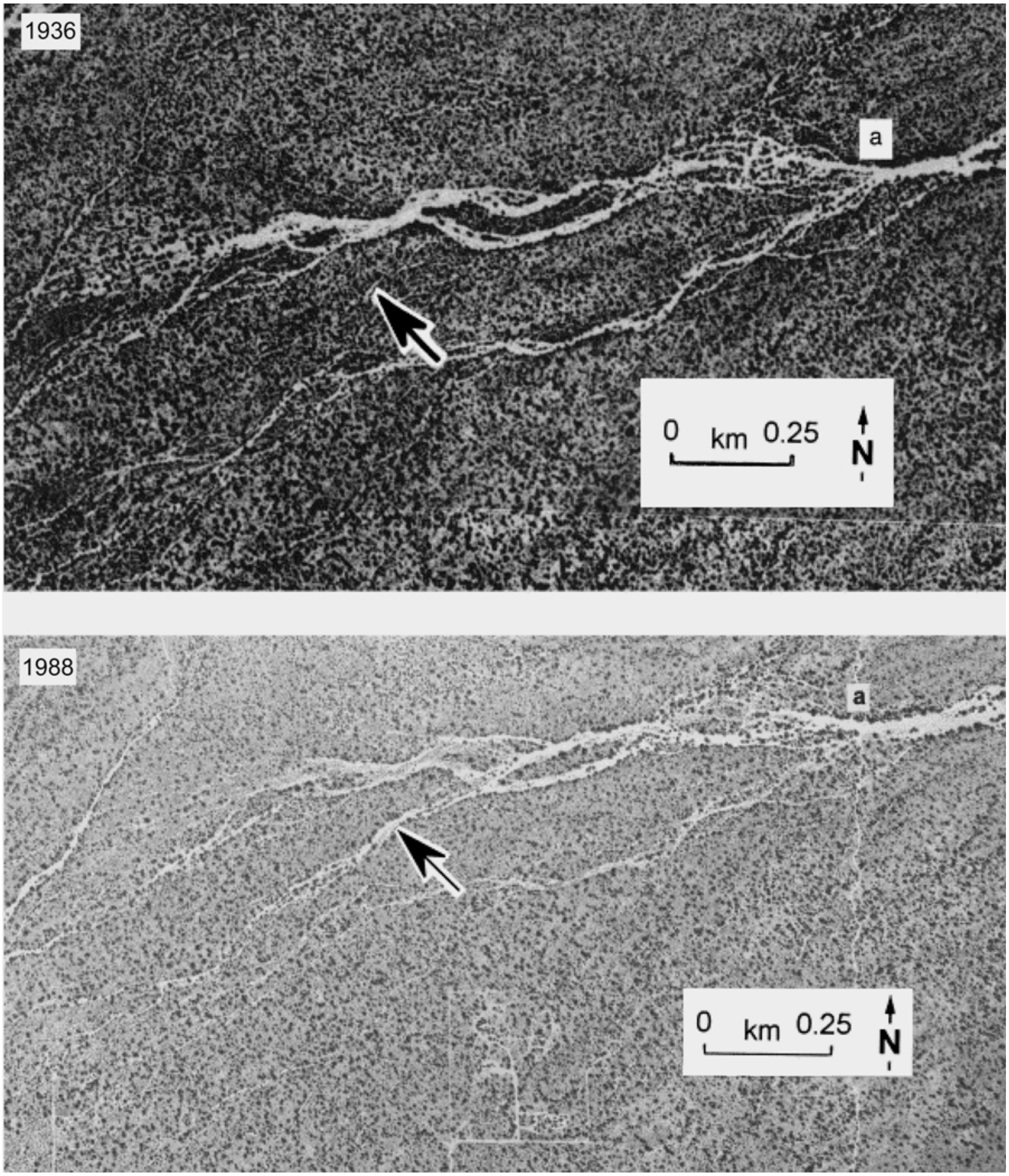

Figure 18. Aerial photographs of Ruelas Fan near Marana, Arizona, taken in 1936 and 1988, showing an avulsion that occurred between 1949 and 1956. The arrow, in the same position on both photos, highlights the pre-existing channel reach into which flow was diverted. The letter "a", indicating the fan apex, is in the same position on both photos. (Modified from Field 2001.)

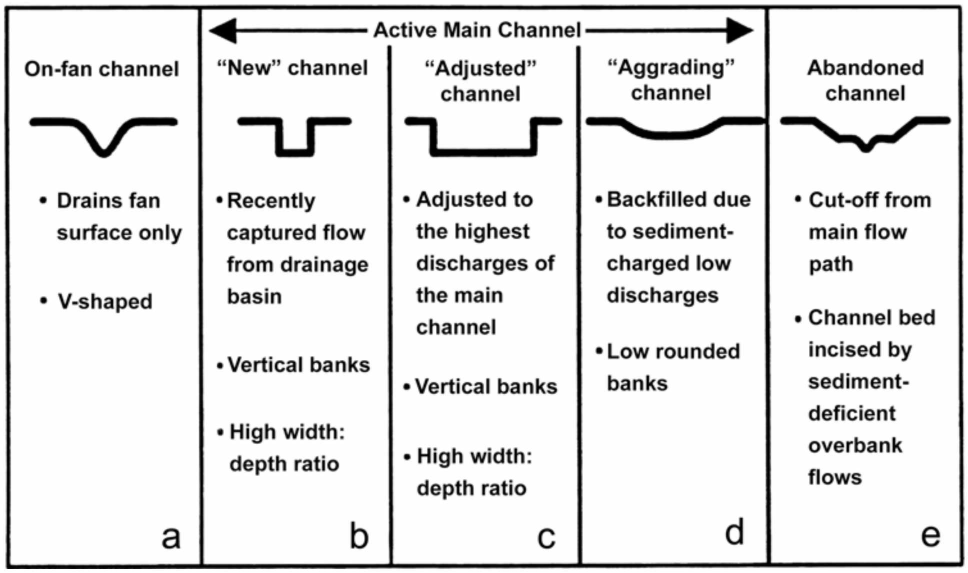

Figure 19. Five channel morphologies observed on alluvial fans in southern Arizona. Note that a single channel reach can go through each phase of channel development through time, and each stage of development can be observed at different places on a fan at the same time. (Modified from Field 2001.)

accompanying an avulsion and the subsequent slow backfilling of the channel due to a series of low-flow events. As the channels evolve through the morphological steps, they become increasingly unstable, explaining why avulsions preferentially occur where banks are low (Field 2001). The dramatic temporal and spatial changes in channel morphology and position associated with channel avulsions should be considered the norm, rather than the exception, on alluvial fans.

Large portions of many piedmonts in the Southwest, the gently sloping plains between mountain ranges and valley bottoms, have been isolated from alluvial fan flooding for 10,000 years or more (Field and Pearthree 1997). These inactive alluvial fans do not need to be managed as flood-prone zones and form by multiple processes including long-term tectonic quiescence (Eckis 1928, Harvey 1987), tectonic uplift (Beaty 1961, Hooke 1967), climate change (Hunt and Mabey 1966, Silva et al. 1992), and base-level fall (Drew 1873, Wasson 1977). Geomorphological analysis and mapping can be used to delineate these active areas and thus identify those areas most susceptible to flooding (Fig. 20) (Rhoads 1986, Kenny 1990, French et al. 1993, Field and Pearthree 1997). A number of in-situ weathering, erosional, and pedogenic features can be used to distinguish flood-prone areas from inactive zones (Table 7), including desert pavement, rock varnish, and salt-split cobbles (Fig. 21).

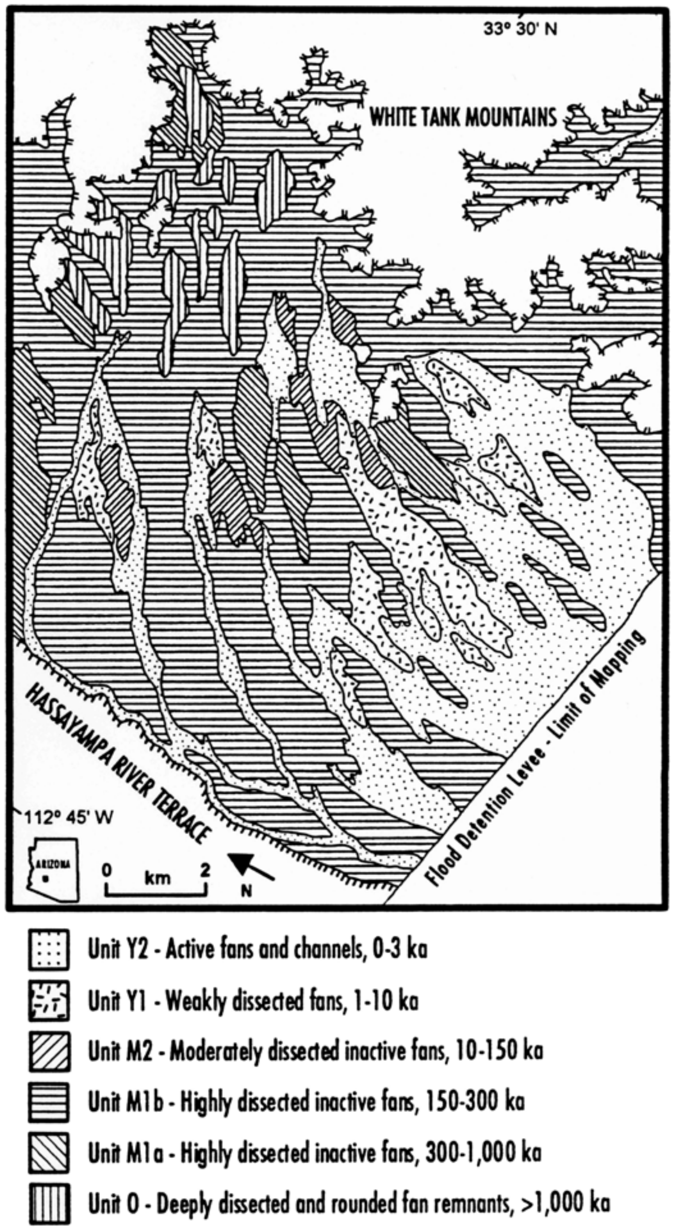

Figure 20. Geomorphic map of alluvial fan surfaces on the southwestern piedmont of the White Tank Mountains, Arizona. Only Unit Y2 is active, so the location of the OHWM would be restricted to within these areas. (From Field and Pearthree 1997.)

a. Desert pavement and rock varnish (dark tone).

b. Close-up of desert pavement and rock varnish.

c. Salt-split cobble.

Figure 21. Well-developed weathering features on an inactive alluvial fan surface on the piedmont of White Tank Mountains, Arizona.

Table 7. Surface features that develop in the absence of fluvial activity. See Field and Pearthree (1997) for a more extensive list of references. (After Field and Pearthree 1997.)

Surface feature	Reference
Weathering	
Desert pavement	Al Farraj and Harvey (2000), Dorn (1988)
Rock varnish	Derbyshire and Owen (1990), Ritter (1986)
Clast weathering	Derbyshire and Owen (1990), McFadden et al. (1989)
Salt splitting	Hooke (1972)
Carbonate etching	Hooke (1972)
Depositional topography	Bull (1991), McFadden et al. (1989)
Soils	
Soil development	Mohindra et al. (1992), Harden and Matti (1989)
Caliche rubble	Dorn (1988), Lattman (1973)
Surface color/tone	Dorn (1988), Lattman (1973)
Vegetation	Hooke (1972)
Erosion	
Drainage development	Dorn (1988), Rhoads (1986)
Surface relief	Hooke (1972), Rhoads (1986)
Surface rounding	Dorn (1988)

Anastomosing Rivers

Anastomosing rivers are sinuous, low-gradient channels consisting of multiple interconnected branches transporting a suspended or mixed load (Fig. 22) (Schumann 1989). In plan view the splitting and rejoining of anastomosing channel branches may at first appear similar to braiding, but many distinct differences exist (Fig. 16 and 22). Whereas flow is fairly evenly divided amidst different braided flow paths, one main channel is characteristic of anastomosing channels, with only overbank flow feeding smaller anabranches. Given the high suspended load content and fine-grained bank material, channel width:depth ratios are lower and sinuosities higher than for braided rivers. Also, channel position is more stable along anastomosing rivers. Anastomosing channels can

Figure 22. Anastomosing channels along Cooper Creek, Australia. Note the primary channel that is active during low flows running from left to right across the center of the photo. (Copyright, Colin P. North, University of Aberdeen, Scotland; used by permission.)

also form in sand-bed rivers where vegetation serves as a stabilizing influence (Wende and Nanson 1998, Tooth and Nanson 2000b). While anastomosing rivers are mostly reported from different climates in Australia (Tooth 2000), they are present in the arid western U.S. (Schumann 1989, Malisce 1993) but are not common in the Southwest, given the necessary prerequisites of high suspended load and/or dense vegetation.

Channel avulsions are an important process in the development of anastomosing rivers, with overland flow from the main channel enlarging and ultimately capturing the smaller anabranches (Schumann 1989). While avulsions on braided rivers tend to occur by lateral migration of banks (Cazanacli et al. 2002), avulsions on anastomosing systems are generally the result of the headward extension of anabranches (Schumann 1989). Processes within the main channel may be similar to meandering rivers, with the formation of cut banks and point bars, but the relief of such features is generally lower in arid climates (Malisce 1993). The morphological evolution of anastomosing river channels and their relationship to avulsions share many similarities to discontinuous ephemeral streams on alluvial fans (Fig. 19) (Field 2001). The development of benches at the base of the main channel due to bank sloughing leads to greater overland flow, which drives the avulsion process (Schumann 1989). As on alluvial fans, the dramatic temporal and spatial changes in channel morphology and position

associated with channel avulsions should be considered the norm, rather than the exception, on anastomosing rivers.

Single-Thread Channels with Adjacent Floodplains

Single-thread, generally meandering channels with adjacent floodplains are characteristic of humid climates but do occur in drylands (Fig. 11) (Graf 1988b). They occur where a dependable water supply is present, as in allogenic rivers (i.e. rivers that drain watersheds extending into more humid climates, such as the Colorado River) (Tooth 2000). Meandering is more pronounced with vegetation (Merritt and Cooper 2000), partially explaining why single-thread channels in arid climates tend toward a lower sinuosity (Schumm 1961). Dryland perennial rivers have morphologies similar to those known for humid regions (Cooke et al. 1993), where vegetation and more constant flow are able to stabilize banks and form vertically accreting floodplain surfaces rather than laterally unstable compound channels. Transmission losses (Reid and Frostick 1997) and debris flow inputs from tributaries (Graf 1979, Webb et al. 1988) are unique occurrences in drylands that may alter the characteristic perennial river form. Decreasing width:depth ratios during large floods may compensate for the decreasing discharge downstream along allogenic rivers (Deodhar and Kale 1999). To the extent that dryland perennial rivers mimic their humid-region counterparts, a stable channel form may develop, and delineation of the OHWM becomes easier.

3.4 DIFFERENCES AMONG STREAM TYPES

A number of factors contribute to the development of differences between dryland and humid-region rivers (Table 8) and among stream types within drylands. Channel morphology and position are highly variable, both spatially and temporally, on most dryland rivers due to limited vegetation, unstable sandy banks, transmission losses, and high interannual variability in peak discharges. Smaller drainage basins have a greater sensitivity to large floods, especially in arid climates, where stream widths remain largely unchanged for drainage areas exceeding 50 km^2 due to transmission losses (Wolman and Gerson 1978). Discontinuous ephemeral stream systems and alluvial fans are most prevalent in, but not restricted to, piedmont settings. Compound channels, anastomosing rivers, and single-thread channels with adjacent floodplains generally occupy the valley bottoms.

Bedrock lithology and soils play a strong role in the size of sediment available and consequently the processes that occur in dryland streams. Discontinuous ephemeral steam processes are enhanced in granitic terrains and with other lithologies that weather to sand and finer particles, as this ensures that sediment is mobilized during even low to moderate flows (Wells 1997, Blair 1999, Field 2001). Drainage basins with mixed lithologies such as dolomite, quartzite, and shale produce clay to boulder-sized particles necessary for the formation of debris flows, a dominant process on some alluvial fans (Blair 1999).

Table 8. Comparison of hydrologic and channel characteristics of arid- and humid-region rivers. (After Knighton and Nanson 1997.)

Characteristics	Arid-region rivers	Humid-region rivers
Hydrologic characteristics	Low and unreliable	Relatively high and dependable
	Limited duration but high-intensity storms	Long-duration precipitation of variable intensity
	Extreme annual variability in peak discharges	Less temporal variability in peak discharges
	Precipitation events of limited spatial extent	Large areas generally affected
	Transmission losses downstream	Tributary inputs downstream
	Ephemeral flow	Perennial flow
	Sharply peaked runoff hydrograph	Runoff hydrographs have lower amplitude
Channel characteristics	Floods as major channel formers	Channels adjusted to frequent discharges
	Long recovery time after disturbance	Quicker channel recovery
	Transient behavior dominant	Tendency for channels to reach equilibrium

Anastomosing patterns are enhanced when the clay and silt content in the channel exceeds 80%, as can occur when the surrounding bedrock is largely claystones and shale (Schumann 1989). Otherwise, soils in arid regions have limited clay because hydrolysis of feldspars and ferromagnesium minerals occurs very slowly with the limited moisture. Very coarse material on a streambed, as is produced by fine-grained volcanics, quartzites, and carbonates in arid regions, increase the geomorphic effectiveness of large floods because of the high response threshold required to scour and rework bouldery deposits (Baker 1977). Consequently the morphological features observed in such drainages, especially in arid climates, are more likely the result of extreme floods and not smaller-magnitude events.

Floods in the arid Southwest usually result from one of three kinds of storms: tropical cyclones with regional extent and intense rainfalls; convective thunderstorms of limited extent but intense rainfall; and winter low-pressure frontal storms from the Pacific Ocean with regional extent but lower rainfall intensities (Ely 1997). Convective thunderstorms affect smaller drainage basins but are generally too localized to produce significant flows on larger rivers. Winter frontal storms, in contrast, can produce moderate flows on larger rivers but have limited impact on small drainage basins that often respond only to flashier flows. When widespread low-intensity rainfall from frontal storms is accompanied with local high-intensity convective storms, large volumes of runoff may result (Burkham 1988). Tropical cyclones have the potential to dramatically impact both large and small drainages (Kresan 1988) but are less common than the other storm types. In many deserts, particularly where precipitation intensities are high, the runoff hydrograph characteristically rises very steeply as the result of limited infiltration capacity and then falls sharply in response to transmission losses (Cooke et al. 1993). The lower infiltration capacities and higher rainfall intensities result in higher runoff coefficients (which express the proportion of rainfall converted to runoff) in arid regions (Knighton and Nanson 1997). The floods most likely to result in significant geomorphic change are those that produce discharges many times above that normally experienced by the river, that is, those with high ratios of maximum peak discharge to mean annual discharge (Kochel 1988). Such high ratios are characteristic of arid regions (Graf 1988a, Knighton and Nanson 1997). Humid-region rivers tend to respond less dramatically to floods because interannual variability in peak discharges is much lower.

The sequencing of prior flood events is critical for understanding the channel morphology observed at any given time (Graf 1988a). A series of low flows over a number of years may produce a smaller channel inset into a compound channel that would be particularly sensitive to morphological change during an extreme event. When two large storms occur close in time, the second event is generally

less effective since the channel has already adjusted its morphology to accommodate high discharges (Kochel 1988).

Vegetation exerts a strong influence on the morphology and stability of stream channels (Millar 2000). Rivers with vegetated channel banks have channel widths half that of their weakly vegetated equivalents (Hey and Thorne 1986). Hydraulic geometry relationships that reflect how channel width, depth, and velocity change with varying discharges consistently show the channel width changing more rapidly with discharge in drylands compared to humid regions (Park 1977). Regional curves show the width increasing more rapidly with drainage area in semi-arid climates (Rosgen 1996). Consequently, braiding (Fig. 16) and sheetflooding (Fig. 14) are more common in arid regions where dense riparian vegetation is lacking. Lateral instability also arises with an absence of bank vegetation (Millar 2000). By inhibiting widening and lateral migration, vegetation leads to the vertical accretion of sediments and the development of floodplains. The effectiveness of large floods is diminished when flow energy is dissipitated on a floodplain, ensuring that the channel morphologies present where vegetation is dominant are reflective of the frequent low flows in the region. Understanding the different processes, patterns, and sensitivities to change that result from various watershed characteristics (e.g., bank vegetation, bank composition, drainage size and lithology, hydrology) is critical for distinguishing between morphological features formed by extreme floods compared with the more frequent low flows.

3.5 IDENTIFYING THE ORDINARY HIGH WATER MARK ON DESERT RIVERS

The OHWM is defined as “the line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation or the presence of litter and debris” (U.S. Army Corps 2001). This definition does not refer to the frequency with which the “fluctuations of water” occur, but the 1.5-year recurrence interval flow is generally the dominant discharge in humid regions and therefore primarily responsible for the formation of the physical features associated with the OHWM.

The morphology of many rivers in humid regions is adjusted to the flows most commonly experienced, that is, the bankfull flow (Wolman and Miller 1960). Numerous features have been reported in the literature to identify the bankfull stage of the river (Table 9), which in many instances is equivalent to or a close approximation of the OHWM. However, the geomorphic effectiveness of floods in arid regions means that morphological features associated with the OHWM in these climates are more likely the result of extreme events, not the 1.5-year flow. This presents difficulties for defining what is meant by “ordinary” and for accurately delineating the OHWM.

Table 9. Physical features that have been used to identify the bankfull stage by previous workers.

Bankfull feature	Reference
Valley flat	Williams (1978)
Active floodplain	Williams (1978)
Low bench	Williams (1978)
Middle bench for rivers with multiple overflow surfaces	Williams (1978)
Most prominent bench	Williams (1978)
Highest surfaces of the channel bars	Williams (1978)
Lower limit of perennial vegetation	Williams (1978)
Upper limit of sand-sized particles	Williams (1978)
Top of point bars	Rosgen (1996)
Break in slope of banks	Rosgen (1996)
Change in particle size distribution	Rosgen (1996)
Small benches	Rosgen (1996)
Staining of rocks	Rosgen (1996)
Exposed root hairs below an intact soil layer	Rosgen (1996)

Table 10. Advantages and disadvantages of different methods for defining the OHWM in arid regions.

Method for defining OHWM	Advantages	Disadvantages
Geomorphically effective event	- Less ambiguous to delineate in the field - Good for establishing probable maximum flood	- Extraordinary events delineated, not ordinary
Exclusion of areas above and below OHWM	- Definitively removes areas from consideration as either above or below the OHWM - Less likely to lead to false positives - Provides a means of checking the accuracy of determinations established by another method	- Provides only range of area within which the OHWM is located, so less precise
Recognition of the transitory nature of desert rivers	- Accounts for dominant process in arid regions - Maximum limit of the OHWM delineated - More precise than geomorphically effective approach when long time since last flood	- Temporal in nature and difficult to define spatially - Imprecise
Hydrologic/hydraulic methods	- Precise elevation of the OHWM established	- Uncertainties in use of gauges in desert regions - Possible inconsistencies with physical features

Consequently four approaches for delineating the OHWM in arid regions are described below with a description of the potential advantages and disadvantages of each approach (Table 10): identification of the limits of the geomorphically effective event; exclusion of areas definitively above and below the OHWM; recognition of the transitory tendency of arid-region rivers; and application of hydrologic and hydraulic methods.

Identification of Limits of Geomorphically Effective Events

In humid regions the geomorphically effective event, or the flow that leaves the most lasting impression on the landscape, is the bankfull flow. Thus, using the limits of the geomorphically effective event to delineate the OHWM is essentially the current practice in humid regions. Applying the same concept to arid regions would be straightforward in terms of identifying physical features on the ground, but the outer limits of extreme flows would be delineated, not the annual flow.

While many of the same features used to identify bankfull features could be used in this approach (e.g., highest surface of bars, rock staining, change in particle size distribution), others might not apply (e.g., lower limit of perennial vegetation, exposed root hairs, active floodplain). Additional features not associated with a bankfull condition might also be useful for identifying the limits of extreme events in arid regions (e.g., outermost or highest scour lines and silt lines, micro-terraces). While morphological features associated with low flows may develop within a compound channel, these features would be continually changing as the channel narrows after the passing of a large flood.

The value of identifying the limits of geomorphically effective events would be to remove the uncertainty of whether the low-flow channels represent physical features associated with more “ordinary” flow conditions or some intermediate condition between the ordinary and extreme events. Given that arid-region rivers generally respond to large floods by dramatically widening their banks, the limits of the geomorphically effective event will likely be much more extensive than the limits of a low-flow channel inset into a compound channel. Consequently, if the OHWM is set at the outer limits of the extreme event, the designated “waters” will encompass a much greater area than is occupied by more ordinary flows.

Exclusion of Areas Definitively Above and Below the OHWM

Precise location of the OHWM is especially difficult in arid regions where the morphological features present on the landscape are possibly the result of:

- Flow events of various magnitude (e.g., high-flow and low-flow channels of compound channels);
- Multiple processes (e.g., sheetfloods and streamflows on discontinuous ephemeral streams); or
- No longer active processes (e.g., channels abandoned by avulsion on alluvial fans and anastomosing streams).

Given these uncertainties, a more effective approach to locating the OHWM may be to identify areas on the land surface that are definitively above or below the OHWM. Vast portions of piedmonts and valley bottoms in the Southwest have been removed from active fluvial processes for thousands, in many places hundreds of thousands, of years (Field and Pearthree 1997). Once isolated from the influence of flooding, a distinctive suite of weathering, erosional, and pedogenic features develop that become more pronounced with age (Table 7). Areas where these features are found can be considered above the OHWM since they have not been inundated by floods for several millennia. Not all of the

features presented in Table 7 will be present at a given site, but using multiple features is more reliable than using single features for establishing the relative length of time that different areas have been isolated from fluvial processes (McFadden et al. 1989). The degree of development of each feature can be quantified and a threshold value established that could be used to determine if the area was safely above the OHWM.

A number of sedimentary structures are associated with ephemeral streams (Table 11), and the presence of fresh undisturbed features at a given location would be evidence of recent fluvial activity. Whether the structures present were deposited by normal low flows or by an extreme flood may be difficult to ascertain, so their occurrence would only be definitive evidence of being below the limits of the geomorphically effective flood. They would represent only possible evidence for being below the extent of the average annual flow unless their presence is coupled with additional information indicating that no significant flow events had occurred in the watershed for a significant period of time. The features listed in Table 11 are easily disturbed, so if no extreme flow events had occurred in the past decade or so, their presence in pristine condition would likely be the result of low flows. Determinations of whether an area is definitively below the OHWM would be strengthened by the presence of multiple sedimentary structures. Many of the features in Table 11 are common to all of the five stream system types described above and thus would be widely applicable.

Delineating the OHWM by this exclusionary approach would require identifying along a given river cross section those areas that are definitively above the OHWM (Table 7) and those areas definitively below the OHWM (Table 11). The OHWM itself would then be located in the zone between those areas excluded. The area not excluded would likely encompass areas inundated by extreme floods since these zones would not possess fresh sedimentary structures (assuming that no recent extreme flood has occurred) nor would they have well-developed weathering features that form only when fluvial activity ceased thousands of years before.

The exclusionary approach will not lead to precise determinations but will provide a definitive way of identifying zones within which the OHWM is located and could serve as a check on other techniques; the OHWM delineated by another method should fall within the zone identified using the exclusionary approach. In some cases delineation of the OHWM using the exclusionary approach will constrain the location of the OHWM to a fairly narrow zone, such as in narrow valleys or where there is large relief between river terraces and the active flood zone. In other areas the zone might be quite wide and perhaps of limited usefulness in reasonably locating the OHWM. A wide zone of uncertainty, however, may be an accurate reflection of the uncertainties present on the

ground surface. Therefore, an exclusionary approach, while less precise than other methods, is less likely to lead to false identifications of the OHWM.

Table 11. Sedimentary structures common to ephemeral streams. See Picard and High (1973) for additional structures.

Sedimentary structure	Reference
Dunes and megadunes - sand bed rivers	Malisce (1993) Williams (1970) Karcz (1972)
Mud drapes	Reid and Frostick (1997)
Sand tongues	Packard (1974)
Cobble bars/trains behind obstructions	Field (1994) Blair (1987)
Scour holes downstream of obstructions	Field (1994) Picard and High (1973)
Transverse sinuous crested ripples	Tooth (1999)
Flaser bedding - ripples covered by mud	Martin (2000)
Narrow berms and levees	Malisce (1993) Wells (1977)
Muddy point bars of low relief	Malisce (1993)
Longitudinal gravel bars	Malisce (1993)
Gravel sheets grading to rippled sands	Malisce (1993)
Streaming lineations	Malisce (1993) Picard and High (1973)
Dessication/mud cracks	Abdullatif (1989) Glennie (1970)
Stepped-bed morphology in gravel	Bowman (1977)
Meander bars	Karcz (1972)
Harrow marks - flow aligned sand ridges	Karcz (1972)
Obstacle marks	Karcz (1972)
Armored mud balls	Picard and High (1973)

Recognition of the Transitory Tendency of Arid-Region Rivers

Rivers in any climatic region are always adjusting to changes in watershed conditions in a direction that will bring the river into equilibrium with the new conditions. Given the wide discrepancy in record and average annual peak flows

in arid regions and the high sensitivity of arid-region rivers to change, dryland rivers rarely reach a state of equilibrium (Graf 1988a, Tooth and Nanson 2000a). Rivers in arid regions respond to large floods by widening their banks. During periods of low flow, these rivers reduce their channel's size to attain equilibrium with the reduced discharge. A constantly transitory state results because the time needed to establish equilibrium with the low-flow conditions is greater than the frequency of large floods that create a larger channel in equilibrium with the high discharge. Immediately after a large flood, the channel will begin to narrow, and the trend will be towards a smaller and smaller channel. Thus, the morphological features generally associated with the OHWM (Table 9) will in successive years be inset into features emplaced previously, as long as a large flow event does not occur. Therefore, the actual location of the OHWM, the one that would be established if the river reached an equilibrium condition, should be considered to be at some point below the current position of the physical features normally associated with the OHWM (Table 9).

With this approach the physical features associated with the OHWM will continue to develop and become more pronounced through time until the next subsequent extreme event reworks the emerging OHWM features. The physical features identified on the ground would be considered to be at some level above the OHWM, and as such, this approach provides a means of establishing the maximum possible extent of "waters." If a large flood has recently passed through the river system, then the physical features mapped on the ground would be high above or outside the actual OHWM. Conversely, if a long time has passed since an extreme event, then the physical features mapped would be close to the OHWM as the channel continues to shrink in the absence of an extreme event. Studies of flood histories and historical aerial photographs could help establish whether the channel is approaching an equilibrium condition or just beginning the recovery process after passage of a large flood.

Application of Hydrologic and Hydraulic Methods

If the OHWM is assumed to occur at a level reached by the discharge at a specified recurrence interval, then hydrologic and hydraulic methods can be used to establish to what level along the channel this discharge would reach, regardless of whether any physical features on the ground are associated with this synthetically determined stage. Rainfall–runoff models (e.g., HEC-1 and HEC-HMS) can be used to establish the discharge that would result from a specified rainfall amount in a given watershed. Gauge records can also be used to establish the discharge at a certain recurrence interval to be used in hydraulic models. Hydraulic models (e.g., HEC-RAS) can then be used to determine the stage of the river at various points along its length for the specified discharge. A more

detailed review of hydrologic and hydraulic methods that might be useful in the arid Southwest is presented in Chapter 2, so only a consideration of the potential value of gauge records in desert regions is provided here.

Desert regions are characterized by wide, shallow channels (Fig. 13) or sheetflood zones (Fig. 14), where dramatic increases in discharge will have little effect on river stage. Consequently, gauges in such localities would be inaccurate measures of discharge. Gauges placed in narrow bedrock canyons are far more sensitive to variations in discharge, but gauge readings from mountain sites are of little utility along alluvial channels several miles from the mountain front, given the significant transmission losses that occur in drylands. Mountain gauges are potentially useful for establishing the ratio between record peak and average annual peak discharges and thereby identifying drainages that might be particularly sensitive to change by large floods (i.e., high peak:average ratio).

3.6 CONCLUSIONS

A review of the geomorphic literature shows that channel morphology on all five arid-region stream system types is spatially and temporally variable. This is unlike humid-region rivers, where an equilibrium condition is reached. Consequently, traditional methods of delineating the OHWM, originally developed in humid regions, are inadequate for the arid Southwest. Four alternative approaches for defining and delineating the OHWM in arid regions each have their own advantages and disadvantages (Table 10). Any method used should be combined with an exclusionary approach because any surface with well-developed weathering features (Table 7) should be considered definitively above the OHWM. Mapping alluvial surfaces of different ages provides a relatively simple method for narrowing the search for the OHWM since large areas of desert piedmonts have been isolated from fluvial processes for tens of thousands of years (Fig. 20) (Field and Pearthree 1997).

Whatever approach is taken to delineate the OHWM, the transitory nature of desert rivers must be recognized and the flexibility provided to adjust OHWM delineations over time. Avulsions on alluvial fans and anastomosing streams change the location of subsequent flows, large and small. Along compound channels, large floods obliterate existing flow paths, and low-flow channels may be re-established in new locations. On discontinuous ephemeral streams, morphological changes to the channel result not only from large floods but also from aggradation caused by small floods.

The normal condition for desert-region rivers is a tendency towards establishing a meandering channel form (compound channels and anastomosing streams) or a sheetflood zone (discontinuous ephemeral streams and alluvial fans). In the absence of an extreme threshold crossing event that would create a braided form, precipitate an avulsion, or initiate arroyo cutting, the features marking the extent of the low-flow channel will become more pronounced, and identifying the extent of the "ordinary" flow will be easier. In many areas, though, the "ordinary" flow event is ineffective at erasing the morphological impact of more extreme events. Consequently physical features associated with the OHWM in these settings will be the result of extreme events.

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3.8 GLOSSARY

Aggradation – An increase in the channel bed elevation through deposition of sediment

Alluvial fan – Depositional landform with a conical shape that develops where confined streams emerge from upland areas into zones of reduced stream power

Anastomosing river – Sinuous, low-gradient channels consisting of multiple interconnected branches transporting a suspended or mixed load

Arroyo – Entrenched ephemeral streams with vertical walls that form in desert environments

Bankfull stage – River level that completely fills the channel and begins to spread out onto the floodplain; sometimes alternatively considered the 1.5-year recurrence interval flow even if it is not associated with the incipient inundation of the floodplain

Channel avulsion – Rapid diversion of flow from one channel into another

Compound channel – Channels with a single, low-flow meandering channel inset into a wider braided flood zone active only during extreme events

Desert pavement – Tightly interlocking gravel at the surface formed after years of surface exposure in the absence of active streamflow over the surface

Discontinuous ephemeral stream – A distinctive stream pattern characterized by alternating erosional and depositional reaches

Equilibrium – A balance between sediment and water supply resulting from adjustments of the river channel's shape, planform, and gradient

Geomorphically effective flood – The flood discharge most responsible for the formation of physical features seen along the channel

Holocene – Geologic epoch spanning the last 10,000 years

Hydrolysis – Chemical weathering process whereby feldspars and iron-rich minerals are converted to clay minerals through the replacement of cations with water

Lithology – Rock type/composition

Ordinary high water mark – The line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of the soil, destruction of terrestrial vegetation, or the presence of litter and debris

Pleistocene – Geologic epoch ending 10,000 years ago and associated with the ice ages

Quaternary – Geologic time period beginning roughly 2 million years ago and continuing until today

Rock varnish – A dark manganese oxide coating that develops on the outer surface of rocks exposed at the surface and becomes increasingly dark with exposure

Sheetflood – Sheet of unconfined floodwater moving down a slope

Terrace – Abandoned floodplain and channel surface isolated above the active floodplain that formed under a previous hydrologic regime

Transmission loss – Decrease in discharge in a downstream direction due to infiltration of water into the channel bed; especially pronounced in arid climates

Chapter 4. Vegetation Literature Review for Ordinary High Water Mark Indicators in the Arid Southwest

GABRIELLE KATZ

4.1 INTRODUCTION

Riparian ecosystems are terrestrial ecosystems that occur alongside rivers in zones that are influenced by both surface and subsurface hydrology. In arid regions the moisture subsidy provided in river valleys often allows for the occurrence of gallery forests, which may be the only naturally occurring forest patches in low-elevation landscapes (Malanson 1993, Patten 1998). These linear corridors of forest contrast sharply with the surrounding upland deserts or grasslands, provide important structural habitat for a variety of wildlife species, play an important role in the dispersal of both animals and plants, and also shade and stabilize fluvial environments, providing habitat for aquatic organisms (Naiman et al. 1993, Patten 1998). Where hydrologic conditions do not support riparian forests, riparian zones may still support vegetation communities distinct in composition or structure from nearby uplands (Stromberg et al. 1993, Evans 2001). The degree of contrast between riparian and upland vegetation communities in the western U.S. is more distinct at low elevations because at high elevations differences in moisture availability are less pronounced (Patten 1998).

The river flow regime, characterized by patterns of variation in surface flow magnitude, duration, frequency, and timing, has been termed the "master variable" shaping aquatic and riparian environments (Poff et al. 1997). In arid regions, however, subsurface hydrologic conditions may be equally important in determining vegetation patterns; the moisture subsidy provided by streams results from both surface and subsurface hydrologic conditions and their interaction. For example, surface streamflows (e.g., annual flow volume) (Stromberg and Patten 1990), overbank flows that replenish floodplain soil moisture (Reily and Johnson 1982, Friedman and Auble 2000), and the level of the subsurface alluvial aquifer (Stromberg et al. 1993, 1996, Scott et al. 1999) have all been identified as hydrologic conditions that strongly influence riparian vegetation.

For identifying reliable vegetative indicators of the ordinary high water mark, it is important to distinguish between the effects of surface flows and the effects of groundwater levels on vegetation patterns. This task is likely to be challenging for at least two reasons. First, surface and ground waters are almost always connected and interacting, which means that the two variables do not vary independently in riparian settings. Riparian sites with shallow groundwater levels are much more likely to be characterized by perennial or near-perennial stream flow than are sites characterized by deeper alluvial water tables. Because these two key hydrologic characteristics co-vary, in some cases it may be difficult to tease apart the specific effects of surface flow on vegetation characteristics at the site scale. Second, riparian sites are characterized by complex environmental gradients, along which multiple physical factors may vary in tandem. Of particular importance are the lateral gradients in inundation duration and frequency, floodwater depth, velocity and unit stream power, and depth to groundwater that occur with distance from the stream channel at many arid-region riparian sites (Stromberg 1993c, Auble et al. 1994, Stromberg et al. 1996, Stromberg 1998, Bendix 1999). That is, in general at a single riparian site, near-channel locations are likely to be characterized by higher inundation frequencies, floodwater depths, velocities, and stream power and also by shallower groundwater than are locations farther from the stream channel. Although these variables are likely to be highly correlated, the relationships are not always consistent. Bendix (1999) found that stream power of the 20-year flood and floodplain surface height (i.e., depth to groundwater) were poorly correlated at sites in California. Arid-region riparian vegetation patterns can be viewed as integrating the physical characteristics of the entire complex floodplain gradient, not solely the surface flow characteristics. Efforts to isolate the effects of surface flow are most pertinent for the present context and will be emphasized in this review.

Any attempt to understand the effects of hydrologic conditions on riparian vegetation must consider that non-hydrologic factors may also strongly impact riparian vegetation patterns and processes. At the regional and landscape scales, climatic patterns and elevation strongly influence riparian plant assemblages (Bendix 1994, Minckley and Brown 1994). At the reach scale, effects of geology, floodplain soil chemistry and sediment particle size, disturbance, and land management are superimposed on the primary hydrologic effects. For example, fire (Bendix 1994, Busch 1995) and livestock grazing (Belsky et al. 1999) may have profound and long-lasting impacts on riparian vegetation patterns in arid regions.

4.2 COMMUNITY-LEVEL PATTERNS

Minckley and Brown (1994) described and classified the riparian biotic communities of the southwestern U.S. and northwestern Mexico. At the most general level they identified four wetland biotic communities in this region: Arctic-Boreal Wetlands, Cold-Temperate Wetlands, Warm-Temperate Wetlands, and Tropical-Subtropical Wetlands. The four major communities can be subdivided into seventeen series, which can be further subdivided into more specific associations based on species assemblages (Table 12). For example, Szaro (1990) identified 28 riparian plant community types on perennial streams in the mountains of New Mexico and Arizona within the Interior Riparian Deciduous Forest: Mixed Broadleaf Series and the Montane Riparian Wetlands: Deciduous Forest of Minckley and Brown (1994) (Table 12). These included communities dominated or co-dominated by *Acer negundo* (boxelder), *Populus angustifolia* (narrrowleaf cottonwood), *Juglans major* (walnut), *Fraxinus velutina* (ash), *Platanus wrightii* (sycamore), *Populus fremontii* (Fremont cottonwood), *Salix gooddingii* and *S. bonplandiana* (willows), and *Sapindus saponaria* (soapberry), among others. Similarly, Durkin et al. (1995) identified 58 community types within the riparian and wetland vegetation of the upper and middle Rio Grande in New Mexico. These included communities dominated or co-dominated by *P. angustifolia*, *Alnus incana* (thinleaf alder), *Salix* spp., *Alnus oblongifolia* (Arizona alder), *P. deltoides* (Rio Grande cottonwood), *Tamarix* spp. (saltcedar), *Eleaegnus angustifolia* (Russian olive), *J. major*, *P. wrightii*, and *P. fremontii*, among others (Durkin et al. 1995). Although such detailed community classification schemes provide valuable information, a coarser level of sub-regional community delineation will be more useful in efforts to determine general vegetative indicators of the ordinary high water mark.

Elevation is probably the most important factor distinguishing riparian plant communities of the arid southwest at a sub-regional scale (Szaro 1990, Bendix 1994, Minckley and Brown 1994). Elevation influences the distribution of the biotic communities described by Minckley and Brown (1994). For example, Arctic-Boreal Wetlands are restricted to subalpine environments in the arid southwest. In central Arizona the Mixed Broadleaf Series of the Interior Riparian Deciduous Forest Association of the Warm-Temperate Wetland community type occurs at mid-elevations, while the *Populus*-*Salix* and *Prosopis* Series of the Sonoran Riparian Deciduous Forest Association of the Tropical-Subtropical Wetland community type occur at relatively low elevations (Minckley and Brown 1994). For the present purpose a first-order distinction between two elevation zones provides a useful framework for considering sub-regional

Table 12. Wetland biotic communities of the southwestern U.S. and northwestern Mexico, according to Minckley and Brown (1992).

Vegetation Community	Physiognomy	Common Species
I. Arctic Boreal Wetlands	Shrubland	*Salix* spp.
II. Cold-Temperate Wetlands		
Montane Riparian Wetlands	Forest and shrubland	*Populus angustifolia, Acer grandidentatum, A. negundo, Alnus oblongifolia, Salix* spp.
Plains and Great Basin Wetlands	Gallery forests and woodlands	*P. deltoides, P. fremontii, S. amygdaloides, Tamarix*
Montane, Plains, and Great Basin Marshlands	Marsh	*Typha latifolia, Scirpus acutus*, *Juncus* spp., *Carex*. spp
III. Warm Temperate Wetlands		
Interior and Californian Riparian Deciduous Forests and Woodlands	Gallery forests and woodlands	*Populus-Salix* Series: *P. fremontii, S. gooddingii, S. exigua* Mixed Series: *Platanus wrightii, Fraxinus velutina, P. fremontii, Juglans major*
Riparian Scrublands	Scrub	*Tamarix, Salix* spp., *Baccharis salicifiolia*
Californian Maritime & Interior Marshlands	marsh	*Spartina foliosa, Allenrolfea occidentalis*
Californian Maritime Strands	Open/bare	*Atriplex leucophylla, Abronia maritima, Calystegia soldananaella*
Interior Strands	Open/bare	*B. salicifolia, Tamarix, Hymenoclea monogyra*
IV. Tropical Subtropical Wetlands		
Sonoran Riparian Deciduous Forest and Woodlands	Forests and woodlands or bosques	*P. fremontii, S. gooddingii, Prosopis velutina*
Sonoran Oasis Forest and Woodlands	Evergreen palm stands	*Washingtonia filifera, W. robusta, Erythea armata*
Sinaloan Riparian Evergreen Forest and Woodland	Forest and woodland	*Populus dimorpha, S. gooddingii, Sabal uresana, Taxodium mucronatum*
Sonoran Riparian Scrubland	Scrub	*B. salicifolia, B. sarothroides, Tessaria sericea, Chilopsis linearis*
Sinaloan Maritime Scrubland	Mangrove swamps	*Avicennia germinans, Rhizophora mangle, Laguncularia racemosa*
Sonoran and Sinaloan Interior Marshlands and Submergent Communities, cienegas	Marsh	*Scirpus* spp., *Phragmites australis*
Sonoran Maritime Strand and Submergent Communities	Open/bare	*Atriplex* spp., *Salicornia* spp.
Sonoran Interior Strands	Open/bare	*B. salicifolia, Nicotiana glauca, Amaranthus palmeri, Solanum* spp., *Xanthium strumarum*

patterns of riparian vegetation: (1) mid- to high- elevation riparian plant communities, predominantly mixed-deciduous riparian forests, and (2) low-elevation riparian plant communities, predominantly *Populus-Salix* forests and *Tamarix* or *Prosopis* woodlands. Examples of higher-elevation riparian community types occur in Zion National Park, Utah (Harper et al. 1991), in the mountains of southern California (Bendix 1994), and in the mountains of Arizona and New Mexico (Bock and Bock 1989, Szaro 1990, Stromberg 1993b, 2001a). Examples of lower-elevation riparian plant community types occur along the lower Rio Grande in New Mexico (Howe and Knopf 1991, Durkin et al. 1995) and on the San Pedro, Hassayampa, Bill Williams, and lower Colorado Rivers in Arizona (Stromberg 1993c, 1998, Busch and Smith 1995, Shafroth et al. 2002).

After elevation, the second most important factor influencing riparian plant community distributions is often local moisture availability. Johnson et al. (1984) classified riparian vegetation into three types: Hydroriparian, Mesoriparian, and Xeroriparian. Hydroriparian systems occur on sites with hydric soils or substrates that are almost never dry (i.e. perennial or near-perennial river reaches), Meso-riparian systems occur on sites with nonhydric soils and substrates that are seasonally dry (i.e. intermittent reaches), and Xeroriparian systems occur on sites that only infrequently experience moisture in excess of direct precipitation (i.e. ephemeral streams). Because details of riparian site moisture status are often not reported in the literature, broader moisture categories will sometimes be used in this review. In particular, riparian ecosystems at the relatively wet end of the riparian moisture gradient may be termed "Hydro-mesic riparian" systems when there is insufficient information to categorize them as clearly Hydroriparian or in cases where moisture conditions have likely changed over time. Although these distinctions are based on hydrologic conditions, geomorphic factors (e.g., channel form, degree of channel stability) are also likely to differ somewhat predictably between categories.

Additional factors influence riparian plant community patterns, usually at local scales. For example, reach-scale stream power or stream gradient, valley width or cross-sectional area, geomorphic setting (e.g., canyon, arroyo, shallow wash), geologic substrate, and fire history have all been shown to influence riparian vegetation patterns (Szaro 1990, Bendix 1994, Minckley and Brown 1994, Evans 2001). To some extent these influences are superimposed on the elevation and moisture-driven biotic patterns. For example, riparian-zone fires can change the species composition of plant communities because of differences in fire tolerance and regeneration ability among species (Busch 1995). In certain cases local factors may override the first- and second-order effects of elevation and moisture on community patterns. For example, high-elevation plant

communities sometimes extend to significantly lower elevations within narrow, shady canyons.

Riparian ecosystems have been strongly impacted by human activities throughout much of the arid southwest, and many riparian community types have been greatly reduced in spatial extent and altered in composition, diversity, and structure. In Arizona, riparian marshes, or ciénegas, have become extremely rare, likely because of the effects of ongoing stream dewatering, as well as widespread historic channel incision, which resulted in the conversion of floodplain marshes to riparian forests (Hendrickson and Minckley 1984, Stromberg et al. 1997a). Other riparian vegetation types, such as *Prosopis* (mesquite) forests or bosques, and *Populus fremontii* – *Salix gooddingii* forests, exist only as remnants of formerly abundant communities (Stromberg 1993a,d). These changes have resulted from a variety of factors, including dams, groundwater pumping, live-stock grazing, and floodplain land use. Another notable change to riparian systems in the U.S. southwest has been the widespread establishment of *Tamarix* (saltcedar), which is now abundant or dominant along many rivers in the region (Brock 1994, Busch and Smith 1995, Everitt 1998, Shafroth et al. 2000).

4.3 SPATIAL PATTERNS

Riparian vegetation in semi-arid and arid regions is typically spatially heterogeneous. Often, distinct vegetation patch types can be readily distinguished on the basis of species composition, species dominance, and/or vegetation structure. For example, common vegetation patch types on the San Pedro River floodplain in Arizona include *Prosopis/Zizyphus*, *Populus/Sporobolus*, *Baccharis*/ young *Populus-Salix*, and *Scirpus/Juncus* associations (Stromberg et al. 1996). On the Bill Williams River in Arizona, distinct vegetation patches have been identified on the basis of dominance by *Populus-Salix*, *Tamarix*, *Prosopis*, or xeric shrubs (Shafroth et al. 2002).

If the spatial distributions of such patches could be shown to reliably reflect the frequency or probability of flooding, they could potentially be used as indicators of specific flow levels. This approach has proven successful in some analyses of humid-region riparian vegetation. In the eastern U.S., riparian vegetation patterns have sometimes been interpreted as equilibrium associations in which certain species assemblages are maintained on specific fluvial landforms by the unique fluvial disturbance regime that characterizes the landform (Hupp and Osterkamp 1985). In this view, species that are strongly associated with particular landforms may be used as indicators of "hydrogeomorphic" conditions, most notably conditions of flood disturbance (Hupp and Osterkamp 1985). In certain arid-region situations, equilibrium interpretations of vegetation–surface hydrology relations may be valid and useful. For example, daily inundation frequency strongly influences the distribution of marsh plant associations on the perennial Colorado River in the Grand Canyon (Stevens et al. 1995). On the perennial Gunnison River in the Black Canyon of the Gunnison National Monument in Colorado, distinct herbaceous plant communities have been shown to occur at discrete fluvial geomorphic locations (e.g., low, middle, and high cobble bars, off-channel pools) relative to the stream channel (Auble et al. 1994). Geomorphic surfaces at lower elevations and closer to the channel have higher probabilities of inundation and support more wetland species than higher and more distant locations. However, on the San Pedro River in Arizona, similar patterns have been interpreted as resulting most strongly from variations in depth to groundwater (Stromberg et al. 1996).

Equilibrium interpretations may be valid for particular well-studied river systems or riparian sites where consistent relations between plant occurrences and surface flow conditions do occur. For example, on the San Pedro River in Arizona, channel incision has led to the creation of a distinct set of geomorphic surfaces and associated vegetation patch types that do occur consistently along much of the upper river. These surfaces/vegetation patch types typically occur at

specific inundation levels and could be used as general indicators of surface flow conditions (Stromberg et al. 1996). However, it is not clear that these vegetation–surface hydrology relations can be applied to other rivers characterized by different geomorphic conditions and hydrologic regimes. Indeed, attempts to relate vegetation patterns to surface flow conditions have sometimes yielded contrasting results in different contexts. For example, on the North Fork Kings River on the west slope of the Sierra Nevada in California, *Rhododendron occidental, Fraxinus latifolia,* and *Alnus rhombifolia* occurred at locations that were flooded infrequently and for short durations (Harris et al. 1985). However, in the Transverse Ranges of southern California, *Alnus rhombifolia* occurred at locations with the highest stream power (Bendix 1999).

The equilibrium approach may not be appropriate in many arid riparian settings. Here, flood disturbance may be infrequent, and ecological and geomorphic recovery processes may be slow, leading to non-equilibrium relations between vegetation patterns and surface hydrology (Friedman et al. 1996, Katz 2001). In such situations, riparian vegetation patterns may be most strongly influenced by time since flood disturbance (and associated successional processes), depth to groundwater, and/or other sources of floodplain disturbance (Harris et al. 1985, Friedman et al. 1996, Stromberg et al. 1996, Bendix 1999). For example, in his study of riparian vegetation of the Transverse Ranges of southern California, Bendix (1999) found relatively low R^2 values for regression models relating 20-year flood stream power to plant distributions along cross-floodplain transects. He argued that the statistical relations would have been stronger if the vegetation data had been collected immediately after the most recent 20-year flood rather than 7 years later. In his words, “the interpretation of the results as they regard stream power must include recognition of the role of history” (Bendix 1999, p. 250). That is, without subsequent flooding, post-flood vegetation composition and structure will continue to change over time, reflecting influences other than ongoing fluvial disturbance.

Despite these difficulties, arid-region riparian vegetation patterns can provide information about historic and present surface flow conditions. The interpretation of vegetation patterns in this context, however, needs to be based on a sound understanding of the ecology of the dominant plant species. The following sections elaborate on this theme and identify vegetation characteristics potentially useful as indicators of recent high flow. The majority of this discussion is focused on hydromesic riparian vegetation, particularly the ecology of pioneer trees, since these are the systems and species for which most scientific information is available. Discussions of herbaceous plants and xeroriparian species are also included, although these groups have not been as extensively studied and many questions remain regarding the effects of surface flow on these taxa.

4.4 ADAPTATIONS OF WOODY PIONEER SPECIES

Recruitment

One of the primary modes of riparian plant adaptation to flooding is via reproduction. In much of arid and semi-arid North America, riparian forests are dominated by pioneer species that depend on fluvial processes for the creation of suitable seedling establishment sites. Most research on the regeneration of pioneer riparian species has focused on cottonwoods and willows, members of the *Populus* and *Salix* genera of the *Salicaceae* (willow) family. These species produce abundant small wind- and water-dispersed seeds in the spring or early summer (Braatne et al. 1996, Shafroth et al. 1998). For example, in Arizona, peak seed release of *P. fremontii* occurs during February through April or May (Fenner et al. 1985, Shafroth et al. 1998), while in Colorado, peak seed release of *P. deltoides* occurs in June, with a mean seed mass of 5.4×10^{-4} grams per seed (Friedman et al. 1995). Individual trees may produce hundreds of thousands to millions of seeds (Braatne et al. 1996, Mahoney and Rood 1998). Seeds are germinable when dispersed, and only remain viable for a few weeks after dispersal (Young and Young 1992). Similar to *Populus* and *Salix* species, *Tamarix* also produces large numbers of very small wind- and water-dispersed seeds (Brock 1994). However, *Tamarix* seeds are dispersed throughout the spring and summer (Warren and Turner 1975). Thus, the reproductive strategy of many riparian pioneer species is to saturate the environment with large numbers of seeds that are capable of germinating immediately upon arrival at a suitable site (Shafroth et al. 1995a).

Initial seedling establishment of pioneer riparian trees typically occurs on “fluvial disturbance patches,” which are moist and free of competing vegetation and plant litter (Auble and Scott 1998). Cottonwood seedlings are intolerant of shade and rarely establish within intact herbaceous vegetation (Friedman et al. 1995, Katz et al. 2001) or beneath forest canopies (Johnson et al. 1976). Seedlings of riparian *Populus* (Segelquist et al. 1993) and *Salix* (Horton and Clark 2001) species are also intolerant of desiccation, relying on the constant availability of moisture for survival. Because of these constraints, in any given year *Populus* and *Salix* seedlings usually become established adjacent to, or within, the active channel zone where bare moist substrate is available for colonization (Everitt 1968, Stromberg 1993c, 1997, Friedman et al. 1997, Galuska and Kolb 2002). Similar establishment patterns have been observed for seedlings of other riparian species, such as *Alnus tenuifolia*, *Salix laevigata*, and *S. lutea* (Russell et al. 2003); *Alnus oblongifolia*, *Fraxinus velutina*, and *Platanus wrightii*

(Stromberg 2001a, Galuska and Kolb 2002); and *Tamarix chinensis*, *Baccharis salicifolia*, and *Tessaria sericea* (Stromberg 1997).

In addition to regeneration from seed, many riparian species are also capable of asexual reproduction. The ability of damaged individuals to resprout in place (by roots and/or shoots) and the ability of water-dispersed fragments to become established may be important traits in flood-prone habitats (Karrenberg et al. 2002). Cottonwoods commonly resprout from fallen branches or toppled trees, and some species also propagate by root suckering or by the shedding of small branchlets (Braatne et al. 1996). Established *P. fremontii* and *S. gooddingii* seedlings can sprout vegetatively following flood-induced prostration and burial (Stromberg 1997), a pattern of "flood training" common to many riparian species. Shrub species such as *B. salicifolia*, *Hymenoclea monogyra*, and *T. sericea* propagate readily by stem-sprouting following flooding (Stromberg 1993c). *H. monogyra* also reproduces clonally by propagation from dispersed root and stem fragments (Stromberg et al. 1997a).

Fluvial Processes and Tree Recruitment

Seedlings that become established within the active channel or at low heights along the channel edge are very vulnerable to removal by subsequent flows (Stromberg 1997, Auble and Scott 1998, Rood et al. 1998). Longer-term riparian pioneer seedling survival and recruitment into older age classes occur on bare patches characterized by both adequate moisture and protection from lethal levels of physical disturbance (Auble and Scott 1998, Mahoney and Rood 1998, Rood et al. 1998). Such protected sites may occur in localized geomorphic situations such as the downstream ends of islands (Scott et al. 1997) but are more commonly found outside of the active channel area. Mahoney and Rood (1998) reviewed the literature on cottonwood seedling establishment and determined that successful recruitment occurred between approximately 60 and 150 cm above the base flow elevation. Presumably, the lower elevation limit is determined by erosional processes, while the upper limit results from the combination of seedling root elongation potential and the depth of the capillary fringe above the riparian water table.

Successful cottonwood recruitment depends on dynamic and episodic fluvial processes that create opportunities for seedling establishment on moist disturbed patches in safe geomorphic positions. The exact nature of the important fluvial effects depends on the geomorphic context, with different processes operating along meandering, braided, and bedrock streams (Scott et al. 1996, Cooper et al. 2003). Along meandering rivers the migration of river bends is accomplished by moderate flows that progressively erode banks on the outsides of bends and

progressively deposit sediment (point bars) on the insides of bends. Point bars provide seedling establishment sites that become increasingly protected from flooding as the river migrates farther away and as sediment deposition builds up the bar elevation (Everitt 1968, Nanson and Beach 1977, Bradley and Smith 1986). Where perennial meandering rivers occur in arid regions (e.g., in some alluvial mountain valleys, Cooper et al. 2003), these processes will be important in determining riparian vegetation patterns. However, many arid-region rivers are not meandering, and in these cases other processes will predominate.

Along braided rivers or sand-bed streams typical of many arid regions, seedling establishment of pioneer species tends to occur on the channel bed during a period of channel narrowing. Channel narrowing occurs when the stream abandons part of the former channel bed, making the surface available for vegetation establishment. The moist alluvium provides ideal conditions for cottonwood seedlings, and the absence of flood disturbance allows long-term survival. Narrowing can occur following flood-induced channel widening (Schumm and Lichty 1963, Friedman et al. 1996, Katz 2001), in association with climate conditions producing several years of low flow (Nadler and Schumm 1981), or as a result of upstream dams (Howe and Knopf 1991, Johnson 1994, Friedman et al. 1998, Shafroth et al. 2002). Riparian trees established during an episode of narrowing tend to be broadly even-aged, with establishment occurring over a period of several years to a few decades (Friedman and Lee 2002).

Where rivers are constrained in narrow valleys, flood deposition and scouring are the most important processes creating recruitment sites for pioneer species (Scott et al. 1996). In these settings, lateral channel movement may be prevented by bedrock, large boulder banks, or debris fans, and infrequent large floods can deposit sediment at high elevations on the floodplain (Nanson 1986, Scott et al. 1997, Cooper et al. 2003). Woody plants may also become established on low-elevation gravel bars, islands, and debris fans in canyons during multi-year droughts (Cooper et al. 2003).

Growth and Survival

Riparian plants occur in habitats subjected to extreme hydrologic conditions that can strongly influence plant performance and survival. Similar to riparian species in more humid regions, arid-region riparian plants may be subjected to occasional flooding. Woody riparian species exhibit a variety of adaptations to inundation and associated anoxia, including techniques to facilitate oxygen uptake, development of aerenchyma tissues that allow enhanced oxygen diffusion, development of adventitious roots, and metabolic adjustments (Kozlowski 2002). Not all species exhibit the same adaptations. For example, *P.*

fremontii, *S. gooddingii*, *P. sericea*, and *B. salicifolia* all develop adventitious roots in response to inundation, although *T. ramosissima* does not (Vandersande et al. 2001).

Drought stress is another factor that may strongly influence arid-region riparian vegetation. A variety of factors influence the ability of plants to survive drought. Not surprisingly, species differ somewhat in their tolerance of dry conditions. On the Bill Williams River in Arizona, *Populus* and *Salix* saplings appeared to be very sensitive to groundwater decline, while *Tamarix* saplings were more tolerant of dry conditions (Shafroth et al. 2000). Similarly, in greenhouse experiments *Tamarix* seedlings had higher survival than *S. gooddingii* seedlings in response to water table decline treatments (Horton and Clark 2001). Adult *Tamarix* on the Bill Williams and Hassayampa Rivers in Arizona was more physiologically tolerant of increased depth to groundwater than were adult *P. fremontii* and *S. gooddingii* (Horton et al. 2001). The latter two species experienced some mortality when the depth to groundwater was greater than 2.5–3 m, though the effect was most severe for *S. gooddingii*. Elevated salinity levels may compound the effects of drought stress, leading to mortality in salt-intolerant species (Vandersande et al. 2001). At elevated salinity levels in greenhouse experiments, rooted cuttings of *T. ramosissima* and *P. sericea* had higher water use efficiency than did *P. fremontii*, *S. gooddingii*, and *B. salicifolia*, although at the control salinity level no inter-species differences existed (Vandersande et al. 2001). Other factors that influence the ability of individual plants to survive dry conditions include plant age, rate and duration of groundwater decline, climate, and soil texture and stratigraphy (Shafroth et al. 2000).

Differences in plant tolerances to drought may reflect differences in the sources of water used for transpiration. For example, *Salix gooddingii* trees used only groundwater at sites on the San Pedro River in southeastern Arizona, while *P. fremontii* and *P. velutina* trees were also able to use precipitation-derived soil water at some sites (Snyder and Williams 2000). Reliance on groundwater makes *Salix* vulnerable to groundwater declines, whereas *Populus* and *Prosopis* may be able to survive periods of groundwater decline by relying on precipitation. *Tamarix* appears to possess significant physiological drought tolerance (Horton et al. 2001), which may include the ability to use water from unsaturated floodplain soils (Busch et al. 1992).

4.5 POPULATION PATTERNS OF PIONEER TREES

The presence of cohorts of adult pioneer riparian trees is almost always evidence of past flooding on undammed rivers, since physical disturbance and adequate moisture are requirements for initial seedling recruitment. However, because such cohorts may have established in association with very large but infrequent flood events (Friedman et al. 1996, Katz 2001, Friedman and Lee 2002), they may not be good indicators of the ordinary high water mark. For example, on the Arikaree and South Fork Republican Rivers in eastern Colorado, riparian forests are dominated by *Populus deltoides* and *Salix amygdaloides* adults that established following the flood of record in 1935 but that occur on geomorphic surfaces that have almost never been inundated since that year (Fig. 23) (Katz 2001). Similarly, large mature *P. fremontii* individuals occur on high flood terraces on the Escalante River in Utah, even though such surfaces are rarely inundated (Irvine and West 1979). Further, even if adult trees did become established in association with an ordinary high flow that occurred several decades previously, their locations may not accurately delineate the present ordinary high water level. That is, channel migration, incision, floodplain aggradation, or other geomorphic processes may change the spatial patterns of the

Figure 23. Mature *Populus deltoides* stand with a xeric understory on the Arikaree River, Colorado.

ordinary high water location over time. For example, large mature *P. fremontii* trees persist on a 3-m-high terrace on the Fremont River in Utah. This surface, which represents the pre-1896 floodplain, is no longer subjected to regular flooding due to channel incision (Everitt 1995). On the Hassayampa River in Arizona, floodplain elevation, distance to the river channel, and depth to groundwater all increased with increasing *Populus-Salix* stand age for trees up to 50 years old, suggesting pronounced changes in the relative positions of the floodplain and channel over time (Stromberg et al. 1991). In such cases, forest patterns may be relicts of past inundation levels and may not provide information about present hydrologic patterns.

On the other hand, the presence of seedlings, saplings, or "poles" of pioneer riparian tree species may be a good indicator of the level of ordinary high flows under the present geomorphic and hydrologic regime. That is, if no rare large floods have occurred within the past several years, then the spatial distribution of young to middle-aged pioneer trees could be a useful indicator of the extent of recent fluvial disturbance (Fig. 24). For example, on the Arikaree and South Fork

Figure 24. Hydromesic riparian vegetation at a perennial site on the San Pedro River, Arizona. The low floodplain forest is dominated by *Populus fremontii* and *Salix gooddingii* poles.

Republican Rivers in eastern Colorado, seedlings and juveniles of *Populus deltoides* and *Salix amygdaloides* were almost entirely confined to the active fluvial zone, although adults occurred over a much larger area (Katz 2001). Similarly, on the Hassayampa River in Arizona, young (10-year-old) *Populus* and *Salix* cohorts occurred close to the river channel, while older cohorts occurred farther away and at higher floodplain elevations (Stromberg et al. 1991).

Although the presence of woody riparian pioneer seedlings and saplings may be a good indicator of recent fluvial disturbance, their absence at a given location in the riparian zone does not necessarily indicate a lack of high flow. Seed germination and seedling establishment may be prevented by a variety of factors, even within a regularly flooded zone. The relative timing of high flows and seed dispersal may result in an absence of seedlings. That is, if peak flows occur earlier or later than the period of seed release for a given riparian species, dispersed seeds may not encounter suitable seed beds and germination will not occur. Even if high flows do coincide with seed dispersal, the shape of the flood hydrograph may preclude seedling establishment. Specifically, for optimal seedling establishment of riparian *Populus* species, flow discharge will decline gradually after seed germination in order for seedling roots to remain in contact with the receding moisture zone (Mahoney and Rood 1998). Seed germination and seedling establishment may also be prevented by factors such as temperature, substrate pH, and salinity (Siegel and Brock 1990, Shafroth et al. 1995b).

Seedlings that do become established in association with ordinary high flows generally experience high mortality rates. In arid-region riparian environments, a primary cause of seedling mortality is a lack of available moisture to plant roots. Although drought-intolerant seedlings of riparian pioneer species may become established and survive for a short period following flooding or a precipitation event, survival is unlikely if soil moisture levels are low and alluvial groundwater levels are out of reach of plant roots. For example, first-year seedlings of *Salix lasiolepis* on Schultz Creek in northern Arizona experienced close to 100% mortality, primarily as a result of desiccation during the summer months (Sacchi and Price 1992). Similarly, 75% of 37,000 first-year *P. wrightii* seedlings censused in Lyle Canyon in southeastern Arizona in 1983 died from desiccation in their first summer (Bock and Bock 1989). After one to two years, *Populus* and *Salix* saplings are still vulnerable to desiccation, and mortality rates of 100% have been observed in response to groundwater decline (Shafroth et al. 2000).

At the other extreme, floods are an equally important mortality agent for riparian seedlings. In experimental studies, *P. fremontii*, *S. gooddingii*, *P. sericea*, and *B. salicifolia* have been shown to possess significant inundation tolerance, surviving saturated soil conditions for 58 days with no reductions in

growth, while *Tamarix* was intolerant of this (Vandersande et al. 2001). However, flood-induced seedling mortality rates can be very high in natural settings. For example, *P. fremontii*, *S. gooddingii*, and *T. chinensis* seedlings that established following a 25-year flood on the Hassayampa River in Arizona had 96%, 96%, and 100% mortality following a 15- to 20-year flood that occurred two years later (Stromberg 1997). Flood-induced mortality is not restricted to seedlings; in 1981, a succession of two 35-year flash floods removed an entire cohort of 11-year-old *P. wrightii* saplings in Lyle Canyon in Arizona (Bock and Bock 1989).

Mechanisms associated with flood-induced mortality of riparian plants include the physical force of floodwaters (which results in stem breakage or mobilization of underlying sediments) and the physiological stress of prolonged inundation (Friedman and Auble 1999). Although often difficult to tease apart, these factors may operate alone or in tandem to reduce seedling numbers. For example, *Acer negundo* seedlings on the Gunnison River in Black Canyon of the Gunnison National Monument suffered significant mortality from extended inundation in 1995, though shear stress clearly influenced the spatial distribution of older individuals, with no established trees having survived shear stresses that exceeded the critical shear stress by more than 24 Pa (Friedman and Auble 1999). Burial effects may also be important, though many riparian species appear to be fairly tolerant of sediment deposition (e.g., *P. fremontii*, *S. gooddingii*, and *T. ramosissima* seedlings) (Levine and Stromberg 2001).

4.6 HERBACEOUS PLANT PATTERNS

Compared to woody species, herbaceous riparian species have received considerably less research attention, especially with regard to the effects of surface streamflow on plant patterns and dynamics. However, because herbaceous plants generally live for much shorter lengths of time than woody plants, herbaceous vegetation patterns may be more likely to reflect present (or recent) ecological conditions. Therefore, to the extent that herbaceous vegetation patterns in riparian systems reflect characteristics of surface flow, they have the potential to be useful indicators of recent inundation levels. Several studies have noted that individual herbaceous plant species tend to occur in specific locations or within particular "patch types" within the riparian zone. For example, species such as *Nasturtium officinale* (water cress) and *Veronica anagallis-aquatica* (water speedwell) are common in wet, stream-edge habitats in central and southern Arizona, while within-channel sandbars are more commonly dominated by *Polypogon monspeliensis* (rabbit's foot grass) and stream banks are often dominated by *Cynodon dactylon* (bermuda grass) and *Melilotus albus* (sweet clover) (Stromberg and Chew 1997, Stromberg et al. 1997b). Vegetation patch types that occur on higher alluvial surfaces, such as *P. velutina* woodlands and *P. fremontii-S. gooddingii* forests, usually support a different suite of herbaceous species (Stromberg et al. 1991, 1997b, Stromberg and Chew 1997). If such patterns could be related to specific streamflow characteristics, herbaceous plant distributions might be a reliable indicator of the ordinary high water level.

Although it is probably not realistic to document the inundation tolerances or responses of all herbaceous species present at a particular riparian site, the classification of plant species into functional groups that share ecological traits and tolerances is a useful approach in this context (Stromberg et al. 1996, Stromberg and Bagstad, in prep). Ecological characteristics of herbaceous plants that have been identified as important in riparian systems include longevity (annual, biennial, perennial), growth form (rhizomatous, caespitose, taprooted), reproductive mode (sexual vs. asexual), and competitive ability (Friedman et al. 1996, Stromberg et al. 1996, 1997b, Stromberg and Bagstad, in prep). Wetland indicator classes can also be used to designate plant functional groups (Reed 1988, Stromberg and Bagstad, in prep). The five recognized wetland indicator classes are based on the probability of species occurrence in wetlands and include Obligate Wetland (>99% frequency of occurrence in wetlands), Facultative Wetland (67–99%), Facultative (34–66%), Facultative Upland (1–33%), and Obligate Upland (<1%). Plant rankings are adjusted for different geographic regions and can be determined by accessing the U.S. Fish and Wildlife Service

web page or the USDA-NRCS Plant Database (Reed 1988, USDA-NRCS 2001, USFWS 2003). While these classes do not isolate the effect of flooding per se, in arid regions they do indicate the overall reliance of a species on supplemental moisture, which is likely to be well correlated with surface flow characteristics.

If riparian plants are classified into functional groups based on traits that reflect adaptation to flooding, the spatial distributions of such functional groups on a given floodplain might be helpful for identifying recent high water levels. For example, “hydromesic ruderals” (e.g., *Xanthium strumarium, Polygonum lapathifolium*, *Polypogon monspeliensus*) are disturbance-adapted herbaceous plants with relatively high moisture requirements that occur in riparian zones in Arizona (Stromberg and Bagstad, in prep). Such plants, by definition, are annuals or biennials with wetland indicator classifications of Obligate Wetland through Facultative Upland, meaning that they require more moisture than is normally provided by direct precipitation. The zone of dominance of hydromesic ruderals on the floodplain might therefore be indicative of the zone of regular flooding, while the point at which herbaceous dominance shifts to more xeric ruderals (e.g., *Acalypha neomexicana, Bouteloua aristidoides, Sisymbrium irio*) might indicate the limit of the regularly flooded zone (Fig. 25) (Stromberg and Bagstad, in prep)[*]. For perennial herbs, dominance by hydromesic rhizomatous or stoloniferous species (e.g., *Paspalum distichum, Cynodon dacytlon*) may be indicative of the zone of regular fluvial disturbance, since clonally reproducing plants may readily recolonize floodplain sites following flood disturbance (Stromberg 1993c) and may be better adapted to persist in the shade of young, dense cottonwood stands (Friedman et al. 1996). Of course, such relationships would need to be fine-tuned in order for such patterns to be used reliably as indicators of specific levels of surface flow, and additional research into the actual water sources (e.g., precipitation, surface flow, groundwater) used by specific herbaceous plant species would be needed.

[*] Also personal communication, J. Stromberg.

Figure 25. Mesoriparian vegetation at an intermittent site on the San Pedro River, Arizona. The hydromesic ruderal *Polypogon monspeliensis* dominates the active channel zone. The banks are dominated by *Tamarix* and *Baccharis salicifolia*.

4.7 XERORIPARIAN SYSTEMS

By far, most research on riparian ecosystems in the southwest has focused on those relatively hydric or mesic wetlands that occur on perennial and intermittent streams. Such hydroriparian and mesoriparian systems are characterized by sufficient moisture to support pioneer riparian trees or shrubs and hydromesic herbaceous species. However, most watercourses in the arid southwest are ephemeral and support a suite of xeroriparian species whose ecology and hydrologic relations are poorly understood (Fig. 26). Xeroriparian systems occur on streams that flow infrequently and where the water table is usually too deep to be accessible to plant roots. However, minor amounts of infrequently delivered supplemental moisture can produce detectable vegetation patterns on small ephemeral streams. Even slightly augmented moisture may allow for greater overall vegetation volume, height, or stem density compared to upland areas and/or the occurrence of unique xeroriparian species that are not present in uplands. Studies of xeroriparian vegetation are complicated by the fact that many species, including some community dominants, occur in both riparian and

Figure 26. Xeroriparian vegetation along a wash near Tucson, Arizona. The dominant plants are *Prosopis velutina*, *Celtis pallida*, and mixed cacti.

adjacent upland habitats (Bloss and Brotherson 1979, Warren and Anderson 1985, Leitner 1987, McArthur and Sanderson 1991), by the subtle effects of small changes in hydrologic conditions on plant distribution patterns or vegetation structure in and along dry stream channels, and by the scarcity of hydrologic data (e.g., gauge records) for small ephemeral streams.

Despite these difficulties a few published studies have identified distinct plant occurrence patterns in xeroriparian settings. Warren and Anderson (1985) found that plant distributions varied with drainage area along desert washes dissecting bajadas in Organ Pipe National Monument in Arizona. Certain species (e.g., *Cercidium microphyllum*) tended to occur both in smaller washes and in uplands, while others occurred only in medium-sized (e.g., *Ephedra nevadensis*, *Celtis pallida*, *Zizyphus obtusifolia*) or large (e.g., *Baccharis sarothroides*, *Hymenoclea salsola*) washes and not in uplands. Hupp and Osterkamp (1996) present similar data for the same geographic area. They report that on the smallest washes, upland plants (*Ambrosia deltoidea*, *Larrea tridentata*) occur on lower, middle, and upper parts of banks. Larger and wetter washes may support less-xeric species (e.g., *Chilopsis linearis*, *Acacia greggii*) on the lower parts of banks but upland species on the upper banks. However, larger and drier washes do not support these species, instead supporting plants with apparently lower moisture requirements (e.g., *Acacia constricta*) (Hupp and Osterkamp 1996). In a study of bajada vegetation in southwestern Utah, McArthur and Sanderson (1991) identified 14 species that tended to occur preferentially in small channels dissecting the slope surface (e.g., *Chyrsothamnus paniculatus*, *Encelia frutescens*, *Gutierrezia microcephala*), 3 that tended to occur in upland areas (*Acamptopappus sphaerocephalus*, *Krameria parviflora*, *Larrea tridentata*), and 13 that exhibited no distributional tendency (e.g., *Yucca brevifolia*, *Ambrosia dumosa*, *Ephedra nevadensis*, *Lycium andersonii*, *Opuntia* spp.).

While these studies provide important information about xeroriparian systems, they do not explicitly address the relationships between species distributions and surface flow characteristics. That is, there appear to be no published studies addressing the role of specific surface flows in influencing the reproduction, growth, survival, or spatial distributions of xeroriparian species. Although xeroriparian vegetation patterns likely reflect surface flow patterns quite strongly because of the inaccessibility of the water table at most xeroriparian sites, we do not know which kinds of surface flows (e.g., in terms of magnitude, frequency, stream power, geomorphic effectiveness, etc.) have the most pronounced impact. Without further research it may be difficult to use xeroriparian vegetation patterns as evidence for the ordinary high water mark on ephemeral streams.

4.8 INDIVIDUAL RESPONSE

Floods may produce both positive and negative effects on established plants. Positive effects of floods on arid-region riparian trees include higher growth rates and greater foliage area, stem basal area, and riparian forest patch width on rivers with higher flow volume (Stromberg 1993b, 2001b). These effects result primarily from augmented floodplain moisture levels produced by flood-induced replenishment of shallow alluvial aquifers, and possibly from the fertilization effects of sediment-laden flows (Stromberg 2001b). Floodwaters may also flush salts from floodplain soils, resulting in more favorable growing conditions for some species (Vandersande et al. 2001). Although growth rate may be a reliable indicator of flow volume at a site and may integrate hydrology over several years (which may be beneficial for the present purpose), it is unlikely to be a useful field indicator of ordinary high water, since within-site variations may not be detectable, and it is not easily measured during a single field visit.

The damaging effects of flood flows on established individuals include death and wholesale removal, or lesser impacts such as flood-training, burial, breakage, and abrasion. Large floods may scour riparian forests. For example, a large flood removed most of the riparian forest on Plum Creek in Colorado in 1965 (Friedman et al. 1996). Flooding on the Hassayampa River in Arizona removed 30% of the *Populus-Salix* forest, 35% of the *Prosopis* woodland, and 90% of the *B. salicifolia* shrub vegetation in 1993 (Stromberg et al. 1997a). Following non-lethal flood damage, many riparian plants sprout vigorously from stem bases or prostrated stems left in situ. Shrub species such as *B. salicifolia* are especially adept at this mode of recovery (Stromberg et al. 1997a). Often, the effects of past flooding are not visible at the ground surface, but excavation of tree and shrub stems will reveal repeated episodes of flood-induced prostration, burial by sediment, and resprouting (Everitt 1968).

There are several sources of visible evidence of recent flooding that could be used to help identify recent high flow levels. First, when floodwaters carry debris that can abrade standing stems, flood scars are often produced. Such scars will eventually “heal” and become covered by bark, making them visible only in stem cross-sections. However, if flooding has been recent, flood scars will still be visible and can provide an indication of the height of floodwaters and the spatial extent of inundation on the floodplain. Flood debris deposits can also provide evidence of the spatial occurrence of past flood flows. In general, larger floods will carry and deposit larger kinds of debris, such as whole trees, and such debris will persist for relatively long periods on the floodplain. Smaller flows will carry and deposit finer kinds of debris, including leaves and twigs, which persist for shorter periods of time following deposition.

4.9 IDENTIFYING THE ORDINARY HIGH WATER MARK: SUMMARY AND SYNTHESIS

Because of the close association between riparian vegetation and stream hydrology, there is considerable potential for using vegetation patterns to assist in identifying the ordinary high water mark in the arid Southwest. To this end, vegetative evidence can be considered for two cases: evidence of locations below the OHWM (Table 13) and evidence of locations above the OHWM or outside of the OHW zone (Table 14).

Several points become clear upon examination of these tables. First, the ecology of some riparian systems is not well understood, and these systems are therefore under-represented. In particular, very little has been published on xeroriparian systems, yielding only speculative entries in the tables. More information regarding the role of streamflow in influencing spatial and temporal patterns of xeroriparian species is needed before the observed patterns can be reliably used to indicate specific levels of surface flow. Also, mid- to high-elevation mixed deciduous forests have not been nearly as well studied as have the lower-elevation *Populus*-, *Salix*-, and *Tamarix*-dominated systems. While the higher-elevation riparian forests contain pioneer tree species (i.e. *Populus, Salix, Platanus*) whose ecology is relatively well understood, they also contain a variety of seral species with different life history traits and environmental tolerances. Efforts to understand the role of hydrology in influencing rates and patterns of ecological succession in these systems would provide helpful information for delineating areas beyond the ordinary high water level.

Second, many of the lines of evidence listed in the tables may be applicable beyond the specific settings addressed in the published examples. For example, fluvial marsh taxa should indicate locations below the OHWM in high-elevation systems, as well as in the low-elevation systems for which examples are provided. For each potential indicator listed, the likely elevation range (mid- to high elevation, low elevation) and riparian moisture type (Hydro-mesic riparian, Mesoriparian, Xeroriparian) for which it is applicable is provided. For cases where published examples are not listed, the potential indicators should be carefully tested.

Third, although analysis of the current scientific literature provides several potential vegetation indicators of the OHWM, in many (or most) cases this was not the purpose of the original research. Therefore, the use of specific indicators based on a single published source is probably not advisable. Rather, these findings should be taken as suggestions regarding the types of patterns that could

Table 13. Potential vegetative evidence of location below the ordinary high water mark.

Indicator*	Elev.	Rip. Type	Selected examples: Representative taxa	River	Source
Herbaceous plants: emergent or fluvial marsh taxa (All, HM)	L	HM	*Phragmites australis*, *Juncus* spp., *Carex* spp.,	Colorado River, AZ	Stevens et al. (1995)
	L	HM	*J. arcticus, Eleocharis palustris*	Green River, CO	Merritt and Cooper (2000)
	L	HM	*E. palustris, Agrostis stolonifera, Euthamia occidentalis*	Gunnison River, CO	Auble et al. (1994)
	L	HM	*Veronica anagallis-aquatica, Eragrostis pectinata*	Plum Creek, CO	Friedman et al. (1996)
	L	HM	*Scripus americanus, Paspalum distichum*	Hassayampa River, AZ	Stromberg et al. (1997a)
Annual herbs: Hydromesic ruderals dominant (All, HM)	L	HM	*Xanthium strumarium, Polypogon monspeliensis*	San Pedro, AZ	Stromberg (unpub. data)
Perennial herbs: Hydromesic clonal plants dominant (All, HM)	L	HM	*Poa pratensis, Aster hesperius*, *Carex* spp., *Juncus balticus*, *Equisetum* spp.	Plum Creek, CO	Friedman et al. (1996)
	L	HM	*Cynodon dactylon, Paspalum distichum*	Hassayampa River, AZ	Stromberg et al. (1993c)
Pioneer tree seedlings within active channel (All, HM)	H	HM	*P. wrightii*	Various, AZ	Stromberg (2001a)
	L	HM	*Populus, Salix, Tamarix*	Green River, CO	Merritt and Cooper (2000)
Pioneer tree seedlings above/beyond active channel (e.g., on floodplain, overflow channels) (All, HM-M)	L	HM	*P. fremontii* and *S. gooddingii* seedlings	Hassayampa River, AZ	Stromberg et al. (1993c)
Pioneer tree saplings and/or poles, on surfaces without mature individuals (All, HM-M)	H	HM	*Populus, Salix, Platanus* spp.	--	
	L	HM	*P. fremontii*, *S. gooddingii* saplings	Hassayampa River, AZ	Stromberg et al. (1991)
	L	HM	*P. fremontii, S. exigua, Tamarix* saplings	Escalante River, UT	Irvine and West (1979)
Bare mineral substrate, sparse vegetation (All, M-X)	L	M	Low herbaceous cover	S. Fk. Republican & Arikaree Rivers, CO	Katz (2001)
Xeroriparian species dominant(?) (All, X)	L	X	*Acacia constricta, A. greggii, Baccharis sarothroides, Hymenoclea salsola*	Sonoran desert washes	Warren and Anderson (1985)
	L	X	*Chrysothamnus paniculatus, Gutierrezia microcephala, H. salsola*	Mojave desert washes	McArthur and Sanderson (1991)

L = mid-low elevation, H = high-mid elevation, HM = hydro-mesic riparian, M = mesoriparian, X = xeroriparian.
* Parentheses indicate (elevation, riparian moisture type) in which the indicator is likely to be applicable.

Table 14. Possible vegetative evidence of location above the ordinary high water mark.

Indicator*	Elev.	Rip. Type	Selected examples: Representative taxa	River	Source
Annual herbs: Xeric ruderals dominant (L, All)	L	HM	*Berteroa incana, Bromus tectorum*, etc.	Plum Creek, CO	Friedman et al. (1996)
	L	HM	*B. tectorum*	Gunnison River, CO	Auble et al. (1994)
Perennial herbs: Clonal and non-clonal species co-dominant (All, HM)	L	HM	*Sporobolis cryptandrus, Heterotheca villosa, Agropyron* spp.	Plum Creek, CO	Friedman et al. (1996)
Perennial herbs: Non-clonal species dominant (All, HM)	L	HM	*S. cryptandrus, H. villosa,*	Gunnison River, CO	Auble et al. (1994)
Mature pioneer trees on surfaces without younger cohorts (All, HM-M)	L	HM	*P. deltoides*	S. Fk. Republican and Arikaree Rivers, CO	Katz (2001)
	L	HM	*P. fremontii, S. exigua, Tamarix*	Escalante River, UT	Irvine and West (1979)
Mature pioneer trees with xeric understory species (L, HM-M)	L	HM	*P. deltoides* overstory with *Chrysothamnus viscidiflorus, Sarcobatus vermiculatus, B. tectorum, Sporobolis airoides*	Green River, CO	Merritt and Cooper (2000)
Mature pioneer trees with seral or upland species (All, HM-M)	L	HM	*Populus* spp. with *Prunus virginiana*, *Cretaegus* spp.	Plum Creek, CO	Friedman et al. (1996)
	L	HM	*P. fremontii* with *Atriplex canescens, S. vermiculatus*	Fremont River, UT	Everitt (1995)
Late-successional species composition (H, HM-M)	H	HM	*Acer negundo, Abies concolor, A. galbrum, A. grandidentatum, Mahonia repens*	Various, ZNP, Utah	Harper et al. (1991)
Upland species dominant (All, All)	L	X	*Fouquieria splendens, Fagonia californica, Olneya tesota*	unnamed canyon arroyo, Sonora, MX	Leitner (1987)
	L	X	*F. splendens, Opuntia fulgida, Echinocereus engelmannii*	New River, AZ	Bloss and Brotherson (1979)
	L	X	*Acamptopappus sphaerocephalus, Krameria parviflora, L. tridentata*	Beaver Dam Slope, UT	McArthur and Sanderson (1991)

L = mid-low elevation, H = high-mid elevation, HM = hydro-mesic riparian, M = mesoriparian, X = xeroriparian.
* Parentheses indicate (elevation, riparian moisture type) in which the indicator is likely to be applicable.

be further studied and developed into reliable indicators of the ordinary high water mark.

Finally, examination of multiple vegetation indicators may be the best way to use vegetative evidence in attempts to delineate the OHWM in the field. That is, not all types of evidence may exist at all sites, making reliance on a single attribute problematic. Or vegetation patterns may be somewhat subtle or diffuse, making clear demarcation of the ordinary high water line difficult. If field investigators assess the preponderance of the evidence, rather than looking for single specific indicators, a stronger OHW signal will likely be detected.

4.10 CONCLUSION

Riparian vegetation is strongly influenced by fluvial processes. For many species, key ecological processes depend on the hydrologic conditions and geomorphic changes associated with floods, and this dependence leads to vegetation establishment patterns that may be useful in identifying the level of ordinary high water. However, straightforward equilibrium interpretations of the relationship between arid-region riparian vegetation assemblages and specific flood regimes are only appropriate in certain settings. In particular, such interpretations are potentially most useful for explaining the distributions of herbaceous species, and possibly short-lived shrubs, on perennial rivers in arid regions (Auble et al. 1994, Stevens et al. 1995). On intermittent and ephemeral streams, flooding may be very infrequent, leading to non-equilibrium relationships between vegetation patterns (particularly spatial distributions of long-lived trees) and surface flow conditions. In these situations, which comprise the majority of arid-region riparian zones, vegetation patterns may constitute evidence of past, but not present, hydrologic conditions or may most strongly reflect the influence of subsurface hydrology or other factors.

We can conduct successful hydrogeomorphic interpretations of arid-region riparian vegetation patterns if we are careful to consider site history and patterns of change over time. In the absence of extreme flooding within the last decade, the distributions of seedlings, saplings, and poles of pioneer riparian trees may be useful in determining the location of the ordinary high water level. In addition, herbaceous plant distributions may be useful in this regard, since the distributions of short-lived species can be expected to reflect recent ecological conditions. The spatial distributions of disturbance-adapted species with high moisture requirements may indicate the extent of recent fluvial disturbance, though more research is needed on this topic. Finally, the distributional limits of upland plant species that do not tolerate flood disturbance may provide some indication of the location of the zone beyond the ordinary high water level.

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14. ABSTRACT
The U.S. Army Corps of Engineers (Corps) delineates the jurisdictional extent of wetlands and other "Waters of the United States" (WoUS) under Corps and Environmental Protection Agency (EPA) regulations implementing Section 404 of the Clean Water Act (33 U.S.C. 1344). As part of this responsibility, Corps districts in the southwestern United States and elsewhere must delineate the extent of WoUS in arid areas, including arid-land stream channels. In non-tidal waters lacking adjacent wetlands, Corps jurisdiction extends to the ordinary high water mark (OHWM). Unlike wetlands, for which there are criteria for hydrology, soils, and vegetation specified in a national wetland delineation manual, there is no hydrologic definition of ordinary high water (OHW), and the identification of WoUS relies entirely on physical features of stream channels. This literature review investigates the climatic and regional conditions controlling hydrologic discharges in arid-land streams and the resulting physical features that develop within channels and floodplains. The review covers three main features associated with arid stream systems that might be useful for delineation purposes: hydrology, fluvial geomorphology, and vegetation. Based on the reviews, certain physical features were selected as potential OHWM indicators and were categorized by location above, at, or below the OHW line. To support the identification of OHW, these potential indicators are intended to be tested in selected locations across the Southwest to identify consistent and reliable indicators of the OHWM.

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