USING GEOLOGY TO IMPROVE FLOOD HAZARD MANAGEMENT ON ALLUVIAL FANS – AN EXAMPLE FROM LAUGHLIN, NEVADA[1]

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ABSTRACT: A study of the piedmont of the Newberry Mountains near Laughlin, Nevada, demonstrates that geologic information can improve the scientific basis of flood-hazard management on alluvial fans in desert areas. Comparison of geologic information against flood insurance rate maps (FIRMs) reveals flaws in conventional methods for flood hazard delineation in this setting. Geologic evidence indicates that large parts of the Newberry piedmont have been isolated from significant flooding for at least the past 10,000 years. This contrasts with existing FIRMs that include large tracts of nonflood prone land in the 100-year and 500-year flood hazard zones and exclude areas of indisputably flood prone land from the regulatory flood plain. From the basis of the geology, flood hazards on at least one-third of the piedmont are mischaracterized on the regulatory maps. The formal incorporation of geologic data into flood hazard studies on desert piedmonts could significantly reduce this type of discrepancy and substantially reduce the scope, hence cost, of more elaborate engineering studies and hazard mitigation strategies. The results of this study affirm the value of new Federal Emergency Management Agency (FEMA) recommendations for characterizing alluvial fan flood hazards and support an argument for mandating geological studies in the regulatory process.
(KEY TERMS: flood; piedmont; alluvial fan; geomorphology; flood insurance rate maps; geographic information systems.)

House, P. Kyle, 2005. Using Geology to Improve Flood Hazard Management on Alluvial Fans – An Example From Laughlin, Nevada. Journal of the American Water Resources Association (JAWRA) 41(6):1431-1447.

INTRODUCTION

Flood hazard management on desert piedmonts is particularly challenging. Desert piedmonts host a variety of complex ephemeral flow networks that convey high velocity flows through steep, alluvial channels and across steep, hydraulically and morphologically complex alluvial fans. Difficulties in characterizing floods in this setting are beset with a relative dearth of measured data on flow frequency and flow hydraulics. The situation can be further exacerbated by rapid urban and suburban growth, a common factor in desert areas throughout the world.

Many founding concepts of flood plain management are not easily transferred to desert piedmonts because they have arisen from studies of perennial channel and flood plain systems. Profound differences between physical characteristics of ephemeral desert channel systems and perennial streams require fundamental differences in the conceptualization of their respective flood hazards. In a lay sense, flow networks on desert piedmonts have many seemingly paradoxical characteristics: they infrequently convey flow but exhibit spectacular fluvial features; have complex, intricate, and diffuse channel networks and unconfined, broad flow swaths; and convey flows along steep, sometimes convex, slopes and not within obvious confined valleys.

Numerous studies have indicated that regulatory models for flood hazard assessment on desert piedmonts can produce erroneous results when they ignore geologic information (e.g., Baker *et al.,* 1990; Fuller, 1990; Pearthree, 1991; House *et al.,* 1991, 1992). This fact was formally stated by a National Research Council (NRC) panel charged with evaluating the overall problem (NRC, 1996). The present report describes a case study that illustrates the value of geologic data by quantifying discrepancies between modeled conceptions of flood hazards and the physical geological record on the piedmont of the Newberry Mountains near Laughlin, Nevada. The results of the research provide a strong affirmation of

[1]Paper No. 04152 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2005). **Discussions are open until June 1, 2006.**
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new FEMA guidelines for characterizing alluvial fan flood hazards and indicate that similar studies should be required, not merely recommended, in the regulatory process.

THE GEOLOGIC FRAMEWORK OF DESERT PIEDMONTS

Rivers, streams, and washes are fundamentally geological entities. Understanding their geological framework can help to better understand and characterize their attendant flood hazards. The geologic history of a desert piedmont has particular relevance to the modern distribution of flood hazards because it contains a mosaic of geologic deposits and related geomorphic surfaces that chronicle a long term history of flooding (hundreds to tens of thousands of years).

Piedmont is the descriptive (nongenetic) term for a relatively broad, generally low relief area at the base of the mountain front that slopes toward the center of the valley. Piedmonts are composed mostly of sediment (alluvium) shed from adjacent highlands by streamflows or debris flows, but they often include complex mixtures of eroded bedrock and various types of surficial geologic deposits and landforms, including active and inactive alluvial fans, river terraces, pediments, sand dunes, sand sheets, spring mounds, and lacustrine beach platforms, all with potentially widely varying ages. The particular array of landforms and related deposits on a given piedmont is dictated by topography, physical setting and the regional tectonic and climatic history. Basic awareness of these types of landforms and their associated deposits can improve piedmont flood hazard characterization by establishing a geologic context.

Alluvial Fans

Alluvial fans are the most common geological features on desert piedmonts and are usually the focus of piedmont flood hazard management. They have been the focus of study by geologists for more than a century, resulting in a wealth of scientific literature concerning their physical characteristics and their geological significance (c.f., comprehensive summary in Blair and McPherson, 1994). In the last 25 years, descriptions of alluvial fans and desert piedmonts have appeared in the context of engineering and flood plain management because of the growing awareness of the problem of piedmont flooding (e.g., Dawdy, 1979; French, 1986, 1987; NRC, 1996, FEMA, 2000).

Geomorphology of Alluvial Fans

Alluvial fans are created by combined processes of sediment erosion, transport, and deposition by streamflows, debris flows, or both. They are composed of sediments ranging in size from silt to boulders and are constructed over time by net deposition of alluvium conveyed through a network of distributary channels and broad areas of unconfined flow. Fans form where a stream channel crosses a transition from a relatively steep and confined channel to a less confined, but rarely less steep, channel where the area of flow can expand relatively freely. Flow processes that create alluvial fans range from sediment-laden water flows to highly viscous, sediment-charged debris flows. Many fans are composed of deposits from both processes (composite fans), and some are composed largely of deposits from one or the other (streamflow fans or debris flow fans) (NRC, 1996; Blair 1999a,b).

Alluvial fans often resemble extended fans, or conic segments when viewed on maps or aerial photographs (Figure 1) (Bull, 1964, 1977); however, the gross planimetric geometry of fans can range from relatively ideal, or classic, fan shapes to more irregular forms bounded laterally by adjacent fans, bedrock outcrops, and relict fan surfaces, among other possibilities. Even when their shape is elegantly expressed, most alluvial fans are comprised of a mosaic of alluvial deposits that record the evolution of the landform over periods of time in excess of several 100,000s of years (e.g., Ritter *et al.,* 1993). Most piedmonts in the western United States, for example, are such composites (Peterson, 1981).

The position, morphology, and extent of alluvial fans generally represent the relationship between the delivery of sediment to the fluvial system and the ability of the system to transport that sediment (Bull, 1979). Large scale changes in regional climate have a profound influence on this balance and thus influence the development of alluvial fans (e.g., Bull, 1991). Tectonic activity, base level changes along a master axial stream, or lake level changes can also have major impacts on alluvial fan dynamics (Ritter *et al.,* 1995).

Terminology

A wealth of terminology exists for piedmont landforms (e.g., Peterson, 1981). Various, more specific definitions of alluvial fans and desert piedmont landforms have been presented in both engineering and geological studies of the problem of piedmont flooding (e.g., Hjalmarson and Kemna, 1991; French *et al.,* 1993; Field and Pearthree, 1997). More recently, FEMA (2000, p. 6; and NRC, 1996 pp. 6-7) has formally defined an alluvial fan as "... a sedimentary deposit located at a topographic break such as the base of a mountain front, escarpment, or valley side, that is composed of streamflow and/or debris flow sediments and has the shape of a fan, either fully or partially extended." This definition is accompanied by physically based distinctions between active and inactive alluvial fans and their respective flood hazards. These distinctions reflect the ranges of fan geometry and geomorphology on most piedmonts by emphasizing different types of flooding characteristic of active and inactive fans, including stable channel flooding (inactive fans), sheet flow (active fans), debris flow (active fans), and unstable flow path flooding (active fans). Further, the term 'flood plain' is used in this report largely in the regulatory sense of 'areas subject to flooding' – the application of this term to alluvial fans is not common in geological parlance. For the sake of consistency, the regulatory terminology is used in this report.

THE PROBLEM OF FLOODING ON DESERT PIEDMONTS

Flooding on active alluvial fans is problematic because high velocity, sediment laden floodwaters may follow multiple paths simultaneously (e.g., French, 1987). The flow paths may shift position during floods or even during low and moderate flows between large floods, further compounding the problem. Flooding can also occur as broad, largely unconfined shallow flow swaths that inundate large areas. The location of these types of flows can also shift during and between large flood events. In addition to flow path uncertainty, alluvial fan floods also involve overall high flow velocities, variable depths, and large amounts of sediment erosion, transport, and deposition. Thus, compared with flood hazards associated with typical river flood plain systems, alluvial fan floods are particularly hard to characterize accurately using conventional engineering methods of flood hazard assessment. Stable alluvial channels on desert piedmonts have obvious flow path predictability but often have complex hydraulic characteristics akin to flow paths on fans.

Evaluating Alluvial Fan Flood Hazards – The Regulatory Approach

The mobility of channels on alluvial fans and the propensity for relatively broad inundation by high velocity flows have presented problems for conventional flood hazard management techniques (cf., NRC, 1996, for more background). The first formal regulatory approach adopted by FEMA for characterizing alluvial fan flood hazards was based on a straightforward model presented by Dawdy (1979). This model invoked the explicit assumption of complete uncertainty, or equal probability of channel location on active alluvial fan surfaces (Dawdy, 1979; FEMA, 1990). The applicability of this model was limited by its overly general treatment of hydraulic processes typical of alluvial fans (e.g., French, 1986, 1992), and its weak consideration of the wide variability and complex geomorphology of alluvial fans and desert piedmonts (Baker *et al.,* 1990; Fuller, 1990; Pearthree, 1991; House *et al.,* 1991, 1992).

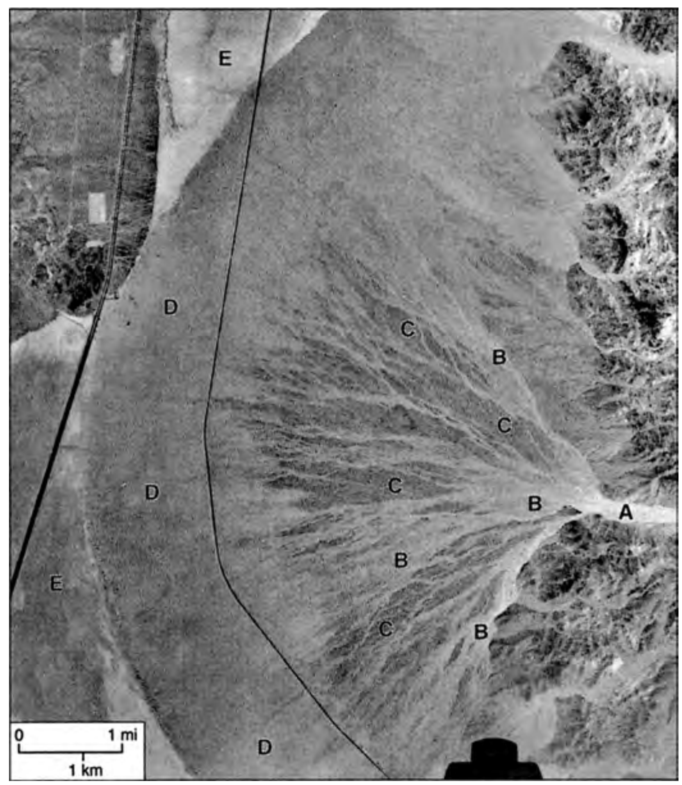

Figure 1. Aerial Photograph of an Exceptionally Well Formed Alluvial Fan in Ivanpah Valley, Nevada, and California. Evident in this photograph are: (A) overall fan shape – a single trunk channel that becomes (B) a complex distributary flow network with channel and sheetflow zones; (C) a series of relict, inactive, subplanar fan surfaces that appear darker because of desert varnish accumulation; (D) a lower fan apron of windblown sand and silt intermixed with shallow sheetflow deposits; and (E) the dry lake, or playa to which the fan drains.

Persistent concerns about the problem of accurately characterizing flood hazards on alluvial fans ultimately led FEMA to charge the National Research Council to convene a panel of experts to develop a set of recommendations for improving the regulatory approach (NRC, 1996). Many of the recommendations from the NRC panel involved the inclusion of geological data and concepts into the early stages of the regulatory process, thus setting the stage for a vast improvement in guidelines for piedmont flood hazard characterization (FEMA, 2000).

THE ROLE OF GEOLOGY IN PIEDMONT FLOOD HAZARD ASSESSMENT

As geologic entities, alluvial fans are chronicles of the cumulative effects of streamflow and flood events over thousands to hundreds of thousands of years. The uncertainty about the channel and flow swath positions over time and the need to discriminate between active and inactive portions of alluvial fans support the rationale for using geologic information to improve piedmont flood hazard delineation. On most desert piedmonts, significant and complex variations in active fan morphology and the extent and distribution of inactive fan surfaces can impart strong influences on the extent and nature of flooding.

The geologic approach to piedmont flood hazard assessment described here closely adheres to the three-step approach to alluvial fan flood hazard determination recently outlined by FEMA (2000):

1. Recognition and characterization of the alluvial fan landform.
2. Defining the nature of the alluvial fan environment and the location of active erosion and deposition.
3. Defining and characterizing areas of "100-year" alluvial fan flooding.

These guidelines are based in part on the following tenet: "… the area of deposition on an alluvial fan shifts with time, but the next episode of flooding is more likely to occur where the most recent deposits have been laid down than where deposits of greatest antiquity occur" (NRC, 1996, p. 62). Steps 1 and 2 are explicitly based on geologic interpretation. Step 3 requires detailed topographic, hydrologic, and hydraulic analyses that are the domain of technical engineering studies required to ultimately develop flood insurance rate maps (FIRMs). However, the geologic information compiled in Steps 1 and 2 offers an important and essential perspective on the information sought in Step 3.

THE VALUE OF GEOLOGIC MAPPING

Detailed geologic mapping integrates observable physical evidence for both the cumulative effects of past floods and the nonoccurrence floods over a range of time scales. Geologic maps compiled with a focus on flood hazards do not supplant conventional flood-risk maps because they do not contain specific information about flow depths, velocities, or probabilities. They do, however, provide a documentation of the physical record of floods, and a delineation of the extent of existing flood hazards. Geologic studies thus constitute an important reality check and a degree of scientific substantiation for flood plain management decisions.

A variety of maps are potentially relevant to piedmont flood hazard evaluation. Many available geologic maps emphasize bedrock geology and only depict surficial geologic deposits very generally. This type of geologic map has only minimal value for flood-hazard characterization. The overall applicability of a geologic map of this type can be inferred from the number and spatial detail of surficial map units. Soil maps (available through the National Resource Conservation Service) are available for many areas, and these can have substantial merit in flood-hazard studies. They are typically more detailed than the types of geologic maps described previously, but often differ in detail and intent from surficial geologic maps. Soil maps depict the spatial distribution of various types of soils, and not geologic deposits of specific ages that are associated with specific surface processes. Occasionally, soil units and surficial geologic units are one in the same, but the different soil types may not directly correspond to distinctly different aged types of surficial geologic deposits. Thus, detailed surficial geologic maps are the most useful because they emphasize deposit type (hence process) and surface age, both of which are key to interpreting the map in the context of flood hazards.

THE STUDY AREA

Laughlin, Nevada, is located on the west bank of the lower Colorado River in the extreme southern tip of the state near its conjunction with Arizona and California (Figures 2 and 3). Laughlin is approximately 160 km south of Las Vegas, immediately across the Colorado River from Bullhead City, Arizona, and 50 km north of Needles, California. It is in the lower Colorado section of the Sonoran Desert and has a warm, arid climate. Maximum temperatures above 48°C occasionally occur in the summer. Laughlin is a casino gaming center and most of the casino strip occupies an abandoned flood plain terrace of the Colorado River. The city is protected from Colorado River floods by a series of dams, including Davis Dam, which impounds Lake Mohave about 3 km up the river from the casino strip. Large parts of the residential section of town are located on the piedmont of the Newberry Mountains.

The Newberry Mountains are underlain by predominantly granite bedrock (Faulds *et al.,* 2004). The granite is coarsely crystalline, weathers easily, and provides copious amounts of sediment to the piedmont drainages. The range is extremely rugged and sparsely vegetated overall. Local relief is high (up to 1,200 m) and drainages emanating from the Newberry mountain front follow steep courses (typical gradients 3 percent to 5 percent) to the Colorado River.

Precipitation Trends and Related Flooding

The largest floods on the Newberry piedmont result from intense, short-lived local precipitation commonly associated with isolated summer thunderstorms and typically less intense, but more prolonged, regional-scale precipitation from dissipating tropical storms (Gatewood *et al.,* 1946; Durrenberger and Ingram, 1978; Smith, 1986; Webb and Betancourt, 1992).

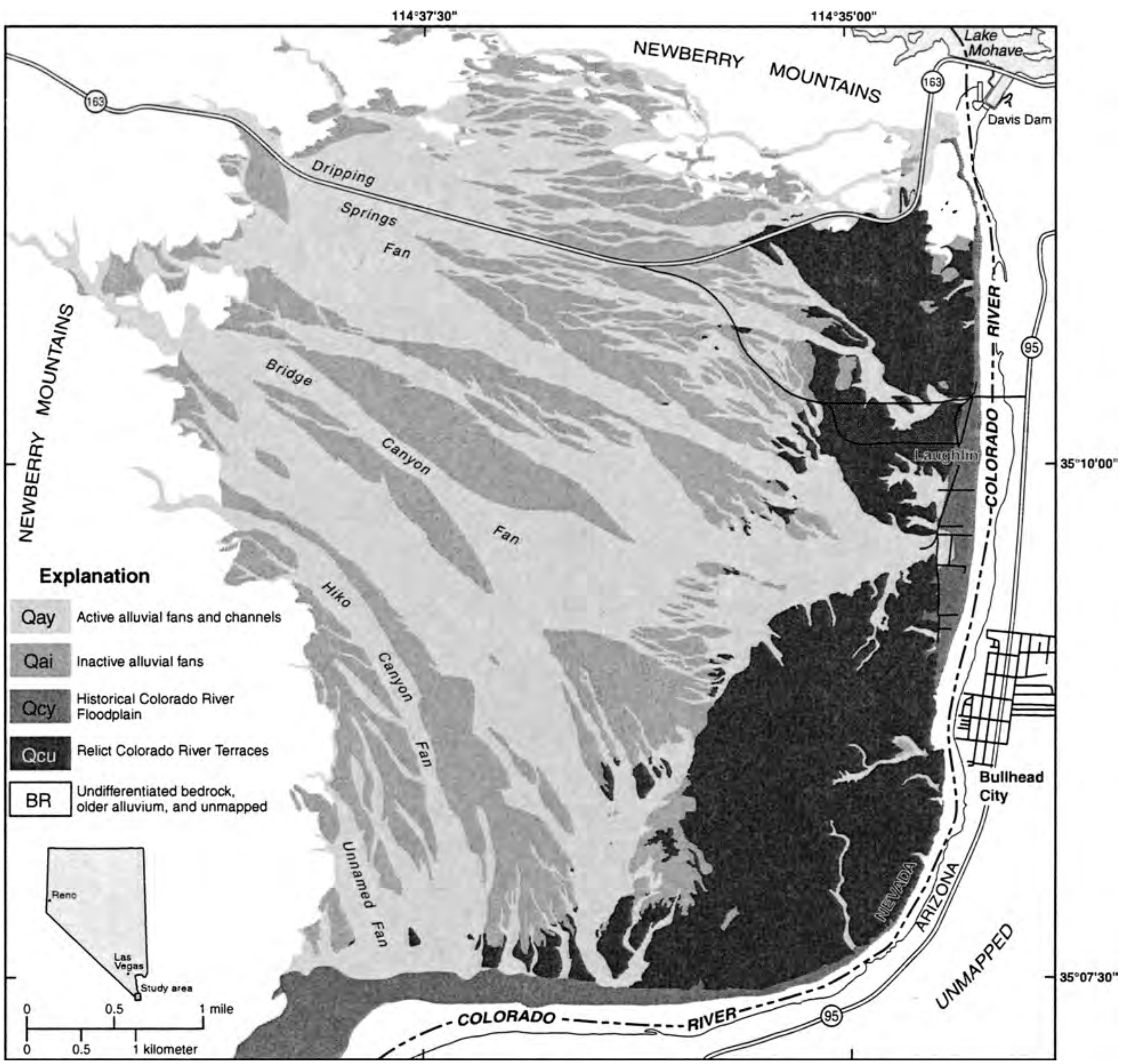

Figure 2. Location Map and Generalized Geologic Map of the Newberry Piedmont.

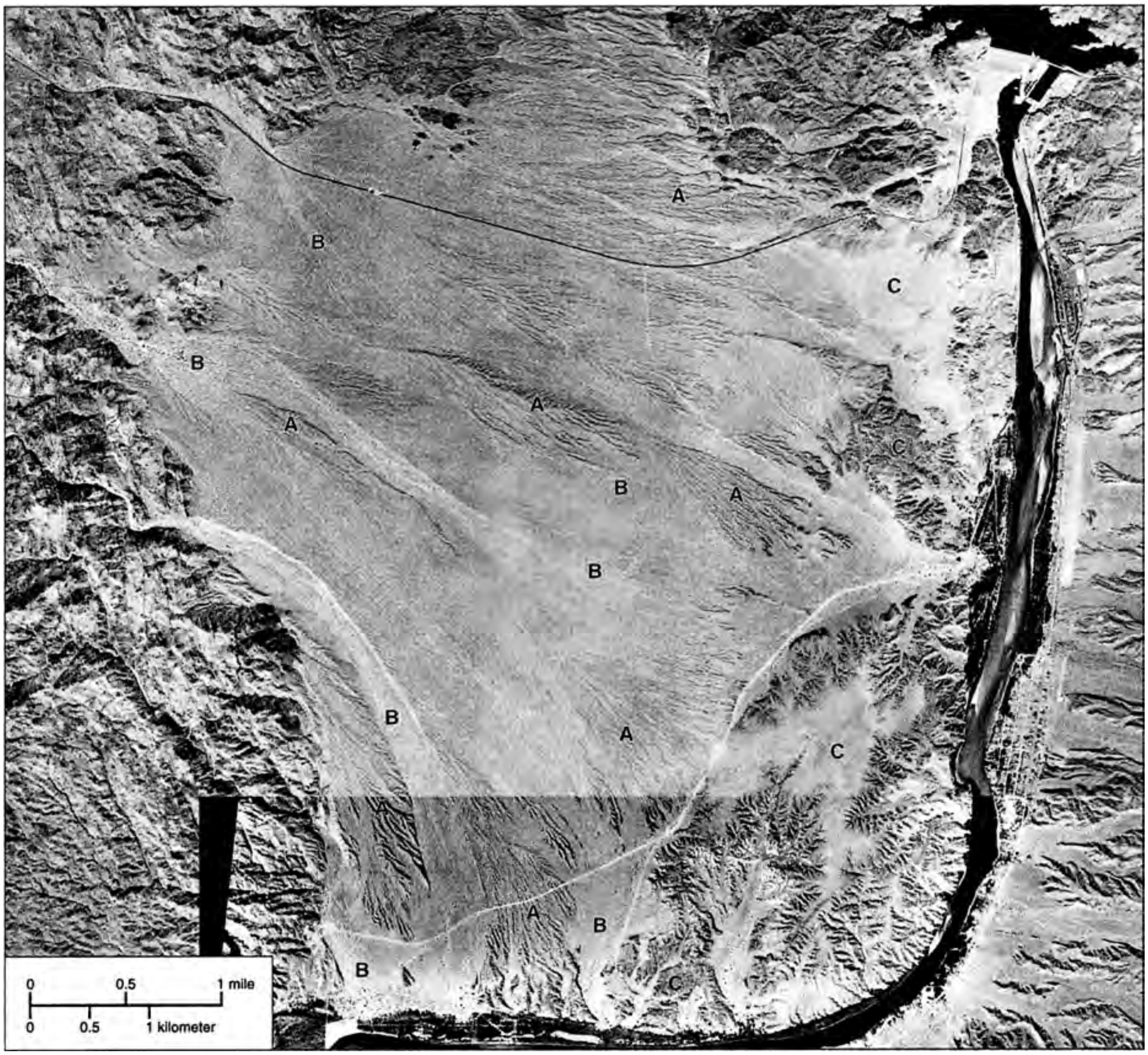

Figure 3. A 1954 Aerial Photograph Mosaic of the Newberry Piedmont. Area in photo is approximately the same as area shown in Figure 2. Easily discernible in this image are: (A) corrugated, high standing inactive fan remnants; (B) active fans and washes; and (C) relict Colorado River terrace treads.

Winter storms occasionally deliver significant precipitation to the region, but are less likely to involve intense, flood-producing bursts of precipitation characteristic of warm season storms.

Dissipating tropical cyclones present the greatest potential for regional flooding in the area. The month of September 1939 offers an extraordinary case in point in which a sequence of three such events resulted in severe and damaging floods from Imperial Valley, California, to Boulder City, Nevada. Regional precipitation data indicate that the Laughlin area could have received at least 102 mm of precipitation in the period September 3 to 7; 50 to 75 mm over the period September 8 to 13, and 50 to 75 mm in the period September 23 to 26 (Gatewood *et al.,* 1946, Plates 2 to 4). Under these conditions it is possible that the principal drainages in the Laughlin area experienced simultaneous, possibly multiple, large floods.

The September 1939 events stand as the most extreme episode of regional precipitation and related flooding recorded in the lower Colorado River area. They resulted from anomalous atmospheric circulation patterns associated with positive El Niño-Southern Oscillation conditions, which are conducive to the incursion of East Pacific tropical cyclones into the Southwest (Smith, 1986; Webb and Betancourt, 1992).

GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

Damaging flash floods in Laughlin occur on alluvial fans and ephemeral washes on the southeast piedmont of the Newberry Mountains (referred to here as the Newberry Piedmont) (Figures 2 and 3). The Newberry Piedmont extends from the mountain front to the Colorado River. It is comprised of a complex mosaic of alluvial deposits and ancient Colorado River terrace deposits that represent the cumulative effects of cycles of erosion and deposition by the river and its tributaries. The most extensive surficial deposits are Quaternary in age (approximately the last 1.8 million years), but older alluvial deposits are exposed locally in deep wash cuts and river bluffs. Many alluvial deposits on the piedmont represent the culmination of phases of climatically induced aggradation followed by isolation of large areas through tributary entrenchment in response to base-level lowering along the Colorado River (Metzger and Loeltz, 1973; Bull, 1991; Faulds and House, 2000; Faulds *et al.,* 2004; House *et al.,* 2005). Other deposits reflect periods of relative stability followed by downcutting.

The presence of large Pleistocene Colorado River terraces on the lower piedmont and a series of correlative, high standing, inactive tributary alluvial fan surfaces impose major topographic constraints on the distribution of active alluvial fans and incised stable channels. The active alluvial fan and channel complexes below the four major washes on the piedmont (from north to south: Dripping Springs Wash, Bridge Canyon Wash, Hiko Springs Wash, and Unnamed Wash) (Figure 2) have distinctly different and complex morphologies, none of which resemble classic alluvial fans, except locally. Most of the fan complexes have irregular and elongate shapes controlled by the distribution of higher and older surfaces. The effect of these confining surface remnants combined with large, flat Colorado River terrace remnants creates a series of topographic constraints that reconcentrate flow from the fan complexes on the upper and middle piedmont into a series of stable tributary drainage channels on the lower piedmont.

Tributary alluvial deposits on the piedmont are composed of subangular to subrounded, predominantly granitic sand and gravel. The deposits are moderately well sorted, obscurely to well stratified, and predominantly clast supported. The combination of these characteristics indicates that sediment charged streamflows are the principal depositional mechanism. Debris flow deposits are rare except within steep drainages confined to the mountain interior watersheds. Deposits of the Colorado River are composed of mud, sand, and gravel. The texture, structure, and composition of the river deposits contrast sharply with the tributary alluvium. They are composed of exotic (far traveled) muds, sands, and gravels that are very well sorted and stratified. The Colorado River sands and gravels are also very well rounded.

METHODS OF MAP COMPILATION

The core of this analysis is a detailed geologic map of bedrock and alluvial deposits in the Laughlin area (Faulds and House, 2000; Faulds *et al.,* 2004). The map spans all or part of three 7.5 ft. quadrangles, including Davis Dam, Arizona-Nevada (all); Bridge Canyon, Nevada (east part); and Mt. Manchester, Nevada-California-Arizona (extreme north part). The geologic map was prepared using conventional geological field studies and aerial photograph analysis. Field observations of stratigraphic relationships and the physical characteristics of alluvial deposits were initially compiled on maps and photos, and the final line work was compiled at 1:24,000 on a composite of the three U.S. Geological Survey topographic maps using a PG-2 stereo plotter. The manual linework was digitized and converted to an attributed geologic information system (GIS) database.

Mapping Criteria

Alluvial deposits on desert piedmonts are associated with distinct geomorphic surfaces. A geomorphic surface is a mappable landscape element formed during a discrete time period by identifiable geologic processes; geomorphic surfaces have distinctive material composition, topographic features, soil profiles, weathering characteristics and stratigraphic relations that can be used to differentiate them by relative age (modified from Bull, 1991, p. 51). Geomorphic surfaces are often associated with contemporaneous geologic deposits, but this is not always the case – this is why the distinction is important. Time correlative geomorphic surfaces were abandoned by active fluvial processes at the same general point in time, but the underlying deposits are not necessarily the same age. In other words, younger surfaces can be associated with older deposits, for example, if the older deposits have been exhumed by erosion. Thus, surface age represents the minimum deposit age, or the duration which the extant deposit surface has been isolated from active constructional processes and exposed to uninterrupted weathering and soil development (Peterson, 1981).

Alluvial geomorphic surfaces on the Newberry Piedmont can be separated by relative age and classified as ‘active’ or ‘inactive’ from the basis of observable physical characteristics. Numerous investigators have established sets of useful guidelines for mapping alluvial fans, both in the context of interpreting Quaternary geology and evaluating flood hazards (e.g. Christenson and Purcell, 1985; Dohrenwend, 1987; Bull, 1991; Field and Pearthree, 1997). Compilation of geologic data for piedmont flood hazard assessment requires a specific emphasis on surface characteristics whose development is precluded by sediment entrainment, transport, and deposition. The following criteria apply in varying degrees to the Newberry Piedmont (cf., Field and Pearthree, 1997, Table 1, for comprehensive reference list).

Stratigraphic Relationships. Basic stratigraphic relationships among and between different geological units of known or estimable ages can be used to establish a relative age framework. The stratigraphic and geomorphic continuity between different piedmont alluvial deposits and river alluvium in the Laughlin area helps evaluate relative ages of the geomorphic surfaces.

Topography. Different aged alluvial surfaces commonly exhibit topographic separation and inset stratigraphic relations. Examination of field relations and aerial photos can help relate the topographic separation to relative degrees of connectedness to active alluvial fans and channels. Depth of channel dissection on a given alluvial surface is another topographic property that generally increases with increasing surface age. Inactive surfaces are often associated with networks of incised, stable channels.

Drainage Pattern. Active alluvial surfaces have obvious distributary or anabranching drainage patterns or are distinct single channels. Inactive alluvial surfaces are characterized by dendritic, or tributary drainage patterns that reflect progressive erosion by local runoff. As noted above, tributary drainage networks on inactive fan surfaces often have incised channels that generally increase in depth with increasing relative surface age.

Soil Development. Over time, inactive alluvial surfaces progress through a predictable series of physical and chemical changes that result in soil horizon development in the upper 1 to 2 m of the deposits (Birkeland, 1999). The type and magnitude of changes that occur are related to the duration of subaerial exposure and absence of active fluvial processes. The most useful changes for evaluating surface age in desert soils occur in the soil B-horizon and include development of soil color and discernible soil structure (Bw horizon), carbonate (or other salt) accumulation (Bk or similar horizon), and accumulation of translocated clay (Bt horizon) (Bull, 1991). Soil carbonate development is typically the master criteria for establishing general surface ages on piedmonts in the western U.S. (e.g., Gile *et al.,* 1966; Machette, 1985).

Surface Morphology. Progressive flattening of depositional topography, formation of desert pavements, development of rock varnish, and disintegration of surface rocks are time dependent changes that occur on abandoned alluvial surfaces in arid regions (e.g., McFadden *et al.,* 1998; Wells *et al.,* 1995). The relative strength of these characteristics reflects varying amounts of time, and they are particularly useful criteria for establishing relative age relationships (e.g., Bull, 1991).

SURFICIAL CHARACTERISTICS OF THE GEOLOGIC UNITS

Surficial geologic deposits that comprise the Newberry Piedmont can be divided on the basis of deposit type and relative age. The primary distinction is between deposits of tributary and Colorado River alluvium. Within each of these divisions are at least three major age related divisions associated with discrete episodes of aggradation and dissection during the Pleistocene and Holocene epochs. The active tributary alluvial deposits on the piedmont are mapped as Qay, and the relict, inactive alluvial surfaces are mapped as Qai. Colorado River deposits are divided into Qcy (the Holocene flood plain) and Qcu (all older river deposits, undivided). The Qai tributary units are graded to past, higher levels of the Colorado River, which are recorded as the Qcu deposits and landforms.

Inactive, Intermediate Aged Alluvial Surfaces – Qai and Qcu

The primary distinguishing characteristics of the Qai surfaces are erosional topography and topographic separation from adjacent, lower active surfaces. In aerial photographs, relict Qai surfaces are distinctly corrugated in appearance because of the presence of relatively deeply incised, and laterally confined local drainages (e.g., Figures 2 and 3). In the field they are associated with locally well developed desert pavements and rock varnish, soils with well developed color and carbonate horizons, and locally deeply weathered clasts. Because of the erodibility of the source rock, the inactive fan surfaces are extensively degraded from planar remnants to deeply corrugated, irregular surfaces. Although these areas are undergoing active fluvial erosion, it is occurring on a local scale and is not connected to fluvial activity of a principal drainage.

All of the Qai units on the Newberry piedmont are graded to levels of the Colorado River that are progressively higher above the river with increasing age (Qcu). The oldest Qai units overlie deposits of Qcu that are no younger than about 35,000 years (Blair, 1996), and may range to as old as 250,000 years or more (Bell, 1978). Younger Qai units are graded to progressively lower terrace levels and are similarly isolated from the active systems. The Qcu surfaces are distinctly planar, have darkly varnished exotic clasts (far traveled river gravels), moderate to strongly developed soil carbonate horizons, and sparsely developed tributary drainages. Specific numerical ages of the deposits are not known, but soil development, topographic position, and relationships with river terraces all suggest that they are no younger than latest Pleistocene (approximately 11,000 years). Thus, a cautiously conservative interpretation is that the Qcu and Qai deposits are all of Pleistocene age. This distinction forms the basis for geologically characterizing the units as nonflood prone and is consistent with recommendations of NRC (1996) and FEMA (2000).

Active Tributary Alluvial Surfaces – Unit Qay

Active alluvial surfaces constitute the flood-prone areas on the Newberry piedmont and are mapped as Qay. The suite of Qay deposits are graded to historical terraces that pre-date Hoover and Davis dams, and to the modern flood plain of the lower Colorado River (Qcy) that has formed in the post-dam era. Unit Qay can be divided into at least two subunits that reflect slightly different ages or source area characteristics, but this distinction is not made in this study to ensure the broadest extent of the geologic piedmont flood plain. Typical aerial photo patterns associated with Qay are clear in Figure 3.

Areas associated with Qay units are subject to frequent sediment entrainment, transport, and deposition. Types of Qay fluvial environments include: active alluvial fans, diffuse sheetflow zones, broad braided channels, and both distributary and tributary networks of stable channels. Surface characteristics of Qay include fresh to slightly muted depositional topography, distinct vegetation assemblages, and minimal surface dissection except locally. Surface stability indicators including soil development, desert pavement, and rock varnish are either nonexistent or weakly developed. Large tracts of Qay are probably no older than a few hundred years, as they are inundated most frequently. The Qay distribution reflects areas of the most vigorous fluvial activity. Parts of Qay are reworked and redistributed in all flow events, regardless of their magnitude. In this study, all Qay units are considered flood prone and comprise the entirety of the flood prone area.

COMPARING THE GEOLOGIC AND REGULATORY MAPS

In the following comparisons, the Newberry Piedmont is defined as the entire area enclosed by mappable alluvial deposits between the southeast face of the Newberry Mountains and the Holocene flood plain of the Colorado River. This includes all tributary alluvial deposits and ancient Colorado River terraces in addition to small bedrock outcrops. The Newberry Piedmont spans 5,078 hectares (ha), and includes many active alluvial deposits not depicted on the regulatory maps. The surficial map units comprising the piedmont were generalized into flood prone (active alluvial fan or stable channel; Qay) and nonflood prone (inactive alluvial fan, stream terrace, or high bedrock outcrop; Qai, Qcu, and unmapped, respectively) for direct comparison with the regulatory flood zones (Figure 2). The flood prone area defined this way is herein called the geologic piedmont flood plain (GPF) and the nonflood prone part of the piedmont is termed the NGPF (for 'not geologic piedmont flood plain').

Digital flood insurance rate maps (DFIRMs) for the Newberry Piedmont have been previously developed using conventional methods and procedures promulgated by FEMA (2000). These data were obtained from the Clark County Regional Flood Control District (CCRFCD, 2002) for this study. Herein, the regulatory flood zones are collectively termed the regulatory piedmont flood plain (RPF), which is divided into the 100-year RPF (Zones A, AO, and AE) and the 500-year RPF (Zone X). The specific regulatory definitions of these zones and related subdivisions are listed in Table 1 (modified from FEMA, 2004). Areas of the piedmont that are excluded from the RPF are termed NRPF (for 'not regulatory piedmont flood plain').

This generalization of the geologic data into the GPF and NGPF assumes that the extent of presently active alluvial surfaces reflects the integrated effects of all floods that have impacted each system over the last several thousands of years, and that all large

TABLE 1. Flood Insurance Rate Zones on the Newberry Piedmont (shortened from FEMA, 2004)

Zone A
The flood insurance rate zone that corresponds to the one percent annual chance flood plains determined in Flood Insurance Studies by approximate methods of analysis. Because detailed hydraulic analyses are not performed for such areas, no base flood elevations or depths are shown within this zone. Mandatory flood insurance purchase requirements apply.
Zone AE
The flood insurance rate zone that corresponds to the one percent annual chance flood plains that are determined in the Flood Insurance Study by detailed methods of analysis. In most instances, Base Flood Elevations derived from the detailed hydraulic analyses are shown at selected intervals within this zone. Mandatory flood insurance purchase requirements apply.
Zone AO
The flood insurance rate zone that corresponds to the areas of one percent shallow flooding (usually sheet flow on sloping terrain) where average depths are between 1 and 3 feet (0.3 and 0.9 m). Average flood depths derived from the detailed hydraulic analyses are shown within this zone. In addition, alluvial fan flood hazards are shown as Zone AO on the Flood Insurance Rate Map. Mandatory flood insurance purchase requirements apply.
Zone X
Zone X corresponds to areas outside the one percent annual chance flood plain, areas of one percent annual chance sheet flow flooding where average depths are less than one foot (0.3 m), areas of one percent annual chance stream flooding where the contributing drainage area is less than one square mile (1.6 km^2), or areas protected from the one percent annual chance flood by levees. No Base Flood Elevations or depths are shown within this zone. Insurance purchase is not required in these zones.

flood events feasible in the present climate, regardless of their frequency, occur on the active fan surfaces. Further, this assumes that regardless of the recurrence interval of the flood in question, its extent will be within or to the limits of the active fan and channel areas. The difference that will accompany floods of different magnitudes, and hence recurrence intervals, will be that the zones of certain values of flood severity (in terms of depth and velocity) will expand or contract accordingly within the active zone. No attempt was made to divide the GPF into flood probability zones because there is no firm basis for such a division. Further, this study does not specifically address the potential for channel avulsion, which can change the distribution of flood hazard areas (Field, 2001). Occurrences of past avulsions are implicit in the geologic data, and the potential for avulsion is highest within the active drainage net on the piedmont, which is included here in the broadly defined geologic flood plain. In the following comparisons, the entire GPF is assumed to be generally representative of Zone A – the high hazard flood plain.

Similarities and discrepancies (matches and mismatches) between the geologic information and the regulatory flood zone boundaries were quantified using simple query routines in a GIS program. The comparison was limited to the Newberry Piedmont as previously defined. Areas zoned as AE along the Colorado River and any A or AO zones coincident with the geologic unit Qcy were omitted from the data to restrict comparison to the piedmont. A composite map illustrating the results of the comparative analysis is shown in Figure 4. The details of the map are described below.

Anthropogenic Features

The influence of anthropogenic features (i.e., roads, buildings, and culverts) was not explicitly considered in this analysis except in areas where significant development has had a prominent geologic impact (i.e., large scale earth movement). There are two major and several minor flood control structures that influence the distribution of piedmont flood hazards. Only the major structures are considered here (also the case with the DFIRM data). They include a large detention basin in Hiko Wash and a flood channel debris basin outfall system on Unnamed Wash. These facilities were required to protect preexisting developments in high hazard areas, and they have allowed for additional development in the protected areas. On the DFIRMs, 100-year flood zones once associated with Hiko Wash and Unnamed Wash were converted to 500-year flood zones. Related GPF areas were similarly affected, but can only be evaluated qualitatively. The protected areas are still subject to hazardous flooding if their structural capacities are exceeded, and their retention in the RFP reflects the fact that hazards have not been eliminated. The area in question totals approximately 200 ha, and it is a variable described in the comparisons to follow.

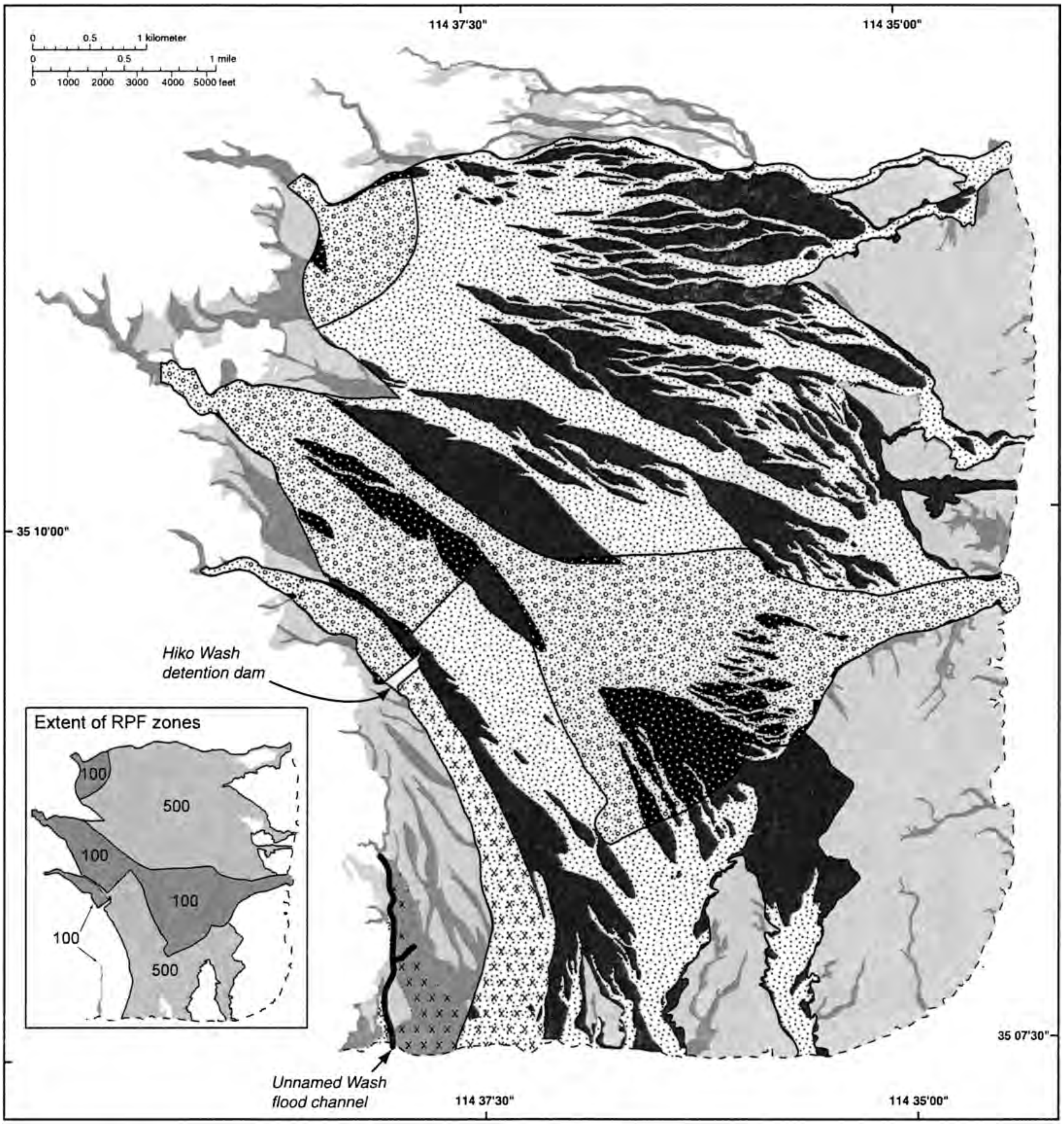

Figure 4. Map Comparing RPF and GPF Derived From GIS Analysis. Geology is the same as in Figure 2. RPF boundaries include 100-year and 500-year zones. See the text and Table 2 for detailed explanation of types of match and mismatch indicated in the map. The inset map shows the extent of regulatory flood zones only.

RESULTS AND DISCUSSION

Comparison of the RPF and the GPF reveals some significant differences and similarities between them, and illustrates less tangible problems associated with conceptual differences between the two types of maps. Results of the comparisons can be summarized as types of match and mismatch. Areas where the GPF and the RPF overlap or exclude common areas constitute instances of match; and areas where one is excluded from the other are instances of mismatch (the data described below are presented in more detail in Table 2; Figure 4 summarizes the same data graphically).

The net overlap between the GPF and the RPF across the piedmont is good overall. The GPF and the RPF both exclude 27 percent of the total piedmont as nonflood prone (Type 1 match; NGPF = NRPF). Similarly, the GPF is within the RPF across 41 percent of the piedmont (Type 2 match; GPF = RPF). Thus, the two maps are in basic agreement over 68 percent of the piedmont where the regulatory flood plain zonation is consistent with the geology. Within the area of Type 2 match, 37 percent of the total match is between the GPF and the 100-year RPF. This constitutes the strongest agreement between the two data sets (Type 2a match; GPF = RPF_{100}). The remaining 63 percent of the total match is between the GPF and the 500-year RPF which ranges from a weak match to a mismatch (herein referred to as Type 2b match/Type 1 mismatch; GPF = RPF_{500}). Characterizing this as a mismatch is a qualitative assessment that reflects distinct differences between the two types of maps. It stems largely from difficulties in characterizing the down piedmont extent of high flood hazards. The two flood control structures described previously improve the overall match by reducing flood hazards in 10 percent of the area of GPF-RPF overlap (Type 2 match).

Despite the good overall match, the actual overlap between the two maps is irregular and incomplete, and this results in several types of mismatch. For example, 15 percent of the GPF does not coincide with the RPF, which constitutes a tacit underestimation of existing flood hazards (Type 2 mismatch; GPF <> RPF). The excluded areas include small, on-piedmont

TABLE 2. Data Derived From Comparison of the GPF and RPF on the Newberry Piedmont

Basic Data	Area (ha)	Percent NP	Percent GPF	Percent RPF	Description
Newberry Piedmont Area (NP)	5,078	100		152	Defined in text
Geologic Piedmont Flood Plain (GPF)	2,455	48	100	74	All active alluvial surfaces
Regulatory Piedmont Flood Plain (RPF)	3,332	66		100	All A and X FIRM zones on piedmont
100-Year (A Zones)	984	19	40[1]	30	A, AO, AE FIRM zones on piedmont
500-Year (X zones)	2,348	46	96[1]	70	X FIRM zones on piedmont
Mitigated Hazard	200	4	8	6	Areas affected by structural mitigation (see text)

Match	Area (ha)	Percent NP	Percent GPF	Percent RPF	Percent Overlap	Description
NGPF = NRPF	1,380	**27**[2]				Type 1 match
GPF = RPF	2,089	**41**	85	63	100[3]	Type 2 match
GPF = RPF_{100} (A Zones)	781	15	32	23	**37**	Type 2a match
GPF = RPF_{500} (X zones)	1,308	26	53	39	**63**	Type 2b match/Type 1 mismatch
Flood Control Effect	200	4	8	6	**10**	Match improvement factor

Match	Area (ha)	Percent NP	Percent GPF	Percent RPF	Percent Excluded	Description
GPF <> RPF	366	7	**15**	11	29	Type 2 mismatch
RPF <> GPF	1,244	24	51	**37**	100[3]	Type 3 mismatch
RPF_{100} <> GPF	204	4	8	6	**16**	Type 3a mismatch
RPF_{500} <> GPF	1,040	20	42	31	**84**	Type 3b mismatch

[1]Total of these numbers exceed 100 because the extent of the RPF is greater than the GPF.
[2]Values in boldface are those used in developing match/mismatch discussion in text.
[3]Calculated from basis of all the GPF in the RPF, hence the 100 percent values.

drainages, small mountain front tributaries, and the upstream extent of large, active alluvial channels associated with each major fan complex. The exclusion of these areas reflects methodological differences between the compilation of geologic data and the development of regulatory maps on the same piedmont.

An additional measure of mismatch indicates overestimation of existing flood hazards in the RPF. Instances where the RPF is not in the GPF are called Type 3 mismatch (RPF <> GPF). This type of mismatch implies that what the RPF assumes is flood prone is actually not, and it comprises 37 percent of the RPF. Within this area, 16 percent of the mismatch involves the 100-year RPF (Type 3a; RPF_{100} <> GPF) and 84 percent involves the 500-year RPF (Type 3b; RPF_{500} <> GPF). The former represents the strongest mismatch and could result in unwarranted flood insurance requirements or structural mitigation measures. The latter is slightly less problematic with respect to flood insurance requirements, but it still represents a distinct and locally extensive mischaracterization of hazards on the piedmont. Mismatches of Types 2 and 3 are the easiest to minimize with geologic data.

Type 1 mismatch (GPF = RPF_{500}) is a qualitative geologic interpretation that is difficult to reconcile with regulatory needs because the GPF cannot be easily divided into analogous hazard zones. It is likely that flow conditions implied by this RPF zone (Zone X, Table 1) are common in many parts of the GPF; however, specific instances where the RPF demonstrably mischaracterizes the piedmont geomorphology raise serious questions about the overall distribution of regulatory hazard zones. This is best illustrated in the Bridge Canyon alluvial fan complex where 93 percent of the Type 3a mismatch (RPF_{100} <> GPF) occurs.

Both Type 1 (GPF = RPF_{500}) and Type 3b (RPF_{500} <> GPF) mismatches are also widespread on the Dripping Springs alluvial fan complex. There, the implied extent of the active fan on the RPF differs greatly from the actual geomorphology (Figure 5). Note how the RPF includes large areas of high-standing, relict alluvial fan surfaces and fails to indicate the extent of flow reconcentration that occurs on the middle and lower piedmont. The reconcentration of flow indicated by the geomorphology is likely to result in a greater down piedmont extension of high flood hazards than indicated by the RPF boundaries.

The degree of match between the GPF and the RPF is highest overall on the Hiko Wash fan complex because it is the most deeply entrenched into older, inactive fan deposits. Each of the other principal active fan complexes exhibit shallower incision, but are flanked by the same suite of inactive alluvial surfaces. Thus, the inactive surfaces reveal the same general history of long term exposure to weathering and isolation from active alluvial fan processes, but they are only evident in the RPF when the erosional topography is extremely well developed. Strongly developed erosional topography and extensive inactive fan surfaces on the middle and lower Dripping Springs fan complex, however, are largely unaccounted for in the RPF.

DISCUSSION

The comparisons indicate significant inconsistencies between the GPF and the RPF on the Newberry Piedmont wherein at least 31 percent of the total piedmont area is mischaracterized with respect to its flood hazardous status (mismatch Types 2, and 3; Table 2). Including areas where the GPF is within only the 500-year RPF raises this value to a maximum mischaracterization of 57 percent (mismatch Types 1, 2, and 3). With respect to the piedmont area within the RPF, the mismatch ranges from 37 percent (mismatch Type 3) to a maximum of 76 percent (mismatch Types 1 and 3). Additionally, 7 percent of the piedmont is clearly flood hazardous but is not included in the RPF. Some of the mismatches are unambiguous and others are less so because of differences between geological and regulatory concepts of the flood plain. Arguably, the most critical problems involve areas where flood hazards clearly exist, but do not fall into a regulatory zone (Type 2 mismatch), and those areas where flood hazards do not exist, but fall into the most restrictive hazard zone (Type 3a mismatch). Similarly, some areas of the GPF that are in the 500-year RPF (Zone X) are very likely subject to higher hazards than indicated (Type 1 mismatch). The least problematic mismatch with respect to flood insurance requirements is when nonflood prone land is included in the 500-year RPF; however, this mismatch still reflects fundamental problems with the application of the regulatory model in this example.

In each case, a judicious evaluation of geologic data would have resulted in more overall agreement between the two datasets. Note, however, that the detailed geologic data presented in this report were not readily available during the development of the DFIRMs for the Laughlin area. The fact that the geologic data were compiled subsequently, however, allows for an independent comparison of the two datasets. The intention of this paper is not to impugn the regulatory maps, but to demonstrate that they could be made more representative of existing flood hazard conditions by incorporating geologic information into their compilation. Clearly, an

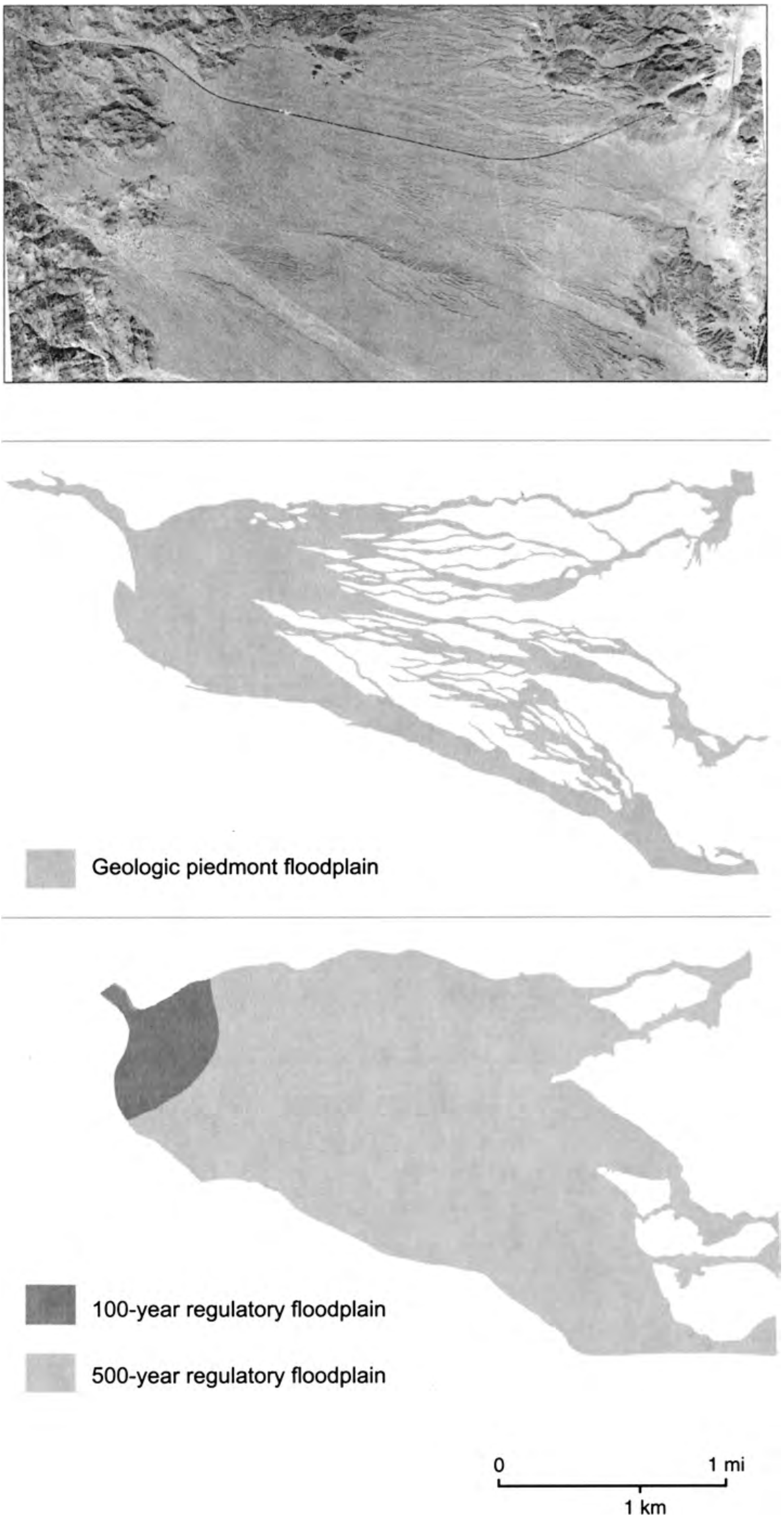

Figure 5. Three Depictions of the Dripping Springs Alluvial Fan Complex: (upper) 1954 aerial photograph; (middle) map of the geologic piedmont flood plain, and (lower) the 100-year and 500-year RPF.

optimal situation is one in which detailed geologic maps of the area are available before a planning or engineering study. The ideal case is one in which the compilation of relevant geologic data by a trained geomorphologist is an integral part of the conventional study. The latter option would likely have the stronger impact through its closer association with the planning process. In the former option, it needs to be clear that the geologic data were compiled by a trained geomorphologist at an adequate level of detail and with the appropriate focus for use in flood hazard assessment.

CONCLUSIONS AND RECOMMENDATIONS

The study on the Newberry Piedmont is presented here as an argument for the collection and explicit inclusion of geologic data into the development of regulatory flood plain maps of desert piedmonts. It is not presented as an argument for supplanting existing regulatory methods, only improving them. Geologic maps have an interpretative basis and types of uncertainty that are less amenable to quantification than have maps derived from numerical models. However, quantitative strength is not equivalent to veracity, and scientific uncertainty is not a valid basis for ignoring relevant information. An improved approach to piedmont flood hazard assessment involves combining geologic data and regulatory models in a way that optimizes a balance between regulatory needs and scientific substantiation. Recently, Pelletier *et al.* (2005) outlined a method that approaches this balance by directly incorporating geological data into a numerically based model of alluvial fan flood inundation. Their recommended approach, or one similar to it, needs to be considered seriously by the regulatory and flood-hazard management communities. For such consideration to actually occur in earnest, the flood plain management community must come to recognize that expertise in geology is comparable to that in hydrology and hydraulic engineering for understanding, managing, and mitigating flood hazards on desert piedmonts.

The compilation of geologic information is extremely cost effective, scientifically based, and constitutes a valid test of theoretical models that are otherwise difficult or impossible to test. Regulatory maps that include extensive tracts of nonflood prone land in formal flood hazard zones are overly cautious and, arguably, erroneous. A systematic process that iteratively compares model predictions with geologic data would be a sound method for developing more realistic and defensible flood plain management strategies on desert piedmonts.

Concern with uncertainties in geologic interpretations could be handled with systematic buffers or setbacks from contacts between surfaces that are not separated by some minimum elevation criteria, among many other scenarios. Uncertainties in geologic data resulting from post-study changes in drainage patterns, flow regimes, or sediment transport regimes are of equal concern for conventional engineering analyses derived from prior conditions. Both types of analyses would require restudies or reinterpretations, which should, again, be performed in tandem.

The collection of geologic data early in the process as recommended by NRC (1996) and FEMA (2000) is the ideal approach to improving piedmont flood hazard management because it helps to narrow the scope of subsequent engineering studies to areas where hazards exist, resulting in potentially large cost savings. A detailed surficial geologic map can also help guide development that is in more accord with existing, natural drainage courses and thus more sensitive to existing and resulting flood risk (Rhoads, 1986). The American Southwest is replete with desert piedmonts that have extensive residential and commercial grid-like development on clearly active alluvial fans. From a geological standpoint, these situations are obviously destined for major flood related problems. Explicit, informed incorporation of geomorphology into land use decisions and piedmont flood plain management can obviate these problematic situations in the future and can greatly reduce property damage, loss of life, and expensive post-facto flood mitigation measures.

ACKNOWLEDGMENTS

Funding for this study was provided by the Federal Emergency Management Agency (FEMA) through the Nevada Division of Emergency Management (with advice from the Nevada All Hazards Mitigation and Advisory Committee), the Nevada Bureau of Mines and Geology (NBMG), and the U.S. Geological Survey Statemap program. Alan Ramelli, Jim Faulds, and John Bell (NBMG) helped compile the geologic data. Robert Chaney and Gary Johnson (NBMG) helped develop the GIS analysis. An earlier version of this manuscript was improved by review comments from Gale Fraser (CCRFCD), Jon Price, and Lisa Shevenell (NBMG). The clarity of the final text was greatly enhanced with suggestions from three anonymous reviewers. All statements herein are solely the opinion and scientific judgment of the author. Their publication represents no specific endorsement by any federal, state, or local agency.

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