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GEOLOGY AND NATURAL HAZARD ASSESSMENT OF THE LAUGHLIN AREA, CLARK COUNTY, NEVADA

Prepared in cooperation with the
Nevada Division of Emergency Management
and the All Hazards Mitigation Advisory Committee

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TABLE OF CONTENTS

Executive Summary.....iii

Chapter 1. Geology of the Laughlin Area, Clark County, Nevada.....1.1-1.56
By James E. Faulds and P. Kyle House

Chapter 2. Geologic Evaluation of Alluvial Fan and Related Flood Hazards in the Vicinity of Laughlin, Nevada.....2.1-2.45
By P. Kyle House

Chapter 3. Evaluation of Water Quality in the Laughlin Area: Potential Contamination and Hazards.....3.1-3.46
By Lisa Shevenell

Chapter 4. Other Geologic Hazards.....4.1-4.7
By Alan Ramelli

EXECUTIVE SUMMARY

The main purpose of this report is to characterize the geologic setting and related natural hazards of the Laughlin, Nevada, area. The principal geologic hazards are flash floods along major washes draining into the Colorado River. Other potential hazards include earthquakes, poor soil conditions, groundwater quality, and inactive and abandoned mines. This assessment provides a strong foundation upon which to conduct more thorough analyses of identified hazards that pose the greatest threat to the growing community. Major components of this study include detailed geologic mapping of surficial and bedrock units, examination of faults and folds, analysis of flood deposits on active alluvial fans and washes, and a hydrogeochemical evaluation of groundwater. This report summarizes the completed work. The general geology of the Laughlin area is described first, followed by three individual chapters that respectively address flood hazards, water quality, and other natural hazards (earthquakes and poor soil conditions). A complete bibliography of cited references is also included for each chapter.

The Laughlin area occupies a highly extended part of the Basin and Range province in which the major physiographic features are the Newberry Mountains, Mohave basin, and Colorado River. A major gently inclined normal fault, here referred to as the Newberry detachment fault, separates the Newberry Mountains from the Mohave basin and divides the area into two major domains. The upthrown side of the detachment fault consists primarily of 17 and 15 million year old (Ma) plutons, which are cut by abundant northerly striking faults and dikes. More than 10 km (>6.5 mi) of displacement on the Newberry detachment produced the Mohave basin. Bedrock units in the downthrown block of the detachment are composed primarily of ~20 to 11 Ma (early to middle Miocene age) stratified volcanic and sedimentary rocks that rest directly on Precambrian granite. These units are riddled by easterly and northerly striking faults and are moderately to steeply tilted. The Miocene strata are warped into a large northerly trending arch (Davis Dam anticline), which projects beneath alluvial fan deposits in the Bullhead City area. Laughlin lies in the northern Mohave basin above the west-tilted limb of this arch. The Precambrian granite is significantly dilated by northerly and easterly striking Miocene dikes and veins, which are the source of gold mineralization in the Katherine mining district.

In the past 20 million years, two major episodes of deformation affected the Laughlin region. Mild north-south extension ~20 to 17 Ma produced the easterly striking faults, dikes, and veins found in the downthrown block of the detachment fault. The second and more significant event involved large-magnitude east-west extension between ~16 and 8 Ma. It generated the northerly striking dikes and faults, such as the Newberry detachment, while also producing the major physiographic features in the region.

Late Tertiary to Quaternary alluvial fan deposits (~8 Ma to recent), shed largely from the 17 and 15 Ma granites exposed in the Newberry Mountains, and far-traveled Colorado River sediments bury the Precambrian and Miocene rocks in the Mohave basin. Only minor faults cut late Tertiary (~5 Ma) sediments in the Laughlin area, and no faults were observed in Quaternary deposits, indicating limited earthquake activity in the past 1.8 million years. However, 30 km (20 mi) southeast of Laughlin, two faults cut Quaternary deposits in the Needles, California area.

Laughlin straddles the geologic boundary separating areas dominated by Quaternary deposits of the Colorado River (lower piedmont) from those dominated by deposits of tributary alluvial fans and washes draining the Newberry Mountains (upper piedmont). The lower piedmont contains four Colorado River terraces that record episodes of significant deposition of river alluvium followed by subsequent entrenchment of the river and formation of new stream terraces. Pulses of deposition along the Colorado River in the Quaternary were probably driven by regional- to global-scale climatic changes. The upper piedmont consists of a mosaic of alluvial deposits that record the response of drainages in the Newberry Mountains to both climatic change and, more importantly, to changes in local base level resulting from these pulses along the Colorado River. Presently, the actively developing tributary alluvial deposits are restricted to broad, but identifiable zones on the upper piedmont, and relatively narrow, confined zones between relict older deposits on the lower piedmont. Flow regulation by upstream dams has effectively isolated the floodplain from active deposition and flooding.

Detailed analysis of the surficial geology, geomorphology, and Quaternary stratigraphy of the Laughlin piedmont provides important insights into the nature and distribution of its flood hazards. Geologic evidence indicates that large portions of the piedmont have been isolated from alluvial fan activity and related flood hazards for at least the last 10,000 years. Furthermore, many portions of the piedmont that actively convey water and sediment are not accurately characterized as alluvial fans. These conclusions contrast with the implications of existing Flood Insurance Rate Maps (FIRMs) for the area. The FIRMs erroneously include large tracts of non flood-prone areas into both the 100-year and 500-year floodplain hazard zones. A direct comparison of the regulatory maps and the geological map indicates that approximately 60% of the piedmont is characterized inaccurately with respect to its flood prone status on the regulatory maps. Of this, approximately 34% is not flood hazardous but is mapped as though it were, and approximately 23% is flood hazardous but mapped as though it were not. These discrepancies arise from the application of an oversimplified model for flood hazard evaluation to a complex surficial geologic setting. This circumstance illustrates the value of geological information as a primary tool in realistic and cost-effective floodplain management strategies.

Earthquakes and problems related to soil conditions are lesser, but not trivial, geologic hazards in the Laughlin area. No evidence of recent large-magnitude earthquakes has been found in the immediate Laughlin area, and the surrounding region has had a low level of historical seismicity. Moderate-sized earthquakes (up to magnitude 6) generally do not cause ground offsets large enough to be recognized in the geologic record, so such events probably represent an upper bound for local seismicity. The most significant regional earthquake source is the Needles graben, located about 35 km (22 mi) south of Laughlin. An earthquake on that fault zone would probably cause moderate to serious damage in Laughlin, and could have secondary impacts such as collapsing river banks and slope failures in unconsolidated surficial deposits. Potential soil-related problems in the Laughlin area include expansive soils, slope failure, and amplification of seismic shaking. The deposits that are most susceptible to such problems are the fine-grained Colorado River deposits. These deposits cover a relatively small area overall, but include much of the urbanized portion of Laughlin.

Existing water quality data from the Colorado River and several water wells near the town of Laughlin were evaluated to determine if any waters were contaminated or could be impacted by anthropogenic activities or proximity to particular natural settings. With some exceptions, surface water and groundwater quality near Laughlin is good, with shallow groundwaters located within ~150 m of the river being dominated by Colorado River water. Contamination (elevated chloride, nitrate, sulfate, and total dissolved solids) from a sewage treatment facility has been detected down gradient from the site. Other wells located closer to the river could also be impacted by these contaminants in the future. No wells were found that indicate any groundwater contamination due to proximity to the Mohave Generating Station slurry ponds. Similarly, no detectable impact on water quality was found that could be attributed to mining practices. Most mining disturbances are for industrial mineral purposes, which typically have low potential for adverse environmental impacts. There is potential for poorer water quality associated with the mineralized zones north of Laughlin due to slightly elevated metals concentrations in rock samples and the presence of potentially acid producing minerals. However, no water quality data were available to evaluate groundwater interaction with these mineralized zones. Similarly, no water quality data were available near the landfill from which to evaluate possible contamination from that source. Anomalous sulfate and manganese in wells located near the detachment fault may indicate the potential for contamination as groundwaters interact with weakly mineralized and highly oxidized fault breccias.

CHAPTER 1:

GEOLOGY OF THE LAUGHLIN AREA,

CLARK COUNTY, NEVADA

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Abstract

The Laughlin area resides in a highly extended part of the Basin and Range province, referred to as the Colorado River extensional corridor. The major physiographic features in the Laughlin area are the Newberry Mountains, Mohave basin, and Colorado River. The gently east-dipping Newberry detachment fault separates the Newberry Mountains from the Mohave basin and divides the area into two lithologic domains. The footwall (upthrown side) of the detachment consists primarily of large 17 and 15 Ma plutons, which are cut by abundant northerly striking faults and dikes. More than 10 km (>6.5 mi) of top-side-down displacement on the Newberry detachment produced the Mohave basin. Most of this basin appears to be a west-tilted half graben, but small east-tilted fault blocks are found along its northern margin. In contrast to the footwall, bedrock units in the hanging wall (downthrown block) of the detachment are composed primarily of ~20 to 11 Ma volcanic and sedimentary strata that rest directly on Precambrian granite. The Precambrian granite is significantly dilated by northerly and easterly striking, early to middle Miocene mafic to silicic dikes and quartz and calcite veins. The silicic dikes and quartz veins are the source of gold mineralization in the Katherine mining district. The hanging-wall bedrock units are riddled by easterly and northerly striking mainly normal faults and are moderately to steeply tilted. In addition, Miocene strata are warped into a large northerly trending arch (Davis Dam anticline), which projects beneath alluvial fan deposits in the Bullhead City area. Laughlin resides above the west-tilted limb of this arch. The hanging-wall bedrock units are best exposed directly north of Laughlin in an east-trending bedrock high that marks the northern end of the Mohave basin.

Late Tertiary to Quaternary fan deposits, shed largely from the 17 and 15 Ma granites exposed in the Newberry Mountains, and far-traveled Colorado River sediments mantle Miocene and Precambrian rocks in the Mohave basin. These sediments completely bury older rocks near Laughlin. Only minor faults cut late Tertiary (~5 Ma) sediments in the Laughlin area, and no faults were observed in Quaternary deposits. However, 30 km southeast of Laughlin, two faults cut Quaternary deposits in the Needles graben.

In the past 20 million years, two major episodes of deformation affected the Laughlin region. Mild north-south extension ~20 to 17 Ma produced the easterly striking faults, dikes, and veins found in the hanging wall of the detachment. The second and more significant event involved large-magnitude east-west extension between ~16 and 8 Ma. It generated the northerly striking dikes and faults, such as the Newberry detachment, while also producing the major physiographic features in the region (Newberry Mountains and Mohave basin). Since 8 Ma, only minor faulting has occurred in the Laughlin area.

The Quaternary geologic history and geomorphology of the Laughlin area is intimately linked to the Quaternary history of the Colorado River. Laughlin resides on the piedmont of the Newberry Mountains and modern floodplain of the Colorado River. The town straddles the geologic boundary separating areas dominated by Quaternary deposits of the Colorado River (lower Piedmont) from those dominated by deposits of tributary alluvial fans and washes draining the Newberry Mountains (upper piedmont). The lower piedmont contains four Colorado River terraces that record episodes of significant aggradation of river alluvium followed by subsequent entrenchment of the river and formation of new stream terraces. Pulses of aggradation along the Colorado River in the Quaternary were probably driven by regional- to global-scale climatic changes. The upper piedmont consists of a mosaic of alluvial deposits that record the response of drainages in the Newberry Mountains to both climatic change and, more importantly, to changes in local base level resulting from the pulses of aggradation and subsequent entrenchment along the Colorado River. It is possible to correlate tributary alluvial deposits with the major stream terrace-building episodes and related deposits of the Colorado River. Presently, the actively developing tributary alluvial deposits are restricted to broad, but identifiable zones on the upper piedmont, and relatively narrow, confined zones between relict older deposits on the lower piedmont. These drainages ultimately terminate on the floodplain of the Colorado River. Flow regulation by upstream dams has effectively isolated the floodplain from active river deposition.

Table of Contents

Abstract 1.2
Table of Contents 1.3
List of Figures, Plates, and Tables 1.4
Introduction 1.5
Geologic Setting 1.5
  Regional Setting 1.5
  Laughlin Area 1.6
Lithologic and Stratigraphic Framework 1.9
  Proterozoic Basement (Ydg) 1.12
  Miocene Dikes and Veins 1.15
  Miocene Plutons 1.15
  Arkosic Conglomerate (Tca) 1.17
  Miocene Volcanics 1.17
  Middle Miocene Conglomerates (Ts and Tc) 1.20
Quaternary Geology and Geomorphology 1.21
  Physical Setting of Laughlin 1.21
  Alluvial Deposits and Geomorphic Features of Laughlin Piedmont 1.21
    Tributary Alluvium 1.22
    Colorado River Alluvium 1.22
    Stream Terraces 1.27
      Davis Terrace 1.27
      Mohave Terrace 1.30
      Emerald Terrace 1.30
      Laughlin Terrace 1.32
  Overview of Quaternary History 1.32
    Colorado River Record 1.32
    Record of Piedmont Alluvium 1.36
Structural Framework 1.37
  Newberry Domain 1.37
  Newberry Detachment Fault 1.39
  Davis Dam Domain 1.40
    Fabric in Davis Dam Granite 1.42
    Faults 1.42
    Davis Dam Anticline 1.44
    Recreation Block 1.45
  Northern Mohave Basin 1.48
Timing of Neogene Deformation 1.48
Summary 1.50
Acknowledgments 1.52
Bibliography 1.52

List of Figures, Plates, and Tables

Plate 1. Geologic map of the Laughlin area, Clark County, Nevada.....In pocket

Figure 1. Regional map of the Laughlin-Bullhead City area 1.7
Figure 2. Oblique aerial view looking southwest at Laughlin and surroundings..... 1.8
Figure 3. Newberry detachment fault..... 1.10
Figure 4. Oblique three-dimensional elevation model of the Laughlin area..... 1.11
Figure 5. Generalized geologic map of the Laughlin area 1.13
Figure 6. Looking north at Davis Dam 1.14
Figure 7. Spirit Mountain..... 1.16
Figure 8. Miocene strata in the Davis Dam domain 1.18
Figure 9. Peach Springs Tuff 1.19
Figure 10. Typical surface of tributary alluvium deposit (Qai) 1.23
Figure 11. Exposure of soil carbonate horizon in Qai alluvium 1.24
Figure 12. Typical surface of Colorado River gravel deposit (Qcg)..... 1.25
Figure 13. Onlap of Colorado River sediments on Davis Dam granite 1.26
Figure 14. Principal Colorado River terraces in the Laughlin area..... 1.28
Figure 15. Exposure of stratigraphy underlying Davis terrace..... 1.29
Figure 16. Exposure of stratigraphy underlying Mohave terrace..... 1.31
Figure 17. Exposure of bouldery alluvium of the Colorado River (Qcb) 1.34
Figure 18. Unconformity between alluvial fan gravels and coarse Colorado River deposit..... 1.35
Figure 19. Equal-area projections, Newberry domain 1.38
Figure 20. Cross sections of Newberry detachment fault 1.41
Figure 21. Equal-area projections of joints, faults, and veins, Davis Dam domain..... 1.43
Figure 22. Equal-area projections of poles to Miocene strata..... 1.46
Figure 23. Schematic model of Davis Dam anticline 1.47
Figure 24. Onlap of Quaternary sediments on Newberry detachment fault..... 1.49
Table 1. Geologic History of the Laughlin Area..... 1.51

Introduction

This chapter describes the geologic framework of the Laughlin area, including the overall stratigraphy and patterns of faulting. The geologic setting of the Laughlin area and evaluation of the natural hazards (subsequent chapters) was characterized on the basis of geologic mapping of surficial and bedrock units. The west half of the Davis Dam Quadrangle and easternmost part of the Bridge Canyon Quadrangle were mapped at 1:24,000 scale (Plate 1). The surficial mapping is applicable to assessing flood and potential debris flow hazards on major washes, which pose the greatest natural hazards to Laughlin. Mapping of bedrock units is relevant for evaluating groundwater and mineral resources, sediment supply to major flood-prone washes (which may affect the character and severity of floods), and seismic hazards.

Conventional techniques of surficial geological mapping were employed on the Laughlin piedmont to reconstruct the recent geologic history of the area and evaluate the extent of flood-prone areas on alluvial fans and washes that drain from the Newberry Mountains to the Colorado River. Physical properties such as surface drainage pattern, relative degree of soil development, condition of original depositional topography, degree of connectivity with primary (mainstem) drainages, and depth of channel incision distinguish active alluvial fans and washes from those that are ancient, relict, and inactive. This geological approach uses physical flood-related properties to delineate areas that are presently subject to flood hazards, thus providing an important point for comparison with conventional regulatory approaches to delineating flood hazardous areas on alluvial fans, which rely on topography as the sole physical property that distinguishes flood-prone from non-flood prone areas.

Conventional techniques of bedrock geologic mapping were combined with structural analysis of faults and folds in the Laughlin area to evaluate the timing of deformation, assess the potential for local earthquakes, establish the general geometry of the northern Mohave basin (within which Laughlin resides), and provide critical information for evaluating groundwater and mineral resources. The bedrock mapping focused on the area directly north of Laughlin, where excellent exposures permitted analysis of faults and folds.

Geologic Setting

Regional Setting

The Laughlin area lies within the southern part of the northern Colorado River extensional corridor (Howard and John, 1987; Faulds and others, 1990), which is a 100-km-wide (~60 mi wide) region of moderately to severely extended crust within the Basin and Range province. The northern Colorado River extensional corridor is bounded to the east by the unextended Colorado Plateau and to the west by the Spring Mountains and Clark Mountain Range. Thick sections (generally > 3 km or 1.9 mi) of Miocene volcanic and sedimentary strata generally rest directly on Proterozoic and Upper Cretaceous metamorphic and plutonic rock within the extensional corridor (Longwell, 1963; Anderson, 1971, 1977, 1978; Anderson and others, 1972; Frost and Martin, 1982; Sherrod and Nielson, 1993; Faulds and others, 1995; Faulds, 1999). Miocene time incorporates the period of geologic history extending from 23.5 to 5.3 Ma (i.e., million years

before present). Paleozoic and Mesozoic (540 to 65 Ma) strata were stripped away by erosion in Late Cretaceous (96 to 65 Ma) and early Tertiary (65 to 23.5 Ma) time.

Calc-alkalic magmatism and large-magnitude extension swept northward across the northern part of the corridor in early to late Miocene time (Glazner and Bartley, 1984; Gans and others, 1989; Faulds and others, 1994, 1999; Smith and Faulds, 1994; Gans and others, 1994). Magmatism began 1-2 m.y. before extension and continued throughout the extensional episode. Thus, the corridor is dominated by highly fragmented, thick volcanic sequences contained within complex arrays of tilted fault blocks. The predominant north-northwest strike of both normal faults and layering in tilted fault blocks, as well as slip data (Anderson, 1971, Angelier and others, 1985; Anderson and others, 1994), indicate an east-northeast- (~N75°E) to east-west-trending extension direction.

Similar to much of the Basin and Range, the alternating basins and ranges within the northern Colorado River extensional corridor are composed of tilted fault blocks. The basins correspond to half grabens, or the downthrown parts of tilted fault blocks, whereas the upthrown parts of tilted fault blocks form the ranges. Many of the fault blocks are tilted nearly 90° and thus reveal cross-sectional views of much of the upper crust (e.g., Faulds and others, 1995).

Laughlin Area

The major physiographic features in the Laughlin area are the Newberry Mountains, Mohave basin, and Colorado River (Figs. 1 and 2). Laughlin resides on the modern floodplain of the Colorado River and tributary alluvial fan deposits in the northern part of the Mohave basin. The fan deposits were derived almost entirely from the Newberry Mountains to the west. A major fault, inclined 15° to 20° to the east, separates the Newberry Mountains from the Mohave basin and is here referred to as the Newberry detachment fault. A detachment fault is a gently dipping (inclined < 30°) normal fault that has accommodated many kilometers of displacement, whereby the block above the fault (i.e., hanging wall) has moved down with respect to the block beneath the fault (i.e., footwall). The Newberry detachment fault extends from the Laughlin area northward along the east flank of the Newberry and southern Eldorado Mountains and southward along the east flank of the Dead Mountains. The detachment fault is well exposed directly north of Laughlin near the Telephone Cove Road and on the southwest fringe of Laughlin near Hiko Wash (Figs. 2 and 3).

More than 10 km (>6.5 mi) of displacement on the Newberry detachment fault produced the Mohave basin. Movement on the detachment fault and development of the basin began more than 15 Ma and probably continued until about 11 Ma. The Black Mountains in Arizona essentially slid off the Newberry Mountains along the detachment fault. As the Black Mountains moved eastward relative to the Newberry Mountains, the widening gap between the two mountain ranges evolved into the Mohave basin (Fig. 1). Most of this basin appears to be a west-tilted half graben, but small east-tilted fault blocks are found along its northern margin directly north of Laughlin.

The Black Mountains and many of the fault blocks within the Mohave basin are largely composed of ~20 to 13 Ma sedimentary and volcanic rocks, including several ancient volcanic centers. In contrast, the uplifted Newberry Mountains consist primarily of ~15 to 17 Ma granitic rocks that originated at relatively deep levels in the crust but were brought to the surface by

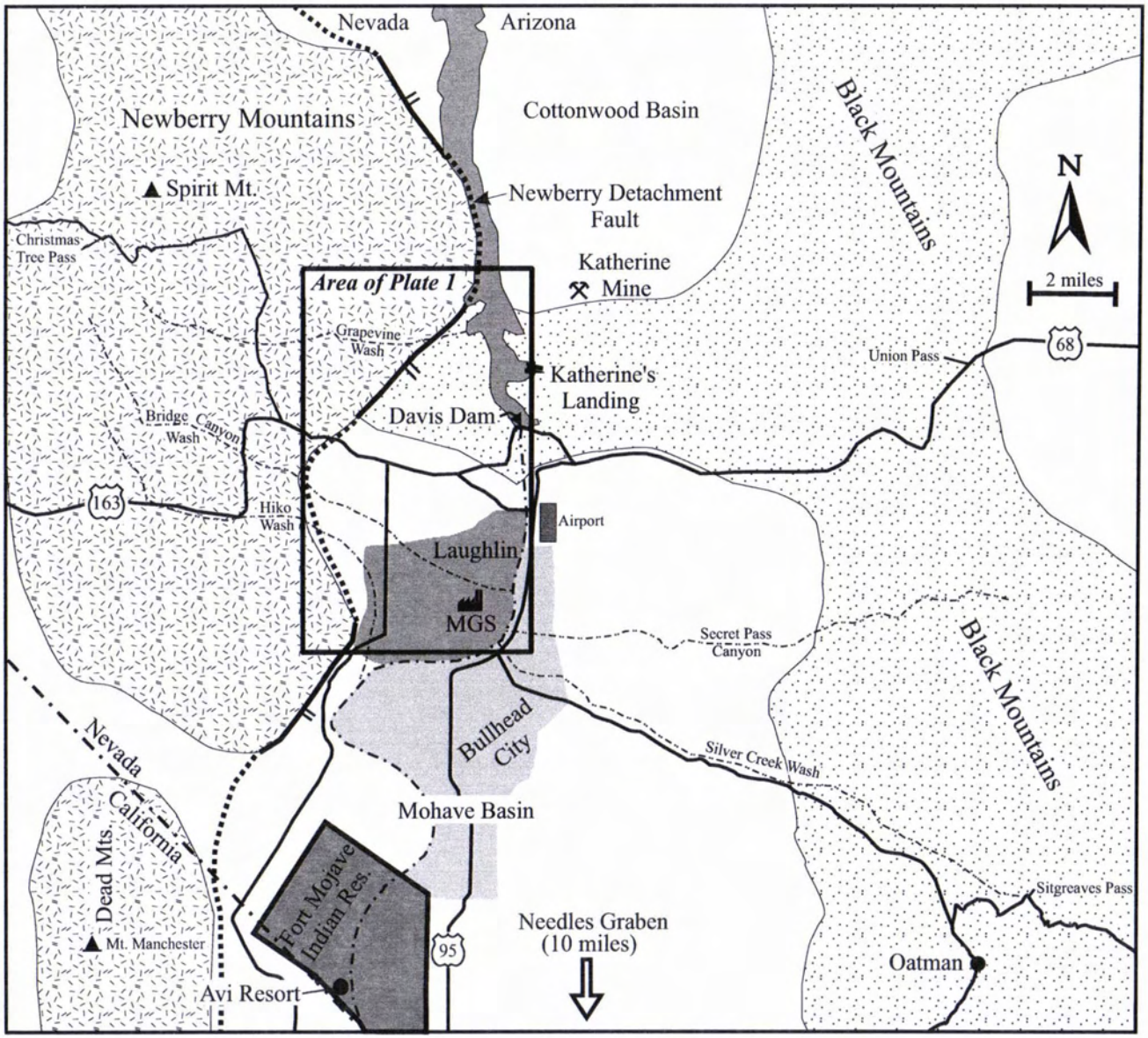


Figure 1. Regional map of the Laughlin-Bullhead City area, showing major physiographic and manmade features. Note that mapped area shown in Plate 1 is outlined. MGS, Mohave Generating Power Station.

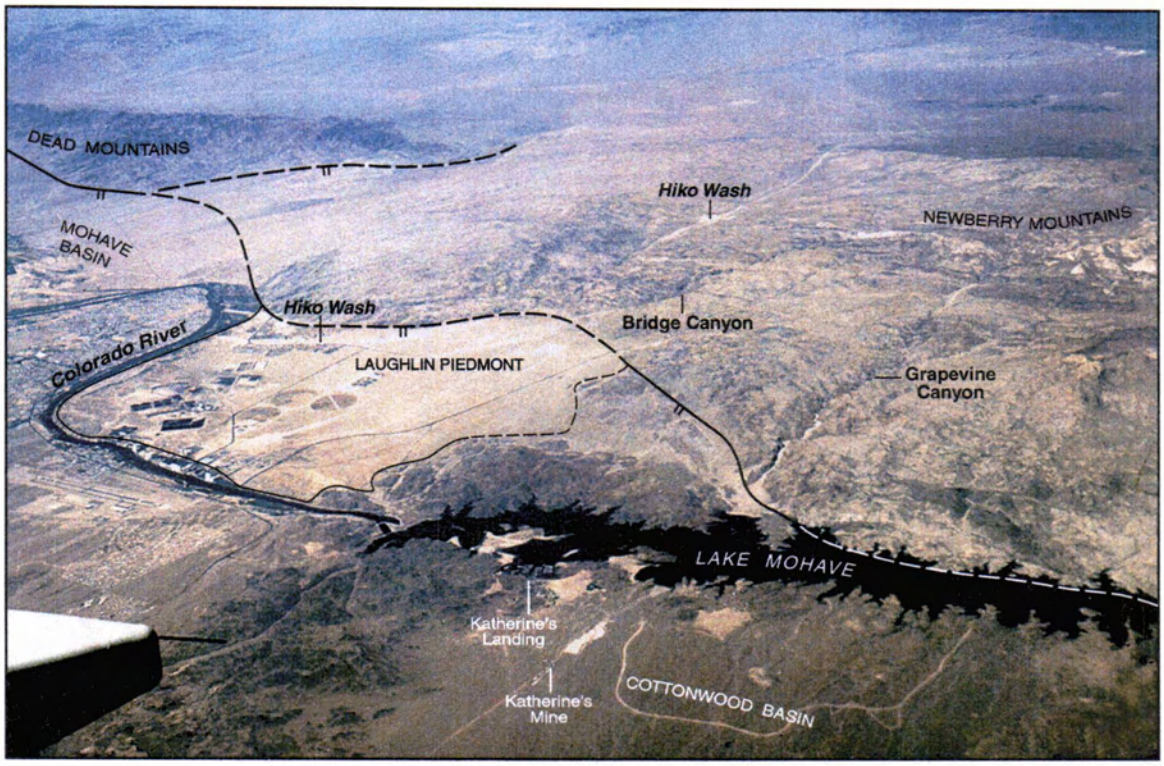


Figure 2. Oblique aerial view looking southwest at Laughlin and surroundings. The city of Laughlin resides on the piedmont of the Newberry Mountains on the west side of the Colorado River. The Newberry detachment fault is shown as the solid and dashed (where covered) line with hachures.

movement on the detachment fault. The granitic rocks in the Newberry Mountains probably represent the roots of some of the volcanic centers in the Black Mountains.

As the surrounding mountain ranges were uplifted and eroded, alluvial fans were shed into the Mohave basin. The readily erodible granitic terrane of the Newberry and Dead Mountains has provided an abundant supply of sediment to alluvial fans and washes in the Laughlin area. The older fan deposits are highly tilted and faulted and were clearly deposited before movement ceased on the detachment fault. All of these deposits are probably older than 8 Ma. The youngest alluvial fan deposits are unfaulted and untilted and probably range in age from Holocene (10,000 years to recent) to Pleistocene (10,000 years to 1.6 million). These deposits clearly postdate seismicity in the immediate vicinity of Laughlin. Minor faults do cut some of the highly dissected, essentially flat-lying fan deposits southwest of Laughlin. These deposits are probably several million years old, however, because they interfinger with a thin limestone deposit, which probably correlates with the 4 to 8 Ma Bouse Formation (e.g., Buising, 1990).

Within a few miles of the present-day course of the Colorado River, the alluvial fan deposits interfinger with Colorado River gravels and sands. The city of Laughlin is built on the younger untilted alluvial fan deposits and ancient and modern Colorado River sediments.

Directly north of Laughlin in the Davis Dam and Katherine's Landing area, an east-west-trending bedrock high separates the Mohave and Cottonwood basins (Fig. 2). Exposed bedrock within this interbasinal high provides important clues to the nature of the subsurface geology beneath the northern Mohave basin, which is relevant to assessing both seismic hazards and groundwater resources. Bedrock units within this area include Precambrian granite, multiple volcanic units that range from ~20 to ~15 Ma, rhyolite dikes, quartz veins, and ~16 to 11 Ma conglomerates. The rhyolite dikes and quartz veins are the source of the gold mineralization in the Katherine and Newberry mining districts. These bedrock units are warped into a large northerly trending arch (Davis Dam anticline), which probably projects beneath the alluvial fan deposits in the Bullhead City area and extends southeastward to join a similar arch near Oatman, Arizona. Laughlin appears to reside above the west-tilted limb of this arch.

The presence of bedrock units, including ancient (> 8 Ma) moderately to steeply tilted alluvial fan deposits, just a few miles north of Laughlin suggests that the northern Mohave basin is not particularly deep. In addition, the gentle inclination of the Newberry detachment fault indicates that the fault blocks that constitute the Mohave basin are not deeply rooted but instead are truncated by the detachment at relatively shallow depth (Fig. 4). Although beyond the scope of this project, these observations are critical for eventually defining the overall geometry of the Mohave basin, modeling groundwater aquifers and flow paths, and assessing the impact of seismic waves from distant earthquakes (see Chapter 4).

Lithologic and Stratigraphic Framework

Establishing the stratigraphic framework of the Laughlin area is critical for assessing flood and earthquake hazards and evaluating groundwater and mineral resources. For example, the distribution of recent surficial alluvial deposits must be determined to assess the location, relative frequency, and intensity of flash floods and debris flows on major washes and to evaluate which areas might be prone to more severe ground shaking in earthquakes. The distribution and composition of bedrock units is relevant to evaluating (a) the sediment supply to major flood-prone washes, which may affect the character and severity of floods, (b) distribution and

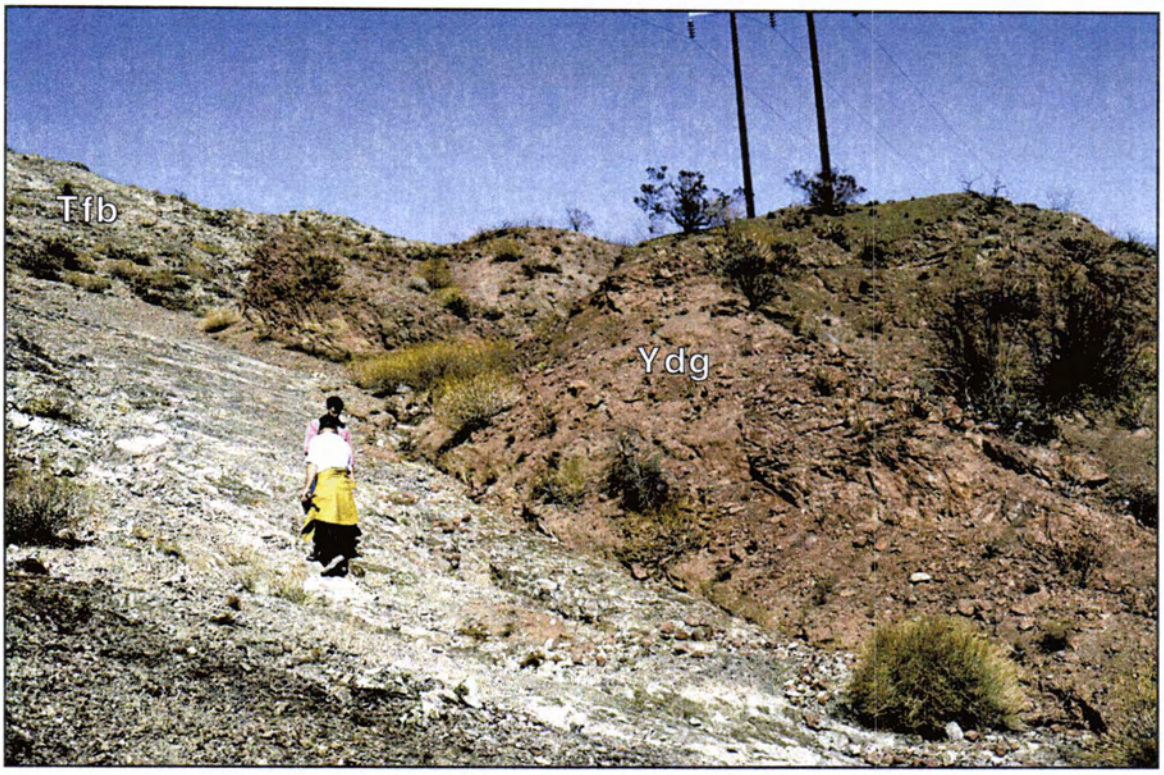


Figure 3. Newberry detachment fault. Looking north at Newberry detachment fault directly southwest of Laughlin. The highly oxidized reddish-brown Proterozoic Davis Dam granite in the hanging wall of the fault is juxtaposed against the chloritized and highly brecciated, greenish-gray Mirage pluton in the footwall (Tfb). The two individuals are standing on a gently east-inclined fault surface that contains striations and corrugations indicative of east-northeast-trending, top-side-down movement. The Newberry detachment was active mainly between 16 and 8 Ma.

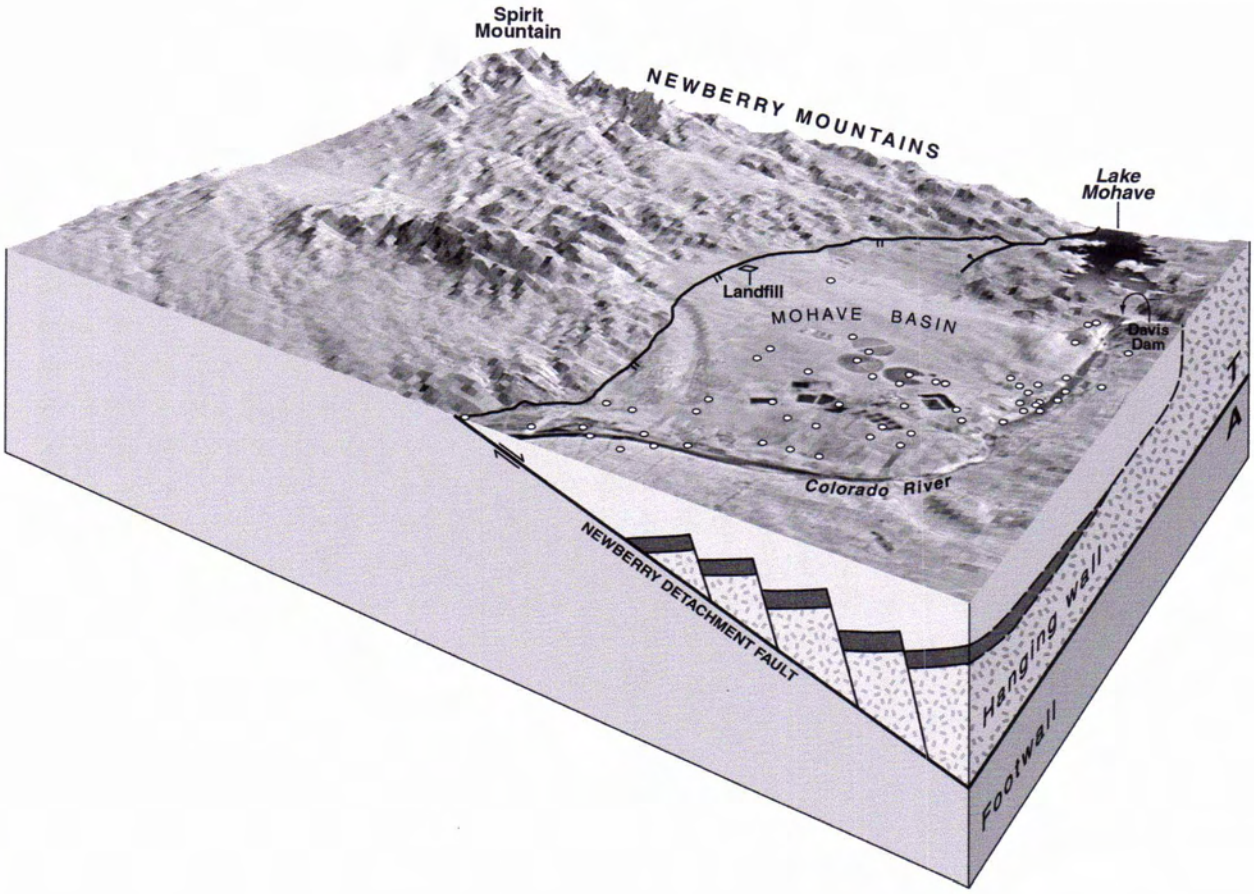


Figure 4. Oblique three-dimensional elevation model of the Laughlin area. Note that the detachment fault forms the interface between the relatively rugged Newberry Mountains and more gently sloping piedmont in the northern Mohave basin. The footwall of the detachment fault is primarily composed of Miocene granites, whereas the hanging consists of Proterozoic granite (stippled pattern), which is overlain by Miocene volcanic and sedimentary strata (dark shading). Water wells are shown as small white circles and discussed in detail in Chapter 3. T, movement toward north-south vertical profile; A, movement away from profile.

controlling structures of mineralization, (c) favored pathways for groundwater flow, and (d) overall geometry of the northern Mohave basin, which is critical for understanding the distribution of groundwater resources and local behavior of seismic waves.

The Newberry detachment fault divides the Laughlin area into two lithologically distinct domains (Plate 1; Fig. 5). In the hanging wall (downthrown block), Miocene volcanic and sedimentary strata rest directly on Proterozoic granite and gneiss. In ascending order, the Miocene section consists of (a) early Miocene prevolcanic arkosic conglomerate; (b) basaltic andesite lavas; (c) 18.5 Ma Peach Springs Tuff; (d) interfingering early to middle Miocene basaltic andesite lava flows, tuffaceous rocks, and lesser rhyolite lavas; and (d) intercalated early to middle Miocene conglomerate, sandstone, and lesser rock-avalanche deposits. The Proterozoic basement is significantly dilated by early to middle Miocene mafic to silicic dikes and quartz and calcite veins. All of these deposits are riddled with faults and tilted moderately to steeply.

In contrast, the footwall (upthrown side) of the detachment fault consists primarily of two large Miocene plutons, the Spirit Mountain and Mirage plutons (Fig. 5), and small isolated pendants of Proterozoic gneiss (Plate 1). The younger Mirage pluton intrudes the older Spirit Mountain pluton. The intrusive contact between these plutons is exposed to the southwest of Laughlin south of State Route 163. Swarms of intermediate to mafic dikes invade the Spirit Mountain pluton. Petrologic relations within the pluton (Hopson and others, 1994) and paleomagnetic data from intruding dikes (Faulds and others, 1992) suggest that the Spirit Mountain pluton is tilted moderately to the west.

Late Tertiary to Quaternary alluvial fan deposits, shed largely from the Miocene granites exposed in the footwall of the detachment fault in the Newberry Mountains, mantle the Miocene and Proterozoic rocks to the east in the hanging wall of the detachment. To the south of Davis Dam, these fan deposits thicken significantly southward and completely bury older rocks near Laughlin. Well-rounded gravels, sands, and siltstones deposited by the ancestral Colorado River interfinger with the fan deposits within about 5 km of the present course of the river (Plate 1).

Proterozoic Basement (Ydg)

The Proterozoic basement consists of ~1.4 billion year old (Ga) megacrystic granite and ~1.7 Ga gneiss and biotite schist. The 1.4 Ga reddish brown megacrystic granite is the dominant bedrock lithology in the hanging wall of the detachment and, due to excellent exposures in the roadcuts and excavations near the dam, is here referred to as the Davis Dam granite (Fig. 6; Ydg on Plate 1). The granite is composed of large potassium feldspar crystals, ranging up to 6 cm in length, and finer-grained quartz, plagioclase, and biotite. The potassium feldspar crystals are commonly rimmed by plagioclase, imparting a rapakivi texture (e.g., Volborth, 1973). The granite is weakly to locally strongly foliated and has yielded a U/Pb date on zircon of 1.425±0.025 Ga (Anderson and Bender, 1989). Small pendants (bodies of older rock surrounded by granite) of gneiss (Xgn) and biotite schist (Xbs), which are probably 1.65 to 1.8 Ga (e.g., Bennett and DePaolo, 1987; Wooden and Miller, 1990), occur in both the 1.4 Ga Davis Dam and 17 Ma Searchlight granites.

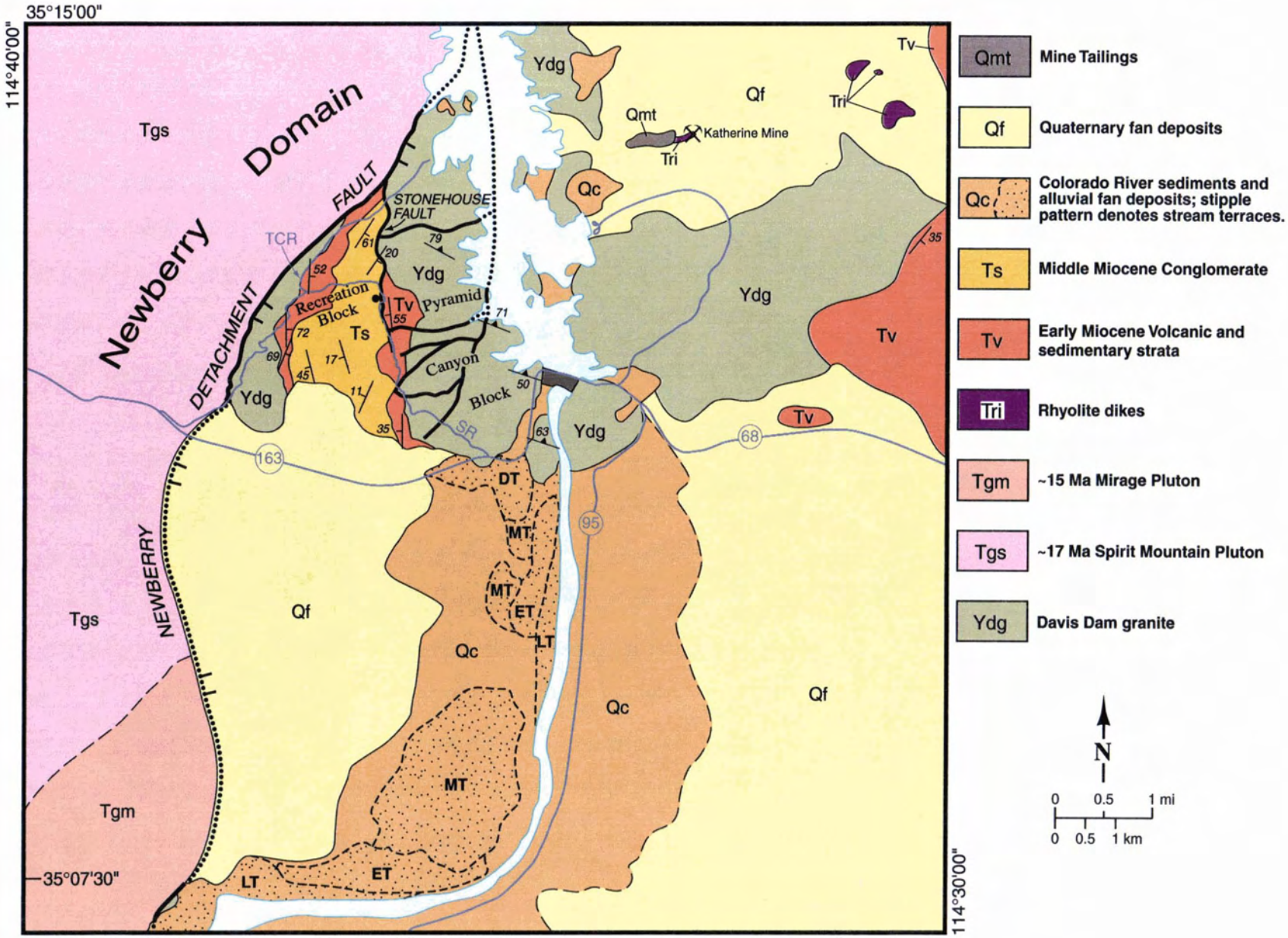


Figure 5. Simplified geologic map of the Laughlin-Bullhead City area. DT, Davis terrace; ET, Emerald terrace; LT, Laughlin terrace; MT, Mohave terrace; SR, Stonehouse Road; TCR, Telephone Cove Road.

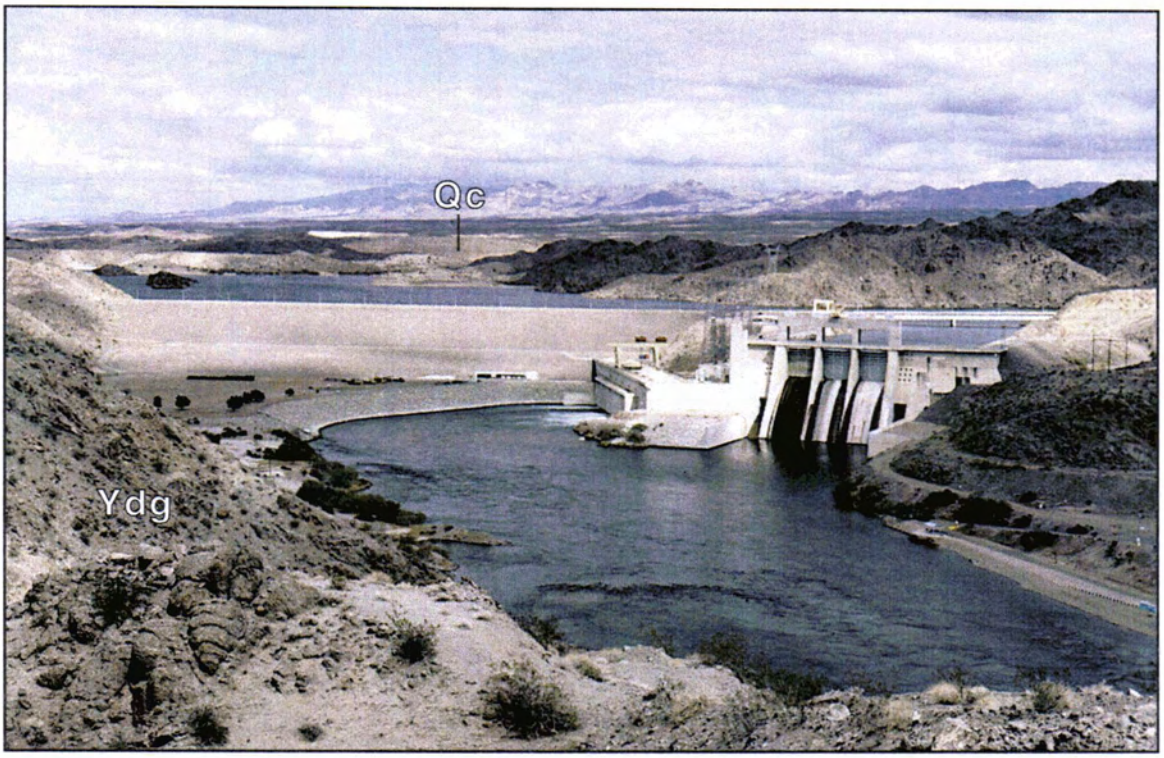


Figure 6. Looking north at Davis Dam. Davis Dam impounds the Colorado River directly north of Laughlin. Lake Mohave is the reservoir formed by the dam and is a major recreational destination for boaters and outdoor enthusiasts from the southern California, Arizona, and Nevada region. The primary purpose of Davis Dam is to regulate the flow of the Colorado River to meet downstream needs. In addition, five turbines at the dam generate 240,000 kilowatts of power. The dam was constructed near the mouth of Pyramid Canyon, which was etched into the Proterozoic Davis Dam granite (Ydg). Foliation and jointing in the granite are typically steeply inclined and oriented west-northwest and do not appear to pose any hazards to the dam. In the middle foreground in the Katherine's Landing area, Colorado River sediments (Qc-mainly Qcm and Qcs) fill a large paleochannel of the Colorado River. Erosion of this channel and/or Pyramid Canyon may be the source of the Quaternary unit Qcb described in the text.

Miocene Dikes and Veins

Miocene dikes and veins occur in two general groups. The first, and apparently older, group strikes east-west to east-northeast and includes rhyolite (Tri) and andesite dikes (Tai) and quartz (Tqv) and calcite veins (Tcv; Plate 1). Many of these dikes and veins intruded preexisting easterly striking faults. Within the map area, the easterly striking dikes and veins are confined entirely to the hanging wall of the detachment fault, where they invade the Proterozoic Davis Dam granite. These dikes and veins continue eastward into Arizona. Mineralization in the Katherine mining district is associated with east-northeast-striking rhyolite and quartz veins (Fig. 5; Lausen, 1931).

The second group includes northerly striking dikes and sparse veins. A swarm of diorite dikes cuts the Spirit Mountain pluton in the footwall of the detachment fault (Plate 1). Sparse granodiorite and basaltic dikes are also found in this area. In the hanging wall of the detachment, compositionally diverse (basalt, andesite, and rhyolite) northerly striking dikes and a few north-striking calcite veins cut the Davis Dam granite.

Only one intrusion invades Tertiary strata within the map area. This is a rhyolite dike or plug that cuts Miocene conglomerate unit near the southern limit of exposure of Tertiary strata (Plate 1, western fringe of section 2, T32S, R66E).

Even though the dikes and veins in the hanging wall of the detachment generally do not cut Tertiary strata, several lines of evidence suggest that most of these intrusions are Miocene in age. First, the northerly striking intrusions parallel the dike swarm that cuts the Miocene plutons in the footwall of the detachments. Thus, many of these dikes are probably younger than ~17 Ma and some may be younger than ~15 Ma. In addition, the northerly striking intrusions generally postdate the easterly striking dikes and veins, some of which invade faults that cut the base of the Miocene section. Finally, both northerly and easterly striking dike swarms that invade Miocene rocks are common elsewhere in the northern Colorado River extensional corridor (e.g., Spencer, 1985; Anderson and others, 1994; Faulds and others, 1995; Howard and others, 1996; Faulds, 1996; 1999; Ruppert and Faulds, 1998). Some of the northerly striking diabase dikes (Ydb) that cut the Proterozoic granite may, however, be Proterozoic in age, as suggested by similarities with other Late Proterozoic diabase intrusions in the region (e.g., Albin and Karlstrom, 1991) and truncation by the erosional surface (i.e., nonconformity) at the base of the Miocene section.

Miocene Plutons

Two large early to middle Miocene plutons occupy the footwall of the detachment fault and dominate bedrock exposures in the Newberry Mountains (Fig. 5; Howard and others, 1994, 1996; Hopson and others, 1994). Only the older ~17 Ma Spirit Mountain pluton (Howard and others, 1996) crops out in the map area (Tgs on Plate 1). It consists of medium- to coarse-grained granite and quartz monzonite. Common minerals within the granite are orthoclase, quartz, plagioclase, and lesser biotite and sphene (Volborth, 1973; Hopson and others, 1994). Within the map area, the Spirit Mountain pluton composes the bulk of the footwall of the detachment fault. It extends, however, about 10 km west of the map area and constitutes much of the higher terrain in the Newberry Mountains (Fig. 7). Small pendants of Proterozoic gneiss are encompassed by the pluton. In addition, the pluton is cut by numerous, northerly striking intermediate to mafic

Figure 7. View looking south at Spirit Mountain. Spirit Mountain constitutes the summit of the Newberry Mountains and is revered by the Mojave people. It largely consists of the ~17 Ma Spirit Mountain pluton (light colored rocks), which intrudes Proterozoic granite and gneiss (darker colored rocks). The roof of the pluton appears to be exposed on the west flank of Spirit Mountain. In the low ridges north of Spirit Mountain, the steeply west-tilted base of the Miocene section rests depositionally on Proterozoic granite. These same exposures of Proterozoic granite continue southward to the margin of the Spirit Mountain pluton. This indicates that the pluton and much of the Newberry Mountains are also tilted steeply westward, as suggested by petrologic (Hopson and others, 1994) and paleomagnetic data (Faulds and others, 1992).

dikes. Petrologic relations (Hopson and others, 1994) and paleomagnetic data from crosscutting dikes (Faulds and others, 1992) suggest that the pluton is tilted significantly to the west.

The younger ~15 Ma Mirage pluton (Howard and others, 1996) intrudes the Spirit Mountain pluton and crops out to the west and southwest of Laughlin in the footwall of the detachment fault (Fig. 5). This pluton is about 4-5 km across and consists of granite and granodiorite (Howard and others, 1994) and is generally finer-grained than the Spirit Mountain pluton. The intrusive contact with the Spirit Mountain pluton trends east-northeast through the southeastern part of the Bridge Canyon Quadrangle, south of State Route 163.

Arkosic Conglomerate (Tca)

The base of the Tertiary section consists of a reddish to purplish brown, poorly sorted, matrix-supported arkosic conglomerate (Tca on Plate 1; Fig. 8). This conglomerate rests directly on the Proterozoic granite and ranges in thickness from a few meters (< 10 feet) to over 210 m (~700 feet). Clasts are generally subangular and composed primarily of Proterozoic granite and gneiss, with lesser amounts of Late Cretaceous two-mica granite. The thickest, best exposed section crops out just east of the Stonehouse Road in the northwest ¼ of section 35 and northeast corner of section 34 (both in T31S, R66E). This arkosic conglomerate correlates with the arkosic conglomerate of Cottonwood Pass (Faulds, 1995) to the north in the Mount Davis area and is widespread across the northern Colorado River extensional corridor, characterizing the base of the Tertiary section. This unit is generally, however, less than 20 m thick. The 210 m thick section of the conglomerate in the northwestern part of the Davis Dam Quadrangle is the thickest observed thus far in the northern Colorado River extensional corridor.

Miocene Volcanics

In ascending order, Miocene volcanic strata include a lower sequence of ~19 to 20 Ma basaltic andesite lavas, the 18.5 Ma Peach Springs Tuff, dacite and rhyodacite breccia and lavas, andesite and basaltic andesite lavas, tuffaceous rocks, basaltic andesite lavas, and rhyolite lavas. The best exposures of the Miocene volcanic rocks crop out in a series of ridges directly east of the Stonehouse Road (Figs. 5 and 8) in sections 34 and 27 (both in T31S, R66E; Plate 1). The volcanic units are generally relatively resistant to erosion and therefore contribute far less detritus than the Tertiary granites to the alluvial fans in the Laughlin area. The lower sequence of basaltic andesite lavas generally rests depositionally on the arkosic conglomerate. Elsewhere in the region, basaltic andesite lavas at similar stratigraphic positions have yielded $^{40}Ar/^{39}Ar$ dates of ~18 to 19.6 Ma (e.g., Faulds and others, 1995, 1999).

A welded rhyolite ash-flow tuff, ranging up to 100 m thick, conformably overlies in most areas either the lower basaltic andesite sequence or arkosic conglomerate (Figs. 8 and 9). Near the Telephone Cover Road (Fig. 5), however, this tuff locally rests directly on Proterozoic granite. Both the stratigraphic position and phenocryst assemblage suggest that this tuff correlates with the 18.5 Ma Peach Springs Tuff (Tps on Plate 1). The Peach Springs Tuff is a distinctive rhyolite ignimbrite found across a broad region of the Southwest, extending from Barstow, California on the west to the Colorado Plateau on the east and from near Lake Mead on the north to Parker, Arizona, on the south (Glazner and others, 1986; Nielson and others, 1990). It contains 10 to 20% phenocrysts composed dominantly of sanidine, with lesser amounts of plagioclase,

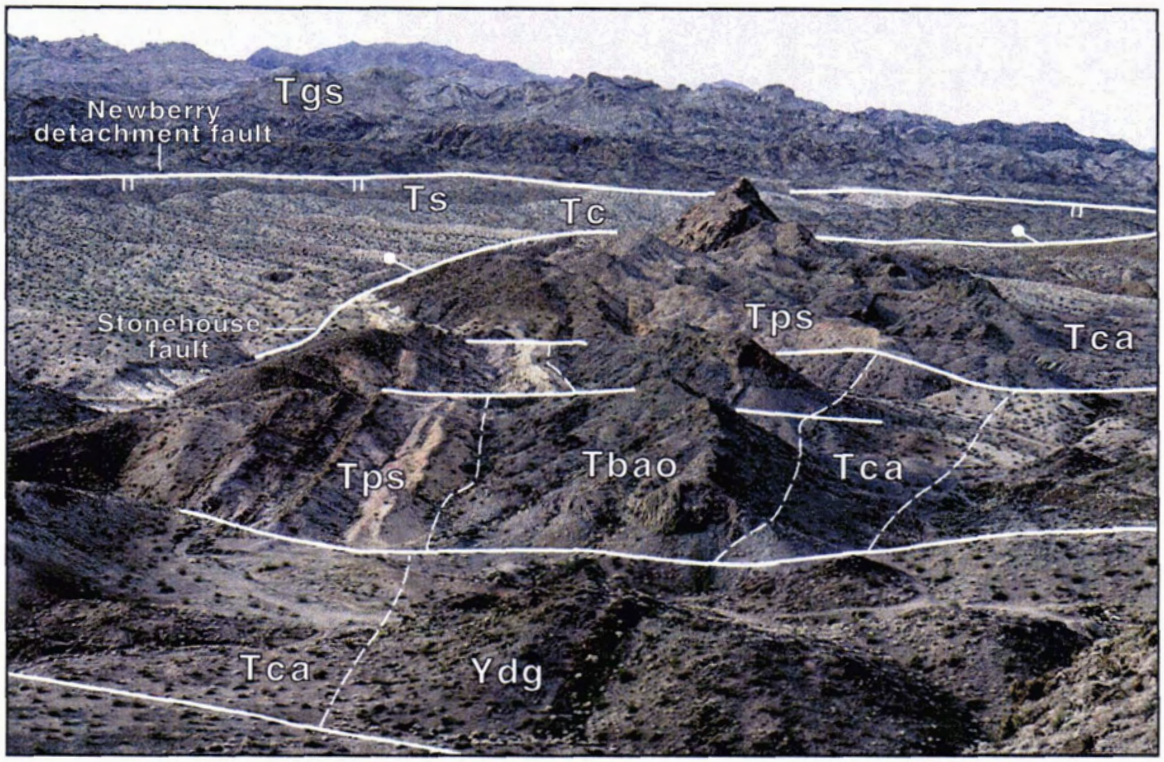


Figure 8. Looking north at Miocene strata in the Davis Dam domain. Strata within the immediate hanging wall of the Newberry detachment, including the Roadside (Ts) and Recreation (Tc) conglomerates, lie within the Recreation block and are tilted gently to moderately east. The west-dipping Stonehouse fault bounds the east-tilted Recreation block on the east. In contrast to the east tilts in the Recreation block, steep west tilts characterize the lower part of the Miocene section to the east of the Stonehouse fault within the Pyramid Canyon block. Tgs, Spirit Mountain pluton; Ts, Roadside conglomerate; Tc, Recreation conglomerate; Tps, Peach Springs Tuff; Tbao, basaltic andesite lava flows; Tca, basal arkosic conglomerate; Ydg, Davis Dam granite.

Figure 9. Looking north at Peach Springs Tuff (Tps). The 18.5 Ma Peach Springs Tuff is one of the thicker and more conspicuous units within the Miocene stratigraphic section. Here, it is tilted about 60° west in the western part of the Pyramid Canyon block, which forms the western limb of the Davis Dam anticline.

biotite, hornblende, and sphene. The sanidine phenocrysts commonly display a blue chatoyance. On the basis of flow fabric defined by anisotropy of magnetic susceptibility, Hillhouse and Wells (1991) suggested that the source caldera for the Peach Springs Tuff may be buried under younger deposits in the Mohave Valley. Although no calderas were identified in this study, it is noteworthy that the Peach Springs Tuff in the Laughlin area commonly contains large (up to 30 cm in length) lithic fragments of andesite and Proterozoic gneiss. Lithic fragments in ash-flow tuffs are typically largest proximal to the caldera. Dacite-rhyodacite breccia and lavas disconformably overlie the Peach Springs Tuff and locally fill small paleochannels cut into the tuff. These lavas and breccia may be genetically related to the Peach Springs Tuff.

A sequence of intercalated felsic volcanic rocks (Tts on Plate 1) and mafic lavas (Ta and Tbay) rests directly on the dacite-rhyodacite breccia and lavas or Peach Springs Tuff. The felsic volcanic rocks include thin nonwelded pyroclastic flows, tuffaceous conglomerate and sandstone, and rhyolite lavas. The mafic lavas are generally andesites or basaltic andesites and contain plagioclase, clinopyroxene, and/or olivine phenocrysts. Tilt magnitudes in this bimodal sequence are similar to that of the Peach Springs Tuff and basal arkosic conglomerate. The uppermost part of the sequence locally interfingers, however, with the basal part of the lower middle Miocene conglomerate unit. These relations suggest that the bulk of the Miocene volcanic section was deposited prior to the onset of major tilting and east-west extension.

Middle Miocene Conglomerates (Ts and Tc)

The uppermost part of the Miocene section consists of two relatively non-resistant conglomerate units that weather into low ridges and hills to the east of the Telephone Cove Road (Fig. 5 and Plate 1). Both units are significantly faulted and tilted, which distinguishes them from the younger essentially flat-lying late Miocene to Quaternary fan deposits. The lower unit (Ts on Plate 1), here referred to as the Roadside conglomerate, consists of reddish to purplish brown, weakly indurated, poorly sorted, generally matrix-supported pebble to cobble conglomerate and lesser medium- to coarse-grained sandstone, siltstone, and megabreccia of Proterozoic granite and early Miocene lavas. This unit appears to rest unconformably on early Miocene dacite, rhyolite, and basaltic andesite lavas. Clasts are typically subangular and include Proterozoic granite and early Miocene volcanic rocks and dikes. In contrast to the upper conglomerate, clasts of Miocene granite are sparse. The bulk of the Roadside conglomerate probably originated as alluvial fan deposits. The megabreccia, however, probably reflects rock-avalanche deposits (i.e., landslide deposits; e.g., Yarnold and Lombard, 1989) derived from nearby mountain fronts. The composition of the conglomerate and megabreccia indicate derivation largely from fault blocks in the hanging wall of the detachment fault in a physiographic setting that differed significantly from that present today, as the granitic terrane of the Newberry Mountains was apparently not extensively exposed. Comparisons with similar units in the Mount Davis area to the north of Laughlin (Faulds, 1995) suggest an age of about 16 to 13 Ma. The presence of the megabreccias and an upward decrease in tilt (i.e., tilt fanning) further implies that this unit was deposited during major extension.

The upper unit, here referred to as the Recreation conglomerate (Tc on Plate 1), is composed of light gray to white, unconsolidated to weakly indurated, poorly sorted, generally matrix-supported cobble to boulder conglomerate (Fig. 8). This unit appears to rest conformably on the Roadside conglomerate. Subangular granitic clasts of the Spirit Mountain pluton dominate the

Recreation conglomerate and indicate a provenance in the Newberry Mountains. This implies that, by the time of deposition, enough displacement had accumulated on the detachment fault to expose much of the Newberry Mountains to erosional denudation. The bulk of this conglomerate originated as debris flows, sheetfloods, and sediment-laden water floods on alluvial fans shed from the Newberry Mountains. The overall setting during deposition of this fanglomerate probably differed little from that present today. In fact, the Recreation conglomerate greatly resembles the Quaternary fan deposits and can be easily mistaken for such deposits in areas of poor exposure. However, stratigraphic and structural relations in the Lake Mohave region to the north of Laughlin (Faulds, 1995; Faulds and others, 1995) suggest that this fanglomerate is of great antiquity and is probably about 11 to 15 Ma. Tilt fanning within this unit implies synextensional deposition.

Quaternary Geology and Geomorphology

The Quaternary Period is the most recent and shortest period of geologic time. It spans approximately the last 1.8 million years and is divided into two intervals: the Pleistocene epoch (roughly 1.8 million years to 10,000 years before the present) and the Holocene epoch (roughly 10,000 years before present to the modern era). Quaternary surficial deposits in the study area record the responses of the Colorado River and its tributary washes to climatic changes of various magnitudes and durations that have occurred during this time. The most recent major change in climate occurred at the end of the Pleistocene epoch when the last major glacial episode ended. This profound change in global climate caused significant changes in fluvial systems that allow for relatively easy differentiation of Holocene fluvial deposits from Pleistocene ones. Stratigraphic and geomorphic relationships allow for differentiation of individual geologic units deposited during each of the epochs.

Physical Setting of Laughlin

The urban commercial corridor of Laughlin occupies a relatively narrow strip of flat-lying land along the lower Colorado River. This was the active floodplain of the river prior to the construction of dams upstream. It is composed of young Colorado River flood deposits and interbedded tributary alluvium. The remainder of the town to the south and west and above the modern floodplain is referred to in this report as the Laughlin piedmont—the broad sloping surface located between the eastern front of the Newberry Mountains and the modern floodplain of the Colorado River (Fig. 2). The Laughlin piedmont is a composite geomorphic surface composed of a complex mosaic of surficial geological deposits and landforms including active alluvial fans, braided washes, extensive relict alluvial fan surfaces, and relict Colorado River floodplain terrace surfaces. The alluvium underlying the piedmont surface is thus a complex mixture of sandy to bouldery tributary detritus and Colorado River deposits composed of silt, sand, gravel, cobbles, and boulders.

Alluvial Deposits and Geomorphic Features of Laughlin Piedmont

The Laughlin piedmont can be divided into upper and lower portions at an elevation of approximately 250 m (840 ft), the elevation of the highest exposed Colorado River deposits to the west of Laughlin. Using this division, the upper portion of the piedmont (that portion nearest

the mountain front) is thus composed exclusively of gravelly alluvial fan deposits, and the lower piedmont (that portion nearest the river) is composed of a complex mixture of alluvial fan and Colorado River deposits. The distribution of these deposits, their degree of interlayering, and their morphologic characteristics are controlled by the long-term interaction between the lower Colorado River and its tributary streams heading in the Newberry Mountains to the west.

Tributary Alluvium

Alluvial deposits of the principal drainages debouching onto the Laughlin piedmont are composed almost entirely of poorly rounded granitic sand and gravel shed from the Newberry Mountains. Clasts of more mafic rock are present in lesser amounts but are preferentially preserved on old surface remnants because of their greater resistance to weathering (Fig. 10). Tributary alluvium comprises deposits of crudely bedded sediments ranging in size from sand to boulders. The relict alluvial deposits are easily distinguished from those of presently active washes by virtue of their comparatively rugged erosional topography and evidence for relatively strongly developed soils, although many of the soil profiles have been stripped to a weakly to moderately cemented carbonate horizon (Fig. 11). The degree of carbonate development in these soil ranges from Stage 2 to Stage 3, which is indicative of significant antiquity (10s of 1000s of years; Machette, 1985). Active alluvial fans and washes are characterized by a varying abundance of channel features largely depositional topography (e.g., well-preserved channels and bars), and very weakly developed to non-existent soil profiles.

On the geologic map, we divided tributary alluvial deposits into two major mappable units. The older series of units (Qai) is divided into three subunits (Qai_1, Qai_2, Qai_3) when possible, based on relations with the major river terraces described below); the younger deposits (Qay) are associated with the presently active fluvial systems and are divided into two subunits when possible. The subunits (Qay_1 and Qay_2) reflect both their relative age as well as their relative frequency of inundation. In cases where Qay_1 and Qay_2, may overlap in age, the distinction is genetic (related to the origin of the deposit)—most Qay_1 is shown in relation to deposits derived from erosion of the older alluvial deposits on the piedmont and to a lesser extent, fluvial terraces adjacent to Qay_2 in major active channels. The unit Qay_2 represents alluvium in the major channels draining mountainous watersheds in the Newberry Mountains. This distinction is relevant to the flood hazard evaluation presented in Chapter 2.

Colorado River Alluvium

Ancient Colorado River deposits are easily distinguished by their sedimentology and typically planar surface expression. Most Colorado River deposits on the piedmont contain a mixture of rounded gravels, cobbles, and boulders that are relatively resistant to erosion (Fig. 12). Other Colorado River deposits that range from mud (silt and clay) to sand are present in some areas of the piedmont (e.g., Fig. 13). These units are considerably less resistant to erosion, and where they are not overlain by more resistant sediments, they erode into a badland-like topography. The majority of deposits associated with the Colorado River are sands and gravels that have been transported many kilometers from their places of origin and thus represent many types of rock that are not found locally. This fact and certain characteristics of their shape (degree of rounding in particular) and depositional landforms make them easy to distinguish from locally derived alluvial fan deposits.

Figure 10. Typical surface of tributary alluvium deposit (Qai). Tributary alluvium is easily distinguished by the abundance of angular gravel derived from bedrock exposed in the Newberry Mountains. The white scale bar and blue pen in the photo are 16.5 cm (6.5 in) long.

Figure 11. Exposure of soil carbonate horizon in Qai alluvium. The older (Pleistocene) deposits of tributary alluvium on the piedmont are characterized by a moderately well-developed and locally cemented soil carbonate ($CaCO_3$) horizon. The zone of greatest carbonate concentration in this exposure is outlined with dashed lines. Also, as is evident here, the soil profiles are often stripped to or near the indurated carbonate horizon. This generally degraded state of relict tributary alluvial deposits is common to most of the Pleistocene deposits on the piedmont. The brown field book in the photo is approximately 20 cm (8 in) long.

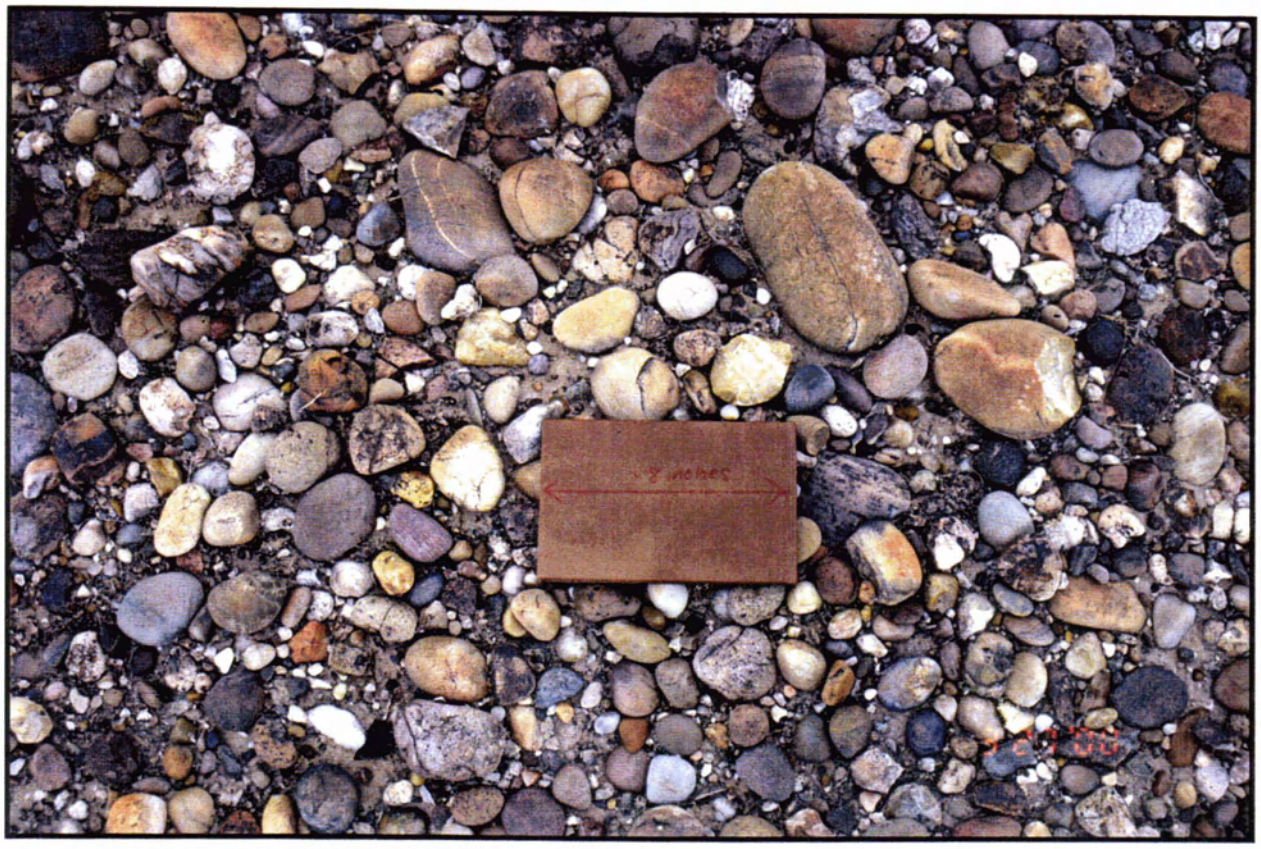


Figure 12. Typical surface of Colorado River gravel deposit (Qcg). Colorado river gravel deposits are easily distinguished in the field by the presence of well-rounded, exotic (far-traveled) gravels. Field book in photo is approximately 20 cm (8 in) long.

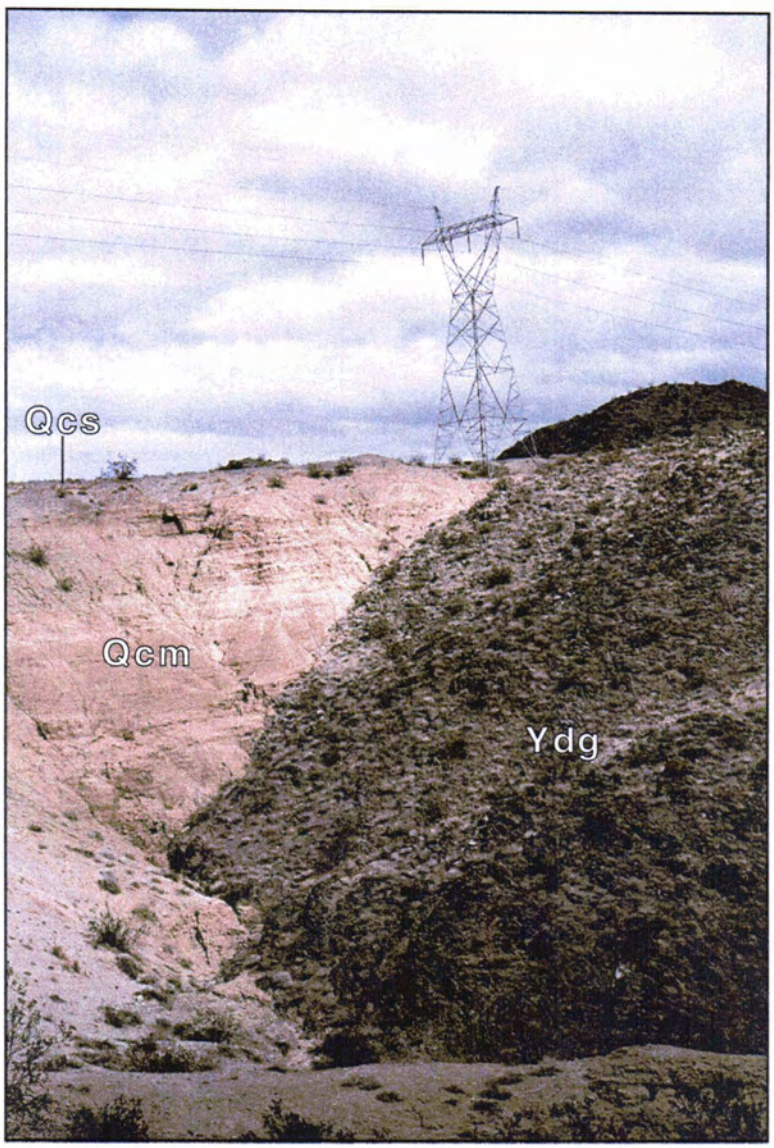


Figure 13. Onlap of Colorado River sediments on Davis Dam granite. Looking northwest at onlap of Colorado River muds and silts (Qcm) and sands (Qcs) on Proterozoic Davis Dam granite (Ydg) about 1.6 km (1 mi) south of Davis Dam. The upper surface of the Colorado River sediments corresponds to the Davis terrace. This sequence of river sediments appears to occupy a paleochannel carved in the granite, which may be a source of unit Qcb.

The Colorado River deposits older than the modern floodplain deposits are not subdivided by age on Plate 1. They are designated as Qc and related subdivisions: Qcs (sand), Qcm (mud/silt), Qcg (gravel) and Qcb (boulders). The label "Qc" refers to areas where the deposits are undifferentiated but clearly associated with the Colorado River. Further detailed evaluation of the geomorphic and stratigraphic relationships between the various exposures of the Colorado River sediments and associated stream terraces (below) will allow for a more detailed chronologic differentiation of these units.

Stream Terraces

The dominant features on the lower piedmont are stream terraces of the Colorado River. A stream terrace is a landform created by a combination of lateral erosion and aggradation by a stream or river. They are generally planar in form and gently sloping in relation to adjacent tributary alluvial deposits. Stream terraces are essentially ancient stream beds, and their presence is a record of the history of the associated river and its episodes of aggradation and entrenchment. The Colorado River serves as the base level for all tributary streams on the Laughlin piedmont and its ancient bed elevations exert a profound influence on the distribution of temporally correlative piedmont alluvial deposits.

Stream terraces are generally of two types: fill and strath. A fill terrace is a surface that represents the culmination of an aggradational episode and is underlain predominantly by deposits associated with the aggradation event. A strath terrace is a beveled surface created by lateral erosion by the river during a period of a relatively stable base level. Strath terraces are characterized by the truncation, or generally planar erosion, of underlying geological units (bedrock or older alluvium). Fill terraces are characterized by the burial of pre-aggradation topography and may bury strath surfaces. Although most of the deposits below a strath terrace may be considerably older than the event which formed the surface, the terrace surface is usually mantled by thin deposits of alluvium associated with the strath-forming event. A range of possible variants and combinations of each of these end-member types of terraces may occur.

For the purposes of this report, each major stream terrace on the Laughlin piedmont has been given an informal name derived from local cultural features. There are four main terraces, including (Figs. 5 and 14): 1) the Davis terrace; 2) Mohave terrace; 3) Emerald terrace; and 4) Laughlin terrace. Each is described below from oldest to youngest.

Davis Terrace

The Davis terrace is a fill terrace underlain by bedded mud, sands, and, to a lesser extent, river gravels and alluvial fan gravels. The upper surface is approximately 100 m (330 ft) above the modern river level and thickness of the alluvial fill is at least 70 m (230 ft) (Figs. 13 and 15). This terrace and its associated alluvium comprise a relatively thick sequence of fine-grained deposits of bedded silt and fine sand likely associated with a period of rapid aggradation by the Colorado River. These deposits are largely correlative with sediments commonly referred to as the Chemehuevi Formation (Lee, 1908, Longwell, 1963). The surface is capped with a veneer of gravel that may indicate the onset of erosion and entrenchment by the river.

Stratigraphic relations indicate that the oldest fan remnants on the Laughlin piedmont overlie sandy Colorado River deposits of the Davis terrace at their distal margins (Plate 1). In some

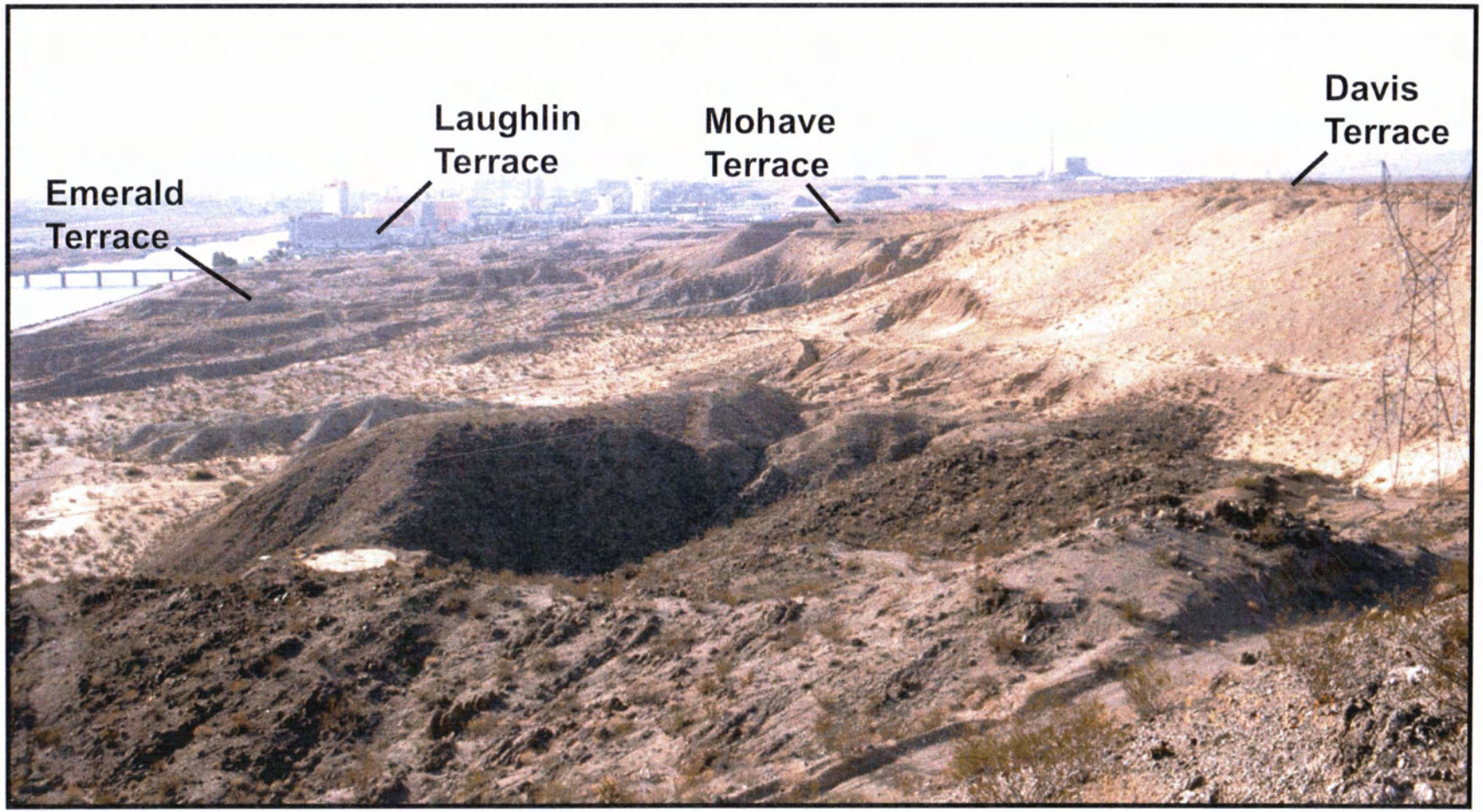


Figure 14. The principal Colorado River terraces in the Laughlin area. This photo was taken from a bedrock outcrop to the southwest of Davis dam. The principal Colorado River terrace assemblage is evident from this vantage point. The Emerald Terrace remnant has been extensively mined for sand and gravel and is quite degraded. The Laughlin Terrace is the location of the large hotel-casinos of the Laughlin Strip.

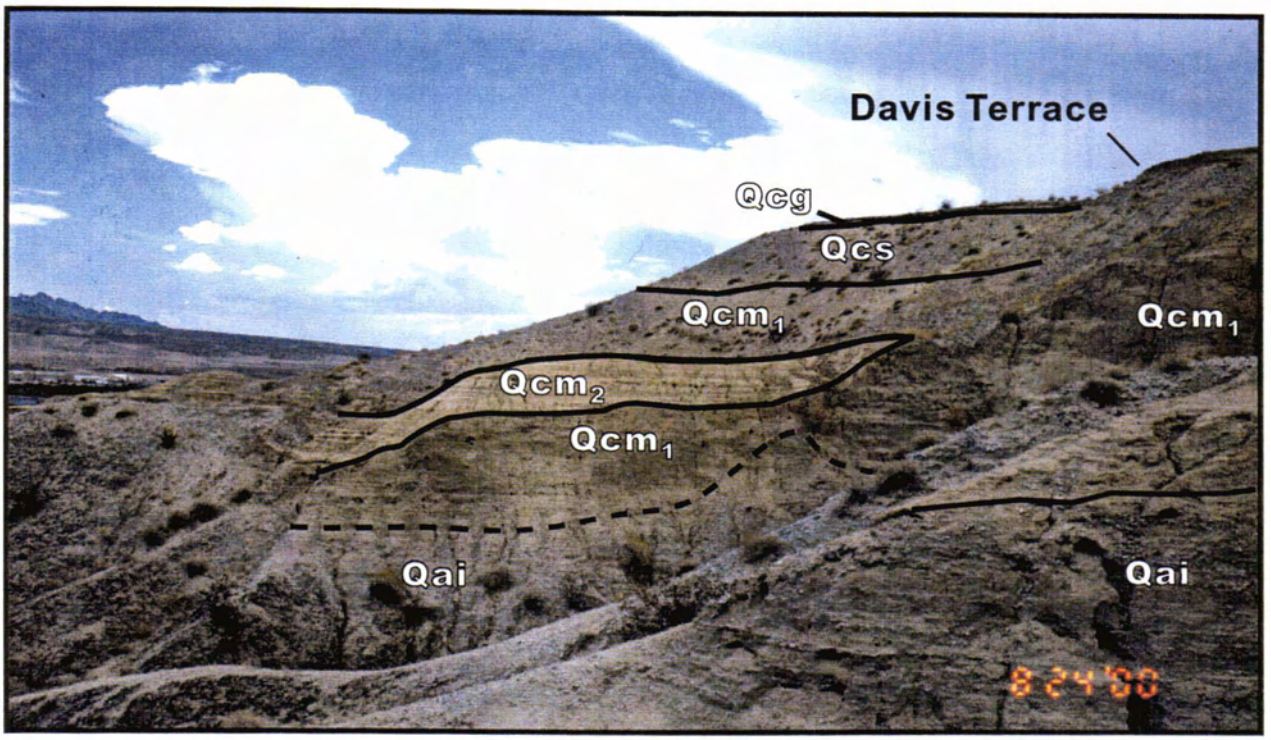


Figure 15. Exposure of stratigraphy underlying the Davis Terrace. The internal stratigraphy of the Davis Terrace includes a variety of deposits from the Colorado River that unconformably overlie tributary alluvium. The photo was taken from a site south of Davis Dam and north of the Laughlin Strip. The view is to the south. The unit designated as Qcm_2 is an onlapping deposit of silty Colorado River sediment that post-dates the deposition of the similar sediments in the Davis Terrace. It is likely that it is correlative with similar alluvium in the Mohave Terrace.

cases, the distal portions of the relict fan surfaces are truncated by erosive action of the river along a level commensurate with the top of the terrace, forming a fluvial scarp. This indicates that at least some of the old fan deposits and the highest preserved Colorado River sands are roughly coeval. Other geological investigations in the area have estimated that this sequence of Colorado River sediments is no younger than 40,000 years and may be as old as 250,000 years (Blair, 1996; Bell, 1978; Lundstrom and others, 1999). This provides a key stratigraphic and geomorphic relationship that, when combined with other types of physical properties of the surfaces, allows for a straightforward division of piedmont alluvial deposits by age. Those alluvial deposits that are interbedded with the Colorado River fine-grained deposits at their distal ends are no younger than 40,000 years. Because these fans were graded to a level of the river some 100 m (~330 ft) higher than the modern bed, subsequent down cutting by the river has induced analogous down cutting along its tributaries resulting in a clear topographic separation between older and younger fan deposits.

Mohave Terrace

The Mohave terrace is predominantly a strath terrace that is cut into sediments of the Davis terrace and older piedmont and river deposits. Locally, the terrace buries irregularly eroded topography with several meters of alluvium indicating that locally, at least, it is a composite cut and fill terrace (Fig. 16). The alluvial fill includes a sequence of interbedded river gravels, muds, sands and piedmont gravels. The terrace surface has a maximum elevation of approximately 700 ft (210 m) in the study area, or approximately 60 m (200 ft) above the modern river. It represents a period of net vertical stability along the Colorado River in which it eroded laterally following a period of incision into the sediments of the Davis terrace and the older underlying deposits. The stratigraphy of the Mohave terrace includes a complex mixture of alluvial fan gravels, river gravels, and fine-grained river deposits. In some locations older geologic units (late Tertiary age) have been observed in deep gullies carved into the terrace. The surface is capped with a variably thin veneer of river gravel. An analogous sequence of deposits but with a less well-preserved terrace surface is located just to the northwest of the Laughlin Strip and is traversed by the recently modified alignments of State Route 163 and Laughlin Civic Drive. These roads intersect near the top of the sequence.

A suite of piedmont alluvial fan deposits is graded to and likely interbedded with deposits of the fill sequence at the top of the Mohave terrace. These deposits can thus be distinguished as being younger than those graded to the top of the Davis terrace, even though their general physical characteristics (topography, soil development) are strikingly similar.

Emerald Terrace

The Emerald terrace is a composite strath and fill terrace with a maximum elevation of 20 m (70 ft) above the modern river. The terrace and its associated alluvium were formed by an episode of aggradation following a period of entrenchment into the Mohave terrace and underlying deposits. The Emerald terrace is poorly preserved because the underlying alluvium is extensively exploited for sand and gravel resources. It is also confined to a relatively narrow strip adjacent to the modern river, and much of it has been removed by erosion. Remnants of the terrace are found in two principal locations along the Nevada side of the river. One is immediately south of Davis Dam. This deposit has been extensively mined and nearly obliterated

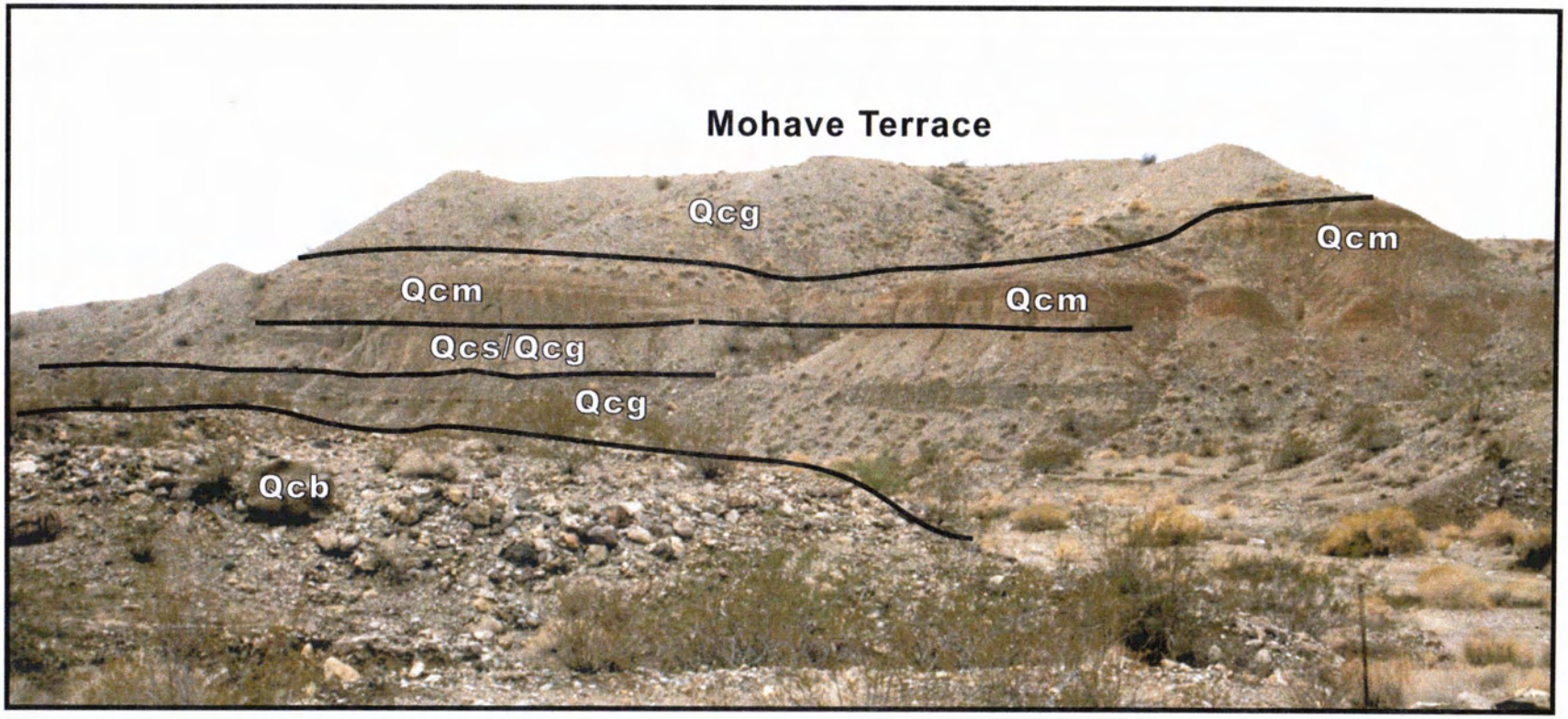


Figure 16. Exposure of stratigraphy underlying the Mohave Terrace. This photograph highlights the alluvial fill that is associated with the Mohave Terrace. At several other sites where the terrace stratigraphy is exposed, the alluvial fill is considerably less thick. Here, the entire sequence above the Qcb (which is in the foreground) and probably the lower Qcg layer is alluvial fill associated with the Mohave Terrace. This particular site is within the property of the Mohave Generating Station. The view is to the southeast.

as a distinct, mappable unit. The other remnant is in the area of Emerald River Golf Course. Here too the alluvium has been extensively mined and otherwise modified by development. Some isolated, pristine remnants of this deposit can be found within the boundary of the Mohave Generating Station. In the Laughlin area, the alluvium of the gravel pit terrace was deposited along a narrow strip no more than about 760 m (2500 ft) from the present channel location. In addition to the gravel mining operations, much of the original alluvium was removed by the river by lateral erosion as it entrenched to its present elevation. A much more extensive remnant of the Emerald terrace is preserved in the Big Bend area in Bullhead City, Arizona.

Relict tributary alluvial fan deposits that are graded to the level of the Emerald terrace are sparse because of the removal of much of the alluvium adjacent to the river. However, there are some remnants of correlative tributary alluvium that emanate from the larger drainages that have formed in the Mohave terrace. Also, there is a relict alluvial deposit of Hiko Wash that appears to overlie the outer margins of the Emerald terrace. It is likely that much of tributary alluvium has also been removed by erosion along the piedmont drainages. Interestingly, the alluvial fans that are graded to the Emerald terrace have physical characteristics that are quite similar to the two older generations of alluvial fans on the piedmont, indicating that the river experienced a rapid period of down-cutting followed by a relatively extensive period of stability.

Laughlin Terrace

The Laughlin terrace is underlain by silt, sand, and lesser deposits of piedmont alluvium. It was the active floodplain of the Colorado River prior to construction of dams upstream (Hoover Dam and Davis Dam, in particular) and received intermittent overbank deposition from the river. This surface is also is the point of termination of most of the washes and alluvial fans draining the piedmont and the Newberry Mountains. Flow regulation by the dams has completely altered the river's flood regime such that this terrace is no longer receiving deposition by the river and, in this sense, is an inactive, or relict feature. In areas where drainage controls are not in place, active washes continue to deposit gravel on the Laughlin terrace.

Overview of Quaternary History

The Colorado River serves as the base level for all tributary streams draining the Laughlin piedmont and adjacent portion of the Newberry Mountains. The history of the river, then, provides the best framework for evaluating the history of the piedmont. During the Quaternary, the Colorado River underwent a series of episodes of aggradation and channel entrenchment most likely associated with the influence of global and regional climatic changes on the river's hydrology and sediment yield (Bull, 1991). The geomorphology and internal stratigraphy of the four terraces in the Laughlin area record the complex history of the river and its interactions with local and regional tributary streams and washes.

Colorado River Record

During most of the Tertiary, as the Mohave Basin was forming by crustal extension, the area in which Laughlin is located was not integrated with the Colorado River. The timing of the integration of the basin is not well-constrained but it may coincide with the some phase of deposition of the upper portion of the Bouse Formation which has a geochemical signature

suggestive of deposition in a fresh water, lacustrine setting (Spencer and Patchett, 1997). The earliest evidence for the Colorado River in the vicinity of Laughlin may be associated with a distinctive topographic discontinuity at approximately the 378 m (1240 ft) level. At this level, there is a prominent erosion surface in the Newberry Mountains that is suggestive of extensive lateral erosion by the river. Moreover, a less well preserved erosion surface is discernible in the bedrock areas near Davis Dam where no peak exceeds 378 m (1240 ft) It is possible that this erosion surface is associated with the earliest presence of the Colorado River in the area, but this is somewhat conjectural. We have not identified any distinctive river deposits associated with this level in the Laughlin area but river gravels have been identified at approximately 365 m (1200 ft) in Secret Pass Canyon east of Bullhead City, Arizona. Following this period of apparently long-term vertical stability and extensive lateral erosion of bedrock, the Colorado River and its tributaries experienced a period of net vertical erosion of an unknown duration to a level of approximately 183 m (600 ft). This created the space for the preservation of alluvial deposits that record several subsequent episodes of aggradation and incision along the river and its tributaries.

The reported maximum depth of incision to the 183 m (600 ft) level is associated with the apparent base of the Quaternary section in the Laughlin area. At this level there is Colorado River deposit of boulders and large cobbles that in some outcrops is nearly entirely composed of clasts of the Davis Dam granite (Ydg) (Fig. 17). Scattered outcrops below the surface of the Mohave terrace indicate an erosional unconformity between this deposit and Tertiary fanglomerates and sediments that are likely of the 4-8 Ma Bouse Formation. Outcrops of the bouldery unit are mapped as Qcb on the map (Plate 1). Small exposures of Qcb are scattered over the lower Laughlin piedmont at approximately the 183-195 m (600-640 ft) level (Plate 1). The age of this unit has not been determined, however, it underlies all of the river terraces and deposit assemblages described previously. A correlative unit on the Arizona side of the river has not yet been described.

The distribution of Qcb, its clast composition, and its texture all suggest the occurrence of one or more extremely large Pleistocene floods on the Colorado River that breached some form of bedrock obstruction upstream composed largely of the Davis Dam granite. Two local possibilities for such a breach are the present location of Davis Dam at the mouth of Pyramid Canyon, or the abandoned channel to the southwest of the dam, which was subsequently backfilled by deposits of the Davis terrace. At a site to the south of Harrah's Casino, a cobble-dominated deposit of Qcb can be seen unconformably overlying cemented Tertiary alluvium (Fig. 18). Near this site, Qcb grades upward into a thick homogeneous deposit of rounded river gravels and cobbles (Qcg) that unconformably overlie a small outcrop of the Bouse Formation.

All alluvial deposits associated with the major terraces on the Laughlin piedmont, with the exception of the Laughlin terrace, overlie Qcb. And are all probably considerably younger. It is likely that the overall durability of this coarse deposit may have resulted in its selective preservation during periods of erosion subsequent to its deposition. Our preliminary interpretation is that Qcb and related overlying gravel deposits represent the base of the oldest preserved Quaternary aggradation event in the Laughlin area. Stream terraces that recorded this event have been largely removed by subsequent erosion and may also be buried by younger deposits.

The alluvium of the Laughlin terrace represents the most recent and presently active phase of Colorado River deposition. Prior to the construction of Davis Dam, this was the active floodplain

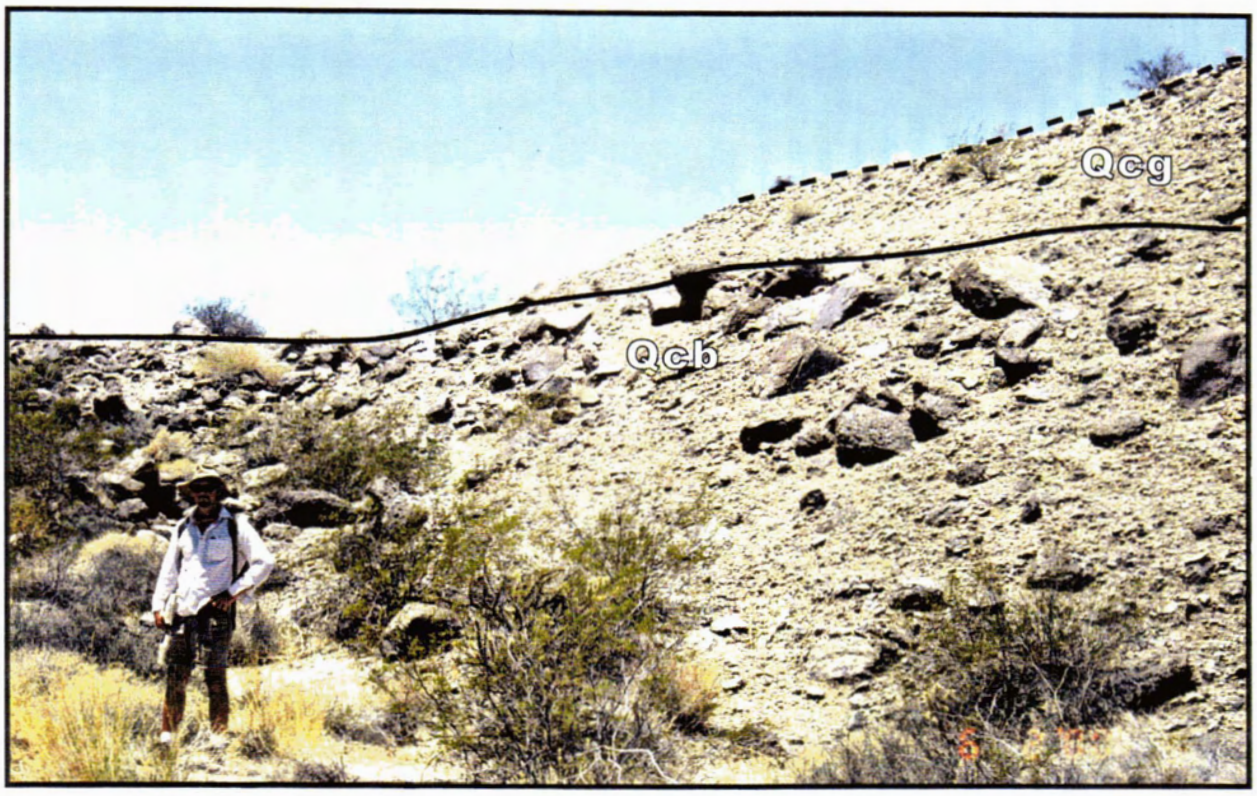


Figure 17. Exposure of bouldery alluvium of the Colorado River (Qcb). The large clasts in this exposure are entirely derived from the Proterozoic Davis Dam Granite (Ydg). It is uncertain whether the overlying gravels (Qcg) consitute the upper portion of the Qcb unit, or if they represent a considerably younger deposit overlying an unconformity. This photo is from a site about 1 mile northwest of the Laughlin Strip.

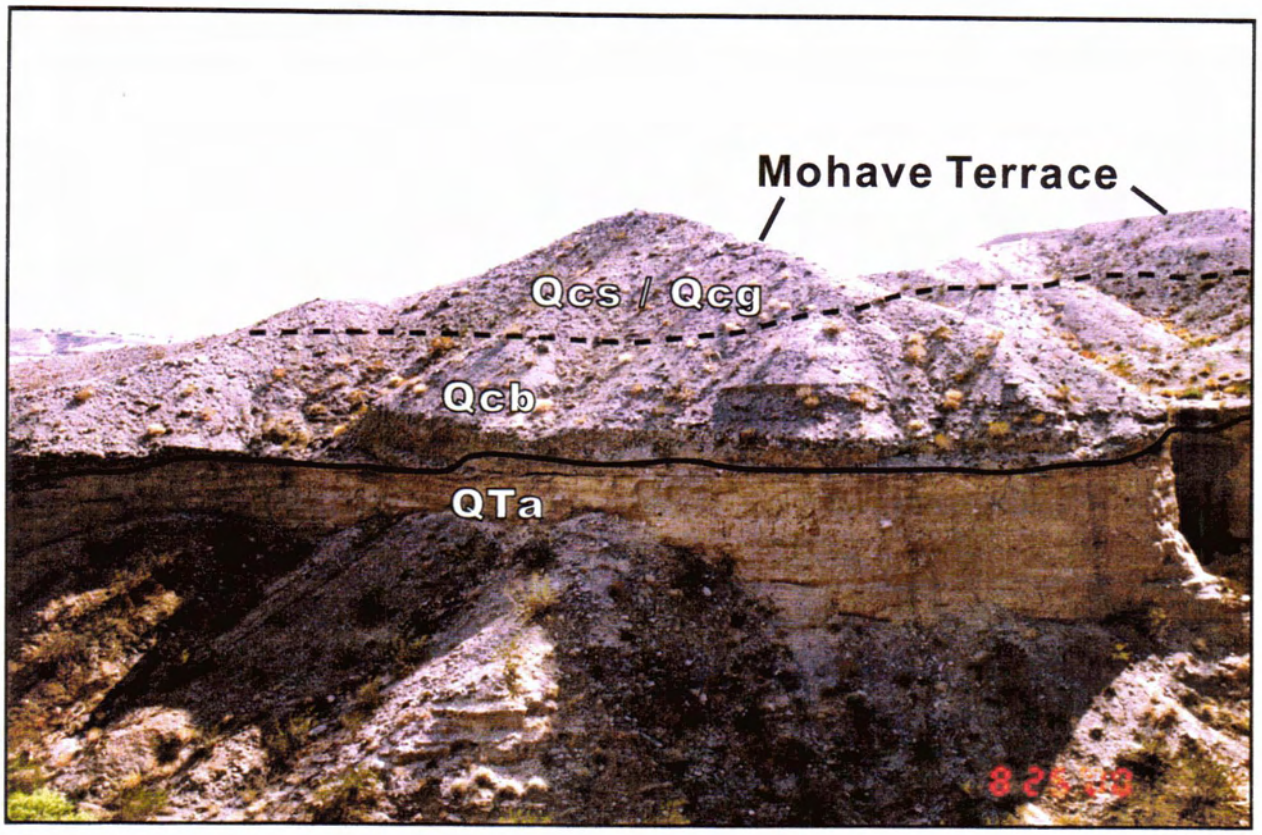


Figure 18. Exposure of unconformity between Tertiary alluvial fan gravels (QTa) and coarse-grained Colorado river deposit (Qcb). Here, the erosional contact between Late Tertiary alluvial fan deposits and Colorado River gravels is clear. The site is in a deep gully in the Mohave Terrace about 0.5 miles south of Harrah's Casino. View is to the southeast. In this particular sequence, Qcb is composed almost entirely of cobbles derived from the Davis Dam Granite (Ydg). Its upper contact with interbedded Qcs and Qcg appears to be an unconformity, and the upper unit is alluvial fill associated with the Mohave Terrace.

of the Colorado River. Presumably, all of the alluvium along the Nevada side of the river is late Holocene in age. Older Holocene deposits have presumably been removed by lateral erosion of the river. In the Big Bend area, however, it is likely that a more comprehensive suite of Colorado River deposits is intact because the relatively interrupted westward migration of the channel has allowed a suite of Quaternary river deposits to remain intact.

Record of Piedmont Alluvium

The oldest Quaternary tributary alluvium on the piedmont appears to be at least somewhat coeval with the Chemehuevi Formation. This is indicated by the interbedded relationship between the top of the Davis terrace sediments and the distal portions of the apparently oldest alluvial fan remnants on the piedmont. However, tributary alluvium is evidently buried by the Colorado River deposits at the base of the Davis terrace. This indicates that this tributary alluvium, at least, is older than the Colorado River deposits. To date, we have not been able to determine the specific relation between the tributary alluvium at the base of the terrace and the tributary alluvium that buries the portions of the top of the terrace. The difference in age between these packages of tributary alluvium is dependent to a great extent on the rate at which the river deposited the intervening sediments. This is not yet fully understood and remains the subject of some debate (Blair, 1996; Bell, 1978; Lundstrom and others, 1999).

Overall, it appears that the majority of the Quaternary surficial deposits on the Laughlin piedmont probably date to the mid-late Pleistocene, or the last 250,000 years. The oldest alluvium on the piedmont probably dates to the middle Pleistocene on the basis of soil characteristics, stratigraphic relationships with dated adjacent stratigraphy, and geomorphic relationships with Colorado River terraces and erosional scarps. The lack of preservation of any significantly older easily identifiable Pleistocene tributary alluvium on the piedmont is attributed to the erodible nature of the constituent granitic sediments and the potential for removal of deposits during subsequent periods. Long term preservation of alluvial deposits requires that the deposits are durable and resistant to erosion—particularly the surface of the deposit. In the case of deposits on the Laughlin piedmont, the lack of surface preservation is the principal detriment in differentiating older units. The older (Pleistocene) deposits are very distinct from the younger (Holocene) deposits by virtue of their surface morphology and position in the landscape.

Following the deposition of the Davis terrace alluvium, the Colorado River entrenched its channel to the elevation of approximately 210 m (700 ft) whereupon lateral erosion ensued. This is the period in which the Mohave terrace was formed and the uppermost deposits (the Mohave alluvium) on this terrace are then younger than the Davis terrace. Other stratigraphic relations indicate, however, that most of the deposits that comprise the Mohave terrace are older than both the Mohave alluvium and the Davis alluvium. Tertiary fanglomerate deposits are exposed in several deep gullies on the Mohave terrace, and the Late Tertiary Bouse Formation crops out in at least one isolated location.

Alluvial deposits below the 256 m (840 ft) level are graded to and interbedded with Colorado River deposits of the Mohave terrace at their distal ends (at approximately the 210 m [700 ft] level). The age of the Mohave Alluvium and related tributary deposits is not precisely known. It is only clear that they are younger than the Davis alluvium (40,000 to 250,000 years). Given the degree of soil development in the Mohave alluvium, it is clearly a Pleistocene deposit (greater than 10,000 years old). The Emerald terrace only locally has a related set of alluvial fan deposits.

It is most likely that these deposits occupied areas that have been evacuated and subsequently filled with the Holocene alluvial deposits.

Presently, the active tributary drainages are generally entrenched into relict deposits on the piedmont reflecting a response to net entrenchment of the Colorado River during the latest Quaternary. In some mid-piedmont areas younger deposits bury older alluvium, but on the lower piedmont all active channels are reconfined between relict tributary and Colorado River alluvial deposits. Ultimately all of the active channels terminate as small alluvial fans on the modern floodplain of the river (the Laughlin terrace).

Structural Framework

The distribution of surficial and bedrock units, groundwater flow paths, and the character of mineral resources is intimately tied to the structural framework of the region. Major structural elements include the Newberry detachment fault, Newberry domain, Davis Dam domain, and northern Mohave basin. The Newberry detachment fault is the most conspicuous and important structural feature in the area. The Newberry domain lies in the footwall of the detachment, whereas the Davis Dam domain and northern Mohave basin reside in the hanging wall.

Newberry Domain

The Newberry domain occupies the footwall of the detachment fault (Fig. 5). It consists almost entirely of Miocene granite cut by numerous, generally intermediate-composition dikes (typically diorite). Some of the diorite bodies have pod-like geometries and may reflect mingling of felsic and mafic magmas (e.g., Falkner and others, 1995) during emplacement of the granite rather than post-emplacement intrusion. The dikes typically strike northerly and dip steeply eastward (Fig. 19a) and probably reflect an east-west extension direction during emplacement. Within the map area, only small pendants of Proterozoic gneiss are found within the Miocene granite, but larger pendants of Proterozoic granite and gneiss crop out to the west and north. Foliation within the pendants strikes northerly and dips steeply, generally to the east (Fig. 19b).

The Newberry domain is cut by many northerly striking normal faults (Plate 1). Similar to the dikes, theses faults probably reflect east-west extension. Most of these faults dip moderately to steeply eastward, but a significant subset dips moderately to the west (Fig. 19c). Due to the homogeneous nature of the Miocene granite, most of the faults are difficult to trace. The faults are best exposed in deep canyons, such as Grapevine Canyon. The density of faults generally increases toward the trace of the Newberry detachment fault. Within about 500 m of the detachment, the granite is commonly shattered and broken by countless minor faults. Chlorite alteration and epidote veinlets are common in these highly fractured areas.

The Newberry domain is probably tilted moderately to steeply westward, as evidenced by petrologic features in the Spirit Mountain pluton (Hopson and others, 1994) and paleomagnetic data from some of the Miocene dikes (Faulds and others, 1992). In addition, the base of the Tertiary section dips steeply westward in the northwestern part of the range, where it rests directly on Proterozoic granite (e.g., Ruppert and Faulds, 1998; Faulds, unpublished mapping). It is noteworthy that easterly striking faults, dikes, and veins, which are so prevalent in the Davis Dam domain, were not observed in the Newberry domain.

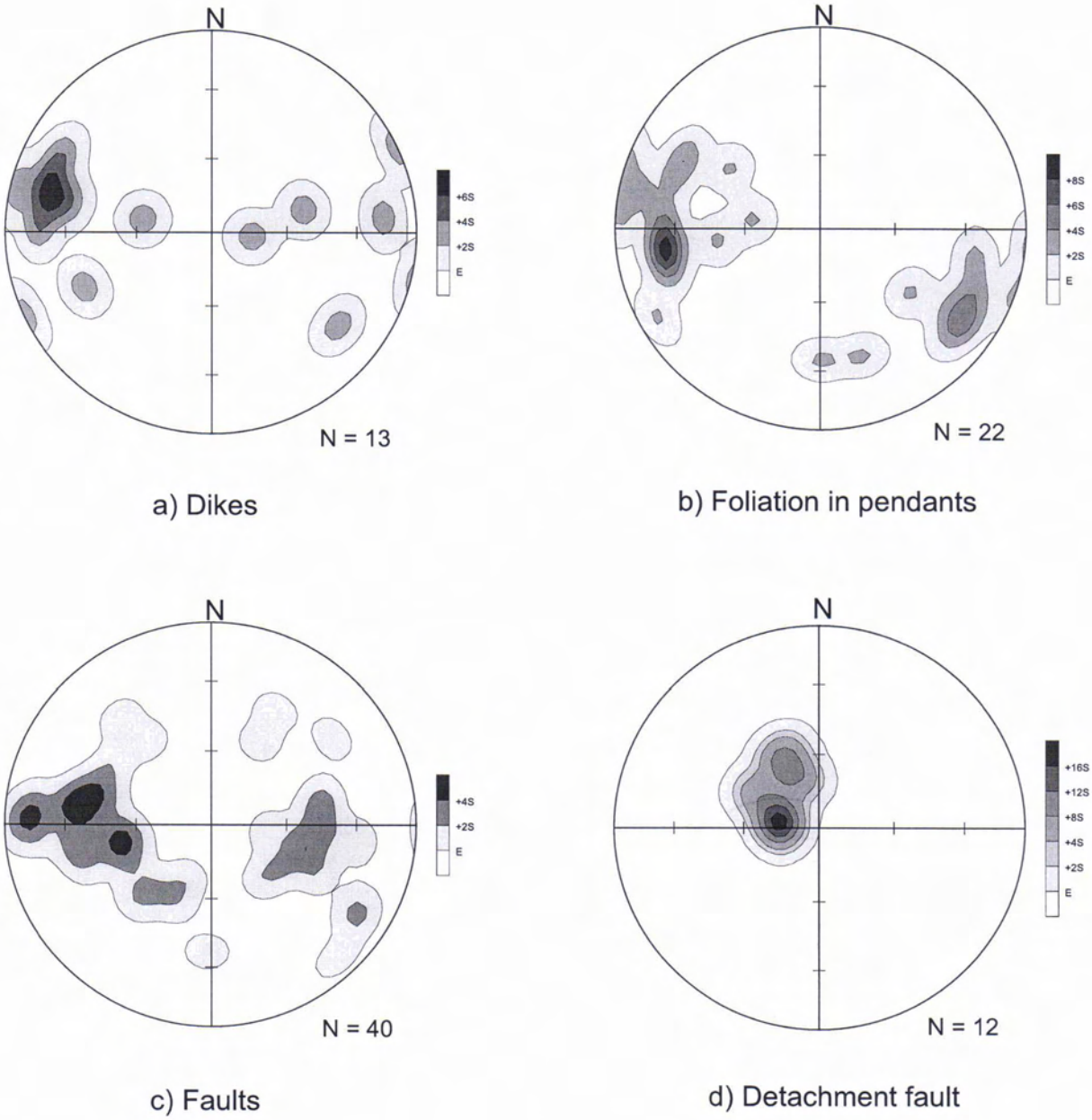


Figure 19. Lower-hemisphere equal-area stereographic projections of poles to dikes, foliation, and faults in the Newberry domain. N, number of measurements. Density contours indicate the percent of data per 1% area. Actual contour intervals are shown to the right of each stereoplot.

The relatively nonresistant Miocene granites in the Newberry domain are the primary source of sediment for Holocene alluvial fans and major washes in the Laughlin area and have been the main source of sediment for alluvial fans for the past several million years since deposition of the Recreation Conglomerate (>10 Ma). As evidenced by relations in Grapevine Canyon, many of the major bends and sediment traps in modern washes are fault controlled. For example, directly northwest of the Davis Dam Quadrangle, a relatively large deposit of recent alluvium (Qay and Qai) accumulated in the hanging wall of a west-dipping normal fault zone (Plate 1). The location of the faults may therefore have a significant effect on downstream sediment supply. Because they can affect the topographic gradient of the washes, at least some of the faults should probably be considered in flood hazard analysis of major washes in the Laughlin area. It is important to note, however, that although the faults may control the location of sediment traps, none of the Quaternary fan deposits observed in the Newberry domain are actually cut by faults. The location of the larger pendants of more resistant Proterozoic granite and gneiss to the west of the map area may also be important for understanding controls on downstream sediment supply in the Laughlin area.

Newberry Detachment Fault

The Newberry detachment fault is probably the most conspicuous structural feature in the Laughlin area. It separates distinct structural, stratigraphic, and physiographic domains. The northern Mohave basin and volcanic-dominated Black Mountains lie in the hanging wall of the detachment, whereas the granitic crystalline terranes of the Newberry and Dead Mountains occupy the footwall. The Newberry detachment fault may connect southward with major east-dipping detachment faults that flank the Sacramento, Chemehuevi, and Whipple Mountains (e.g., Spencer, 1985; Howard and John, 1987; Yin and Dunn, 1992; John and Foster, 1993; Campbell and John, 1996) and clearly links northward with the gently east-dipping Dupont Mountain fault, which bounds the northern Newberry and southern Eldorado Mountains on the east. The Newberry detachment fault was first described by Mathis (1982), who mapped its trace in the Laughlin area.

The Newberry detachment fault is well exposed at several localities directly west of both Telephone Cove Road and the Big Bend area to the southwest of Laughlin (Fig. 5). The fault strikes north-northeast and dips gently eastward (about 15° to 20°; Fig. 19d). It is marked by a distinct color change between the reddish-brown Proterozoic granite in the hanging wall and light greenish-gray Miocene granites in the footwall (Fig. 3). A thick breccia zone, consisting primarily of crushed and pulverized Miocene and Proterozoic granite, characterizes the fault trace (Tfb on Plate 1) (Adams, 1985). The breccia contains relatively sparse, microscopic pyrite, which has been oxidized and completely replaced by hematite and titanomagnetite. As noted by Mathis (1982), the breccia zone is commonly capped by a resistant ledge of microbreccia, which typically contains good indicators of the sense of motion (e.g., striated surfaces, corrugations, rough facets, and minor secondary shear planes referred to as Riedel shears). These features indicate east-northeast-trending, east-side-down normal displacement.

Although not tightly constrained, the magnitude of offset on the Newberry detachment fault is large. For example, major features within the hanging wall of the detachment, such as the base of the Tertiary section and extensive exposures of Proterozoic granite are found on the far

northwestern and western flanks of the Newberry Mountains within the footwall of the detachment. This suggests that total offset on the Newberry detachment fault exceeds 12 km (~8 mi). Movement on the Newberry detachment fault occurred many millions of years ago. The lack of offset Quaternary units along the detachment indicates that it does not pose a seismic hazard.

Although movement on the detachment fault ceased long ago, it has continued to impart a significant control on depositional patterns of Quaternary sediments. The detachment fault essentially forms the interface between the uplifted terrane of the Newberry and Dead Mountains and downthrown Mohave basin. Alluvial fan deposition has occurred primarily on the downthrown, basinward side of the fault (i.e., within the Mohave basin). Most of the Quaternary fans pinch out near the trace of the fault. Thus, major drainages are generally incised in bedrock channels west of the fault but spread out in a distributary fashion on the alluvial fans to the east of the fault (Plate 1 and Figs. 2 and 4).

The detachment fault has also influenced groundwater flow paths, as suggested by the alteration of bedrock units near the fault. Within a few hundred meters (500 to 1000 ft) of the fault, hanging-wall rocks are highly oxidized, whereas footwall rocks are typically chloritized. This produces the conspicuous aforementioned color change across the fault, from reddish-brown hanging-wall rocks to the greenish-gray footwall rocks. In addition, veinlets of epidote are common in footwall rocks near the detachment, and minor amounts of pyrite are found in the fault breccia (Tfb on Plate 1). These alteration patterns indicate that aqueous fluids once migrated through the highly fractured rocks along and near the fault. The epidote and chlorite within the footwall rocks probably formed at appreciable depth and were brought to the surface by subsequent movement on the detachment fault, whereas the oxidation of the hanging-wall rocks probably occurred relatively close to the surface.

Although the current fluid regime probably differs significantly from that responsible for the alteration, the highly fractured rocks along the detachment fault may still provide a channelway for groundwater, particularly for down-gradient flow from the upper reaches of the alluvial fans into the lower parts of the Mohave basin. Several water wells have been drilled near the detachment in the Big Bend area directly southwest of Laughlin (Fig. 20b). Some of these wells contain anomalous Mn and SO_4. Shevenell (Chapter 3 of this report) discusses whether the altered rocks along and near the detachment are responsible for these anomalous values. It is also noteworthy that the Laughlin landfill is situated about 365 to 730 m (~1200 to 2400 ft) east of the fault, or about 64 to 150 m (210 to 500 ft) above the detachment (Plate 1 and Fig. 20a). Vertical leakage from the landfill could potentially intercept the fault zone and flow eastward. We stress, however, that no such leakage or eastward flow have been documented.

Davis Dam Domain

The Davis Dam domain incorporates the easterly trending bedrock high that separates the Cottonwood and Mohave basins (Figs. 2 and 5) and extends from the Newberry detachment fault on the west to the Union Pass area of the Black Mountains on the east. It lies entirely within the hanging wall of the Newberry detachment fault. In contrast to areas to the north and south, which are dominated by west-tilted fault blocks bounded by east-dipping normal faults, the Davis Dam domain contains both west- and east-tilted fault blocks and both east- and west-dipping major

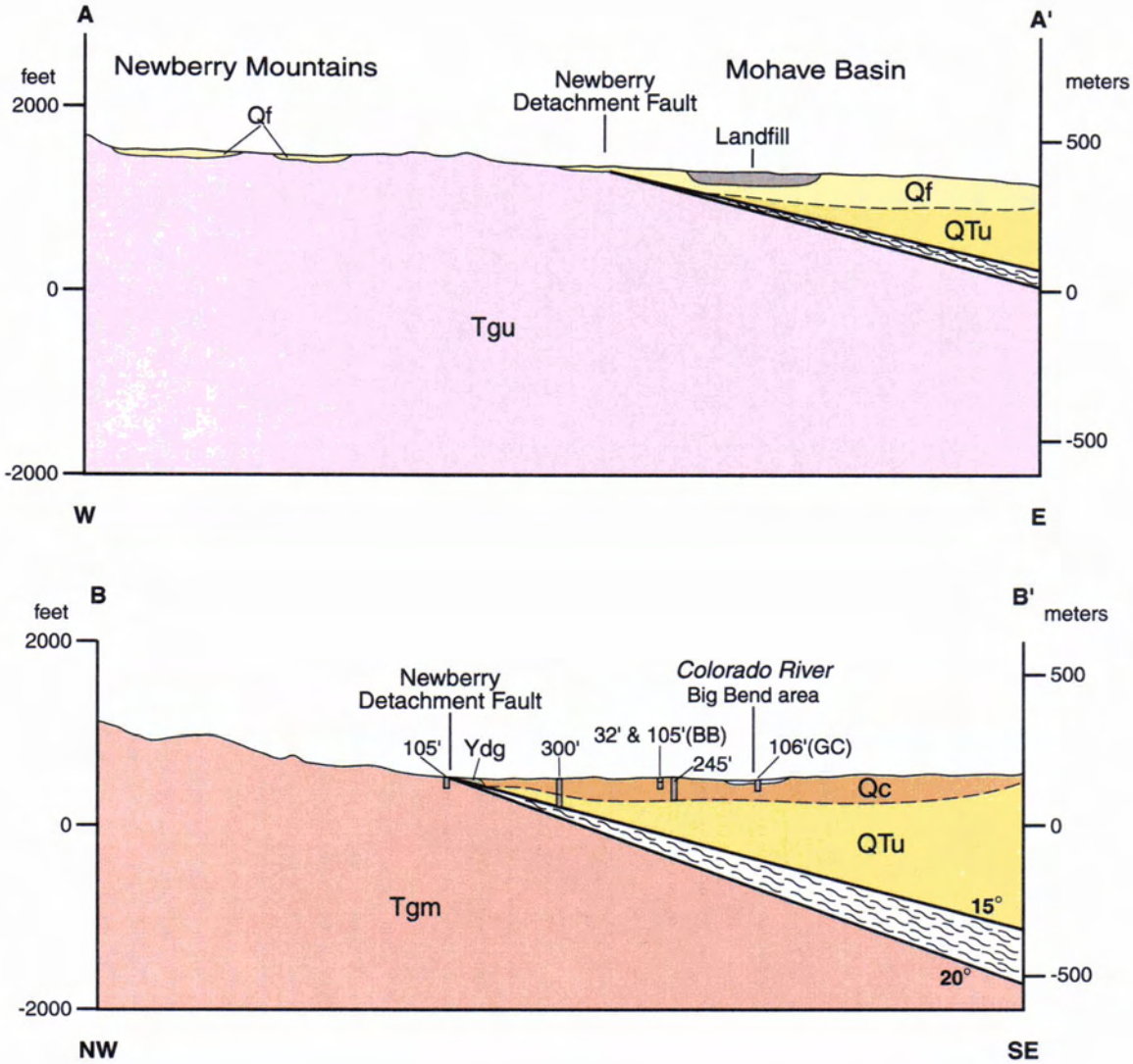


Figure 20. Cross sections of the Newberry detachment fault. A) Cross section A-A' shows proximity of the detachment to the Laughlin landfill. B) Cross section B-B' shows proximity of the detachment to several water wells in or near the southwest part of Laughlin. See Plate 1 for locations of cross sections. BB, Big Bend area wells (2 wells); GC, Griffith Canoe Base well; Qc, Colorado River sediments; Qf, Quaternary fan deposits; QTu, Late Tertiary-Quaternary sediments, undifferentiated; Tgm, Mirage pluton; Tgu, Spirit Mountain pluton and lesser Proterozoic gneiss, undifferentiated; Ydg, Davis Dam granite.

normal faults. The fault blocks are composed largely of Proterozoic granite (Davis Dam granite) and Miocene volcanic and sedimentary strata.

Fabric in Davis Dam Granite

The 1.425 Ga Davis Dam granite is weakly to locally strongly foliated and commonly mildly to moderately jointed. The foliation typically strikes west-northwest and dips steeply, although a significant subset dips moderately southeast (Fig. 21a). The joints follow a similar pattern, with westerly striking, steeply north-dipping joints predominating over a subordinate northeast-striking, moderately southeast-dipping subset (Fig. 21b). The Davis Dam granite also contains a few thin, west-northwest-striking mylonite zones, the most conspicuous of which lies directly west of Davis Dam (Ymy, Plate 1).

The foliation and mylonite within the Davis Dam granite were produced by intense ductile deformation at relatively deep crustal levels (relatively high temperature and pressure). The lack of any pervasive ductile deformation features within Miocene rocks in the area, including the Spirit Mountain pluton, indicates that this deformation predates Miocene volcanism and extension within the region. The ductile deformation may have occurred in the late Proterozoic, perhaps coincidental with or immediately after emplacement of the granite, similar to that noted in the Lucy Gray Range in southern Nevada (Duebendorfer and Christensen, 1995), or possibly during crustal shortening in Mesozoic to early Tertiary time, when the region was subjected to significant uplift and erosion.

In the vicinity of Davis Dam, west to west-northwest-striking, moderately to steeply north-dipping foliations and joints predominate (Plate 1) and impart a relatively pervasive fabric to the granite at the dam site. Foliations and joints represent planar weaknesses in rock that can, under some circumstances, pose hazards for slope failure and landslides. The potential for such a hazard at Davis Dam is very slim, because (a) the area lacks significant topographic relief, and (b) the orientation of the dam nearly parallels that of the rock fabric. Thus, even if slope failure did occur, the northward dip of the fabric and position of the dam (e.g., dam is oriented roughly east-west at the north end of a northerly trending bedrock channel) ensures that most rock slabs would fall harmlessly into Lake Mohave well away from the foundation of the dam. Furthermore, such failures are generally more prevalent in areas prone to heavy precipitation, diurnal freeze-thaw cycles, or earthquakes, none of which is common in the Laughlin area.

Faults

Two distinct sets of faults cut the Davis Dam domain. The first and older set consists of easterly striking faults that have commonly been invaded by rhyolite and andesite dikes and quartz and calcite veins (Plate 1). On average, this set of faults strikes east- to east-northeast and dips steeply northward (Fig. 21c), as do the veins (Fig. 21d). This pattern is oblique to, and therefore not controlled by, the predominant west-northwest-striking foliation in the Davis Dam granite (Fig. 21a and Plate 1). Prospect pits and small adits and tunnels are common in the easterly striking faults and veins to the west of Lake Mohave. These features clearly controlled minor mineralization on the Nevada side and also continue across Lake Mohave into Arizona, where they controlled significant mineralization in the Katherine mining district (Lausen, 1931). The Katherine Gold Mine, located about 9 km (6 mi) north of Laughlin just northeast of

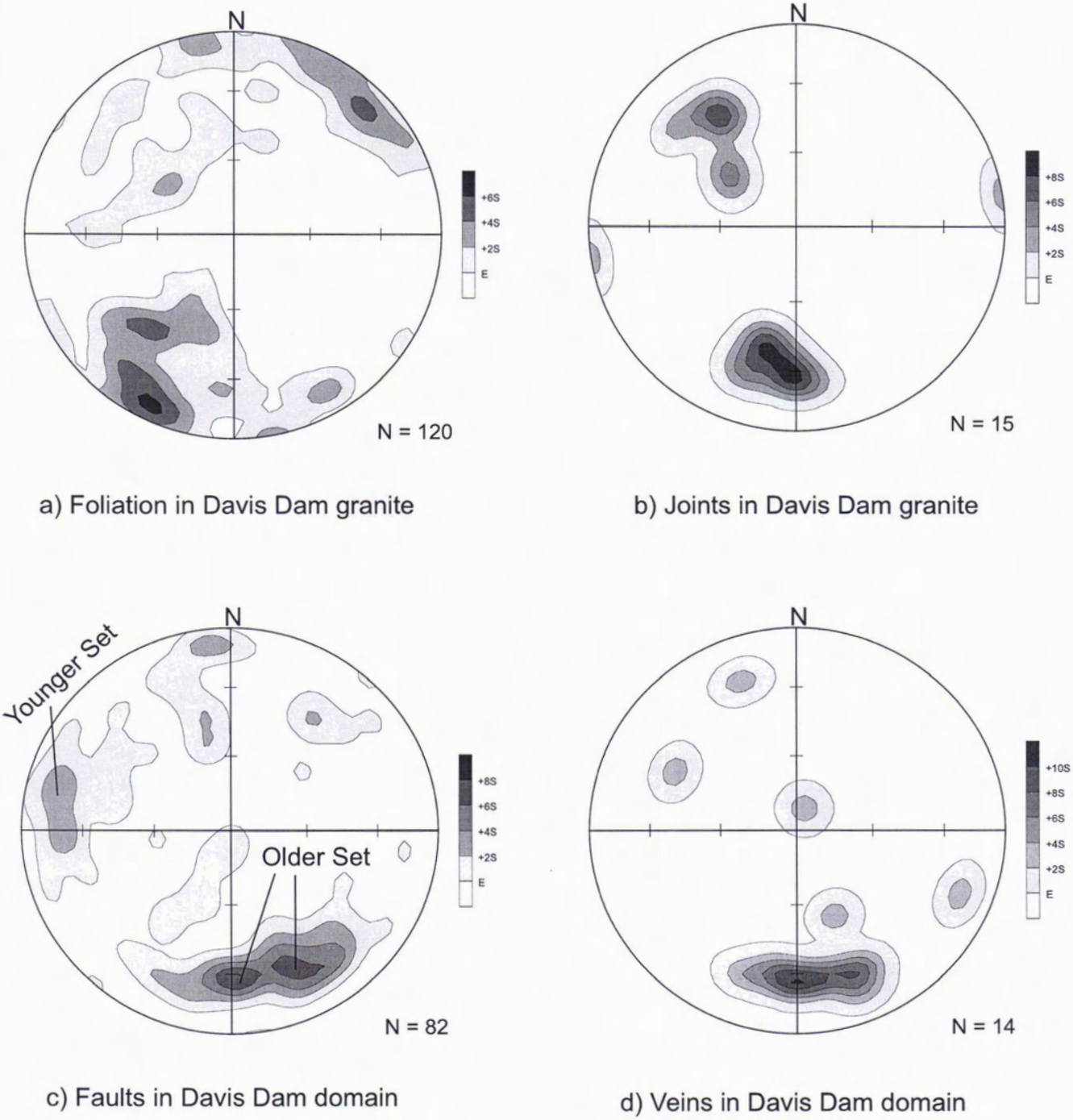


Figure 21. Lower-hemisphere equal-area stereographic projections of poles to foliation, joints, faults, and veins in the Davis Dam domain. N, number of measurements. Density contours indicate the percent of data per 1% area. Actual contour intervals are shown to the right of each stereoplot. a) Foliation in Davis Dam granite; average attitude strikes N63°W and dips 82°NE. b) Joints in Davis Dam granite. c) Faults in Davis Dam domain, with one cluster striking N87°E and dipping 60°N, and a second cluster striking north and dipping ~70°E. d) Veins, which on average strike east-west and dip 64°N.

Katherine's Landing (Figs. 2 and 5), is the largest historic mine in the area. It was discovered in 1900, operated intermittently until 1942, and produced over $12 million worth of gold.

Many of these faults cut the lowermost part of the Miocene section, including the basal arkosic conglomerate and Peach Springs Tuff, but generally do not project into units above the Peach Springs Tuff (Plate 1). With respect to lower Miocene strata, both normal and reverse separation have been noted along the easterly striking faults. Depositional patterns of the lower Miocene units were locally affected by the easterly striking faults, as evidenced by thicker sections of the Peach Springs Tuff and underlying basaltic andesite lavas on the downthrown sides of some faults and channel fills of unfaulted dacite breccia (Tdb, Plate 1), which rests directly on the Peach Springs Tuff, along the projection of a few faults. No easterly striking dikes or veins were observed in the Miocene section. Moreover, easterly striking faults, veins, and dikes were not observed in the Spirit Mountain pluton. These relations suggest that the easterly striking faults predate both emplacement of the ~17 Ma Spirit Mountain pluton and deposition of the bulk of the Miocene volcanic and sedimentary section.

The second and younger set of faults strikes northerly, dips moderately to steeply, and accommodated normal offset. To the west of Lake Mohave, this set is dominated by east-dipping normal faults (Fig. 21c). It is important to note, however, that a few major west-dipping normal faults, such as the Stonehouse fault (Figs. 5 and 8; Plate 1), occur in this area. West-dipping normal faults appear to be more common east of Lake Mohave. The northerly striking faults commonly offset or truncate the older easterly striking faults and veins. In addition, many of the northerly striking faults appear to merge northward with the Newberry detachment fault. The predominant east-dipping normal faults in the Davis Dam domain to the west of Lake Mohave mimic the dominant fault set that cuts the Spirit Mountain pluton in the Newberry domain (i.e., footwall of the detachment fault) (Fig. 19c). These relations suggest that movement on the northerly striking faults in the Davis Dam domain coincided with that on the detachment and that most of the activity postdated emplacement of the Spirit Mountain pluton.

The easterly and northerly striking faults form a latticework of intersecting fractures that may have a significant impact on groundwater flow. Highly fractured rock along subvertical lines of intersection between the two fault sets may effectively channelize groundwater within the Davis Dam domain, perhaps providing vertical conduits either to or from the subjacent Newberry detachment fault. Although field work for this study was conducted during drought conditions, one spring was observed in the Davis Dam domain west of Lake Mohave. This lone spring is structurally controlled, as it is situated along the trace of the Stonehouse fault.

No major faults were observed near Davis Dam. Several minor east- to northeast-striking faults do, however, cut the Davis Dam granite in the vicinity of the dam. None of these minor faults appear to pose any hazard to the structural integrity of the dam site, as only thin zones (<2 m thick) of breccia accompany the faults. Furthermore, the location and orientation of these faults do not favor down-gradient transport of water from Lake Mohave to beneath the dam site, suggesting that undermining of the dam during periods of high water is highly unlikely.

Davis Dam Anticline

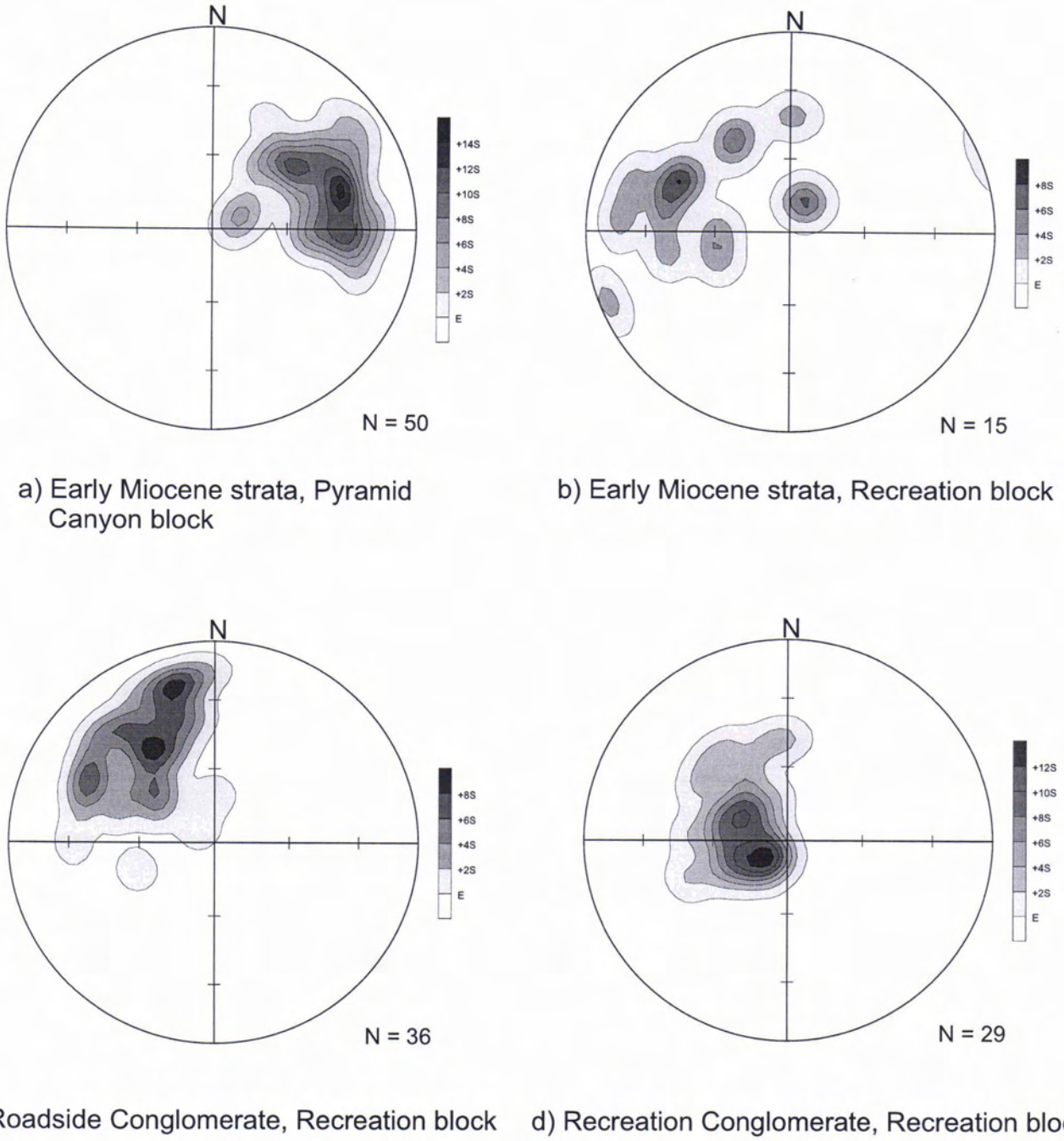
In the vicinity of Davis Dam, Miocene strata are warped into a broad northerly trending, southward plunging arch, here referred to as the Davis Dam anticline. The base of the Miocene section is tilted moderately to steeply westward directly west of Lake Mohave (Plate 1; Fig. 8)

and moderately eastward to the east of Lake Mohave. The west-tilted fault block that constitutes the west limb of the anticline is here referred to as the Pyramid Canyon block. On average, lower Miocene strata in the Pyramid Canyon block strike N15°W and dip 54°SW (Fig. 22a). However, Miocene strata have been eroded from the bulk of the anticline, leaving a core of unstratified Proterozoic granite near Lake Mohave. The Davis Dam anticline probably projects south-southeastward beneath untilted alluvial fan deposits in the Bullhead City area and may link with a similar north-trending anticline that extends from the Oatman, Arizona area southward through the southern Black Mountains.

The Davis Dam anticline is not a typical fold, because it did not result from crustal shortening. Instead, it formed at the intersection of two opposing rollover folds (e.g., Hamblin, 1965; Dula, 1991) developed in the hanging walls of major listric (i.e., concave upward geometry) normal fault zones that dip toward one another (e.g., Faulds and Varga, 1998; Fig. 23). West-tilting of the west limb was probably accommodated by movement on the curviplanar east-dipping Newberry detachment fault, whereas east-tilting of the east limb resulted from movement on a major west-dipping normal fault exposed in the western part of the Union Pass Quadrangle about 8 km (5 mi) east of Lake Mohave. Accordingly, east-dipping normal faults dominate the west-tilted limb of the anticline west of Lake Mohave, whereas west-dipping normal faults appear to prevail on the east-tilted limb east of Lake Mohave. Similar anticlines have been observed elsewhere in the northern Colorado River extensional corridor and in many other areas of the Basin and Range province (Faulds and Varga, 1998). Laughlin resides largely above the buried west-tilted limb of the Davis Dam anticline.

Recreation Block

A small, moderately to steeply east-tilted fault block, here referred to as the Recreation block, is sandwiched between the Newberry detachment and Stonehouse fault in the westernmost part of the Davis Dam domain (Plate 1; Fig. 5). The east-tilted base of the Miocene section is exposed about 366 m (1200 ft) east of the detachment fault. East-tilting of the block was probably accommodated by down-to-the-west normal movement on the west-dipping Stonehouse fault and possibly in part by normal drag along the east-dipping detachment fault. The fault block appears to narrow southward in conjunction with the southward termination of the Stonehouse fault. The Recreation block is an east-tilted half graben, within which thick sections of Miocene conglomerate accumulated (Ts and Tc, Plate 1). The magnitude of east-tilting decreases appreciable upward from about 50° in the basal part of the Miocene section to less than 20° in the upper conglomerate unit (Fig. 22 b, c, d; Plate 1). The truncation by the Stonehouse fault of west-tilted strata in the Pyramid Canyon block and thick accumulation of Miocene conglomerate in the Recreation block suggest that both the Stonehouse fault and Recreation block developed, at least in part, after west-tilting of the Pyramid Canyon block. However, because the Stonehouse fault appears to merge northward rather than cut the Newberry detachment fault, it is inferred that the Stonehouse fault soles into the detachment at depth and also that the Recreation block is floored by the detachment.



a) Early Miocene strata, Pyramid Canyon block

b) Early Miocene strata, Recreation block

c) Roadside Conglomerate, Recreation block

d) Recreation Conglomerate, Recreation block

Figure 22. Lower-hemisphere equal-area stereographic projections of poles to Miocene strata. N, number of measurements. Density contours indicate the percent of data per 1% area. Actual contour intervals are shown to the right of each stereoplot. a) Early Miocene strata in the Pyramid Canyon block; average attitude strikes N15°W and dips 54°SW. b) Early Miocene strata in the Recreation block; average attitude strikes N24°E and dips 50°SE. c) Early to middle Miocene Roadside Conglomerate, Recreation block; average attitude strikes N57°E and dips 45°SE. d) Middle Miocene Recreation Conglomerate, Recreation block; average attitude strikes N66°E and dips 12°SE.

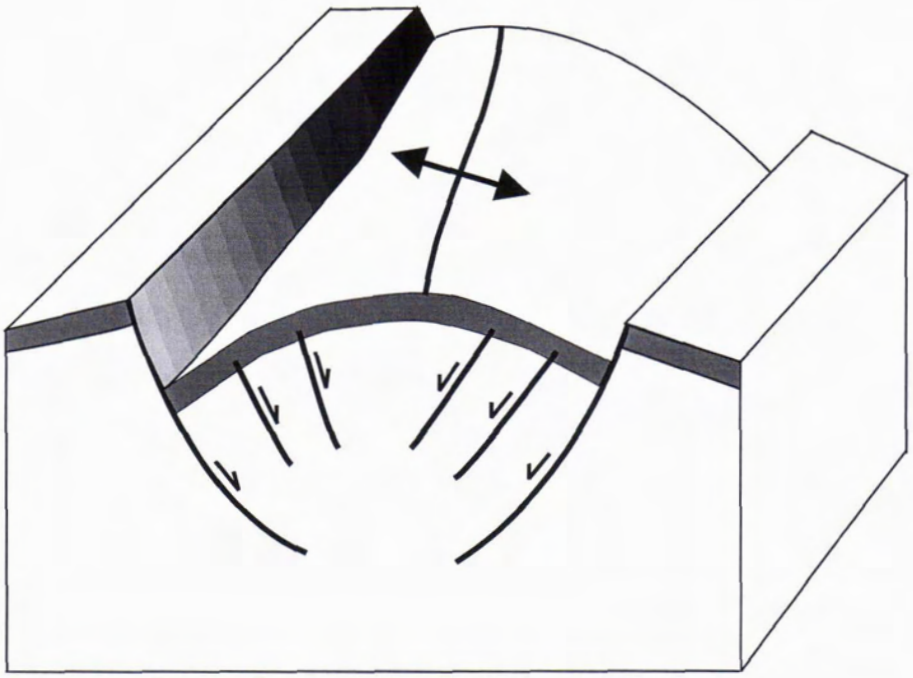


Figure 23. Schematic model of Davis Dam anticline. The Davis Dam anticline is extensional in origin, having formed due to the intersection of two opposing rollover folds developed in the hanging walls of oppositely dipping listric normal faults that dip toward one another. Movement on the curved fault surfaces induces the folding in the hanging-wall rocks. Miocene strata in the core of the Davis Dam anticline have been largely eroded, leaving only Proterozoic basement exposed in the hinge zone (e.g., Pyramid Canyon area).

Northern Mohave Basin

The northern Mohave basin is the sedimentary basin developed in the hanging wall of the Newberry detachment fault. The subsurface of the basin probably consists of a series of tilted fault blocks and associated subbasins (half grabens) and is therefore quite irregular (Fig. 4). West-tilted fault blocks probably predominate, but the east-tilted Recreation block may continue southward adjacent to the detachment. Similarly, the Davis Dam anticline (and the east-tilted fault block on the east limb of the anticline) probably extend southward in the Bullhead City area. The myriad of fault blocks that comprise the floor of the basin are blanketed by thick, essentially flat-lying, late Miocene to Quaternary alluvial fan deposits and, in the lower part of the basin, by Colorado River sediments. The fan deposits and Colorado River sediments progressively onlap tilted fault blocks, such as the Recreation and Pyramid Canyon blocks, up-section (Fig. 13). In addition, the uppermost parts of some fans locally cover the detachment fault and onlap the Tertiary granites in the footwall of the detachment within the Newberry domain (Fig. 24).

Geophysical data (Mariano and others, 1986; Bracken and Kane, 1982) suggest that the northern part of the Mohave basin is relatively shallow, perhaps less than a few kilometers in depth. This implies that the Newberry detachment maintains a relatively gentle dip ($<20^{o}$) beneath the basin and that the thickness of the sedimentary cover above the buried fault blocks is not excessive. More detailed gravity surveys are needed, however, to comprehensively define the subsurface nature of the basin. Such studies will be needed to determine whether the northern Mohave basin is prone to amplification of seismic waves from distant earthquakes.

Timing of Neogene Deformation

Two major episodes of deformation affected the Laughlin area during Neogene time (i.e., past 23 million years). The first episode generated the easterly striking faults, dikes, and veins found in the Davis Dam domain. Dikes and veins are generally emplaced along dilational fractures associated with regional extension oriented perpendicular to the strike of the fractures. We therefore conclude that mild north-south extension was responsible for the easterly striking faults, dikes, and veins. Some of the easterly striking faults cut, and control depositional patters within, the lower part of the Miocene section (e.g., 18.5 Ma Peach Springs Tuff), but none of the easterly striking faults, veins, and dikes cut the ~17 Ma Searchlight pluton. Thus, the episode of north-south extension probably occurred between approximately 20 and 17 Ma. Mild early Miocene north-south extension affected much of the northern Colorado River extension corridor (Faulds, 1999) and has also been documented elsewhere in the Basin and Range province (e.g., Best, 1988; Bartley, 1990).

The northerly striking normal faults and dikes within both the Davis Dam and Newberry domains, as well as the Newberry detachment, are associated with major east-west extension. The northerly striking faults clearly cut and postdate the easterly striking structures. Tilt fanning within half grabens to the north of the Laughlin area constrain the episode of east-west extension and basin development to between about 16 and 11 Ma (e.g., Anderson and others, 1972; Faulds and others, 1995, 1999), whereas to the south in the southern Black Mountains, major east-west extension occurred between about 19 and 16 Ma (Faulds and others, 1999). Thus, the Laughlin area resides in the transitional area between two temporal domains of extension.

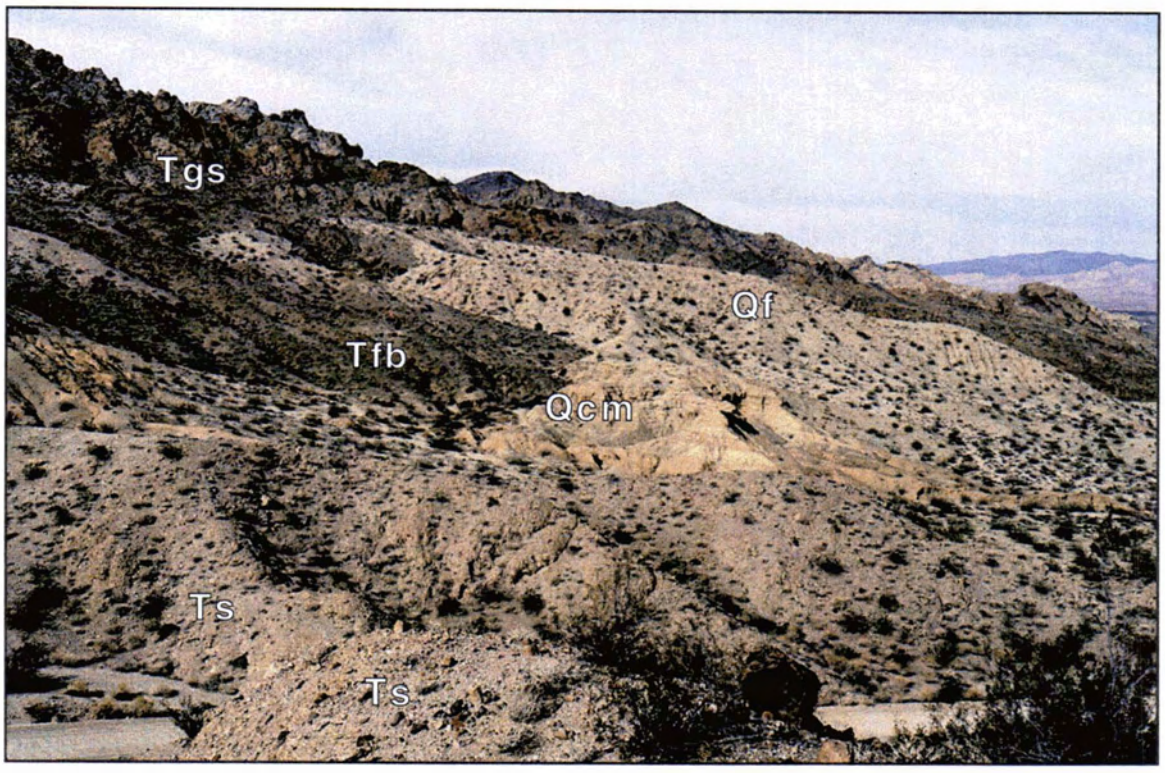


Figure 24. Onlap of Quaternary sediments on Newberry detachment fault. Looking north at onlapping Quaternary fan deposits (Qai) and Colorado River sediments (Qcm) directly south of Grapevine Canyon. These sediments onlap fault breccia along the Newberry detachment (Tfb), but the sediments themselves are not faulted. In the foreground, the Quaternary deposits also onlap the east-tilted Miocene Roadside conglomerate (Ts) within the Recreation block. The rugged ridges in the background are composed of the Spirit Mountain pluton (Tgs).

Major extension in the Laughlin area appears, however, to be primarily related to that of the younger northern domain. For example, major east-west extension at least partly postdates emplacement of the ~17 Ma Spirit Mountain pluton, as evidenced by truncation of the pluton by the detachment and abundant northerly striking normal faults and dikes that cut the pluton. This alone does not preclude appreciable east-west extension prior to 17 Ma. However, the easterly striking faults cut volcanic units as young as about 18 to 17 Ma. Moreover, the Recreation conglomerate records the bulk of the tilt fanning in the Recreation block (compare Fig. 22d with 22b; Plate 1) and is dominated by clasts of the Spirit Mountain pluton, indicating that major east-west extension largely postdates emplacement of the ~17 Ma pluton. The rock avalanche deposits in the older Roadside conglomerate directly below the post-17 Ma Recreation conglomerate are also probably synextensional. They may record the approximate onset of major east-west extension, as significant topographic relief developed and small landslides were shaken loose from fault scarps during major earthquakes. In the Black Mountains directly northeast of Laughlin, significant tilt fanning is expressed in a thick sequence of basalt lavas within a west-tilted half graben, whereby a 14.87±0.09 Ma lava is tilted ~35° and a 13.8±0.3 Ma basalt is tilted ~10°. Thus, tilting and extension had abated significantly by about 13.8 Ma. Flat-lying to very gently (0-10°) tilted 11.3 to 8.7 Ma basalt flows in the region (e.g., Faulds and others, 1995; Price and Faulds, 1999) suggest that extension in the Laughlin area had essentially ceased by about 11 to 8 Ma.

Since 8 Ma, only minor faulting has occurred in the Laughlin area. Directly southwest of Laughlin, minor faults cut untilted fan deposits that are intercalated with the 8 to 4 Ma Bouse Formation. No faults were observed in any of the Pleistocene or Holocene fan deposits within or directly surrounding either Laughlin or Bullhead City. However, northerly striking normal faults do cut Quaternary deposits in the Needles graben about 30 km (20 mi) southeast of Laughlin (Purcell and Miller, 1980) (Fig. 1). Analysis of the Needles graben was beyond the scope of this study. Nonetheless, the Quaternary faults in the Needles graben warrant further study, because they pose a potential seismic hazard to the Laughlin-Bullhead City area (see Chapter 4).

Summary

The rocks and surficial deposits in the Laughlin area record a long and complex geologic history. Major geologic events and their relevance are summarized in Table 1. The table provides a generalized time column for the Laughlin area, with the youngest events at the top and oldest events at the bottom.

Table 1. Geologic History of the Laughlin Area

Age	Event	Relevance
1947 AD-present	Isolation of the Laughlin terrace from Colorado River deposition by construction of Davis Dam	Essentially eliminates Colorado River flood hazard; reduced shallow groundwater recharge from overbank flooding
Holocene (0-10 ka)	Entrenchment of the Emerald alluvium and formation of Laughlin terrace; roughly simultaneous and ongoing deposition of young piedmont alluvium (Qay)	Produces terraces and alluvial deposits that have been extensively mined for sand and gravel
Latest Pleistocene (~10-20 ka)	Entrenchment of Mohave terrace and formation of Emerald terrace; roughly simultaneous deposition of piedmont alluvium (Qai_3)	Period of rapid down-cutting followed by lateral erosion; progressive westward shift in river generates Big Bend area
Late Pleistocene (10-125 ka)	Entrenchment of Davis terrace and formation of Mohave terrace; roughly simultaneous deposition of piedmont alluvium (Qai_2)	Period of rapid down-cutting followed by extensive lateral erosion; Colorado River migrates to east
Late Pleistocene ? (10-125 ka)	Needles graben develops	Possible source of large earthquakes near Laughlin
Early-Late Pleistocene ? (40-125 ka)	Deposition of Davis alluvium and formation of Davis terrace; period of apparently rapid aggradation of fine sands and muds of Colorado River (Qcm, Qcs); roughly simultaneous deposition of piedmont alluvium (Qai_1)	Oldest fan remnants on upper Laughlin piedmont overlie highest part of this terrace
Middle Pleistocene (125-790 ka)	Period of erosion in which river apparently migrated westward allowing for alluvial fans from Arizona to extend across modern valley bottom	No record of piedmont alluvium; presumably, it was removed by erosion
Middle Pleistocene (125-790 ka)	Deposition of QCb and related gravels at and above about 183 m (600 ft)	Unit Qcb suggests occurrence of large Pleistocene floods
Early Pleistocene ? (790-1650 ka)	Deep incision to near the 183 m (600 ft) level	Much of bedrock topography below 378 m (1240 ft) may have been generated in this interval
Late Pliocene-Early Pleistocene (~1.6-2.0 Ma)	Formation of the Newberry erosion surface (strath) at approximately the 378 m (1240 ft) level	Earliest evidence for extensive erosion associated with Colorado River
Latest Miocene ~6 Ma	Integration of drainage; Colorado River develops; excavation of Grand Canyon begins; Mohave basin provides convenient path for Colorado River	Major physiography of region established
Late Miocene (11 Ma) to present	Tilted fault blocks progressively onlapped by alluvial fan deposits and later (post 6) Ma by Colorado River sediments; thick alluvium accumulates in Mohave basin	Major aquifers develop in Mohave basin
Late Miocene 11-8 Ma	Probable end to east-west extension; modern piedmont begins developing	Modern physiography of Laughlin region largely established
Middle to late Miocene ~16-11 Ma	Deposition of thick fanglomerate sequences; younger deposits shed from Newberry Mountains	Modern physiography of Laughlin region taking shape
Middle Miocene 16-13 Ma	Main episode of east-west extension—Newberry Mountains and Mohave basin form; Black Mountains slide eastward relative to Newberry Mountains; fault blocks tilted and Davis Dam anticline forms; Newberry detachment accommodates >10 km of displacement	Newberry detachment becomes a major channelway for fluids; detachment, other N-striking faults, and tilted strata may control modern groundwater flow paths
Middle Miocene ~15 Ma	Mirage pluton emplaced	Forms major rock unit in southern Newberry Mountains
~16 Ma	Probable onset of major east-west extension	Newberry detachment forms
Early Miocene ~17 Ma	Emplacement of Spirit Mountain pluton	Forms major rock unit in Newberry Mountains; major source of sediment in alluvial fans
Early Miocene 20-17 Ma	Mild north-south extension, producing easterly striking faults, dikes, and veins; voluminous volcanism	Dikes and veins are source of gold mineralization in Katherine mining district; faults may control modern groundwater flow paths
Early Miocene 18.5 Ma	Eruption of Peach Springs Tuff (Tps), possibly from a local source; continued eruption of mafic lavas	Some dike emplacement and mineralization (?)
Early Miocene ~19 Ma	Onset of Tertiary volcanism—deposition of mafic lavas	Preserves non-resistant base of Tertiary section
Early Miocene-20 Ma	Deposition of arkosic conglomerate (Tca)	Forms base of Tertiary section
Jurassic-early Miocene ~140-20 Ma	Uplift and erosion of Paleozoic and Mesozoic strata	Precambrian basement (Davis Dam granite) exposed by erosion
Cambrian-Jurassic ~550-140 Ma	Periodic marine incursions; episodes of sedimentary deposition and erosion (Paleozoic-Mesozoic time)	These strata are missing due to later erosion
Middle Proterozoic ~1.4 Ga ?	Deformation of Davis Dam granite—development of foliation	Fabric in granite forms—poses no apparent engineering problem to dam abutments
1.425 Ga	Emplacement of Davis Dam granite (Ydg) into gneiss and schist	Forms basement for Laughlin area; major rock unit in Pyramid Canyon
Early Proterozoic ~1.7 Ga	Oldest rocks (Xgn, Xbs) in Laughlin area deposited and deformed	Forms basement for much of region

ka, thousands of years before present; Ma, millions of years before present; Ga, billions of years before present

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CHAPTER 2:

GEOLOGIC EVALUATION OF ALLUVIAL FAN AND RELATED FLOOD HAZARDS IN THE VICINITY OF LAUGHLIN, NEVADA

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Abstract

Detailed analysis of the surficial geology, geomorphology, and Quaternary stratigraphy of the Laughlin piedmont provides important and unique insights into the nature and distribution of its flood hazards. The geologic evidence indicates that large portions of the piedmont have been isolated from active fluvial processes and related flood hazards for at least the last 10,000 years. Furthermore, many portions of the piedmont that actively convey water and sediment are not accurately characterized as alluvial fans. These conclusions contrast with the implications of recent Flood Insurance Rate Maps (FIRMs) for the area. The FIRMs erroneously include large tracts that are not flood-prone into both the 100-year and 500-year floodplain hazard zones. Furthermore, assumptions in the regulatory model also result in mischaracterization of decidedly flood-hazardous areas as either non-flood-prone or considerably less flood-prone than the geologic data indicate. A direct comparison of the regulatory maps and the geological map indicates that approximately 60% of the piedmont is characterized inaccurately with respect to its flood-prone status on the regulatory maps. Of this, approximately 34% is not flood hazardous but is mapped as such, and approximately 23% is flood hazardous but mapped as though it were not. In each instance, the discrepancy arises from the application of an oversimplified model for flood hazard evaluation to only a selected number of complex fluvial systems that constitute the flood hazards of the piedmont. This circumstance illustrates the value of the compilation of geologic information as a necessary, preliminary component in realistic and cost-effective floodplain management strategies.

Table of Contents

Abstract 2
Table of Contents 3
List of Figures, Plates, and Tables 4
Introduction 5
Flood Hydrometeorology and Flood History 5
The 1939 Floods 6
Geomorphology of Alluvial Fans and Desert Washes 10
Alluvial Fans 10
Geomorphic Surfaces and Surficial Geologic Deposits 11
Other Terminology Used in this Chapter 11
Piedmont 12
Alluvial Fan Complex 12
Active Alluvial Fan 12
Inactive Alluvial Fan 12
Fan Apex 13
Distributary Flow System 13
Braided Wash 13
Flooding on Alluvial Fans 13
Overview 13
Evaluating Alluvial Fan Flood Hazards 14
Geological Evaluation of Flood Hazards on the Laughlin Piedmont 14
Methods 15
Methods of Map Compilation 16
Mapping Criteria 16
The Geologic Map of the Study Area 17
Characteristics of Quaternary Map Units 19
Inactive Alluvial Surfaces—Unit Qai 19
Active Alluvial Surfaces—Unit Qay 22
Drainage Patterns Characteristic of Qay Deposits 22
Stable Distributary Flow Networks 22
Diffuse Sheetflow Zones 24
Braided Channel Networks 24
Active Alluvial Fans 24
Flood Hazard Interpretation of the Surficial Geology 24
Aerial Photo Evidence of Large Floods 25
Types of Flood Hazard Zones 25
Anthropogenic Features 28
Characteristics of the Principal Washes 28
Dripping Springs Wash 29
Geomorphology and Flood Hazards 29
Flood-Control Structures 31
Bridge Canyon Wash 31
Geomorphology and Flood Hazards 31
Flood-Control Structures 33

Hiko Springs Wash 33
Geologic Setting and Geomorphology 33
Flood-Control Structures 35
Relationship of the Hazard Maps to Existing FIRMs 35
Conclusions 41
Recommendations: 42
Acknowledgments 43
Bibliography 43

List of Figures, Plates, and Tables

Plate 1. Geologic map of the Laughlin area, Clark County, Nevada ..... In pocket

Figure 1. Regional annual precipitation data from four stations in the tri-state area 7
Figure 2. Seasonal distribution of annual precipitation at Searchlight, 1914-1999. 8
Figure 3. Comparison of daily precipitation totals from significant regional storm events. 9
Figure 4. Aerial photograph comparison of the Laughlin area, 1954-1997 18
Figure 5. Typical surface characteristics of unit Qai. 20
Figure 6. Typical surface characteristics of unit Qay. 21
Figure 7. Drainage patterns typical of active alluvial surfaces. 23
Figure 8. Upper piedmont, 1947-1993 26
Figure 9. Location of the principal drainages and the primary alluvial fan complexes 27
Figure 10. Geologic flood-hazard map of the Dripping Springs alluvial fan complex. 30
Figure 11. Geologic flood-hazard map of the Bridge Canyon alluvial fan complex 32
Figure 12. Geologic flood-hazard map of the Hiko Springs Canyon alluvial fan complex 34
Figure 13. Regulatory floodplain zones (FIRMs) compared with geologic information. 36
Figure 14. Areal distribution of the regulatory floodplain compared with geologic information. 38
Figure 15. Effect of structural flood-control measures on flood hazard distribution 40

Table 1. Aerial photographs used in compiling the map. 17
Table 2. Areal distribution of units shown in Figure 13 37
Table 3. Components of the lack of correspondence between the RFP and GFP. 39
Table 4. The effect of structural flood-control measures on the extent of flood-prone areas 39

Introduction

This chapter describes the use of the surficial and Quaternary geologic information described in Chapter 1 to help characterize flood hazardous areas on the Laughlin piedmont. The technique employed here, which is based on geological mapping and geomorphic interpretation, represents an efficient, realistic, and cost-effective method for characterizing the spatial distribution of flood hazards in this area and on desert piedmonts in general. This type of analysis is a necessary initial step in flood hazard management. The principal goal is to determine the actual extent of flood hazardous areas on the basis of physical geological information that is evidence for both the cumulative effects of floods and evidence for non-inundation by floods for hundreds to thousands of years. This approach provides real data from past floods against which to compare predictions of regulatory models that are theoretical or empirical in basis. Geologic analyses can narrow the spatial scope of conventional flood risk studies by providing a comprehensive characterization of the relative flood-hazard status of the entire piedmont, not solely the areas associated with selected principal drainages.

The geological approach involves a combination of surficial geologic mapping based on detailed aerial photograph analysis and field study. The resulting map and related interpretations of the geomorphology offer unique and critical insights into the nature and extent of flood hazards in the Laughlin area. The geologic data and interpretations are not presented as specific guidelines for flood-insurance rate determination because they have no actuarial basis. However, they provide an accurate delineation of areas presently subject to active fluvial processes and related flood hazards, which is a key and often overlooked element of floodplain management in desert areas. In this sense, the geological mapping constitutes an essential management tool.

Residential and commercial development, transportation facilities, and flood control structures on portions of the piedmont have altered the natural pattern of surface runoff and have compromised some value of geological mapping as a first-step land management tool in this specific case; however, this has affected relatively small areas thus far. Furthermore, by relying on predevelopment aerial photographs for much of the mapping, the relative efficacy of existing and proposed flood-control structures can also be evaluated and depicted in the context of the geological map.

Flood Hydrometeorology and Flood History

The largest floods on the Laughlin piedmont arise from intense precipitation events most commonly associated with isolated summer thunderstorms and regional-scale precipitation from dissipating tropical storms. This is supported by meteorological data from stations in the vicinity of Laughlin, studies of regional flood hydrometeorology and hydroclimatology (e.g. House and Hirschboeck, 1997; Webb and Betancourt, 1992; Smith, 1986;), and flood-related reports from the region (Durrenburger and Ingram, 1978; Gatewood and others, 1946). Isolated summer thunderstorms probably present the most consistent threat of local flooding from year to year, but dissipating tropical storms in the fall, though less frequent, carry a much greater threat of catastrophic regional flooding. Historically, winter storms have occasionally delivered large amounts of precipitation to the region, but are less likely to deliver the intense bursts of precipitation characteristic of warm-season storms. Some exceptions to this exist, of course, and such incidents are typically isolated occurrences (for example, locally heavy rain in December 1978 and February 1993).

Precipitation records from stations in this portion of the lower Colorado River area are sparsely distributed in both space and time. The most representative stations for evaluating flood hydrometeorology in the vicinity of Laughlin are: Needles, California; Searchlight, Nevada; Davis Dam / Bullhead City, Arizona; and Laughlin, Nevada (Western Regional Climate Center, 2000). The annual precipitation totals from each of these stations are shown in Figure 1. The record from Searchlight spans the period 1914-1999 and is thus the best representation of regional precipitation trends. The seasonal contribution to the long record from Searchlight is shown in Figure 2.

There are some notable examples of intense thunderstorms generating large floods in small basins in the lower Colorado River region (e.g., Glancy and Harmsen, 1975; Durrenburger and Ingram, 1978), and there is little doubt that these storms are a common source of flash floods; however, based on historical information, it is clear that the greatest potential for large floods occurring in multiple basins in the region is from the incursion of dissipating tropical cyclones originating in the eastern Pacific Ocean. An excellent example of such events occurred on three occasions in September 1939. Although no reports are available from the immediate vicinity of Laughlin for those storms, regional meteorological records and anecdotal accounts indicate that the Laughlin area was hit extremely hard. For example, at Searchlight, daily precipitation totals in excess of 2 inches were recorded on two days in that month. The monthly total of 8.45 inches for September 1939 is the largest monthly value in the period of record (1914-1999). Daily precipitation totals from Needles and Searchlight are shown in Figure 3 where they are compared from daily totals for the anomalously wet winter of 1993.

Anecdotal accounts of destructive local floods in the Bullhead City area are summarized by Durrenberger and Ingram (1978). They report notable events occurred on July 19, 1974 (isolated thunderstorm), September 25, 1974 (isolated thunderstorm), September, 1976 (effects of dissipating tropical storm on September 11 and an isolated thunderstorm on September 24), and August 16-17, 1977 (dissipating tropical cyclone).

The 1939 Floods

Regional flooding of the lower Colorado River valley in 1939 is probably the best example of a likely worst-case scenario of flash flooding in the Laughlin area. The 1939 floods were catastrophic, having affected the Imperial Valley, California, north to Kingman, Arizona. Reports from regional newspapers (e.g., the Las Vegas Evening Review Journal and the Los Angeles Times) indicate the severity of the floods in southern Nevada and adjacent portions of California. The entire sequence of floods is associated with the incursion of four dissipating tropical storms into the region in less than one month. Regional precipitation fields based on the existing stations at that time indicate that the Laughlin area received at least 4 inches of precipitation in the period September 3-7; 2-3 inches over the period September 8-13, and 2-3 inches in the period September 23-26. These totals are impressive, but it is important to note that at Needles, for example, 2.94 inches of rain was recorded in a portion of a single day on Sept. 6, and Searchlight recorded single day totals of 3.84 in and 2.18 in on September 12 and 24, respectively (Figure 3). Given the distribution of heavy rainfall, it is virtually certain that most if not all principal drainages in the Laughlin area experienced catastrophic floods at essentially the same time, and many sites may have experienced multiple large floods over a short period of time.

The flooding of September 1939 was linked to anomalous atmospheric circulation patterns associated with the effects of El Niño conditions in the eastern Pacific Ocean. El Niño conditions result in an increased tendency for Eastern Pacific Tropical Cyclone tracks to recurve into the

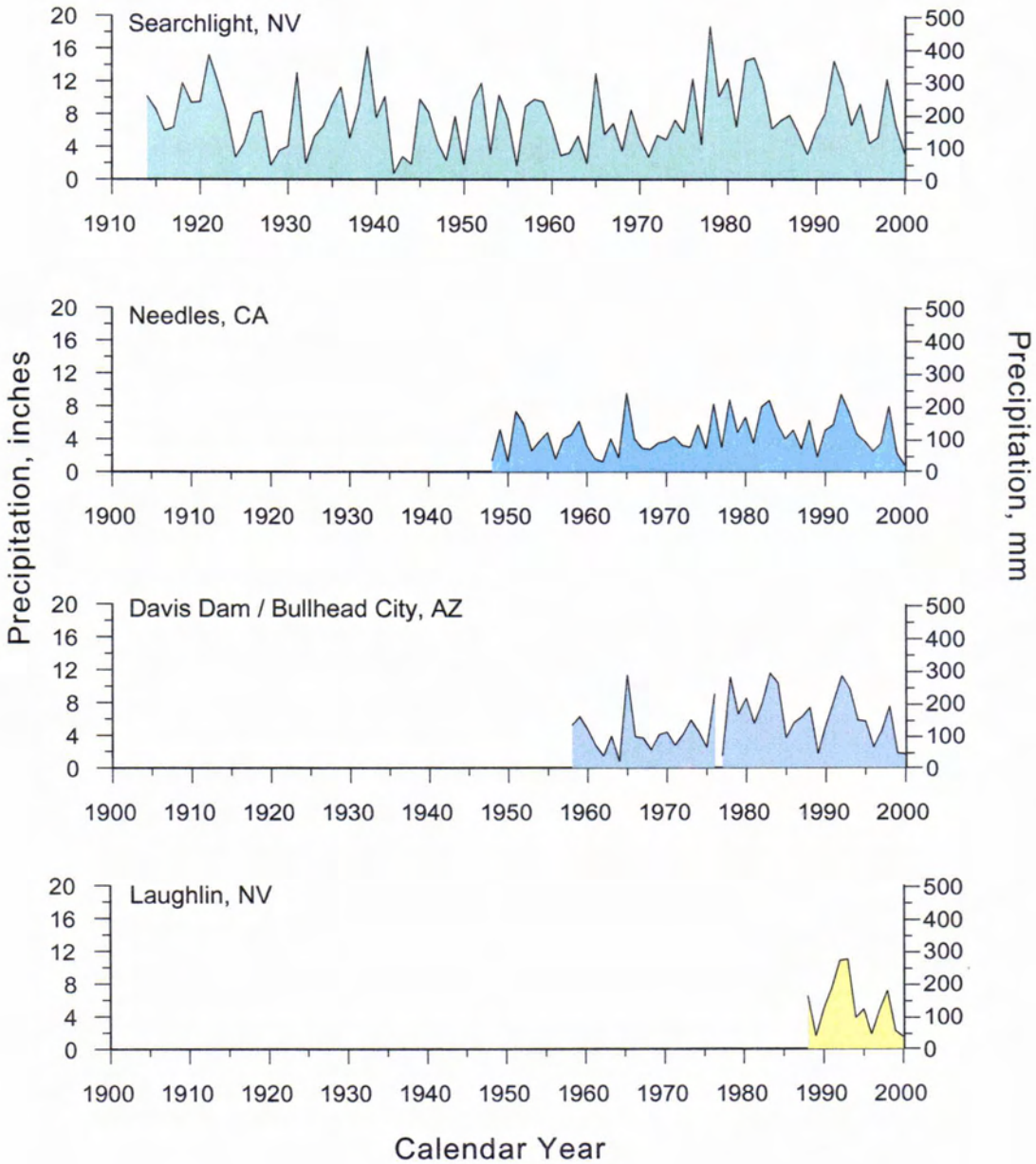


Figure 1. Annual precipitation totals from four stations in the tri-state area.

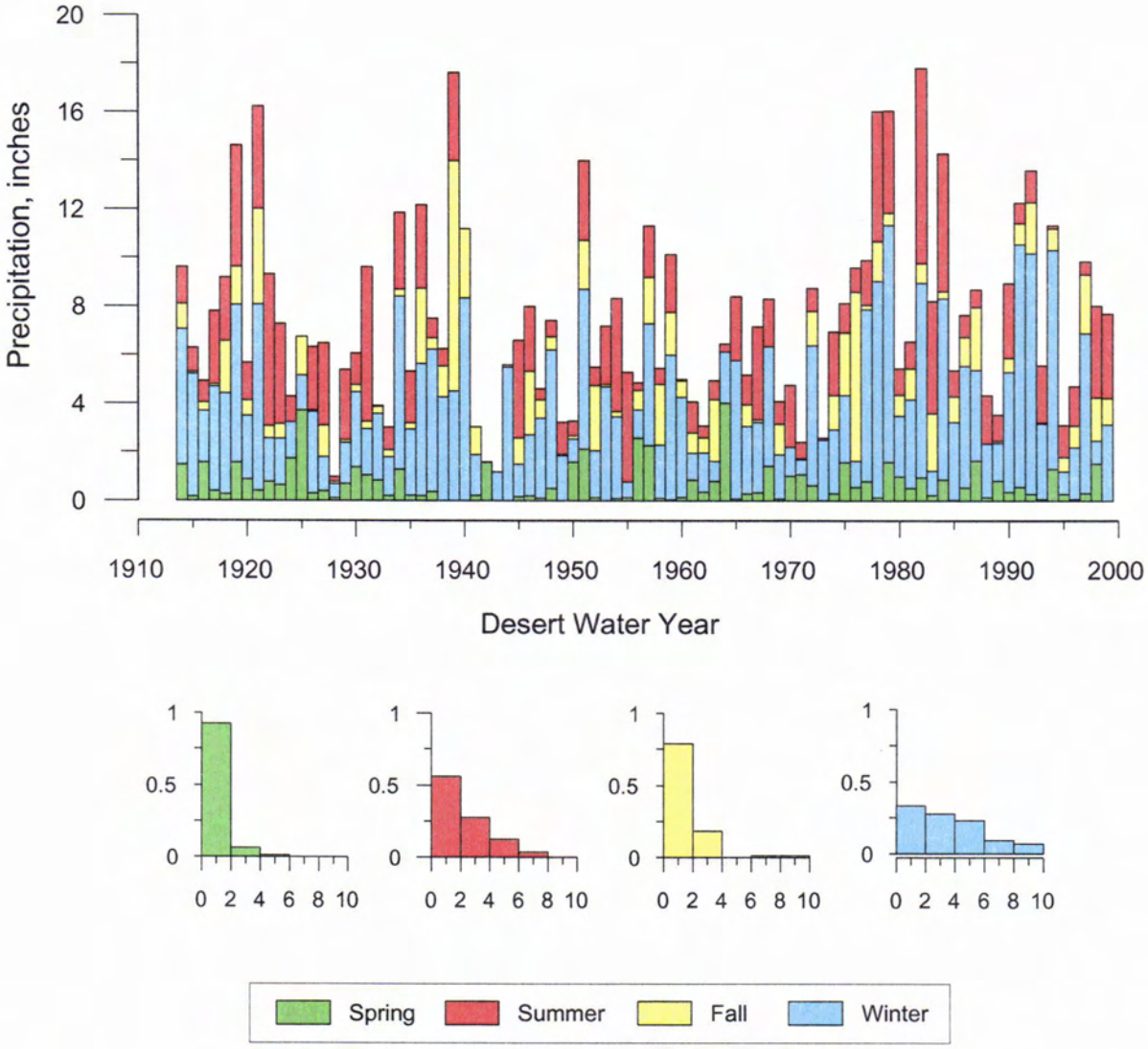


Figure 2. Seasonal distribution of annual precipitation at Searchlight, Nevada, 1914-1999. The upper graph illustrates the seasonal components of the annual precipitation with respect to a "Desert Water Year" which is from June 1 through May 30. This temporal division allows for a more realistic depiction of the annual precipitation because it terminates in the dry season and not in the midst of a typical wet season. The histograms below the main graph illustrate the relative frequency of monthly totals with respect to season of occurrence.

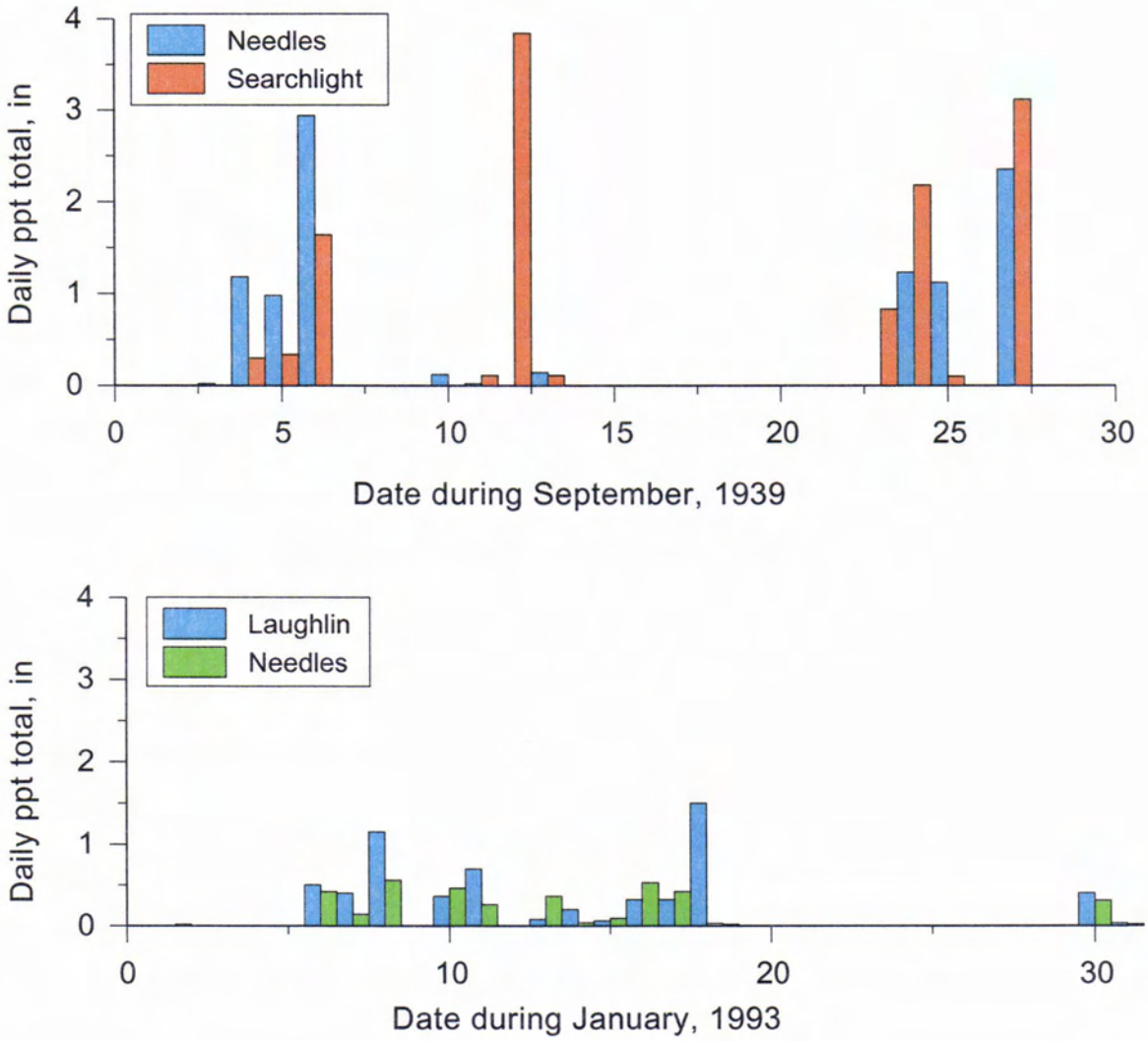


Figure 3. Comparison of precipitation totals from significant regional storm events. A. Totals from multiple dissipating tropical storms in September 1939; B. Totals from multiple frontal storms in January 1993.

desert southwest (Smith, 1986; Webb and Betancourt, 1992). This circumstance has great potential for catastrophic regional-scale flooding. Historically, this type of event occurs more frequently in southern Arizona and southern California than it does in Nevada, and it appears that only extreme southern Nevada is particularly susceptible. The September 1939 flooding event stands as the most extreme episode of regional flooding yet recorded in the area and appears to be a truly anomalous event in terms of the regional scale of heavy precipitation. Geomorphic evidence described in a later section suggests that its impact on the Laughlin piedmont was significant and related evidence remains largely intact. Given the apparent anomalous occurrence of four tropical storms in less than one month and the deep precipitation totals, such an event should be considered as a worst-case scenario for flood-control planning in the region, assuming a planning horizon of 50-100 years.

Geomorphology of Alluvial Fans and Desert Washes

Floods in the Laughlin area that pose a real threat to life and property are those that occur along desert washes that drain across the Laughlin piedmont. Despite the fact that most of the commercial center of town occupies the active floodplain of the Colorado River, the influence of flow regulation by Davis Dam, Hoover Dam, and Glen Canyon Dam upstream greatly reduces the potential of catastrophic flooding along the river, barring failure of one of the dams.

The emphasis of this chapter is on the geologic record and geomorphology of the Laughlin piedmont. The discussion requires some general explanations of the geologic concepts and terminology that are invoked. The following sections provide a general description of the geomorphology of alluvial fans in general, definitions of relevant terminology, and a comparison of regulatory approaches for evaluating alluvial fan flooding with geologic techniques.

Alluvial Fans

Alluvial fans are geological features created by natural processes of streamflow, sediment transport, and sediment deposition. They are distinctive landforms composed of unconsolidated deposits of sedimentary particles ranging in size from silt and sand to cobbles and boulders. Alluvial fans are ubiquitous landscape features in mountainous regions, but are best expressed and preserved in desert regions. They have been the focus of study by geologists for more than a century (see, for example, the extensive discussions and bibliographies in Blair and McPherson, 1994a and 1994b). 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. In the case of fans on the Laughlin piedmont, streamflow is apparently the dominant constructional process that is evident in surface depositional morphology and in stream-cut exposures of geologically recent alluvial deposits (e.g. Qay and Qai on Plate 1). The position, morphology, and extent of alluvial fans represent the relationship between the delivery of sediment to the fluvial system and the ability of the system to transport that sediment. Large-scale changes in regional climate have a profound influence on this balance and thus influence the development of alluvial fans.

Alluvial fans are so named because their morphology often resembles an extended fan, or a segment of a cone when viewed on maps or aerial photographs (Bull, 1975, 1977). They form where a stream crosses a transition from a relatively steep and confined channel to a less-confined (but rarely less steep) reach where the area of flow expands. A common misconception exists that alluvial fans form because of a break in slope from steep to less steep. Although that may be the case in certain, limited circumstances, it is an incorrect generalization. Alluvial fans

develop because of a change in lateral boundary conditions from confined to unconfined. Directly below the point of expansion, sediment is deposited over a broad area as the trunk channel widens and/or diverges into multiple channels and broad areas of relatively shallow unconfined flow. In the simplest sense, the cumulative effects of multiple flows and shifts in the locations of distributary channels over 100s to 1000s of years result in the construction of the alluvial fan landform, although notable instances in which alluvial fans were constructed by an individual catastrophic event have been documented (e.g., Blair, 1987; Wells and Harvey, 1987). However, despite the often uniform shape of alluvial fans on topographic maps, they are composite features comprised of a mosaic of alluvial deposits that record the evolution of the landform over periods of time in excess of several 10,000s of years (e.g., Ritter and others, 1993). The vast majority of piedmonts in the western United States are composed of such composite landforms.

In some physical settings, alluvial fans progressively widen downslope and reflect the idealized fan-like planimetric geometry. In most cases, however, the geomorphology and geologic history of fan development on the piedmont can have a strong influence on the shape and distribution of active alluvial fans and washes. As will be discussed below, alluvial fans and washes on the Laughlin piedmont do not adhere to the idealized alluvial fan geometry, and in many cases do not adhere to the definition of an alluvial fan. Many active fluvial systems on the Laughlin piedmont are complexly braided channels that decrease in overall width as they collect runoff that is progressively reconfined between relict alluvial surfaces as flow moves down the piedmont toward the Colorado River (note the down-piedmont distribution of Qay on Plate 1).

Geomorphic Surfaces and Surficial Geologic Deposits

Quaternary surficial geologic deposits on desert piedmonts are often associated with distinct geomorphic surfaces. There is a distinction between *geomorphic surfaces* and *surficial geologic deposits* that has important implications for using surficial geologic data to evaluate piedmont flood hazards. 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, and weathering characteristics 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.

The interpretation of areas as flood-hazardous or not is not necessarily a function of the age of the deposit—just because a deposit is 10s of 1000s of years old, it cannot be concluded that it is not subject to flooding. It is the age of the geomorphic surface, or the time at which it was abandoned by fluvial processes along the principal drainage, that is important. The bottom of a channel carved in 17 million year old granite is obviously flood-prone despite the age of the substrate. It is the presence of a stable geomorphic surface—a landform bearing physical characteristics that directly relate to its degree of connectedness with an active fluvial system and the duration of its exposure to weathering—that has flood-hazard implications. Once an alluvial surface is abandoned or removed from active erosion and or deposition by the principal channel, the surface undergoes a predictable sequence of physical changes (both on the surface and in the shallow subsurface). These are described in a subsequent section.

Other Terminology Used in this Chapter

Important distinctions exist among a variety of fluvial landforms that are commonly grouped under the general heading "alluvial fan," particularly in engineering and floodplain management

literature. Some distinctions are largely semantic points, but others have a direct bearing on the nature of flooding that is likely to occur in a certain area. Large and complex variations in fan morphology and channel patterns exist on the Laughlin piedmont, and fluvial landforms associated with the principal drainages do not always adhere to the conventional definition of an alluvial fan. This is particularly true for the presently active fluvial systems that pose the threat of significant flooding to the town of Laughlin. This will be illustrated and described in individual discussions of the geomorphology of Hiko Springs, Bridge Canyon, and Dripping Springs Canyon in a subsequent section of this chapter.

The following terms are used throughout this chapter and are defined and discussed individually below for the sake of clarity.

Piedmont

This is a descriptive (non-genetic) term for the relatively broad, generally low-relief area at the base of the mountain front that slopes toward the center of the valley. Geologically, piedmonts are mostly composed of sediment (alluvium) shed from highland areas by flood events, but they can also be complex mixtures of eroded bedrock and various types of surficial geological deposits. Constituent surficial deposits on the Laughlin piedmont include Colorado River and tributary alluvium spanning a wide range of ages.

Broad desert piedmont areas are generally composite landforms composed of deposits of widely different ages, some of which are actively being fed by a main channel and some of which have been isolated from active sedimentation for 1000s of years (Bull, 1964, 1977; Ritter and others, 1993). These different portions of a composite alluvial fan can be characterized as active or inactive.

Alluvial Fan Complex

The mosaic of tributary alluvial fan deposits, possibly spanning 10s of 1000s of years in age, that are found on the piedmont. This can refer to all of the alluvial deposits collectively (i.e., the Laughlin piedmont alluvial fan complex) or to the series of deposits associated with a master drainage (i.e., the Dripping Springs Canyon alluvial fan complex).

Active Alluvial Fan

That portion of the alluvial fan complex that is presently (or recently) active in the conveyance of water and sediment. It is characterized by a dynamic and unstable distributary channel network and approximates the shape of a fan—partly or fully extended. The period of time used to define activity (or potential activity) in this report is the Holocene Epoch, or approximately the last 10,000 years of earth history. This distinction is based on a recommendation by the National Research Council's Committee on Alluvial Fan Flooding (NRC, 1996).

Inactive Alluvial Fan

This refers to portions of an alluvial fan complex that are detached from the master drainage and do not actively convey water and sediment from the contributing watershed. Geomorphic surfaces associated with inactive alluvial fans have been separated from active fluvial processes (other than local runoff) for at least 10,000 years, often longer. Inactive fans are relict landforms that are generally associated with distinctly different hydrological conditions (a period of time in which the sediment production and runoff in the watershed were quite different than at the present—a period of wetter climate and alpine glaciation, for example). In some areas, relict fan

surfaces have been isolated from active alluvial fan deposition due to faulting, but this is not a factor on the Laughlin piedmont. The critical point is that inactive fans are no longer being constructed by active fluvial processes (i.e., flooding) and have considerably lower flood risk than active alluvial fans. However, portions of inactive fan remnants that are immediately adjacent to areas of active fluvial processes may be subject to erosion during large floods.

Fan Apex

Two definitions of fan apex are common in the geologic and floodplain management literature—the geologic apex and the hydrologic apex. The geologic apex is also referred to as the topographic apex.

The topographic apex of an alluvial fan is the highest point on an active or a relict alluvial fan surface located at the point where the main channel issues from the principal canyon draining the mountain watershed or other source of lateral confinement. The area of active alluvial fan building may or may not occur at this point. It is quite common for the upper portion of alluvial fan deposits to be entrenched, and for the geological apex to then be associated with a relict, inactive portion of the alluvial fan. Large-scale changes in the balance between sediment yield and the amount of available runoff enhances channel erosion and is a primary mechanism for fanhead entrenchment and concomitant shift in the location of alluvial fan deposition.

The hydrologic apex of an alluvial fan is the point below which the active channels adopt a distributary pattern; therefore it is the active apex of the alluvial fan, and it may or may not coincide with the topographic apex. The position of the hydrologic apex may shift with respect to flood magnitude.

Distributary Flow System

A fluvial system that has a network of distributary channels (i.e., the number of channels increases in a downslope direction). Active alluvial fans are distributary flow systems, but distributary flow systems are not active alluvial fans if it can be shown that the configuration of channels is stable over time (e.g. it is entrenched into relict alluvial deposits or bedrock).

Braided Wash

This refers to an unstable alluvial channel pattern characterized by a network of interconnected ("anabranching") channels that do not show a systematic pattern of increasing or decreasing numbers in a downslope direction. Thus, it is not an alluvial fan *sensu strictu*, but it is a system of individually unstable channels located within a definable zone that is less extensive than an active alluvial fan. On the Laughlin piedmont, braided washes are common in areas where piedmont-derived runoff is concentrated, in broad entrenched channels feeding active alluvial fans, and in areas where runoff from the upper piedmont and mountain watersheds is reconfined and funneled through relict alluvial deposits on the lower piedmont.

Flooding on Alluvial Fans

Overview

Flooding on alluvial fans and broad desert washes is problematic because high velocity, sediment-laden floodwaters may follow multiple paths simultaneously; moreover, these paths may gradually or abruptly shift position during extreme floods. Flooding can also occur as broad, unconfined shallow sheet flows that inundate large areas. Sediment-charged debris flows are typical of some alluvial fans, and these processes can also impart considerable uncertainty to channel location during extreme events. The most important characteristics of flood processes on

alluvial fans are that the paths of individual floods are generally unpredictable and that the floods involve high flow velocities and large amounts of sediment transport, particularly when compared to flooding on single-thread rivers with generally stable channel positions (where most flood hazard regulation models have been developed). However, using the geologic information, the overall spatial extent of zones with the highest potential for flood occurrence can be delineated. Of course, determination of the specific paths that future floods would take within that zone is difficult to predict with any confidence regardless of the method used.

Evaluating Alluvial Fan Flood Hazards

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. Originally, the regulatory approach was to invoke the explicit assumption of complete uncertainty, or equal probability of channel location below the point at which channel position variability begins (Dawdy, 1979; FEMA, 1990). This is a broad assumption that may be valid on a small subset of alluvial fans, but it is an oversimplification and overly cautious assumption for fans with well-defined channels and local topographic constraints (French, 1992; NRC, 1996). Furthermore, the application of this simplistic model was commonly flawed by misinterpretation of the geomorphology of alluvial fans and the related implications for the spatial distribution of flooding on broad desert piedmonts. The mischaracterization of alluvial fan and related piedmont flood hazards resulting from omission of geological information has been discussed extensively by several investigators (e.g., Pearthree and others, 1999, 2000; Field and Pearthree, 1997; O'Brien and Fuller, 1993; French, 1992; House and others, 1991, 1992; Baker and others, 1990). Formal recognition of the problem led the National Academy of Sciences to provide FEMA with a set of recommendations for improving the approach for characterizing the problem of alluvial fan flooding (NRC, 1996). FEMA has since modified its guidelines to reflect these recommendations and has largely disavowed the original, overly simplistic approach. Most importantly, the agency has formally recognized the value of geologic studies and the evaluation of fans on a site-by-site, individual basis (FEMA, 2000).

Geological Evaluation of Flood Hazards on the Laughlin Piedmont

Active alluvial fans are geological features that reflect the cumulative effects of streamflow and flood events over 100s to 1000s of years and longer. The inherent uncertainty about the positions of channels on alluvial fans over time and the need to discriminate between active and inactive portions of alluvial fans constitute the best rationale for using geologic information to improve flood hazard delineation because it represents the cumulative effects of flooding and evidence for non-inundation by floods for 100s to 1000s of years.

A geologic map focusing on the distribution of different ages of alluvial fan deposits conveys a faithful representation of the distribution of flood hazardous areas. In fact, the flood-hazardous status of a given area is integral to the set of criteria used to compile the geologic map, at least to the level of distinguishing active surfaces from inactive ones. Various observable physical characteristics are diagnostic evidence for the isolation of an alluvial surface from active processes of erosion and deposition. 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 and necessitate geologic studies.

Methods

The approach used here to evaluate flood hazards on the Laughlin piedmont adhere to guidelines presented in the recent report on alluvial fan flooding from the National Research Council (NRC, 1996). As mentioned above, the NRC (1996) report was commissioned by FEMA to provide a reasoned, objective appraisal of their technique of alluvial fan flood hazard assessment. The recommendations in the report involve a considerably more substantial consideration of the physical characteristics of alluvial fans and their related hazards than in previously published FEMA guidelines. Three principal steps in flood hazard evaluation are presented in the NRC report:

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.

This report emphasizes points one and two, which call for detailed surficial geological mapping and geomorphic analysis. Point three requires detailed topographic and hydrologic analysis and the domain of the engineering analyses that are required to develop explicit floodplain zones and insurance rates. The geologic approach in steps 1 and 2 does offer a conservative perspective on the information sought in step 3. It assumes that the extent of presently active alluvial surfaces reflects the integrated effect of all floods that have impacted each system over the last several 1000s of years. This suggests that all large flood events feasible in the present climate, regardless of their frequency, occur on the active fan surfaces and portions of surrounding areas that are relatively low with respect to the active areas. The primary difference between floods of different magnitudes is that the severity of flooding within the active fan area will be accordingly different but will occur within a reasonably definable area. Subsequent flood-risk determinations based on hydrologic and hydraulic analyses that are strongly at variance with the geologic data should probably be re-evaluated to ensure a scientific basis and a defensible regulatory scheme. Because geologic data constitute the only actual physical information that reflects long-term processes of flooding, they should not be discounted with respect to predictions of regulatory models based on extrapolation from short records and untested, or untestable, assumptions.

The guidelines established by the NRC (1996) committee on alluvial fan flooding are based on the following tenet: "...although areas of deposition on an alluvial fan shift with time, it is most likely that subsequent flooding events will occur in areas with the youngest alluvial deposits as opposed to areas of deposits with the greatest antiquity." This is the conceptual basis for using geologic information to evaluate the extent of flood hazardous areas and it is an extension of the logic of building a home adjacent to a stream as opposed to in the bottom of the channel. The statement is very appropriate to the situation on the Laughlin piedmont because of the relative ease of delineating young and old alluvial surfaces and because dramatically rapid and unprecedented changes in channel geometry, sediment yield and flood magnitude would be required to involve most of the older fan remnants in active flooding aside from lateral erosion and local flooding from on-fan runoff. For a large percentage of the Laughlin piedmont, the geological approach to the problem of flood-hazard analysis is the most cost-effective, and arguably the most realistic approach. It provides essential information for detailed engineering analysis and floodplain management.

Methods of Map Compilation

The geologic map in Plate 1 was prepared using conventional geological techniques of aerial photograph analysis and field reconnaissance. The final line work was compiled on the topographic map base using a PG-2 stereo-plotter. This device allows for a precise transfer of mapping from the aerial photographs to the paper map. The surficial geologic information (the Quaternary deposits that overlie the older bedrock units) was prepared for final compilation through stereoscopic analysis of a chronological series of aerial photographs (Table 1). Use of numerous series of photos allowed for the piedmont to be viewed over a range of scales and, more importantly, at points in time when the geomorphology was essentially unaffected by any form of human disturbance (Figure 4). Also, use of a chronological series of aerial photographs allowed for an assessment of the potential occurrence of large floods in the major drainages over a 50-year period (1947-1997).

Mapping Criteria

Alluvial surfaces on the Laughlin piedmont can be separated into young and old (i.e., active and inactive) relatively easily. The oldest extant surfaces on the Laughlin piedmont are easily identifiable and very distinct from active surfaces. However, they are poorly preserved because of the erodible nature of the constituent granitic sediments. In contrast, alluvial surfaces on the Arizona side of the river exhibit much greater degrees of preservation because they are composed of sediments from rock types that are more resistant to erosion. The generally poor preservation of the oldest alluvial surfaces on the Laughlin piedmont represents a gap in the Quaternary geologic history, but it does not hamper the evaluation of the surficial geology in the context of flood hazards because the distinction between the range of older and younger deposits remains clear, it is subdivision of the older surfaces by age that is more challenging.

Numerous investigators have established useful guidelines for mapping alluvial fans, both in the context of interpreting Quaternary geology and evaluating flood hazards (Christenson and Purcell, 1985; Bull, 1991; Ritter and others, 1993; Field and Pearthree, 1997). In developing the map of the Laughlin piedmont, we relied on the following criteria:

1. *Presence, degree and nature of drainage development.* Active alluvial fans have an obvious distributary drainage pattern (number of channels increase down fan), whereas relict, inactive alluvial fan surfaces are characterized by a dendritic drainage pattern (number of channels decreases down fan). This reflects the progressive erosion of relict alluvial surfaces by local runoff.
2. *Topography.* Different aged alluvial surfaces are typically topographically separated from each other, the degree of separation depends somewhat on the scale of the system and its history. In delineating active vs. inactive fan surfaces, it is important to evaluate the degree of continuity with the active feeder channel. Relict fan surfaces are distinctly disconnected from the active channel.
3. *Patterns of faulting.* Fault relations are important criteria for differentiating different aged alluvial surfaces. Some of the topographic separation in the different map units may be due to faulting, and older deposits may be faulted whereas immediately adjacent, younger fans may not be. This criterion was not applicable to the Laughlin piedmont.
4. *Stratigraphic relationships.* Stratigraphic relationships with different geological units of known or estimable age can be used to evaluate the age of the alluvial fan deposit in

question. The overall stratigraphic framework of Quaternary deposits on the piedmont is described in Chapter 1.

5. *Soil development.* Over time, inactive alluvial surfaces progress through a predictable series of time-dependent physical changes. Soil development proceeds through a slow series of physical and chemical changes to the upper portion of the deposit. The type and magnitude of change that occur are related to the duration of exposure. A typical soil characteristic in desert areas is the development of a soil carbonate horizon.
6. *Surface characteristics.* Inactive alluvial surfaces undergo a variety of time-dependent physical changes. The formation of desert pavements, development of rock varnish, and the physical disintegration of rocks are typical changes in arid regions that reflect varying amounts of time. Their development is accompanied by the progressive muting of original depositional topography by redistribution of surface sediments. The result is a progressive flattening of an initially irregular surface of channels and gravel bars typical of an active alluvial surface. Over time, the flattened surface is progressively eroded into a series of ridges and gullies and the soil profile is often stripped to the resistant carbonate horizon.

For the most part, each characteristic reflects the degree to which an individual surface has been isolated from active deposition from the principal drainage and exposed to progressive decomposition and disaggregation by chemical and physical weathering. Some characteristics indicate the effects of a variety of geomorphic processes that mold the surface into a feature that is progressively different from its original depositional form. Each of these physical characteristics provides a clear indication of the absence of active fan building processes.

Table 1. Aerial photographs used in compiling the map

Source	Date	Scale	Film
USGS	20-Oct-47	1:24,000	B/W
AMS	06-Mar-54	1:80,000	B/W
USAF	06-Sept-68	1:126,720	B/W
USGS	04-Jul-74	1:83,300	B/W
USGS	24-Aug-76	1:24,000	Color
NDOT	11-Dec-78	1:5,000	B/W
BLM	10-Jun-80	1:24,000	Color
BLM	02-Sept-93	1:24,000	Color
NAPP	26-Aug-92	1:40,000	B/W
NAPP	28-Jun-97	1:40,000	B/W

The Geologic Map of the Study Area

In the course of this study, a comprehensive geologic map of the Laughlin area was compiled (Plate 1). The map depicts the distribution of a complex variety of bedrock units and all the extant surficial geologic deposits associated with the Colorado River and its tributaries that drain the Newberry Mountains and the Laughlin piedmont. These surficial deposits represent the recent geologic history of the principal drainages that pose a threat of flooding to the town of

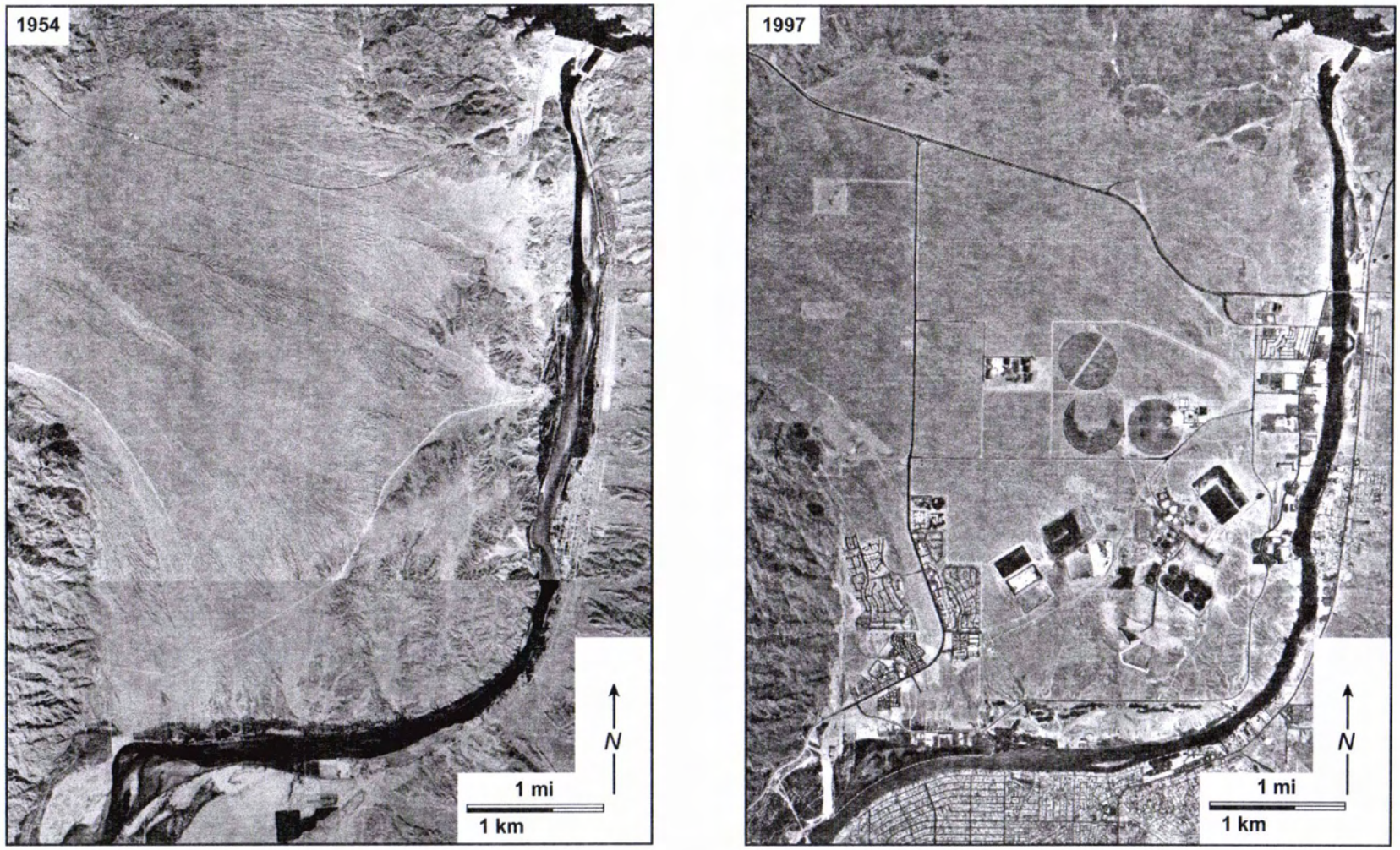


Figure 4. Aerial photograph comparison of the Laughlin area, 1954-1997. Photos are approximately matched and, in the case of the 1954 images, include multiple photos. Scale is approximate for each image.

Laughlin. The map of their spatial distribution provides a physical context for evaluating the related flood hazards.

The piedmont is composed of a variety of alluvial geomorphic surfaces that reflect the variable influence of Quaternary climate change on the long-term production and delivery of sediment to the Colorado River and its tributary streams. Many alluvial geomorphic surfaces on the piedmont represent the culmination of phases of climatically induced aggradation followed by isolation of large areas from tributary entrenchment in response to base level lowering along the Colorado River. Some alluvial surfaces along the Colorado River also reflect periods of relative stability followed by down cutting. The ultimate cause of cycles of aggradation and degradation is change in the balance between watershed sediment delivery and the sediment transport capacity of the trunk stream or alluvial fan system.

The oldest alluvial surfaces on the Laughlin piedmont constitute a suite of at least three generations of inactive alluvial fans. Extensive, continuous periods of fan inactivity are reflected as progressively greater amounts of chemical weathering (decomposition) and physical disaggregation of relict deposits of tributary alluvium. Specific characteristics of these processes are identifiable in the field and in aerial photographs. Their occurrence is precluded by active processes of sediment entrainment, transport, and deposition by active fluvial processes characteristic of alluvial fans. For example, the Qai surfaces on the piedmont are not subject to active alluvial fan building processes, so they become progressively more weathered and eroded over time. The duration of the period of exposure can be inferred from the relative magnitude of the characteristic or apparent stage of progress along a predictable continuum of morphological development.

Characteristics of Quaternary Map Units

The most significant piedmont flood hazards in the Laughlin area are restricted to areas underlain by young deposits of tributary alluvium. The geological map included with this report (Plate 1) depicts these units with the designation of Qay, Qai, and related subdivisions of each. The piedmont alluvial deposits that are subject to the most significant flood hazards are mapped as Qay. The unit Qai represents relict alluvial fan surfaces that are graded to past, higher levels of the Colorado River, and their physical characteristics indicate that they have not been subject to active, main-channel fluvial processes for 1000s to 10,000s of years. Areas where Qai remnants are widely dispersed or penetrated by relative young, active channels have not been separated out in the mapping at this scale (1:24,000). These areas are too isolated and small not to be considered flood-prone.

Inactive Alluvial Surfaces—Unit Qai

The primary distinguishing characteristic of the Qai surfaces is their erosional topography. Even through a cursory evaluation of the floodplain the distribution of the Qai units is relatively easy to grasp. In the aerial photographs, relict Qai surfaces are distinctly crenulated / corrugated in appearance because of the presence of relatively deeply incised, and laterally confined local drainages that are actively eroding the deposits (e.g., Figure 5). A range of surface characteristics typical of this unit is shown in Figure 6. 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 Laughlin piedmont are graded to levels of the Colorado River that are progressively higher above the river with increasing age (see Chapter 1 for explanation). The oldest extant Qai units can also be placed into a stratigraphic context that supports interpretations

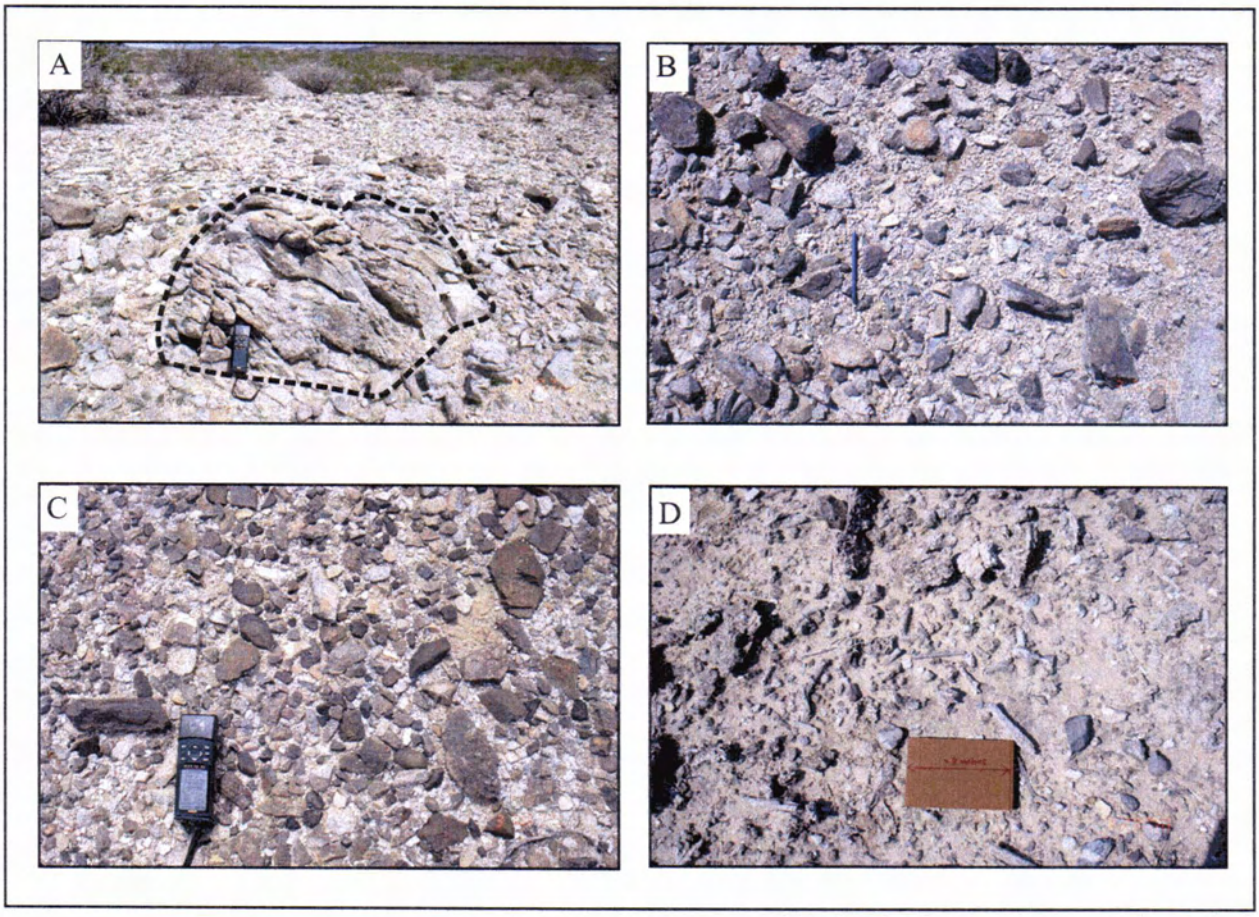


Figure 5. Typical surface characteristics of unit Qai. A. Stable Qai surface characterized by a moderate desert pavement, locally varnished clasts, and in situ shattered rocks (shown with outline). B. Disrupted desert pavement with scattered, darkly varnished angular rock fragments. C. Reasonably well-developed desert pavement with numerous darkly varnished rock fragments. D. Characteristic surface of Qcs deposit overlain by thin, and eroding veneer of Qai. Stick-like clasts on surface are petrified wood fragments that are common in the Qcs deposits.

Figure 6. Typical surface characteristics of unit Qay. A. Typical mid-channel surface with sand and gravel. B. Typical gravel bar.

of significant antiquity. The oldest Qai units (Qai_1) on the piedmont overlie deposits of Qcs that range in age from no younger than 40,000 years (Blair, 1996, Lundstrom and others, 1999) to as much as 250,000 years old (Bell, 1978). Somewhat younger Qai units (Qai_2 and Qai_3) are graded to progressively lower terrace levels and are also clearly isolated from the presently active systems. The specific ages of these deposits are not known. Soil development, topographic position, and relationships with river terraces all suggest that the deposits are no younger than the latest Pleistocene. A conservative assumption is that the deposits all predate the Holocene Epoch (i.e., they are older than at least 10,000 years). Better age-estimates for the deposits and related geomorphic surfaces could be obtained using radiometric and surface-exposure dating techniques.

Active Alluvial Surfaces—Unit Qay

The flood-prone areas on the Laughlin piedmont are the active alluvial surfaces. All active alluvial surfaces on the piedmont are mapped as Qay on Plate 1. A variety of surface characteristics and drainage patterns typify this unit and make it relatively easy to delineate. It can also be subdivided into at least two units (Qay_1 and Qay_2) that convey the relative age of the deposit and the relative frequency of inundation. Typical surface characteristics of this unit are shown in Figure 6.

The subunit Qay_2 represents the youngest and most active portions of the major fluvial systems on the Laughlin piedmont. It is associated with active processes of sediment entrainment, transport, and deposition. Large portions of this unit are probably no older than a few hundred years, as it is inundated most frequently. Its distribution comprises areas of the most vigorous fluvial activity, portions of it are reworked and redistributed in all surface flow events, regardless of their magnitude. The subunit Qay_1 includes the oldest and least frequently activated portion of the Qay sediments. This subdivision includes areas adjacent to extensive Qay_2 deposits that do not presently convey significant amounts of surface flow but are likely subject to inundation in particularly large (rare) events or in association with large shifts in the positions of principal channels. Qay_1 is also used to indicate young deposits associated with piedmont drainages that convey water and sediment from the old and eroding deposits. Locally, these areas do constitute a local flood hazardous condition, but it is of a lesser magnitude than that associated with the principal drainages. In this study, all Qay units are considered flood-prone.

Drainage Patterns Characteristic of Qay Deposits

The planimetric pattern of ephemeral stream channels on the Laughlin piedmont varies considerably with distance from the mountain front and the apices of active alluvial fans. The variation occurs in both a lateral sense away from the principal drainages and in a distal sense in the down-piedmont direction. The following types of patterns are typical of active channel systems on the piedmont. Examples of each are highlighted on Figure 7.

Stable Distributary Flow Networks

These are characteristic of areas on the distal margins of active alluvial fans and local (piedmont) drainages. In these zones, a distributary network of active channels is incised into relict alluvial fan and Colorado River deposits. The pattern of channels is stable because of their lateral confinement by older deposits. These areas are most common on the distal portions of the active alluvial areas where the profile of the active alluvial surface intersects a relict surface that was graded to a higher level of the Colorado River. In most areas on the map, these are depicted as multiple channels of Qay separated by distinct islands of Qai. In some areas, the Qai

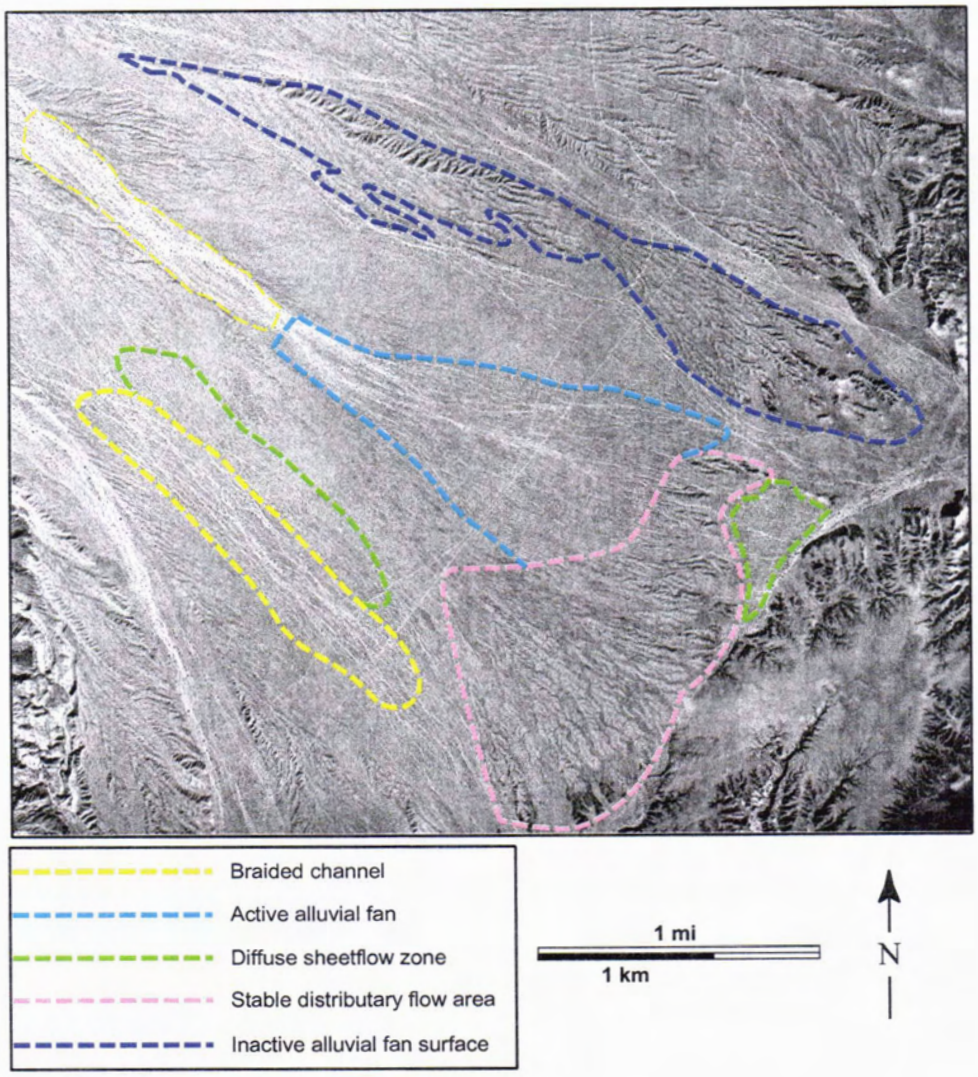


Figure 7. Drainage patterns typical of active alluvial surfaces. Representative examples of each of the principal drainage patterns are highlighted on the aerial photograph (October 1947). The inactive alluvial surface is outlined for comparative purposes. See text for explanation.

remnants are so small and dispersed they are simply lumped-in with the Qay to convey the overall predominance of active alluvial surfaces in those areas. In contrast, the opposite convention is adopted in areas where the Qai remnants are most extensive and the unit is labeled as Qai. In these areas there may be small, active channels that are entrenched into the Qai alluvium and are laterally stable. Such channels are flood-hazardous, but they constitute a local hazardous condition and could be mapped easily at a smaller-scale. In the individual alluvial fan flood hazard assessments below, these areas are qualitatively ranked with respect to their flood hazard status.

Diffuse Sheetflow Zones

These are common in medial and distal portions of active alluvial surfaces on the piedmont and in areas below very small watersheds in the mountain front and piedmont drainages. The zone is typified by an intricate drainage network of numerous small channels separated by broad areas of essentially unconfined flow. Low, relict fan surfaces with well-developed desert pavements and dark rock varnish are relatively common in these zones. Typically, these small relict surfaces are too small and widely dispersed to be mapped adequately. Another important location is below overflow points on active alluvial fans, where entrenched channels diverge from active fans and route flow through relict fan surfaces and onto broad areas that also convey piedmont runoff. In most cases, these areas are mapped as Qay_2. They are mapped as Qay_1 in areas that are somewhat detached from the most recently active channels.

Braided Channel Networks

These are found in areas of deeply entrenched, broad alluvial channels and zones of runoff re-concentration at the distal margins of alluvial fans. These zones cannot be accurately classified as alluvial fans because they are not associated with a distributary flow pattern, but they are associated with uncertain flow paths, high velocity flow and complex patterns of erosion and deposition. In cases where this type of pattern is directly linked to runoff emanating from a principal mountain watershed, it is mapped as Qay_2. Where it is linked to a local piedmont drainage, it is mapped as Qay_1.

Active Alluvial Fans

This refers to areas that have the characteristics of active alluvial fans as previously described in this report. In short, they are characterized by a complex distributary pattern of unstable channels and sheetflow areas. Here, the highest velocity flows are most likely and the most aggressive sediment transport regime is found. All principal active alluvial fans on the piedmont are mapped as Qay_2 on Plate 1.

Flood Hazard Interpretation of the Surficial Geology

The active alluvial surfaces on the piedmont are geological features composed of flood deposits and areas where the substrate of active channels may be eroded, older alluvium or bedrock. The inactive alluvial surfaces constitute evidence on non-inundation by floods over long periods of time. Thus, the geological map can be interpreted in the context of potential flood hazard severity. However, it is important to realize that such a map is not intended to convey any specific element of probability (the location and severity of the "100-year" flood, for example). This requires integration with a theoretical, probabilistic model of flooding in addition to more extensive analysis of fan stratigraphy and geochronology.

Aerial Photo Evidence of Large Floods

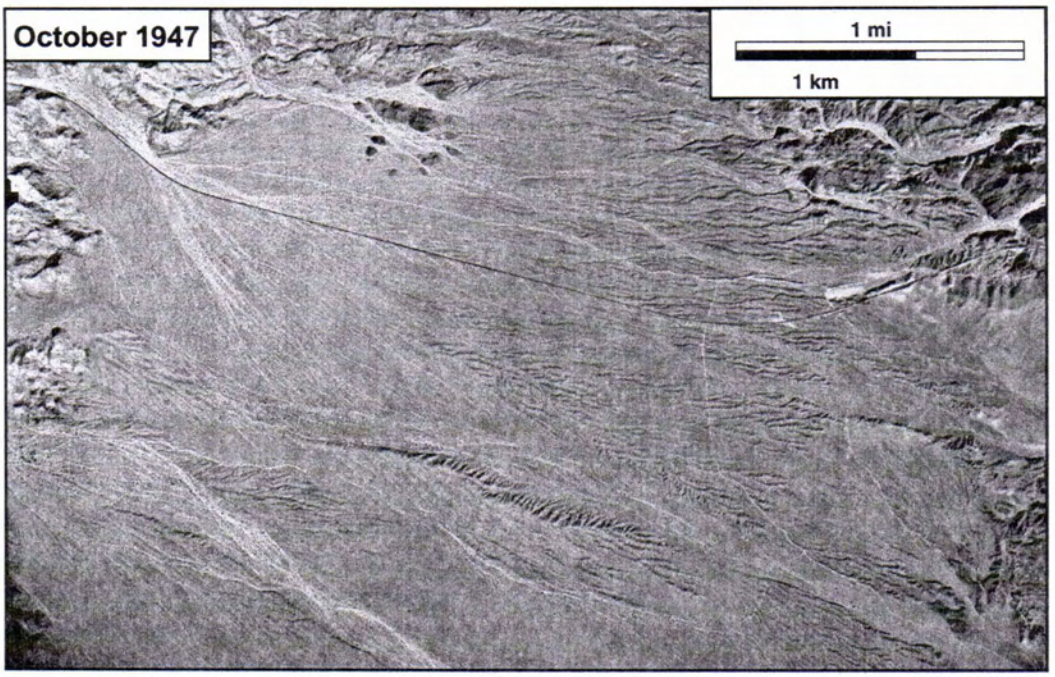
It is notable that systematic comparisons of the sequence of aerial photos listed in Table 1 indicate surprisingly few and only relatively minor changes in channel configurations on the Laughlin alluvial fans over the period 1947-1997. This is a surprising conclusion given the passage of 50 years and the likely occurrence of floods (of unknown magnitude), for example in 1976, 1978, and 1993. In the 1947 photos a pattern of widespread fresh channels (i.e., cleared of vegetation) is evident on portions of most of the active alluvial surfaces below the principal drainages, Bridge Canyon and Dripping Springs Wash, in particular. These general patterns persist to the present day and are easily detectable on recent aerial photographs (Figure 8). It is likely that the fresh channels were formed by catastrophic floods in 1939. The occurrence of only minor changes since 1947 indicates that no flood in the intervening time has been of sufficiently high magnitude and duration to significantly alter the drainage patterns established prior to 1947. In general, the most notable changes are the growth of vegetation in the channels. Flow-related change in 1993 is evident in some locations (e.g., Hiko Springs Wash, and Grapevine Canyon), but these are not large-scale changes expected from high-magnitude flash floods. Field reconnaissance in these and many other drainages indicates that the 1993 floods were not of particularly high magnitudes from the basis of extant high-water indicators. It is possible that they may have been of a prolonged duration that contributed to local erosion and sedimentation in some of the washes.

This observation of the relative persistence of the channel patterns likely associated with floods in 1939 has two important implications: 1. subsequent flood events in each of the drainages have been of inadequate size to significantly alter the channel patterns presumably created by the 1939 floods despite the passage of 60 years since their occurrence; and 2. the effects of the likely catastrophic flooding were restricted largely (entirely?) to portions of areas mapped as Holocene alluvium on the geologic map of the piedmont.

Types of Flood Hazard Zones

The interpretation of the surficial geologic map in the context of flood hazards involves a generalization of the mapped units associated with the major alluvial fan complexes into different zones or hazard classes that comprise the geologic floodplain and adjacent, non flood-prone areas (Figure 9). The maps described in the following sections were compiled on aerial photographs taken in October 1947 (shown on each figure) and, therefore, predate any development aside from a few dirt roads and the principal road to Davis Dam (under construction at the time). The geologic mapping has been transferred to the photos and, in some cases, the details have been generalized to convey the predominant hazardous condition. These cases are discussed in the following sections that deal with each major fan complex. The resulting flood hazard maps illustrate the distribution of hazards at a point in time when the major fans were in a pristine, undisturbed state. Additionally, the maps have been modified to illustrate the likely influence of existing flood-control measures on the distribution of hazardous areas. The differentiation of the hazardous areas within the geologic floodplain is intentionally generalized to emphasize that all of the active fluvial surfaces are distinctly flood hazardous and that the severity of the hazard at any given point may vary with time and flood magnitude. However, the differentiation of the flood-prone areas from non flood-prone areas is relatively straightforward with the geologic information, and these boundaries are not generalized.

The active fan complexes of the major drainages (Dripping Springs Canyon, Bridge Canyon, and Hiko Springs Canyon) (Figure 9) are subject to the greatest degree of flood hazard and are



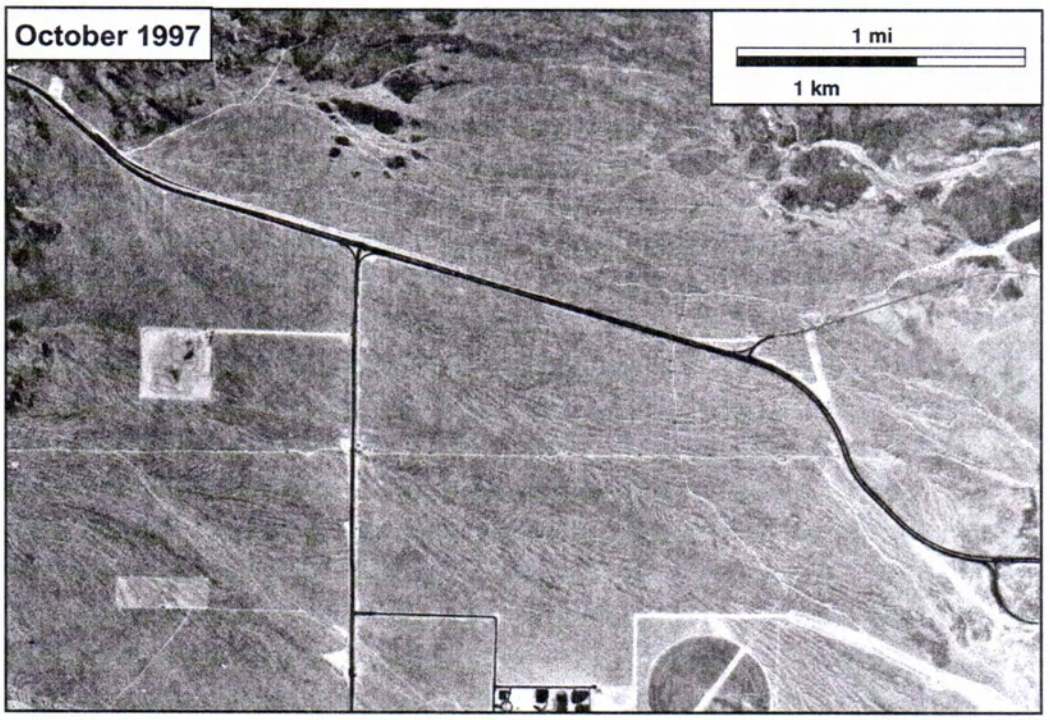


Figure 8. Upper piedmont, 1947-1993. This comparison illustrates the lack of change in the configuration of the principal channels on the Bridge Canyon and Dripping Spring Wash active alluvial fan complexes over a period of 50 years. Presumably, the fresh channels evident in the 1947 photos were significantly impacted by flooding in 1939. The general configuration of channels has not changed since then, but they have become more vegetated. North is to the top of each figure.

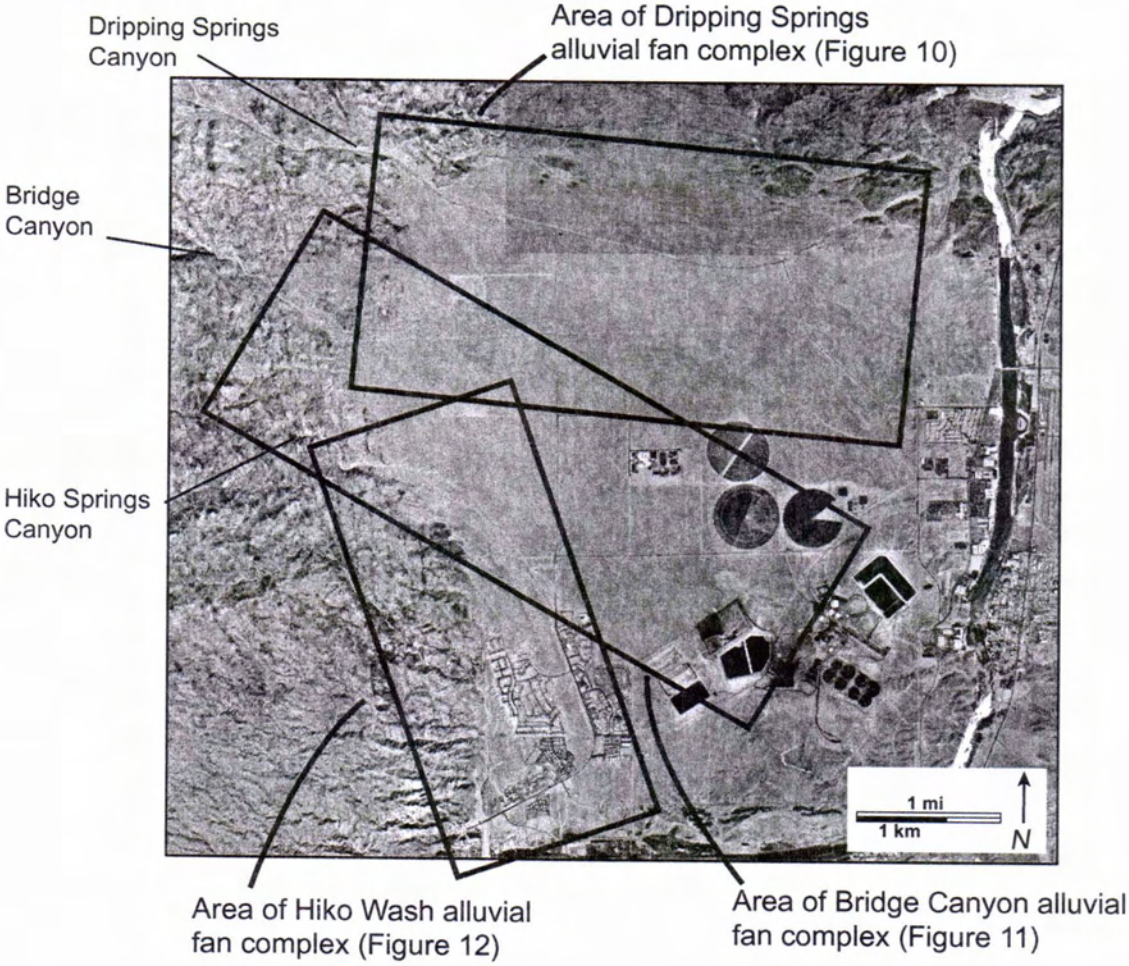


Figure 9. Location of principal drainages and the primary alluvial fan complexes.

mapped in red on the flood hazard maps described in the following sections. Areas mapped in orange are recently abandoned alluvial surfaces adjacent to the principal drainages. They represent Holocene surfaces that have not been inundated for possibly 100s of years, but occupy vulnerable positions near the presently active channels. These surfaces have been involved in active fluvial processes recently enough to preclude them from being considered non-flood hazardous or even of relatively low hazard potential. Areas that convey predominantly piedmont runoff (no mountainous source area) are flood hazardous and may be subject to relatively frequent inundation, but typically by much lower magnitude and localized flows. These areas are classified as less hazardous than the areas mapped in red, and are shown in yellow (Figures 10-12). This classification largely coincides with areas mapped as Qay_1 that are restricted to local sources of runoff.

Many areas where piedmont runoff generally predominates have been grouped with the highest hazard class (red). In these cases, direct connections between the primary active fans and adjacent (secondary) piedmont drainages are present in the form of "link" channels. These are distinct, active channels entrenched into inactive alluvial surfaces that separate the primary and secondary areas. These channels can convey significant flow from primary areas to secondary areas, thus posing a threat of significant flooding. It is also possible that major channel relocation (avulsion) on the primary active fan can exploit these channels and shift the position of the primary zone into the secondary zone. In some cases, the linking channels convey flow to widely separated areas on the piedmont. Some also convey flow back from the secondary areas to the primary areas. The presence of the link channels imparts an interesting and complex drainage network to the active alluvial surfaces on the Laughlin piedmont. Inactive alluvial surfaces on the piedmont (unit Qai and related subdivisions) have been classified as having the lowest flood hazards. In almost all cases, these surfaces have essentially no hazard of significant inundation by large floods, but the low hazard connotation was adopted for the sake of conservatism. In cases where portions of the boundaries of these surfaces are ambiguous with respect to hazardous areas, they have been mapped in yellow to indicate a slightly greater hazard.

Anthropogenic Features

In the following site-specific evaluations, the influence of anthropogenic (human-made) features other than flood-control structures on the distribution of flood hazardous areas was not considered. Many features disrupt natural drainage patterns and shift the loci of flood hazards. It is not possible to use the geologic approach to evaluate the effects of these features except in cases where they have impacted processes recently and significantly enough to be expressed in the distribution of young geological deposits. This issue underscores two important points: 1. the geologic approach is best applied prior to extensive development, and 2. development in ways that better conform with fan morphology are less likely to require expensive post-development flood-control improvements. The utilization of rectangular grids for streets is cost-effective in the short term, but its lack of conformance with natural patterns of runoff inevitably leads to flooding problems in the future.

Characteristics of the Principal Washes

The principal washes on the Laughlin piedmont emanate from rugged and relatively barren desert watersheds in the Newberry Mountains to the west of the town. The drainages with the greatest potential to impact Laughlin are: Hiko Springs Canyon, Bridge Canyon, and Dripping Springs Canyon. Additionally, numerous smaller, unnamed drainages are certain to contribute variable amounts of flood flow to the larger systems. In general, the active alluvial surfaces

associated with these drainages do not adhere to idealized alluvial fan geometry, e.g. a simple system of a main channel feeding a conical alluvial fan that terminates at the center of the valley or coalesces with adjacent fans into a more gently sloping bajada. Instead, the Laughlin fans are characterized by great morphological variability that is influenced significantly by the Quaternary history of the piedmont and its linkage to the Colorado River. In general, the most areally extensive active fluvial processes occur on the upper and middle piedmont, with the exception of Hiko Springs Wash and Unnamed Wash #1, which terminate as a relatively broad coalescent fan on the Colorado River floodplain (the Laughlin terrace) (Plate 1). The other main drainage systems are initially diffuse and are ultimately re-concentrated and funneled through multiple well-defined channels entrenched in relict alluvial landforms and deposits of the Colorado River. The diffusion of flow on the upper and middle portions of the piedmont is such that the principal drainages ultimately terminate as relatively small fans on the Colorado River floodplain.

Dripping Springs Wash

Geomorphology and Flood Hazards

The active portion of the Dripping Springs fan complex is, in its upper portions, the most alluvial fan-like system on the Laughlin piedmont (Plate 1 and Figure 10). The geologic apex of the alluvial fan complex is located immediately adjacent to the south side of State Route 163 near the canyon mouth and is associated with a relict fan surface (Qai). The hydrologic apex of the fan is located just below the mountain front where the active wash spreads laterally into a broad, steeply sloping alluvial fan with a multitude of distributary channels and broad areas of sheetflow. The uppermost portions of the active part of the Dripping Springs alluvial fan complex coalesce with portions of adjacent drainages and ultimately distribute flow widely across the piedmont through a series of stable distributary flow networks. Approximately one kilometer below the hydrologic apex, near the intersection of the Needles Highway and State Route 163, the Dripping Springs fan is divided into multiple, stable flow-paths that, in an undisturbed state, would distribute flow to points as far apart as the present-day intersection of Edison Way with Casino Drive and the base of Davis Dam approximately 2.4 km (1.5 mi) to the north. This constitutes the most extensive stable distributary flow network on the Laughlin piedmont.

The flow that is split to the north merges with an active alluvial fan (unnamed drainage #2), which ultimately forms an intricate, stable distributary flow network. Further downstream this network re-concentrates flow into a single channel that terminates near the base of the Davis Dam. The flow that splits to the south is confined between relict fan surfaces and conveyed to the Edison Way-Casino Drive intersection where it merges with the active surfaces that presently convey most of the runoff from Bridge Canyon Wash.

The distribution of flood hazardous areas on the Dripping Springs fan complex is easy to delineate with geologic information. The most extensive, high-hazard area is associated with the broad alluvial fan just below the canyon mouth. Along the margins of the active fan, flow coalesces with other primary and secondary active areas, thus maintaining a high-hazard condition. Most flow along the southern margin of the fan is re-concentrated into a major braided channel that conveys flow directly to the present-day intersection of Edison Way and Casino Drive. Here, the flow converges with runoff from the Bridge Canyon fan and numerous piedmont sources.

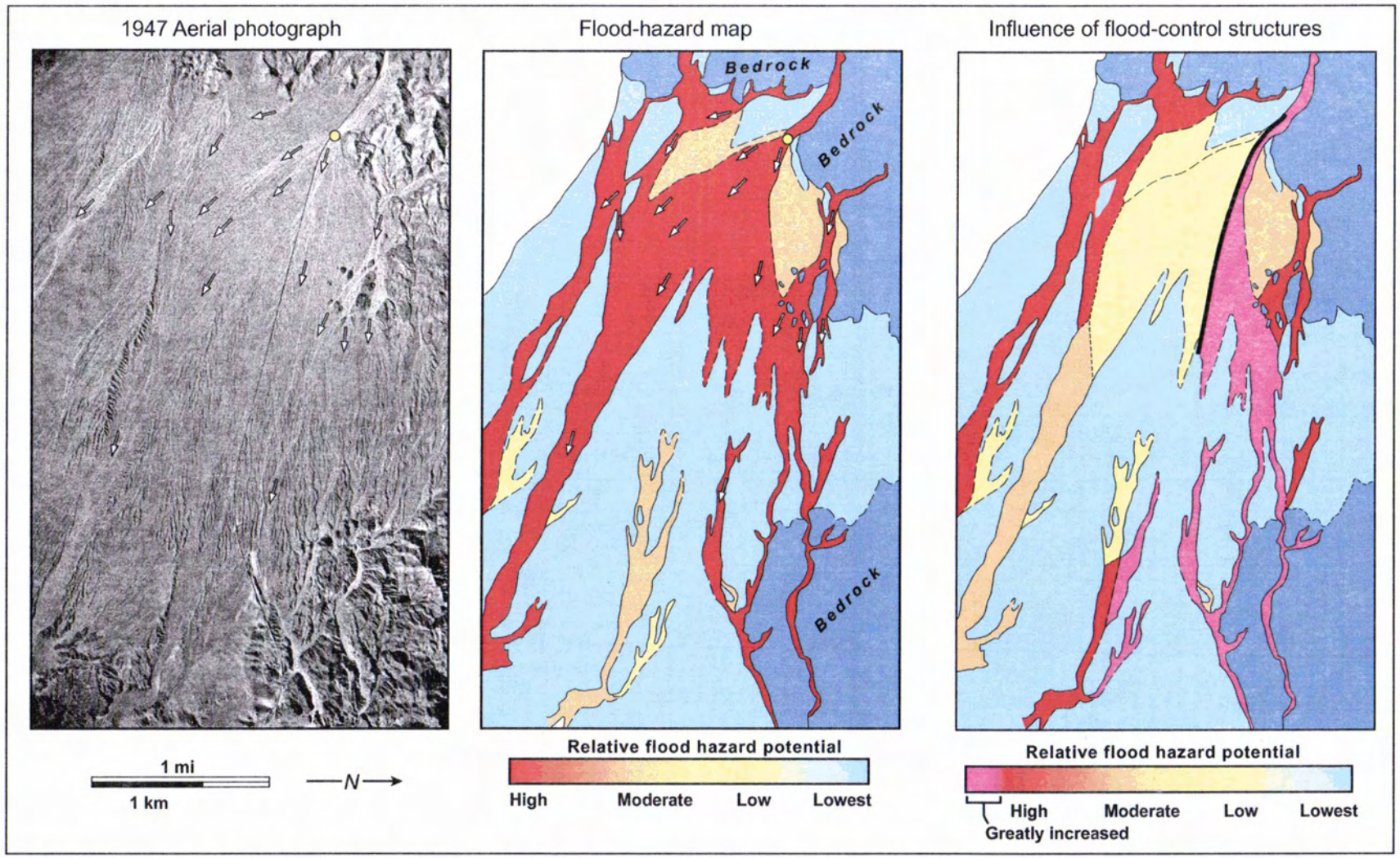


Figure 10. Geologic flood-hazard map of the Dripping Springs Canyon alluvial fan complex. Also shown is a qualitative evaluation of the influence of flood-control sturctures on the distribution of flood hazardous area. Arrows indicate predominant flow directions, and yellow circles mark fax apex locations.Also shown is a qualitative evaluation of the influence of flood-control sturctures on the distribution of flood hazardous area. Extensive bedrock outcrops (purple) are not subject to flood hazards.

Flood-Control Structures

An extensive flood-control berm constructed parallel to the alignment of Highway 163 effectively removes a large portion of the Dripping Springs fan from the high hazard classification. The effect of the 2.7 km (1.7 mi) berm is to divert all flood flow from the Dripping Springs watershed into the northern half of the stable distributary flow network that characterizes the middle and lower portion of the alluvial fan complex. Most of this drainage network is shared with the a fan complex associated with the unnamed wash to the north, and it ultimately converges near the base of Davis Dam. This diversion is an effective means of significantly reducing the flood hazard potential of the active portion of the Dripping Springs fan complex and the primary flow confluence at Edison Way while significantly increasing the hazard in the area to which the flow is diverted (Figure 10).

Bridge Canyon Wash

Geomorphology and Flood Hazards

Bridge Canyon Wash emanates from the Newberry Mountain front approximately 1.5 km to the south of the mouth of Dripping Springs Wash. The active part of this wash adopts a distributary pattern directly below the mountain front (Figure 11). Remnants of relict fan deposits are sparsely distributed at the mountain front and most have been removed by erosion during the initial development of the presently active system (Plate 1). Thus the geologic apex of the fan complex is dominated by young deposits and is spatially coincident with the hydrologic apex. Relict fan deposits flanking the channel directly below the mountain front indicate approximately 6 m (~20 ft) of entrenchment.

The active, flood hazardous portion of the Bridge Canyon fan complex has a complicated spatial distribution (Figure 11). Link channels convey flow out of the primary active fan area (described in a previous section) and result in a greatly expanded flood hazardous area. Immediately below the hydrologic apex, the distributary channel pattern of the active fan is split into three main segments. One segment is diverted to the south along a series of link channels that distribute flow to a secondary area of piedmont drainage with a complex mixture of braided channels and diffuse sheetflow zones. Another segment splits flow to the north along a link channel that converges with piedmont runoff and flow split-off from the Dripping Springs fan complex producing a predominantly braided channel network with minor sheetflow zones. These ultimately rejoin flow from the main channel on the lower piedmont. Below these natural diversions, the third and main segment of the active channel of Bridge Canyon Wash becomes reconfined between relict alluvial fan surfaces for approximately 1 km (0.6 mi). Over this length, it adopts a distinctly braided channel pattern. Below the confined reach (near the site of Laughlin High School), the wash again adopts the form of an active alluvial fan (thus resulting in a second hydrologic apex). The gradient of the active fan decreases as it approaches the Mohave terrace, and the distal portion of the second fan broadens into a diffuse sheetflow zone with numerous channels.

The lateral limits of distal fan area are difficult to delineate. It eventually encounters relict fan surfaces (Qai) graded to the Mohave terrace and adopts a stable distributary flow pattern along the western edge of the terrace. In the southern part of this zone a few relatively deeply entrenched channels convey runoff to the south along the terrace margin. The northern portion has numerous relatively wide channels separated by a series of "islands" of Qai deposits. Downslope from this area, the active channels adopt a diffuse sheetflow pattern that ultimately

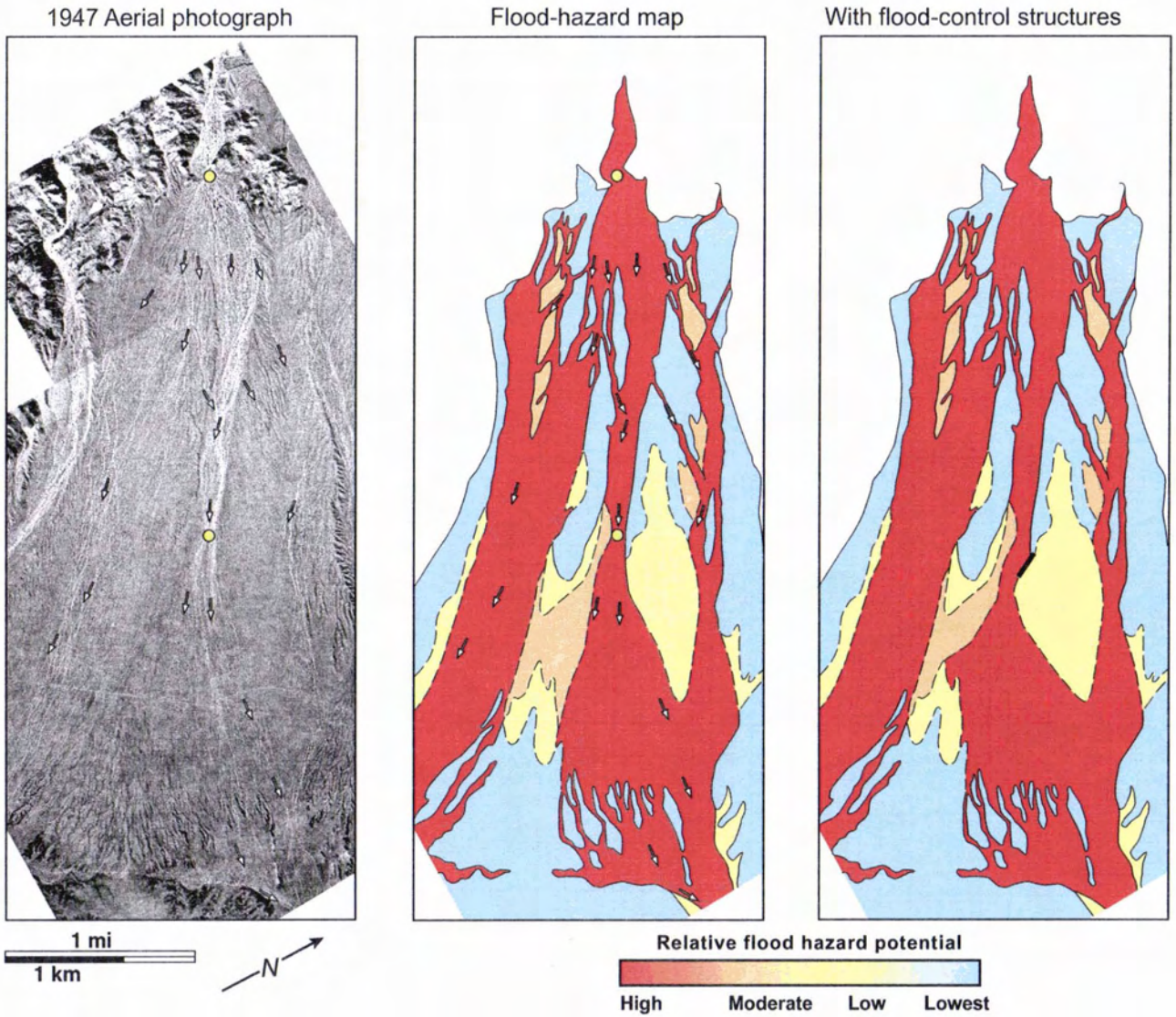


Figure 11. Geologic flood-hazard map of the Bridge Canyon alluvial fan complex. Also shown is a qualitative evaluation of the influence of flood-control sturctures on the distribution of flood hazardous area. Arrows indicate predominant flow directions, and yellow circles mark fax apex locations.

converges on a major braided channel draining flow to the north along the western and northern margin of the Mohave terrace. All but the channels diverted to the south ultimately converge on the Colorado River floodplain in the vicinity of the intersection of Edison Way and Casino Drive.

The distribution of flood hazardous areas on the Bridge Canyon fan complex mimics the complexity of the geomorphology described above (Figure 11). Because of the potential for large shifts in active channel position, areas of piedmont drainage that are occasionally fed by the link channels are deemed as potentially flood hazardous as areas associated with the principal active fan. In the stable distributary flow areas in the vicinity of the Mohave terrace, the southwestern portion is dominated by relict surfaces for which the flood hazard is low. In the northeastern portion, the relict alluvial surface is more dissected and the flood hazardous areas (channels) are easy to delineate. The active portion of the Bridge Canyon alluvial fan complex poses the most significant threat of flooding to the town of Laughlin.

Flood-Control Structures

The only significant flood control structure that influences the active portion of the Bridge Canyon alluvial fan complex is a large berm to the west of Laughlin High School, which deflects flow to the south. The site of Laughlin High has also been leveled and elevated, which removes most of it from a flood-prone position. The influence of the berm on the distribution of flood hazardous areas is illustrated qualitatively in Figure 11. Its principal effect is to create a low hazard shadow in the zone of intended protection and a slight increase in the already hazardous area where the flow is likely to be deflected.

Hiko Springs Wash

Geologic Setting and Geomorphology

Hiko Springs wash is deeply entrenched into Pleistocene alluvial fan deposits (Qai) along much of its length below the mountain front (4.2 km, 2.6 mi) (Plate 1, Figure 12). The geologic apex of the Hiko Springs alluvial fan complex is located directly at the mountain front, but the presently active channel network is entrenched up to 24 m (80 ft) below the relict fan surface. Within most of the entrenched portion of its course, Hiko Springs Wash follows a complex braided channel pattern with numerous dividing and reconnecting flow paths. Although the channels are steep, alluvial, and clearly unstable, this portion of the system is not an alluvial fan in the conventional sense. However, it does follow a gradual transition from a braided channel to an active alluvial fan. This morphological transition makes it difficult to accurately identify a single hydrologic apex that separates the braided portion of the system from the distributary portion. An approximate apex is indicated in Figure 12. Below this point, the active portion of Hiko Wash gradually becomes wider and more distributary in nature. Below this tentative apex, the active alluvial fan remains confined by remnants of older, inactive alluvial fan surfaces. In fact, the Hiko Wash alluvial fan remains rather narrow over its entire length. At its widest point, the fan is only confined on its east side and it coalesces with the alluvial fan from Unnamed Wash #1 along its western margin. This relatively broad, composite active alluvial fan surface also includes deposits from an extensive network of piedmont drainages that originate on the relict surface that separates Hiko Wash from Unnamed Wash #1 over most of their lengths. Ultimately, the composite alluvial fan terminates on the floodplain of the Colorado River.

Flood hazardous areas associated with Hiko Wash are easy to delineate because of rather narrow confinement between high, inactive fan surfaces. Within the confined channel, a series of

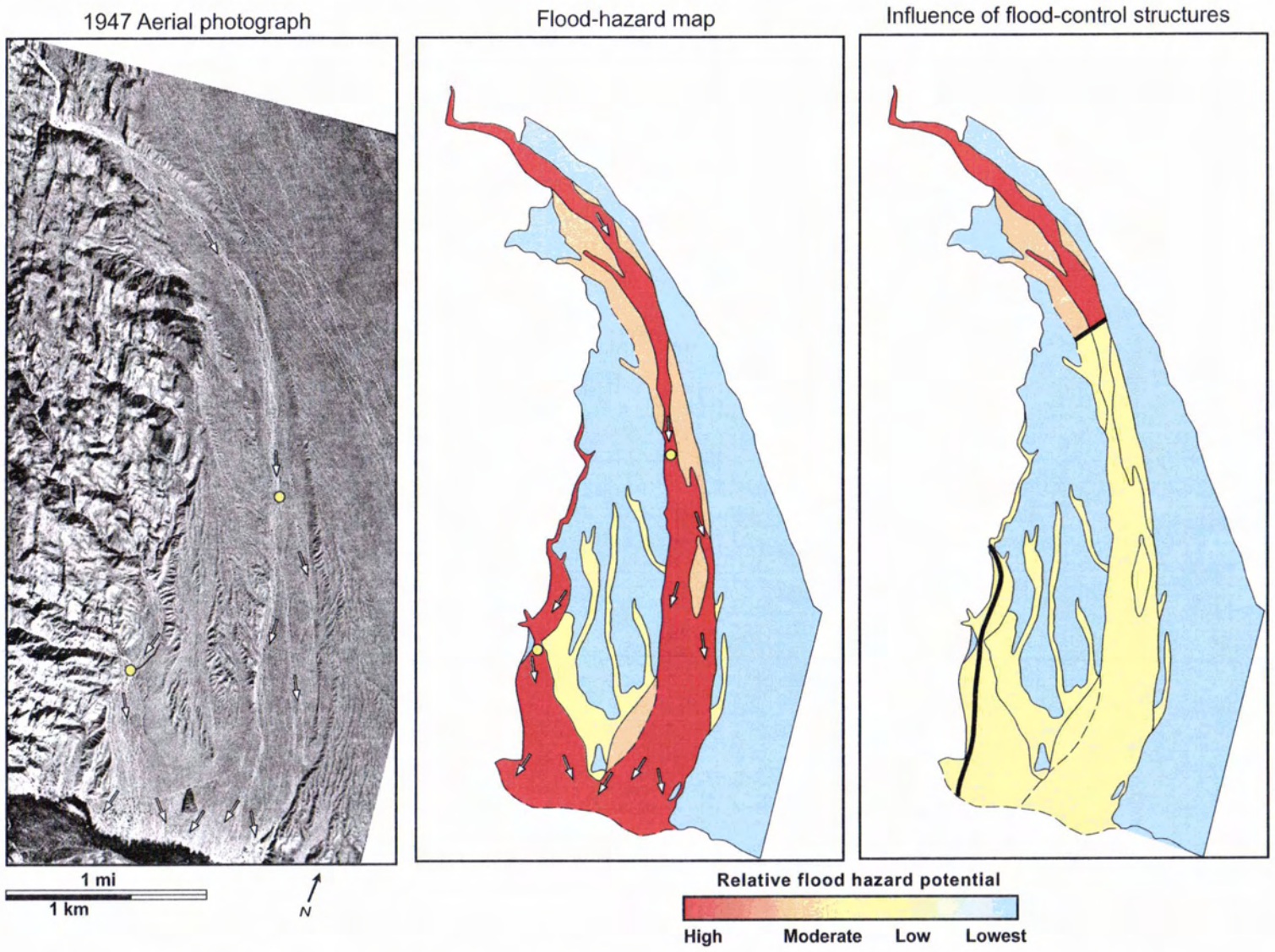


Figure 12. Geologic flood-hazard map of the Hiko Springs Canyon alluvial fan complex. Also shown is a qualitative evaluation of the influence of flood-control sturctures on the distribution of flood hazardous area. Arrows indicate predominant flow directions, and yellow circles mark fax apex locations.

relatively recently abandoned stream terraces flanks the active, braided wash and is presumably less flood hazardous by virtue of their elevated position relative to the main channel (shown in orange, Fig. 12). However, these features remain hazardous due to their relative age and proximity to the active channel. The most hazardous area overall is where the Hiko Wash fan coalesces with the piedmont drainages and the fan from Unnamed Wash #1.

Flood-Control Structures

A relatively large portion of the active alluvial fan complex of Hiko Wash has undergone residential and commercial development, and this has necessitated the construction of elaborate flood-control facilities on both Hiko Wash (a large dam) and Unnamed Wash #1 (a flood channel) that decrease the flood hazard considerably. Their influence on the distribution of flood hazardous areas is shown in Figure 12. In each case, the flood-control structures are likely to essentially eliminate flood hazards in the downstream areas. This is assuming that sedimentation is kept in check between flood events and that individual floods do not overwhelm the structures. In the case of Hiko Wash, the latter circumstance is particularly unlikely given the scale of the structure with respect to the size of the drainage.

Relationship of the Hazard Maps to Existing FIRMs

The purpose of the flood hazard maps presented in the previous section is to demonstrate that site-specific information regarding the flood hazard of each major fan complex can be compiled using a straightforward approach that is based on physical evidence specific to each fan complex. A composite perspective of this in relationship to formal Flood Insurance Rate Map (FIRM) flood-zone boundaries is shown in Figure 13. In this map, the surficial geological deposits mapped in Plate 1 have been classified with respect to flood-hazardousness and integrated with the digital FIRM flood-zone boundaries. All of the mapping has been projected relative to the same geographic datum using a GIS model. The overall discrepancy between the geological information and the conventional flood zone boundaries is highlighted and can be quantified. The FIRM data are the most recent available in digital form and the files were provided by the Clark County Flood Control District.

FIRM boundaries include the so-called "100-year" and "500-year" floodplains. The comparison with the geologic information remains valid because these distinctions are largely arbitrary and do not reflect the nature of flooding on the active fans. Areas that are shown on Figures 10 through 12 as having high to moderate flood potential are those areas that have been consistently and significantly inundated by the largest floods over the last several 1000s of years up through duration of the Holocene (the last 10,000 years). Thus, regardless of the recurrence interval of the flood in question, its extent will be within or to the limits of the areas shown as high, moderate, and possibly low potential severity. 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 zone of potential flooding.

Table 2 lists the areal extent of the various map units shown in Figure 13. The total area of the Laughlin piedmont is approximately 20.47 sq mi. Of this, geologic information indicates that 9.48 mi^2 is comprised of active alluvial surfaces (the geologic floodplain: GFP). Within the GFP, Qay_2, the area of the most frequent and intense alluvial activity spans 8.54 mi^2, and Qay_1 spans 0.94 mi^2. In contrast, the FIRMs indicate that the regulatory floodplain (RFP—including 100-yr and 500-yr boundaries in this case) encompasses approximately 12 mi^2 of the piedmont. Despite the greater areal extent of the RFP, it excludes slightly more than 2 mi^2 of the GFP. More than

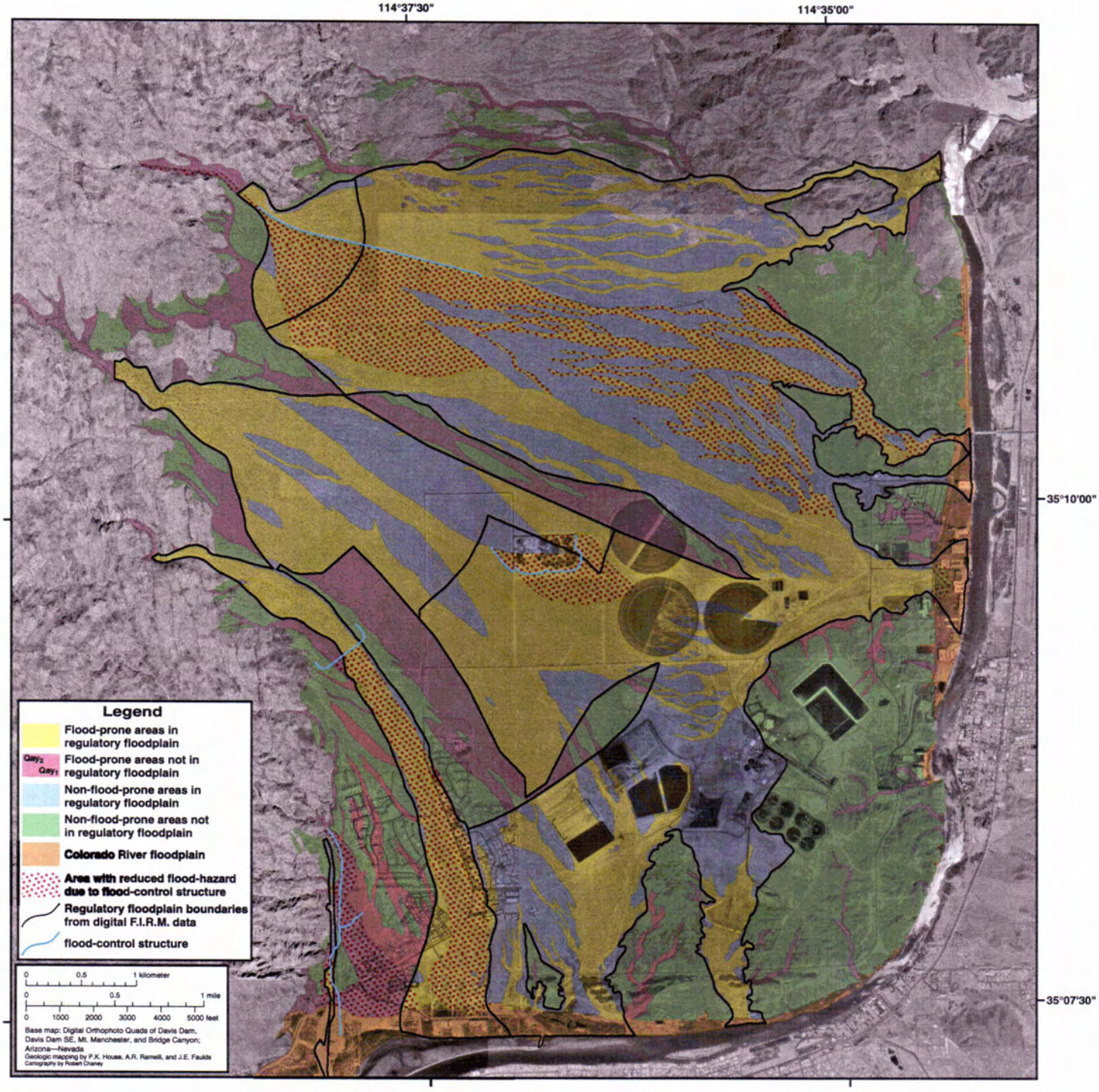


Figure 13. Geologic floodplain zones (FIRMs) compared with geologic information.

80% of the excluded portion corresponds to Qay_2, the most flood-hazardous area. The various components of the GFP and RFP are shown schematically in Figure 14.

Table 2. Areal distribution of units shown in Figure 13.

Map Units	sq. mi.	%	In RFP 100-yr	In RFP 500-yr	Not in RFP
Qay_2	8.54	42%	1.76	4.96	1.81
Qay_1	0.94	5%	0.24	0.35	0.36
Qcy[1]	0.85	4%	0.1	0.19	0.55
Q	9.12	45%	0.90	3.63	4.58
BR[2]	1.02	5%			
Total	20.47	100%	3.00	9.13	7.30

Notes
1. Colorado River floodplain not included in piedmont floodplain comparison
2. Bedrock and pre-Quaternary alluvium. Non-flood-Prone as mapped (flood-prone portions included in Qay units)

The following discussion refers to the flood-hazard status of the Laughlin piedmont prior to the implementation of several structural flood-control measures (described in previous section and below). The geologic evidence indicates that approximately 39% of the piedmont is flood hazardous (regardless of recurrence interval), and the FIRMs indicate that 65% is flood hazardous. However, this overall difference of 26% is a composite of two sources of error, herein termed Type 1 Error and Type 2 Error. Type 1 error refers to the situation in which non-flood-prone areas are included in the RFP (i.e. areas not in the GFP but in the RFP). On the Laughlin Piedmont, Type 1 Error includes 0.69 mi^2 in the 100-yr floodplain and 3.44 mi^2 in the 500-year floodplain. Overall, this amounts to a Type 1 Error of 34%. These areas are shown in blue in Figure 13. Type 2 Error refers to the situation in which flood-prone areas are excluded from the RFP (i.e. areas in GFP but not the RFP). On the Laughlin Piedmont, Type 2 Error includes 1.81 mi^2 of Qay_2 and 0.36 mi^2 of Qay_1.These correspond to 19% and 4% of the GFP, respectively, resulting in a Type 2 Error of 23%. Areas associated with Type 2 Error are indicated in purple (where it involves Qay_2) and reddish-purple (where it involves Qay_1) on Figure 13.The various components of these errors are listed in Table 3 and illustrated schematically in Figure 14. Overall, Type 1 and Type 2 errors indicate that 57% of the piedmont is mischaracterized with respect to its flood-prone status as inferred from the geologic information. Areas in which the GFP and the RFP are in agreement as to flood-hazardousness are shown in yellow in Figure 13, and areas where both methods agree that areas are non-flood-prone are shown in green.

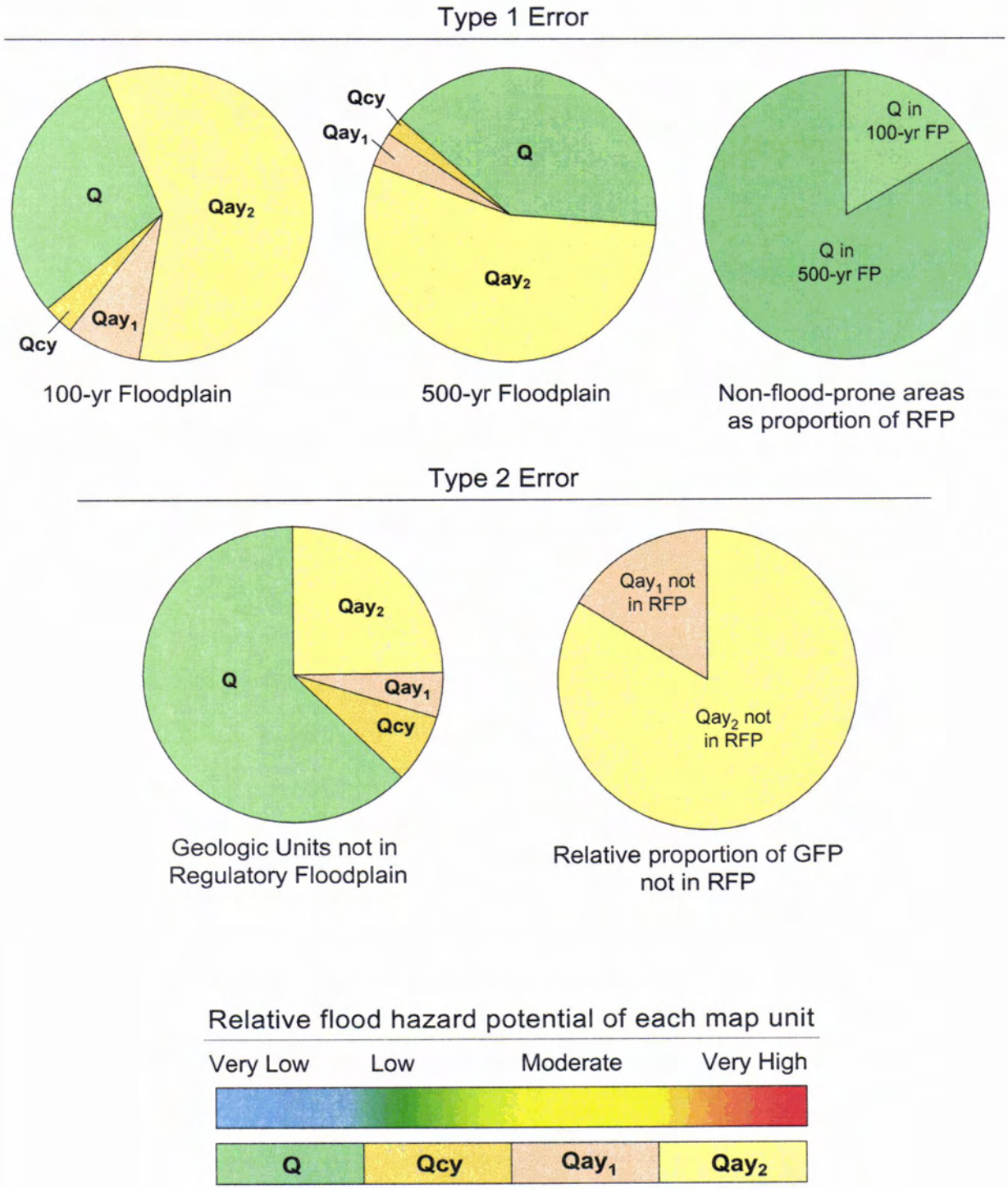


Figure 14. Areal distribution of the regulatory floodplain compared with geologic information

Table 3. Components of the lack of correspondence between the RFP and GFP.

Type 1 error[1]			Type 2 error[2]		
Q in RFP	**sq. mi**	**% of RFP**	**Unit not in RFP**	**sq. mi**	**% of GFP**
100-yr	0.69	24%	**Qay_2**	1.81	19%
500-yr	3.44	37%	**Qay_1**	0.36	4%
Total RFP	4.13	34%	**Total Qay**	2.17	23%

Notes
1. Inclusion of non-flood-prone area into regulatory floodplain
2. Exclusion of flood-prone area from regulatory floodplain

Table 4. The effect of structural flood-control measures on the extent of flood-prone areas.

Geologic Floodplain				Regulatory Floodplain			
Unit	**sq. mi.**	**Qa_x[1]**	**%Change[2]**	**Zone**	**sq. mi.**	**Qa_x**	**%Change**
Qay_2	8.54	2.12	25%	**100-year**	2.88	0.68	24%
Qay_1	0.94	0.20	22%	**500-year**	9.20	1.41	15%
Total	9.48	2.32	25%	**Total**	12.08	2.09	17%

Notes
1. Flood-prone-area with significantly reduced hazard due to structural flood-control measures
2. The percentage decrease in flood-hazardous area due to structural flood-control measures

Structural flood-control measures on the Laughlin piedmont act to decrease the magnitudes of the discrepancies reported above. Their relative effect can be assessed by approximating the spatial extent of their influence on flood-hazardous areas. On Figure 13, the influence of the following structures were accounted for: the flood-control berm adjacent to Dripping Springs Wash, the dam on Hiko Wash, the berm and elevated area near Laughlin High School, the culvert at Edison Way, and the flood-channel along Unnamed Wash. The relative influence of each of these structures was approximated for the purposes of this illustration, and they are shown as areas with red stippling (Figure 13). The influence of each structure is shown only with respect to areas that are in the GFP in order to illustrate the effect on areas that are actually flood-prone. In the cases of Unnamed Wash, Hiko Wash, and Dripping Springs Wash, the effects are significant. As indicated on Figure 15 and in Table 4, the combined effect of these measures is to reduce the flood-prone area in the RFP by 17%. In the GFP, the effects are a reduction in the extent of Qay_2 by 22% and the extent of Qay_1 by 2.1%. The overall larger change in the GFP reflects the fact that it is larger than the extent of the area within the RFP that is actually flood-hazardous (a consequence of Type 2 Error). On the basis of the effects on the extent of the GFP, structural flood-control measures have reduced the extent of flood-hazardous areas on the Laughlin piedmont by nearly 25%. However, it remains clear that the rendition of piedmont flood hazards provided by the current FIRMs is not representative of the real characteristics of fluvial processes. Evaluation of the geologic information for planning additional flood-control measures may help increase their effectiveness in areas that are most flood-hazardous.

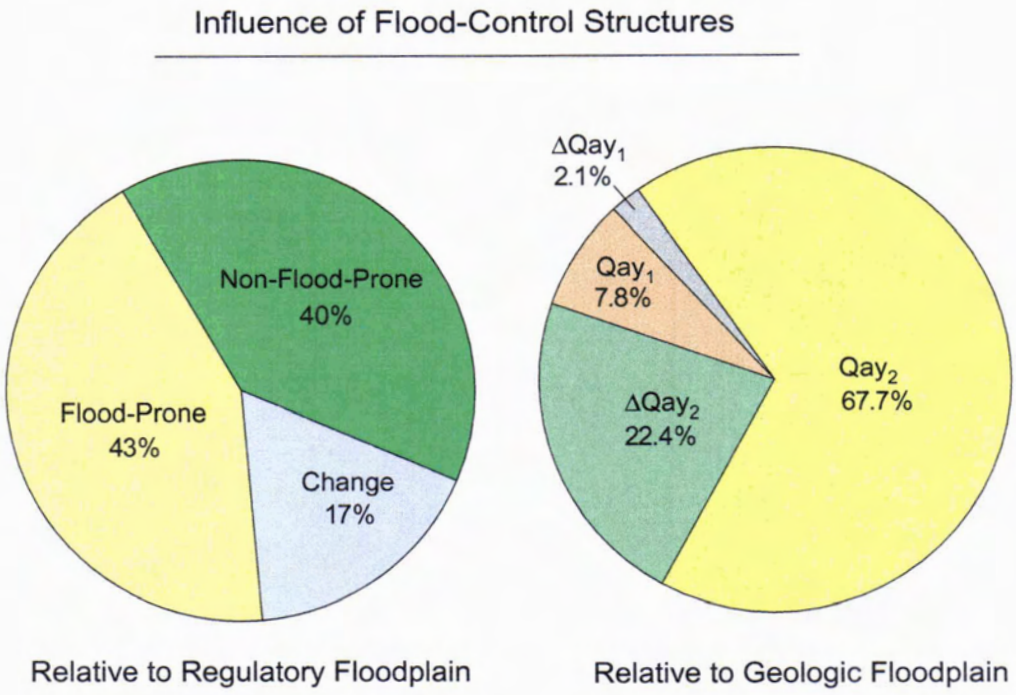


Figure 15. Effect of flood-control measures on the extent of flood-prone areas

Conclusions

The compilation of geologic evidence of flood occurrence and non-occurrence over a millennial time frame provides significant physically based insights into the most likely location of floods in the future, particularly in the context of a planning horizon of 100 years. Compilation of geologic information across the entire Laughlin piedmont allows for an assessment of potential flood hazards that is specific to each individual alluvial fan complex and adjacent areas typically ignored in FIRM compilations. The map of the extent of geomorphic surfaces on the piedmont that indicate extensive periods of non-inundation by floods and of the extent of surfaces that are, in the long-term, consistently subject to flooding over a large range of magnitudes represents a uniquely insightful tool for land management. The compilation of geologic information is a necessary first-step in flood hazard assessment of large piedmont areas. It is considerably more cost-effective and scientifically based than conventional approaches that are reliant on generalized theoretical models. In fact, the geologic information constitutes a scientific test of the veracity of a flood hazard model. A theoretical model that conflicts with real data by including extensive tracts of non-flood-prone land as portions of a regulatory floodplain is overly cautious. A systematic process involving iterative comparisons of model predictions with geologic data would be a sound method for developing more realistic floodplain boundaries.

Uncertainty inherent in the geological mapping does not approach the nearly 60% uncertainty in the FIRMs. One reason for this, in the case of the Laughlin area, is that the active alluvial surfaces are easily differentiated from the inactive ones. The distinction can be more variable in other settings. Inactive fan surfaces on the Laughlin piedmont can be readily identified in the field and with aerial photographs. They have distinctive topography, soil development, and geographic distribution. Cases where inactive surfaces are mapped on flood insurance rate maps (FIRMs) as being subject to alluvial fan flooding are erroneous. These are ancient surfaces that have been isolated from active fluvial processes for millennia. To involve them in flooding as the FIRMs depict would require unprecedented, rapid changes in fluvial behavior that are extremely unlikely given the present climate and configuration of the Colorado River. In some cases, inactive alluvial fan surfaces present on the piedmont are simply too low, small, or diffuse to be mapped separately as non-flood-prone.

Floodplain boundaries on the FIRMs of the Laughlin piedmont that are inconsistent with the geologic data involve two types of mischaracterization: 1) non flood-prone land deemed flood-prone (34%), and 2) flood-prone land deemed not flood-prone or unclassified with respect to flood hazards (23%). Circumstance 1 is probably the most critical problem for a developing area because it has the effect of either precluding development or requiring measures in the form of structural solutions and flood insurance that are not necessary (at least not to the extent implied by the formal flood zones). Circumstance 2 has the potential to place people and property in harm's way. Similarly, the FIRMs erroneously depict flood-hazard zones as corresponding to an idealized fan geometry. This has the unintended effect of predicting less flood hazardous conditions in zones which, in actuality, involve the re-concentration of flow and a comparably high, if not higher, flood hazard potential as sites nearer to the mountain front. Thus, implied attenuation of the flood hazard in the down-piedmont direction is, in many cases, erroneous and may contribute to improper regulations. It has been demonstrated that circumstance 1 can be minimized through detailed geologic mapping. Circumstance 2 is minimized as well because the geologic mapping covers the entire piedmont and is not restricted to the fan complexes associated with the primary drainages.

It is unlikely that even a flexible (i.e., cautiously conservative) interpretation of the geologic map would compromise its value as a management tool. Moreover, it is not at all likely that this could result in concluding that 60% of the mapping is inaccurate or an unacceptable characterization of relative flood risk. By weighing this against the comparatively low cost of the geologic analysis, it is clear that such mapping is a valuable tool for assessing flood hazards, particularly as a first step in the process. In contrast to conventional methods, the geologic approach is a testable scientific approach based on physical information related directly to the long-term history of flooding. Thus, it is more defensible than techniques based largely on poorly tested theoretical concepts, despite the fact that they are codified and promulgated by a federal agency.

Recommendations

The following recommendations are separated into ones that are generally applicable throughout Nevada and ones that are specific to the Laughlin area.

General Recommendations

1. Site-specific, detailed geologic information should be collected from desert piedmont areas that are undergoing or are slated for extensive development. This should be initiated as early in the process as is feasible (i.e. the first step). Detailed mapping by professional geologists is a demonstrably cost-effective and essential tool for land management on desert piedmonts.
2. The extent of Holocene alluvium on the piedmont should be considered a cautiously conservative estimate of the extent of the geologic floodplain or flood-prone area. This is considered by the NRC panel (1996) as the most extreme (conservative) approach in most settings because it spans 10,000 yrs. This information should be used to narrow the scope of expensive engineering studies that may be required to determine flood insurance rates and structural requirements for flood control measures.
3. Rely on geologic information in addition to detailed topographic information and modeling for evaluating the flood potential of a given area. A surficial geological map can provide a much greater amount of useful information concerning flood-hazard distribution than can a contour map with 10 m (20-40 ft) contours, and even a reconnaissance level geologic study can help identify needs for detailed topographic data by delineating the most obviously flood hazardous areas. This can reduce the scope of subsequent, more detailed investigations.

Recommendations Specific to the Laughlin Piedmont

4. Try to promote development that is conformable with natural topography and drainage patterns. Juxtaposition of a rectangular grid of streets to topographically complex areas will inevitably result in drainage problems.
5. Restrict (or disallowing) future development in demonstrably flood-prone areas on the piedmont (unit Qay_2 on Plate 1) with the recognition that existing flood-control measures may have eliminated some areas from harm's way. The general instability and concomitant uncertainty of flow locations in these areas is such that they are poor choices for development and will present persistent difficulties without large-scale and expensive flood-control measures.

6. Allow conscientious development in areas dominated by local piedmont runoff (unit Qay_1 on Plate 1). This is the least risky use of marginally flood-prone land and is most conducive to relatively simple flood-control measures.
7. Use detailed analysis of aerial photos in conjunction with geologic and topographic information to identify the best sites for drainage diversion from principal active washes to minimize the likelihood of major flooding. For example, the long flood-control berm adjacent to the State Route 163 along Dripping Springs Wash serves this purpose well. Simple blockage or closure of distinct channels that convey flow from active fans to disparate areas of piedmont drainage can greatly reduce existing hazards in those areas.

Acknowledgments

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CHAPTER 3:

EVALUATION OF WATER QUALITY IN THE LAUGHLIN AREA: POTENTIAL CONTAMINATION AND HAZARDS

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Abstract

Existing water quality data from the Colorado River and several water wells near the town of Laughlin were evaluated to determine if any of the waters were contaminated, or could be impacted in the future, by human-induced activities or by proximity to particular natural settings. The data were obtained from the Clark County Health District, Nevada Department of Health, U.S. Environmental Protection Agency, and the U.S. Geological Survey. This report provides a preliminary assessment of groundwater quality in the Laughlin area, identifies areas that currently have degraded water quality, and highlights areas that may be threatened with contamination in the future. As part of this work, a geographic information system (GIS) database was designed and constructed so that it could be easily queried to address concerns relevant to future development and land-use planning. The database was consulted to determine (1) the extent to which data were available in particular areas surrounding Laughlin from which evaluations could be made, (2) the presence or extent of any poor water quality, and (3) the causes of any identified poor water quality.

The results of the data evaluation indicate that the surface water and groundwater quality near Laughlin is good, with some exceptions. Contamination (elevated chloride, nitrate, sulfate, and total dissolved solids) from the sewage treatment facility has been detected down hydrologic gradient from the site at Monitor Well 116. Other wells located closer to the river could also be impacted by these contaminants in the future: the Riverside Wells, Nevada Club Well, any existing or future wells in Area 1 of Big Bend, and perhaps the Sundance Shores Well. However, the Sundance Shores Well is over 90 m deep and may not experience contamination from the sewage treatment facility. In fact this well has very good water quality, in spite of the fact that it is the well located closest to the Mohave Generating Station slurry ponds.

No detectable impact on surface water or groundwater chemistry was found that could be attributed to mining practices in the Laughlin area. Most mining disturbances are for industrial mineral purposes (e.g., quarries, gravel pits), which typically have low potential for adverse environmental impacts. There is potential for poorer water quality associated with the mineralized zones north of Laughlin due to slightly elevated metals concentrations in rock samples and the presence of potentially acid producing materials in the rocks. However, no water quality data were available to evaluate groundwater interaction with these mineralized zones. Similarly, no water quality data were available near the landfill from which to evaluate possible contamination from that source.

Based on chemical data from wells and the Colorado River, eight shallow wells within 150 m of the river appear to be dominated by Colorado River water. Eight additional wells apparently have little to no influence from the Colorado River. Of the remaining wells for which there are data, all tap groundwaters that are variable mixtures of Colorado River water and groundwaters recharged on the basin margins. All of the deeper wells have no contribution from the Colorado River, whereas the shallower wells located within approximately 150 m of the river have contributions from Colorado River water. However, without more detailed studies that would include temporal well and river water level measurements and dating of groundwaters, it is unknown if the mixed well waters have mixed with current Colorado River water or from mixing that occurred in the past, possibly following over-bank flooding of the river prior to construction of Hoover and Davis Dams.

Table of Contents

Abstract 3.2
Table of Contents 3.3
List of Figures 3.4
Introduction 3.5
Introduction 3.5
Background 3.5
  Geology 3.5
  Hydrogeology 3.6
Methods 3.7
  General Data Compilation 3.7
  Well Data 3.10
  Hydrogeochemical Data 3.10
Results 3.12
  Precipitation/Climate 3.12
  Mining Disturbances 3.13
  Well Data 3.18
  Groundwater Geochemical Data 3.18
    Major Element Chemistry 3.18
    Trace Element Chemistry 3.26
  Surface Water Geochemical Data 3.26
    Major Element Chemistry 3.26
    Trace Element Chemistry 3.27
Discussion 3.34
  Groundwaters 3.34
    Contamination from Sewage Disposal 3.34
    Contamination from Mining 3.34
    Potential Contamination due to Flooding 3.35
  Surface Waters 3.35
    Decreases in Concentrations from November 1982-1987 ..... 3.35
  Interaction of Groundwaters and Surface Waters 3.37
  Role of Detachment Fault 3.42
Conclusions 3.43
Recommendations 3.43
Acknowledgements 3.44
Bibliography 3.44

List of Figures

Figure 1. Annual precipitation at Bullhead City, Laughlin, and Searchlight 3.16
Figure 2. Locations of wells and surface water sampling sites near Laughlin 3.17
Figure 3. Locations of wells in the database suppled by the State Engineer's office..... 3.22
Figure 4. pH versus time in 8 wells sampled in the Laughlin area..... 3.23
Figure 5. Chloride versus time in 13 wells sampled in the Laughlin area..... 3.23
Figure 6. Nitrate versus time in 8 wells sampled in the Laughlin area..... 3.24
Figure 7. Sulfate versus time in 13 wells sampled in the Laughlin area 3.24
Figure 8. Total dissolved solids versus time in 13 wells sampled in the Laughlin area..... 3.25
Figure 9. Magnesium versus time in 13 wells sampled in the Laughlin area..... 3.25
Figure 10. Iron versus time in 12 wells sampled in the Laughlin area 3.28
Figure 11. Manganese versus time in 12 wells sampled in the Laughlin area 3.28
Figure 12. Calcium concentrations versus time for Colorado River water samples..... 3.30
Figure 13. Magnesium concentrations versus time for Colorado River water samples 3.30
Figure 14. Sodium concentrations versus time for Colorado River water samples..... 3.31
Figure 15. Chloride concentrations versus time for Colorado River water samples 3.31
Figure 16. Bicarbonate concentrations versus time for Colorado River water samples..... 3.32
Figure 17. Sulfate concentrations versus time for Colorado River water samples..... 3.32
Figure 18. Total dissolved solids concentrations versus time for Colorado River waters..... 3.33
Figure 19. Plot showing variations in sulfate concentrations and monthly precipitation at the Bullhead City weather station through time..... 3.33
Figure 20. Plot showing variations in sulfate concentrations and monthly water level measurements in Lake Mohave as a function of time..... 3.36
Figure 21. Plot showing variations in sulfate concentrations and daily flow rate in the Colorado River below Davis Dam as a function of time. 3.36
Figure 22. Map showing the locations of wells discussed in this report 3.40
Figure 23. Plot showing temporal variations in sulfate to chloride ratios in the Riverside Distribution system and well samples..... 3.41

Introduction

The purpose of this report is to evaluate the potential natural and anthropogenic hazards to surface waters and groundwaters in the Laughlin area. Existing data were compiled, tabulated and evaluated, and results from previous reports were incorporated into the study to evaluate the water resources in the Laughlin area. This initial assessment provides the foundation upon which to conduct more thorough analyses of identified data gaps, and issues or hazards related to water supplies in the Laughlin area. Potential threats to groundwaters used for water supply in the Laughlin area were evaluated using geographic information systems (GIS) to determine proximity of water supplies to local faults, active, inactive and abandoned mines, landfills, and sewage disposal facilities/agricultural areas, all of which have the potential to degrade water quality. This report provides a preliminary assessment of groundwater quality in the Laughlin area, identifies areas that currently have degraded water quality, and highlights areas that may be threatened with contamination in the future.

As part of this work, a GIS database was designed and constructed so that it could be easily queried to address concerns relevant to future development and land-use planning. This GIS database can also be used by Laughlin officials to help answer questions as additional issues become relevant in the future.

Water needs of Laughlin are forecast to increase by more than four times between 1990 and 2010 (Nevada Division of Water Planning, 1999). Continued population growth will place additional demands on the water resources in the region. Thus, careful planning and thorough knowledge of the potential natural and anthropogenic hazards are critical to the future vitality of the region.

The geochemical data compiled in the final databases are used to help evaluate current water quality conditions, changes through time, and potential future adverse impacts due to proximity to human activities or geological formations and structures that may impact water quality. These data were consulted to determine (1) the extent to which data were available in particular areas surrounding Laughlin from which evaluations could be made, (2) if the data suggested poor water quality, and (3) evaluate the causes of any identified poor water quality.

Background

Laughlin is located in southern Nevada in Clark County, the most populous county in the state of Nevada. Because the population of Laughlin is growing and the community is in an arid area, groundwater quality is a particularly vital issue. Given the number of human induced activities and associated data in this area, it is prudent to utilize a system allowing visualization and correlation of relevant data to help in evaluating which sites may have an impact on water resources. A Geographic Information System (GIS) is ideally suited for visualizing and evaluating large amounts of spatial data.

Geology

The geology of the Laughlin area is described in detail in other portions of this report (see Chapters 1 and 2 by J. Faulds and P.K. House).

Hydrogeology

Numerous hydrogeologic studies have been conducted near Laughlin. Most of the studies are of a regional nature and are not specific to Laughlin, yet many of the general findings in the studies are applicable to Laughlin. These major findings are summarized here.

The water resources of the Laughlin area are influenced by the town's location adjacent to the Colorado River and Lake Mohave reservoir. Laughlin's location on the Colorado River is one of the more important controls on the local hydrology as surface waters and groundwaters near the river are closely connected. Wilson and Owen-Joyce (1994) conducted a regional analysis of the interaction of the Colorado River with adjacent alluvial aquifers. In that study, the contact between the alluvial slopes and the bedrock was mapped both geologically and with gravity data. The authors assumed that this contact marks the extent to which the Colorado River contributes to local aquifers. However, their designation of the extent of the aquifer receiving river water did not include evaluation of water level data, which are critical to verify the results of their findings.

In a more rigorous study, Robertson (1991) used geochemical and stable isotope data to determine the percentage of Colorado River-derived water versus groundwater contained in samples collected from individual wells located on the adjacent flood plain. In this regional study (Arizona, California, and Nevada) of shallow aquifers adjacent to the Colorado River, Robertson (1991) noted that groundwater development is primarily from the flood plain deposits. Almost all of this water originates as either seepage from the river channel or from overbank flooding of the river, as evidenced by deuterium (δD), SO_4 and Cl values in the groundwaters (Robertson, 1991). However, the construction of Hoover Dam in 1936 essentially ended the annual flooding (in the Mojave Valley) and largely stopped the component of recharge to the shallow aquifers from overbank flooding (Metzger and Loeltz, 1973). Nevertheless, geochemical modeling of aquifer waters show that water in shallow flood plain wells is Colorado River-derived water that has been altered by concentration, evapotranspiration, precipitation of Ca and $MgCO_3$, and reduction of SO_4 (Metzger and others, 1972).

In this work, isotopic values for groundwater recharged from the basin flanks were assumed to be δD = -61.25 per mil, and $\delta^{18}O$ (oxygen-18) = -8.25 per mil. For some mixing calculations, the river water end-member was assumed to have a δD content of -117 per mil, and $\delta^{18}O$ content of -15.3 per mil, although the δD value of the Colorado River at Hoover Dam is -106 per mil (Robertson, 1991). The δD and $\delta^{18}O$ contents in groundwaters in the Mohave Valley (and other valleys adjacent to the river) indicate mixing between river and recharge water and that water movement from the Colorado River enters the floodplain deposits and extends a considerable distance into the piedmont areas (Robertson, 1991).

In evaluating the aquifer-river water interactions adjacent to the Colorado River, Robertson (1991) also utilized salinity and SO_4/Cl ratios. Robertson (1991) reported that groundwaters have higher salinity and lower SO_4/Cl ratios than Colorado River water, where the weighted average from 1941 to 1965 is $\approx$3 (Olmsted and others, 1973). Groundwaters derived from recharge on the flanks of the basin typically have SO_4/Cl ratios of <1. Additionally, bicarbonate (HCO_3) in the river water ($\approx$150 mg/L) is commonly one-third of the concentration observed in groundwaters ($\approx$450 mg/L). From 1941 to 1973, Colorado River water below Hoover Dam had a total dissolved solids (TDS) ranging from 606 to 813 mg/L, SO_4 ranging from 261 to 355 mg/L, and Cl varying from 62 to 108 mg/L, with a variability of <10% on a daily basis (Metzger and Loeltz, 1973). After construction of Hoover Dam, the annual variability in water quality parameters in the river decreased.

Metzger and Loeltz (1973) also evaluated the river-aquifer interactions adjacent to the Colorado River by investigating water levels in the Mojave Valley aquifer near the river. Water level data from wells from 1961-62 and 1962-69 indicated nearly stable water levels through time. Annual water level fluctuations were on the order of only ≈0.6 m (2 ft), except near pumped wells, beneath irrigated lands, and within the river, which fluctuates ≈1.8 m (6 ft) annually in its channel in Mojave Valley. In contrast, the water level in the Colorado River has a daily range of ≈2.1 m (7 ft) during summer months just below Davis Dam. Based on higher water levels in the Colorado River than in the adjacent alluvial aquifer, Metzger and Loeltz indicate that the Colorado River was losing water to the groundwater aquifer throughout its course in Mojave Valley. Based on some water balance estimates, these authors estimate that ≈150,000 acre-ft/yr (or ≈4000 acre-ft/yr per mile length of river) of river water infiltrates the shallow groundwater aquifer in Mojave Valley (Metzger and Loeltz, 1973).

In a hydrogeologic evaluation of the Needles area, Metzger and Loeltz (1973) reported that the average annual lake evaporation is 86 in/yr, whereas the average amount of precipitation falling on the lake annually is only 5 in/yr. Annual recharge along the mountain fronts was estimated based on recharge from numerical models, previous recharge estimates, and water budgets of basins. Using these data from south-central Arizona and surrounding states, Anderson (1995) developed an expression to estimate recharge over the entire study area:

$$\log(Q)_{rech} = -1.4 + 0.98 \bullet \log(P)$$

where P is precipitation in excess of 8 in/yr. In a separate study, recharge was found to be only ≈0.5% of precipitation in the nearby Eldorado-Piute Valley area (Rush and Huxel, 1966).

Anderson and Freethey (1993) simulated regional groundwater flow in central and western Arizona, and included the Mohave Basin, partly located in southern Nevada. Their groundwater flow simulations in the Mohave Basin were only partially successful, yet they obtained an estimate of hydraulic conductivity (K) of the older alluvium (K=1.8 m/d) and the stream alluvium (K = 95 m/d). Additional data were reported by Metzger and Loeltz (1973). In this study of the Mojave Valley, Metzger and Loeltz (1973, pg 26-27) reported K varying from ≈134 to 823 m/d, and storage capacities of 32 to 42%. Pumping tests at several wells in the Laughlin locality would be required to refine these values. However, these generalized values could be used in constructing initial, preliminary groundwater flow models of the Laughlin area, because the authors suggested that general hydrologic characteristics along the Colorado River can reasonably be transferred to adjacent basins.

Methods

General Data Compilation

The Nevada Bureau of Mines and Geology compiled available geographic, geologic, and hydrologic information relevant to the evaluation of the potential environmental hazards related to groundwater interactions with abandoned mine sites, landfills and other anthropogenic impacts, and natural conditions related to the local geology and structure. Relevant information was assembled into a GIS database from which graphical representations of the distribution of potentially environmentally sensitive areas is evaluated here.

Several existing databases were searched for a variety of parameters detailed below. Numerous data types were compiled by location and date of measurement and selected

parameters were plotted on maps for visualization purposes as well as on standard time series plots.

The purpose of this section is to describe the different sources and types of data compiled for the GIS database. Data in the Laughlin area were compiled from the area between latitude 35° to 35°30'N and longitude 114°30' to 115°W. Existing data, along with the latitude, longitude, elevation and site name, were compiled into Excel spreadsheets that were converted into an ArcInfo accessible database including the data types listed in Table 1. The general contents of each of these types of data follow, and sources of the data are listed in Table 1:

Climate data - monthly precipitation data from Laughlin (12 years) and two nearby weather stations (Searchlight, 85 years of record; Bullhead City, 23 years of record).

County, digitized Geologic Map - 1:250,000 scale geologic map including lithologic contact and faults

DEM's - Topography (elevation) on a 90 m grid spacing.

DLG's - Major rivers and streams from 1:24,000 maps.

DOQ's - Digital orthophotoquads (1:6000 scale)

Evapotranspiration - Potential evapotranspiration calculated from ≥20 yrs of temperature data at weather stations and extrapolated to different elevations. Values are available on a 1-km grid spacing.

Historical information - For example, conversations were conducted with Mr. Jerry Bender concerning wells in the big Bend Water District, and which ones were plugged due to poor water quality

Land use - Coverages showing distribution of BLM, Forest Service, Native American, private lands, etc.

MILS/MRDS data - Combined coverage of MILS and MRDS data sets including mine type, lithologies, presence of mills/smelters, commodities, deposit type and size, alteration, rock type, location, etc.

Mine openings - All mine openings (shafts, adits, pits, waste dump areas, leach pad areas) digitized from 7.5' quadrangle maps.

Mining districts - Areal coverage showing location and extent of known mining districts in Nevada.

Precipitation - Computed average monthly and annual precipitation data based on 30 years of record. Values available on a 5-km grid spacing throughout the study area, and continuously over selected years at nearby weather stations.

Road network - Line coverages of major and minor roads and streets in Nevada.

Rock geochemistry - Chemical analyses from over 4,200 samples collected statewide at most of the mining districts. Analyses include percent major oxides and trace element concentrations

Stream/River Flow - Daily river flow rates of the Colorado River at Davis and Hoover Dams, January 1967 through September 1998 (USGS, 1999).

Water chemistry data - Major, trace element chemistry of waters, limited isotopic data, organic chemistry of possible contaminants, limited water level depths, field parameters (pH, temperature, etc.) for sampled waters.

Well locations - Location, owner, depth and completion information, drilling method, date completed, use, yield, etc.

Table 1. Sources of data used in the hydrogeological investigations.

Data Type	Original Format	Format* Used	Source	Reference/ Phone
7.5' quadrangle boundaries	digital	GIS	USGS	digital files
Climate	digital	SS	Western Reg. Climate Center	http://www.wrcc.dri.edu/
County boundaries	digital	GIS	BLM	digital files
County geologic map	digital	GIS	NBMG OFR 97-1	Hess & Johnson, 1997
DEM's	digital	GIS	USGS	USGS, 1993a
Evapotranspiration	digital	GIS	NBMG Report 48	Shevenell, 1996; 1999
Known faults	digital	GIS	NBMG OFR 97-1	Hess & Johnson, 1997
Historical information	verbal	SS	Big Bend Water District	702-298-3113; Jerry Bender
Land use	digital	GIS	USGS	USGS, 1990
MILS data	digital	GIS	US Bureau of Mines	MAS/MILS, 1994
Mine openings	digital	GIS	NBMG OFR 96-4	Hess & Johnson, 1996
Mining districts	digital	GIS	NBMG Report 47d	Tingley, 1998a
MRDS data	digital	GIS	USGS	USGS, 1993b
Precipitation	digital	GIS	PRISM	Daly et al., 1993
Railroads	digital	GIS	Tiger files	U.S. Census digital files
Rivers/streams	digital	GIS	DLG	USGS, 1994
Colorado River	digital	GIS	BRRC/Nevada GAP	digital files
Road network	digital	GIS	Tiger files	U.S. Census digital files
Rock geochemistry	digital	GIS	NBMG OFR 98-8	Tingley, 1998b
Stream/river flow	digital	SS	USGS	waterdata.usgs.gov/nwis-w/NV/
Topographic maps	digital	GIS	USGS	.tif files
Water chemistry	paper	GIS	Clark County Health District	702-385-1291; Edmund Wojcik
Water chemistry	digital	SS	EPA-STORET	800-424-9067; Joyce Boyd
Water chemistry	paper	SS	Nevada Division of Health	775-6881335; Dana Pennington
Water chemistry	digital	SS	USGS, Carson City	775-887-7664; Robert Bostic
Well locations	digital	GIS	Nevada State Engineer	775-687-4380; Kim Groenewold

* Note GIS indicates the data were imported into ArcInfo and ArcView for spatial analysis. SS indicates the data were used in a spreadsheet for temporal, and other, analyses.

From these various data sources, the following topics are evaluated

-measured impacts on groundwater and surface water chemistry (e.g., elevated metals, acidity, and TDS may allow detection of leachate from nearby sites).

-measured trace element content of mineralized rocks (possible sources of natural trace element anomalies) and background geochemistry of rocks where data are available.

-interaction of surface waters (Colorado River water) and local groundwaters.

Most of the data sets listed in Table 1 and above were imported into the GIS database with minimal manipulation and changes. However, the water quality data were acquired from several different sources in widely different formats, and considerable manipulation of the data was done to obtain the final data set discussed here. The Hydrogeochemical Data section outlines some of the manipulations conducted on the data sets.

Well Data

A subset of the well database maintained by the Nevada State Engineer's office was acquired to determine locations and completion information (total depth, screened or open intervals, etc.) for wells located in the Laughlin study area. The State Engineer's office has recorded permitting, location, ownership, and limited completion and hydrologic information for 159 wells drilled in and near Laughlin. This database was manipulated in MS Excel and edited to decrease the size of the database. Several fields were removed from the database because either no data were reported for any of the 159 wells, or the data entry reported for all wells was identical. Deleting these fields resulted in 14 columns being removed for the dataset. Several important fields for which data were not reported in the Laughlin study area include depth to bedrock, aquifer description, and elevation. However, numerous other data including well status and use are included in the dataset, and these data are included as part of the GIS.

Hydrogeochemical Data

Surface and groundwater data for the Laughlin area were obtained from the Clark County Health District (CCHD), the U.S. Environmental Protection Agency (EPA) STORET database, the Nevada Division of Health (NDH), and the U.S. Geological Survey (USGS) Carson City District Office of Water Resources Division (see Table 1). All data were entered into MS Excel spreadsheets in which the following manipulations and changes were made.

Many entries for particular chemical constituents had no data entries in any of the files, and all of these entries were deleted to reduce the size of the files to be manipulated. Other samples were also eliminated from the dataset if it was unclear what the samples represented (e.g., if it could not be discerned if the sample was from a well versus stream or spring).

All chemical analyses are reported in mg/L, unless otherwise noted. An entry was added to the major element chemistry file for total dissolved solids (TDS) in mg/L. This was calculated using the following fields: Ca (dissolved), Na (dissolved), K (dissolved), Mg (dissolved), HCO_3, Cl (total), SO_4 (total), F (dissolved), PO_4 (dissolved), NH_4 as N (dissolved), and NO_3 as N (dissolved). Entries were added for cation and anion sums, and charge balances. The charge balances were calculated in equivalents for all records. The cation sum was calculated as follows:

$$\Sigma \text{ cat} = Ca/20.04 + Mg/12.15 + Na/22.99 + K/39.098 + Ba/68.665 + Fe/18.616 + Mn/18.313$$

The anion sum was calculated as follows:

$$\Sigma \text{ an} = Cl/35.435 + B/77.617 + F/18.998 + HCO_3/61.006 + CO_3/30.004 + SO_4/48.025 + PO_4/31.6471 .$$

Balances were calculated from the following:

$$(\Sigma \text{ cat} - \Sigma \text{ an})/(\Sigma \text{ cat} + \Sigma \text{ an})$$

Charge balances were calculated for any record that contained either a HCO_3 analysis or a total alkalinity analysis, with the HCO_3 analysis being used preferentially. It was assumed that all of the alkalinity (reported in mg/L $CaCO_3$) results from HCO_3, given that the pHs of all of the

waters are generally near 7 or slightly greater (maximum pH of all records = 8.1). The charge balance was computed with this HCO_3 value when no HCO_3 value was reported for the record. Charge balances were calculated when no HCO3 data were available, but poor charge resulted in these cases as expected.

Next, all duplicate analyses were deleted. The same sample locations and dates were often listed in both the EPA and USGS datasets, resulting in duplicate analyses, which were deleted. However, in some of these cases, the EPA dataset did not list all constituents that were measured at the sampling location on the particular date, yet the USGS dataset included these additional analyses. When the USGS data entry included additional analytical constituents, these data were added to the EPA entry, and the reference to the data is listed in the last two columns of the database as STORET, USGS.

Separate files containing (1) major element analyses, (2) trace element analyses, (3) field parameters, and (4) organic analyses were constructed for the water samples. Insufficient isotope data were reported for any of the surface water or groundwater samples, and hence, no data table was created for those sparse analyses. Only one detectable analysis for organics in the groundwater samples was reported. This data value showed small concentrations (approximately an order of magnitude less than MCL) of bis (2-Ethylhexyl) phthalate in the Riverside Well #3 on 11/15/95. Several analyses from the Riverside Wells and distribution system were conducted with GC/MS for SDWA volatiles plus lists 1 and 3 unregulated compounds (EPA 524.2) and SDWA Herbicides (EPA 515.1), and all analyses showed all concentrations below detection limits. Only one component was measured at another well (Griffith Canoe Base Well), and these analyses all show coliforms of either 0 or <2.2 per 100 ml. Due to this sparse organic data from the wells, no data table was created.

The elevation, depth, latitude, and longitude fields were not noted on all entries in the individual databases, but were commonly noted for at least one entry from a particular site. Because these parameters would not vary at a site between sampling events, these data were copied into the appropriate location in the records in the other files that did not contain these location data. Some of the location data required estimation based on the information provided in the respective data sources. The Griffith Canoe Base Wells and the Laughlin Well data provided by the Nevada Division of Health only listed either a location relative to a milepost (Griffith Canoe Base) or quarter section information (Laughlin). Therefore, the plotted locations of these wells are only approximate because they do not represent survey coordinates, but estimated coordinates.

In the case of the wells at the Riverside Resort and Casino, numerous methods of naming and designating samples were used. In order to alleviate the confusion, Bill Lynn of the Clark County Health District Office was contacted to ascertain the naming conventions and determine which of the sites with different names were actually the same sampling sites. According to Lynn (pers. comm. 11/9/99), all of the following naming conventions indicate waters were sampled from the Riverside Resort and Casino Well #1: POE #001, POE #001 Tank, POE #001 Old Tower, Tower Old, Old Tower Pantry, and Old Tower. Mr. Lynn also indicated that any records reported as simply "Riverside Resort and Casino" or "Riverside," without any additional designations, were data from samples collected from their distribution system, which represents waters from a combination of wells. A total of 33 of the Riverside sample analyses where available from the distribution system.

Two sets of data files were created with the chemical analyses: (1) one data file containing all analyses, and (2) another file containing only one selected analysis for each sampling location.

This second file is the one used in the GIS coverages, and the complete file was used to construct all temporal plots of the data based on all available information from each sampling site.

In the data set (1) above, wells for which no coordinates or quarter section information were available were deleted from the data set as their locations could not be ascertained: (Well 1 and Well 2 from the NDH, Riverside Trailer Park Well from NDH and CCHD, Colorado River at Griffith Canoe Base, Harrah's Del Rio Beach, and Laughlin Bay Village from STORET). All fields that were identical for all wells were deleted from the database. These included state and county codes, among others.

The smaller subset of the data in (1) that was extracted to form the (2) GIS data was selected as follows. Only one analysis from each sampling location was selected to be included in the GIS data set. In the major element chemistry file, the most temporally recent analysis was selected that also had a charge balance error of ≤10%. Often HCO_3 or alkalinity was not reported, and hence, many of the analyses had poor charge balances. The record for a sampling location with the same date as that selected in the major element chemistry file was also retained in the smaller data set files for the trace element analyses and field data files. When the data for the selected date were incomplete relative to fields that do not change through time (e.g., land surface elevation, well depth), these values were copied into the retained record before the other analyses from other dates were removed from the dataset.

Data were selected for one date to be included in the GIS file as indicated above, except in the following three cases. (1) All of the more recent analyses from the Nevada Club Well, and two Colorado River sample sites (0.5 miles below Davis Dam and Colorado River at Laughlin) did not include cation analyses, and hence, all charge balances are poor (100% error). None of the reported analyses from the Nevada Club Well had charge balance errors ≤10%, and hence the analysis with the best charge balance was retained in the data set. (2) Similarly, neither of the analyses from the Riverside trailer park well had a charge balance error of ≤10%. (3) On the date (5/20/97) for which the major element record was selected for the Riverside Casino Well #1, there was not a corresponding analysis for the trace elements or field parameters for that date. The next earlier date (11/15/95) with any trace element data reported was selected for inclusion into the data set. No reported field data exist for that date or any date of sampling at this well.

Results

Precipitation/Climate

The Laughlin study area is in an arid region that experiences relatively low rainfall and high evaporation rates. Precipitation data are only available for Laughlin over the last 12 years, and, due to data gaps, only seven of those years are used by the Western Regional Climate Center for calculating annual average rainfall (Table 2). These limited data indicate average annual precipitation at Laughlin is 127 mm/yr (≈5.0 inches). Average annual calculated potential evapotranspiration for Laughlin is 2687 mm/yr (Shevenell, 1996; 1999), resulting in a net deficit of water of 2560 mm (≈100 inches) annually. In no month does precipitation exceed expected evapotranspiration.

Because the Laughlin station does not have a record of precipitation for years prior to 1988, and many of the chemical analyses discussed in later sections were collected prior to 1988, the precipitation data from the Searchlight and Bullhead City weather stations were also compiled. Data from the Searchlight weather station were collected over a longer period of time than at the

Bullhead City station, where measurements only began in 1977. The Searchlight data indicate a long-term (70 year) average annual precipitation value of 195.8 mm/yr (7.7 inches). The data from Bullhead City, which is closer to and at a more comparable elevation (177 m) to Laughlin, indicate a 23-year average of 171 mm (6.7 inches). This annual average is closer to the 12-year Laughlin average of 127 mm/yr. Because Searchlight is at a higher elevation than Laughlin (1079 m at Searchlight versus 207 m above sea level at Laughlin), its annual deficit (precipitation minus evaporation of 2089 mm) is lower and equal to –1893 mm (≈74.5 inches). During the time period over which the records at Searchlight and Laughlin coincide (1988-1999), rainfall at Laughlin is lower, except in 1988. Precipitation is both higher and lower than average in the same years at the Laughlin and Searchlight stations indicating the same general patterns of precipitation (Fig. 1). Similar patterns between the Laughlin and Bullhead City stations are also observed, although less consistently, with Laughlin's precipitation being higher than that in Bullhead City in three separate years (Fig. 1). For discussions regarding chemical data collected prior to 1977, the Searchlight data are used (Table 3), and for accompanying chemical data collected after 1977, the Bullhead City data are consulted.

Mining Disturbances

The Laughlin area contains only 8 of the 629 Mineral Industry Location System (MILS; MAS/MILS, 1994) and Mineral Resource Data System (MRDS; USGS, 1993b) sites in Clark County, along with only two of the 204 sites from the NBMG Geochemical data sets (Tingley, 1998b) within Clark County. Both of these samples were collected from the shaft locations illustrated in Figure 2 (within the Newberry mining district). Only 11 sites within the Laughlin study area are represented in the dataset of mine sites digitized from 7.5' quadrangles. Although the majority of these sites are located close to the Colorado River, most of these sites are borrow pits or quarries (Fig. 2), indicating little likelihood of adverse impacts from the features on surface waters or groundwaters. Only one mining district occurs within the study area (the southern part of the Newberry, or Searchlight district), and this segment of the district occurs approximately over the northern third of the study site. Polymetallic vein deposits occur in this district, and historically, this area was mined for gold, with accompanying occurrences of silver, copper, antimony, and thorium (Tingley and others, 1998a). Some acid producing potential exists in this type of deposit due to the presence of gold-bearing sulfides such as pyrite, chalcopyrite, and galena in the hydrothermal veins, and some fresh sulfide-rich zones occur only a few feet below the surface within the Newberry mining district (Smith and others, 1983).

Although several mining disturbances occur near the shafts located on Figure 2 (J. Faulds, pers. comm.), these features are the only ones for which digital data (e.g., locations) are available. Geochemical analyses of rocks collected near two of the shafts located on Figure 2 indicate slightly elevated concentrations of the following metals in comparison to average crustal abundances (Levinson, 1974): Au, Ag, Be, Fe, La, Mo, Pb, and Ti (Tingley and others, 1998b). Arsenic concentrations are also elevated relative to average crustal abundances (≈30 ppm), yet are relatively low in comparison to other mineralized areas throughout the state of Nevada. Furthermore, no elevated As or metals concentrations were identified in any of the groundwaters. The general paucity of data related to mining disturbances, and the fact that most of the mine sites are borrow pits or quarries producing industrial minerals, suggest that mining impacts on surface water and groundwater quality are minimal and will pose little threat to these resources in the future.

Table 2. Precipitation data (in millimeters) for the entire period of record at the Laughlin weather station.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1988	0.00z	21.59	0.00	55.88	0.00	0.00	19.05	59.18	0.00	0.00	5.59	2.03	163.32
1989	28.96	0.00	3.56	0.00	1.02	0.00	0.76	0.00	0.00	4.06	0.00	1.27	39.62
1990	23.88	6.60	7.11	4.06	12.45	1.52	35.81	13.46	11.43	8.13	1.27	0.00	125.73
1991	0.00	22.86	96.01	0.00	0.00	0.00	0.00	24.38	40.64	0.00	0.00a	4.57a	188.47
1992	33.02	47.75	110.74a	0.00	0.00	0.00	0.00	4.57	0.00	53.34	2.54	21.84	273.81
1993	153.92	100.84	0.00z	0.00	0.00	2.29	0.00	6.60	0.00	0.25	12.95	0.51	277.37
1994	2.03	12.95	29.97	0.00	0.00	0.00	7.62	0.00	1.02	1.52	17.27	23.62	96.01
1995	76.45	20.83a	18.54	4.06	0.00	0.51	0.00	0.00	0.00	0.00	0.00	1.78	122.17
1996	4.57	4.57	1.02	0.00	0.00	0.00	3.56	0.00	3.56	7.62	20.32	0.00	45.21
1997	50.29	8.89	0.00	0.00	0.00	0.00z	4.57	11.43	36.07	0.00	8.38	0.25a	119.89
1998	9.40	142.49	0.00z	9.14	1.52	0.00	0.00z	0.00z	13.97	1.27	1.52	0.25	179.58
1999	7.62	6.86	0.00a	6.10	0.00	16.51	53.34	0.25i	12.19o	0.00z	0.00z	0.00z	90.42
MEAN	35.56	33.02	26.67	6.60	1.27	1.78	11.43	11.94	9.65	6.86	6.35	5.08	127.25
S.D.	45.72	44.20	41.66	15.75	3.56	4.83	17.78	18.29	14.99	15.75	7.37	8.89	82.30
SKEW	44.20	42.16	34.04	71.63	73.91	69.09	38.35	47.75	33.53	67.56	21.34	40.13	17.27
MAX	153.92	142.49	110.74	55.88	12.45	16.51	53.34	59.18	40.64	53.34	20.32	23.62	273.81
MIN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	39.62
NO YRS	11	12	10	12	12	11	11	10	11	11	11	11	7

Note, 'a' indicates one day's data are missing, 'b' indicates 2 missing days, ..., and 'z' indicates 26 or more days of data are missing from the monthly summary.

Calculated potential evapotranspiration(in millimeters) at Laughlin (after Shevenell, 1996; 1999):

Ave.	39.6	74.9	152.8	237.4	341.3	405.4	460.9	378.9	303.8	176.8	74.4	40.3	2686.6

Precipitation minus evaporation (water deficit when negative) in millimeters.

	-4.04	-41.88	-126.13	-230.80	-340.03	-403.62	-449.47	-366.96	-294.15	-169.94	-68.05	-35.22	-2559.35

Table 3. Precipitation data at the Searchlight weather station for the period of time represented by the geochemical analyses reported in this work. Data are reported in millimeters per month.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1967	16.26	0.00	0.00	4.83	2.54	0.00	17.53	79.25	2.79	0.00	23.88	27.18	174.24
1968	0.00	9.91	12.70	0.00	1.02	7.62	45.21	4.06	0.00	0.00	7.11	0.76	88.39
1969	70.36	34.54	12.45	0.00	23.37	12.70	21.08	2.54	29.21	3.05	6.60	0.00	215.90
1970	1.27	12.95	25.40	0.00	0.00	2.03	6.35	58.17	0.00	0.00	7.11	14.48	127.76
1971	0.00	9.14	0.00	0.00	25.65	0.00	0.00	17.02	0.00	1.52	1.52	13.97	68.83
1972	0.00z	0.00	0.00	13.46	3.81	10.16	0.00	23.88	10.16	25.65	39.12	10.41	136.65
1973	13.46	45.47	37.34	0.00	6.10	10.16	0.00	2.29	0.00	0.00	8.13b	0.00z	122.94
1974	37.59	1.27	16.26	0.51	0.00	0.00	62.23	4.06	2.54	33.53	8.38	18.03	184.40
1975	1.27	2.79	36.07	3.81	3.81	0.00	0.00	30.23	54.10	11.43	0.00	0.00	143.51
1976	0.00	58.17	12.19	17.02	22.86	0.00	25.40	0.00	150.62	25.40	0.76	0.00	312.42
1977	11.94	0.00	14.48	1.52	11.68	1.02	17.53	28.70	0.00	4.83	0.00	16.00	107.70
1978	54.61	48.77	59.69	20.32	0.00	0.00	30.73	104.39	17.53	23.88	71.37	42.42	473.71
1979	31.50	11.94	68.33	0.00	0.76	2.54	82.04	23.88	0.00	12.70	0.00	22.86	256.54
1980	68.83	125.73	29.21	34.04	6.35	0.00	26.92	0.51	18.54	3.30	0.00	0.00	313.44
1981	2.03	9.40	52.32	0.00	22.86	2.29	11.43	16.51	23.88	8.13	13.46	0.51	162.81
1982	12.70	20.83	45.47	6.10	7.11	0.00	4.32	198.63	6.86	13.21	27.69	24.89	367.79
1983	64.52	19.56	66.29	23.37	0.76	0.00	25.40	91.19	24.13	36.32	0.25	24.89	376.68
1984	0.00	0.00	0.00	1.52	0.00	4.32	126.24	16.76b	4.57	3.05	40.64	103.38a	300.48
	36.58b	7.11a	0.76	20.32	0.76	1.02	27.43	0.00	16.51	10.16	34.54	1.78a	156.97
1986	13.21	13.97	18.03	0.76	0.00	0.00	4.32	18.54	15.75	14.22	6.86	76.20	181.86
1987	17.02	20.83	6.10	4.83	8.13	1.02	18.03	0.00	8.13	57.15	36.32	21.34	198.88
1988	22.35	14.73	0.00	38.86	0.76	2.29	13.72	36.83	0.00	0.00	9.91	4.06	143.51
1989	32.26	7.11	3.05	0.00	3.56	0.00	21.08	6.10	0.00	2.03	0.00	1.52	76.71
1990	29.72	5.33	3.30	2.54	6.10	12.19	42.16	35.05	11.94	2.79	1.02	0.00	152.15
1991	32.77	38.10	53.59	0.00	8.89	0.25	3.30	18.03	17.02	4.83	5.84	21.34	203.96
1992	31.24	65.02	128.78	0.00z	13.21	1.27	2.29	30.48	0.00	53.34	0.00	41.15	366.78
1993	94.49	98.04	16.76	0.00	2.54	4.32	0.00	59.44	0.00	1.27	11.68	1.78	290.32
1994	2.03	35.56	28.19	0.00	1.52	0.00	2.03	1.27	19.05	3.56	14.73	59.44	167.39
1995	80.77	20.57	52.07	23.88	9.14	0.00	7.87	25.15	15.24	0.00	0.00	0.00	234.70
1996	6.60	16.76	0.25	0.00	7.11	0.00	36.58	4.83	15.49	7.11	9.65	6.60	111.00
1997	21.84	16.00	0.00	0.00	0.00	1.78	9.40	3.81	61.21	0.00	5.08	10.92	130.05
1998	11.68	96.01	42.67	4.83	3.30	0.00	55.37	39.62	30.73	14.48	8.38	3.05	310.13
1999	6.35	6.10	0.51	31.50	0.25	6.86	84.07	0.00z	0.00z	0.00z	0.00z	0.00z	135.64
MEAN	23.37	22.61	20.83	10.67	5.59	3.05	24.89	29.46	16.76	12.45	11.18	19.05	195.83
S.D.	24.64	26.67	26.92	18.03	7.87	4.57	26.16	36.07	33.53	15.24	16.26	22.86	95.50
SKEW	27.94	44.20	45.47	67.06	42.42	42.67	39.12	58.67	115.57	38.10	56.39	43.69	9.65
MAX	94.49	125.73	128.78	98.81	30.99	21.59	126.24	198.63	240.03	61.72	80.01	103.38	473.71
MIN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	41.66
NO YRS	82	82	84	82	81	81	79	81	82	81	81	83	70

Note, 'a' indicates one day's data are missing, 'b' indicates 2 missing days, ..., and 'z' indicates 26 or more days of data are missing from the monthly summary.

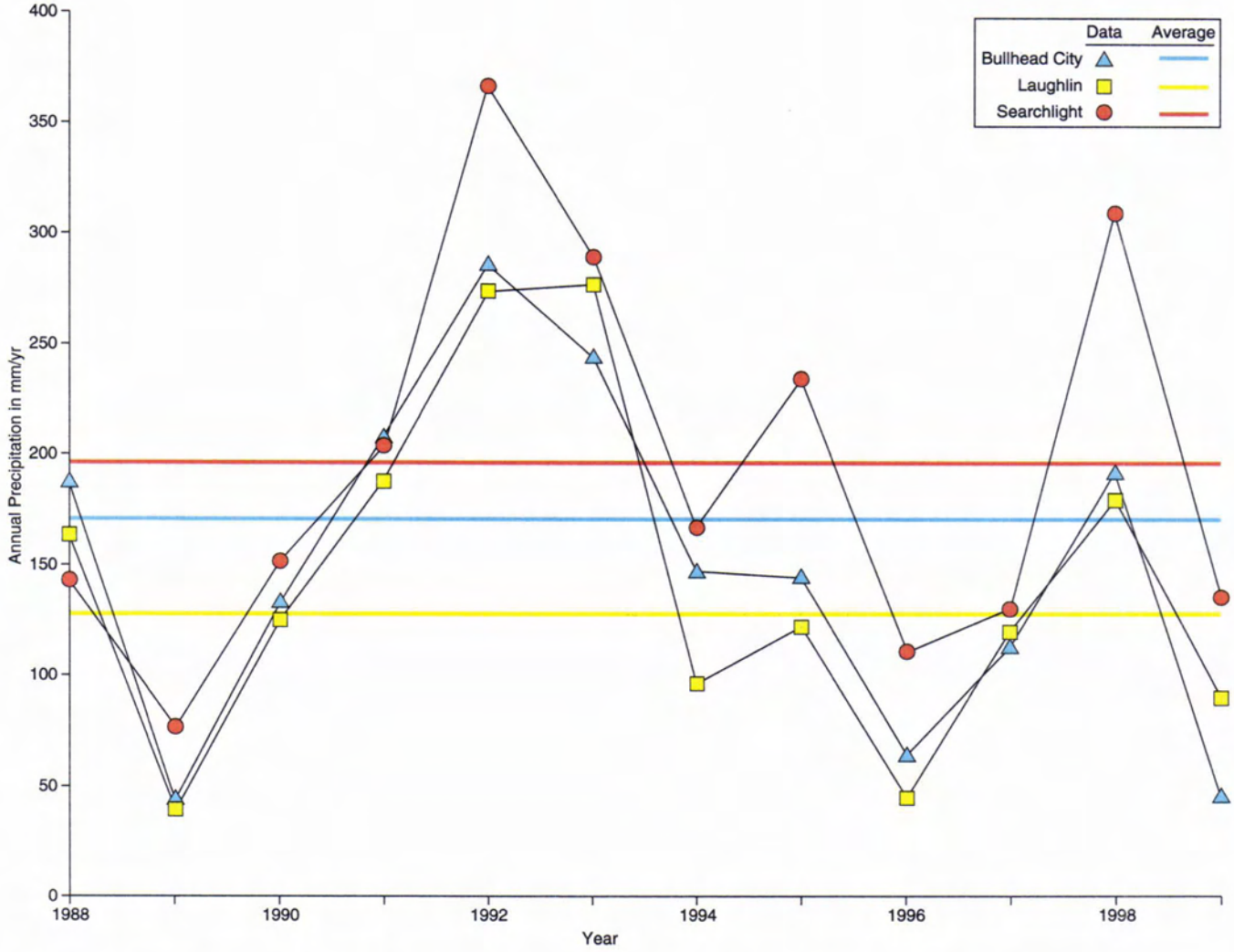

Figure 1. Annual precipitation at the Bullhead City, Laughlin, and Searchlight weather stations from 1988 to 1999.

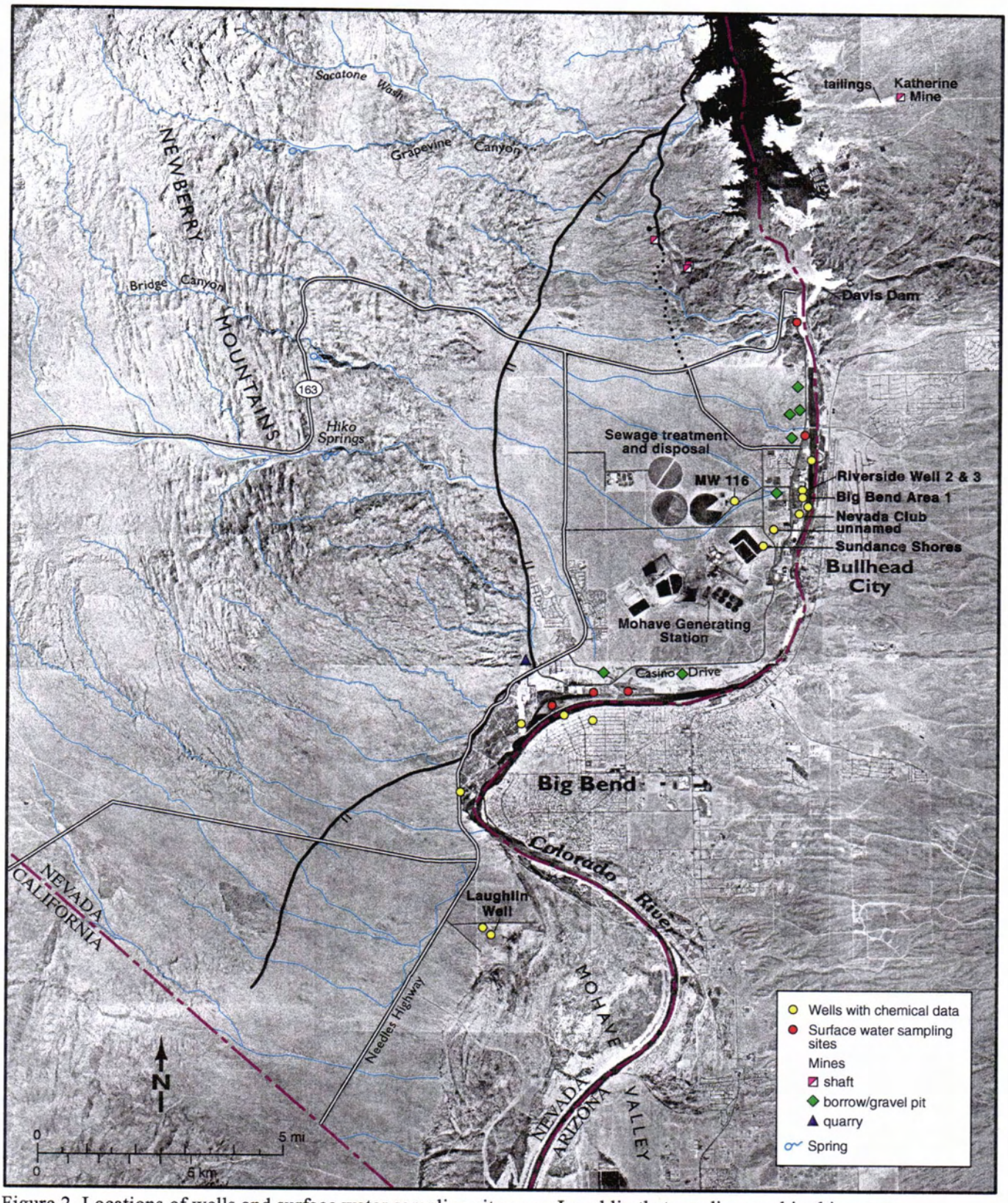

Figure 2. Locations of wells and surface water sampling sites near Laughlin that are discussed in this report.

Well Data

Although 159 wells (Fig. 3) are listed in the data set obtained from the Nevada State Engineer's Office, which tracks permitting of well installation, only 22 separate wells have known locations and geochemical data based on the compilation of chemical analyses from the four sources noted in the Methods section (Hydrogeochemical Data). Both Table 4 and Figure 3 show that it was difficult to correlate wells listed in the geochemical database with those listed in the State Engineer's database due to slightly differing names and locations between the databases.

More than 22 entries appear in Table 4 for the following reasons. The undesignated Griffith Canoe Base Well is believed to be either Well 1 or Well 2 at that site, yet it cannot be determined because both wells list the same coordinates. Both the Distribution System and Kitchen Sink sample designations at the Riverside Resort and Casino are included because both have reported chemical data. However, both are a combination of inputs from one or more wells at the Riverside Resort, and hence, are not individual well samples. In addition, no location data could be determined for three of the wells (Riverside Trailer Park, Well 1, and Well 2). Other wells have very few water quality analyses available. For these various reasons, only 13 wells are discussed in detail, and these wells are highlighted in bold in Table 5. Figure 3 shows the location of wells sampled in the Laughlin area relative to some notable landmarks.

Groundwater Geochemical Data

Where data are available, temporal plots are constructed for individual chemical constituents, with the Nevada drinking water standard noted for comparison. Not all analyses are complete; therefore, the number of analyses and wells represented on each of the plots is not consistent. In the first plot, pH for eight wells is shown versus time between 8/16/73 and 8/17/98 (Fig. 4; no pH data were reported for the Griffith Canoe Base Wells or the Riverside Wells.). This plot shows pH fluctuates through time, but in an erratic manner that is not correlated with seasonal fluctuations. All fluctuations are very small and insignificant, and are well within the Nevada Drinking water standards that stipulate waters must have pH between 6.5 and 8.5

Major Element Chemistry

Figure 5 shows chloride (Cl) versus time for 13 wells in the Laughlin area for which there are sufficient data to construct temporal plots. All wells, except Monitor Well 116, consistently had Cl concentrations below the Nevada Drinking water standard (400 mg/L). Figure 6 shows temporal data for eight of the wells. Two of the wells had all reported nitrate (NO_3) values of zero (Cromer and Riverside DS), whereas five wells had no reported NO_3 analyses (Griffith Canoe Base Wells, and Riverside Wells). As was observed with the Cl data, all wells have NO_3 concentrations well below the drinking water standard (10 mg/L), except for Monitor Well 116.

Sulfate (SO_4) concentrations are also slightly elevated compared to the drinking water standard (500 mg/L) in Monitor Well 116, with concentrations increasing slightly through time (Fig. 7). Ten of the 13 wells plotted on Figure 7 consistently have SO_4 concentrations below the drinking water standard. However, the two wells at Griffith Canoe Base (Wells #1 and #2) have had elevated SO_4 concentrations that vary markedly through time. The elevated SO_4 and Cl

Table 4. Comparison of well coordinates and depths in the chemical database with those in the Nevada State Engineer's well database.

Name in Chemistry Databases	Name in State Engineer's Database	Latitude		Longitude		Difference		Depth (ft)	
		Chem	Eng	Chem	Eng	Latitude	Longitude	Chem	Eng
0007377	DAVIS, EBBIE	35.4736	35.4689	114.8519	114.8539	0.00472	-0.00195	?	83
213 S28 E65 24CBC2	COTTONWOOD COVE CORP	35.4900	35.4903	114.6850	114.6867	-0.00028	-0.00167	?	126
	U S NATIONAL PARK SERVICE	35.4900	35.4903	114.6850	114.6867	-0.00028	-0.00167	?	150
213 S33 E66 17AAB 1	(none)	35.0794	35.0775	114.6458	114.6453	0.00194	0.00056	?	?
B. LAUGHLIN (KNIGHT) WELL	ORION LAND DEVELOPMENT (MW-03)	35.1178	35.1208	114.6197	114.6161	-0.00306	0.00361	50	32
BIG BEND WELL 1 AREA 1	CLARK CO SANITATION DISTRICT	35.1586	35.1581	114.5711	114.5878	0.00056	-0.01667	?	65
	CLARK CO SANITATION DISTRICT	35.1586	35.1581	114.5711	114.5878	0.00056	-0.01667	?	145
BIG BEND WELL 1 AREA 2	ORION LAND DEVELOPMENT (MW-03)	35.1225	35.1208	114.6342	114.6161	0.00167	0.01806	?	32
BIG BEND WELL 2 AREA 2	CLARK COUNTY SANITATION DIST (PW-02)	35.1175	35.1153	114.6358	114.6467	0.00222	-0.01083	?	105
	CLARK COUNTY SANITATION DIST (OW-01)	35.1175	35.1153	114.6358	114.6467	0.00222	-0.01083	?	105
	CLARK COUNTY SANITATION DIST (OW-02)	35.1175	35.1153	114.6358	114.6467	0.00222	-0.01083	?	105
	CLARK COUNTY SANITATION DIST (PW-01)	35.1175	35.1153	114.6358	114.6467	0.00222	-0.01083	?	111
	ORION LAND DEVELOPMENT (MW-03)	35.1175	35.1208	114.6358	114.6161	-0.00333	0.01972	?	32
CROMER WELL	ORION LAND DEVELOPMENT (MW-03)	35.1189	35.1208	114.6261	114.6161	-0.00194	0.01000	96	32
GRIFFITH CANOE BASE	BOULDER DAM COUNCIL AREA INC	35.1050	35.1022	114.6500	114.6489	0.00278	0.00111	?	104
GRIFFITH CANOE BASE WELL 1	BOULDER DAM COUNCIL AREA INC	35.1050	35.1022	114.6500	114.6489	0.00278	0.00111	?	106
GRIFFITH CANOE BASE WELL 2	BOULDER DAM COUNCIL AREA INC	35.1050	35.1022	114.6500	114.6489	0.00278	0.00111	?	106
LAUGHLIN	SOPER, I S	35.0780	35.0764	114.6440	114.6442	0.00161	-0.00017	?	150
	SOPER, I S	35.0780	35.0764	114.6440	114.6442	0.00161	-0.00017	?	165
	(none)	35.0780	35.0775	114.6440	114.6453	0.00050	-0.00128	?	?
MONITOR WELL 116	CLARK CO SANITATION DISTRICT	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	300
	CLARK CO SANITATION DISTRICT (SW-01)	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	65
	CLARK CO SANITATION DISTRICT (FW-06)	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	145
	CLARK CO SANITATION DISTRICT (FW-05)	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	182
	CLARK CO SANITATION DISTRICT (FW-03)	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	195
	CLARK CO SANITATION DISTRICT	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	210
	CLARK CO SANITATION DISTRICT	35.1583	35.1581	114.5864	114.5878	0.00027	-0.00139	?	210
NEVADA CLUB WELL	DEL WEBB NEVADA CLUB	35.1556	35.1581	114.5719	114.5736	-0.00250	-0.00167	64	109

Name in Chemistry Databases	Name in State Engineer's Database	Latitude		Longitude		Difference		Depth (ft)	
		Chem	Eng	Chem	Eng	Latitude	Longitude	Chem	Eng
RIVERSIDE RESORT AND CASINO -									
[1]Distribution System		35.1569		114.5700				89	
[1]KITCHEN SINK		35.1569		114.5700				480	
[2]Well 1	SHIPKEY	35.1656	35.1656	114.5689	114.5689	0.00000	0.00001	400	400
[2]Well 2	RIVERSIDE RESORT & CASINO	35.1600	35.1600	114.5711	114.5711	0.00000	-0.00001	480	480
[2]Well 3	RIVERSIDE RESORT & CASINO	35.1600	35.1600	114.5711	114.5711	0.00000	-0.00001	489	498
Riverside Trailer Park		?		?				?	
SUNDANCE SHORES WELL	SO CALIFORNIA EDISON CO (MH-55)	35.1497	35.1469	114.5803	114.5783	0.00278	0.00194	480	306
SUNDANCE SHORES WELL	SO CALIFORNIA EDISON CO	35.1497	35.1506	114.5803	114.6161	-0.00083	-0.03583	480	309
Unnamed #1	FW-04	35.15556	35.15444	114.57194	114.59250	0.00111	-0.02056		175
Unnamed #2	(none)	35.15278	35.15083	114.57778	114.57361	0.00194	0.00417		480
	FW-04	35.15278	35.15444	114.57778	114.59250	-0.00167	-0.01472		175
Well 1		?		?					
Well 2		?		?					

[1] Combination of discharge from several wells. No direct comparison to the State Engineer's files can be made.
[2] Depths obtained from Clark County Health District.

Table 5. Summary of wells sampled in the Laughlin area.

Well Name	Other Well Name	No. of Analyses	First Date	Last Date	Location Unknown	Location Estimated
0007377		1	3/12/1977			
213 S28 E65 24CBC2		1	10/15/1979			
213 S33 E66 17AAB 1		1	5/30/1984			
B. Laughlin (Knight) Well		47	8/16/1973	8/31/1992		
Big Bend Well 1 Area 1		29	6/12/1985	9/1/1992		
Big Bend Well 1 Area 2		28	6/12/1985	9/1/1992		
Big Bend Well 2 Area 2		2	9/9/1988	9/9/1988		
Cromer		49	11/17/1973	8/31/1992		
Griffith Canoe Base		1	9/3/1986			X
Griffith Canoe Base Well 1		5	2/18/1982	6/27/1984		X
Griffith Canoe Base Well 2		5	2/18/1982	6/27/1984		X
Laughlin		2	2/4/1988	6/13/1989		X
Monitor Well 116		13	8/11/1989	9/1/1992		
Nevada Club Well		22	8/16/1973	10/18/1979		
Riverside Resort and Casino	Distribution System	33	2/7/1974	8/5/1998		
Riverside Resort and Casino	Kitchen Sink	1	6/6/1990			
Riverside Resort and Casino	Well #1	17	12/27/1993	8/17/1998		
Riverside Resort and Casino	Well #2	4	7/8/1983	12/1/1995		
Riverside Resort and Casino	Well #3	3	7/8/1983	3/4/1994		
Riverside Trailer Park		2	12/13/1967	8/31/1972	X	
Sundance Shores		38	8/16/1973	11/22/1988		
Unnamed #1		2	8/16/1973	11/17/1973		
Unnamed #2		2	8/16/1973	11/17/1973		
WELL 1		1	4/20/1982		X	
WELL 2		1	4/22/1982		X	
Total:		307	12/13/1967	8/17/1998		

Note:
-The Riverside "Distribution System" samples are a composite of multiple wells.
All of the following well names were used in the Clark County Health District files to refer to Riverside Casino Well #1 (Bill Lynn, pers. comm. 11/9/99): POE #001, POE #001 Tank, POE #001 Old Tower, Tower Old, Old Tower Pantry, and Old Tower.
-Those with unknown locations were omitted from the master data set.
- bold names denote those wells that are discussed in detail in this report, and for which temporal chemical plots are constructed.

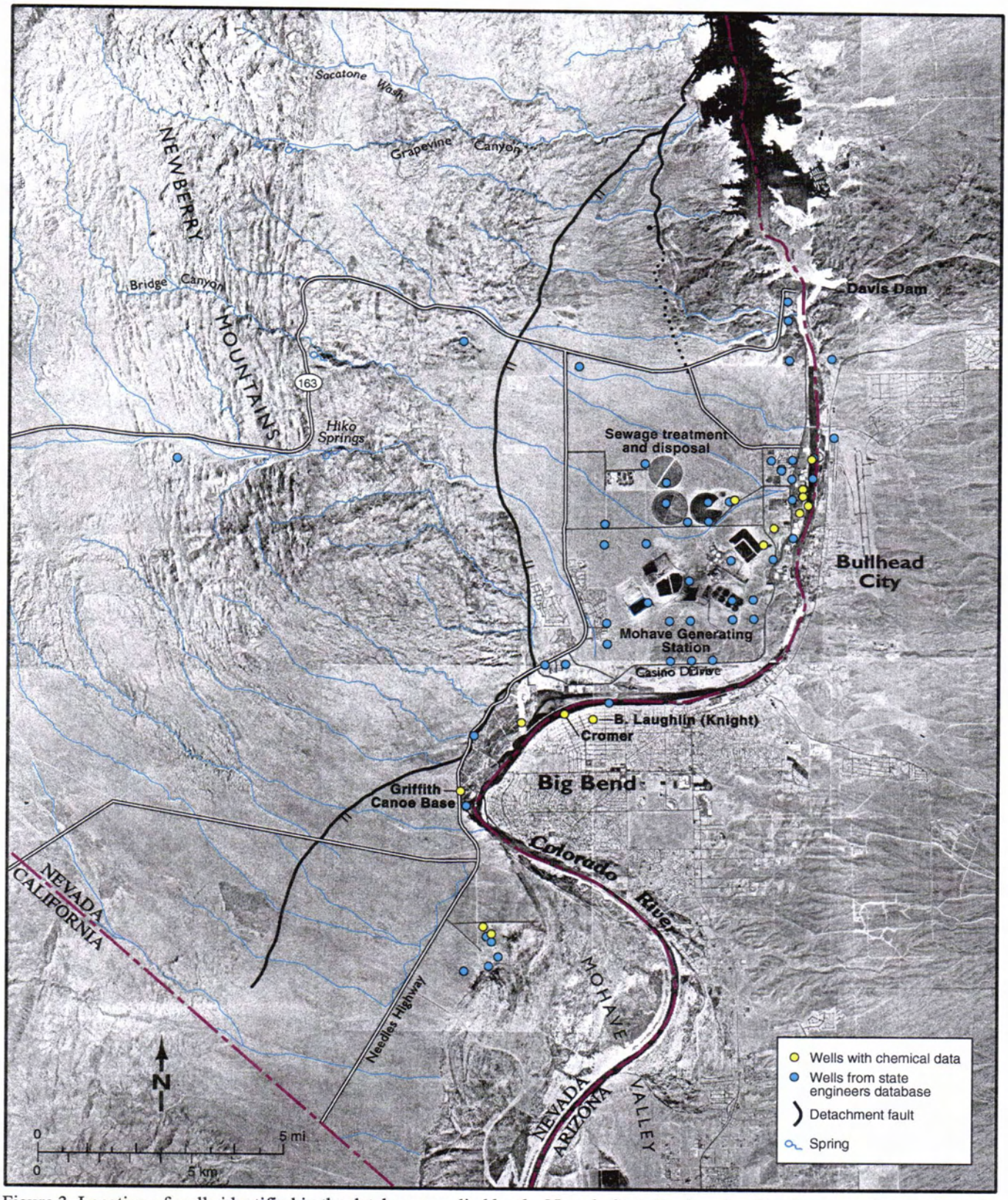

Figure 3. Location of wells identified in the database supplied by the Nevada State Engineer's office in comparison to those for which water quality data are available and discussed in this report.

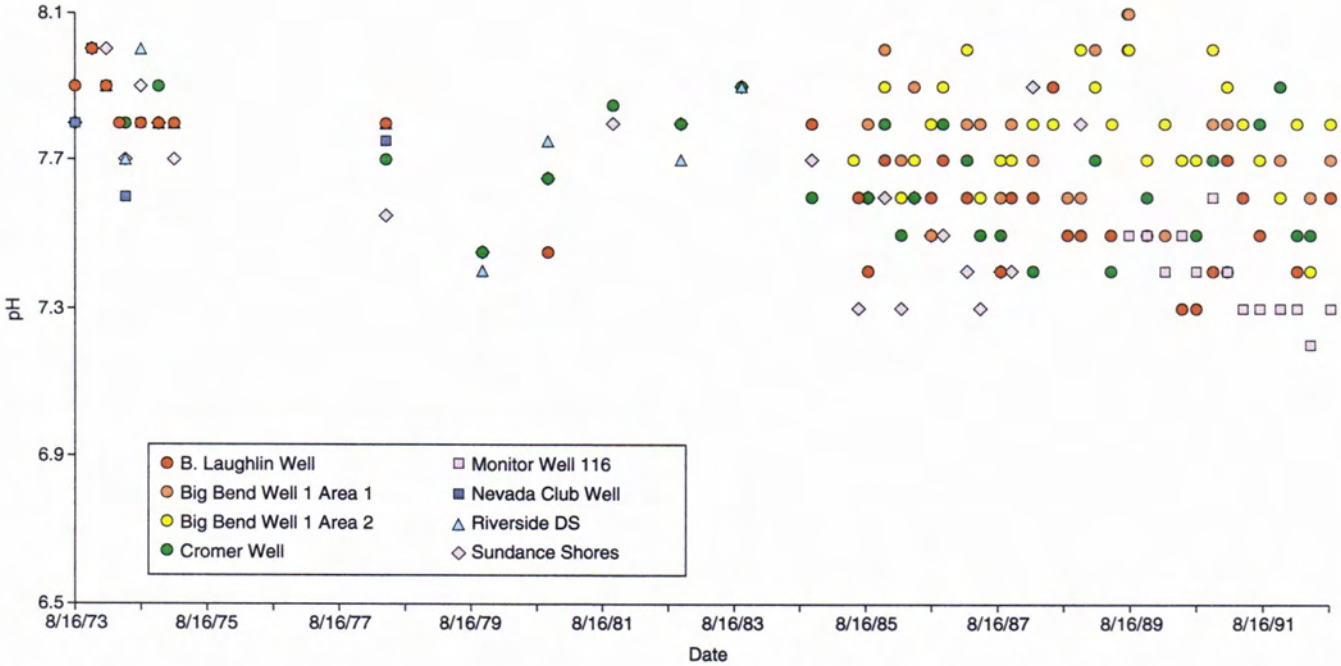

Figure 4. pH versus time in 8 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

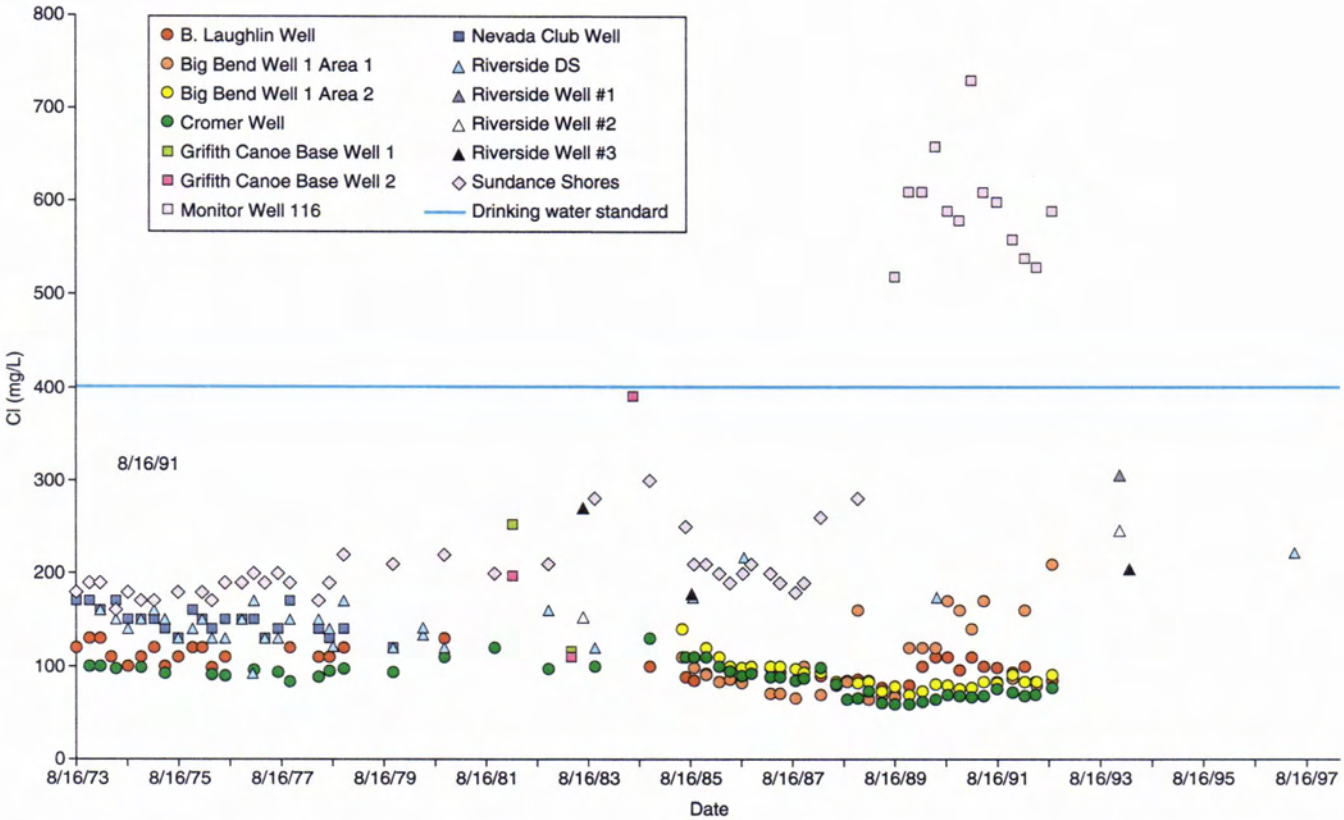

Figure 5. Chloride (Cl) versus time in 13 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

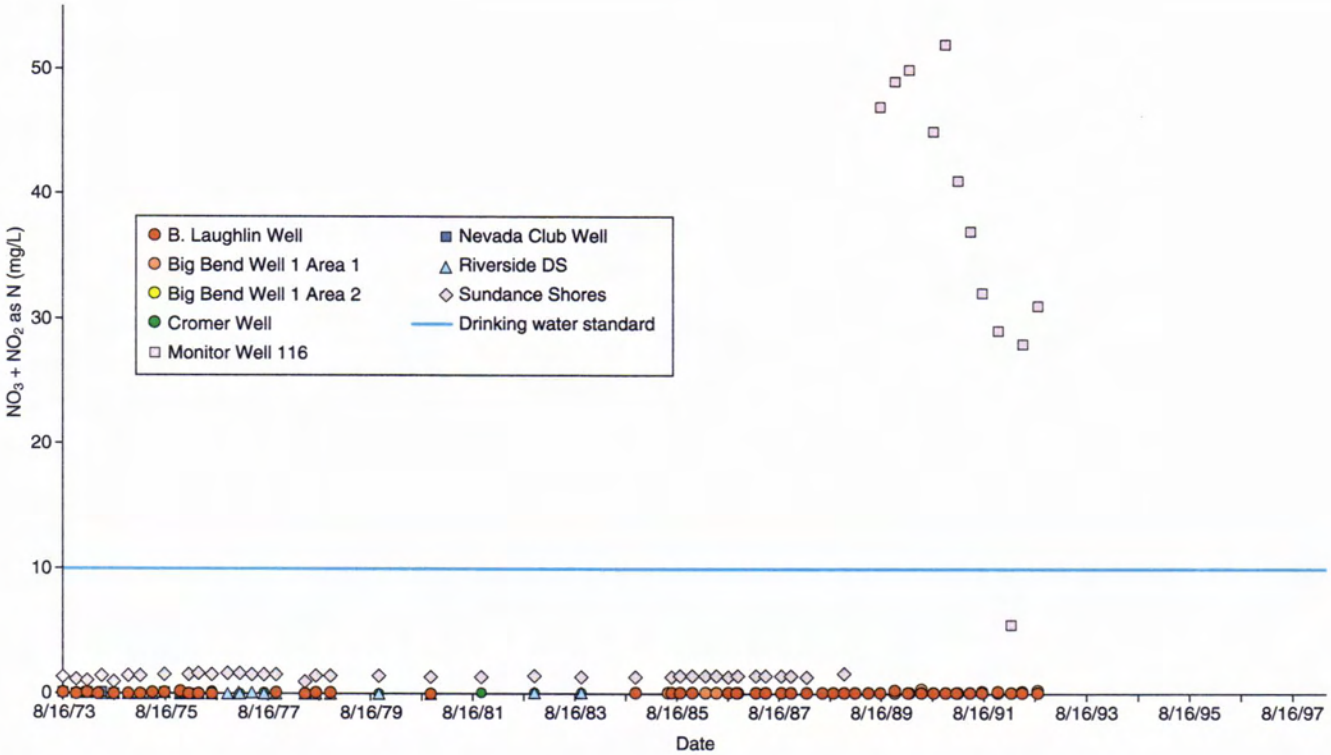

Figure 6. Nitrate (NO_3) versus time in 8 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

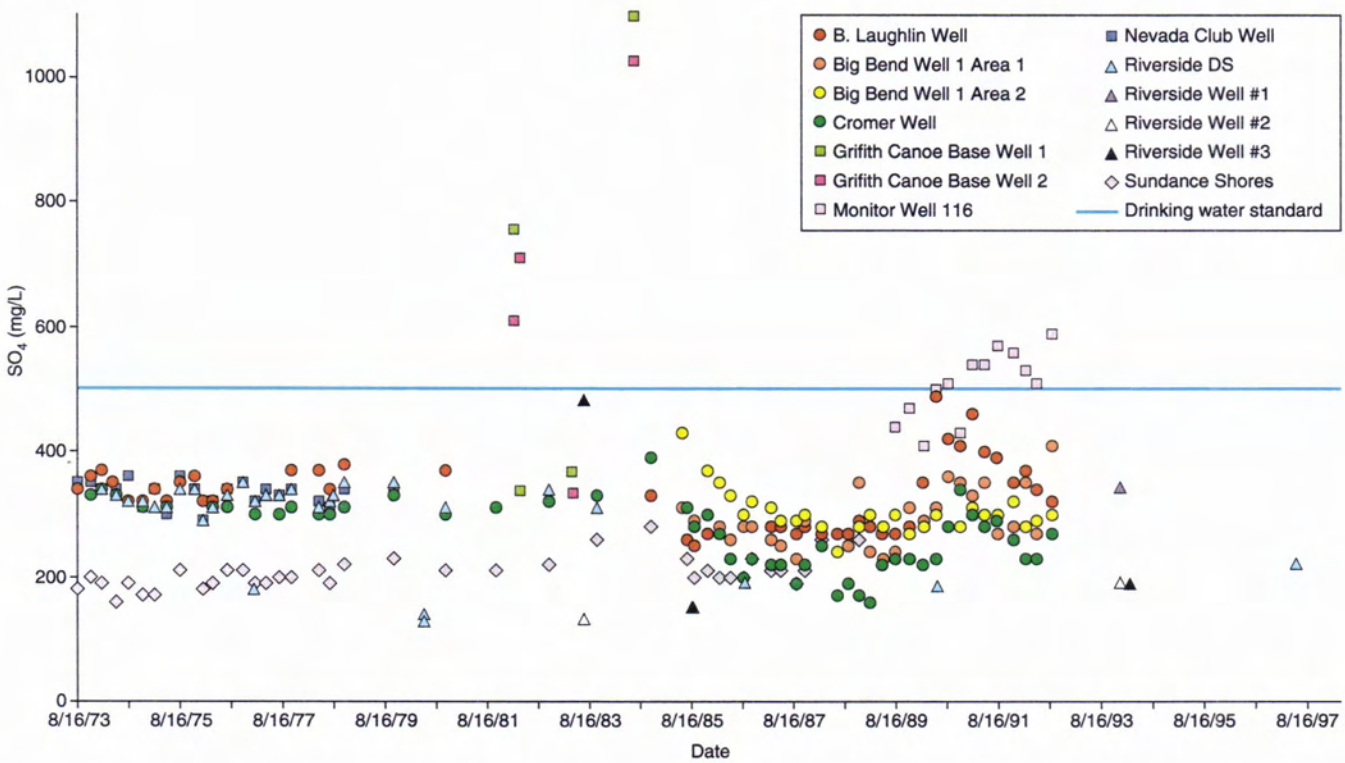

Figure 7. Sulfate (SO_4) versus time in 13 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

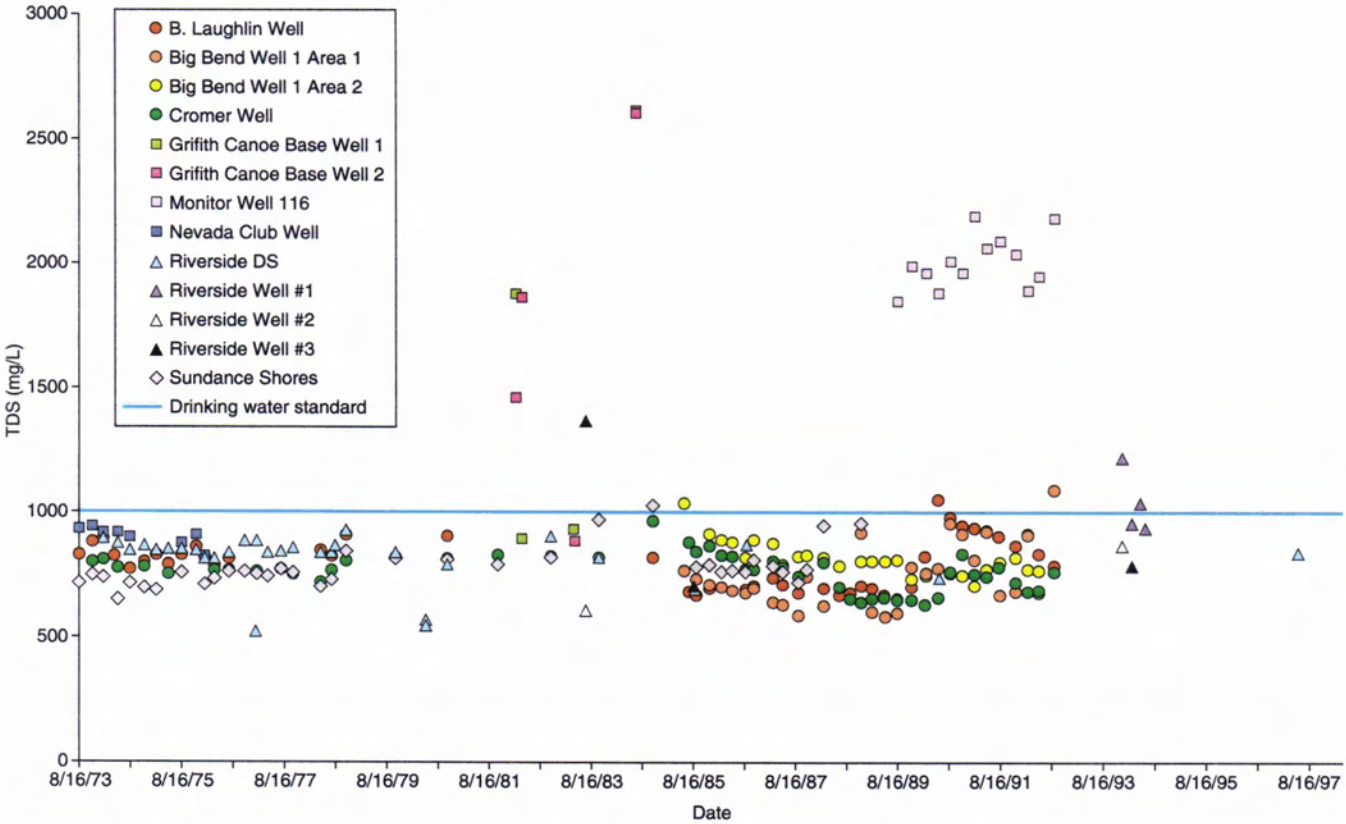

Figure 8. Total dissolved solids (TDS) versus time in 13 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

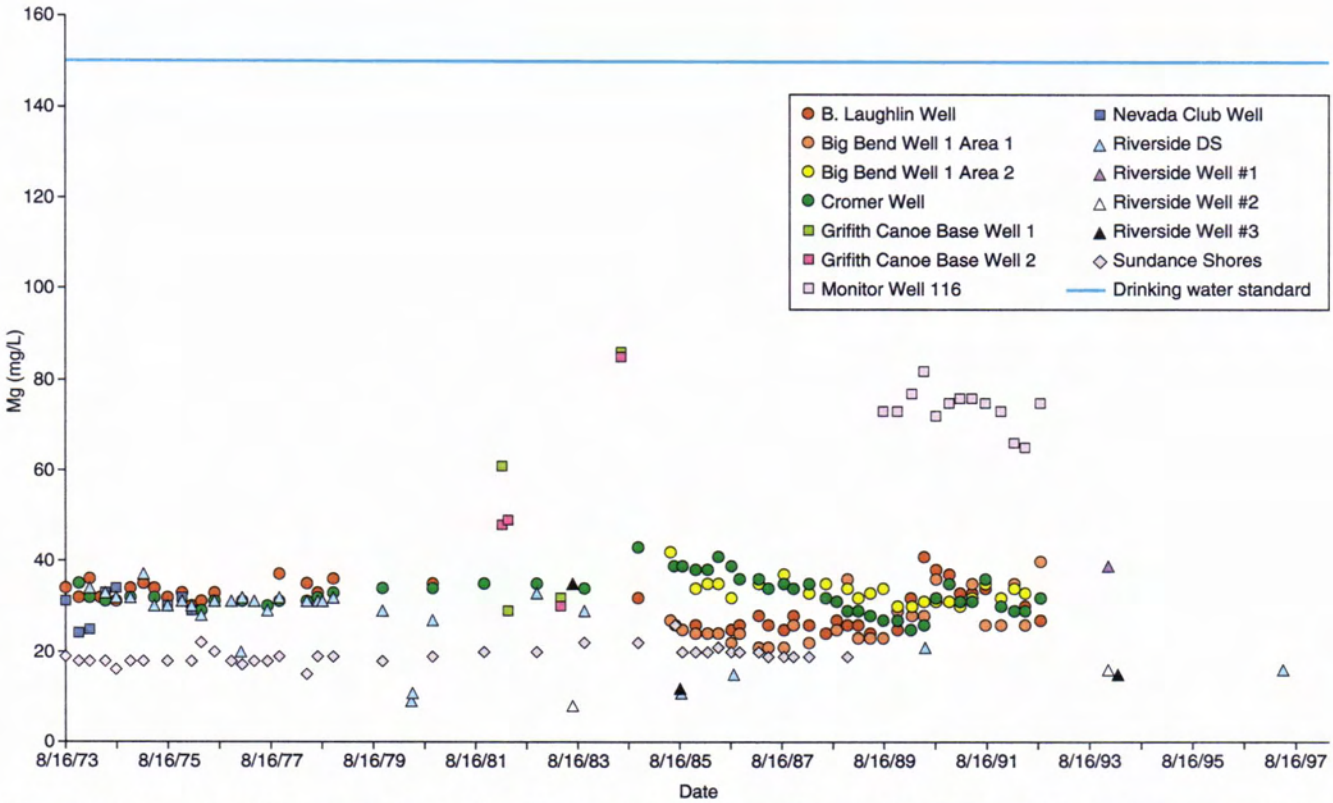

Figure 9. Magnesium (Mg) versus time in 13 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

observed in the Griffith Canoe Base Wells and Monitor Well 116 are also reflected in a plot of TDS versus time (Fig. 8). These three wells have had analyses that are slightly to considerably greater than the maximum TDS concentrations stipulated by the Nevada drinking water standards of 1000 mg/L. Other wells have had TDS concentrations slightly above the drinking water standard on some sampling dates. On 12/27/93 and 5/6/94, the TDS in Riverside Well #1 was 1220 and 1036 mg/L respectively, yet other values are also close to the standard (e.g., 956 and 938 mg/L). On 7/8/83, TDS in Riverside Well #3 reached 1364 mg/L. This value is 1.7 times higher than values reported subsequent to that date suggesting a possible erroneous data value for this well.

Chemical analyses for all other reported major element constituents are below the Nevada drinking water standard, or there are no standards for particular elements (e.g., calcium (Ca), potassium (K), sodium (Na)). The typically low concentration for other major elements is illustrated in Figure 9. Water samples from all wells show the quality of the water is very good relative to magnesium (Mg), with all concentrations being ≤50% of the Nevada drinking water standard of 150 mg/L.

Trace Element Chemistry

Concentrations of most trace elements in wells were either below detection limits, or not reported. For instance, of the 165 analyses for F (fluoride) none reported a value >1.86 mg/L for any of the wells discussed in this report, and the drinking water standard for F in Nevada is 2 to 4 mg/L. All of the following elements had reported values, but all were also less than the Nevada Drinking water standard: aluminum (1 analysis), antimony (3 analyses), arsenic (167 analyses), barium (55 analyses), cadmium (35 analyses), chromium (35 analyses), copper (55 analyses), cyanide (3 analyses), lead (31 analyses), nickel (3 analyses), selenium (36 analyses), silver (33 analyses), thallium (3 analyses), and zinc (55 analyses). There are no Nevada drinking water standards for three other trace elements: boron, lithium and molybdenum. Although there are only three analyses, beryllium exceeded the drinking water standards in the Riverside Resort Well #1 and Well #2. Of the 40 analyses reported for mercury, only one sample had a concentration exceeding drinking water standards, and this occurred in a sample collected from the Riverside Resort and Casino kitchen sink on June 6, 1990.

The only other elements that exceeded drinking water standards were iron (Fe, Fig. 10) and manganese (Mn, Fig. 11). Eight of the wells have Mn in excess of the drinking water standard, and two wells (Griffith Canoe Base Wells) have Fe exceeding the standard. Two other wells (Riverside Well #3 and Big Bend Well 1 Area 2) have one sample with elevated Fe, but these may be spurious results. Elevated Fe and Mn are not currently thought to cause any adverse health effects, and the standards have been promulgated due to aesthetic considerations. Plots for other metals are not included here because of either limited data availability or very low reported values.

Surface Water Geochemical Data

Major Element Chemistry

Locations of surface water sampling sites on the Colorado River are depicted in Figure 2, and a summary of the sampling sites is listed in Table 6. In cases where a Nevada drinking water standard exists for a particular element or compound (Cl, Mg, NO_3, SO_4, and TDS), all Colorado

River water samples are lower than the standards. NO_3 was analyzed in 121 Colorado River water samples, and these values have an average of 1.2 mg/L, with none exceeding the drinking water standard. A plot of the NO_3 concentration with time shows no trends, and is hence, not included here. In contrast, several elements or compounds (Ca, Mg, Na, Cl, HCO_3, SO_4, and TDS) show a decrease in concentration in the river waters beginning in November 1982, with the minimum value of 190 mg/L SO_4 being measured on 11/6/87 (Figures 12 through 18). Although all concentrations are consistently low, these plots show a consistent decrease in concentration between those dates, except in the case of HCO_3 and TDS for which data are missing between 11/82 and 11/87. Note, no Ca, Na, Cl, SO_4 or TDS data were reported for the monitoring station "0.5 miles downstream of Davis Dam," and that no Ca, Mg, or Na concentrations were reported for the station "Colorado River at Laughlin."

Trace Element Chemistry

Of the 181 analyses for Fe in Colorado River water, values averaged 0.015 mg/L, and none exceed the drinking water standard. Of the 187 analyses for F in Colorado River water, values averaged 0.35 mg/L, and none exceed the drinking water standard. Very few river water samples were analyzed for any of the other trace elements. Table 7 shows which trace elements were analyzed at least once in river samples. As can be seen, for many of the elements, the Colorado River was only analyzed once for the particular element (e.g., Ag, Cd, Cr, etc.), with the greatest number of analyses having been conducted for zinc (Zn). All available analyses show that water quality for trace elements is consistently below the Nevada drinking water standard.

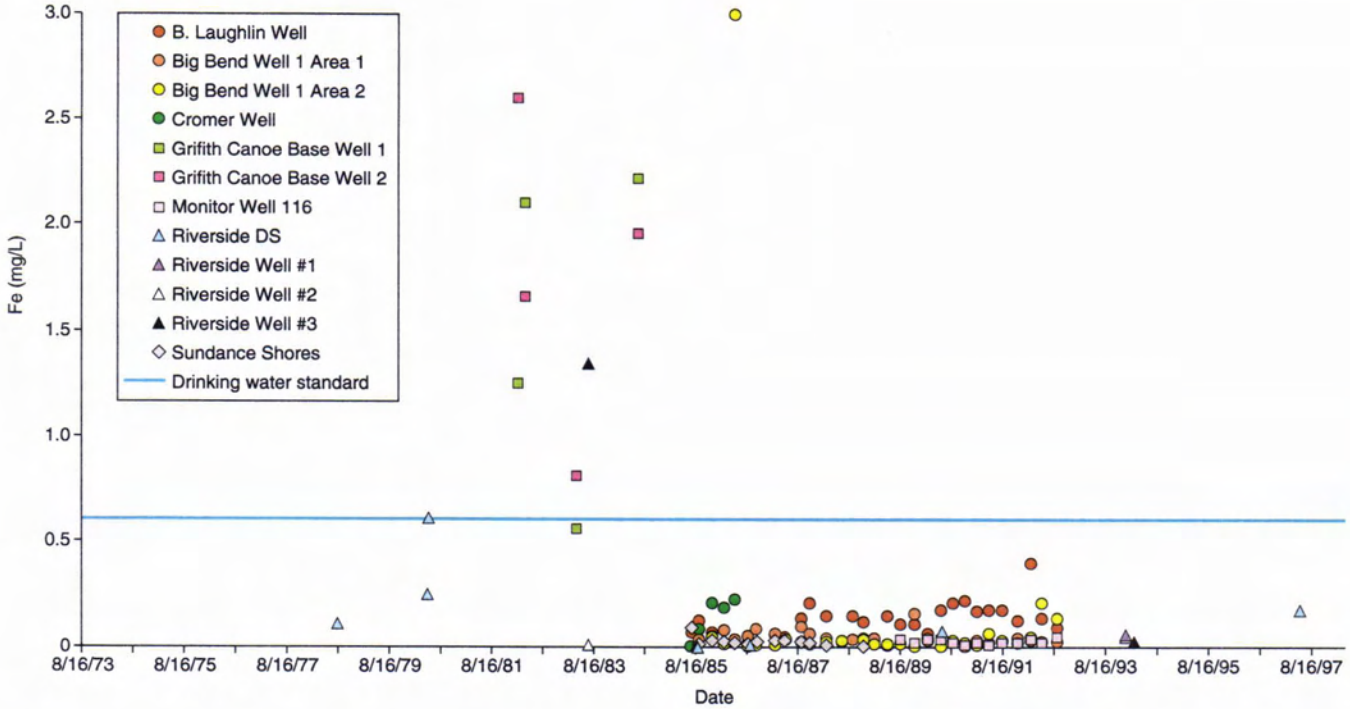

Figure 10. Iron (Fe) versus time in 12 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

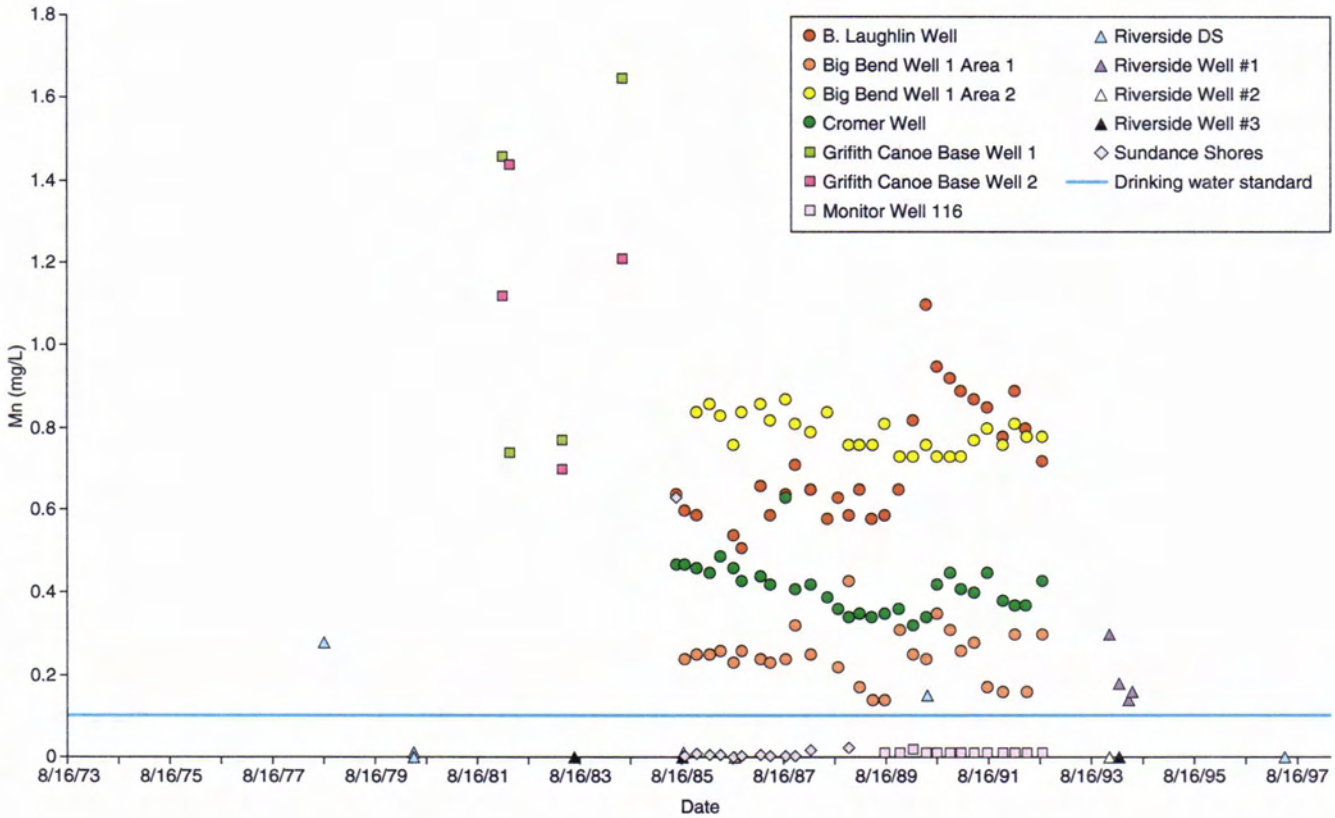

Figure 11. Manganese (Mn) versus time in 12 wells sampled in the Laughlin area for which multiple analyses are available to evaluate temporal variations.

Table 6. Summary of surface water sampling locations in the Laughlin area.

Sampling Site Name	No. of Analyses	First Date	Last Date
Unnamed - 350723114371000	1	8/16/1973	
.5 MILE DOWNSTREAM OF DAVIS DAM	88	6/28/1967	7/29/1998
Unnamed - 213 S28 E65 24CBD	1	10/15/1979	
COLORADO RIVER AT LAUGHLIN	8	1/29/1997	7/29/1998
COLORADO R BL LAGOON NORTH OF RIVIERA, ARIZ	33	8/16/1973	11/25/1991
COLORADO R LAGOON NORTH OF RIVIERA, ARIZ	33	8/16/1973	11/25/1991
COLORADO RIVER BELOW DAVIS DAM, NV-AZ	251	7/31/1969	7/21/1992
GRIFFITH CANOE BASE, COLORADO RIVER	1	2/18/1982	
HARRAH'S DEL RIO - BEACH	3	3/14/1990	3/16/1990
LAUGHLIN BAY VILLAGE	12	3/13/1986	3/19/1986
Total	431	6/28/1967	1/29/1997

Table 7. Summary of trace element analyses of Colorado River Water.

Element	Minimum	Maximum	Average	Standard Deviation	Number of Analyses
Ag (μg/L)	1	1	1.00	--	1
As (μg/L)	0	4	2.25	1.71	4
Ba (μg/L)	90	110	100.00	10.00	3
Cd (μg/L)	1	1	1.00	--	1
Cr (μg/L)	10	10	10.00	--	1
Cu (μg/L)	0	10	6.67	5.77	3
Hg-Diss (μg/L)	0.1	5	2.55	3.46	2
Hg-Tot (μg/L)	0.1	0.8	0.45	0.17	19
Mo (μg/L)	4	4	4.00	--	1
Ni (μg/L)	4	4	4.00	--	1
Pb (μg/L)	0.63	7	4.46	1.64	19
Se-Diss (μg/L)	2	2	2.00	--	1
Se-Tot (μg/L)	0.94	3	2.12	0.53	19
V (μg/L)	1	1	1.00	--	1
Zn (μg/L)	0	10	4.35	4.80	21

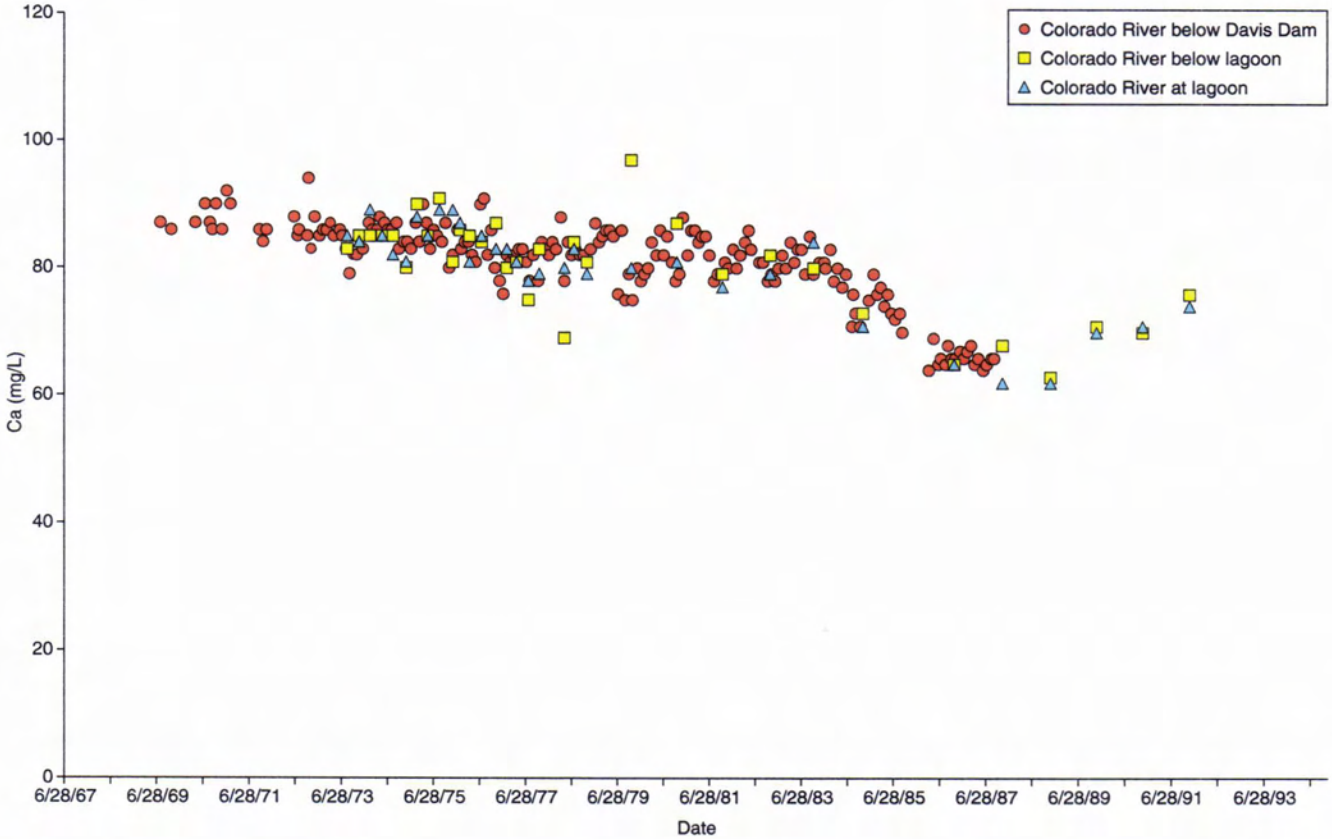

Figure 12. Calcium (Ca) concentrations versus time for Colorado River water samples collected in the Laughlin area.

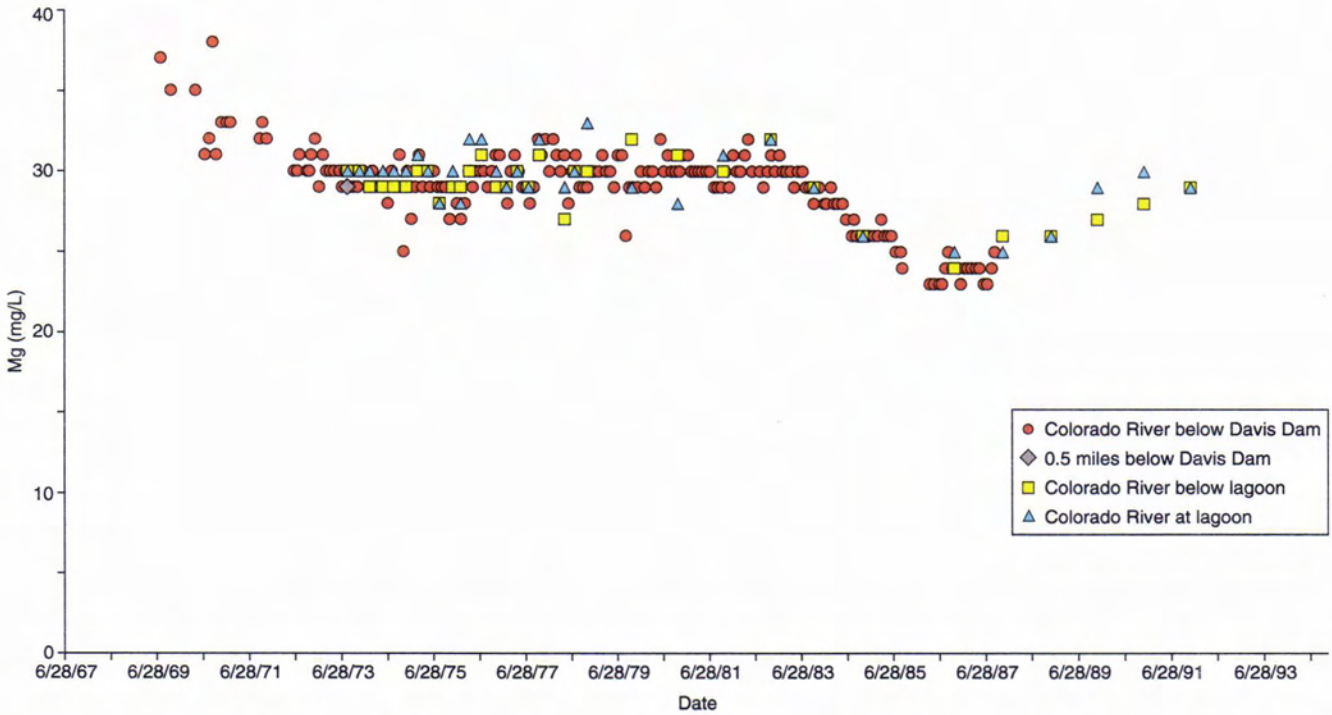

Figure 13. Magnesium (Mg) concentrations versus time for Colorado River water samples collected in the Laughlin area.

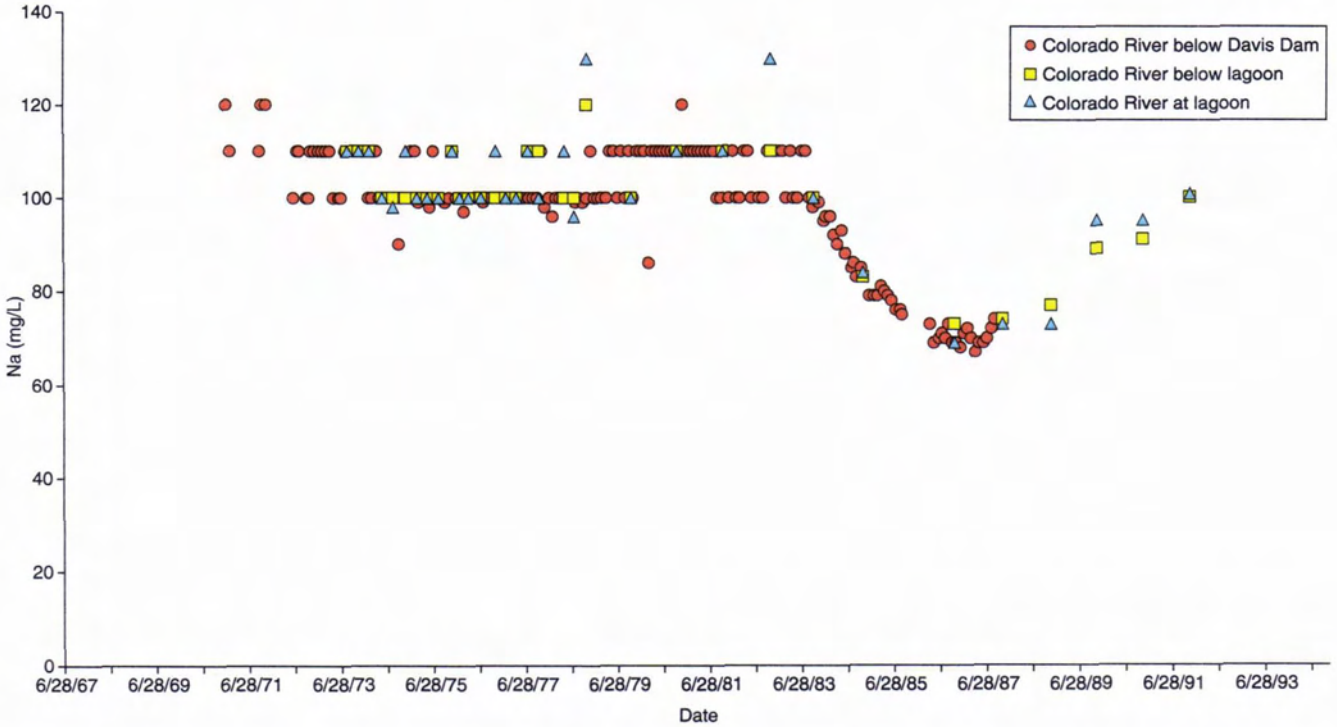

Figure 14. Sodium (Na) concentrations versus time for Colorado River water samples collected in the Laughlin area.

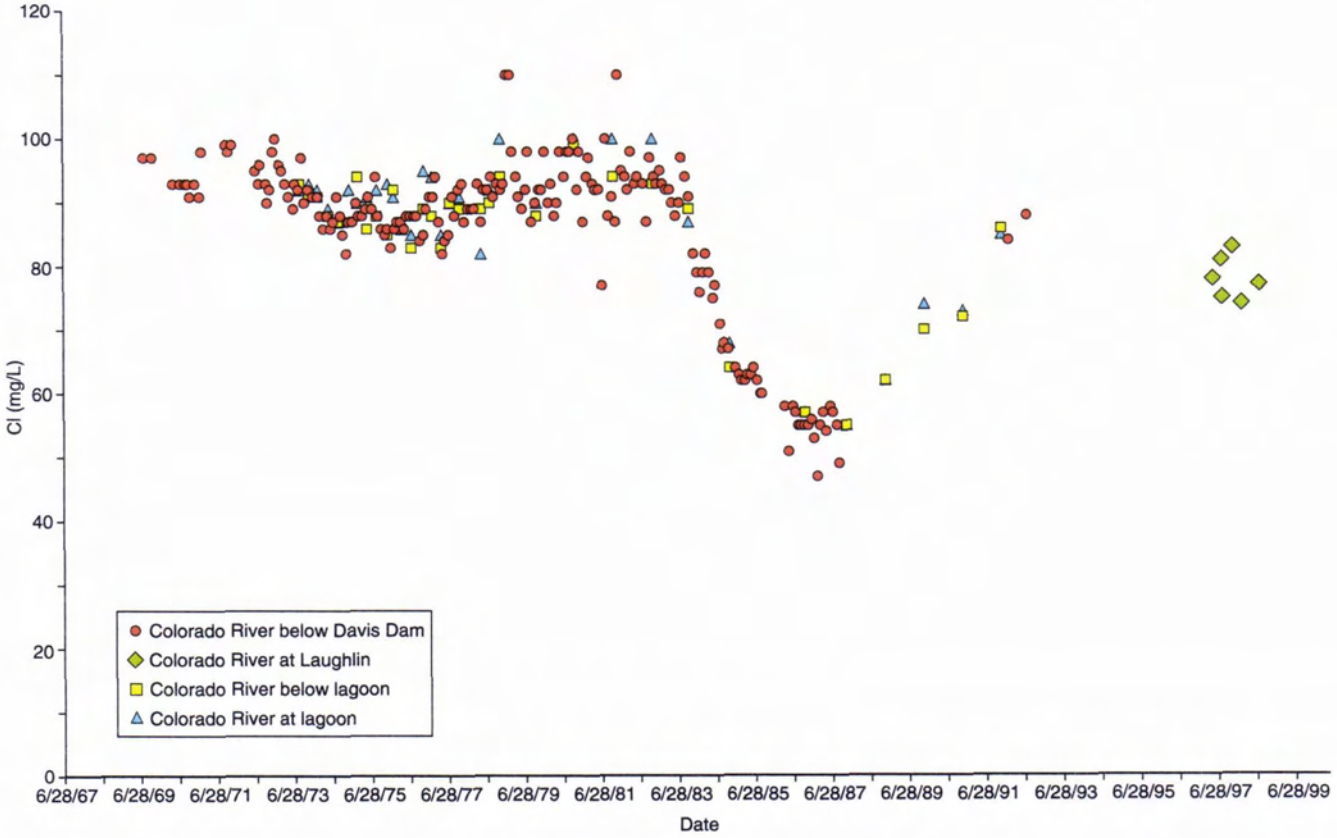

Figure 15. Chloride (Cl) concentrations versus time for Colorado River water samples collected in the Laughlin area.

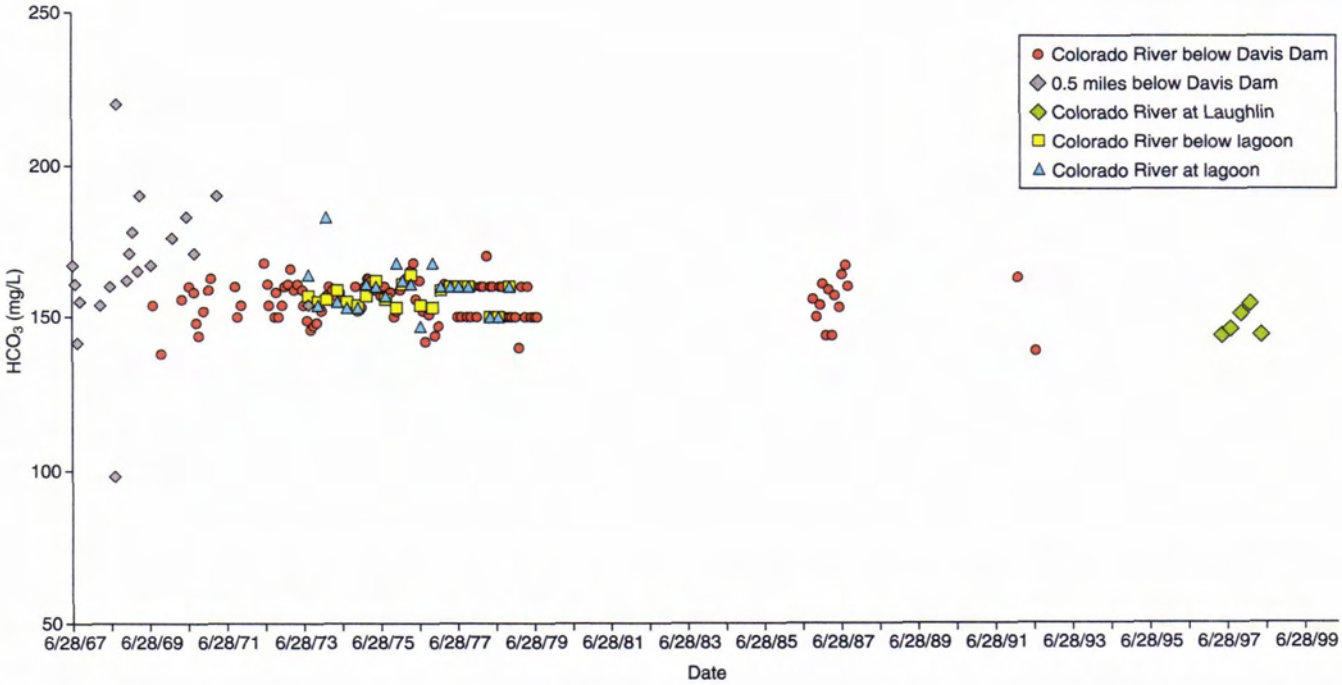

Figure 16. Bicarbonate (HCO_3) concentrations versus time for Colorado River water samples collected in the Laughlin area.

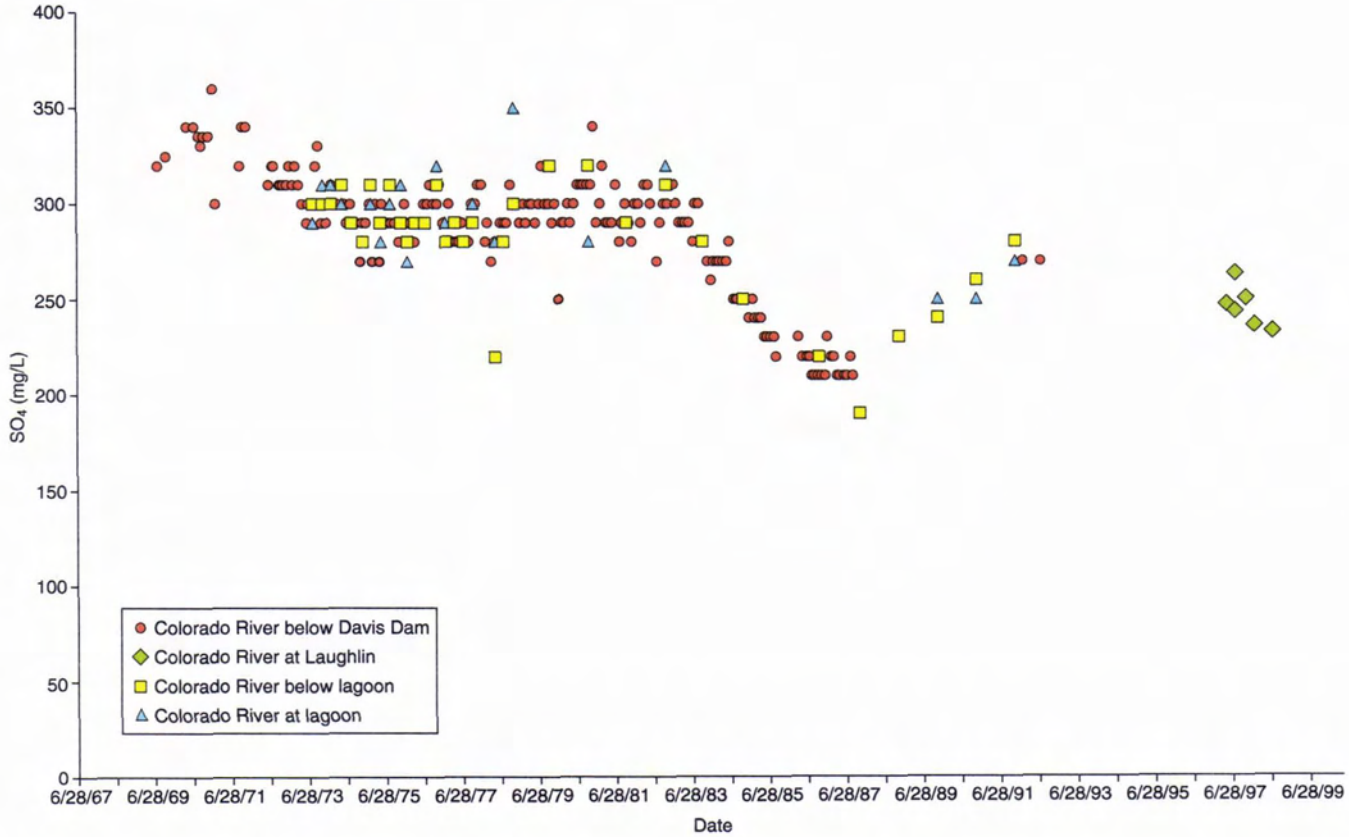

Figure 17. Sulfate (SO_4) concentrations versus time for Colorado River water samples collected in the Laughlin area.

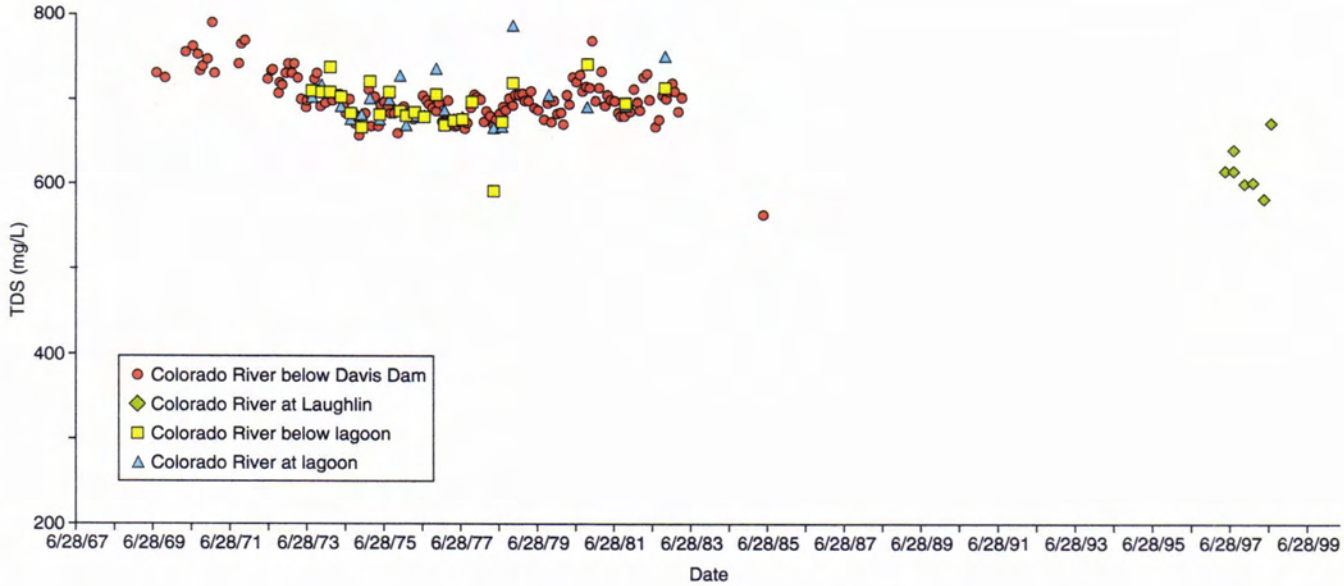

Figure 18. Total dissolved solids (TDS) concentrations versus time for Colorado River water samples collected in the Laughlin area.

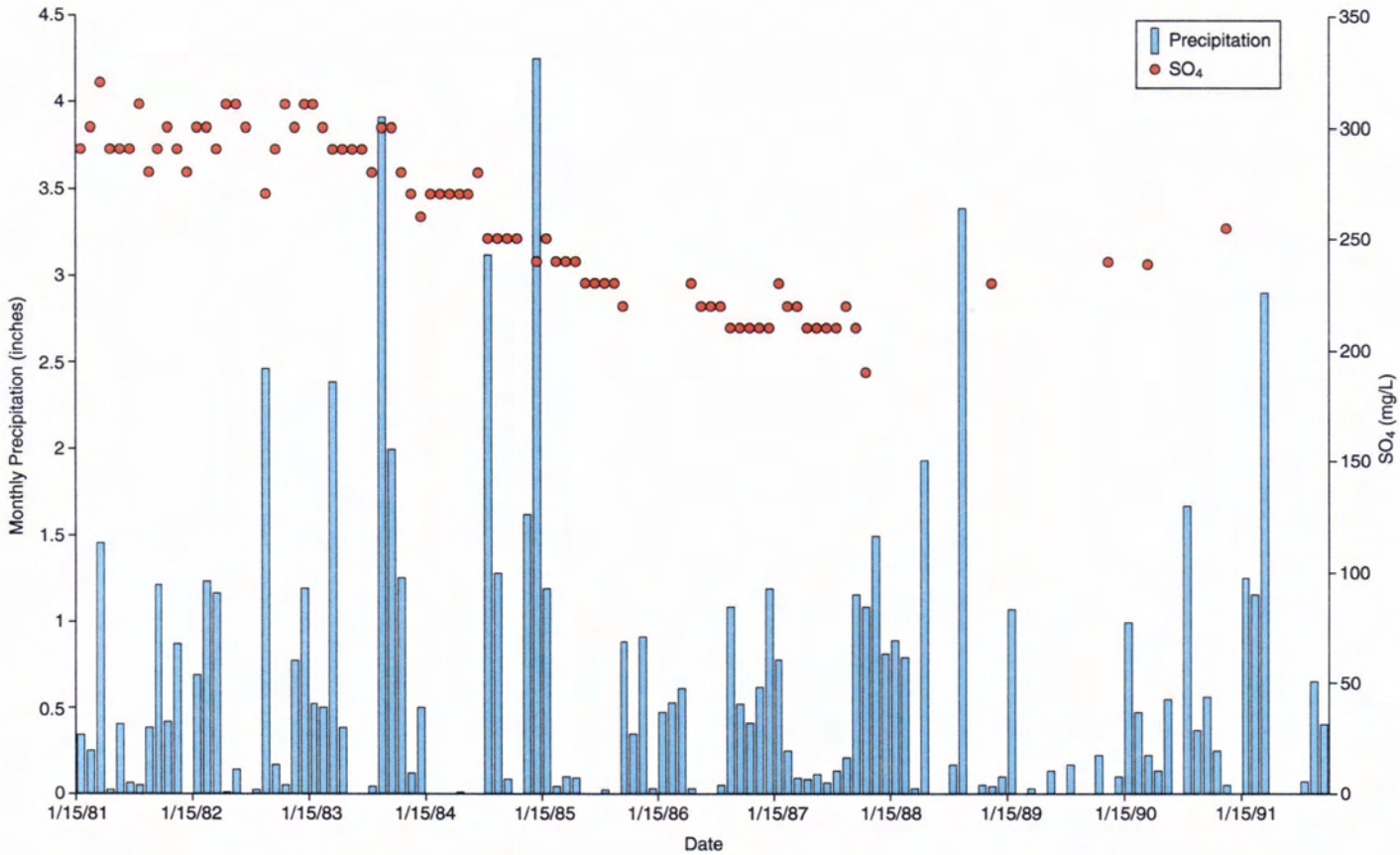

Figure 19. Plot showing variations in SO_4 concentrations and monthly precipitation at the Bullhead City weather station through time. Precipitation data is from the Western Regional Climate Center (2000).

Discussion

Groundwaters

Contamination from Sewage Disposal

Anomalous Cl, SO_4, NO_3, and TDS are reported in Monitor Well 116, which is located directly down hydrologic gradient from the sewage disposal facility (Fig. 2). The groundwater intercepted by this well likely derived contamination from the upgradient sewage disposal/agricultural activities. Other water wells that are located downgradient of the sewage treatment facility, and downgradient from Monitor Well 116 could become contaminated in the future. The wells that may be impacted in the future include the Riverside Wells, Nevada Club Well, any existing or future wells in Area 1 of Big Bend, and perhaps the Sundance Shores Well. Monitoring should continue at these locations in the future in order to allow for the detection of any possible contaminants that may originate from the sewage disposal facility.

Figure 3 shows the location of Monitor Well 116, which is down hydrologic gradient from a small area of agricultural activity associated with sewage disposal. The elevated NO_3 and Cl likely result from treated sewage contaminants entering shallow groundwaters beneath the irrigated areas and flowing laterally away from the site toward Monitor Well 116. Note that Na is also elevated in Monitor Well 116 indicating that the source of the Na and Cl could be from dissolution of natural salts (e.g., halite, or sodium chloride (NaCl)). However, no such natural halite deposits were identified during geologic mapping (see Chapters 1 and 2 of this report). In addition, elevated Na and Cl as a result of sewage effluent contamination is not uncommon, and has been clearly documented by Vengosh and Keren (1996), for example, in another arid area near Tel Aviv, Israel. Hence, the elevated Na and Cl in the groundwaters likely have a source from the upgradient sewage disposal, perhaps with the original source being the discharge to the sewer system from water softeners and cleaning products.

Contamination from Mining

No impact on surface water or groundwater chemistry was detected that could be attributed to mining practices in the Laughlin area. Most mining disturbances are for industrial mineral purposes (e.g., quarries, gravel pits) that typically have low potential to result in adverse environmental impacts. The elevated metals concentrations in rocks in the Newberry Mining District currently pose little threat to water quality because these metals are not typically mobile in neutral to basic waters as occur in the Laughlin area. However, there is potential for poorer water quality associated with the mineralized zones in the Newberry Mining District north of Laughlin due to the slightly elevated metals concentrations in rock samples and the presence of potentially acid producing sulfides. However, no water quality data were available in this study to evaluate groundwater interaction with mineralized rock in the mining district or to determine if groundwaters in contact with these rocks become acidic. Similarly, no water quality data were available near the landfill from which to evaluate possible contamination.

One other area related to mining may also impact local water resources, although the site is outside the Laughlin study area in Arizona. The Katherine Mine site has some historical mine tailings and dumps that are located within Katherine Wash that drains into Lake Mohave (Fig. 2). During a flood, elevated flow rates through this wash could result in materials from the dumps

being flushed into Lake Mohave, potentially adding contaminants to the lake, and perhaps, to downstream portions of the Colorado River.

Potential Contamination due to Flooding

Some of the wells are located within areas subject to flooding, as is the sewage treatment facility (see Chapter 2 by P.K. House, this volume). Wells within the potential flood-prone areas are Monitor Well 116, Riverside Wells 2 and 3, and the Big Bend area wells. Although the potential hazards to groundwater quality due to flooding in this area are relatively minor, flooding of the sewage treatment facility could impact the groundwater quality. This could occur if any of the wells in the flood-prone areas were completed improperly or have become damaged in such a way to allow vertical flow of water down the well bore or well annulus as floodwaters pass over or by the wells.

Surface Waters

Decreases in Concentrations from November 1982-1987

As noted in a previous section, the concentrations of several elements and compounds were noted to decrease (Figs. 12-18) in samples collected from the Colorado River between November 1983 and November 1987. Several plots were constructed in an attempt to ascertain possible reasons for the improvement in water quality over this time period. Relationships with SO_4 changes are investigated because the SO_4 data are representative of the variations observed in other constituents, and the greatest number of analyses (267 analyses) is available for SO_4 relative to the other constituents (although there are also 267 analyses of Cl). Factors that might influence changes in concentrations in the river are variations in flow or dilution. Therefore, SO_4 variations are compared with changes in precipitation (Fig. 19; data from Western Regional Climate Center, 2000), water level in Lake Mojave (Fig. 20; data from U.S. Bureau of Reclamation, 2000), and flow rate measured below Davis Dam (Fig. 21; data from USGS, 1999). Collection of weather data at the Laughlin station did not commence until 1988, and hence, the more complete dataset from the Bullhead City station is used in plotting data in Figure 19. As noted previously, the same general trends in precipitation are observed at Bullhead City and Laughlin, although the precipitation totals at Laughlin are lower. The increments over which data are plotted on Figures 19-21 vary because of data availability. Figure 21 has flow rate data on a daily basis, whereas water level and precipitation data on the other two plots are reported on a monthly basis.

Decreases in SO_4 (and other constituents) in Colorado River water samples began in November 1983. No apparent cause-effect relationship between this decrease and precipitation is evident (Fig. 19). Precipitation was above normal (189 ± 25.5 mm, or 7.71 ± 3.76 inches) on an annual basis at the Searchlight weather station in 1982, 1983 and 1984 (368 mm (14.5 inches), 376 mm (14.8 inches), and 300 mm (11.8 inches) annual precipitation, respectively). The same is the case for the Bullhead City station where annual precipitation was higher than average in these three years (200 mm (7.89 inches), 294 mm (11.59 inches), and 261 mm (10.26 inches), respectively). Total annual precipitation values in 1985, 1986 and 1987 were at or slightly below average annual values at both the Searchlight and Bullhead City weather

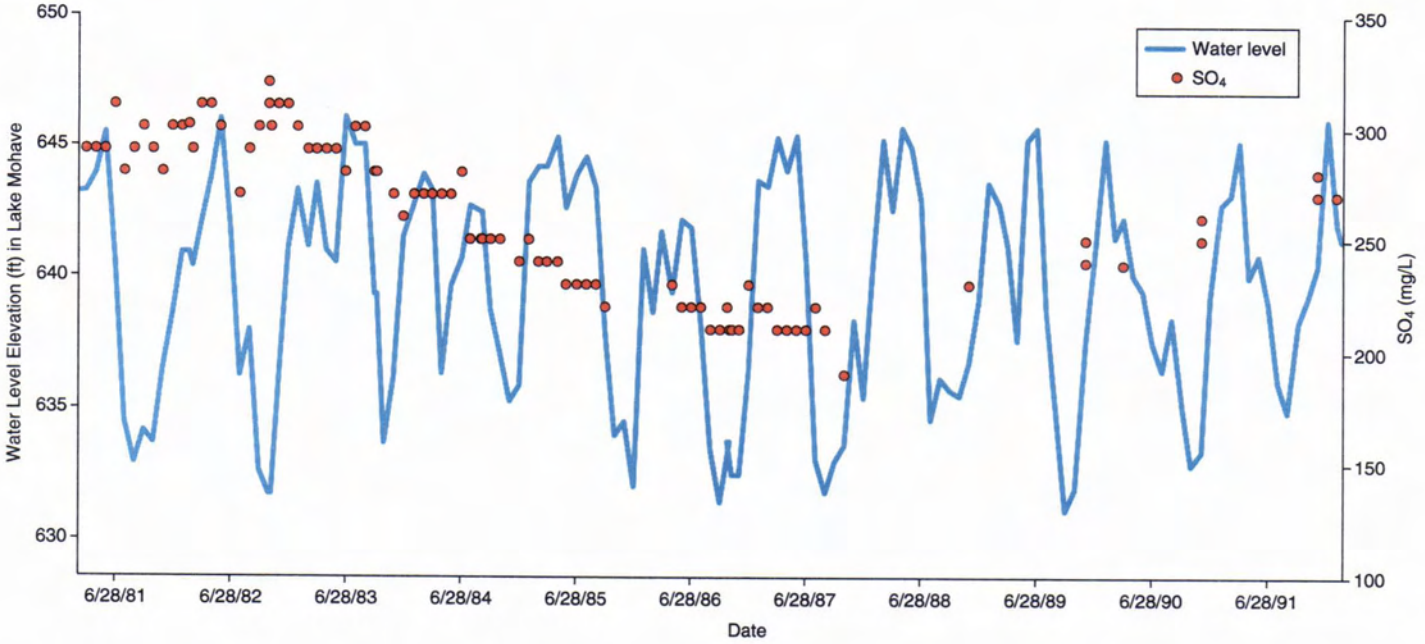

Figure 20. Plot showing variations in SO_4 concentrations and monthly water level measurements in Lake Mohave as a function of time. Water level measurements in Lake Mohave are from the U.S. Bureau of Reclamation (2000).

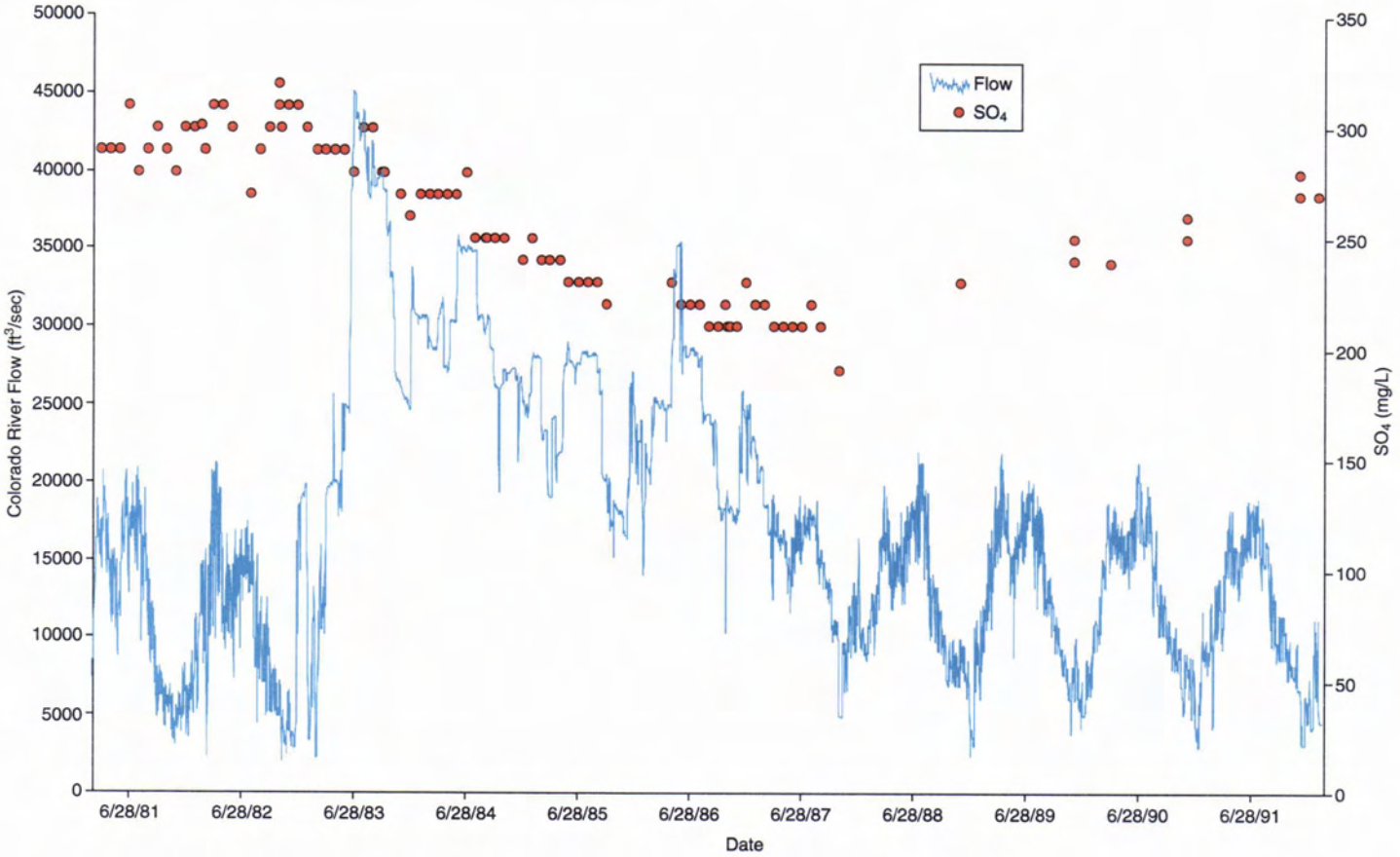

Figure 21. Plot showing variations in SO_4 concentrations and daily flow rate in the Colorado River below Davis Dam as a function of time. Flow rate data are from the U.S. Geological Survey (1999).

stations. Hence, the variations in SO_4 concentrations cannot be attributed to any consistent annual pattern of precipitation over these years. Similarly, water level variations in Lake Mojave fluctuate as a function of inflow rates and reservoir management practices, and these fluctuations do not correlate with variations in SO_4 (Fig. 20).

Although the above average annual precipitation in 1982 does not correspond with greater flow in the river in 1982, the above normal precipitation in 1983 is correlated with increases in flow in 1983 (Figs. 19, 21). Flow rates peaked at approximately two times the average, maximum yearly flow in July 1983 as a result of a spring-summer flood in the area (Fig. 21). Following this peak, the flow rates show a general decline corresponding to SO_4 concentration decreases (and SO_4/Cl ratio increases) following August 1983. A nearly identical flow rate pattern occurred below Hoover Dam over the same time period as is depicted in Figure 21. Following 11/16/87, SO_4 concentrations begin to increase in the Colorado River water, approaching levels measured prior to November 1983. Sulfate concentrations decrease almost immediately after the peak flow in the river, yet continue to decrease for almost four years as flow rates in the river decrease and return to the normal fluctuation observed prior to the 1983 high flow period. Before November 1983, and after November 1987, the pattern of releases from Davis and Hoover Dams are cyclic and very similar, and SO_4 (and other constituents) concentrations are similar over these two time periods, suggesting that more erratic release patterns may influence water quality downgradient of the dam. Alternatively, a significant flood event, as occurred in 1983, could serve to improve water quality over extended periods of time (11/83 to 11/87), although this scenario is improbable.

Interaction of Groundwaters and Surface Waters

No stable isotope data are available from the wells discussed here from which to evaluate the percentage of river water that enters the shallow groundwater system. However, abundant Cl and SO_4 data are available, and based on previous work (Robertson, 1991), ratios of these two constituents can be used to evaluate contributions of river water to the groundwater system. Based on data collected from 1941 to 1965, Robertson (1991) reported a SO_4/Cl ratio of ≈ 3 for the Colorado River, and <1 for groundwaters derived from recharge on the flanks of the basin. Data from the current evaluation of water data near Laughlin suggest slightly different values for the SO_4/Cl ratio of Colorado River water (Table 8). Two Colorado River sampling sites are not included in this table because they had no reported analyses for SO_4 (0.5 mile downstream of Davis Dam, and Laughlin Bay Village sampling sites). The average value of SO_4/Cl at the eight Colorado River sampling locations on Table 8 for which there are data is 3.36 ± 0.29, similar to, although slightly higher than, the value used by Robertson (1991).

Based solely on the SO_4/Cl ratios, eight wells appear to be dominated by Colorado River water as their SO_4/Cl ratios are similar to, or slightly lower than, the average for the river (B. Laughlin (Knight) Well, Big Bend Well 1 Area 1, Big Bend Well 1 Area 2, Big Bend Well 2 Area 2, Cromer, the undifferentiated Griffith Canoe Base Sample, and Griffith Canoe Base Wells #1 and 2). All eight wells are located south of Laughlin, very close to the Colorado River (Fig. 3). Eight additional wells apparently have little to no influence from the Colorado River as their SO_4/Cl ratios are all near 1 (Laughlin, Monitor Well 116, Riverside kitchen sink, Riverside Wells 1, 2, and 3, Sundance Shores, and Unnamed Well #2). Anomalous SO_4/Cl ratios

Table 8. Comparison of SO_4 to Cl ratios in the Colorado River and groundwaters near Laughlin.

Site/Well Name	No. of Analyses	Probable Source*	SO_4/Cl ratio	Std. Dev.	Probable Depth (ft)	Distance to River
Colorado River Sites						
Unnamed - 350723114371000	1		3.26	--	--	--
Unnamed - 213 S28 E65 24CBD	1		3.33	--	--	--
At Laughlin	7		3.21	0.19	--	--
Below Lagoon N. of Riviera, AZ	33		3.34	0.26	--	--
Lagoon N of Riviera, AZ	33		3.30	0.23	--	--
Below Davis Dam, NV-AZ	190		3.38	0.30	--	--
Griffith Canoe Base	1		3.34	--	--	--
Harrah's del Rio - Beach	1		3.37	--	--	--
Average	266		3.36	0.29		
Groundwater Wells						
213 S28 E65 24CBC2	1	M	2.21	--	126-150	70
213 S33 E66 17AAB 1	1	GW	0.42	--	?	1700
B. Laughlin (Knight) Well	47	CO R	3.30	0.44	32-50	**381**
Big Bend Well 1 Area 1	29	CO R	2.93	0.55	65-145	20
Big Bend Well 1 Area 2	28	CO R	3.40	0.33	32-111	250
Big Bend Well 2 Area 2	2	CO R	3.18	0.00	32-111	250
Cromer	49	CO R	3.17	0.62	32-96	**141**
Griffith Canoe Base	1	CO R	3.10	--	104-106	224
Griffith Canoe Base Well 1	3	CO R	2.99	0.18	104-106	224
Griffith Canoe Base Well 2	3	CO R	2.92	0.25	104-106	224
Laughlin	2	GW	0.50	0.04	150-165	1787
Monitor Well 116	13	GW	0.86	0.11	65-300	1389
Nevada Club Well	22	M	2.27	0.24	64-109	60
Riverside Distribution System	31	M	2.04	0.59	--	**100**
Riverside Kitchen Sink	1	GW	1.07	--	--	**100**
Riverside Well #1	1	GW	1.12	--	400	**108**
Riverside Well #2	2	GW	0.82	0.06	480	40
Riverside Well #3	3	GW	1.19	0.52	489-498	40
Riverside Trailer Park	2	M	1.59	0.37	?	?
Sundance Shores	38	GW	1.03	0.07	306-480	582
Unnamed #1	2	M	2.06	0.00	?	456
Unnamed #2	2	GW	1.03	0.04	?	60
Total:	283		1.96	1.03		

* Likely sources of the well waters are designated as follows: CO R indicates the well sample is dominated by Colorado River water; GW indicates the source is recharge to groundwaters at the basin margins; M indicates a mixture of groundwater and Colorado River water.
Distances highlighted in bold are questionable. See text and Figure 22.
-The Riverside "Distribution System" samples are a composite of multiple wells.

(0.5) are observed in the Laughlin Well, which is located farther from the river than any of the other wells investigated here. The Laughlin Well, with the lowest measured SO_4/Cl ratio of 0.5,

is the least influenced by Colorado River water and apparently has not experienced any mixing with river water or overbank flood waters. One other well (unnamed 213 S28 E65 24CBC2) is located near the Laughlin Well, but its SO_4/Cl ratio is indicative of mixed water. The Laughlin Well's depth is either 45.7 or 50.4 m (150 or 165 ft), whereas the other well is 38.4 or 45.7 m (126 or 150 ft; Table 4), both being deeper than the wells with SO_4/Cl ratios near 3.

Of the remaining wells for which there are data, all five have SO_4/Cl ratios between those observed in pure groundwater (≈1) and pure river water (≈3.36) suggesting these wells tap groundwaters that are variable mixtures of Colorado River water and groundwaters recharged on the basin margins (213 S28 E65 24CBC2, Nevada Club Well, Riverside Distribution System, Riverside Trailer Park Well, and Unnamed Well #1).

Table 8 also lists approximate distances of the wells from the center of the Colorado River. The distances were computed in ArcView using the difference between UTM coordinates of the wells reported in the geochemical databases and the center line of the river as included in the 1:24,000 DLG, 1990 data file. Based on the results of this calculation, it is clear that the coordinates of at least some of the wells are not known sufficiently well to correlate with the 1:24,000 scale data (bold entries in Table 8). Due to differences in scale of the different maps and data used, the 1:24,000 centerline of the river does not exactly match the actual centerline as mapped with the 1994 digital orthophotoquad data that is at a scale of 1:6000. Overlaying the datasets (Fig. 22) shows the difficulties inherent in plotting datasets that were compiled at different scales. Given the obvious difficulties in noting the accuracies of well locations and the river center line, the computed distances in Table 8 are only approximate, and only useful in identifying general trends and relative distances.

The Riverside Wells are the closest to the Colorado River based on the computations (Table 8) and visual inspection of the map (Fig. 22), yet these wells are dominated by groundwater. The depths of these wells are, however, significantly greater than that in the other wells investigated. Interestingly, the Riverside Distribution System samples have average SO_4/Cl ratios greater than the ratio measured in any of the Riverside Wells that feed into the distribution system for which data were available in this study. The distribution system average ratio is similar to other mixed waters, suggesting another source of water either from another well or directly from the Colorado River that is included in the distribution system in the earlier years of sample reporting. The SO_4/Cl ratio of the distribution system varies markedly through time from a low of 0.86 on 8/27/95, indicative of groundwater values, to a high of 2.92 on 10/18/79, suggesting that sample may contain an appreciable component of Colorado River water (Fig. 23). All higher ratios near or >2 occur prior to 8/15/78 (before Riverside Wells #2 and 3 were drilled in 11/79 and 2/83, respectively), and all samples collected after 5/15/80 have ratios near 1.0 as do all three Riverside Wells that feed into the distribution system. The source of this high SO_4/Cl ratio water is unknown and is not represented by the Riverside well data presented here. Perhaps during the 1970s some water was withdrawn directly from the Colorado River for use in the Riverside distribution system. Individuals at Clark County Health District and the Riverside Casino were contacted in an attempt to verify or refute the use of Colorado River water in the Riverside distribution system in the 1970s. This practice could not be confirmed.

It is likely that some of the differences among wells are a function of their depths, with deeper wells having smaller (or no) contributions from the Colorado River. Unfortunately, depth control on the wells is poor (Table 4), and only general observations can be made based on the

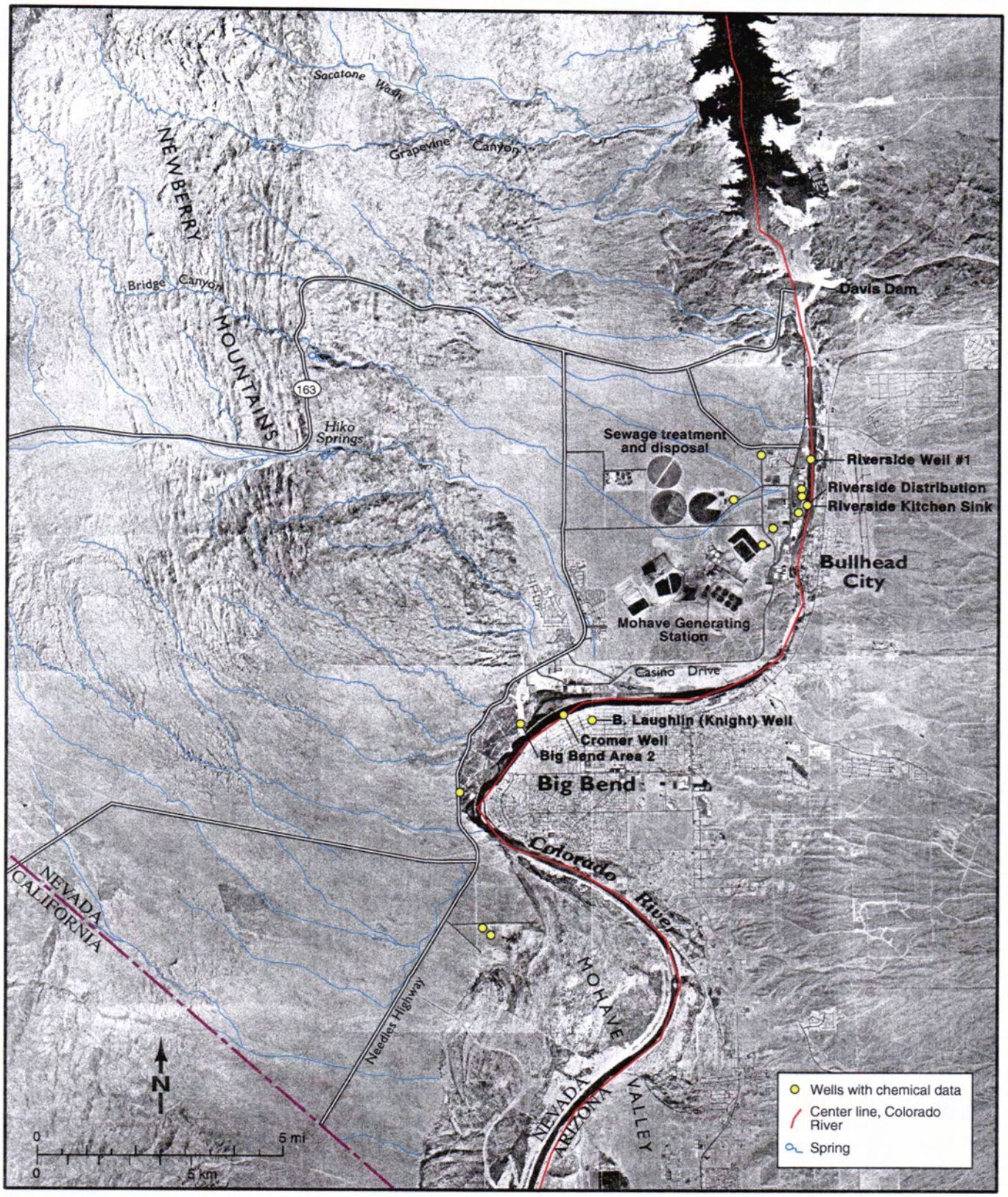

Figure 22. Map showing the locations of wells discussed in this report, the 1;6000 scale orthophotoquad data, and the 1:24,000 Digital Line Graph (DLG) data for the Laughlin area. This figure shows the inherent difficulties of using data compiled at different scales. Some well locations are clearly not know to the 1:6000 scale, as they plot in the middle of the Colorado River (Cromer, Riverside Distribution System, Kitchen Sink, and Well #1), or to the east of the river (B. Laughlin (Knight) Well). See text for additional discussion.

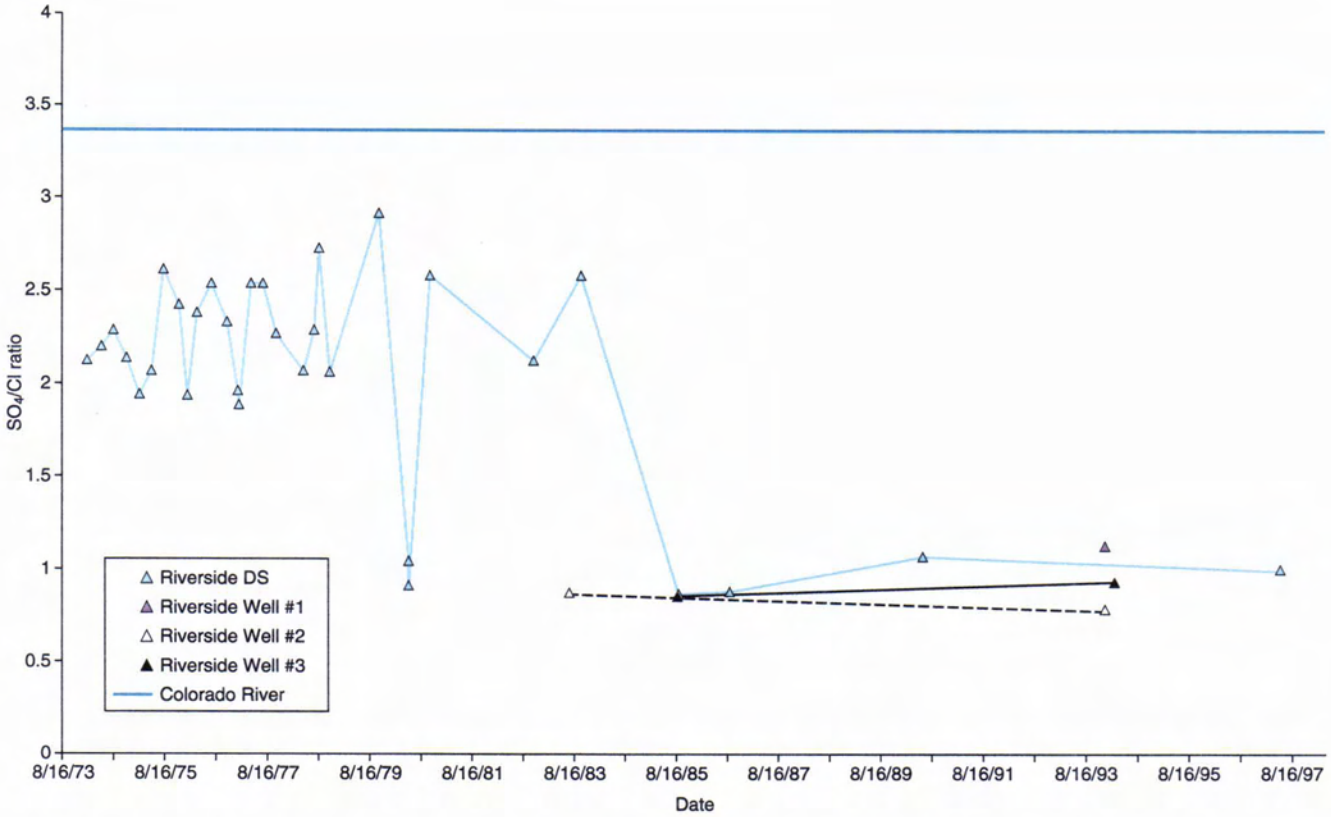

Figure 23. Plot showing temporal variations in the SO_4/Cl ratios in the Riverside distribution system samples. Average SO_4/Cl value for the Colorado River is shown on the plot, as are data from Riverside wells #1, 2, and 3.

depth interval over which the particular well is completed. For instance, it is unknown if the B. Laughlin (Knight) Well has a total depth of 9.8 or 15 m (32 or 50 feet), but in either case, the well can be considered "shallow." Its SO_4/Cl ratio of ≈3.3 and its close proximity to the river both suggest a strong influence of Colorado River water, and minimal contribution from groundwaters recharged on the basin margins. Similarly, the following "shallow" wells with depths likely to be less than or near 30 m (≈100 ft) have a large component of Colorado River water (i.e., SO_4/Cl ratios near 3): Big Bend Well 1 Area 1, Big Bend Well 1 Area 2, Big Bend Well 2 Area 2, Cromer, Griffith Canoe Base Wells. Most of the wells that are likely to be deeper have SO_4/Cl ratios indicative of groundwater recharge from the basin margins or mixtures of this water with Colorado River water (e.g., Riverside Wells, and Sundance Shores Well all exceed 300 foot depths).

In summary, all of the deeper (>45.7 m, or >150 ft) wells have no contribution from the Colorado River, whereas the shallower wells located within ≈150 m (500 feet) of the river have contributions from Colorado River water. However, without more detailed studies that would include temporal well and river water level measurements and dating of groundwaters, it is unknown if the mixed well waters have mixed with current Colorado River water. The wells with the river water SO_4/Cl signatures may have originated from mixing that occurred in the past, possibly following over-bank flooding of the river prior to construction of Hoover and Davis Dams. Using stable isotopes, Robertson (1991) identified three wells in Mohave Valley that were recharged, at least in part, from seepage from the river. They identified an additional well water that they believe was recharged by overbank flow prior to dam construction. Detailed groundwater dating, isotope studies, and water level measurements would be required to more clearly describe any mixing between groundwaters and past, or possibly current, Colorado River water.

Role of Detachment Fault

Several wells are located near, and down hydrologic gradient of the detachment fault mapped and described in detail by Faulds (Chapter 1, this report). These include the B. Laughlin (Knight) Well, Big Bend Area 2 Wells, Cromer Well, and the Griffith Canoe Base Wells (Fig. 3). The chemistry of some of these wells is somewhat anomalous. For instance, the Griffith Canoe base wells exhibit spurious data indicating elevated SO_4 and TDS concentrations on three of the four dates for which data are available. Although no sulfate or sulfur-bearing minerals were identified from the breccias in the fault, Faulds (2000) identified the presence of very fine-grained cubic minerals in thin sections of the breccias. It is likely that these grains were originally pyrite and that all of the grains that were observed have been totally replaced with titanomagnetite and hematite. Hence, it is possible that sulfur-bearing minerals were originally associated with the detachment fault and these minerals may still be present at some depth along the fault. If this is the case, the elevated SO_4 in the Griffith Canoe base wells could result from dissolution of sulfur-bearing minerals by groundwaters flowing in the vicinity of the detachment fault.

Although many of the wells throughout the Laughlin area had elevated Mn concentrations, all wells located directly downgradient of the detachment fault had Mn concentrations significantly in excess of the Nevada Drinking water standard (≥4 times the standard). Wells located at some distance away from the fault generally had Mn below the standard, or only

slightly above the standard as in the case of the Big Bend Area 1 Wells. The Griffith Canoe Base Wells also had elevated Fe concentrations, yet none of the others near the fault did except for a spurious (likely erroneous) value noted in Big Bend Well 1 Area 2 (now abandoned). Based on these data, there is currently limited evidence that the minerals in the detachment fault are impacting groundwater quality downgradient of the fault. However, all wells located near the fault that have water quality data are relatively shallow (<33.8 m, or <111 ft) and do not penetrate the fault. Furthermore, all of these wells are dominated by Colorado River water (Table 8) based on SO4/Cl ratios. Other wells reported by the state engineers office have been drilled into the fault, but water quality data could not be obtained for these wells (wells OW-1, PW-1, OW-2, PW-2 owned by Clark County Sanitation District, and an unnamed well owned by Southern Nevada Water Corp.). The fault may serve to provide a preferential flow path in some locations, or a barrier to flow in others, and hence, it may impact the groundwater flow characteristics, if not the chemical quality, in the area. However, additional studies would be required to ascertain the influence of the fault on groundwater flow directions, velocities, and quality.

Conclusions

The current and past quality of water in most wells for which data are available has been good and within Nevada drinking water standards. The most notable exception is in Monitor Well 116, which contains elevated Cl and NO_3, likely derived from contamination from the upgradient sewage disposal/agricultural facilities.

Current and past mining activity in the area is expected to pose minimal risks to the surface water and groundwater resources near Laughlin. There has been limited mining, and these activities are largely restricted to quarries and borrow pits.

Some wells appear to be dominated by Colorado River water, whereas others are mixtures of river water and groundwaters recharged on the basin margins. Additional studies are required to determine the degree to which current Colorado River water interacts with groundwaters in the Laughlin area.

Recommendations

In future sampling, complete analyses should always be conducted. In particular, HCO_3 or total alkalinity should always be measured and reported.

Survey locations for wells are needed, particularly for those sampled by the Clark County Health District and Nevada Department of Health: Griffith Canoe Base Wells, Laughlin Well, and Riverside Trailer Park Well. Clearly, some wells are currently mislocated due to erroneous latitude and longitude that situate the wells either in the center of the Colorado river, or to the east of the river (e.g., Cromer, B. Laughlin, Riverside Well #1 and the distribution system). All wells should be surveyed and plunked for total depth to try to reconcile which wells in the field correspond to those in the various data bases used in this work.

Long term monitoring of water levels in wells in conjunction with those currently measured in the Colorado River and Lake Mohave are required to better assess the interaction of surface water and groundwater in the area.

Periodic monitoring and evaluation of channel conditions, river discharges, water-surface elevations in drainage ditches, and reservoir operations would provide information needed to determine the extent that Colorado River water contributes to nearby, shallow groundwaters adjacent to the river. Many of these data are currently collected, and merely require evaluation in a cohesive manner.

Monitoring of wells in the Laughlin area should include analyses of deuterium and oxygen-18 to be used to determine the percent of Colorado River water that may comprise some of the groundwater samples.

The well waters should be dated to determine mean residence times and determine how long it takes for Colorado River water to influence individual wells. This is needed to determine if all water with the Colorado River signature is pre-dam river water.

Wells located both closer to the river than Monitor Well 116 and downgradient of the well should continue to be monitored to determine if sewage effluent contaminants may also impact other utilized water resources. Wells east of the landfill should also be monitored in the future to determine if any contaminants are being released from that facility.

Springs in the area should be monitored for major and trace element chemistry and deuterium and oxygen-18 to help in the overall characterization of the source and recharge to groundwater resources in the area. The following springs should be monitored (Fig. 2): Hiko Springs (elevation = 573 m, or 1880 feet), spring in Sacatone Wash (elevation = 667 m, or 2190 feet), spring in Bridge Canyon (elevation = 695 m, or 2280 feet), and the spring in Grapevine Canyon (elevation = 793 m, or 2600 feet). One other spring should also be monitored. This particular spring is west of Lake Mohave at an elevation of 887 feet, is located on a fault, and is currently labeled as a well on the topographic map.

If the two shafts in the Newberry mining district contain water, they should be sampled to ascertain if either elevated metals or low pH occur in local groundwaters.

The waste rock dumps located in the wash at the Katherine Mine should be sampled to determine their likely potential to contribute to poor water quality. The location of the dump should also be monitored to determine if and the degree to which they may be migrating toward Lake Mohave.

The database produced here should be maintained and updated, and information should be added to it that was not available in this study.

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CHAPTER 4:

OTHER GEOLOGIC HAZARDS

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Abstract

Earthquakes and problems related to soil conditions are lesser, but not trivial, geologic hazards in the Laughlin area. No evidence of recent large-magnitude earthquakes has been found in the immediate Laughlin area, and the surrounding region has had a low level of historical seismicity. Moderate-sized earthquakes (up to magnitude 6) generally do not cause ground offsets large enough to be recognized in the geologic record, so such events probably represent an upper bound for local seismicity. The most significant regional earthquake source is the Needles graben, located about 35 km (22 mi) south of Laughlin. An earthquake on that fault zone would probably cause moderate to serious damage in Laughlin, and could have secondary impacts such as collapsing river banks. Potential soil-related problems include expansive soils, slope failure, and amplification of seismic shaking. The deposits that are most susceptible to such problems are the fine-grained Colorado River deposits. These deposits cover a relatively small percentage of the area, but include much of the urbanized parts of the area.

Table of Contents

Abstract 4.2
Table of Contents 4.3
Introduction 4.4
Earthquake Hazards 4.4
  Historical Seismicity 4.4
  Regional Earthquake Sources 4.5
  Potential for Local Earthquakes 4.6
Soil Conditions 4.6
Bibliography 4.7

Introduction

In addition to floods, two other geologic hazards occur in the Laughlin area: earthquakes and problems related to soil conditions. Neither of these are major problems in the area, but they nonetheless have the potential for causing damage that can be mitigated. On an individual level, these problems can be devastating.

Earthquakes are inevitable, but the damage they cause is not. Damaging earthquakes are rare events, and in areas where they have not occurred during most peoples' memories, they are typically viewed as external problems. Laughlin is not alone in experiencing a low level of historical seismicity; several large-magnitude earthquakes in the Basin and Range province have occurred in areas that previously had low levels of seismicity and were viewed as unlikely sites for such events. Preparing for earthquakes includes building structures strong enough to withstand them, but it also includes simple, inexpensive measures, such as attaching bookcases and water heaters to walls, and removing heavy (or valuable) objects from precarious positions. Such measures have extraordinary benefit-to-cost ratios, but they must be carried out before the earthquake occurs.

At Laughlin, potential soil-related problems are generally confined to areas proximal to the Colorado River. Although this encompasses a fairly restricted area, it includes much of the urbanized part of the area. Recognizing and designing for potential soil-related problems (expansive soils and slope failure in particular) is much cheaper than trying to fix the problem after it arises.

Earthquake Hazards

Earthquake hazards in the Laughlin area are considered to be low, based on published information, geologic mapping, and evaluation of air photos. The most definitive report on earthquake hazards in the region is a U.S. Bureau of Reclamation study of earthquake potential at dam sites along the lower Colorado River, including Davis Dam (Anderson and O'Connell, 1993).

This study included examination of published information on regional earthquake hazards and a search for evidence of fault activity in the mapped area. No evidence of recent large-magnitude earthquakes has been found in the immediate Laughlin area, but much additional work is required to fully address the problem, and the expression "absence of evidence is not evidence of absence" should be kept in mind.

Historical Seismicity

Laughlin is located in a region of low historical seismicity. The nearest notable earthquakes have occurred about 95 km (60 mi) to the north in the Lake Mead area and include events as large as magnitude (M) 5 (Anderson and O'Connell, 1993). These earthquakes began occurring shortly after Lake Mead was filled, and they appear to be reservoir induced (i.e., triggered by stresses caused by the weight of impounded water, and/or by increases in pore pressure). The filling of Lake Mohave did not trigger earthquakes in a similar manner, but that reservoir contains only a small fraction (about 6%) of the capacity of Lake Mead, and therefore imposes much smaller stresses on the earth's crust.

The October 16, 1999 Hector Mine earthquake (M 7.1) occurred near Ludlow, California, about 160 km (100 mi) to the southwest of Laughlin (the event has also been referred to as the Lavic Lake earthquake). That earthquake was distinctly felt in the Laughlin area, particularly in the upper levels of high-rise buildings, and was locally severe enough to knock poorly secured trailers off their foundations (Ralph Patterson, Ranger at Lake Mead Recreation Area, personal communication). However, the shaking was not strong enough to cause significant damage. The intensity of shaking in Laughlin and surrounding regions was somewhat higher than might be expected, given the distance from the earthquake, suggesting that characteristics of the northern Mohave basin may amplify seismic waves. Evaluation of this possibility is a geophysical and seismological problem that is beyond the scope of this project.

The 1999 Hector Mine earthquake was one of several large-magnitude historical earthquakes that have occurred within a zone of seismicity referred to as the eastern California seismic belt. Other major earthquakes within this seismic belt include the 1992 Landers earthquake (M 7.3), the 1872 Owens Valley earthquake (M 7.6), and poorly understood earthquakes in 1908 and 1916 in the Death Valley region (M 6? and 6.1, respectively). The eastern California seismic belt has a high probability of additional earthquakes, and such events would likely cause shaking in the Laughlin area similar to the 1999 earthquake.

Regional Earthquake Sources

Prehistoric earthquakes can commonly be identified from fault scarps (i.e., offsets of the ground surface). With rare exceptions, only earthquakes greater than M 6 produce fault scarps large enough to be recognized in the geologic record, so only the largest events are represented by such features. In the Basin and Range province, historical earthquakes that have produced recognizable fault scarps generally have been greater than M 6.5 (dePolo, 1994). For Laughlin, the nearest such identified features are a relatively short zone of fault scarps, about 7 km (4 mi) long, located 6.5 km (4 mi) east of Needles (about 35 km (22 mi) south of Laughlin). This zone, which is commonly referred to as the Needles graben, offsets alluvial fan deposits that Anderson and O'Connell (1993) described as late Pleistocene or early Holocene in age. An earthquake along this zone would be close enough to Laughlin to cause at least moderate damage.

The Needles graben and a similar feature (the Chemehuevi graben) located just northwest of Lake Havasu City about 65 km (40 mi) south of Laughlin suggest that a modest amount of extension is occurring along the lower Colorado River. If so, the potential for large earthquakes near Laughlin may be somewhat higher than indicated by historical seismicity and lack of local fault scarps. Evaluation of this possibility probably requires high-precision geodetic data collected over several years or decades.

Another significant fault zone with identified fault scarps is located about 80 km (50 mi) north of Laughlin along the northwest side of Eldorado Valley. Anderson and O'Connell (1993) estimated that the most recent large-magnitude earthquake along this zone, which they refer to as the Black Hills fault, occurred during mid- to late Holocene time and involved displacements of 1.7 to 2.7 m (5 to 9 ft). This zone is far enough away from Laughlin that it is unlikely to cause major damage, but it is closer than the 1999 Hector Mine earthquake and would probably cause stronger shaking than that event.

Potential for Local Earthquakes

No evidence of large earthquakes in the recent geologic past was found in the mapped area. Preliminary reconnaissance identified fault offsets in alluvial gravels of unknown age in the south part of Laughlin. Based on conformable relations with younger deposits and minimal induration, these faulted gravels were initially thought to be Quaternary in age. However, geologic relations established through the mapping efforts of this study indicate that they are actually Tertiary in age (probably more than 4 million years old), and therefore these faults are not considered to be active. Other suggestive evidence of Quaternary fault activity, including scarps on older fans in the southern part of Bullhead City, are either erosional or are related to sedimentary features of the Colorado River and do not mark the trace of recently active faults.

Full characterization of earthquake hazards in the Laughlin area awaits additional study of the Needles graben and other regional earthquake sources, geophysical investigations of the subsurface nature of the northern Mohave basin to assess potential for seismic wave amplification, and detailed geodetic measurements to assess the possibility of active extension along the lower Colorado River. Furthermore, faults that ruptured during the 1999 Hector Mine earthquake and some other historical Basin and Range province earthquakes (e.g., 1954 Fairview Peak earthquake) had not previously ruptured during the Holocene, indicating a need to assess late Pleistocene scarps within the region as well.

Soil Conditions

The most important potential hazards related to soil conditions in the Laughlin area are expansive soils, amplification of seismic shaking, and slope failure. These hazards are directly related to soil physical properties, degree of saturation, and slope characteristics.

Expansion (or shrink/swell) of soils is caused by clay particles in the soil, and in some cases, by evaporite deposits (e.g., gypsum or anhydrite). The expansiveness of soils (i.e., the degree and rate of volume change) is principally dependent on the mineralogy of clay particles, relative proportion of clay present, moisture conditions, and stress conditions. Expansive soils occur in many environments, and worldwide they cause a tremendous amount of damage. Geologic mapping provides basic information on the distribution of materials having potential expansive properties. In the Laughlin area, such materials are generally limited to mud and silt deposits of the Colorado River. On Plate 1, these deposits are designated as Qcm. In some locations they can not be easily distinguished at the map scale of 1:24,000, and they are grouped with Qc. Soil expansion within Qcm deposits was observed during mapping efforts, so we recommend that the expansive properties of this unit be studied in detail from an engineering perspective.

Alluvial materials commonly act to amplify shaking during earthquakes, and the intensity of shaking during the 1999 Hector Mine earthquake indicates this likely occurs in the Laughlin area. Thorough evaluation of this phenomenon is a geophysical and seismological problem that is beyond the scope of this study, but in general, such behavior is related to material properties, and the relative degree to which it occurs can be inferred from the distribution of map units. The map units likely to experience the greatest degree of shaking amplification are Colorado River deposits (Qc, Qcm and Qcy). Other alluvial materials are likely to amplify shaking to a lesser degree. Bedrock areas should experience the least shaking, although rock fall caused by ground shaking is a potential hazard near steep bedrock hillslopes.

Slope failure includes a variety of events distinguished by materials and type of movement

(e.g., rock fall, landslide, mudflow, etc.). Geologic mapping depicts the distribution of materials most susceptible to slope failure, and combined with slope maps can provide a relative representation of the areas where this is most likely to occur. The deposits in the Laughlin area most prone to slope failure are again Colorado River sediments (Qcm, Qcs, or Qc), due to these materials' fine-grained and nonindurated (soft) nature. Slope failure can also occur in alluvial fan deposits in the Laughlin area, but is unlikely except where slopes are steepened by erosion or excavation. Rock fall is a potential hazard near steep bedrock hillslopes. Detailed analyses of slope failure problems are generally site-specific, geotechnical issues.

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