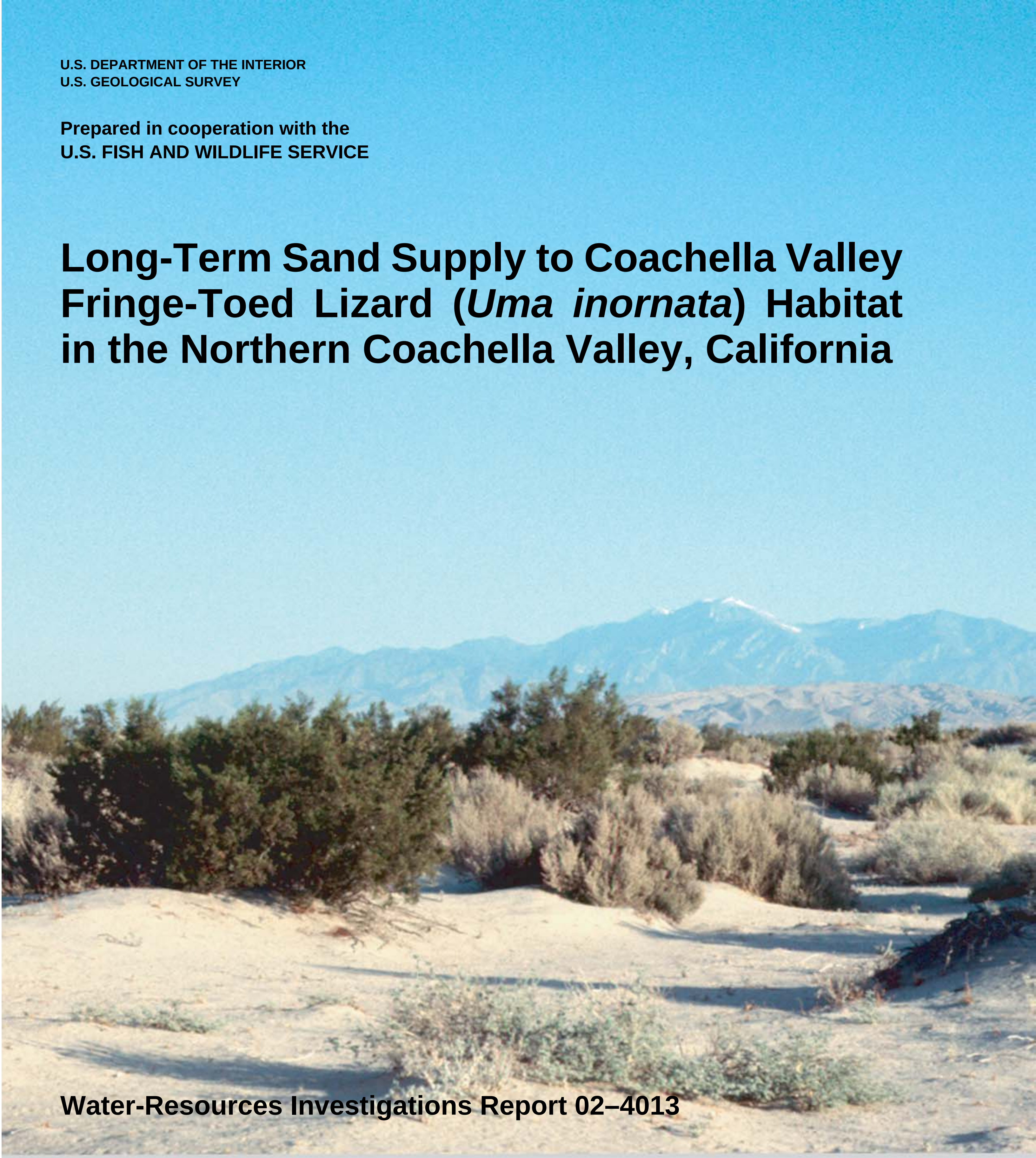
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
U.S. FISH AND WILDLIFE SERVICE

Long-Term Sand Supply to Coachella Valley Fringe-Toed Lizard (*Uma inornata*) Habitat in the Northern Coachella Valley, California



Water-Resources Investigations Report 02–4013

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COVER PHOTOGRAPH

June 21, 1978. View of Mount San Gorgonio from the Bermuda Dunes, Coachella Valley (photograph by Phil Medica, used with permission).

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Tucson, Arizona
2002

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND DATUMS

CONVERSION FACTORS

Multiply	By	To obtain
inch (in)	25.41	millimeter
foot (ft)	0.3048	meter
yard (yd)	0.9144	meter
mile (mi)	1.609	kilometer
miles per hour (mi/hr)	1.609	kilometer per hour
knots	1.852	kilometer per hour
acre	0.4047	hectare
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
pound, avoirdupois (lb)	0.4536	kilogram
ton, short (2,000 lb)	0.9072	megagram
ton per year (ton/yr)	0.9072	megagram per year
ton per year (ton/yr)	0.9072	metric ton per year
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

VERTICAL DATUM

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

HORIZONTAL DATUM

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83), unless otherwise noted.

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ABSTRACT

The Coachella Valley fringe-toed lizard (*Uma inornata*) is a federally listed threatened species that inhabits active sand dunes in the vicinity of Palm Springs, California. The Whitewater Floodplain and Willow Hole Reserves provide some of the primary remaining habitat for this species. The sediment-delivery system that creates these active sand dunes consists of fluvial depositional areas fed episodically by ephemeral streams. Finer fluvial sediments (typically sand size and finer) are mobilized in a largely unidirectional wind field associated with strong westerly winds through San Gorgonio Pass. The fluvial depositional areas are primarily associated with floodplains of the Whitewater – San Gorgonio Rivers and Mission Creek – Morongo Wash; other small drainages also contribute fluvial sediment to the eolian system. The eolian dunes are transitory as a result of unidirectional sand movement from the depositional areas, which are recharged with fine-grained sediment only during episodic floods that typically occur during El Niño years. Eolian sand moves primarily from west to east through the study area; the period of maximum eolian activity is April through June. Wind speed varies diurnally, with maximum velocities typically occurring during the afternoon.

Development of alluvial fans, alteration of stream channels by channelization, in-stream gravel mining, and construction of infiltration galleries were thought to reduce the amount of fluvial sediment reaching the depositional areas upwind of *Uma* habitat. Also, the presence of roadways, railroads, and housing developments was thought to disrupt or redirect eolian sand movement. Most of the sediment yield to the fluvial system is generated in higher elevation areas with little or no development, and sediment yield is affected primarily by climatic fluctuations and rural land use, particularly livestock grazing and wildfire. Channelization benefits sediment delivery to the depositional plains upwind of the reserves by minimizing in-channel sediment storage on the alluvial fans.

The post-development annual sediment yield to the Whitewater and Mission Creek – Morongo Wash depositional areas are 3.5 and 1.5 million ft^3/yr, respectively, covering each depositional area to a depth of 0.2 to 0.4 in. Given existing sand-transport rates, this material could be depleted by eolian processes in 8 to 16 months, a rate consistent with the presence of persistent sand dunes. However, these depletion times are likely minimum estimates, as some eolian sand is seen to persist in the immediate vicinity of depositional areas for longer time periods. Transport rates may be reduced by the presence of vegetation and other windbreaks.

Because they are perpendicular to prevailing winds, the infiltration galleries on Whitewater River trap fluvial and eolian sediment, reducing sediment availability. Also, the presence of the railroad and Interstate 10 redirect eolian sand movement to the southeast along their corridors,

potentially eliminating the Whitewater depositional area as a sand source for the Willow Hole Reserve. Using directional wind data, we discuss the potential for eolian sand transport from the Mission Creek – Morongo Wash depositional area to Willow Hole.

INTRODUCTION

The Coachella Valley fringe-toed lizard (*Uma inornata*) is a federally listed threatened species that inhabits active sand dunes and their margins in the vicinity of Palm Springs, California (fig. 1). As part of the Habitat Conservation Plan for this species (Nature Conservancy, 1985), a series of reserves has been established to benefit this species and other species that are restricted to active dunes and their margins. Two of these reserves, the Whitewater Floodplain and Willow Hole – Edom Hill Reserves, are in the northern Coachella Valley between the towns of Palm Springs, Thousand Palms, and Desert Hot Springs (fig. 1).

The U.S. Fish and Wildlife Service is concerned that flood-control and water-management structures on Whitewater River and other smaller desert washes are reducing the sand supply to these reserves, potentially stabilizing the dunes and thereby degrading *Uma* habitat. Development of alluvial fans, alteration of stream channels by channelization, in-stream gravel mining, and construction of infiltration galleries were thought to reduce the amount of fluvial sediment reaching the depositional areas upwind of *Uma* habitat. Also, the presence of roadways, railroads, and housing developments was thought to disrupt or redirect eolian sand movement. Most of the sediment yield to the fluvial system is generated in higher elevation areas with little or no development, and sediment yield is affected primarily by climatic fluctuations and rural land use, particularly livestock grazing and wildfire. Channelization benefits sediment delivery to the depositional plains upwind of the reserves by minimizing in-channel sediment storage on the alluvial fans.

Previous studies of sediment supply to *Uma* habitat have generally been non-quantitative and, to a lesser extent, divergent in their conclusions as to the long-term sand budget in the northern Coachella Valley and how it might change given modifications to the major watercourses that provide sand to the eolian system. This study addresses specific questions of fluvial supply of fine-grained sediments to fetch areas upwind of two reserves in the northern Coachella Valley and eolian transport of these sediments to the reserves.

Purpose and Scope

The objective of this project is to describe the sand-delivery system and to quantify the sand budget for Coachella Valley fringe-toed lizard (*Uma inornata*) habitat in the northern Coachella Valley. This project will focus on the Whitewater Floodplain Reserve and the western half of the Willow Hole – Edom Hill Reserve – referred to in this study as the Willow Hole Reserve – and their sand sources, both before and after major development in the Coachella Valley. In particular, this study addresses the interrelations between fluvial and eolian processes that create the unique sand-delivery system to *Uma* habitat in the northern Coachella Valley and attempts to quantify sand transport rates.

In addition, this report addresses major questions asked of the U.S. Geological Survey by the U.S. Fish and Wildlife Service. These questions are:

- For both reserves, is the sand supply sufficient to maintain *Uma* habitat in the Willow Hole and Whitewater Floodplain Reserves?
- How would channelization of Mission and Morongo Creeks and urban development on their adjacent floodplains affect sand supply to both reserves?
- Do the infiltration galleries and associated retention dikes along the Whitewater River affect sand supply to the Whitewater Floodplain Reserve, and by how much? Could the design of the recharge ponds be modified to increase the sand supply to the reserve?
- How much of the floodplain of the washes supplying sand upwind of the reserves has to be preserved to ensure a perpetual sand supply? What areas are essential to preserve to maintain an adequate sand supply and sand-transport corridor for these two reserves?

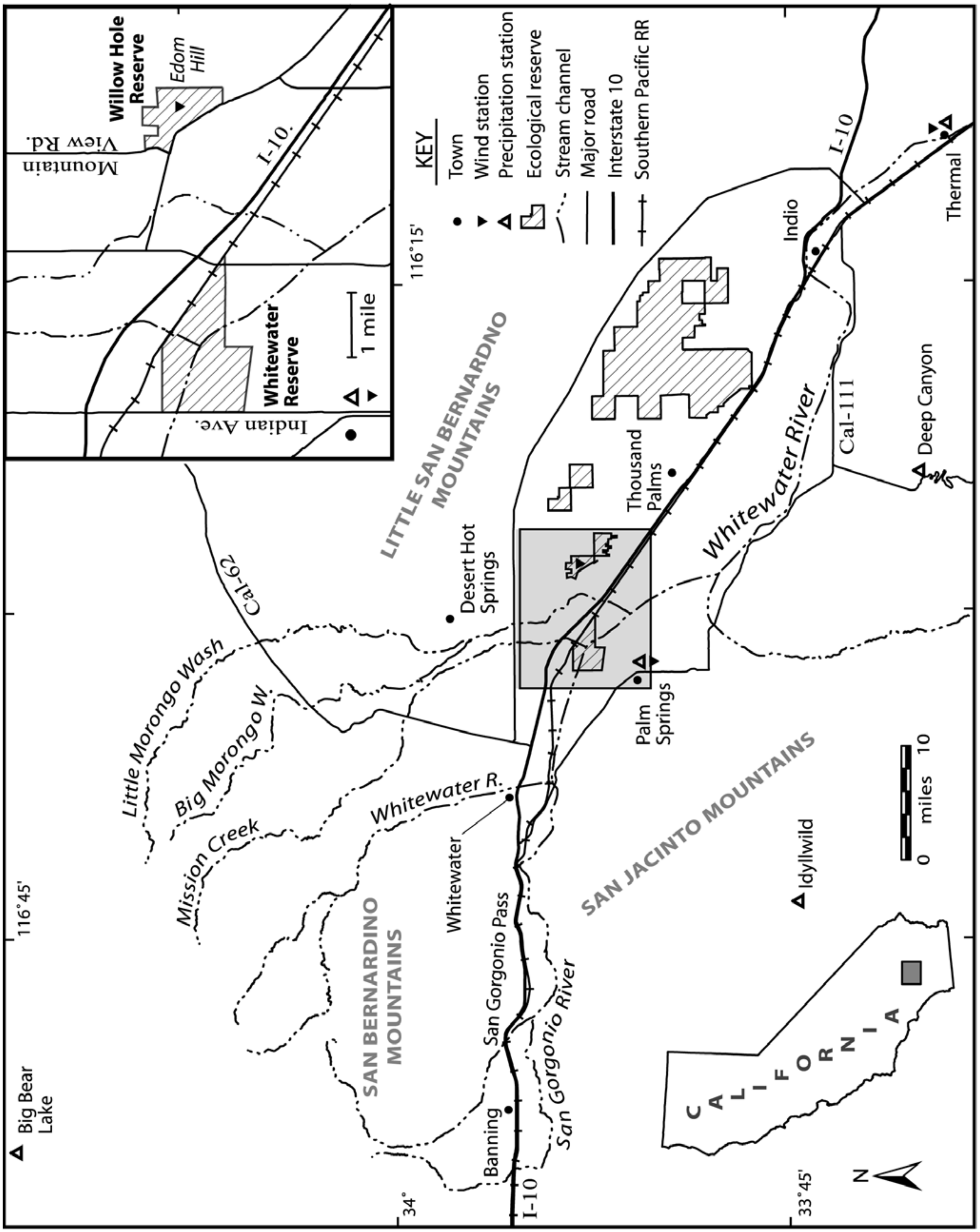

Figure 1. Map of the northern Coachella Valley. Inset shows details of the area including the Whitewater River and Willow Hole Reserves.

Acknowledgments

The authors thank Jessica Young of the U.S. Geological Survey for her contributions to the geographical information system (GIS) analysis of the drainages contributing sand to the Coachella Valley. Mimi Murov of the U.S. Geological Survey helped considerably with the field work on this project. Daniel Farris of the Coachella Valley Water District supplied key wind and dredging data. Kurt Cupp of the Desert Research Institute collected and scanned the air photographs and Ed Corbett of the Desert Research Institute helped with image and wind-data analysis. We thank R.R. Shroba and J.C. Matti of the U.S. Geological Survey for helpful discussions during Quaternary geologic mapping of the area. Mark Fisher of the Boyd Deep Canyon Desert Research Center provided precipitation data for his facility. Van Williams, also of the U.S. Geological Survey, provided invaluable GIS support for the geologic mapping. The manuscript was critically reviewed by Fisher, Allan Muth, and Cameron Barrows, collectively known as the Science Advisory Committee of the Coachella Valley Multiple Species Habitat Conservation Plan; Bill Havert of the Coachella Valley Mountain Conservancy; and Pete Sorensen and Ken Corey of the U.S. Fish and Wildlife Service.

BACKGROUND

Habitat Requirements of Uma inornata

The Coachella Valley fringe-toed lizard (*Uma inornata*) is a sand-dwelling species that is narrowly endemic on active dunes and their stabilized margins in the northern Coachella Valley. One of its closest relatives is the Mojave fringe-toed lizard (*Uma scoparia*), which is a species of special concern in California (Trepanier and Murphy, 2001). *Uma scoparia* is endemic to eolian sand habitats in the Mojave Desert in California and western Arizona, particularly within eolian systems associated with the Mojave and Amargosa Rivers (Hollingsworth and Beaman, 1999). The remaining habitat for *Uma scoparia* is substantially larger than that of *Uma inornata*, and *Uma scoparia* is not a federally listed threatened species.

Uma inornata was once relatively common in the Coachella Valley, and its original range was about 324 mi^2. By 1976, the eolian habitat available to this species had decreased by 27 percent to 236 mi^2, and the most-suitable habitat was estimated to be only 120 mi^2 (England and Nelson, 1976). The 1985 Habitat Conservation Plan (Nature Conservancy, 1985) created the Willow Hole – Edom Hill Reserve of 3.8 mi^2 (2.2 mi^2 of suitable habitat) and the Whitewater Floodplain Reserve of 1.9 mi^2, all of which is considered suitable habitat. A larger Coachella Valley Reserve (also known as the Thousand Palms Reserve) was also created east of the study area.

The numbers of *Uma inornata* began decreasing because of habitat destruction for a variety of human uses, including agriculture, development of subdivisions, and construction of railroads and highways. The active sand dunes that are required for *Uma* appear to have decreased in area, in part owing to road construction, the erection of windbreaks using non-native *Tamarix* trees, and modifications to stream channels; the operation of power-generating windmills upwind may possibly have contributed to the decline (Turner and others, 1984). Because its habitat, which was never very large, was reduced by at least two thirds, *Uma inornata* was listed as a threatened species by the U.S. Fish and Wildlife Service in 1980. The habitat conservation plan developed to protect this lizard (Nature Conservancy, 1985) is often cited as a model for species preservation under the Endangered Species Act (Barrows, 1996).

Uma inornata habitat consists of active or minimally stabilized dunes of late Holocene age or active eolian surfaces on dunes of greater antiquity. The lizards may use active, relatively large barchanoid dunes, or their habitat may consist of relatively large coppice mounds around mesquite (*Prosopis glandulosa*), creosote bush (*Larrea tridentata*), or other shrubs. *Uma* requires loose sand to create burrows, and the range in b-axis diameter of sand must fall between 0.1 and 1.0 mm with a mean of about 0.2 to 0.4 mm, as reported by Turner and others (1984), or 0.180 to 0.355 mm as reported by Barrows (1997). Turner and others (1984) conclude that *Uma inornata* may be very sensitive to minor variations in eolian sand size. Therefore, small alterations of sand supply may have significant effects on this species.

These lizards prefer the leeward side of dunes and hummocks and seldom use the windward (or more stabilized) side. However, Turner and others (1984) found positive correlations with the amount of surface crusting on the windward sides of dunes, indicating that some stabilization of dunes may be a desirable attribute of *Uma* habitat; they note that *Uma* may use the windward sides at night. Barrows (1997) found that sand compaction, as defined by a standardized penetration depth, was consistently the most important determinant of appropriate habitat for *Uma*; this species requires the deep, loose sand that generally occurs only in active sand dunes as protection from predators and summer heat.

Uma require some proximity to vegetation for their food supply, which suggests that the dune systems they occupy must be relatively small or have a thin cover of loose sand over more stable substrates anchored by vegetation. Barrows (1997) found that *Uma* preferred the presence of such native plant species as *Dicoria canescens* and *Atriplex canescens* as well as the non-native *Salsola tragus*. *Dicoria* is an important food source, particularly in late summer (Barrows, 1997). Another factor noted by Barrows (1996) is ground-water overdraft, which may be killing mature *Prosopis* and thereby facilitating degradation of coppice mounds that provide dune anchorage as well as negatively affecting food supplies.

The Fluvial System in the Coachella Valley

The fluvial system in the Coachella Valley consists of stream channels that are ephemeral downslope from the mountain front and that pass through large, coalescing alluvial fans called bajadas. These ephemeral streams, also known as washes, deliver sediment in flash floods that occur infrequently. These floods occur during large winter storms that drop most of their precipitation in the mountains west and north of the Coachella Valley (larger drainages), or during intense summer thunderstorms (smaller drainages). The last large flood on the Whitewater River was in 1938, and most floods that occur at a frequency of every 2 years or more often are relatively small and transport only small amounts of fine-grained sediments in comparison with the larger events.

Streamflow is the most common sediment-transport process that occurs in the washes entering the Coachella Valley. Streamflow typically has a sediment concentration of less than 40 percent by weight (Pierson and Costa, 1987). In addition to streamflow, “hyperconcentrated flow” and debris flows occur in the Coachella Valley and particularly in the surrounding mountainous terrain (Sharp and Nobles, 1953). Hyperconcentrated flow, as originally defined by Beverage and Culbertson (1964) and modified by Pierson and Costa (1987), contains 40 to 70 percent sediment by weight. Debris flows are slurries of clay- to boulder-sized sediment with volumetric water concentration ranges from about 10 to 30 percent (Pierson and Costa, 1987; Major and Pierson, 1992) and are an important sediment-transport process in a variety of geomorphic settings throughout the world (Costa, 1984).

A variety of classifications has been proposed for distinguishing streamflow, “hyperconcentrated flows,” and debris flows, with the most recent work focused on rheological properties (Pierson and Costa, 1987) and the interactions of fluid and solid forces (Iverson, 1997). Hyperconcentrated-flow deposits are differentiated from those of streamflow and debris flow by sedimentological criteria based on differences in particle-size distribution, sedimentary structures such as slight laminar bedding, and an overall coarse-sand, upward-coarsening texture commonly containing erratic cobbles and boulders (Pierson and Costa, 1987). In this study, hyperconcentrated flow is grouped with streamflow in calculating sediment transport in the Coachella Valley, and the sediment contribution of debris flows is not calculated owing to lack of information on their occurrence.

Fluvial sediment is mostly generated in the headwaters areas of drainage basins within the mountains that surround the western and northern parts of the Coachella Valley. During infrequent floods, sediment is entrained from hillslopes and channels in the headwaters and is transported downstream into channels that pass through the bajadas. Some sediment is stored within channels in small terraces; during larger floods, sediment is stored on the bajada surface as floodplain deposits. Sediment transported through the bajada in the channelized washes is deposited over broad, low-angle depositional plains, referred to in this report as depositional areas. The largest of these areas is the Whitewater depositional area, most of which historically was west of Indian Avenue and south of Interstate 10 (fig. 1).

The particle-size distribution of sediments transported by these ephemeral streams varies depending on the transport process. Debris flows, which occur infrequently, transport particles ranging from clay to boulders; abundant debris-flow deposits appear along the channel of Whitewater River upstream from Interstate 10 and on alluvial fans emanating from the San Jacinto Mountains. No historical debris flows have been reported, however. Most sediment transported by streamflow ranges in size from sand to small gravel, with a relatively small (<10 percent) component of silt and clay. This range in particle size reflects the sizes of particles generated from weathering of granitic terranes in the San Bernadino and San Jacinto Mountains.

At various times, flood-control and water-management projects that were proposed to solve regional problems were thought to reduce the sand supply issuing from major tributaries, particularly the Whitewater River. One flood-control project proposed but not implemented by the U.S. Army Corps of Engineers could have reduced the sand supply by half (Turner and others, 1984).

Water-spreading structures and earthen dikes are used to infiltrate low flows from the Whitewater River into the regional aquifer. A total of 19 infiltration galleries, also known as percolation ponds, are formed from these dikes. The initial diversion dikes into the infiltration galleries are designed to breach during floods; this has occurred several times since construction, particularly during floods in early 1977 and again in 1979 at the site of the spillway between the ponds (Daniel Farris and Patti Schwartz, Coachella Valley Water District, oral commun., 2002). The intake channel to the galleries is designed to trap much of the sand transported downstream in the Whitewater River, potentially making it available to downstream transport to the Whitewater River depositional area.

Flow in the lower Whitewater River is occasionally artificial. Water imported from the Colorado River is released into the channel of the Whitewater River about one mile upslope (north) of the Interstate 10 bridge at Whitewater (fig. 1). These aqueduct releases typically range from less than 100 to 500 ft^3/s, and the releases are redirected from the main channel into the infiltration galleries. This flow too is episodic and aseasonal, depending on negotiations between the local water district and the Metropolitan Water District of Los Angeles. This sediment-free water quickly entrains fine-grained sediments of the size range required for *Uma* habitat and moves at least some of the sediment out of the fetch area that supplies sand to the Whitewater Floodplain Reserve. In addition, because of their steep windward sides, the dikes impounding the infiltration galleries trap fluvial sand moving down the corridor of the Whitewater River and prevent eolian sand from escaping.

The Eolian System in the Coachella Valley

The sand dunes of the northern Coachella Valley have been described in several previous studies (Russell, 1932; Sharp, 1964, 1980; Beheiry, 1967; Lancaster and others, 1993; Lancaster, 1997). Abundant evidence of significant prehistoric eolian activity is preserved in ventifacts (sandblasted rocks), fossil dunes, and altered vegetation form and distribution (Proctor, 1968; Sharp and Saunders, 1978). The dune forms that have been previously described in the northern Coachella Valley range from knob dunes (now called nebkha or coppice dunes; Lancaster, 1995) – small and ephemeral mounds up to 6 ft high and 35 ft long and anchored by perennial vegetation – to barchan dunes up to 35 ft high and 100 ft long (Beheiry, 1967). Parabolic dunes occur in the Coachella Valley Reserve to the east. Sand veneers on surfaces that are not eolian in origin (also called sand sheets) are relatively common, particularly following pulses of fluvial sediment input, but mesquite-anchored coppice dunes are the only relatively permanent dune forms in the northern Coachella Valley.

The actual rates of dune movement and sand transport are determined by the supply of sediment for transport and its availability. Sand availability is limited by vegetation cover and soil moisture, the influence of which is indicated by the dune-mobility index (Lancaster and Helm, 2000). A climatic index of dune mobility developed to predict the mobility of sand dunes (Lancaster, 1988) has been used to understand dune mobility in a variety of environments, including the Kalahari Desert (Bullard and others, 1997), the Great Plains of the USA and Canada (Muhs and Maat, 1993; Wolfe and Nickling, 1997), and southern Washington State (Stetler and Gaylord, 1996). The index is based on the two factors of wind strength and the ratio of precipitation to potential evapotranspiration as a surrogate for vegetation cover. It has been shown to accurately reflect eolian sand transport measured at long-term monitoring sites in the southwestern United States (Lancaster and Helm, 2000). One major assumption is that dune movement and eolian activity are determined by sediment availability as determined by vegetation cover. Lancaster and others (1993) and

Lancaster (1997) used the dune mobility index to show that dunes in the Coachella Valley migrated on a temporal pattern that was predicted by the index.

As previously discussed, the sand supply for the eolian system comes from ephemeral washes, most of which have headwaters in either the San Bernardino or Little San Bernardino Mountains. Wasklewicz and Meek (1995) used geochemical analyses to attempt to quantify the sources of sands for the *Uma* reserves. These sources are predominantly the major watercourses, particularly the Whitewater River for the Whitewater Floodplain Reserve and Mission Creek and Morongo Wash for the Willow Hole Reserve. Floods down these watercourses occur infrequently, leading to episodic addition of fine-grained fluvial sediments to the channels and alluvial fans upwind of the reserves.

Westerly winds through San Gorgonio Pass (fig. 1), which shift to northwesterly winds with distance into the Coachella Valley, provide the dominant force for moving fine-grained fluvial sediments deposited by major watercourses on the valley floor into eolian deposits that become *Uma* habitat (Lancaster and others, 1993). Winds can shift to other directions during occasional thunderstorms, but these events are sporadic and very localized. Wind energy is not a limiting factor to wind transport in this region (Lancaster, 1997). Because of the episodic nature of fluvial sediment input into the system and the high energy of the wind regime, depletion of upwind sand sources as well as ephemeral eolian landforms are expected. With increasing time after fluvial deposition, wind can erode fine sediments from both the channel margins and the downwind habitat, thereby depleting the source for eolian sand as well as *Uma* habitat.

Accumulation of eolian deposits requires: (1) a source of available sediment, (2) sufficient wind energy to transport that sediment, and (3) conditions that promote accumulation in the depositional zone. A key principle in the understanding of eolian sand deposits is the recognition that they occur as part of recognizable sediment transport systems in which sand is moved from source areas (*e.g.*, distal fluvial deposits) and transported along distinct transport corridors to depositional sinks (Lancaster, 1995).

The dynamics of eolian sediment transport systems on any time scale are determined by the relations between the supply, availability, and mobility of sediment of a size suitable for transport by wind (Kocurek and Lancaster, 1999). In turn, sediment supply, availability, and mobility are determined in large part by regional and local climate and vegetation cover. Sediment supply is the presence of suitable sediment that serves as a source of material for the eolian transport system. It may be affected by variations in flood magnitude and frequency, fluvial sediment-transport rates, and rates of bedrock weathering at sediment source areas. Climatic changes impact sediment availability (the susceptibility of a sediment surface to entrainment of material by wind) and mobility (transport rates) via vegetation cover, soil moisture, and changes in the magnitude and frequency of winds capable of transporting sediment.

Rates of eolian transport and deposition are affected by a number of factors. Wind fetch, or the length of unobstructed area exposed parallel to the wind, is the primary factor. Because the natural surfaces along the floor of the arid northern Coachella Valley are mostly flat with sparse perennial vegetation, fetch is generally not a restriction unless anthropogenic obstacles are present. Other factors influencing eolian transport include wind speed and duration, availability and size fractions of sand in channel bottoms, the presence and dimensions of natural or artificial windbreaks, and the density and size of natural vegetation in channels and among sand dunes. Lancaster and others (1993) add the factor of channel entrenchment and (or) change, which decreases eolian entrainment of particles and transport out of channels. Some of these factors – particularly wind speed, availability of appropriately sized sediment, channel stability, and natural vegetation – are affected by regional climatic variability on a decadal or longer time scale. Other factors – particularly wind fetch – are directly affected by development and modification of river channels and the landscape.

Eolian processes transport a relatively narrow range of sand sizes. In the mid-1960s, Beheiry (1967) found that the median diameter (D_{50}) of eolian sand at sixteen sites in the Coachella Valley ranged from 0.09 to 0.44 mm with an average of 0.28 mm. The particle-size distributions he measured had a bimodal component, suggesting that several sand sources were being mixed in transport. The range of eolian sand preferred by *Uma inornata* is 0.180 to 0.355 mm (Barrows, 1997), indicating that these lizards have a more narrow habitat preference than what is available throughout the eolian dune fields.

Accumulation of sand is the product of spatial changes in transport rates and temporal changes in sediment concentration such that:

$$\frac{dh}{dt} = -\left(\frac{dq_s}{dx} + \frac{dC}{dt}\right) \qquad (1)$$

where

h is the elevation of the deposition surface,

t is time,

q_s is the spatially averaged bulk volume sediment-transport rate,

x is the distance along the transport pathway, and

C is the concentration of sediment in transport.

In this model, the transport rate (q_s) consists of two components, a first owing to bedform migration (bedform transport, q_b) and a second that is throughgoing (q_t) as a result of saltation or bedload transport. The sediment concentration (C) is a measure of the total amount of sediment in transport, and can be approximated by the average height of the dunes or other eolian bedforms (Havholm and Kocurek, 1994).

Although sediment-transport rates over sandy surfaces are almost always at the capacity of the wind to transport sediment (sediment saturated), those over other desert surfaces such as bedrock, alluvial fans, or playas are frequently below transport capacity, or undersaturated or metasaturated (Wilson, 1971) because the sediment supply is limited. Thus actual sand transport rates (q_a) may be less than potential rates (q_p) in proportion to the ratio q_a/q_p, which ranges between zero for completely undersaturated flows to 1 for fully saturated conditions. The wind is potentially erosional until its transport capacity is reached, regardless of whether the wind is accelerating, steady, or decelerating. Deposition occurs wherever there are local decreases in transport capacity (*e.g.*, deceleration in the lee of obstacles or change in surface roughness). The wind may still be transporting sand, as deposition only occurs until the transport rate is in equilibrium with changed conditions.

Following principles of sediment-mass conservation, if transport rates decrease in the direction of flow, deposition will occur. If, however, sediment-transport rates increase, then sediment will be eroded. If there is no spatial change in transport rates, then net sediment bypassing will occur (Havholm and Kocurek, 1994). The change in transport capacity in both time and space, defined as the ratio between the potential transport rate upwind and downwind of the area of concern, determine the domains of erosion, bypass, and accumulation of sand. These concepts can be used to assess the nature of changes that may occur through time. For example, assuming that the basic wind regime characteristics of an area do not vary with time, changes in sediment availability from source zones and thus the saturation level of the input will determine the behavior of the system.

Sand depletion is considered an on-going problem in the northwestern part of the Coachella Valley because wind velocities and therefore sand-transport rates are highest in this area and the watercourses that supply sediment have been subjected to considerable modification. Lancaster and others (1993) concluded that the northern Coachella Valley has been strongly affected by changes in sand supply and transport rates through the 20th century. They note that eolian transport rates were relatively high between 1948 and 1974, which is generally regarded as a period of prolonged drought, and lower thereafter, a period that is relatively wet but with highly variable conditions. Lancaster (1997) concluded that variations in precipitation and perennial vegetation on dunes control the eolian systems in the California Deserts. Although the extreme flood events needed to supply large amounts of fine-grained fluvial sediments to alluvial fans are extremely episodic, higher frequency variations in annual precipitation and particularly prolonged periods of climatic shifts – to either wetter or drier conditions – may strongly affect the stability of *Uma* habitat. In addition, development increased dramatically after the mid-1970s and human effects on trapping sand through windbreaks and altering the sand supply cannot be ignored.

METHODS

Quaternary Geologic Mapping

Geologic units of Quaternary age (last 2 million years) were mapped for the Desert Hot Springs and Seven Palms Valley quadrangles (scale 1:24,000) as part of ongoing studies under the Southern California Areal Mapping Project (SCAMP) of the U.S. Geological Survey (Lundstrom and others, 2001; and unpublished mapping of Lundstrom, R. Shroba and J. Matti). The geology of the study area previously was mapped at a scale of 1:250,000 as compiled by Rodgers

(1966), but he had little differentiation of Quaternary surficial geologic units. Similarly, Proctor (1968) provided a map of the Desert Hot Springs area at a scale of 1:62,500 and differentiated Pleistocene units from Holocene but provided no subdivisions within these eras.

Our mapping improves upon that of Proctor and Rodgers by using a larger scale map base as well as differentiating the ages of geomorphic surfaces within the Pleistocene and Holocene eras and by distinguishing the deposits by the geomorphic processes that resulted in their deposition. Mapping was based mostly on National Aerial Photography Project (NAPP) false-color infrared imagery (nominal scale of 1:40,000) from August 18, 1989, supplemented by National Historical Aerial Photography (NHAP) black-and-white imagery (scale of 1:80,000) from 1984. For the Indio Hills mapping, we used natural color aerial photography (scale of 1:24,000) flown on April 9, 1999. The descriptions of mapping units appears in Appendix 1; readers are referred to Birkeland (1974), McFadden (1982), and Cooke and others (1993) for more information on the use of soils geomorphology for age discrimination of geomorphic surfaces.

Climatic and Hydrologic Data

We analyzed existing precipitation and hydrologic data concerning the Coachella Valley and its watercourses to evaluate the hypothesis that climatic change affects *Uma* habitat in three ways: (1) by altering flood frequency, and thereby affecting sediment supply; (2) by increasing landscape roughness by increasing the amount and size of perennial native vegetation; and (3) by increasing the perennial vegetation in the vicinity of dunes, leading to increased stabilization. Monthly precipitation data were obtained from the Western Region Climatic Center in Reno, Nevada (www.wrcc.edu), and the University of California Philip L. Boyd Deep Canyon Desert Research Center (Mark Fisher, written commun., 2001). Discussions of standardization techniques for monthly and seasonal precipitation appear in Hereford and Webb (1992).

Streamflow gaging data from the U.S. Geological Survey were obtained from the California District of the Water Resources Division; gaging data availability for the northern Coachella Valley appears in Appendix 2. Streamflow data is relatively sparse in this region, and most records are only 10-20 years in length. In addition, many of the stations on major watercourses have been moved, in some cases repeatedly. The Southern Oscillation Index (SOI), the most commonly used indicator of El Niño conditions in the equatorial Pacific Ocean, is regularly updated on various web sites; for more information on this index, see Webb and Betancourt (1992) and Cayan and Webb (1992).

Delineation of Drainage and Depositional Areas

Drainage areas of principal washes that contribute sediment to depositional areas upwind of the Coachella Valley reserves were hand drawn on 7.5-minute topographic maps and digitized (fig. 2). Drainage areas were calculated within a GIS and are given in table 1. Topographic information associated with the drainage areas was obtained from U.S. Geological Survey 30-m digital-elevation models.

Predevelopment, or historic, depositional areas were identified as late Holocene surfaces on the Quaternary geologic map. Active channels and current, or modern, depositional areas were determined by a combination of digitization of SPOT imagery provided by C.W. Barrows (written commun., 2001) and field evaluation. The Mission Creek – Morongo Wash depositional area in particular was determined as the entire area between the west splay of Mission Creek and the east splay of Morongo Creek north of Interstate 10 and south of the Banning (San Andreas) Fault (figs. 1 and 2). In March 2001, after a small flow on Mission Creek, sediment appeared to be recently deposited throughout this area, indicating reasonably active deposition even during modest floods. Because of these observations, we could not quantitatively evaluate whether some parts of the Mission Creek – Morongo Wash depositional area were more active than other parts. In both the predevelopment and modern eras, the boundaries of the Willow Hole depositional areas are difficult to map at a landscape scale and we chose not to formally delineate them.

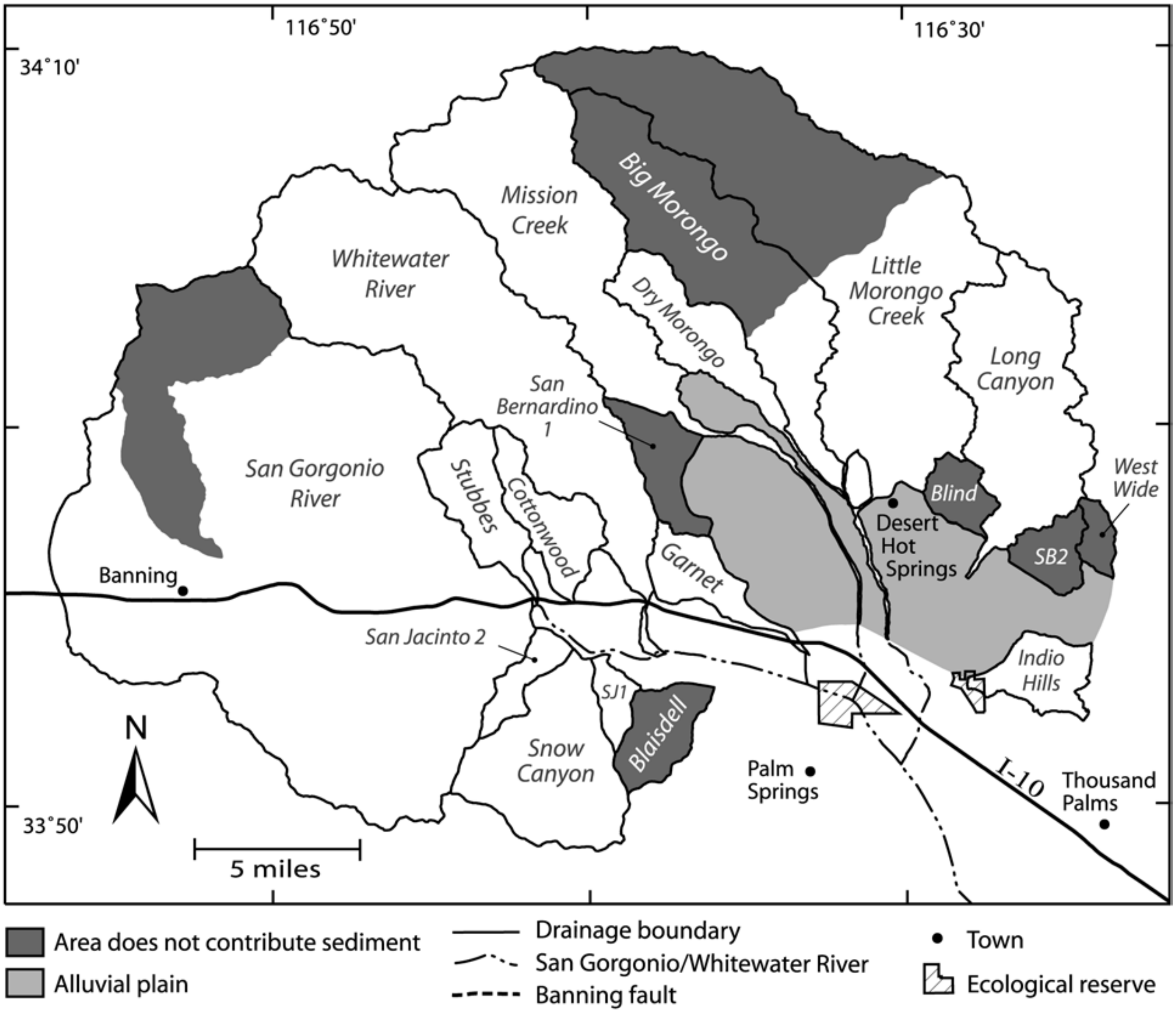

Figure 2. A. Drainage areas for principle watersheds contributing fluvial sediment to the northern Coachella Valley.

Fluvial Sediment Yield

Fluvial sediment yield (sediment moved by rivers) was analyzed using indirect techniques because little sediment-transport data has been collected in the study area (Appendix 2). We rejected standard approaches such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978; Peterson and Swan, 1979), the CREAMS and WEPP models of the Agricultural Research Service (Knisel, 1980; Gilley and others, 1988), and the procedure outlined by the PSIAC (Pacific Southwest Inter-Agency Committee, 1968). The USLE was developed strictly for low-slope agricultural land and is not appropriate for the steep terrain of drainages entering the Coachella Valley. Likewise, the CREAMs and WEPP models were developed for relatively low-slope agricultural and rangeland and require considerable watershed data for proper application. The PSIAC method involves rating a watershed on the basis of nine factors related to erosion (surface geology, soil, climate, runoff, topography, land use, upland erosion, and channel erosion/sediment transport) to produce an estimate of sediment yield. This method can be applied to large areas using pre-calculated PSIAC sediment-yield ratings mapped by the Soil Conservation Service (Soil Conservation Service, 1975). It generally produces high sediment-yield estimates in arid regions of high relief (Webb and others, 2000).

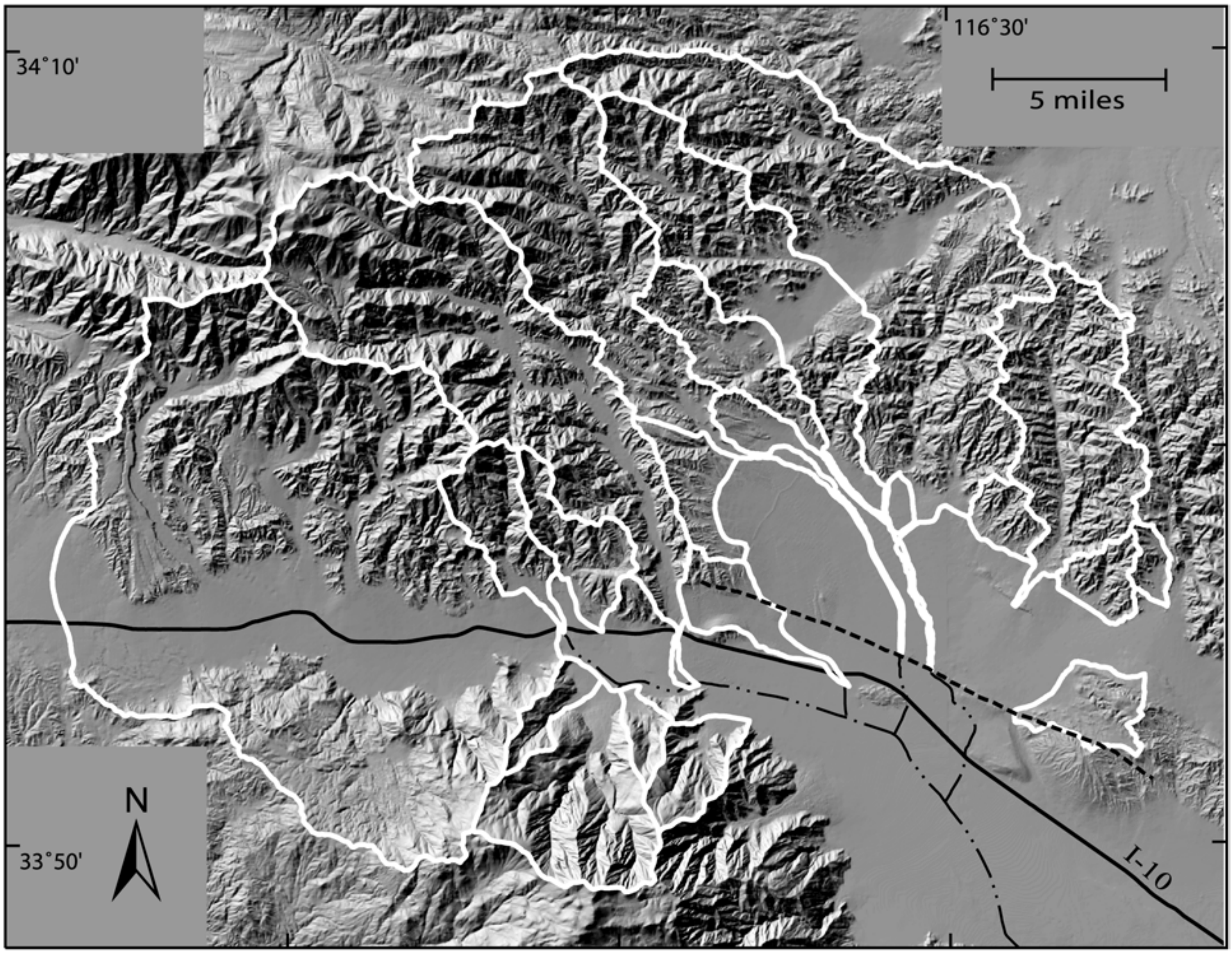

Figure 2. *Continued.*

B. The shaded relief map is based on a 30-m digital-elevation model of the northern Coachella Valley and the San Bernardino, Little San Bernardino, and San Jacinto Mountains. White lines indicate drainage boundaries.

The Power-Function Approach

The power-function method of estimating fluvial sediment yield is purely empirical and uses power functions fit to empirical data (*e.g.*, Renard, 1972). Some approaches include more-intensive statistical modeling (*e.g.*, Flaxman, 1972) and deterministic sediment-yield models that are data intensive (*e.g.*, Gilley and others, 1988). In places like the Coachella Valley, where little sediment data have been collected (Appendix 2), the best technique is to apply an empirical function from a similar region. For example, from the Colorado Plateau, one estimator based on regional data is of the form:

$$Q_s = 493 \cdot A^{1.04} \qquad (2)$$

where

Q_s is sediment yield in short tons per year (t/yr), and

A is drainage area (mi^2).

In relations of this type, sediment yield typically is a function of drainage area to a power close to 1.0, a nearly linear relation.

In the Coachella Valley, we elected to use the Renard (1972) equation, which, converted from units of volume to weight by assuming a sediment density of 0.0375 tons per cubic foot (t/ft^3), is

$$Q_s = 895 \cdot A^{0.88}, \qquad (3)$$

Table 1. Sediment source areas for the northern Coachella Valley.

Tributary	Area (mi^2)	Mean elevation (ft)	Depositional area[1]
San Gorgonio River[2]	153.5	3612	San Gorgonio/Whitewater
Little Morongo Creek[3]	67.7	3725	Mission/Morongo
Whitewater River	59.6	5540	San Gorgonio/Whitewater
Mission Creek	38.4	5488	Mission/Morongo
Big Morongo Creek[3]	31.0	3988	Mission/Morongo
Long Canyon	26.3	3100	Willow Hole
Snow Canyon	19.3	5231	San Gorgonio/Whitewater
Dry Morongo Creek	10.7	3126	Mission/Morongo
Stubbes Canyon	8.4	3500	San Gorgonio/Whitewater
Cottonwood Canyon	7.5	2889	San Gorgonio/Whitewater
Garnet Wash	6.0	1407	San Gorgonio/Whitewater
Blaisdell Canyon[2]	6.0	3101	San Gorgonio/Whitewater
"Indio Hills"[4]	5.9	1132	Willow Hole
"San Bernardino 1"[4]	5.8	2493	n.a.
"San Bernardino 2"[4]	3.8	1748	n.a.
Blind Canyon	3.4	1835	Mission/Morongo
"San Jacinto 2"[4]	3.4	2825	San Gorgonio/Whitewater
"San Jacinto 1"[4]	2.4	2552	San Gorgonio/Whitewater
West Wide Canyon	1.9	2059	n.a.

[1] na, not applicable; sediment does not reach deposition zones.

[2] Upper San Gorgonio River and Blaisdell Canyon do not supply sediment in the modern setting.

[3] Sediment from Upper Little Morongo and Upper Big Morongo Creeks does not reach deposition zones.

[4] Tributary has no official name.

where

Q_s is sediment yield in short tons per year (t/yr), and

A is drainage area (mi^2).

Sediment yield (and therefore the sediment contribution) is estimated from the contributing drainage area alone. Other factors, such as variation in slope angle within the drainage area as well as elevational gradients in precipitation, are very important to sediment yield but are not considered in this approach because of lack of data. The Renard equation is based on watershed data collected in the southwestern United States and has been successfully applied to other arid landscapes of high relief in the southwest (Webb and others, 2000).

The Flood-Frequency, Rating-Curve Technique

We developed a flood-frequency, rating-curve technique to estimate streamflow sediment yield based loosely on the work of Strand (1975) and Strand and Pemberton (1982). This technique requires numerous assumptions, one of the most important of which is that the decadal streamflow sediment yield in a tributary can be estimated by summing the sediment delivered by several floods of recurrence intervals described by regional flood-frequency relations (table 6; Thomas and others, 1997). Accordingly, we assumed that sediment yield can be calculated using:

$$Q_s = \Sigma[(m/n) \cdot \Theta(Q_n)] / m, \qquad (4)$$

where

$\Theta(Q_n)$ is the sediment yield of a n^{th} year flood,

m is the rarest flood return period (years) in the summation, and

n are the more frequent flood return periods (years) ranging irregularly from 2 to m.

We assumed that sediment yield could be calculated from an expected value for the number of floods to occur in a decade. This expected value contains five 2-yr floods, two 5-yr floods, and one 10-yr flood which are thought to deliver most of the sediment in an arid region such as the Coachella Valley. We assume that the annual flood does not contribute significant sediment. Considering the intermittent-flow regime of these tributaries, which probably have flow less than one percent of the time, this is likely not an egregious assumption. Also, regional flood-frequency relations do not produce annual floods, so we have no means of determining the effect of neglecting the smallest events on ungaged tributaries, and we chose not to include the influence of long recurrence-interval floods in the analysis. The regional-regression equations reported by Thomas and others (1997) for the 2-year, 5-year, and 10-year floods in Region 10 (the Southern Great Basin Region, which includes the Coachella Valley) are listed in table 2.

In order to calculate sediment yield for an n-year flood, we derived two relations based on daily sediment data collected on the Whitewater River near Whitewater, California (10256000). Sediment-concentration data was collected daily from October 1, 1970, to September 30, 1972, with daily streamflow discharge ranging from 0.2 to 126 ft^3/s (Appendix 2). The first relation was a sediment rating curve for that gaging station. Owing to evidence of channel change in the sediment data, data collected prior to December 21, 1971, was not used to calculate the rating curve. In addition, data for very low discharges (< 1.8 ft^3/s) was clearly non-linear with a high degree of scatter and was also not used in the calculation of the rating curve relation. The rating curve relation took the form of:

$$Q_d = Q_a \cdot 10^b, \qquad (5)$$

where

Q_d is sediment yield in short tons per year (t/yr),
Q is daily discharge in ft^3/s, and
a, b are coefficients determined using linear regression.

We next calculated the relation between total event sediment yield and peak daily discharge for each of the 50 largest floods recorded at the Whitewater stream gage. The streamflow record is much longer than the sediment record, extending from October 1, 1948, to September 30, 1979 (Appendix 2). The 50 largest floods range between 59 and 4,970 ft^3/s, with 26 floods (52 percent) peaking at 126 ft^3/s (the maximum flood in the sediment record). Total sediment yield for each flood event was calculated as the sum of all daily sediment yields for the duration of the flood. We then calculated the regression relation between peak discharge and total event sediment yield for each flood, resulting in an equation of the form:

$$Q(Q_p) = Q_p{}^a \cdot 10^b, \qquad (6)$$

where

$Q(Q_p)$ is the total sediment yield for the flood in tons,
Q_p is peak daily flood discharge in ft^3/s, and
a, b are coefficients determined empirically using regression techniques.

We used this final relation of peak discharge to total flood sediment yield to in the calculation of expected annual sediment yield from each tributary as expressed in (4).

Table 2. Regression equations for streamflow flood-frequency in Region 10 (Thomas and others, 1997).

Recurrence interval	Flood-frquency relation[1]
2-year flood	$Q_p = 12A^{0.58}$
5-year flood	$Q_p = 85A^{0.59}$
10-year flood	$Q_p = 200A^{0.62}$

[1] Q_p = peak discharge for flood (ft^3/s); A = drainage area (mi^2).

Non-Contributing Drainage Areas

In estimating fluvial sediment yield, it became apparent that some drainage areas, although having the potential to produce sediment, do not deliver sediment to the main depositional areas on a regular basis. In the case of upper Little Morongo and upper Big Morongo Washes this is a factor of topography: sediment from these basins is mostly trapped in the low-gradient Morongo Valley and does not reach Coachella Valley (fig. 2). Other drainage areas – San Bernardino 1, Blind Canyon, and San Bernardino 2 – are too small to generate streamflow sufficient to move sediment across the alluvial fans. This is evident from the absence of significant channels or areas of Late Holocene sediment at the mouths of these tributaries. In the modern era, man-made impediments prevent the delivery of sediment from both the upper San Gorgonio

River, which feeds into a gravel pit near the town of Banning, and Blaisdell Canyon, which is cut off from the Whitewater depositional area by California Highway 111 (figs. 1 and 2). Similarly, flood control projects at the mountain front of the Little San Bernardino Mountains eliminate West Wide Canyon as a sediment source, although whether it was ever a significant source of sediment is unknown. These tributaries and sub-tributaries were deemed non-contributing and were not included in sediment-yield estimates.

Particle-Size Distributions

To evaluate the fraction of streamflow sediment yield that is of the appropriate particle size for use by *Uma*, we collected samples of streamflow sediment from most of the prominent stream channels in the study area (fig. 3). Most of these channels consisted of left and right overbank areas, which are typically inundated during most floods, as well as the center of the channel. In most cases, we collected samples from the left and right overbank areas as well as the center of the channel. For sediment particle sizes, we use the standard unit ϕ, defined as

$$\phi = \log^2 (D), \tag{7}$$

where D is the diameter, in millimeters, of the intermediate axis, also known as the b-axis (Folk, 1974). After sieving and analysis, the samples were composited into one sample for each channel cross section sampled.

The samples were oven dried and sieved following standard techniques (Kellerhals and Bray, 1971; Folk, 1974) using brass sieves at 1 ϕ intervals and a rotational shaker. Particles retained on each screen were weighed and the percent of the subsample in each ϕ class determined and combined to yield a channel-averaged particle-size distribution.

Historical Wind Energy and Direction

The primary source of wind data used for this report was the weather station at Palm Springs International Airport; additional data were obtained for Thermal, California and Edom Hill (fig. 1). Neither the Palm Springs nor the Thermal stations are truly representative of wind on the two reserves – Palm Springs is south of the study area and is slightly south of the main wind jet from San Gorgonio Pass, and Thermal is 25 miles southeast of Edom Hill and about 25 miles east southeast of Palm Springs International Airport – but these are the only available records of suitable length. Wind data collected at Palm Springs and Thermal from 1992 to May 2001 were analyzed. These data are available from the Western Region Climate Center. The Edom Hill data are of limited extent, with only the data collected in 2001 sufficiently complete (90 percent). Data from Edom Hill were collected by SeaWest on the western slopes of Edom Hill just east of Varner Road. These data are very well situated for directional analysis with regard to the Mission Creek – Morongo Wash depositional area, but are not applicable to any other depositional area.

Before 1998, observations at Palm Springs were made only 18 hours a day (6 am-12 am) and data availability averages about 67 percent. Starting in February 1998, observations were made on a 24-hr basis and data availability increases to about 95 percent. One result of this change in instrumentation is that the magnitude of the sand drift potential changes significantly after February 1998 and is reduced by a factor of 3.6, apparently because the new system appears to provide generally lower hourly average wind speeds. The other impact of this change is that there are differences in recorded wind directions, so that the vector direction of the sand-transport potential changes by approximately 30°. Because of these uncertainties, we have concentrated our analysis on the more recent continuously recorded data that began in 1998.

Wind directions at Palm Springs International Airport and Edom Hill were summarized by calculating the percentage of observations that fall within each of the sixteen standard compass directions, such as “west” or “west southwest.” This results a division of the compass into sixteen intervals, or sectors, of 22.5° each. Frequency values were calculated for all winds measured as well as for only sand-transporting winds. Sand-transporting winds are defined as those winds that exceed the minimum velocity necessary to transport sand at a given location. This threshold velocity varies between Palm Springs and Willow Hole owing to differences in the height at which winds are measured.

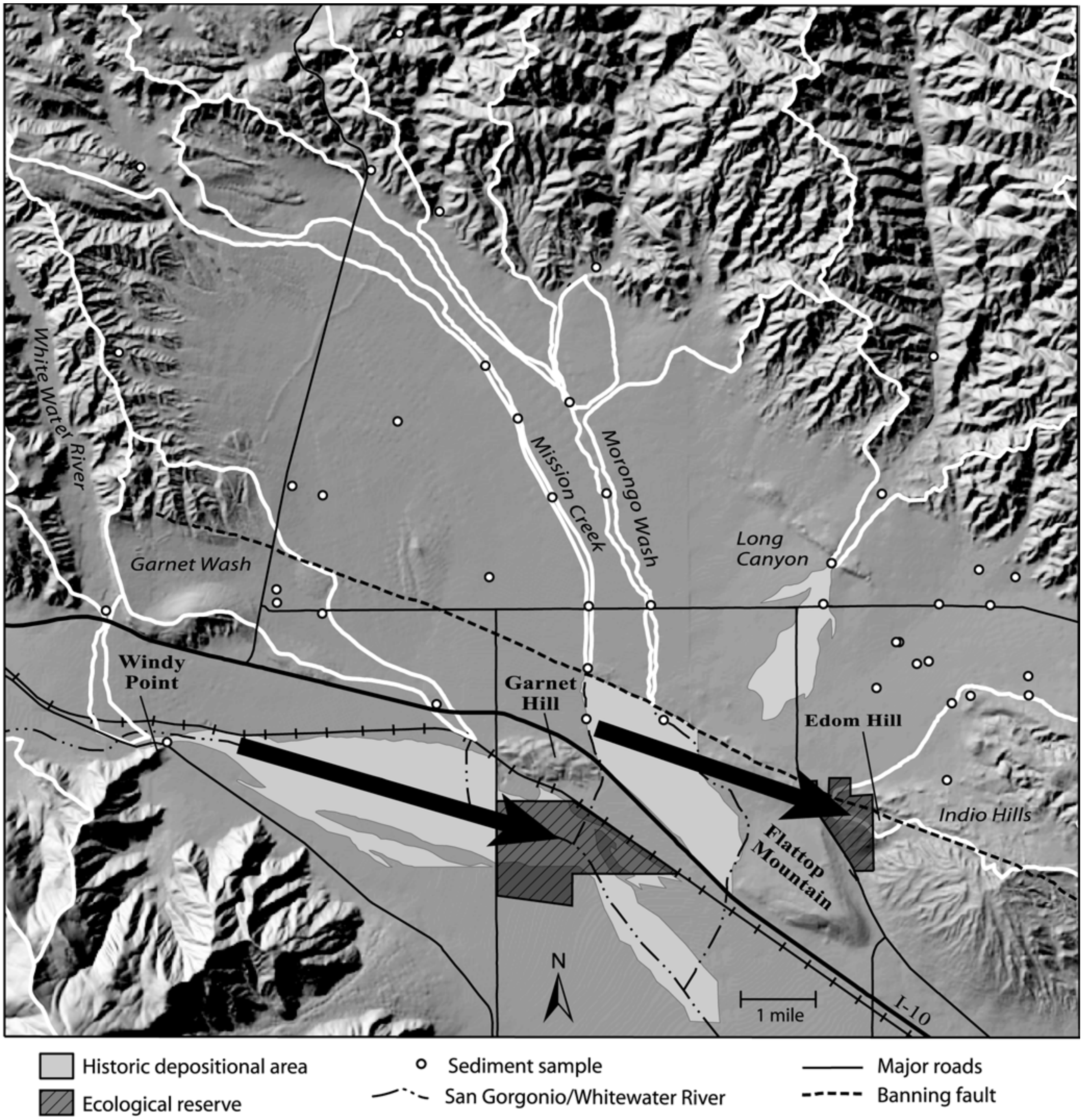

Figure 3. Shaded relief map of the northern Coachella Valley showing general paths of eolian transport from areas of fluvial deposition to the Whitewater Floodplain and Willow Hole Reserves and locations of sampled fluvial sediment. White lines indicate drainage boundaries.

Because the Edom Hill wind data were collected at the approximate center of the Willow Hole Reserve, wind-direction frequency derived from these data for a given compass sector can also be used as a measure of the percent frequency of time – expressed as a probability – that winds crossing that sector in the neighborhood of the Reserve are headed directly toward the center of the Reserve. For example, if winds at Edom Hill come from the North sector 7.3 percent of the time, then, conversely, winds across the Northern sector will be headed directly toward Edom Hill 7.3 percent of the time. We applied this principle to the Mission Creek – Morongo Wash depositional area for sand-transporting winds, presenting the frequency with which sand-transporting winds are headed directly towards the center of Willow for each sector that crosses the depositional area. For increased resolution over the depositional area, we recalculated frequencies for smaller 10° sectors, which resulted in seven sectors between 235° and 305° crossing the Mission – Morongo depositional area. These frequencies reflect the probability that a sand-transporting wind can deliver sand to the Reserve from each sector in the Mission Creek – Morongo Wash depositional area and give one measure of the relative value of different parts of the Mission Creek – Morongo Wash depositional area as it relates to sand transport to Willow Hole. Slight differences in summed percentages result from the differences between defining 22.5° and 10° sectors and the accuracy with which the original wind data were collected.

Sand-Transport Potential

Sand-transport potential is a measure of how much sand can be transported by the wind, assuming that: (1) there is a supply of sand for transport by wind and (2) this sand is available for transport. That is, the surface is not protected by vegetation, the sand is dry, and the surface is not crusted (Kocurek and Lancaster, 1999).

A commonly-used method for analyzing wind data was developed by Fryberger (1979). This method assigns a weighting to the measured wind speed based on how much it exceeds a threshold velocity for transport to estimate a potential sand transport rate (q). Thus:

$$q = V^2 (V - V_t) \cdot t, \qquad (8)$$

where

q is the sand transport potential in arbitrary velocity units (VU),

V is the wind speed,

V_t is the threshold wind speed for sand transport at the height of the wind recorder, and

t is the percentage of the time the wind blows from a given direction.

Values of q are calculated for each wind speed class and summed to estimate a sand drift potential (DP) in vector units for all winds above threshold at a given location. In addition, a vector sum (resultant drift potential, or RDP) and direction is calculated for sand transport potential.

Fryberger (1979) presented a classification scheme in which the DP of a location could be grouped into low-, intermediate-, and high-energy environments based on values of the drift potential (DP). For a station where wind speed is measured in knots (1 nautical mile/hour), low-energy environments have a DP <200, intermediate-energy environments have $200<DP<400$, and high-energy environments have $DP>400$.

The Dune Mobility Index

Whether or not eolian dunes are expected to be mobile or stable under specific wind regime and climatic conditions can be calculated as a function of wind conditions and climate. The dune mobility index (M) is calculated as:

$$M = W / (P/PE), \qquad (9)$$

where

W is the percentage of the time that the wind is above the threshold for sand transport,

P is the annual precipitation (mm),

PE is the threshold wind speed at the height of the wind recorder, and

t is the annual potential evapotranspiration (mm) calculated using the Thornthwaite method (Thornthwaite and Mather, 1957).

Threshold values of the mobility index are: $M<50$, dunes are inactive (stabilized by vegetation); $50<M<100$, only crests of dunes are active;

100<M<200, dunes are active but lower slopes are vegetated; and >200, dunes are fully active (Lancaster and Helm, 2000).

Historical Changes in Eolian Deposits

Following Lancaster and others (1993), we analyzed aerial photography taken in various years to evaluate changes in the spatial extent of eolian deposits (table 3). Aerial photography was analyzed in a geographical information system (GIS) by georeferencing the aerial photography to 7.5' topographic maps. Using these techniques, we have revisited the findings of Lancaster and others (1993) and also qualitatively assessed the areas of active sand in the vicinity of the two reserves and extended the temporal coverage of these eolian systems.

A CONCEPTUAL MODEL OF THE SAND-DELIVERY SYSTEM IN THE NORTHERN COACHELLA VALLEY

This section provides a qualitative description of the sand-delivery system that ultimately produces the eolian habitats in the northern Coachella Valley. Basic geomorphic terms and the elements of the delivery system are defined for clarity and for use in later sections. The sections that follow will provide quantitative estimates of fluvial and eolian transport that logically follow from this conceptual model.

Sand-size particles that eventually become eolian sand in the northern Coachella Valley are generated in the headwaters and steep areas of the San Jacinto, San Bernardino, and Little San Bernardino Mountains. Most sediment is produced on steep slopes at higher elevations in these mountains, where precipitation is more than five times greater than precipitation on the valley floor (table 4). Floods are of higher magnitude below 7,500 ft elevation (Thomas and others, 1997), primarily because most precipitation at higher elevations falls as snow in winter or gentle rainfall in other seasons. Development has not affected sediment sources significantly because most of the areas where sediment is produced is currently under federal or state management. The alluvial fans that coalesce to form the Desert Hot Springs bajada produce insignificant amounts of sediment from most of their surfaces because of the low precipitation, the sandy substrate that readily absorbs rainfall, and the low slope angle of the fan surface.

Sediment is transported from headwaters to depositional areas in Coachella Valley in episodic streamflow floods that are not necessarily even annual in recurrence. Channels through the alluvial fans in the northern Coachella Valley are mostly sediment conduits with little change in storage. Some of these channels, particularly Mission Creek and Morongo Wash, were naturally channelized because the south branch of the Banning (San Andreas) Fault crosses both washes (figs. 2b and 3). Vertical fault offsets prehistorically created nickpoints that migrated upstream on both Mission Creek and Morongo Wash, creating entrenched channels known as arroyos.

Table 3. Aerial photography of the Whitewater and Willow Hole Reserves used to analyze historical changes in eolian deposits.

Photo year	Series title	Date of photograph	Number of photographs	Type of photograph[1]	Photo scale	Coverage of Whitewater?	Coverage of Willow Hole?	Comments
1996	USGS Orthophotos	June	4	Digital	1:12,000	Yes	Yes	1m pixels
1989	USGS NAPP	7/25, 8/16	9	CIR	1:40,000	Yes	Yes	
1984	USGS NHAP	8/24	4	CIR	1:58,000	Yes	Yes	
1979	Oblique	11/15	1	B&W	n.a.[2]	Yes	Yes	one oblique
1977	7	2/4	1	B&W	1:40,000	Partial	Partial	single photo
1972	472	8/17	9	B&W	1:40,000	Yes	Yes	
1965	Universe Special	unknown	2	B&W	1:24,000	No	Yes	
1959	AXM-6W & 10W	June	9	B&W	1:20,000	Yes	Yes	
1953	AXM-1K, 3K, 9K, &10K	8/19, 9/19, 10/24	22	B&W	1:20,000	Yes	Yes	
1939	C6060	12/7	4	B&W	1:18,000	No	Yes	

[1] Digital, orthophotographs derived from aerial photography; CIR, color infrared; B&W, black-and-white aerial photography.

[2] A scale is not applicable because the photograph is oblique.

Table 4. Mean and range in annual precipitation at selected long-term stations in or near the Coachella Valley, California.

		ANNUAL PRECIPITATION[1]		
Location	**Elevation (ft)**	**Annual**	**Minimum**	**Maximum**
Idyllwild Fire Department	5,400	26.09	10.60	56.87
Big Bear Lake	6,760	22.44	6.99	55.76
Deep Canyon	800	5.78	1.37	18.82
Palm Springs	420	5.00	0.76	13.72

[1] Data are from Western Region Climate Center (period of record through 2000), except for University of California Philip L. Boyd Deep Canyon Research Center (M. Fisher, Deep Canyon Preserve, written commun., 2001).

Downstream from the confluence of the San Gorgonio and Whitewater Rivers, and particularly downstream (east) from Windy Point, the Whitewater River channel broadens into what historically was a depositional plain more than a mile in width. This flat depositional plain historically had several channel splays with low banks and may have originated from prehistoric debris-flow deposition. The combined floodwaters of the San Gorgonio and Whitewater Rivers debouch onto the depositional plain, depositing fluvial sediments in a low-energy environment (fig. 3). Because little non-anthropogenic topography is present on these floodplains, fluvial sediments can be assumed to be deposited evenly over the area instead of in discrete packets of relatively thick floodplain deposits as occurs on more entrenched rivers.

Sediment is entrained from the Whitewater depositional area by the unidirectional wind field and is moved across eolian plains downwind from the depositional areas (fig. 3). Much of this eolian transport is unimpeded across the Whitewater Floodplain Reserve, but flow on the north and south sides of the depositional area and the Reserve is influenced by local obstructions. Interruptions in a continuous fetch by buildings, windbreaks, or small or large dikes will create local windbreaks that store eolian sand. Because of this, the windbreaks, as well as raised roadbeds of both the railroad and Interstate 10, interrupt the flow of sand from the Whitewater flood plain, likely storing much of that sand along the windbreaks and embankments and diverting some of it towards the southeast. Other artificial features, such as excavations on the south side of Garnet Hill and recharge and flood-control levees, create sand-storage sites on their lee (downwind) sides even if sand does not overtop the surface.

The Mission Creek – Morongo Wash depositional area is bounded on the north by the vertical offset of the south branch of the San Andreas Fault, which creates a natural channelization of these water courses upstream (fig. 3). Downstream from the fault, and upstream from the embankments and dikes associated with Interstate 10, floodwaters spread over a broad floodplain with little significant topography other than local bar-and-swale features. This depositional area is bounded on the west by the westerly splay of Mission Creek and on the east by the main splay of Morongo Creek at the footslope of Flattop Mountain (fig. 3). Dikes associated with the raised roadbed of Interstate 10 enhance deposition on this floodplain because floodwaters are forced to pass under the freeway at relatively constricted culverts.

Eolian sand is entrained from the Mission Creek – Morongo Wash depositional area in the same manner as from the Whitewater depositional area. The prevailing wind direction is westerly and impinges directly upon Flattop Mountain and a low pass just north of this hill. Flattop Mountain has a gentle slope on its west side, possibly shaped by wind erosion, and this slope allows sand transport over the hill and into the Willow Hole Reserve and to another deposit locally known as Stebbins Dune. During very intense windstorms, and presumably when fluvial sediment is not limiting, some eolian sediment is swept over the Willow Hole Reserve area and is transported onto the hillslopes of the Indio Hills drainage to the north of Edom Hill. Certainly urbanization and the introduction of windbreaks – particularly *Tamarix* trees – has reduced the amount of eolian sand transported by an unknown amount. However, many windbreaks were in place by 1925, and aerial photography since then indicates that a substantial amount of sand has still been transported over Flattop Mountain and into Willow Hole.

Historically, Long Canyon deposited sediment across a two-mile long area stretching south from the mouth of the canyon across the Hot Springs bajada (fig. 3). With the Willow Hole Reserve positioned slightly east of south from this depositional area, only a small fraction of available sand likely would have been transported directly to the Reserve in the prevailing winds. Predominantly westerly winds transport most eolian sand either along the northern edge of the Indio

Hills or into the Indio Hills drainage north of Edom Hill. That the Indio Hills drainage acts as a trap for eolian sand from fluvial deposits to the west is evidenced by the deposits of eolian sand several yards thick that blanket the hillslopes of this area. Much of this sand was likely deposited during the Pleistocene, but sand may still be transported from the Mission – Morongo area during very intense windstorms, as well as from the Long Canyon area. Trapped in a fluvial source area, this eolian sand is recycled into the system as fluvial sediment, entrained and transported out of the Indio Hills drainage during intense summer thunderstorms. Historically, this sediment was deposited locally within the Willow Hole Reserve, where it was available for local redistribution by eolian processes. However, recent storms have entrenched the channel through Willow Hole with the result that much of the fluvial sediment is now deposited just outside the southern boundary of the Reserve where the channels are less entrenched. This material has the potential to be carried back into the Reserve by eolian processes only if sufficient southerly winds occur along the topographic low between Flattop Mountain and the western end of the Indio Hills (fig. 3).

FLUVIAL SEDIMENT TRANSPORT

Quaternary Geologic Units

The Desert Hot Springs bajada is comprised of a mosaic of geomorphic surfaces of Pleistocene and Holocene age (fig. 4). This mosaic is useful for evaluating the potential sediment contributions from the Desert Hot Springs bajada to the depositional areas of Whitewater River and Mission Creek – Morongo Wash. A total of 15 mapping units were identified on this bajada (table 3); descriptions of these units are given in Appendix 1.

Active channels and depositional areas (**Qayy**) comprise 22.3 percent of the mapped bajada area (table 5), and much of this area defines the Whitewater, Mission Creek – Morongo Wash, and Long Canyon depositional areas. These areas are considered to be the most significant to the sand-delivery system of the northern Coachella Valley. Most of the bajada (50.1 percent) is mapped as young fan alluvium of both Holocene and latest Pleistocene age (**Qay**). Units of early Holocene to Pleistocene age comprise 18.1 percent of the alluvial fans. These units, combined with **Qay**, likely produce little fluvial or eolian sediment that reaches the depositional areas for reasons of low precipitation, high infiltration rates, and low slope angles. Reflecting the ephemeral nature of eolian deposits in this part of the Coachella Valley, only 6.1 percent of the area was mapped as eolian sand (**Qe**) or sand dunes (**Qd**). Most of these units are in the southeast corner of the mapped area in the Willow Hole Reserve (fig. 4). Despite this, **Qayy** and **Qay** units on the south edge of the mapping area (fig. 4) historically have had significant ephemeral dune migration across their surfaces.

Table 5. Quaternary geologic units of the Desert Hot Springs and Seven Palms Canyon 7.5′ quadrangles, California.

RANKED BY AGE			RANKED BY SURFACE AREA		
Quaternary unit	Area (mi2)	Coverage (percent)	Quaternary unit	Area (mi2)	Coverage (percent)
Afd	1.0	1.0	Qay	48.3	50.1
Qd	0.5	0.5	**Qayy**	**21.5**	**22.3**
Qe	5.4	5.6	Qe	5.4	5.6
Qayy	**21.5**	**22.3**	Qai	4.8	5.0
Qayi	**2.4**	**2.5**	Qayo	4.1	4.2
Qay	48.3	50.1	Qao	3.1	3.3
Qayo	4.1	4.2	**Qayi**	**2.4**	**2.5**
Qfy	0.7	0.7	Qtps	2.0	2.1
Qaiy	0.7	0.7	Qtpc	1.1	1.2
Qai	4.8	5.0	Afd	1.0	1.0
Qao	3.1	3.3	Qaiy	0.7	0.7
Qau	0.7	0.7	Qfy	0.7	0.7
Qcf	0.2	0.2	Qau	0.7	0.7
Qtpc	1.1	1.2	Qd	0.5	0.5
Qtps	2.0	2.1	Qcf	0.2	0.2

Fluvial Sediment Yield and Delivery

Flood-Frequency, Rating-Curve Relation

The sediment rating curve calculated for the Whitewater River near Whitewater took the form:

$$Q_d = Q^{2.72} \cdot 10^{-1.21}, \tag{10}$$

where

Q_d is the daily sediment yield (t/day), and

Q is the daily flood discharge (ft^3/s).

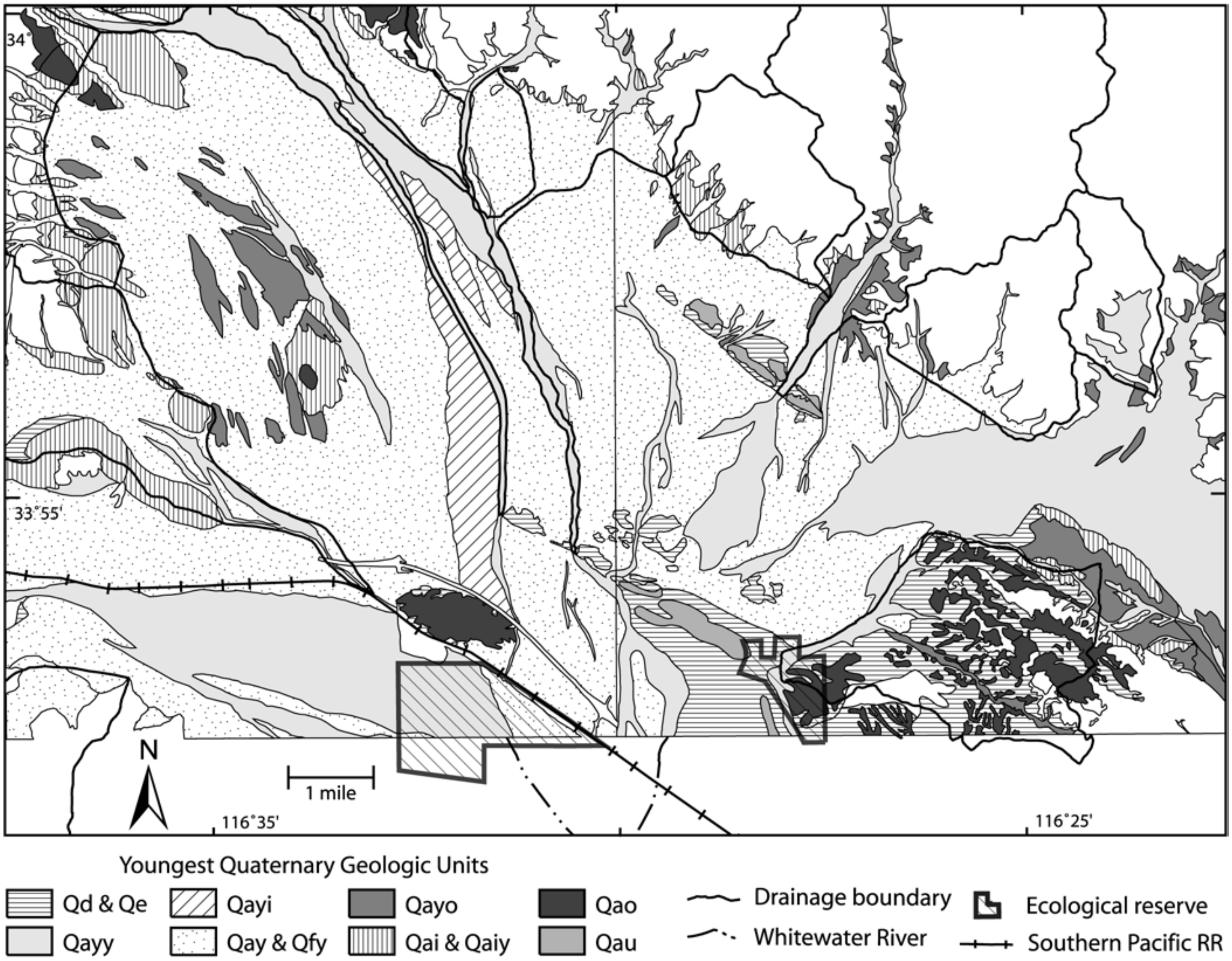

Figure 4. The eleven most recent Quaternary geomorphic surfaces and deposits in the Desert Hot Springs and Seven Palms Valley 7.5′ Quadrangle Maps in the northern Coachella Valley, California (Lundstrom and others, 2001). See Appendix 1 for a description of map units.

R^2 is 0.90 for this rating curve, indicating a high degree of relation between streamflow discharge and sediment yield (fig. 5). Using this relation to calculate total event yield for the 50 largest floods on the Whitewater River, we derived the relation between event sediment yield [$\Theta(Q_p)$] in tons/yr and peak discharge (Q_p) in ft^3/s as:

$$\Theta(Qp) = Q_p^{2.751} \cdot 10^{-1.092}. \qquad (11)$$

R^2 for this relation is 0.91. Equation (11) was used in combination with flood frequency relations (table 2) to estimate annual sediment yields for drainages contributing sediment to the northern Coachella Valley.

Sediment-Yield Estimates

Sediment-yield estimates calculated using the flood-frequency/rating-curve technique (equation (11)) were in reasonably close agreement with those calculated using the Renard (1972) relation (equation (3)), being of the same order of magnitude and consistently twice the quantity (table 6). Estimates from both techniques are given in the tables to provide minimum and maximum estimates of sediment yield. For simplicity, the following discussion and analysis will only use the estimates based on Renard (1972).

Sediment yield to the Whitewater depositional area in the modern era is slightly less than in the predevelopment period owing to the absence of the

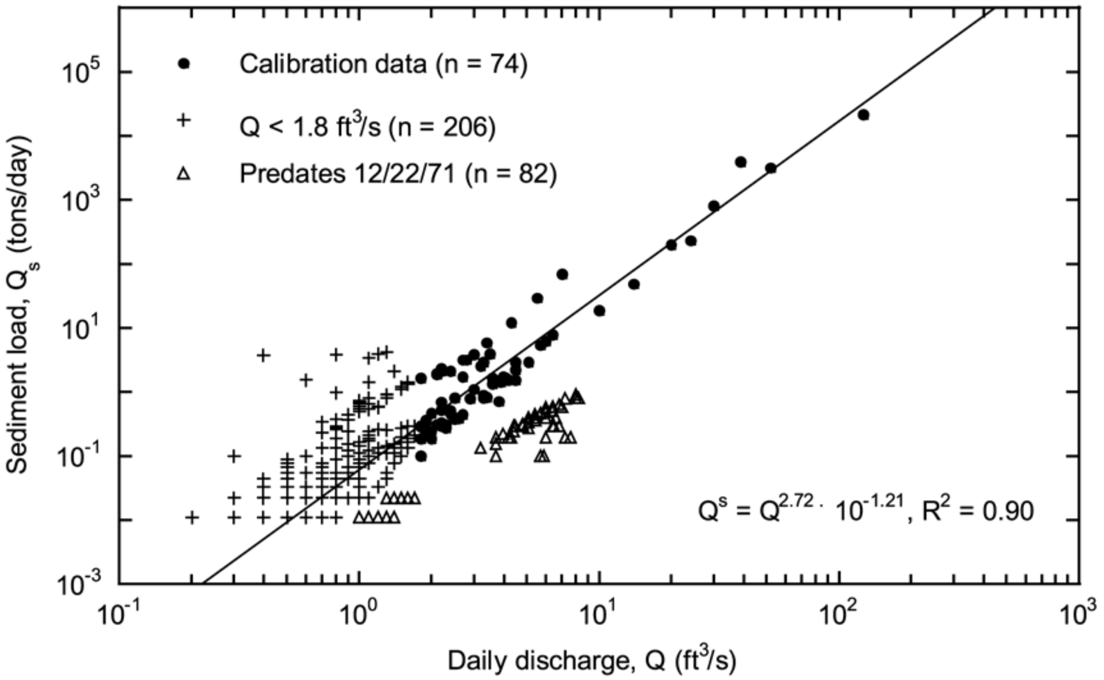

Figure 5. Sediment-rating curve for the Whitewater River near Whitewater, California (station number 10256000). Daily sediment samples were collected between October 1, 1970, and September 30, 1972

upper San Gorgonio River and Blaisdell Canyon as sources of sediment. The in-stream mining operation on the upper San Gorgonio River appears to reduce sediment yields in the entire San Gorgonio basin by 14 percent (table 6). Reflecting differences in drainage area, the volume of sediment delivered to the Whitewater depositional area at 3.5 million ft^3/yr is roughly double that delivered to the Mission Creek – Morongo Wash depositional area at 1.5 million ft^3/yr. Long Canyon delivers 0.42 million ft^3/yr and the Indio Hills drainage area 0.11 million ft^3/yr. Actual sediment yield from the Indio Hills may be higher than this estimate due to the abundant loose sediment available on hillslopes in these drainages.

Sediment yield from the non-channel area (all but **Qayy**) of the Desert Hot Springs bajada, also calculated using the Renard (1972) relation, is an estimated 0.74 million ft^3/yr (table 6), or about 12 percent of the total estimate for all tributary drainage areas. The flood-frequency, rating-curve technique for estimating sediment yield could not be applied to these poorly-defined drainage areas. However, the estimate using the Renard equation should be considered a maximum value, at best, because the sediment-yield relation used was developed for an area with more than twice the mean annual precipitation than occurs on the alluvial fans.

Most sediment production occurs in high-relief parts of the San Bernardino, Little San Bernardino, and San Jacinto Mountains. On average, 56 percent of the area of contributing drainages has a ground slope in excess of 30 percent (table 7), with an additional 27 percent having a slope of 10 to 30 percent. The steepest drainages, such as Snow Canyon, which heads at San Jacinto Peak (10,804 feet), can have more than 80 percent of their area steeper than a 30 percent slope. In contrast, 95 percent of the alluvial fans have less than a 10 percent slope (table 7), and sediment production would be expected to be much lower than from the steeper mountain drainages. This interpretation is supported by the Quaternary geologic mapping, which labels most of the alluvial fans as alluvium that dates to as long ago as the late Pleistocene (**Qay**), in contrast to the younger, more active sediment of the tributary channels (**Qayy**; fig. 4).

Table 6. Estimates of sediment yield from drainages entering the northern Coachella Valley for historic (predevelopment) and modern periods.

Tributary	HISTORIC SEDIMENT YIELD[1] ($10^6 \cdot ft^3/yr$) Drainage area (mi^2)	Renard (1972) equation	Flood-frequency method	MODERN SEDIMENT YIELD[1] ($10^6 \cdot ft^3/yr$) Drainage area (mi^2)	Renard (1972) equation	Flood-frequency method
San Gorgonio/Whitewater depositional area						
San Gorgonio River[2]	154	2.1	3.3	132	1.8	2.5
Whitewater River	60	0.87	1.5	60	0.87	1.5
Snow Canyon	19	0.32	0.78	19	0.32	0.78
Stubbes Canyon	8	0.16	0.47	8	0.16	0.47
Cottonwood Canyon	7	0.14	0.44	7	0.14	0.44
Garnet Wash	6	0.11	0.38	6	0.11	0.38
Blaisdell Canyon[3]	6	0.11	0.38	0	0	0
San Jacinto 2	3	0.069	0.27	3	0.069	0.27
San Jacinto 1	2	0.051	0.22	2	0.051	0.22
TOTAL	266	3.9	7.8	238	3.5	6.6
Mission/Morongo depositional area						
Mission Creek	38	0.59	1.18	38	0.59	1.18
Little Morongo (lower)	34	0.54	1.10	34	0.54	1.10
Dry Morongo	11	0.19	0.55	11	0.19	0.55
Big Morongo (lower)	9	0.16	0.49	9	0.16	0.49
TOTAL	92	1.5	3.3	92	1.5	3.3
Long Canyon depositional area						
Long Canyon	26	0.42	0.94	26	0.42	0.94
Willow Hole depositional area						
Indio Hills	6	0.11	0.38	6	0.11	0.38
TOTAL (all drainage areas)	390	6.0	12.4	362	5.5	11.2
Alluvial fans	49	0.74	–	49	0.74	–

[1] Estimates have been converted from mass to volume by assuming a sediment density of 0.0375 tons/ft^3.

[2] The San Gorgonio River above Banning, California, does not contribute sediment in the modern era.

[3] Blaisdell Canyon does not contribute sediment in the modern era.

Historical Changes in the Size of the Depositional Areas

Fluvial sediment from each contributing drainage area is deposited onto one of four depositional areas (figs. 3 and 6, table 6). The nine westernmost tributaries deposit sediment downstream from the confluence of the San Gorgonio and Whitewater Rivers in the Whitewater depositional area, which extends from Windy Point to the east and from the railroad south (figs. 3 and 6). Immediately to the east, Mission Creek and Morongo Wash (a composite of three drainages) deposit in an area between the west splay of Mission Creek and the east splay of Morongo Creek north of Interstate 10 and south of the Banning (San Andreas) Fault (figs. 3 and 6). Long Canyon deposits at a third area, stretching southwest from the mouth of the wash onto the Desert Hot Springs bajada. Sediment from the Indio Hills tributary was historically deposited directly into Willow Hole and the Willow Hole Reserve. As stated previously, recent storms have channelized the reach through Willow Hole, causing sediment to be deposited outside the southern boundary of the Reserve and temporarily decreasing the potential for eolian additions directly from the channel. This poorly defined area was not evaluated as a distinct depositional area.

Table 7. Slope classes of sediment source areas and alluvial fans in the northern Coachella Valley.

		DRAINAGE AREA IN SLOPE CLASS (percent)		
Tributary	**Drainage area (mi^2)**	**> 30 percent slope**	**10 - 30 percent slope**	**< 10 percent slope**
San Gorgonio River	153.5	46	22	32
Little Morongo	67.7	63	25	13
Whitewater River	59.6	78	14	8
Mission Creek	38.4	74	19	7
Big Morongo	31.0	62	21	17
Long Canyon	26.3	73	24	4
Snow Canyon	19.3	84	10	6
Dry Morongo	10.7	54	31	15
Stubbes Canyon	8.4	78	12	10
Cottonwood Canyon	7.5	70	22	9
Garnet Wash	6.0	11	28	62
Blaisdell Canyon	6.0	77	15	9
“Indio Hills”[1]	5.9	8	50	42
“San Bernardino 1”[1]	5.8	37	47	16
“San Bernardino 2”[1]	3.8	55	30	15
Blind Canyon	3.4	52	39	9
“San Jacinto 2”[1]	3.4	69	11	20
“San Jacinto 1”[1]	2.4	69	17	14
West Wide Canyon	1.9	49	31	20
MEAN	–	56	27	17
Alluvial fans	49.3	1	4	95

[1] Tributary has no official name.

Before the construction of infiltration galleries, retention dikes, railroad, and major highways (the predevelopment period), the areal extent of the three main depositional areas strongly reflected the amount of annual sediment deposited in each zone (tables 6 and 8; fig. 6a). The historic Whitewater depositional area received roughly three times the sediment received by the Mission Creek–Morongo Wash depositional area and was about 2.5 times larger (7 mi^2 as opposed to 3 mi^2). Similarly, the Mission Creek–Morongo Wash depositional area received roughly three times the sediment deposited in the Long Canyon depositional area and was also about three times larger (3 mi^2 as opposed to 1 mi^2).

In the modern era, the extent of two depositional areas – the Whitewater and Long Canyon depositional areas – has been reduced by alteration of channels and floodplains (fig. 6b, table 8). The Whitewater depositional area has been reduced by nearly 50 percent to 3.6 mi^2 by the installation of the infiltration galleries along the south edge of the river (fig. 6b). These galleries necessarily trap fluvial sediment, which is then unavailable for eolian transport owing to the geometric arrangement of the galleries perpendicular to wind direction. In addition, there is a loss of fetch area between the infiltration galleries and the reserve; the Whitewater depositional area has been reduced to a thick band along what was the northern edge of the river. Similarly, the Long Canyon depositional area has been truncated by major roads on three sides, reducing depositional area by over 80 percent to 0.2 mi^2. Although small culverts pass beneath the roads, most sediment appears to be effectively trapped within the reduced depositional area unless flow substantially overtops the roads.

Table 8. Change in depositional areas upwind of reserves in the Northern Coachella Valley

Depositional area	**Historic area (mi^2)**	**Modern area (mi^2)**	**Change (mi^2)**	**Change (percent)**
San Gorgonio/ Whitewater	7.1	3.6	-3.5	-49.2
Mission/Morongo	2.7	2.7	0	0
Long Valley	1.1	0.2	-0.9	-80.2
TOTAL	10.8	6.5	-4.3	-40.1

The modern Mission Creek – Morongo Wash depositional area is approximately the same size as the historic area. Dikes associated with Interstate 10 and railroad construction limit the depositional area to mostly north of the freeway and reduce the connectivity with the Whitewater depositional area. Because these washes fan out over a broad depositional area upstream from the freeway dikes, most habitat-building sand is likely deposited in a position that makes it available for eolian transport. This condition may have been the case in the predevelopment period.

Depth of Deposition

After converting sediment-yield estimates from mass to volume, we distributed fluvial sediment over the three historic depositional areas, both as a check on the magnitude of the fluvial sediment yields and to determine if prevailing winds could entrain this amount of sediment. The depth of fluvial sediment deposited in the historic period is very consistent among the three

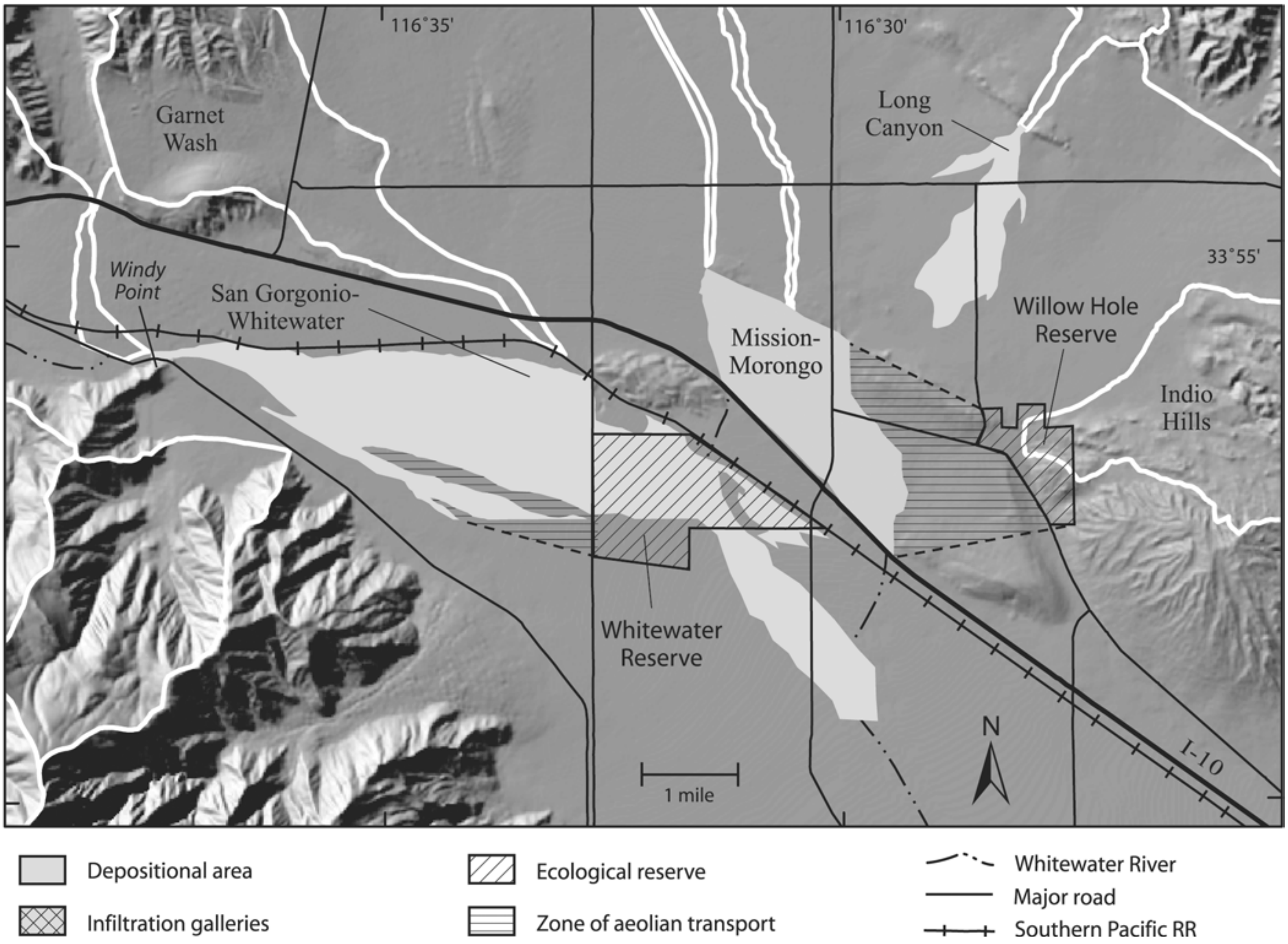

Figure 6. Shaded relief map showing the location of historic and current areas of fluvial deposition for the San Gorgonio – Whitewater River, Mission Creek – Morongo Wash, and Long Canyon drainages. White lines indicate drainage boundaries.

A. Historic (predevelopment) areas of fluvial deposition.

depositional areas, about 0.2 in./yr (table 9). This depth agrees well with field observations made at the depositional areas and suggests that the sediment-yield estimates made using both approaches are of an appropriate order of magnitude.

The artificial reduction of the size of the depositional areas is clearly evident in the large increase in estimated deposition depth on the Whitewater depositional area from 0.2 (predevelopment) to 0.4 in./yr (modern). Similarly, the increase is particularly large on the Long Canyon depositional area (from 0.2 to 0.9 in./year). The modern estimate of depth of deposit at Long Canyon is high, perhaps too high, with an unknown quantity of material spilling over the adjacent roads at higher flows to be deposited further downstream. The estimate for the Whitewater depositional area, however, does not take into account the trapping of sediment in the infiltration galleries and therefore should be considered a maximum.

Given that the diversion dikes are designed to breach above a given flood level, it is difficult to effectively estimate the amount of sand actually trapped by the infiltration dikes. In 1996, 8.1 million ft^3 of "silt" was dredged from 3 of the 19 percolation ponds (Daniel Farris and Patti Schwartz, Coachella Valley Water District, oral commun., 2002), and the remaining ponds were ripped to enhance infiltration. Without knowing the period over which the trapping occurred, it is impossible to evaluate precisely what percentage of total sediment yield from the San Gorgonio – Whitewater system this sediment

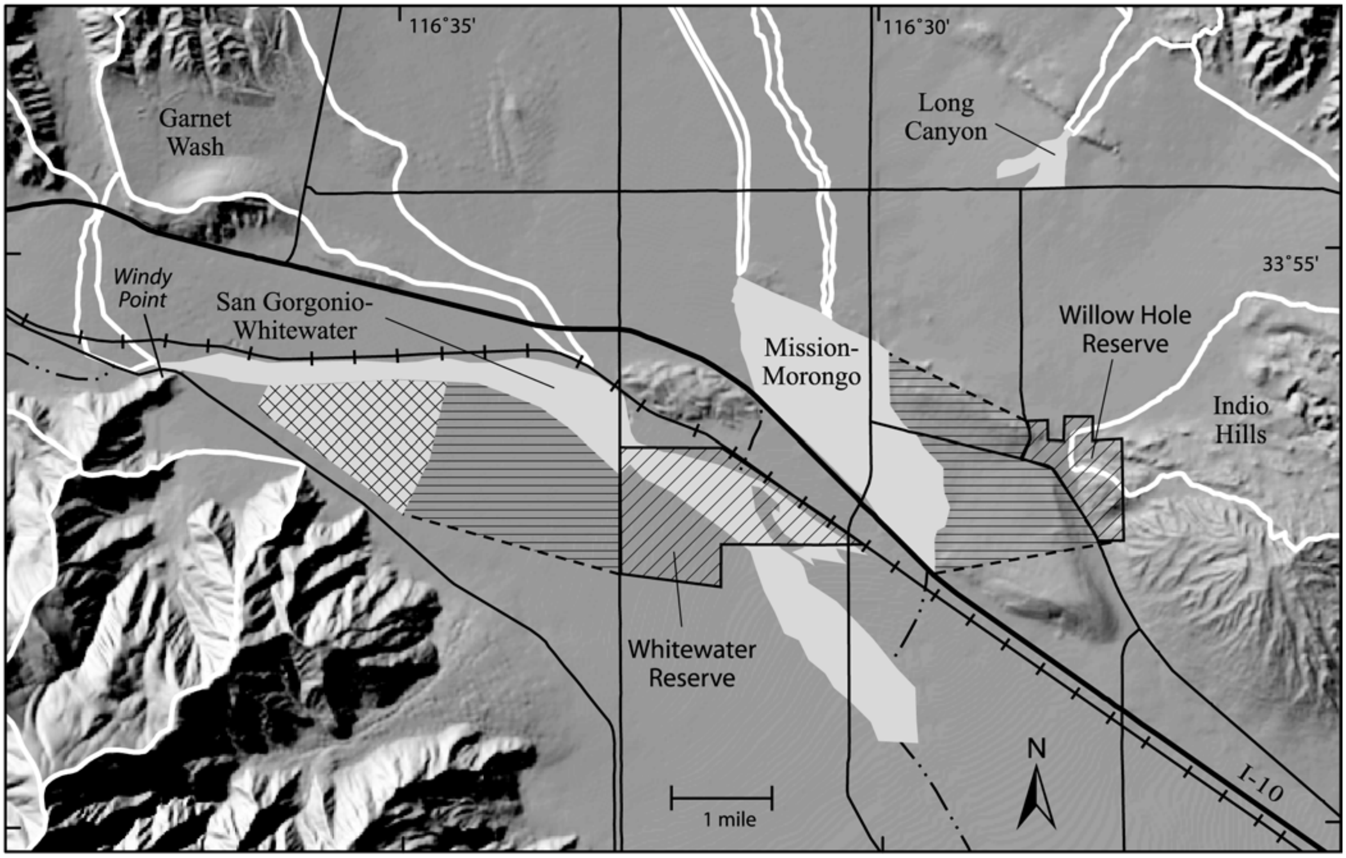

Figure 6. *Continued.*

B. Current (1993) areas of fluvial deposition and the infiltration galleries (also known as percolation ponds) in the Whitewater River.

Table 9. Estimates of total sediment delivered to zones of deposition in the northern Coachella Valley.

Depositional area	HISTORIC SEDIMENT YIELD (in/yr)			MODERN SEDIMENT YIELD (in/yr)		
	Depositional area (mi^2)	Renard (1972) equation	Flood-frequency method	Depositional area (mi^2)	Renard (1972) equation	Flood-frequency method
San Gorgonio/Whitewater	7.1	0.24	0.47	3.6	0.41	0.79
Mission/Morongo	2.7	0.24	0.53	2.7	0.24	0.53
Long Canyon	1.1	0.17	0.38	0.2	0.86	1.91
MEAN	–	0.22	0.46	-	0.51	1.08

represents. In its entirety, this volume of sediment represents 100 to 230 percent of the average annual sediment yield. However, the same amount of sediment distributed over a twenty-year period results in an average annual sediment loss of 5 to 12 percent. Actual sediment loss probably is somewhere between these extremes. In addition, the particle-size distribution of the trapped sediment must be known in order to calculate what percentage of this sediment is eolian sand, let alone lizard habitat sand. If this trapped material was largely silt-sized particles with very little sand, its loss has had little direct effect on *Uma* habitat. Both the time period of trapping as well as an accurate understanding of the particle-size distribution of the trapped sediment is necessary to understand the long-term sediment trapping that occurs in these infiltration galleries and the effects it has on the sediment-delivery system in the northern Coachella Valley.

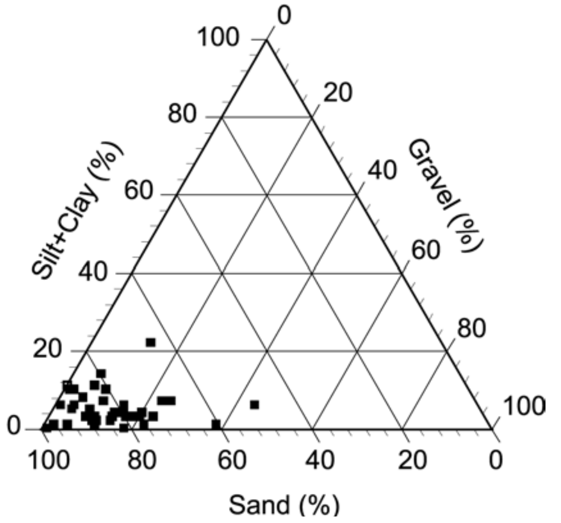

Figure 7. Ternary diagram showing sediment particle-size distributions for samples collected from washes in the northern Coachella Valley.

Table 10. Percent of total fluvial sediment yield composed of sand sizes preferred by *Uma inornata*.

Source	Preferred sand[1] (wt percent)	Standard deviation (±wt percent)	Sample (n)
San Gorgonio – Whitewater River	18.7	8.6	8
Mission Creek – Morongo Wash	17.6	6.3	15
Long Canyon	17.1	8.3	15
Edom Hills	35.0	9.1	2
ALL SITES	18.5	8.3	41

[1] The range in sand preferred by *Uma* has an intermediate diameter ranging between 0.172 and 0.328 mm ($1.6 < \phi < 2.5$; Barrows, 1997).

Particle-size Distributions

The sediment transported in channels of the northern Coachella Valley is relatively well sorted and is composed of 82.5 percent sand-size particles (fig. 7). The proportion of fluvial sediment in the 0.172 to 0.328 mm range preferred by *Uma* was remarkably consistent across the study area and had a mean value of 18.5 ± 8.3 percent (table 10). By source area, sand in the 0.172 - 0.328 mm range comprised 18.7 percent of the San Gorgonio – Whitewater River sediment yield, 17.6 percent of the Mission Creek – Morongo Wash sediment yield, 17.1 percent of the Long Canyon sediment, and 35.0 percent of the Indio Hills sediment yield. The eolian origin of much of the Indio Hills sand is evident in the significantly higher percentage of preferred sand – double that of the other sand sources – making this a particularly rich potential source of sand for *Uma* habitat.

Climate, Precipitation, and Flood Frequency

As shown in table 4, mean annual precipitation varies by a factor of five within the drainages that supply sediment to the northern Coachella Valley. Because the valley floor receives only 5 in. of precipitation, sediment yields from alluvial fans such as those that comprise the Desert Hot Springs bajada would be lower than the overall average sediment yield from the higher elevation sites. Because of this, the sediment contribution from the Desert Hot Springs bajada is expected to be much lower than the 11 percent calculated by assuming equal contributions from the entire drainage area.

The range in annual precipitation at each station is even larger than the elevational differences in annual precipitation. Interannual precipitation ranges by a factor of more than 5 at higher-elevation sites to a factor of more than 15 on the valley floor. This climatic variability undoubtedly affects fluvial sediment delivery to the Coachella Valley in significant ways. During drought years, little sediment is expected to be delivered from the headwaters to the valley floor. During wet periods, sediment delivery is greatly increased.

Periods of negative Southern Oscillation Index (SOI), otherwise known as El Niño conditions, have a large influence on the climate of the Coachella Valley and its surrounding mountains. Although El Niño strictly speaking is an oceanic phenomena off the western coast of Peru, the term has come to apply to overall changes in the equatorial Pacific Ocean that create conditions favorable to increases in winter precipitation in the southwestern United States. One definition of El Niño calls for 5 or more months of negative SOI (Cayan and Webb, 1993); El Niño recurs every 4-7 years in the equatorial Pacific Ocean with no definite historical change in frequency (Webb and Betancourt, 1992). The SOI is shown in (fig. 8a).

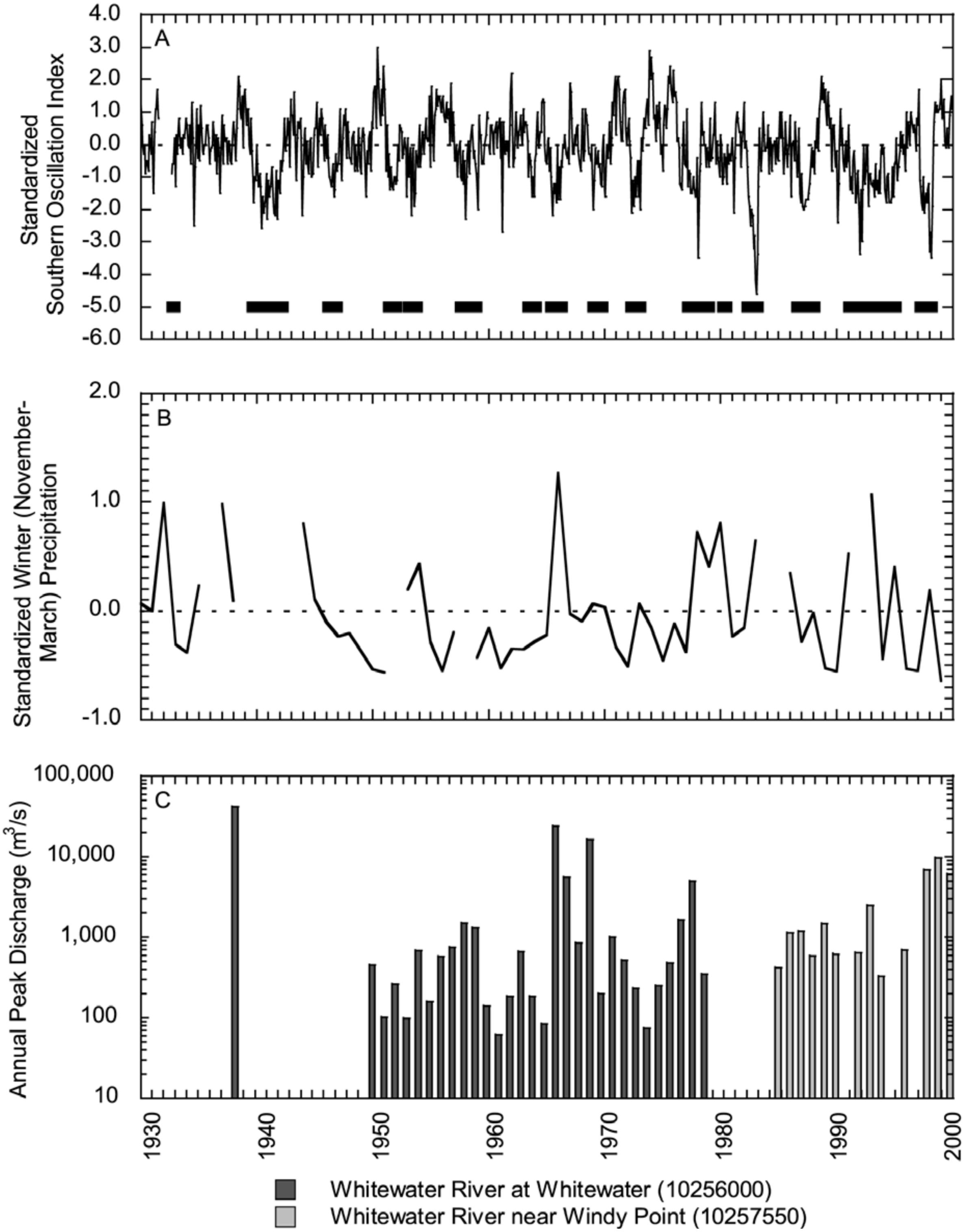

Figure 8. Climate, precipitation, and flood-frequency data for the northern Coachella Valley.

A. The Southern Oscillation Index (in standardized form) from 1930-2000. El Niño conditions are considered to occur when the SOI is negative for protracted periods (*e.g.*, greater than about 5 consecutive months) and are shown in thick lines at bottom.
B. Standardized precipitation for Palm Springs, California. C. The annual flood series for the Whitewater River, combined from the gaging stations at Whitewater and Windy Point, California.

Precipitation within the Coachella Valley is affected by the SOI (fig. 8b). El Niño periods are generally periods of above-average precipitation at Palm Springs. Unfortunately, the Palm Springs precipitation record has many missing values (fig. 8b), which precludes a quantitative assessment of El Niño effects. As is evident in a close comparison of figures 8a and 8b, not all periods with El Niño conditions correspond to periods of increased precipitation. For example, average or below-average conditions prevailed at Palm Springs during 3 of 4 El Niño periods in the 1960s.

With the exception of 1938, most significant floods on Whitewater River have occurred during El Niño conditions (fig. 8c). In the last 25 years, floods have occurred in 1978, 1983 (not recorded in the gaging record of figure 8c), 1993, and 1998, which represent four of five El Niño episodes in that period. Streamflow is greatly increased in the southwestern United States during El Niño conditions (Cayan and Webb, 1993), and historically El Niño conditions produce wet periods and some of the largest flood years in the history of the southwestern United States (Webb and Betancourt, 1992), but drought conditions may occur also, as was the case in many areas during the El Niño conditions of 1986-1987.

La Niña conditions are the opposite of El Niño conditions and are likewise defined as a protracted period of positive values of the SOI. Unlike El Niño, however, La Niña conditions reliably produce drought conditions. As is apparent in figure 8, periods of positive SOI are related to both below-average precipitation at Palm Springs and low-flood years on the Whitewater River.

Some observers have forecasted 20-30 years of protracted drought for the region, partially in response to expected future patterns of the Pacific Decadal Oscillation (PDO), which is related to the SOI (Schmidt and Webb, 2001). If such protracted drought were to occur, the delivery of fluvial sand to the northern Coachella Valley would be reduced because of the decrease in flood occurrence. However, as discussed in a later section, drought could potentially increase eolian sand-transport rates by decreasing the cover of perennial vegetation and thereby decreasing surface roughness, although the amount of sand available for transport would be greatly reduced owing to less frequent floods.

EOLIAN TRANSPORT

Historical Wind Speed and Direction

Abundant wind energy is available in the northern Coachella Valley to transport eolian sand. Data are available for National Weather Service stations at Palm Springs and Thermal, and for instruments maintained by SeaWest at Edom Hill during the period 1999-2002. Because the wind data were recorded for different purposes and with different instrumentation, rigorous inter-comparison of wind speeds, for example, is not possible, but the data provide useful information about changes in wind regimes in this part of the Coachella Valley (Tables 11 and 12). Table 12 shows the annual frequency of winds from different directions recorded at Palm Springs for the period 1998-2001 (these data are also shown as a rose diagram in fig. 9a). About 63 percent of all winds at this station are from directions between northwest and north, giving rise to a wind vector of 343° or northwesterly. This concentration of winds from one directional sector is because wind directions are strongly controlled by the topography of the area, in which winds are funneled through the San Gorgonio Pass and blow down the Coachella Valley.

Table 12 also shows the percentage of winds from different directions at Edom Hill (these data are also shown as a rose diagram in fig. 9b). At this locality, 47 percent of all winds are from directions between west and northwest, with westerly directions dominating (20.4 percent of all winds). The annual wind vector for Edom Hill is 298° or west-northwest. Because suitable data at Edom Hill are available for only one year (2001), the remaining analyses are for the wind data from Palm Springs International Airport, which has a longer record. We assume that the characteristics of wind other than direction are similar between Palm Springs and Edom Hill.

The strongest winds experienced at Palm Springs are from the NW and NNW (average speed = 11.7 mi/hr) and occur mostly during the afternoon (fig. 10). There is a regular daily cycle of wind speed, as shown in figure 10. In the early morning hours, wind speed is low (< 5 mi/hr) and direction is variable. After about 8 am, wind speed increases, and wind direction becomes steady at 310-320° (NW). Maximum wind speed usually occurs in the late afternoon or early evening (4 to 8 pm). Average scalar wind speed varies through the

Table 11. Percentage frequency of winds at Palm Springs International Airport (1998-2000).

	WIND SPEED (mi/hr)									
Direction	**0-5**	**6-10**	**10-15**	**15-20**	**20-25**	**25-30**	**30-35**	**35-40**	**40+**	**All speeds**
N	22.7	3.0	1.0	0.5	0.2	0.0	0.0	0.0	0.0	27.4
NNE	0.4	0.6	0.2	0.1	0.1	0.0	0.0	0.0	0.0	1.4
NE	0.3	0.4	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.9
ENE	0.3	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.0
E	1.0	2.8	0.3	0.1	0.0	0.0	0.0	0.0	0.0	4.2
ESE	1.0	3.9	0.8	0.1	0.0	0.0	0.0	0.0	0.0	5.8
SE	1.3	2.8	0.4	0.1	0.0	0.0	0.0	0.0	0.0	4.6
SSE	1.3	1.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3.0
S	1.8	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
SSW	1.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7
SW	1.2	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	2.0
WSW	1.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1
W	1.8	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3
WNW	1.4	2.4	0.3	0.0	0.0	0.0	0.0	0.0	0.0	4.1
NW	1.7	6.2	5.0	3.4	1.0	0.1	0.0	0.0	0.0	17.4
NNW	1.5	8.2	3.9	3.0	1.3	0.2	0.0	0.0	0.0	18.1
All directions	40.1	37.3	12.3	7.4	2.6	0.3	0.1	0.0	0.0	100.0

Table 12. Comparison of winds at Palm Springs Airport and Edom Hill.

	PROBABILITY OF OCCURRENCE (percent)			
	All winds		**Sand-transporting winds**	
Wind direction	**Palm Springs**	**Edom Hill**	**Palm Springs (>12 mi/hr)**	**Edom Hill (>14.3 mi/hr)**
N	27.4	7.3	6.8	1.9
NNE	1.4	4.1	1.9	1.0
NE	0.9	1.9	1.0	0.1
ENE	1.0	1.0	0.0	0.0
E	4.2	1.7	1.0	0.2
ESE	5.8	5.0	1.0	1.1
SE	4.6	6.6	1.0	0.0
SSE	3.0	6.0	0.0	0.0
S	3.0	2.9	0.0	0.0
SSW	1.7	1.4	0.0	0.0
SW	2.0	1.8	0.0	0.5
WSW	2.1	5.1	0.0	7.3
W	3.3	20.4	0.0	50.5
WNW	4.1	12.4	0.0	23.8
NW	17.4	14.0	43.7	12.6
NNW	18.1	8.3	43.6	1.0
Wind Vector Direction	343°	298°	282°	282°

year, but the months of maximum wind speed typically are April through June, with May having the highest average wind speed (9.9 mi/hr), as shown in figure 11. The overall character of the wind regime at Thermal is similar to that at Palm Springs International Airport, but with much lower wind speeds. For example, mean annual wind speed at Palm Springs International Airport is 7.2 mi/hr, but the mean annual wind speed is only 6.1 mi/hr at Thermal. The wind regime at Edom Hill follows a similar pattern to elsewhere in the valley, but average wind speeds in this area are somewhat higher, with a mean annual wind speed of 11.4 mi/hr. Therefore, eolian transport calculations based on wind data from Palm Springs International Airport should be considered minimums, given that actual velocities upwind of the reserves may be more than 50 percent higher.

Sand-Transport Potential

Wind data from Palm Springs and Edom Hill were analyzed using the methods of Fryberger (1979) as described in the Methods section. For the period 1998-2000, Palm Springs has a drift potential (DP) of 277 VU and an RDP of 261 VU (velocity units). This classifies the area as a moderate-energy, near unimodal

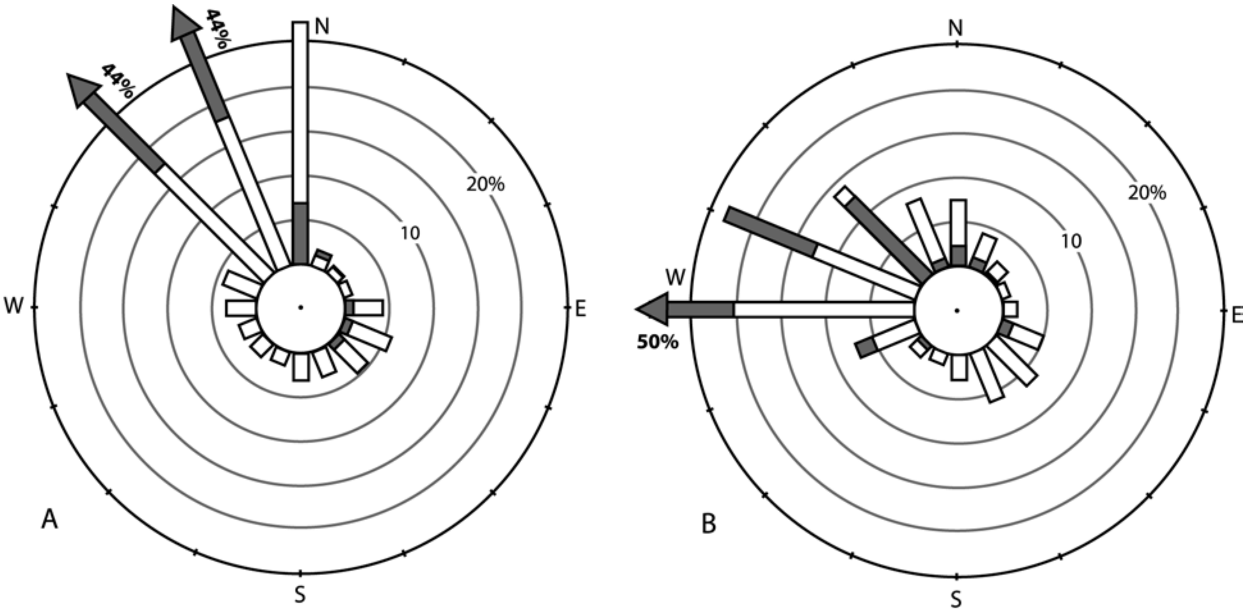

Figure 9. Rose diagram showing annual directional frequency of winds at selected sites in the Coachella Valley.
A. Palm Springs International Airport for the period 1998-2000. B. Edom Hill (Willow Hole Reserve) for the period of 2001. White bars represent all wind velocities; gray bars represent winds of sufficient velocity to transport sand.

wind regime. The annual resultant (vector sum) potential sand transport direction is 342°. For Edom Hill, the total DP is 646 VU, with a RDP of 556VU and a resultant direction of 282°.

For the period 1998-2000, 89 percent of the annual drift potential at Palm Springs is generated by winds from the NW and NNW directions. These directions are important in all months with a range from 15 percent in December to 97 percent in May. Winds from the NNE and N contribute significantly (up to 74 percent) to drift potential during the winter months of November-February, but these months are a time of generally low drift potentials (fig. 12). At Edom Hill, 72 percent of the potential sand transport is generated by winds from the west and west-northwest, with the majority from the west.

Drift potential varies with the percentage of the time that the wind is blowing with higher velocity. At Palm Springs, monthly drift potential varies with the seasons, and reaches a peak in May (fig. 12). About 65 percent of the annual drift potential (DP) and 67 percent of the resultant drift potential (RDP) occurs in the period March through June. There is very little drift potential (15 percent of the annual total) during the winter months (November–February). The pattern at Edom Hill is similar.

In February 1998, the system used to measure wind speed at Palm Springs International Airport changed. One result of this change is that the magnitude of DP and RDP changes significantly after that time and is reduced by a factor of 3.6, compared to the period 1992-1998. However, the interannual variability of the sand drift potential does not change. Annual drift potential varies from 67 to 122 percent of the mean value and is mainly caused by changes in the duration and frequency of strong winds from year to year.

Spatial Variations in Sand-transport Potential

There is a very large drop in wind energy between Palm Springs and Thermal, as evidenced by the change in DP values from 277 VU at Palm Springs to only 7 VU at Thermal. This change reflects the expansion of airflow and reduction in wind speed away from the San Gorgonio Pass. Such expansion of the airflow and reduction of wind speed leads to deposition of sand down valley, as evidenced by the areas of dunes occurring in this part of the valley (*e.g.*, Coachella Valley Reserve). As expected, the acceleration of wind over Edom Hill produces a high energy wind regime at this location, with a total DP of

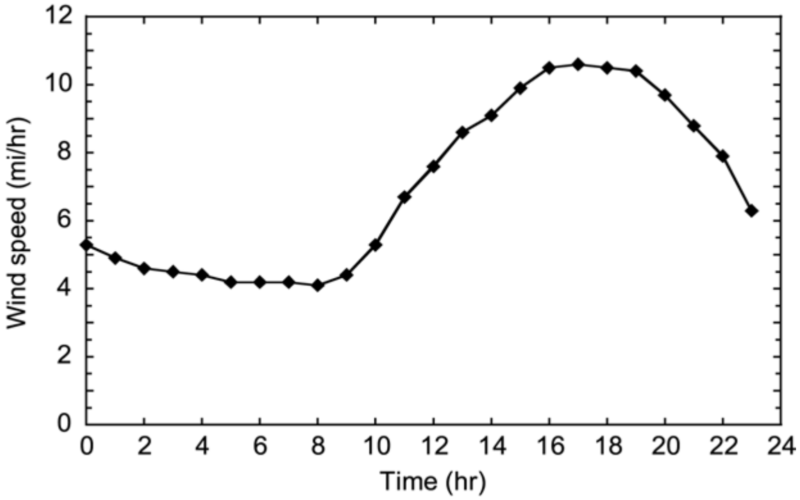

Figure 10. Diurnal cycle of winds at Palm Springs International Airport.

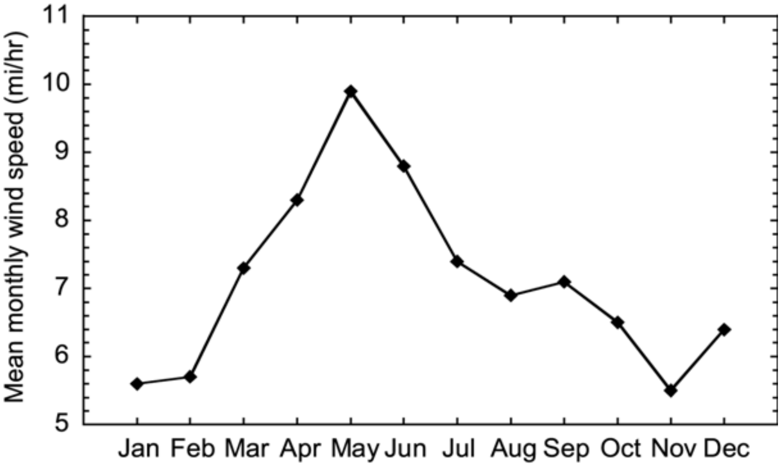

Figure 11. Variation in monthly wind speeds at Palm Springs International Airport.

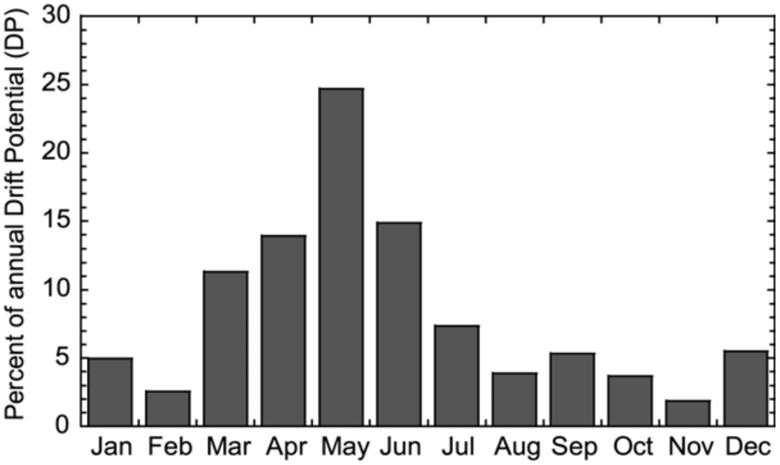

Figure 12. Variation in monthly values of Drift Potential (DP) calculated from wind data at Palm Springs International Airport.

646 VU. There is also a change in the vector sum sand-transport potential direction from 295° at Edom Hill to 332° at Palm Springs and 312° at Thermal.

Dune Mobility

The dune mobility index, M, was calculated from the wind data at the Palm Springs. Values of W, or the percentage of time the wind was above the sand-transport threshold, were estimated using a threshold value of 12.3 mi/hr (10.6 knots). Wind exceeding this threshold were observed 25-30 percent of the time on an annual basis before 1998 and dropped to 15-20 percent of the time once 24-hour readings became available. This is an artifact of the inclusion of the usually calmer early morning period of 12 am to 6 am. Because of the change in the recording system in 1998, increasing the amount of valid data, the mobility index values for 1998 on were adjusted to take account of this extra time.

Over the period of record, the average M for Palm Springs was 557, indicating that the northern Coachella Valley is a very active eolian environment with fully active dunes. As in many other parts of southern California, the actual state of dunes tends to be less active than predicted by the mobility index (Bach, 1995), and field observations suggest that locally this is the case in the Coachella Valley. Over the period of record, changes in the amount of rainfall received gave rise to changes in the mobility index (fig. 13a). The index was above the threshold value of $M=200$ (dunes fully active) for 71 percent of the period of record (1973-2000), and within the range $100<M<200$ (dunes are active but lower slopes are vegetated) for 28 percent of the time (fig. 13b). The period 1984-1991 was the longest interval in which the index was consistently above 200. Intervals and individual years when dune mobility was low occurred in 1978-1980, 1983, and 1992-1993. The temporal variation in the dune mobility index was generally similar to that observed elsewhere in the southwestern United States (Lancaster and Helm, 2000), with low values of the index being recorded in or following El Niño years.

Actual Sand Transport

The calculated sand drift potential discussed above represents the amount of sand that could be transported by the winds of the area, assuming that sand is available for transport (i.e., the sand supply is unlimited). In the case of the flood plain of the Whitewater River, this is unlikely, given the seasonal or ephemeral nature of flow in the river and the armoring of the surface by gravel.

Some information on actual rate of sand transport in the area is provided by Sharp (1964, 1980). He maintained sand traps in the area of the Whitewater River, just south of Garnet Hill and likely within the current boundaries of the Whitewater Floodplain Preserve, for 5 periods from1953 through 1955. His data on sand-transport rates were later analyzed by Williams and Lee (1995). Sand-transport rates in the study area varied from 1.0 - $6.5 \cdot 10^{-6}$ lbs ft^{-1} s^{-1} (table 13).

The variation in sand transport rates could be explained by reference to changes in the discharge of the Whitewater River (fig. 5). The highest sand-transport rates follow periods of high discharge in the river, and low rates either preceded or coincided with high runoff. These data suggest that changes in fluvial sediment supply significantly influence rates of eolian sediment transport in this environment.

Table 13. Eolian sand transport rates in the Whitewater River floodplain (from Williams and Lee, 1995).

Measurement interval	Sand transport rate (lbs ft^{-1} $s^{-1} \cdot 10^{6}$)
2/3 – 3/4, 1953	3.0
7/18 – 12/11, 1953	1.0
4/16 – 11/25, 1954	1.6
3/2 – 5/27, 1954	6.5

Historical Changes in Area of Sand Dunes

Historical changes in the area of sand dunes proved difficult to quantify for the Whitewater Floodplain Preserve and the area between the Mission Creek – Morongo Wash depositional area and Willow Hole. Existing aerial photography lacked a consistently sufficient resolution to allow differentiation of the small coppice dunes characteristic of these eolian plains from perennial vegetation or other features on

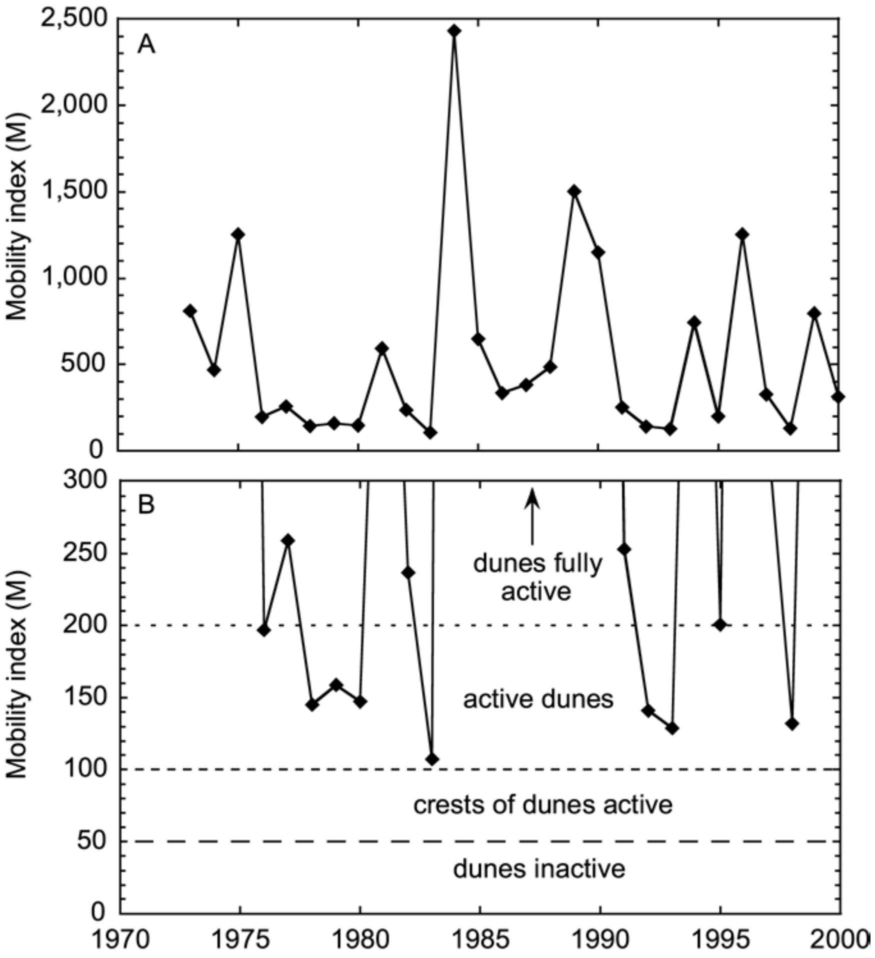

Figure 13. Dune Mobility Index calculated for the northern Coachella Valley. A. Variation of the Dune Mobility Index (M) from 1973-2000. B. The same data for M up to 300 showing exceedence of several classes of dune activity.

the landscape. A summary of the observations from the aerial photography of the study area appears in tables 14 and 15.

The 1939 aerial photography shows active channels and abundant fluvial sediment in the aftermath of the 1938 floods on both the Whitewater River and Mission Creek. By 1953, modifications were significant on the Whitewater River floodplain, and the infiltration galleries were established by 1984 (table 14; fig. 14a). In 1953, sand cover and nebkha dunes were extensive on the Whitewater Floodplain Reserve, and even by the late 1980s, active sand sheets extended eastward from active fluvial channels. By 1996, this sand cover appeared to be depleted.

Comparison of the aerial photographs from 1939 to 1996 indicate that there have been minor changes in the vegetation cover in the Willow Hole area but important changes to the channels of some of the washes in the area, and significant changes in land use in the areas immediately north and west of the dunes (table 15; fig. 14b). From 1939 to 1953, there are slight decreases in the density of mesquite in both western and eastern parts of the dunes; vegetation cover also decreased in the lower reaches of Wide and Long Creeks. In 1953, there is more bare sand in the northern part of the Willow Hole area that at any other time. Between 1953 and 1972, vegetation cover decreases in the western parts of the area, but increases slightly in the east. The outlet channel to the south from Willow Hole is less vegetated, and becomes vegetation free after 1972. From 1972 to 1996, there are no significant changes in the mesquite cover, but the area of bare sand

Table 14. Historical changes in the eolian environment of the Whitewater depositional area detected in aerial photographs, 1939-1996.

Year	Observed Changes
Cultural features in channel west (upwind) of Whitewater Preserve	
1953	Large dike across western channel; small dike on western side
1972	Cross channel dike breached in several places
1977	Percolation ponds breached causing outwash channel
1979	Percolation ponds breached causing outwash channel
1984	Infiltration basins established west of preserve, southern dike is re-aligned
1989	Wind generators constructed by this year
Fluvial and aeolian features	
1939	Effects of the 1939 flood deposition are considerable along Whitewater River and Mission Creek; a channel avulsion appears in Mission Creek on the Desert Hot Springs bajada
1953	Active channel (darker tone) in center of preserve area Extensive sand cover and nebkha dunes
1972	Area east of road is very featureless either as a result of a poor photograph or extensive thin eolian sand sheet cover
1977	Well-developed active channel to south of preserve formed after breaching of percolation ponds by flood. Alluvial morphology very clearly developed
1984	Flow in Whitewater River to gaging station Clear fluvial morphology with bars and channels visible Wide active channel to south
1989	Active flow in Garnet Wash (August) and across flood plain in eastern part of Reserve Drainage channel across southern part of preserve Active sand sheets extend east of fluvial channels
1993	Well developed channel with active flow south of Garnet Hill and gravel pit
1996	Fine-grained fluvial deposits appear to be stripped from the Whitewater depositional area downstream of infiltration galleries

Table 15. Historical changes in the eolian environment of the Willow Hole area detected in aerial photographs, 1939-1996.

Year	Observed Changes
Cultural features	
1972-1975	Mission Creek channelized
1984-1989	Golf course established north west of Willow Hole Reserve
Fluvial and aeolian features	
1953	Thin sand sheets cover most of area east of depositional zone of Mission Creek and Morongo Wash
1972	Thin sand sheets cover most of area east of depositional zone of Mission Creek and Morongo Wash
1984	Sand sheets replaced by sand streaks extending from depositional area
1989	Sand streaks very thin
1996	Sand streaks extremely thin and discontinuous east of depositional zone
Vegetation changes	
1939-1953	Slight decreases in density of mesquite in Willow Hole area
1953-1972	Decrease vegetation cover to west, increased to east
1972-1996	No significant changes in mesquite cover infiltration galleries

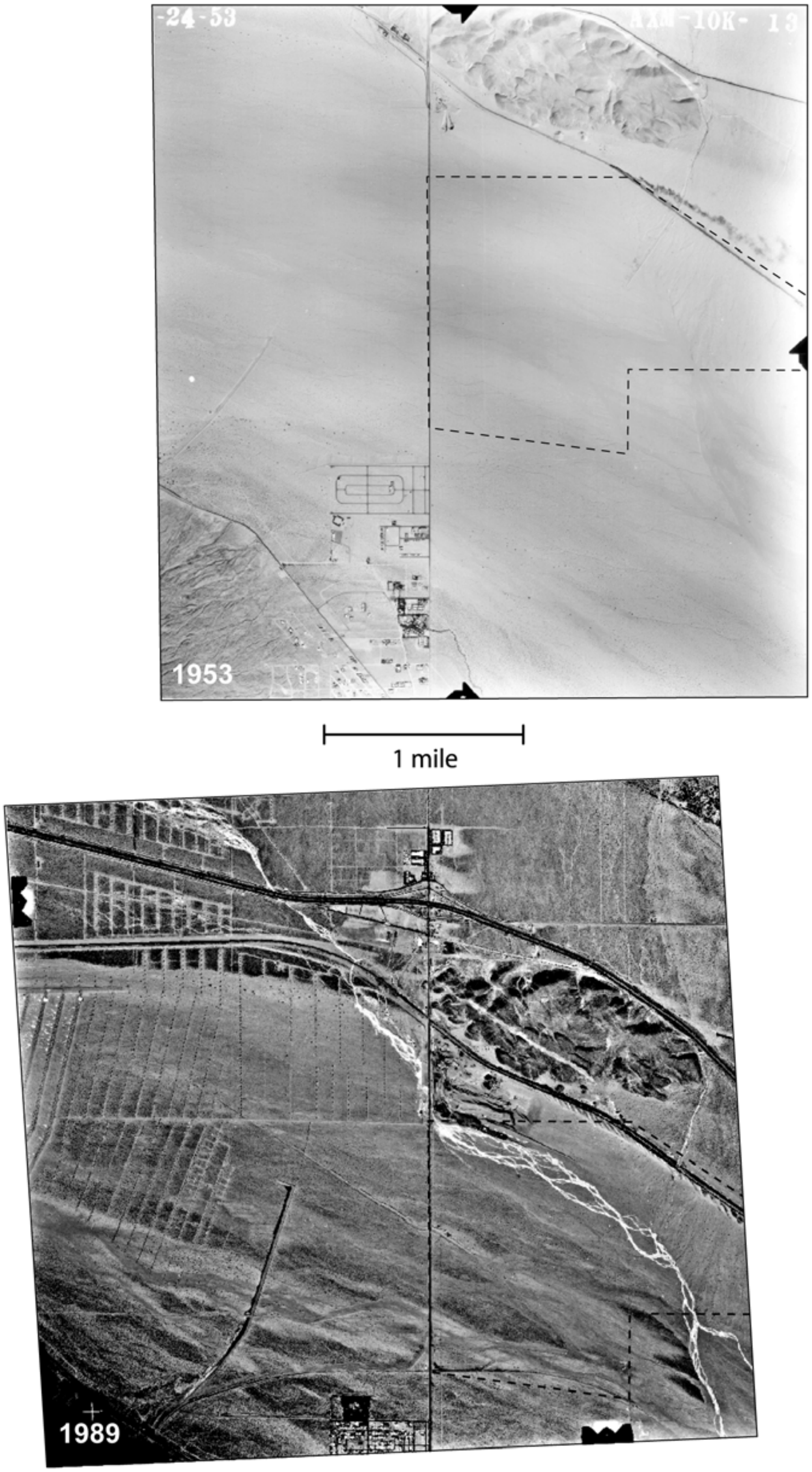

Figure 14. Aerial photographs showing historical changes in sedimentary deposits in the Whitewater depositional area.

A. Aerial photographs of the Whitewater River floodplain in the area of the Whitewater reserve (dashed lines) in 1953 and 1989. Note extended dike across river and extensive wind-generator arrays in 1989. There also appears to be much more extensive sand cover in 1953 compared to 1989.

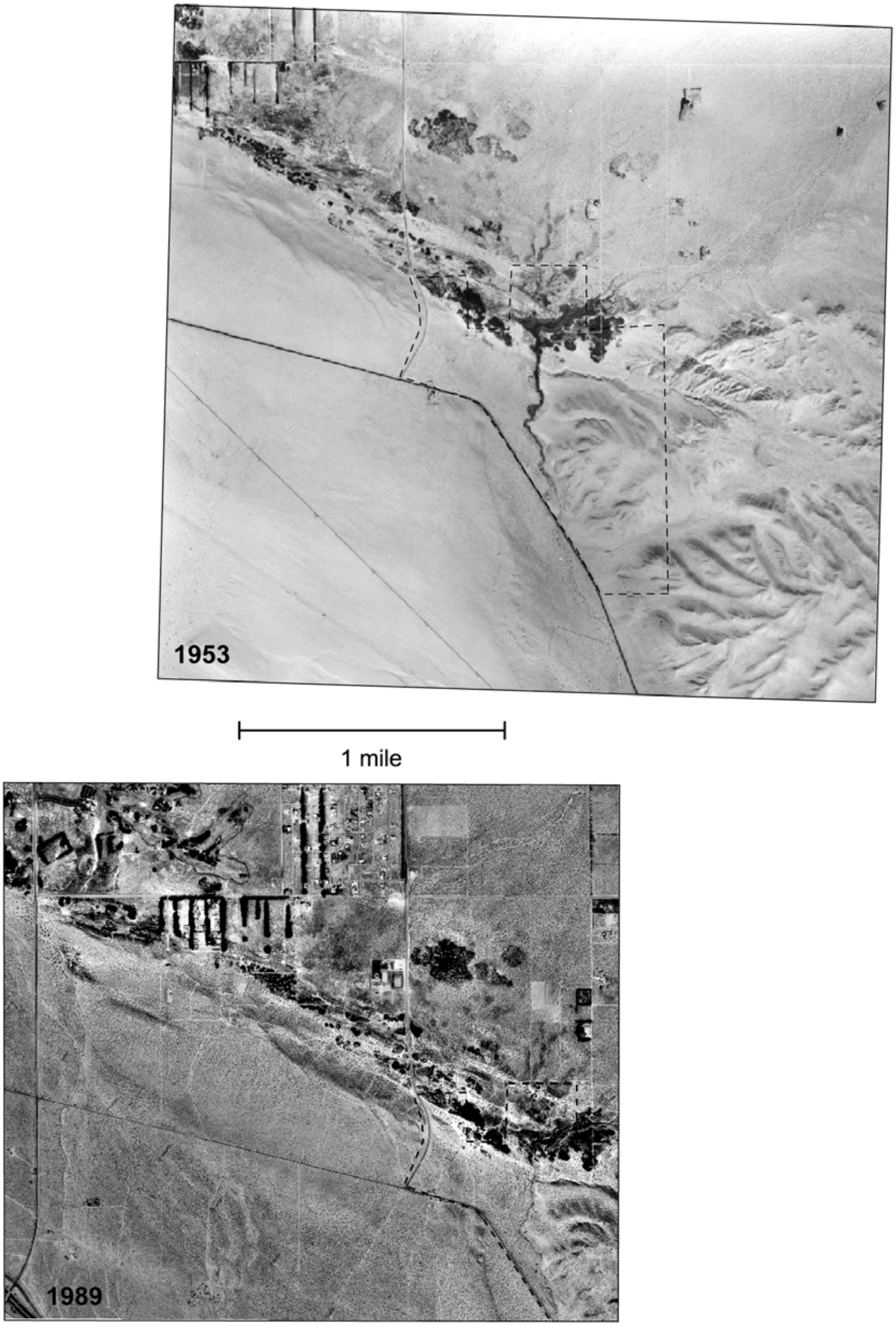

Figure 14. *Continued.*

B. Aerial photographs of the area of the Willow Hole reserve (dashed lines) in 1953 and 1989. Amount of change in mesquite dunes appears to be minimal.

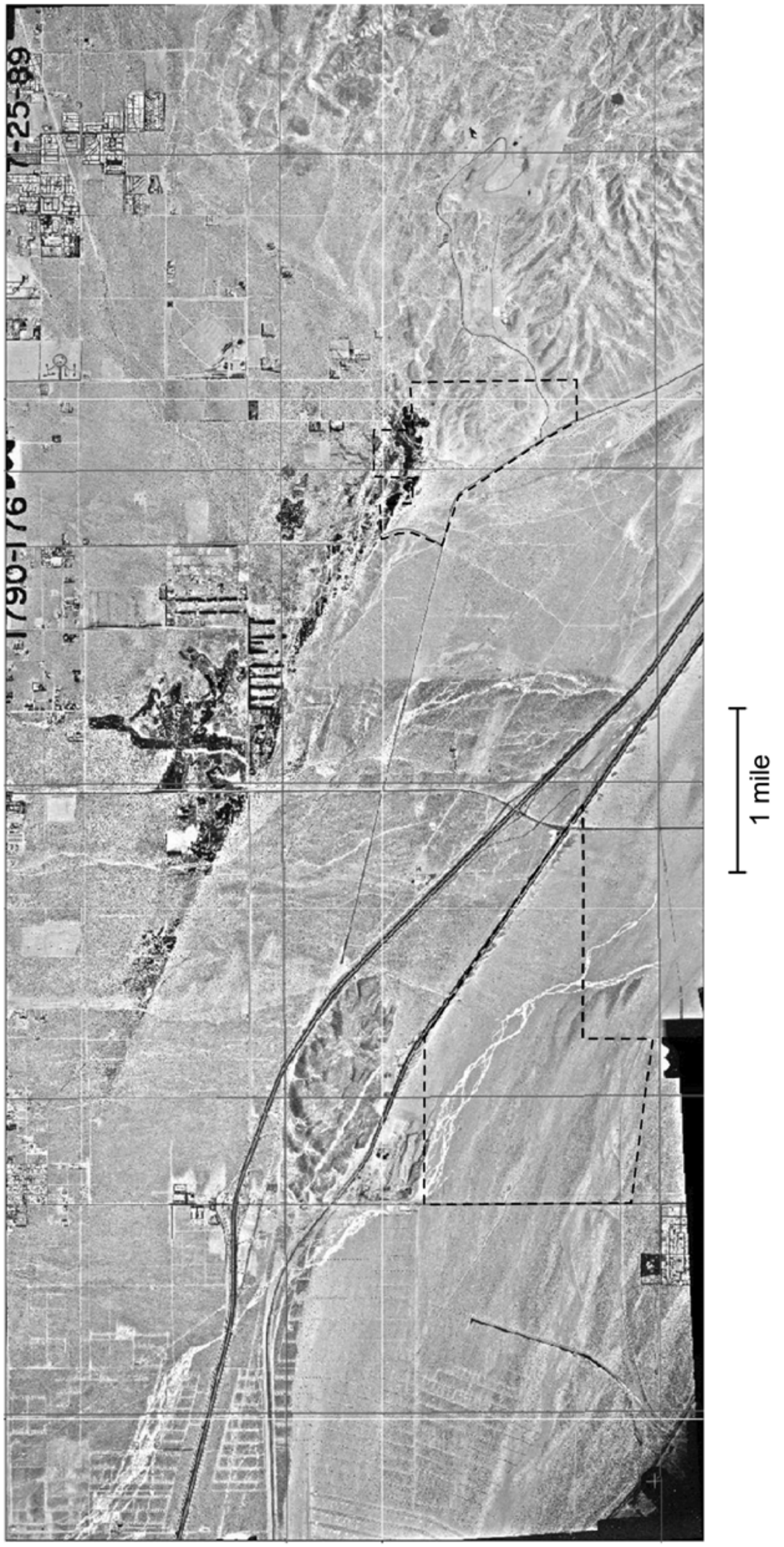

Figure 14. *Continued.*

C. Photomosaic of the depositional areas and eolian-transport zones upwind of both reserves in 1989. Dashed lines indicate reserve boundaries.

near Mountain View Road decreases in size. A golf course was constructed immediately north of the dunes in the late 1980s.

The 1953 photographs indicate thin sand sheets covering as much as 75 percent of the area east of Mission Creek and especially Morongo Wash. The sand sheets persisted in this manner until at least 1972, and probably 1977, although Mission Creek had been artificially channelized by the latter date. By 1984, the extensive sand sheets had largely dispersed, and the most prominent eolian features were sand streaks and tongues of sand (sand sheets) that extend east or east-southeast from the depositional area of these washes for several hundred yards. By 1989, these sand sheets appear to have thinned considerably (fig. 14c). This trend is continued to 1996, when these features are barely discernible on the images.

LINKAGES BETWEEN THE FLUVIAL AND EOLIAN TRANSPORT SYSTEMS

Rates of Eolian Transport

The supply of wind-blown sediment to the Whitewater and Willow Hole Reserves is determined by two factors: (1) the supply of sand-size sediment by the fluvial system (as discussed in the previous section on Fluvial Sediment Yield) and (2) the rates of eolian transport. Comparison of these two sediment-transport systems was carried out the following way. Data on fluvial sediment yields and the area of the depositional zones (table 9) was used to estimate a volume of sediment being deposited in each of these areas on an annual basis. The total volume of sediment was adjusted in proportion to the amount of this material that is of sand size (mean = 82.5 percent), as well as the proportion of the sediment that is of a size preferred by *Uma* (table 10).

Rates of eolian sediment transport potential were derived from the Palm Springs wind record and the velocity units were converted to an estimate of sediment volume transported based on the relation illustrated by Fryberger (1979). This relation is expressed as volume per unit width per year. The rate of eolian sediment removal from each of the depositional zones was estimated as:

$$Q_e = A^{0.5} \cdot q_r, \qquad (12)$$

where

Q_e is the eolian transport rate,
A is the area of entrainment, and
q_r is the volumetric transport rate.

The relations between eolian and fluvial deposition can also be expressed in terms of the time required for the fluvial sediment supply to be depleted. This is expressed as:

$$t_{ed} = V / Q_e, \qquad (13)$$

where

t_{ed} is the time for eolian depletion (months), and
V is the volume of fluvial sediment available for transport (ft^3).

These relations assume that all available sediment can be transported, and the surface cannot be armored with the accumulation of sediment that is larger than the eolian system can transport.

The estimated depletion times for both historic and modern scenarios, using the Renard (1972) and flood-frequency methods for estimating fluvial sediment yield are given in table 16. Our results indicate that periods ranging from several months to two years are required for eolian processes to deplete sediment supplied by the fluvial system. In the predevelopment setting, all sand was removed from the Whitewater area in 13 months, from the Mission – Morongo area in 8 months and from the Long Canyon area in 4 months. With reduced fetch areas and deeper fluvial deposits in the modern scenario, it requires 16 months to remove all sand from the Whitewater area and 8 months to do so from the Long Canyon depositional area. Rates of sand removal from the Mission – Morongo depositional area remain constant. In all cases, sand of a size suitable for *Uma* habitat is removed in about one-fourth the time required for all sand (table 16).

When the record from the aerial photographs is compared to depletion estimates, it is clear that eolian sand persists in the immediate vicinity of the fluvial-depositional zones for periods that are much longer than the estimated depletion times discussed above. This is likely because the amounts of sediment deposited in episodic floods to these zones are much greater than the time-averaged rates used in this analysis. It is also likely that the eolian-transport rates are less than used in this analysis, because they are reduced by the presence of vegetation in the transport corridors. As a result, the depletion times in table 16 should be regarded as minimum values. In general, however, the eolian removal of expected annual sediment yields in approximately one year – both before and after development – is consistent with the presence of persistent sand dunes in the Coachella Valley.

Table 16. Eolian depletion rates of fluvial sediment deposited in depositional areas upwind of the Coachella Valley reserves.

	MONTHS TO REMOVE ALL SAND		MONTHS TO REMOVE "UMA SAND"	
Depositional area	**Renard (1972) equation**	**Flood-frequency method**	**Renard (1972) equation**	**Flood-frequency method**
		Historic record		
San Gorgonio/ Whitewater	12.9	25.3	2.5	4.9
Mission/Morongo	8.0	17.6	1.7	3.8
Long Canyon	3.6	7.4	0.8	1.7
		Modern record		
San Gorgonio/ Whitewater	15.7	30.3	4.1	8.1
Mission/Morongo	8.0	17.6	1.7	3.8
Long Canyon	7.8	17.3	2.0	4.4

Mission Creek – Morongo Wash Depositional Area

Although the Indio Hills drainage area – and Long Canyon by way of the Indio Hills drainage – has the potential to contribute sand to the Willow Hole Reserve, almost all sand delivered to the Reserve in the modern setting comes from the Mission Creek – Morongo Wash depositional area. The existence of wind data collected within the Willow Hole Reserve itself allows us to begin to differentiate subsections within the Mission Creek – Morongo Wash depositional area in terms of potential to contribute sand to the Reserve. By analyzing the frequency of wind directions bearing on Willow Hole, we calculated the probability that a given sand-transporting wind will be headed toward the Willow Hole Reserve for subsections of the Mission Creek – Morongo Wash depositional (table 17 and fig. 15). (Absence of local wind data precludes a similar analysis for the San Gorgonio – Whitewater depositional area.) Across the Mission Creek – Morongo Wash depositional area as a whole, winds of velocity sufficient to transport sand are headed toward Willow Hole 83 percent of the time. Segregating these data into the seven 10° compass sectors, keyed from one sector that represents westerly winds from directions of 265° to 275°, that cross the depositional area, the probability that sand-transporting winds will be headed toward Willow Hole is highest through the middle of the depositional area, drops off rapidly to the south to a low of 1.1 percent, and declines less rapidly to the north to a low of 10.4 percent (figure 15).

These probability values can be used as a rough measure of the relative value of each subsection of the depositional area in terms of potential sand transport to Willow Hole. A more precise measure of the relative amounts of sand actually contributed to Willow Hole from each subsection would require the consideration of other variables in addition to wind direction. The depositional subsection illustrated in figure 15 are not of equal area, and the larger subsections to the north would consequently contribute more sand to Willow Hole than the smaller southern subsections. Additionally, it is unlikely that fluvial sediment is distributed equally over the depositional area. Sand deposited per unit area likely decreases in the downstream direction so that sand deposits thin from north to south. Similarly, particle-size distribution typically varies in the direction of flow, with mean particle sizes decreasing with flow energy from north to south, resulting in a variation in the presence of preferred sand. The presence of local wind breaks may also vary from subsection to subsection hindering the eolian transport of *Uma* sand to varying degrees. The proximity of the interstate and railroad to the southern subsections may be a significant factor in this regard. A more precise measure of relative sand contribution from the Mission Creek – Morongo Wash sectors would require the quantification of these variables. However, it is evident that such data would weight sand contribution toward the northern subsections of the depositional area.

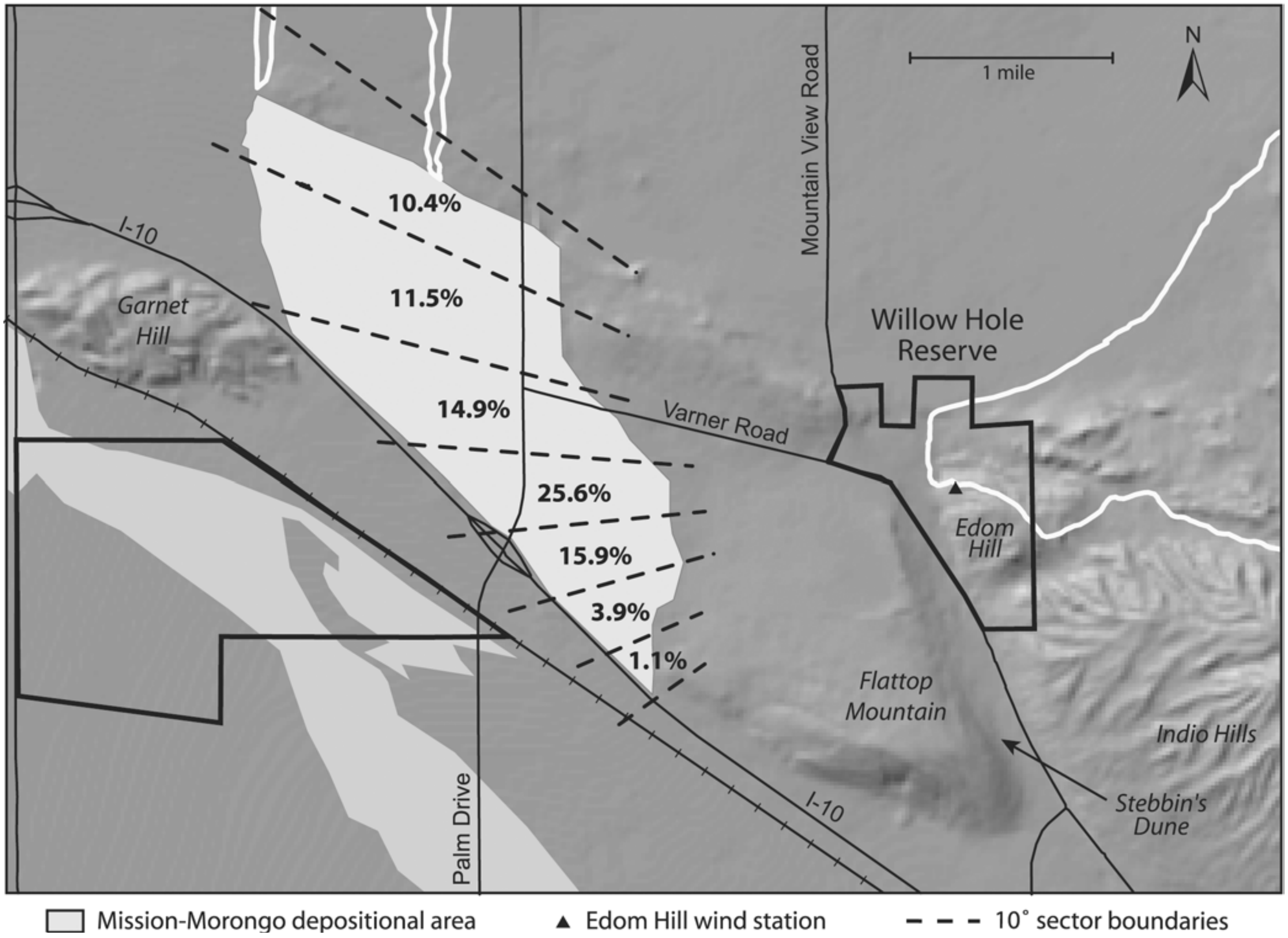

Figure 15. Map showing the percent probability that any sand-transporting wind (>14.3 mi/hr) headed directly toward the center of the Willow Hole Reserve will cross a given 10° sector of the Mission – Morongo depositional area. White lines indicate drainage boundaries.

Winds favorable for sand transport directly to Willow Hole cross some part of the depositional area 83.4 percent of the time. Sector boundaries are arbitrary lines that divide a continuous wind field into discrete 10° segments. Probabilities that sand transporting wind is headed to any other point location – such as Stebbin's Dune – would require a separate set of data collected at that point location and result in different sector boundaries.

Table 17. Percent probability that a sand-transporting wind headed toward Willow Hole will cross each sector of the Mission Creek-Morongo Wash depositional area.[1]

COMPASS SECTORS (22.5°)[2]		10° SECTORS	
Sector	Probability (percent)	Sector	Probability (percent)
		295-305°	10.4
281 - 304° / WNW	23.8	285-295°	11.5
		275-285°	14.9
259 - 281° / W	50.5	265-275°	25.6
		255-265°	15.9
236 - 259° / WSW	7.3	245-255°	3.9
		235-245°	1.1

[1] Data is for winds >14.3 mph measured at Edom Hill in 2001.

[2] Complete compass sector data is presented in Table 12.

CONCLUSIONS

The sand-delivery system to Coachella Valley fringe-toed lizard reserves in the northern Coachella Valley have been significantly altered historically. Much of the alteration has been in the stream channels that deliver fluvial sediment from the headwaters to the depositional areas upwind of the reserves. With the exception of the San Gorgonio River upstream from Banning, California, the fluvial part of the sediment delivery system is intact to the edges of the valley floor.

Modifications of channels within the northern Coachella Valley have had both positive and negative effects on sediment delivery to the depositional plains. The construction of dikes and infiltration galleries on the Whitewater River downstream from Windy Point has both trapped some fluvial sediments upstream from the Whitewater depositional area as well as blocked westerly eolian sand transport from crossing much of the depositional area. Channelization of Mission Creek probably has increased delivery of sediments from the bedrock headwaters to the depositional area by minimizing within-bajada sediment storage. Recent flooding has incised channels through Willow Hole that drain the western Indio Hills, shifting at least some of the deposition of fluvial sand from within the Willow Hole Reserve (and just south of the main mesquite-stabilized dunes) to just south of the Reserve, potentially limiting eolian contributions from this sediment source.

Estimated eolian-transport rates predict that annual sand yields delivered to depositional areas are entrained and removed in 8 to 16 months given modern conditions, suggesting a continued balance between the fluvial and eolian transport systems and a constant sand supply to *Uma* sand dunes at present. Analysis of local wind directions at Willow Hole suggests that the potential to supply sand to the Willow Hole Reserve is not uniform among subsections of the Mission – Morongo depositional area. Quantification of the actual amounts of sand contributed by depositional area subsections would require the collection of additional data concerning the evenness of fluvial sediment deposition across the depositional area, as would the making of similar distinctions at other depositional areas.

Abbreviated Answers to Questions Posed by the U.S. Fish and Wildlife Service

Is there sufficient sand supply (in the fluvial system) to maintain the Willow Hole and Whitewater Floodplain Reserves?

Answer: The answer is a very tentative yes, there appears to be a sufficient sand supply to maintain the reserves, but the following issues are pertinent. (1) Sediment delivery in the northern Coachella Valley is highly episodic, and long periods of no delivery must be anticipated during drought conditions. These periods of deficient fluvial sediment supply will likely result in degraded *Uma* habitat irrespective of anthropogenic factors. Therefore, separation of human-induced from climate-induced changes to sediment supply will be difficult to determine with confidence. (2) The sediment-delivery system is largely intact except the headwaters section of the San Gorgonio River, which currently is blocked by a sand-and-gravel in-stream mining operation, resulting in an estimated 14 percent reduction in sediment yield. (3) Sediment source areas are largely unaffected by development and are mostly managed by the State of California and the federal government. (4) Depositional areas have been reduced, but some of this reduction may be reversed by redesign of the infiltration galleries east of Windy Point. (5) Historical alteration of the channel issuing from Long Canyon for flood-control purposes may affect the already much reduced depositional area within the northern Coachella Valley, further limiting eolian transport to the Indio Hills and – indirectly – to Willow Hole. (6) Fluvial sediment from the Indio Hills that once deposited directly within Willow Hole now is mostly deposited downstream and south of the reserve due to recent channel entrenchment, making this a potential but unreliable source of eolian sediment for Willow Hole.

Problems: The infiltration galleries at Windy Point affect the Whitewater depositional area, pushing this critical depositional area downstream from where eolian sand is desired. Redesign of these galleries to allow for throughflow of eolian sediment and entrainment of fluvial sediment may be expensive.

How would channelization of Mission and Morongo Creeks and urban development on their adjacent floodplains affect sand supply to both reserves?

Answer: Channelization, if designed to minimize sediment storage on the alluvial fans, would probably benefit the sand-delivery system to the reserves by minimizing in-channel storage of sediments on the Desert Hot Springs bajada. Channelization would not reduce sediment yields because most of the sediment that reaches the depositional areas is not generated within the Desert Hot Springs bajada.

Problems: This conclusion involves only the sediment-delivery system and does not consider other biological impacts of channelization. Channelization in the depositional areas would decrease wind entrainment of fluvial sediment by decreasing the area available for fluvial sediments to accumulate as well as disrupting the wind fetch.

Do the retention dikes along the Whitewater River affect sand supply to the Whitewater Floodplain Reserve, and by how much? Could the design of the recharge ponds be modified to provide a continued sand supply to the reserve?

Answer: Given that 8.1 million ft^3 of sediment was excavated from the retention ponds in 1996 the retention ponds clearly do trap fluvial sediment. This material may include a substantial amount of *Uma* sand, but an accurate estimate is not possible without evaluating both the time period over which this sediment was deposited as well as the proportion of *Uma* sand it contains. This sediment is entrained from the Whitewater River channel at flows of 200-400 ft^3/s between the Colorado River aqueduct crossing and the infiltration galleries, although some of this material is deposited in the channel immediately upstream from the galleries. This sediment is trapped upstream from the Whitewater River depositional area owing to diversion dikes designed to channel water into the infiltration galleries and would be available for downstream transport if the diversion dikes are breached by a flood capable of transporting this sediment.

Alignment of the infiltration galleries perpendicular to the prevailing winds and the high slope angles on the downwind dikes minimize the amount of sand that can be entrained by eolian processes. Sediments dredged from the galleries and upstream channel could be spread in a flat surface in the historic Whitewater depositional area, allowing it to be entrained for eolian transport. Alternately, the galleries might be redesigned such that the long dimension is parallel to prevailing winds (long direction east-west instead of north-south), and the eastern dike of each gallery could be designed with a shallow slope to allow eolian sand to escape.

Problems: The redesign and modification of the infiltration galleries may be expensive.

How much of the floodplain of the washes supplying sand upwind of the reserves has to be preserved to ensure a perpetual sand supply? What areas are essential to preserve and maintain an adequate sand supply and sand-transport corridor for these two preserves?

Answer: Floodplains on the bajadas produce minimal sediment owing to the arid environment and infrequent nature of high-intensity rainfall. Most of the sediment that eventually is deposited upwind of the reserves is generated in mountainous headwaters areas to the west and north of the valley floor. Channelization of major washes is beneficial to the sand-delivery system in the Coachella Valley reserves because sediment storage on the bajada upslope from the depositional areas is minimized. Thus, it is the channels on the fans that should be preserved, or enhanced, as they are the critical feature linking fluvial sediment sources in the mountains to the eolian sediment source areas downstream.

Low-elevation drainages at the western end of the Indio Hills north of Edom Hill are a potential source of eolian sand and should be preserved in their entirety. These drainages are not strictly part of the alluvial floodplain, nor are they typical of the high-elevation fluvial source areas in other drainage areas. This source is unique in that it has already been sorted by eolian processes, so that it is nearly twice as rich in potential habitat sand than other sources, and the sand supply, though largely a relict of the Pleistocene and not strictly renewable, is very large. Transport of this sand to Willow Hole is dependent on fluvial, rather than eolian processes. Given the potential of increased urbanization to further interrupt eolian sources of habitat sand, this fluvial source may become increasingly important in the future. Current natural channelization of the washes through Willow Hole reduces the potential for entrainment of this sand, but this channelization could be healed through natural processes or human intervention and should not be eliminated as a potential source of fluvial-eolian sand.

In contrast to the alluvial floodplains, the historical depositional plains at the downstream end of the channels depicted in figure 6a should be preserved in their entirety or developed with respect to the relative contribution of different area subsections to the overall *Uma* sand budget. Variables that should be measured to determine relative sand contribution include differential distribution of fluvial sediment across depositional areas, both in terms of volume and proportion of *Uma* sand, plan area of subsections, and frequency with which sand-transporting winds are directed toward the appropriate reserve, as illustrated in figure 15. The San Gorgonio – Whitewater and Mission Creek – Morongo Wash depositional areas are the fundamental source areas of eolian sand that maintain lizard habitat in both reserves. The construction of infiltration galleries to the west of the Whitewater Reserve has reduced the amount of sand available for eolian transport both by trapping sand and reducing the total area of sand exposed to the wind. At a minimum, areas between historic deposition zones and downwind reserves should also be preserved to maintain an unobstructed eolian transportation corridors (fig. 6). Similarly, general consideration should be given to the effect that development of additional windbreaks in the area of the deposition zones would have on available wind energy.

The substantial reduction of the Long Canyon depositional area to the northern 20 percent of its historic extent has the duel effect of greatly decreasing the rate at which fluvial sediment is removed by eolian transport and shifting the dominant direction of transport northward, reducing sand supplied to the Indio Hills drainage north of Edom Hill. This alteration is unlikely to have an immediate effect on Willow Hole given that this sand is only indirectly supplied to the reserve through the Indio Hills, that there is an substantial amount of relict sand stored in the Indio Hills drainage area, and that fluvial sediment from the Indio Hills drainage currently pass through the reserve entirely. The long term effects of the Long Canyon alterations, however, are unknown.

Problems: This conclusion does not consider other potential biological impacts of channelization, including loss of ephemeral wash habitat and disruption of migration corridors.

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APPENDICES

APPENDIX 1. DESCRIPTIONS OF QUATERNARY GEOLOGIC MAP UNITS

Alluvial Units

Alluvial units mapped in the northern Coachella Valley include deposits created by the processes of streamflow, hyperconcentrated flow, and debris flow. The following characteristics apply to all alluvial units below, which are further subdivided on soil development and associated characteristics related to age. Alluvial deposits consist of sandy gravel and interbedded sand. Gravel clasts are angular to subrounded, range in size from pebbles to boulders, and generally are composed of granitic and gneissic rock types from the San Bernardino and Little San Bernardino Mountains, as well as reworked from older gravel sedimentary units. Deposits commonly are matrix-supported, but include some clast-supported beds. Bedding is massive to crudely stratified, and is defined by changes in clast size and sorting, which ranges from well sorted to poorly sorted.

Qayy. Youngest fan alluvium is of late Holocene age and is associated with intermittently active channels. Vegetation is absent to sparse in intermittently active channels, which are more abundant in this unit than in adjoining units. In the fan that emanates from the Wide Canyon area, the top of **Qayy** generally includes a cemented coarse-sand-rich, clast-poor bed, and a discontinuous eolian sand mantle. The eolian sand is usually fine sand that includes common biotite. Surface soil is very weakly developed with almost no oxidation. There is some cementation mainly as case-hardening along natural exposures. Depositional bar and swale morphology generally is well expressed but is more muted in areas of high rates of eolian sand deposition.

Qay. Young fan alluvium is of Holocene and latest Pleistocene age. Surface soil is generally very weakly developed, similar to that of **Qayy** and **Qayi** which are locally subdivided from this unit, but **Qay** includes areas of greater soil development up to the degree found in **Qayo** (see below) which is also locally subdivided from this unit. Pedogenic carbonate morphology does not exceed stage I–II, and occurs as thin carbonate and silica coatings on clast undersides. Depositional bar and swale morphology generally is characteristic of this unit, but its expression decreases with maximum clast size, which generally decreases away from upland source areas.

Qayi. Intermediate young fan alluvium is of late Holocene age. This unit is only locally differentiated as a subdivision of **Qay** along Mission Creek and Morongo Wash where sharper bar and swale morphology occurs relative to adjoining areas of **Qay**.

Qayo. Older young alluvium of fan remnants and terraces is of early Holocene and latest Pleistocene age. The surface soil of this unit has a distinctive oxidized, eolian dust-rich cambic Bw horizon but has not attained the development of the reddened argillic horizon that is characteristic of **Qai** and older units. Pedogenic carbonate morphology does not exceed stage I-II, and occurs as thin carbonate and silica coatings on clast undersides. Depositional bar and swale morphology is apparent but is muted relative to adjacent **Qay**. Surface clasts include greater varnish, and give this unit a darker tone on aerial photographs.

Qfy. Young fan alluvium of the San Jacinto Mountains includes debris-flow deposits of Holocene and latest Pleistocene age. This unit is extremely bouldery. Surface soil is generally very weakly developed. Pedogenic carbonate morphology does not exceed stage I-II and occurs as thin carbonate and silica coatings on clast undersides. Depositional bar and swale morphology generally is characteristic of the unit, but its expression decreases with maximum clast size, which generally decreases away from upland source areas.

Qai. Intermediate age alluvium in fan remnants and terraces is of late and middle (?) Pleistocene age. Strong soil development (McFadden, 1982) includes a characteristic red-brown argillic horizon within the top 1 ft of the unit. Pedogenic carbonate morphology is variable within the map area and probably related to a climatic gradient of effective moisture decreasing eastward from San Gorgonio Pass. Along the west side of the Desert Hot Springs quadrangle, carbonate morphology does not exceed stage I-II and is probably largely Holocene. In the Seven Palms Valley quadrangle, carbonate morphology is typically stage III, with the deposit moderately to well cemented below the argillic horizon. Depositional morphology is generally absent; instead the surface has been somewhat reworked and eroded during and preceding formation of the argillic horizon. Surface clasts are commonly highly pitted and eroded, though some resistant rock types have developed dark coatings of desert varnish. Along Mission Creek in the northwestern part of the map area, a sample from a silty sand bed at a depth of about 13 ft yielded a thermoluminesence date of about 60 ka to 80 ka, depending on assumptions about moisture history (S. Mahan, written commun., 2001).

Qaiy. Younger intermediate alluvium of fan remnants and terraces is of late Pleistocene age. **Qaiy** is a locally distinguished subdivision of **Qai** where **Qaiy** forms an inset terrace within the **Qai** fan remnant complex at the mouth of Mission Creek in the northwest part of the map area. It has a similar surface soil to **Qai** and is characterized by a red-brown argillic Bt horizon within 1.6 ft of the surface.

Qao. Older alluvium of Pleistocene age is characterized by erosional surface morphology and the lack of remnants of an upper depositional surface. This unit forms resistant ridges in the Indio Hills, is generally poorly exposed, and is mantled and flanked by eolian sand (**Qe) and** colluvium (**Qcf**). Much of the surface area of **Qao** in the Indio Hills and Garnet Hill includes marble and other metasedimentary rock types that are probably derived from the San Jacinto Range. **Qao** forms poorly exposed deformed sediments cemented by pedogenic carbonate at Garnet Hill.

Qau. Undivided Pleistocene alluvium includes faulted and folded alluvial gravel and sand in ridges along the Banning and Mission Creek strands of the San Andreas fault system.

Qtpc. As mapped by Allen (1957) and Proctor (1968), the Painted Canyon Formation is a deformed and dissected fanglomerate that occurs between the Banning and Mission Creek Faults near the western boundary of the map area. This map unit includes the intercalated basalt flow near Devils Garden (Matti and Morton, 1993).

Qtps. The Palm Spring Formation consists of unconsolidated gravel, sand, silt, and mud to consolidated conglomerate, sandstone, siltstone, and mudstone and is exposed in badlands in the dissected, folded core of the Indio Hills.

Colluvial and Eolian Deposits

Colluvial deposits in the northern Coachella Valley are created by mass wasting processes, such as landslides, avalanches, and isolated rockfalls. Eolian deposits in the map area generally are thin, ephemeral sand dunes or sheets that change greatly in size with time as the fluvial sand supply on the depositional areas increases after a flood or is depleted by wind erosion.

Qcf. Colluvium and interbedded alluvium and eolian deposits generally occur in a footslope position.

Qe. Eolian sand and sandy colluvium and alluvium form sheets and sand ramps on slopes.

Qd. Eolian sand dunes of Holocene age are intermittently active but may be locally vegetated with mesquite.

Afd. Artificial fill and disturbed ground are created by human disturbance or development.

APPENDIX 2. AVAILABLE DAILY STREAM-FLOW DATA FOR THE NORTHERN COACHELLA VALLEY THROUGH 2001

Station name[1]	Period of record (water year)[2]	Missing record (water years)	Drainage area (mi^2)	USGS station umber	Latitude[3]	Longitude[3]
Whitewater River at Whitewater	1949-1979 (discharge)	None	57.5	10256000	33°56’48”	116°38’24”
	1972 (suspended sediment)	None	57.5	10256000	33°56’48”	116°38’24”
Whitewater MWC Diversion at Whitewater	1966-1981	1971, 1974, February 1977	–	10256050	33°56’44”	116°38’25”
Whitewater River at Whitewater Cut at Whitewater	1986-1987, 1989-1990	None	59.1	10256060	33°55’31”	116°38’07”
San Gorgonio River near Banning	1976-1977	None	14.8	10256200	33°59’54”	116°54’29”
San Gorgonio River at Banning	1981	First 4 months	44.2	10256300	33°55’52”	116°49’37”
San Gorgonio River near Whitewater	1963-1978	First 5 months	154.0	10256400	33°55’14”	116°41’45”
Snow Creek near Whitewater	1921-1931 (missing 36 months), 1960-2001	1932-1959	10.9	10256500	33°52’14”	116°40’49”
Snow Creek and Div Combined	1921-1931 (missing 36 months), 1960-2001	1932-1959	10.9	10256501	33°52’14”	116°40’49”
Snow Creek Div near Whitewater	1978-2000	1985, 1989	–	10256550	33°52’14”	116°40’49”
Falls Creek Div near Whitewater	1995-2001	None	4.1	10257499	33°52’10”	116°40’15”
Falls Creek near Whitewater	1923-1926, 01/28- 07/31, 1995-2001	1932- 1994	4.1	10257500	33°52’10”	116°40’15”
Combined Flows Falls Creek near Whitewater + Diversions	1995-2000	None	–	10257501	33°52’10”	116°40’15”
Whitewater River at Windy Point Main Channel	1999-2001	13 days	264.0	10257548	33°53’56”	116°37’13”
Whitewater River at Windy Point Overflow Channel	1999-2001	14 days	264.0	10257549	33°53’56”	116°3713”
Whitewater River at Windy Point near Whitewater	1985-1987, 1989-2001	September 1989	264.0	10257550	33°53’56”	116°37’13”
Mission Creek near Desert Hot Springs	1968-2001	9 days	35.6	10257600	34°00’40”	116°37’38”
Chino Canyon Creek near Palm Springs	1975-1985	13 days + last 2 months	3.8	10257710	33°50’21”	116°36’45”
Chino Canyon Creek below Tramway near Palm Springs	1987-2001	10 days	4.7	10257720	33°50’39”	116°36’16”
Long Canyon Creek near Desert Hot Springs	1964-1971	None	19.6	10257800	33°57’53”	116°26’35”

[1] R, river; MWD, Metropolitan Water District; Div, diversion; BL, below

[2] Records are daily-value streamflow discharge, unless otherwise noted.

[3] Referenced to the North American Datum of 1927 (NAD 27).

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COACHELLA VALLEY, CALIFORNIA—U.S. Geological Survey Water-Resources Investigations Report 02–4013