Changes in active eolian sand at northern Coachella Valley, California

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ABSTRACT

Climate variability and rapid urbanization have influenced the sand environments in the northern Coachella Valley throughout the late 20th century. This paper addresses changes in the spatial relationships among different sand deposits at northern Coachella Valley between two recent time periods by using satellite data acquired from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The approach employed here, involving multispectral thermal infrared (TIR) data and spectral mixture analysis, has shown that the major sand deposits can be spatially modeled at northern Coachella Valley. The “coarse-grained (quartz-rich) sand” deposit is associated with active eolian sand, and the “mixed sandy soil” and “fine-grained (quartz-rich) sand” deposits are associated with inactive eolian sand. The fractional abundance images showed a significant decrease between 2000 and 2006 in the percentage of active sand in the major depositional area for fluvial sediment, the Whitewater River, but also in two downwind areas: the Whitewater and Willow Hole Reserves. The pattern of the active sand appears to be related to variations in annual precipitation (wet and dry years) and river discharge in the northern Coachella Valley. We suggest here that recent human modifications to the major watercourses that supply sand affect the capability of fluvial deposition areas to restore sediments over time and consequently the responses of the sand transport system to climate change, becoming more sensitive to dry years where areas of active sand may shrink, degrade, and/or stabilize faster. The approach utilized in this study can be advantageous for future monitoring of sand in the northern Coachella Valley for management of these and similar environments.

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1. Introduction

The northern Coachella Valley of southern California (Fig. 1) is an area of active eolian processes and sand transport. It is also undergoing rapid urbanization. Eolian landforms in the area include smooth, sand-covered surfaces, known as sand veneers or sand sheets on which smaller areas of knob (nebkha) and barchan dunes are distributed, yet their forms are subject to obliteration and eventual removal by wind erosion or by human activity (Beheiry, 1967; Lancaster, 1997). Sand-depletion is considered an on-going problem in northern Coachella Valley. Wind velocities and therefore eolian sand-transport rates are high in this area and the watercourses that supply sediment have been subjected to variation in annual precipitation and considerable landscape modification. Lancaster et al. (1993) concluded that northern Coachella Valley has been affected by changes in sand supply and transport rates through the 20th century. They noted that eolian transport rates were relatively high between 1948 and 1974 during a period of prolonged drought, and lower transport rates after a period that is relatively wet. A later work of Griffiths et al. (2002) shows continuous changes in the nature of the sands in northern Coachella Valley, including a net loss in the area covered by sand sheets and a net decrease in the total area composed of eolian materials. These changes were related to alterations in processes operating in the source areas and the transport corridors that have resulted from variations in annual precipitation and particularly prolonged periods of climatic shifts to either wetter or drier conditions that affect flood events needed to supply fluvial sediments to alluvial fans. Nonetheless, the rapid urbanization and population growth at northern Coachella Valley cannot be ignored as an affect on sediment transport. The sand-delivery system has been significantly altered historically mainly due to modifications of channels within the valley that deliver fluvial sediment from the headwaters to the depositional areas upwind of the sand reserves (Fig. 1). Historic and recent images of the area near Whitewater Reserve are presented in Fig. 2.

The sands support a variety of animals and plants specially adapted to living in this geographically isolated arid-environment. The Coachella Valley fringe-toed lizard (Uma inornata) for example is a sand-dwelling species that is narrowly endemic on active loose sands and their stabilized margins (Turner et al., 1984; Barrows, 1997). In order to preserve this species, the Coachella Valley Preserve System (CVPS) has been set aside by local agencies, but concern has been expressed that its habitat is still threatened by environmental changes and therefore the long-term survival of the species is uncertain.
Fig. 1. Map of northern Coachella Valley, California containing the Coachella Valley Preserve System (Whitewater, Willow Hole, and Coachella) shown on the background of a shaded relief map. Stream channels are indicated by dashed-black lines.
The primary objective of this study is to spatially-quantify the eolian sand transport system in the northern Coachella Valley at different times using TIR data from the ASTER satellite instrument. A key principle in the understanding of sand areas is the recognition that they occur as part of recognizable sediment transport systems in which sand is moved from source areas and transported along distinct transport corridors to depositional sinks (Lancaster, 1997).

The sands in northern Coachella Valley were described by Reed (1930) and Beheiry (1967) as immature, torrential-eolian sands that would have required a "large additional amount of wearing and sorting during transportation to reach the stage considered normal (eolian) in many parts of the Valley". The random mixing of different surface sediments as a result of joint fluvial and eolian deposition was a trigger here to retrieve sub-pixel information about the sediment composition using TIR remote sensing data and spectral unmixing methods.

2. TIR remote sensing of sands

Satellite remote sensing provides a useful means to spatially-quantify the land surface features at a regional scale. Satellite visible and shortwave infrared data have been widely used in sand studies because datasets covering this wavelength range are available globally. Blount et al. (1990) and Paisley et al. (1991) have attempted to demonstrate in studies in the Gran Desierto (Mexico) and the Mojave Desert (southwest United States), respectively, that active sand is consistently brighter (high albedo) in the visible and near infrared satellite data than inactive sand as a result of grain size and composition. Albedo and these wavelengths used in remote sensing are diagnostic of sand composition. Fewer studies have focused on the use of multispectral remotely sensed data in the TIR (8–14 μm) part of the electromagnetic spectrum, in which spectral features related to composition (i.e., Si–O bonding of silicate minerals) can be discriminated.

The spectrum of quartz for example exhibits a diagnostic emissivity minima at approximately 9 μm while a clay such as montmorillonite shows weaker absorption and the spectral feature shifts to a higher wavelength (approximately 9.5 μm) (e.g., Hunt, 1980). Ramsey et al. (1999) used airborne multispectral TIR (8–12 μm) data acquired from Thermal Infrared Multispectral Scanner (TIMS) to study eolian deposits and landforms in the Kelso Dunes eolian system, California, and to map a variety of sand surfaces containing abundant silicate minerals, employing spectral mixture analysis to retrieve sub-pixel information. Hook et al. (2005) used the MASTER airborne multispectral data (7–13 μm) to remotely determine the weight percent silica of the surface in Hiller Mountains, Nevada, and La Reforma Caldera, Mexico. ASTER has proven useful for mapping key minerals in the visible-near infrared (VNIR), shortwave infrared (e.g., Gomez et al., 2005), and TIR regions, especially for discriminating carbonates and silicates (e.g., Rowan et al., 2005). Spectral mixture analysis of ASTER TIR data was used to retrieve sub-pixel information about sediments and lithologic distribution in the Meteor Crater ejecta blanket, Arizona (Ramsey, 2002; Wright and Ramsey, 2006). Katra and Lancaster (2008) used ASTER TIR data and spectral mixture analysis to
retrieve variations in clastic and chemical sediments of a complex surface for a wet playa in the Mojave Desert, California. The present study utilizes ASTER TIR images (see Section 5.3) and the approach of spectral mixture analysis (see Section 6.4) to investigate the sand areas at northern Coachella Valley.

3. Geographic setting

The Coachella Valley, located in the Colorado Desert of south-central California, extends southeast from the San Gorgonio Pass to the Salton Sea, a distance of 81 km (Fig. 1). The narrow, deep valley is considered to be the northern apex of the Salton Basin, a structural depression associated with the extensional development of the Gulf of California. California’s most active strike-slip fault zone, the San Andreas, passes through the area. The northern Coachella Valley is bounded on the northeast by the Little San Bernardino Mountains and to southwest by the San Jacinto Mountains of the Peninsular Range. These ranges, which reach altitudes in excess of 3050 m, are predominately composed of felsic igneous and metamorphic rock assemblages: granite, granodiorite, quartz diorite, gneiss, and to a lesser extent, gabbro, quartzite, marble, and schist (Wasklewicz and Meek, 1995). During the past three million years, erosion of the ranges has resulted in filling of the basin floor with alluvial, colluvial, and eolian materials. Russell (1932) estimated that the fill near San Gorgonio Pass may exceed 305 m, while fill near northern limits of the Salton Sea may reach 4267 m according to Remeika and Lindsay (1992). Weathering of the felsic igneous and metamorphic rock assemblages in an arid to semi-arid climate produces large quantities of sand-sized and finer sediment composed primarily of feldspar and quartz with minor amount of hornblende, muscovite, biotite, epidote, apatite, titanite, zircon and garnet (Reed, 1930). Production of the fine-grained materials combined with frequent, strong winds that blow southeastward through San Gorgonio Pass and an arid- to semi-arid climatic regime, have allowed eolian processes to distribute wind blown sediments throughout large areas of the northern Coachella Valley (Sharp, 1964; Beheiry, 1967). These eolian deposits are concentrated in a region extending from San Gorgonio Pass to just beyond Route 111 near Indio, a distance of 52 km (Weaver, 1979).

4. The sand transport system

The sand transport system in northern Coachella Valley is described in detail in Griffiths et al. (2002). Fluvial sediment is mostly generated in the headwaters areas in either the San Bernardino or Little San Bernardino Mountains (Fig. 3). The ephemeral streams (washes) deliver sediment in flash floods that occur infrequently during large winter storms, or during intense summer thunderstorms, from the hillslopes downstream into channels that pass through large coalescing alluvial fans (bajadas). Sediment transported through the bajada in the channelized washes is deposited over broad, low-angle depositional plains. These sand sources are predominantly the major watercourses, particularly the Whitewater River and San Gorgonio Wash for the Whitewater Reserve, and the Mission Creek and Morongo Wash for the Willow Hole Reserve (Fig. 1).

Westerly winds through San Gorgonio Pass shift to northwesterly winds with distance into the Coachella Valley, and provide the dominant force for removing fluvial sediments deposited by major watercourses on the valley floor into eolian deposits (Lancaster et al., 1993). Winds can shift to other directions during occasional thunderstorms, but these events are sporadic and 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 is expected. The sand forms in northern Coachella Valley have been described in several previous studies (Russell, 1932; Sharp, 1964; Beheiry, 1967; Sharp, 1980; Lancaster et al., 1993; Lancaster, 1997). Sand veneers on surfaces that are not eolian in origin (also called sand sheets) occupy a considerable part of the valley floor, 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 dunes range from knob dunes (nebkha or coppice dunes) — small and ephemeral mounds anchored by perennial vegetation — to barchan dunes (Beheiry, 1967). Parabolic dunes occur in the Coachella Valley Reserve to the east.

5. Data sets

5.1. Hydrological and climate data

Precipitation data were obtained from the Western Region Climatic Center (http://wrcc.dri.edu/) recorded in the Valley floor (Palm Springs), San Jacinto Mountains (Idyllwild Fire Department), and San Bernardino Mountains (Big Bear Lake) during the years 1994–2007 (Fig. 4a). Streamflow gauging data (Fig. 4b) were obtained from the U.S. Geological Survey (http://waterdata.usgs.gov/nwis) recorded in the Whitewater River (Station Number 1027550) at Windy Point near Whitewater (see location in Fig. 3).

5.2. Surficial geologic units

Geologic units of Quaternary age for the northern Coachella Valley were obtained from U.S. Geological Survey (Lundstrom et al., 2001; unpublished mapping of Lundstrom, R. Shroba and J. Matti) as part of the Southern California Areal Mapping Project (SCAMP). The georeferenced map (Fig. 5) distinguishes the deposits by the geomorphic processes that resulted in their deposition (alluvial and eolian units) and differentiates the ages of geomorphic surfaces within the Pleistocene and Holocene eras.

5.3. ASTER TIR images

The ASTER records spectral radiance in five TIR channels with a spatial resolution of 90 m/pixel and a NEΔT<0.3 K (Yamaguchi et al., 1998). The five channels are centered on 8.29, 8.63, 9.08, 10.66, and 11.32 μm. For this study, we acquired the orthorectified (AST14OTH) data from the Land Processes Distributed Active Archive Center (LP DAAC) at the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS) (http://lpdaac.usgs.gov). The AST14OTH products are terrain-corrected and provide radiometrically calibrated radiance values (w/m²/sr/μm). Several ASTER TIR scenes were selected based on overall quality from the ASTER database to have complete, cloud-free coverage of the Coachella Valley for this study. Mosaics of the ASTER TIR data were created to represent two time periods. The first set refers to the years 2000–2001, in which

Fig. 4. Hydrological data for northern Coachella Valley. (a) Annual precipitation for the valley floor (Palm Springs), San Jacinto Mountains (Idyllwild Fire Department), San Bernardino Mountains (Big Bear Lake). Average annual precipitation: Palm Springs 213 mm (1927–), Idyllwild Fire Department 1000 mm (1948–), and Big Bear Lake 854 mm (1960–). (b) Annual discharge for Whitewater River at Windy Point near Whitewater.
Fig. 5. Surficial geologic units in northern Coachella Valley near Whitewater and Willow Hole ecological reserve (Fig. 1) (Lundstrom et al., 2001). Eolian units: Qd (eolian coarse sheetwash sand), Qe (eolian sand, fine to coarse sand, and colluvium/alluvium on slopes); Alluvial units (Holocene): Qayy (youngest fan alluvium/wash deposits), Qayi (intermediate young fan alluvium), Qayo (young fan alluvium), Qay and Qfy (young fan alluvium); Alluvial units (Pleistocene): Qai and Qaiy (younger intermediate fan alluvium), Qao (older alluvium), Qau (undivided Pleistocene alluvium).

Fig. 6. ASTER TIR non-normalized mosaics of northern Coachella Valley: (a) first time period, and (b) second time period. Dates of images acquisition are indicated on the ASTER channel 10 (8.29 μm) radiance. The black dashed line denotes the region of interest for the image analysis.
earlier ASTER data and surficial geologic units (Fig. 5) are available. The second set is from later years, i.e., 2005–2007. Thermal imagery from different dates is expected to have different scene characteristics (i.e., surface temperature, atmospheric conditions, and instrument noise), therefore, in order to ensure accurate spectral analysis of the spectral emissivity, a relative radiometric normalization technique was used to create coherent image mosaics (Scheidt et al., 2007). Scenes of the first time period were normalized to the reference date (Apr-00, Fig. 6). The data of May-07 were adjusted to the data of Apr-00, and then used as reference data for the other scenes of the second time period. Because most of the study area is within the scenes of Apr-00 and Jul-06 (see region of interest in Fig. 6) for the first and the second time periods, respectively, the image-mosaics are defined herein as 2000 and 2006. The low precipitation amounts received in the valley floor suggest that except for scene Oct-05, the soil surface at the study area was dry in all the other scenes.

6. Image-data analysis

Several steps were undertaken in the data analysis process (Fig. 7). The steps are described in the following sections.

6.1. TIR data evaluation

In order to evaluate the trend in surface composition of northern Coachella Valley of the two dates, a decorrelation stretching (DCS) technique was performed on these data. The DCS is a transformation of the original data that removes the high correlation commonly found in TIR multispectral data sets and allows the thermal and emissivity variations to be distinguished visually (Gillespie et al., 1986). In the DCS results, emissivity (compositional) variations are shown as color differences, whereas the intensity of those colors relates to the surface brightness temperature. For the DCS of the channels 14, 12, and 10 (Fig. 8), the red areas correspond to quartz-rich materials. The image transformation results therefore may indicate changes in the pattern of the quartz-rich areas at northern Coachella Valley over time.

6.2. Emissivity extraction

The dominant absorption features of the silicate minerals of interest in the study area (e.g., Thomson and Salisbury, 1993; Ramsey and Christensen, 1998) are retrieved and retained by the emissivity spectra of the ASTER TIR data. Emissivity was extracted using all five bands of the ASTER TIR data with the emissivity normalization
method (Realmuto, 1990), where the assumed maximum emissivity value is 0.960. The product of this step is a five-channel emissivity mosaic image for each time period for which spectral mixture analysis is performed.

6.3. Emissivity ratio images

Emissivity ratio images show the spectral contrast that is characteristic of certain lithologic compositions based on specific spectral features (Rowan et al., 2005). The ASTER filtered spectrum of quartz shows a characteristic emissivity minimum at channel 12 (9.08 μm), where most other materials lack deep spectral features. Therefore the probability of a higher areal abundance of quartz rich rock/soil is represented by relatively higher pixel values in a ratio image of channel 13 to channel 12 compared to other quartz-poor areas. This ratio was applied for the emissivity mosaics in order to distinguish areas that are quartz-dominated, before the spectral mixture analysis (see next section). Comparison of the emissivity ratio images (Fig. 9) with the DCS TIR images (Fig. 8) shows that the higher ratio values corresponded well with abundance of red-magenta color in both time periods.

6.4. Spectral mixture analysis

It has been demonstrated that the thermal infrared spectrum of a mixed surface may be closely modeled using a linear combination of a few spectrally unique components (endmembers) weighted by the areal abundance of each endmember (Gillespie, 1992; Ramsey and Christensen, 1998; Ramsey et al., 1999; Katra and Lancaster, 2008). Spectral mixture analysis allows generation of fraction images with sub-pixel information that can be interpreted as surface-material abundance maps.

6.4.1. Image endmembers

An endmember spectrum is typically either a laboratory spectra of a pure mineral or pixel spectra extracted from the image thought to represent a specific, pure abundance of a material. The goal of spectral unmixing is to explain or model the spectral variance in the remainder of the image space based on these endmembers. The careful selection of endmembers therefore is an important step to generate physically-meaningful fractional images. The selection of endmembers for spectral analysis was limited to spatial areas of the image that were determined as quartz-rich sediments from the emissivity ratio (Fig. 9). Spectral endmembers were derived from the emissivity data of the first time period (Fig. 9) using an automated algorithm, the Sequential Maximum Angle Convex Cone (SMACC) tool (Gruninger et al., 2004), due to the following reasons: (a) endmembers are not known, (b) no laboratory endmembers are available for the known image components, and (c) in this study, scene endmembers are mixtures themselves. Four endmembers (A, B, C, and D) with different spectral characteristics were selected by the SMACC (Fig. 10). Spectral endmembers A to D were used to unmix the emissivity images of

Fig. 9. Emissivity ratio images for quartz absorption feature: ASTER channel 13/ASTER channel 12 (threshold at 1.095). Higher values are associated with white color. (a) First time period, and (b) second time period. Note the similarity in the pattern of the quartz-rich areas between these images and the DCS TIR images (red-magenta areas in Fig. 8).

Fig. 10. The spectral endmembers derived from the mosaic of the first time period along with a quartz spectrum at laboratory and ASTER resolutions (ASU thermal emission spectral library, Christensen et al., 2000). Spectra are offset on the vertical axis for clarity at 0.10 segments. Emissivity values at quartz absorption band (9.08 μm) for A, C, and D are 0.83, 0.86, and 0.87, respectively.
northern Coachella Valley. A geomorphic interpretation of the endmembers is given in Section 7.

6.4.2. Fractional abundance images

A linear spectral unmixing algorithm was utilized in this study to generate fractional abundance images of sand deposits. The algorithm, demonstrated by Ramsey and Christensen (1998), has been used successfully in mapping areal abundances of surface materials (Ramsey et al., 1999; Michalski et al., 2004; Katra and Lancaster, 2008). The algorithm employs a numerical chi-squares minimization technique with two main constraints. First, endmembers that result in negative values are assumed to have no physical meaning, and are presumed not present in the mixed spectrum and removed. Second, a unity constraint produces fractional percentages which sum to 100% rather than a renormalization of the fractions as a final step. For this study, the selected endmembers A to D (Fig. 10) were used as an input (a spectral library) to unmix the emissivity images of 2000 and 2006. The output of the algorithm consists of image layers for each of these endmembers with pixel values equal to the fractional abundance (in percentages) of that endmember, and root-mean squared (RMS) error image, quantifying the difference between the observed and modeled emissivity spectra. Fig. 11 shows the results of the fraction image set for each time period. RMS errors ranged from zero to a maximum of 3.5% in emissivity.

7. Results

7.1. Sand-deposit types

The endmembers A to D (Fig. 10) are assumed to represent the surface sediments in the image of northern Coachella Valley. The locations in the image space of most of the selected endmembers were found to be associated with distinct deposits in the georeferenced unit map (Fig. 5):

- Endmember A was selected by the model in the Whitewater Reserve in the youngest wash deposits (Qay). Generally, these alluvial deposits in the northern Coachella Valley are composed of granitic and gneissic rock types from the San Bernardino and Little San Bernardino Mountains, as well as material reworked from older gravel sedimentary units. The Qay unit (late Holocene) commonly includes a sand-rich surface layer (with weak cementation) where the sand-size fraction is mostly medium to very coarse sand that is locally overlain by a discontinuous mantle of eolian sand.
- Endmember B was selected in areas of Qay and Qfy, young alluvial fans north to Whitewater Reserve with alluvium and minor debris-flow deposits (Holocene and latest Pleistocene) on partly developed soil.
- Endmember C was selected in the Indio Hills, where two units dominate that area. The first unit (Qao) is comprised of alluvial fan deposits of Pleistocene age, mantled by eolian sand and sandy colluvium. The second unit (Qe and Qd) comprises eolian sand deposits of Holocene and latest Pleistocene age, sand-rich sheetwash and small dunes, composed of mostly fine to coarse sand that contains minor amounts of very fine and very coarse sand.
- Endmember D was selected in pixels that are located out of the geologic map coverage, in foot-slope positions near the San Bernardino and Little San Bernardino Mountains, but also in some other areas.

The following description of the endmembers is geomorphic. Nevertheless, the geomorphic differences among the endmembers are related here to differences in the sediment composition (grain size, soil formation), which are reflected in the characteristics of the spectra (e.g., absorption features). Spectra A, C, and D exhibit a relatively strong absorption feature at 9.08 µm, indicating that silicate is an important constituent. Even though the convolution of quartz laboratory spectra to ASTER shows the characteristic doublet feature (Fig. 10), this is not always seen with ASTER image emissivity spectra. Spectrum C is also fitted well by a spectrum of the quartz mineral, while in spectrum A, low emissivity values occur also in the shortest wavelength. The difference between spectra A and C is probably related to the compositional differences in the fine-grained soil fractions of these different geomorphic units (Salisbury and D’Aria, 1992). Grain size has an important affect on the depth of spectral features. As the grain size decreases, the spectral feature depth is also decreased (i.e., higher emissivity) (Hunt, 1980; Clark, 1999). In this case, endmembers A and C may correspond to coarse-grained and fine-grained quartz-rich materials, respectively, with different surface soil formation characteristics (i.e., duricrust, induration of fine material, etc.). Spectrum D has the highest emissivity value at the quartz absorption band (9.08 µm) and the sharpest emissivity slope toward the 8.29 µm band, and does not appear to correspond to a specific mineral/desert type. Since the endmembers (A to D) were selected from a quartz threshold image (Fig. 9), where the number of the surface components is assumed to be small and thus variation in emissivity characteristics, endmember D is assumed to represent an unknown mixture of quartz and other material. Spectrum B has an unusual shape of a downward slope from the 10.66 µm toward the shorter wavelengths. A similar emissivity spectrum was demonstrated by Rowan et al. (2005) for a sample of a sandy soil where the quartz was mixed with weathered minerals. However, this spectrum may also point to the presence of vegetation.

Although the ability to link the endmembers to specific minerals does exist, it is more realistic in the scope of this study to define the image spectra of Coachella Valley as mineralogical mixtures representing distinct surface deposit types because of the spatial scale of the remotely sensed data. Accordingly, endmembers A, B, C, and D are defined here as geomorphic endmembers of mixed quartz materials and are distinguished as “coarse-grained (quartz-rich) sand”, “mixed sandy soil”, “fine-grained (quartz-rich) sand”, and “unknown mixed quartz materials”, respectively.

7.2. Areal percentage of endmembers

It was revealed from the fractional abundance images (Fig. 11) that the areal abundance values for most of the pixels are less than 100% (grey tones) in both images, 2000 and 2006, leading to overlapping in the spatial distributions of the associated endmembers in the image space. Significant overlapped distributions were observed for endmembers A and B, which are defined here as “coarse-grained (quartz-rich) sand” for youngest wash deposits and “mixed sandy soil” for young alluvial fans, respectively. In both image-mosaics, areas of high areal abundance (>70%) of “coarse-grained sand” (a in Fig. 11) were observed along the Whitewater River where it passes the Whitewater Reserve. Areas of “mixed sandy soil” (b in Fig. 11) with high areal abundances are shown mainly in the Mission Creek wash, but also south to the Coachella Valley Reserve and the Indio Hills (mosaic 2006). An abundance of “fine-grained sand” (c in Fig. 11) was found in the Indio Hills, the Whitewater River near Windy Point, and on the piedmont of San Bernardino Mountains. The spatial distribution of the “unknown mixed quartz materials” (d in Fig. 11), in contrast, is not associated with a realistic spatial distribution of abundance, resulting in a similar spatial distribution for both time periods and relatively small areal coverage in northern Coachella Valley. The spatial distributions of the “coarse-grained sand”, “mixed sandy soil”, and “fine-grained sand” appear to reflect reasonable spatial distributions, and these are observed to have changed over the time between the image acquisition dates. For example, there was a reduction of abundance of “coarse-grained sand” deposit southeast to Palm Springs, between the Whitewater River and the Southern Pacific Railroad, in 2006, parallel to expansion of the high areal abundances of “mixed sandy soil” deposits. It revealed from Fig. 12 that the areal abundance values for the “coarse-grained sand” (A) range from 0% to 100%, with a trend for higher values at the first time period; meaning that the total area that is associated mainly with “coarse-grained sand” in northern...
Fig. 11. Fractional abundance images for the spectral endmembers a, b, c, and d. Endmembers areal abundance is >10% to 100%, where higher values are associated with white pixels. RMS errors: 0–0.035 for the set of 2000, and 0–0.029 for 2006. endmembers a to d represent "coarse-grained (quartz-rich) sand", "mixed sandy soil", "fine-grained (quartz-rich) sand", and "unknown mixed quartz materials", respectively (see text).
The range of “mixed sandy soil” for image pixels ranges between approximately 25 to 80%, and higher values of this deposit are found in the second time period compared with the first time period. Endmember C is characterized by relatively low values of areal abundance (0 to 50%) for both time periods; almost no change is interpreted from the trend of the value distribution. The decrease in the areal abundance of the “coarse-grained sand” can be connected to the increase in the areal abundance of the “mixed sandy soil” and vice versa. About 15% of the total image-pixels of northern Coachella Valley are involved in this change, most of which are concentrated along the Whitewater River area.

8. Discussion

8.1 Active and inactive sands

Sand deposits may change in extent with time as the fluvial sand supply to the depositional areas increases after a flood or is depleted by wind erosion. A deposit that contains saltation-size grains (0.125–0.250 μm) is assumed to be eolian active (loose) sand, while deposits that contain mainly finer grains (<0.125 μm) and/or coarser grains (>250 μm) are assumed to be inactive sand with possible induration and cementation present. Beheiry (1967) found that the median diameter of eolian sand at sixteen sites in the Coachella Valley ranged from 90 to 440 μm with an average of 280 μm. Endmember A “coarse-grained (quartz-rich) sand” can be linked here to potentially active eolian sand. Its higher areal abundance in the fraction image for 2000 (a in Fig. 11) corresponds to areas of eolian sand deposition, including the Whitewater and Willow Hole Reserves observed in 2000 by Griffiths et al. (2002) (Section 4 and Fig. 3). In this context, the two other major deposits, represented by “mixed sandy soil” (endmember B) and “fine-grained sand” (endmember C), can be closely linked with inactive eolian sands.

Such discrimination between sand areas is essential for interpretation of changes in supply, availability, and mobility of sand in northern Coachella Valley. To illustrate the spatial relationships among these three major sand deposits, the fraction images of each set (Fig. 11) were displayed in RGB format (Fig. 13). Abundances of red, green, and blue, are associated with high percentage fraction of the spectral endmembers A (“coarse-grained sand”), B (“mixed sandy soil”), and C (“fine-grained sand”), respectively. Pixels with color composites (i.e., cyan, magenta, orange, yellow, or purple tones) indicate that more than one spectrum/sand deposit occupies the image space. Obvious changes can be seen in the spatial distribution of the active sand areas (red), in which most of the areas that were occupied by this deposit in 2000 were replaced by inactive sand of “mixed sandy soil” deposit in 2006. An explanation for this change can be found in changes in precipitation and fluvial sedimentation.

8.2 Changes in sand activity

Decadal and annual variations in precipitation impact sediment supply, availability, and mobility (transport rates) via rates of overland flows, changes in vegetation cover, and changes in the magnitude and frequency of winds capable of transporting sediment (e.g., Bach, 1995; Lancaster, 1997; Catto and Bachhuber, 2000; Lancaster and Helm, 2000). 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 and brought into the valley floor by the main seasonal or ephemeral streams. Lancaster et al. (1993) and Griffiths et al. (2002) have noted the impact of variations in the precipitation amounts on flood events, and thus, sand transportation rates in northern Coachella Valley, suggesting that changes in fluvial sediment supply significantly influence rates of eolian sediment transport in this valley. When examining the hydrological data (Fig. 4), it revealed that the variations in the annual precipitation received in San Jacinto and San Bernardino Mountains control the discharge of the combined (channelized) floodwater of the San Gorgonio and Whitewater Rivers near Windy Point with some lag of time. In the last 25 years, significant floods on Whitewater River have occurred in 1978, 1983, 1993 and 1998, during El Niño conditions, in which streamflow is greatly increased in the southwestern United States (Griffiths et al., 2002). The floods of 1998 are clearly demonstrated in the hydrological data given in Fig. 4b. The combined floodwaters of the San Gorgonio and Whitewater Rivers debouch onto the Whitewater depositional area, depositing fluvial sediments in a low-energy environment that is today occupied by a series of water-spraying structures and earthen dikes designed to infiltrate low flows from the Whitewater River into the regional aquifer (Fig. 3). The intake channel to the infiltration galleries is designed to trap much of the sand transported by the Whitewater River, potentially making it available for downstream transport to the Whitewater River depositional area. Water imported from the Colorado River is released into the channel of the Whitewater River about 1500 m upslope (north) of the Interstate 10 bridge at Whitewater. This sediment-free water quickly entrains fine-grained sediments and moves at least some of the sediment out of the 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.

In 1953 sand cover was extensive on the Whitewater floodplain, and even by the late 1980s (east to W in Fig. 2), after the establishment of the infiltration galleries in 1984, active sand sheets extended eastward from active fluvial channels (Lancaster et al., 1993). It is possible that sufficient fluvial sediments were transported by the Whitewater River across the infiltration galleries during a period of
relatively wet years and high discharge rates between 1994 and 1999 (Fig. 4), leading to high areal abundance of eolian active sand deposits in the Whitewater floodplain. The sediment that was entrained from the Whitewater depositional area by wind, moved downwind to cover the reserve areas. Moreover, expansion of the airflow and reduction of wind speed between Palm Springs and Thermal (Beheiry, 1967), south of the Coachella Valley Reserve, allowed deposition of sand down valley. The reserve and the area down valley, between the Whitewater River and the Southern Pacific Railroad, appear therefore as areas of high areal abundance of active sand in the fraction images 2000 (Figs. 11 and 13). At the same time, sufficient eolian sand was delivered also to the Willow Hole and Coachella Valley Reserves in the same manner (Fig. 3). Under these wetter conditions, each flood brought more sand to the depositional areas, so even after drought years (e.g., 1977, 1988–1989) with expected low discharges, the eolian and the eolian depositional areas (i.e., reserve areas) were still completely covered by active sands (see for example 1977 and 1989 in Fig. 2). Although variation in precipitation amounts occurred on the decadal timescale, the balance in the sand transport system remained. Later, a continuity of wet years (1994–1999) and high discharge in the rivers, allowed for maintenance of the sand delivery system with a high percentage cover of sands during 2000. Nonetheless, due to landscape modifications over time (Fig. 2), in particular the infiltration galleries that trap fluvial sediment, it is reasonable to believe that the sand delivery system became more sensitive to dry period like that of 1999–2004. This is the reason why a high abundance of active sand in the fraction image 2006 was observed in the northern part only of the Whitewater depositional area, where the combined (channelized) Whitewater River passes through the infiltration galleries (Fig. 13). Sand was not resupplied to the southern parts of the Whitewater depositional area even after high discharge in 2005 and 2006 following the dry period. The high areal abundance of active sand in the area west to Windy Point is support for this assumption, indicating that under
conditions of low discharge the fluvial sand of the Whitewater and San Gorgonio Rivers accumulates upstream of Windy Point rather than being passed through the infiltration galleries and accumulating in the Whitewater floodplain. Dikes associated with Interstate 10 and Southern Pacific Railroad construction also reduce the connectivity with the Whitewater depositional area (Griffiths et al., 2002), and therefore, explain some of the reduction in active sands in the Mission Creek – Morongo area during that time. If the fluvial sand supply was decreased starting from 2000, the available sand deposit for eolian activity and its transportation rates over the valley were also decreased, with some lag of time. Thus, the reduction in the areal abundance of the active sands in those areas that are associated with eolian deposition (Reserves, downvalley southeast to the Whitewater Reserve) had started already in 2002 or 2003. Otherwise, the sand in these areas was stabilized and it appears as “mixed sandy soil” in the fraction images for 2006 (Figs. 11 and 13).

9. Conclusions

It was demonstrated in this study that the spatial relationships among the major sand deposits in northern Coachella Valley have significantly changed in recent years. The approach utilized in this study, spectral mixture analysis of multispectral TIR data, was found to be useful to investigate the distribution and composition of sands in the northern Coachella Valley, including identification of different sand deposits and retrieval of sub-pixel information. In the northern Coachella Valley, where different grain-size sands are deposited by fluvial and/or eolian processes, fraction images of sand deposit types were useful to discriminate the dominant sand type in specific areas. It revealed from the fractional images that the abundance of sand available for eolian transportation in the fluvial depositional areas as well as in downwind areas has decreased in the last years. Lancaster et al. (1993) hypothesized that decadal and annual variation in precipitation leading to periods of sand accumulation alternate with periods of eolian deposit migration, modification, and degradation. Nonetheless, modifications to the major watercourses that provide sand to the eolian system in the northern Coachella Valley, in particular, channelization of the Whitewater–San Gorgonio Rivers and establishment of infiltration galleries in the historical Whitewater depositional area, may have consequences for the long-term equilibrium between fluvial supply of sand and eolian transportation rates. It is concluded here that due to the artificial structures, and thus, the capability of the main fluvial deposition areas to restore sediments over time, the sand delivery system has become more sensitive to dry periods compared to the past few decades, responding by a faster reduction, degradation, and/or stabilization of the major active sand areas. Ecologically, this may impact on the survival of critical habitat of threatened and endangered species such as the fringed-toed lizard (U. inornata). With continued data acquisition from the area, it is relatively easy to monitor changes, leading to a better understanding and development of future management strategies of the sand environments in northern Coachella Valley.

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References


Weaver, D.C., 1979. Assessment of effects of flood control alternatives on blowsand conditions in the Coachella Valley, Whitewater River Basin. Report to the US. Department of the Army, Los Angeles District, Corps of Engineers, Contract No. DACW09-78-C-0052.
