Owens Lake Shoreline Study Technical Services

Preliminary report on the detrimental effects of flood control berms on the Keeler Dunes, Inyo County, California

AECOM

December 12, 2012

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1 EXECUTIVE SUMMARY

This preliminary report provides summary findings regarding the effects of flood control berms on the Slate Canyon fan (Keeler Fan) to the Keeler Dunes. It is clear that the Older Keeler Dune mound system slowly developed during repeated depositional events beginning approximately 2000 years ago. The origins of the Older Keeler Dunes are natural. This older dune system consisted of coppice mounds, coppice dunes, sand sheets, shoreline dunes and at times southeastward migrating transverse dunes similar to recent times. The Older Keeler Dune mound system likely looked similar to that shown in 1944 and 1968 aerial photographs. However based on historical photographic analysis and review of the Great Basin Unified Air Pollution Control District (District) Staff report (2012) conclusions, it is clear that about 30 years ago the Older Keeler Dune mound system ceased to grow and instead began to erode away. Geomorphic mapping and numerical age dating of the Older Keeler Dune deposits indicate that this magnitude of erosion had likely not occurred during Older Keeler dune development in the past 2000 years. This destruction is limited to the Keeler Dunes system. The nearby Swansea Dunes have not experienced deep erosion or destruction in recent times. Other dune systems in the vicinity as well have not experienced deep abrasion in recent times including the Swansea Bay (Lizard Tail) and the Southeast Keeler dunes located just southeast of the town of Keeler. These observations that only the Keeler Dunes were being destroyed led to the obvious question as to what caused the destabilization of the Keeler Dunes.

An important factor was discovered during field mapping of the extent of flooding on the Slate Canyon fan (Keeler Fan) on July 31, 2012. The entire flood waters were observed to be diverted by the flood control berms located immediately northeast of Highway 136. These berms diverted the flood water around the Keeler Dunes and in particular the portion of the Keeler Dunes where internal erosion in the early 1980s initiated. The flood flow diversions began in approximately 1953 with the construction of the northwestern berm. A second flood control berm was constructed in the late 1960's (by 1968) southeast of the older berm. Both of the berms have been maintained over the years and still exist today. Collectively, these two berms essentially divert all flood moisture from entering the northwestern Keeler Dune system. Flash floods with sufficient strength to reach the Keeler Dunes occur every 3 to 5 years at a minimum. The Keeler Dunes, and additionally the Swansea and Southeastern Keeler Dunes all developed over time in areas where they receive flood waters routinely and played an important role in their origin, development, and stability. The Swansea and Southeast Keeler dunes continue to receive moisture as flash floods waters routinely pond on their upslope side. Neither of these dune systems have undergone internal erosion as witnessed in the Keeler Dunes in the past 30 years.

Further investigation and research showed that the diversion of storm waters disrupted a natural process important to the stabilization and growth of the Keeler Dunes. The berms diverted critical flood waters from entering the northwestern portion of the Older Keeler Dune mound system which over time caused the internal core moisture content within the dunes to decrease, thus greatly increasing the rate of erosion of the dunes by sand baring wind (abrasion). In addition, the decrease, in moisture entering the dune system also caused a decrease in vegetation density and health, which had assisted in stabilizing the dunes. The decrease in vegetation in the region where the flood waters are being diverted strongly suggests the water content in the dunes is reduced. As a result, the berms disrupted the natural process of infiltrating waters entering the northwest Keeler Dunes and caused their erosion and eventual destruction.

The internal erosion of the Keeler Dunes due to the berms has had a number of important consequences.

- The eroded sands from the Older Keeler Dune mound system contributed an internally derived and relatively large new source of eolian sands to the Younger Keeler Dune system. This led to the development of transverse dunes southeast of the abrasion areas soon after the abrasion began in the late 1970s to early 1980's.
- The erosion into the older eolian sand deposits also exposed interbedded older fine-grained flood deposits (referred to by the District, 2012 as "silts"), which provided an internal local source for dust emissions. Additionally, the eroded Older Keeler Dune sands may also be emissive and thus contribute to dust in the Keeler Dunes.
- Recent floods deposit fine-grained sediments over relatively large unprotected areas within the Keeler Dune system are also internal sources of dust emissions. This was directly observed during a local wind event on October 22, 2012.
- The flood waters entering the Keeler Dunes from the southeastern berm occur in the region just upwind from the active transverse dunes and downwind from the active linear dunes. In other words, these flood waters flow exactly in the location separating the two geomorphic terrains within the Younger Keeler Dune system.

Had the berms not been constructed, the Old Keeler Dunes would likely have remained stable and Younger Keeler Dune sands would have simply deposited over them like the Swansea Dunes. But, instead the flood control berms starved the northwestern Keeler Dunes of moisture critical for their stability. This decrease in moisture within the dune deposits greatly increased the rate of wind erosion which caused the dune sands to deeply erode removing much of the approximate 2000 year old dunes. The erosion of the Keeler Dunes exposed the Older Keeler Dune sands which may be more emissive than the Younger Dune sands. In addition, the flood control berms cause fine grain flood water sediment to no longer pond behind the Keeler Dunes mound where they were protected from wind erosion. Instead, the berms divert the flood water sediment to spread out over large areas that are unprotected and exposed to wind erosion. These wider deposited are highly exposed flood deposits are also sources of dust emissions.

1.1 GOALS AND OBJECTIVES

AECOM was retained by LADWP to geomorhically evaluate all of the dune systems in the Owens Lake area with an emphasis on the Keeler dunes, many of which to our knowledge had never been evaluated. The objective was to gain an understanding of all of the local dune systems in the region in order to better resolve their differences, if any, between the systems such as the Swansea Dunes and the Keeler Dunes. Geomorphic data was obtained for numerous eolian systems bounding Owens Lake including their location, relative age, sand sources, dune types, dune health, and possible Historic changes associated with Historic anthropogenic activities.

2 METHODOLOGY AND SCOPE OF WORK

The results herein are primarily based on the review of existing literature, information from AECOM team members and Los Angeles Department of Water and Power (LADWP) staff, site field mapping (which provided and personal observations), numerical age dating, historical aerial-imagery analysis, including Google Earth. These sources are discussed individually.

2.1 LITERATURE REVIEW

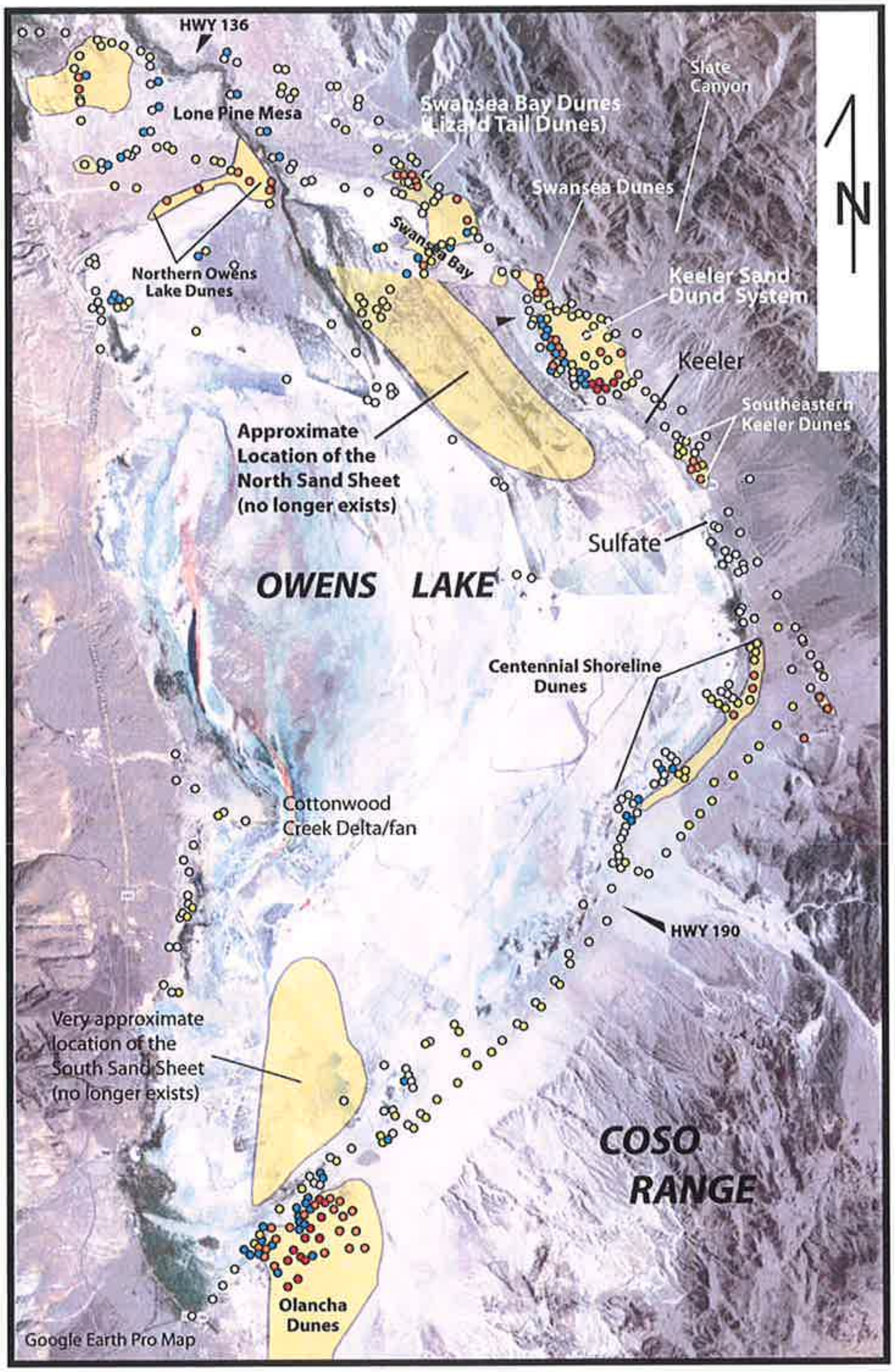
The literature review provided a great deal of information regarding eolian studies of the Keeler Dunes, and dust emissions across Owens Lake. The Keeler Dunes, in particular, have been intensely studied during the past 5 to 10 years by many investigators; however, very little literature was identified regarding studies of the other dune systems in the Owens Lake area or the effect of the flood control berms and highways on the stability of the local dunes systems.

2.2 FIELD MAPPING

A minimum of 31 days of field mapping was conducted in the Owens Lake area between August of 2011, and October of 2012. A total of 652 field sites were evaluated involving geomorphic field notes, latitude and longitude, and photographs. Field work provided considerable data concerning the type and relative age of eolian deposits; eolian sand sources and migration direction; areas of active sand transport; relative "health" of the dunes, and areas containing active, dormant, and relict dune fields. Figure 1 shows the approximate location of most of the field sites visited in the Owens Lake area.

The field mapping activities also provided the opportunity to personally observe several flood events including those on July 31, 2012 and September 12, 2012. It was these personal observations that led to the discovery that the flood control berms were preventing critical moisture from reaching the Keeler Dunes.

Figure 1. Approximate locations of geomorphic evaluation field sites (colored dots). The color within the dots represents the relative eolian sand migration rate/activity in the area. White, yellow, orange and red correlate to very low, moderate, moderately strong, and strong eolian sand migration rates respectively. White dots indicate areas where eolian sand transport magnitudes are very low with essentially no active dune sand. Yellow and orange sites typically exhibit active sand sheets and coppice dunes. Red areas exhibit active sand dunes with avalanche faces.



2.3 HISTORICAL IMAGERY ANALYSIS

Historical aerial images of the Keeler Dunes, Swansea Dunes, and North Sand Sheet, which date from 1944 to 2011, were evaluated. Most of these images have been evaluated during other investigations of eolian activity of these dune systems during recent times (i.e. District, 2012). Selected images with pertinent interpretation are provided in this report.

2.4 GOOGLE EARTH PRO

Google Earth Pro is an internet program provided by Google. The program allows for evaluation of photographic images of the surface of the earth, with scale and location. Locations are provided with latitude, longitude, and of activity and direction of local sand migration. Most elevations provided in this report were obtained from Google Earth Pro.

3 FINDINGS

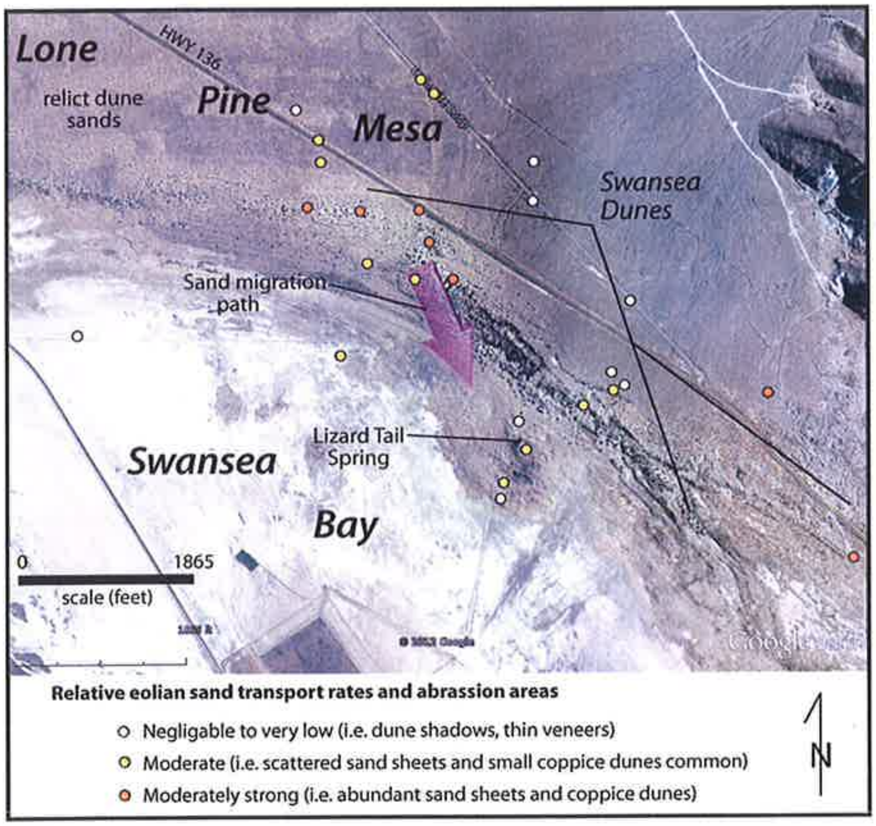
3.1 LOCAL EOLIAN DEPOSITIONAL AREAS AND SOURCES

Numerous eolian sand dune systems were identified during this study. In many ways, most of these dune systems are similar to the Keeler Dunes. Some of the similarities include that most of the dune systems are fairly small consisting primarily of active and inactive dune mounds, and active sand sheets and coppice dunes. In addition, most of the dune systems occur in approximately the same elevation range as the Keeler Dunes between approximately 3620 and 3650 feet above sea level. Select dunes systems are discussed below, including Swansea Dunes, Keeler Dunes, Southeast Keeler Dunes, South Sand Sheet (SSS) and Olancha Dunes are discussed below and the location of the Swansea Dunes is provided on Figure 2.

3.1.1 SWANSEA DUNES

The Swansea dunes occur in the southeastern Swansea Bay, north of the Keeler Dunes and near the base of the Inyo Mountains. The dunes deposits occur at elevation between approximately 3607 and 3650 feet. The dune system consists primarily of a long dune mound that formed approximately parallel to shorelines (topographic contours). Actives sand sheets, coppice and coppice mounds are the dominant eolian deposits across the long dune mound. No avalanche faces were observed, however, the Swansea Dunes receive sufficient eolian sand to produce a nearly continuous exposure of active loose sand across the dune area mostly in the form of sand sheets (ripples). The dune system receives sand from the Keeler Dunes in the south especially in recent times, but likely had also received sand from Swansea Bay to the northwest. A relatively small component of eolian sand from the Swansea Dunes also likely travels toward the southeast and onto the Keeler Fan during northwesterly prevailing winds.

Figure 2: The approximate location of the Swansea Dunes and path of eolian sand.

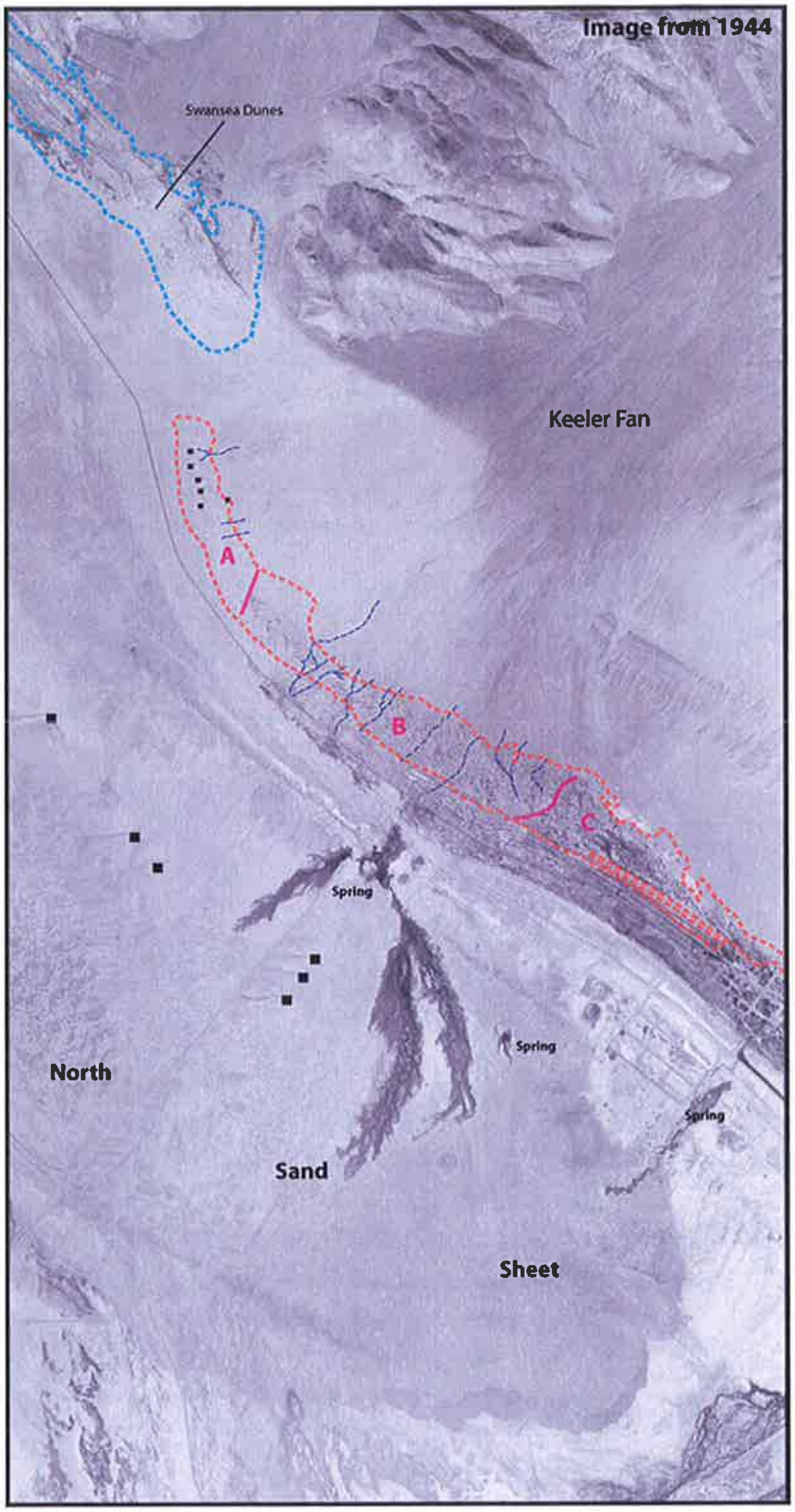


3.1.2 KEELER DUNES

The Keeler Dunes occur northwest of the town of Keeler and south of the Swansea Dunes along the toe of the Keeler Fan which juts out into Owens Lake approximately one half mile. The dune system is complex and consists of both older dune deposits referred herein as the Older Keeler Dunes, and more recently actively moving sand deposits referred herein as the Younger Keeler Dunes. These dune units are discussed independently below.

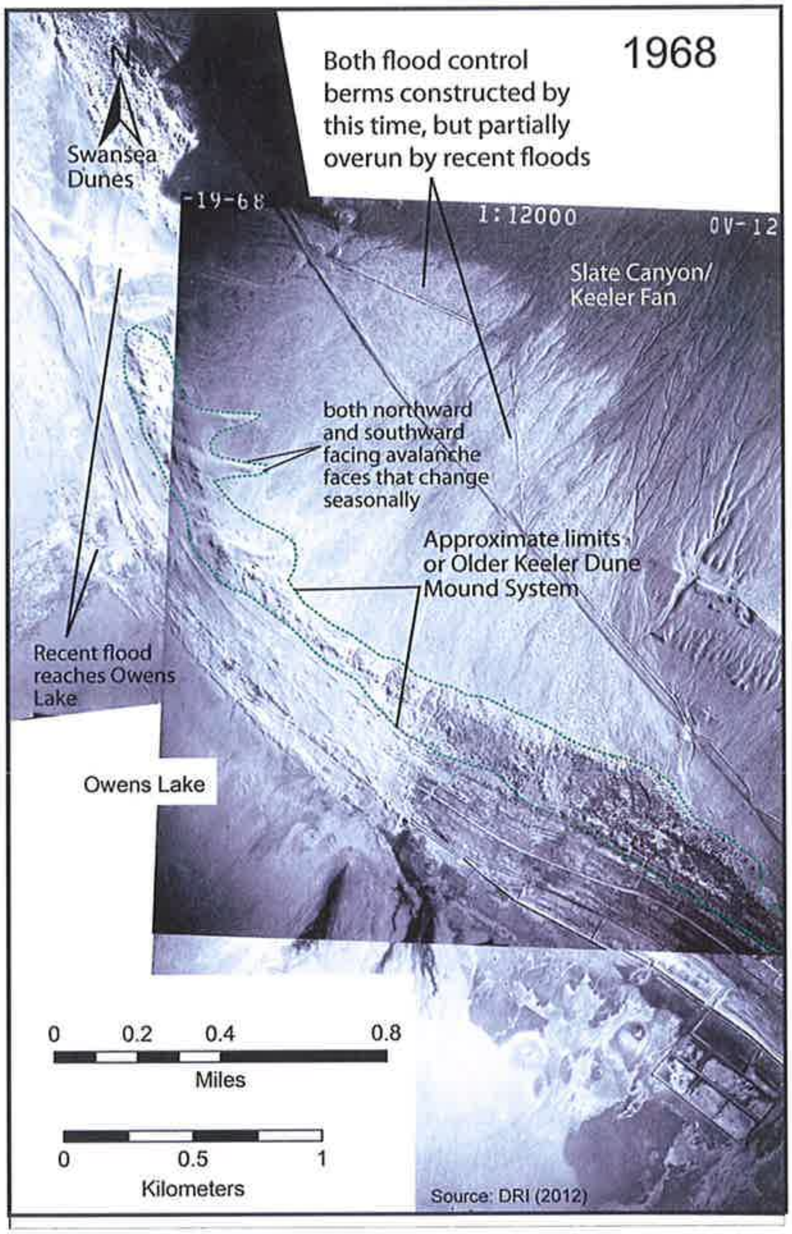
The Older Keeler Dune deposits occur at elevations approximately between 3620 and 3650 feet across the toe of the Keeler Fan. In the southeastern region of the Keeler Dunes, original stabilized dune mounds trending parallel to ancient shorelines occur. These dunes have likely changed very little for hundreds of years. The northwestern and central regions of the Keeler Dunes expose Older Keeler Dune deposits within recent erosion areas where the original Older Keeler Dune mound and coppice system has been eroded away during the past 30 years. A few original dune mounds occur within these ablation areas. A narrow zone of Older Keeler Dune mounds may occur in some places along the approximate 3623 foot contour. The approximate locations of the Older Keeler Dune mound system are provided on Figures 3 and 4.

Figure 3: 1944 historical image with interpretation showing the approximate limits of the Older Keeler Dune mound system (within orange dashed line area). It also shows three distinct geomorphic terrains A, B and C. Black squares are located near identified dune avalanche faces. See text for details.



The Older Keeler Dune mound system as identified in the 1944 Historical image, exhibits three distinct geomorphic zones, which are labeled A, B and C on Figure 3. Zone A, in the northwest represents exhibits a region where Younger Keeler Dune sands have recently deposited on top of the Older Keeler Dune mound system. A few very small dunes exhibiting avalanche faces occur in Zone A, but the region is dominated by sand sheets which appear to be draping over Older Keeler Dune mounds. Vegetation density is fairly low in Zone A. Zone B located in the central Keeler Dunes exhibits moderately stabilized (moderate vegetation) and degraded Older Keeler Dunes that likely represent eroded older transverse dunes that once migrated toward the southeast similar to the transverse dune occurring in recent times. Zone C is located in the southeastern Keeler Dunes and exhibits preserved dune mounds that trend parallel to shorelines. These dunes exhibit relatively dense and healthy vegetation, thus strongly stabilized, and for the most part, still exist today.

Figure 4: 1968 Historical image with interpretation showing the approximate limits of the Older Keeler Dune mound system and some Younger Keeler Dunes in the region bounded by the green dash line.



The Younger Keeler Dunes are designated herein to represent recent eolian sands within the Keeler Dune system. These deposits extend from approximately elevation 3612 in the southeastern Keeler Dunes to approximately 3892 feet toward the northeast on the Keeler Fan. They consist of active sand sheets, coppice, linear, shoreline and complex dunes. Very young dune deposits occur just upslope and adjacent to the 1872 historic shoreline that develop parallel to the shoreline and referred to as shoreline dunes. Within the ablation depression areas, thin sand sheets and small coppice dunes occur which are likely seasonal. Immediately upslope from the ablation areas thin sand sheets and a few linear dunes occur that are deposited on primarily Older Alluvial fan deposits. The linear dunes likely began to form by 1954 and continued to grow for decades until the flood control berms prevented moisture from reaching the dunes. These deposits generally occur above elevation 3550 feet. Younger Keeler dunes in the form of scattered sand sheets, and small coppice occur on the Keeler Fan to an elevation of approximately 3892 feet. In many areas Younger Keeler Dune sands are overlain by small gravels associated with underlying alluvial sediments of the Keeler Fan. The initiation of the development of the Younger Keeler Dune deposits is not known, but may have begun since the late 1800's if not earlier. It should be noted that some thin Older Keeler sand sheet deposits were identified northeast of Highway 136 similar to the Younger Keller sands in the area.

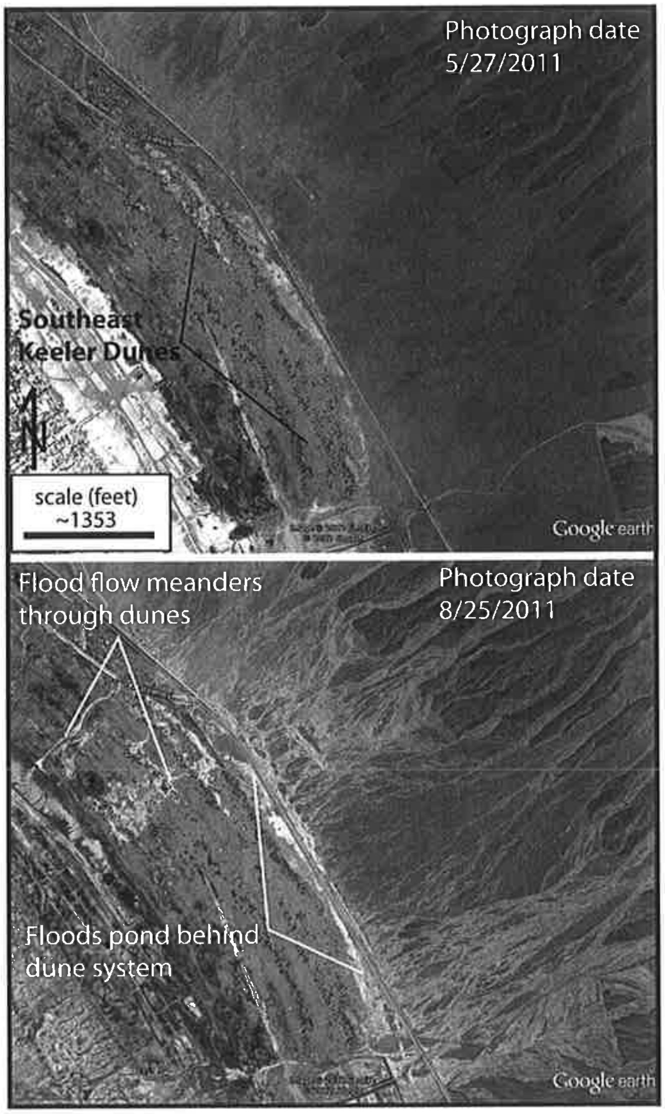
In the southeast, the Younger Keeler Dune deposits consist of a series of active and poorly stabilized complex transverse dunes, coppice mounds, coppice dunes, and sand sheets. These are the largest dunes in the Keeler Dune system and have grown in size during the past 30 years. Dunes in this area exhibit avalanche faces that change seasonally associated with the primary northwest prevailing wind in the winter and early spring, and the subordinate southern prevailing winds occurring during the summer and early fall. However, winds with sufficient strength to transport sand can occur from numerous directions within the Keeler Dunes throughout the year.

The source of sand for the Younger Keeler Dunes has changed over time. Since at least the early 1980's, abrasion began to occur in the northwestern Keeler Dunes, which provided an internal (local) sand source for the Younger Keeler Dune deposits. The magnitude of internal abrasion within the Keeler Dune system was relatively strong between the early 1980s until recent times, and was sufficient to erode into the underlying Older Keeler Dune deposits more than 10 to 15 feet. During this period of time, the linear and complex dunes in the Younger Keeler Dunes increased in height and aerial extent as the Older Keeler Dune mound system was eroded away. Thus, in a sense the Younger Keeler Dunes have partially grown at the expense of the destruction of the Older Keeler Dunes.

3.1.3 SOUTHEAST KEELER DUNES

The Southeast Keeler Dunes occur southeast of the town of Keeler and northwest of Sulfate (Figure 1). These dunes occur between approximate elevations of 3610 and 3633 feet. The dunes consist of a series of coppice mounds that trend parallel to contours and shorelines and thus are essentially shoreline dunes (Figure 5). The mounds are over 10 feet tall and exhibit abundant active sand sheets and coppice dunes developed on the mound system. Flood waters from alluvial fans to the east pond along the eastern side of the dune mound system and in the area of Highway 136. These dunes likely provide a good example of what the Keeler Dunes looked like in the past before the presence of the flood control berms.

Figure 5: Aerial images of the Southeast Keeler Dunes before and after a flood in 2011. These dunes are located immediately southeast of the town of Keeler and northwest of Sulfate.



3.1.4 SOUTH SAND SHEET ON OWENS LAKE

The South Sand Sheet (SSS) is located south of the Cottonwood Creek fan/delta and north of the southern shoreline of Owens lake (Figures 1 and 6). This sand dune system has been destroyed by dust mitigation measures on Owens Lake that were required to be installed by Great Basin Unified Air Pollution Control District. Discussions with Ms. Kathy Bancroft indicated that very tall dunes existed on the Owens Lake just north of the Olancha Dune system. She informed me that the dunes were sufficiently tall that during some flooding and lake level rise on Owens Lake in 1969, that cattle had been stranded on dune islands. This dune system is considered analogous to the North Sand Sheet (NSS) in terms that the South Sand Sheet was fed by a large fluvial system entering Owens Lake. For the NSS it was the Owens River Delta, and for the South Sand Sheet it was the Cottonwood Creek fan/delta system.

3.1.5 OLANCHA DUNES

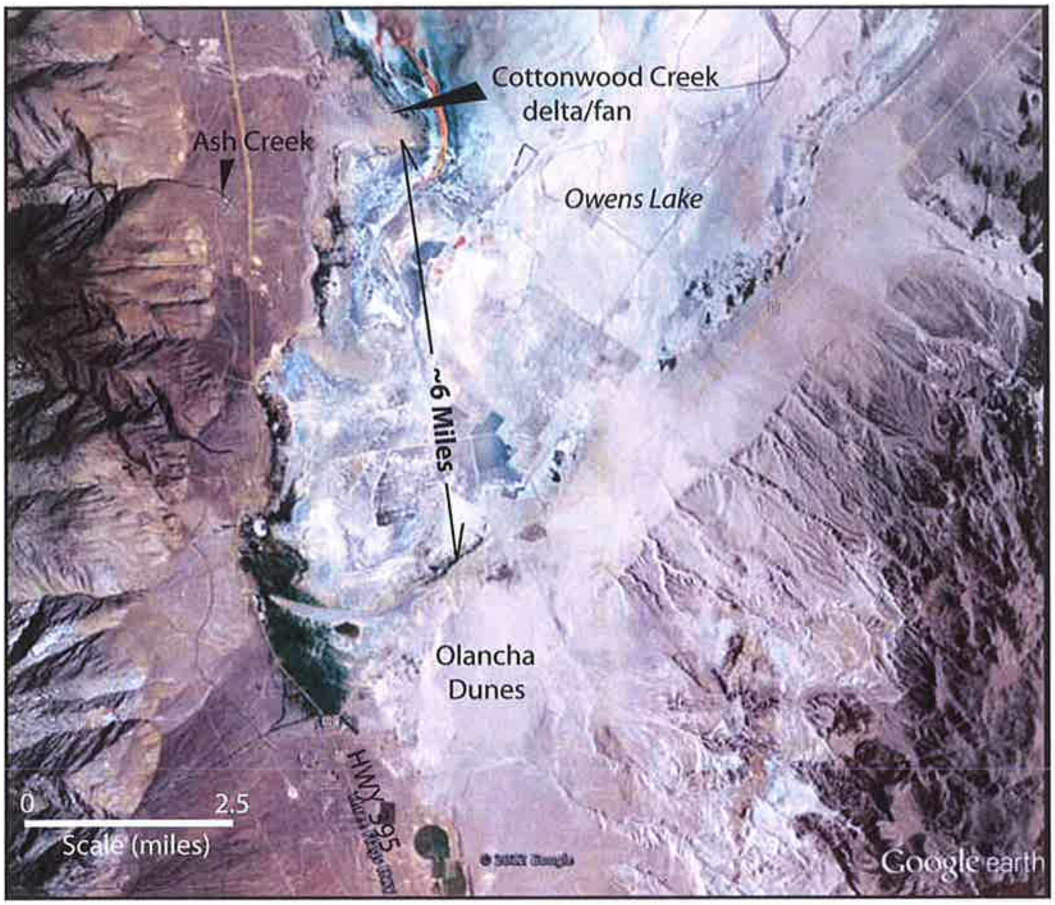
Geomorphically, the Olancha Dunes exhibit the largest and most robust dune system in the study area (Figure 1). The dunes occur between approximate elevations of 3620 and over 3800 feet, however, most of the active dune deposits occur below elevation 3650 feet. These elevations are similar to those of the Keeler Dunes indicating that most of the Olancha Dunes likely formed during the past 2000 years. Review of lake levels reported by Bacon et al, (2006), elevations above 3635 feet of the Olancha Dunes may have been exposed since approximately 4,300 Cal. years Before Present (B.P.). Some dunes in this area are over 20 feet tall that exhibit active avalanche faces, and there are fairly extensive areas of active sand sheets and coppice dunes. The area exhibiting the tall, destabilized active dunes are primarily located above elevation 3635 feet and thus may have formed prior to 4,300 Cal. years B.P.

The primary eolian sand source for these dunes is Cottonwood Creek delta/fan located approximately 6 miles to the north (Figure 6). Abundant eolian sand was able to travel the approximate 6 miles over Owens Lake from the Cottonwood Creek Delta/fan in a similar way that abundant eolian sand was able to travel approximately 7 miles southeast of the Owens River delta to form the North Sand Sheet. This observation indicates that Owens Lake was dry for significant periods of time during the past 2000 years in order to provide a sand pathway sufficient to create the relatively large Olancha Dune system.

Eolian sand feeding the Olancha Dunes from the north has decreased dramatically during recent times. This is likely due to dust mitigation measures conducted on Owens Lake involving construction of ponds. Thus, it terms of the health of the Olancha dunes, it is natural for the dunes to receive sand periodically when Owens Lake was dry, which occurred quite frequently during their development (past 2,000 to 4,300 years). Currently, the northwestern region of the Olancha Dunes is experiencing deep ablation (deflation) because it is no longer receiving sand from the lake and this sand is blown toward the south to feed the more active and relatively large dunes in the system and maintain their health. Interesting to note that these ablation hallows are relatively strong dust emitters during heavy wind events.

The relatively tall unstabilized dunes in the Olancha dune system are complex in that the avalanche faces switch seasonally due to north-northwest prevailing wind in the Winter and early Spring and southerly winds in the Summer and early Fall. This process in addition to topographic controls likely controls the location of the most active regions of the Olancha Dune system.

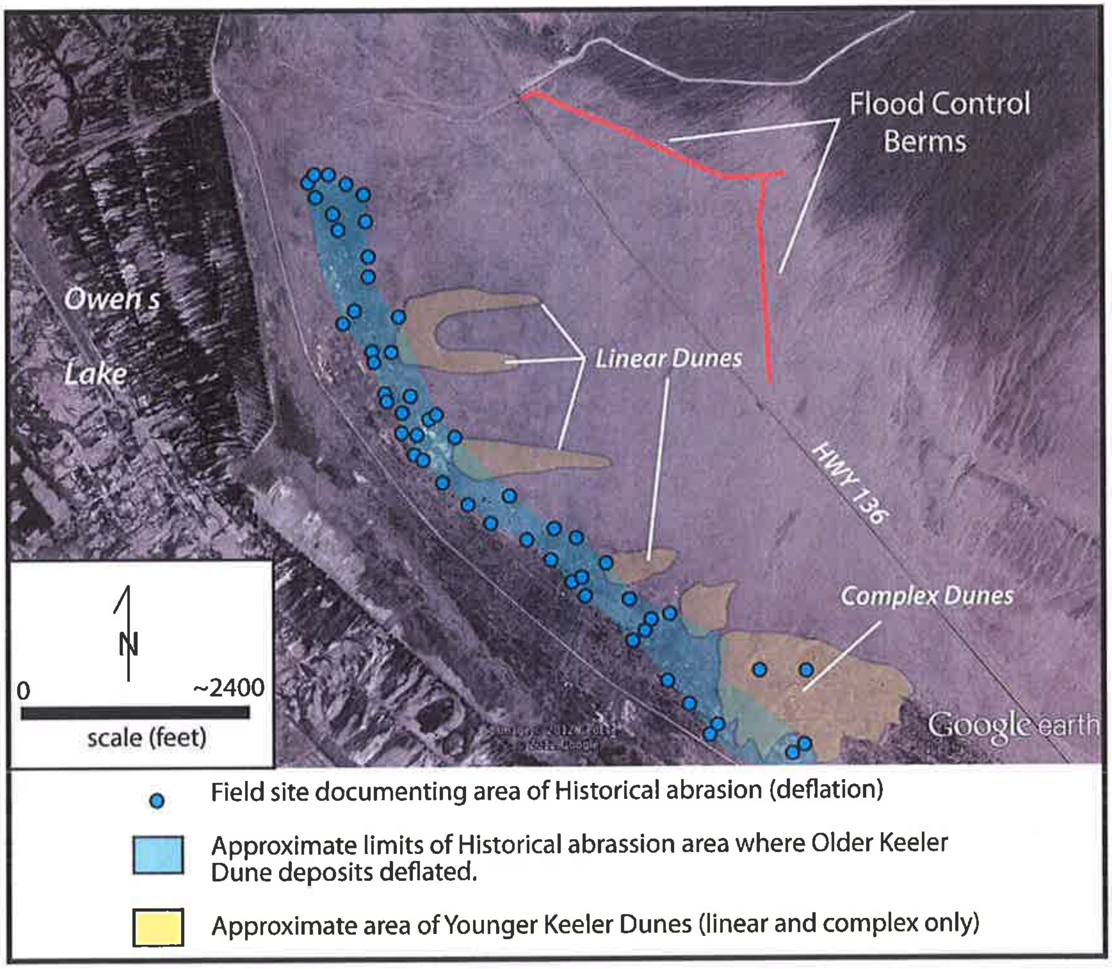
Figure 6: Shows the 6 miles sand migration path from the Cottonwood Creek to the Olancha Dunes across Owens Lake.



3.2 ABLATION (DEFLATION IN THE KEELER DUNES)

The Keeler Dunes region exhibits a northwest-trending zone of ablation that is approximately 400–650 feet wide and over a 1 mile long, which essentially bounds the southwestern margin of the Keeler Dunes between approximate elevations 3623 and 3650 (Figure 7). These geomorphic ablation features were originally identified by DRI (2010), but were not mapped in their entirety. The deflation zones represent erosion of dominantly interbedded eolian sands and relatively minor (in terms of mass) thinly bedded clayey-silt flood deposits. The erosion areas exhibit local depressions exposing a stacked sequence of relict eolian sands (Older Keeler Dunes) that are generally 1–2 feet thick and bounded by fine-grained interdune deposits that are generally several inches thick. The magnitude of internal eolian sand erosion of older dune deposits observed in the Keeler Dunes is only matched in the study area by similar erosion in the northern regions of the Olancha Dunes.

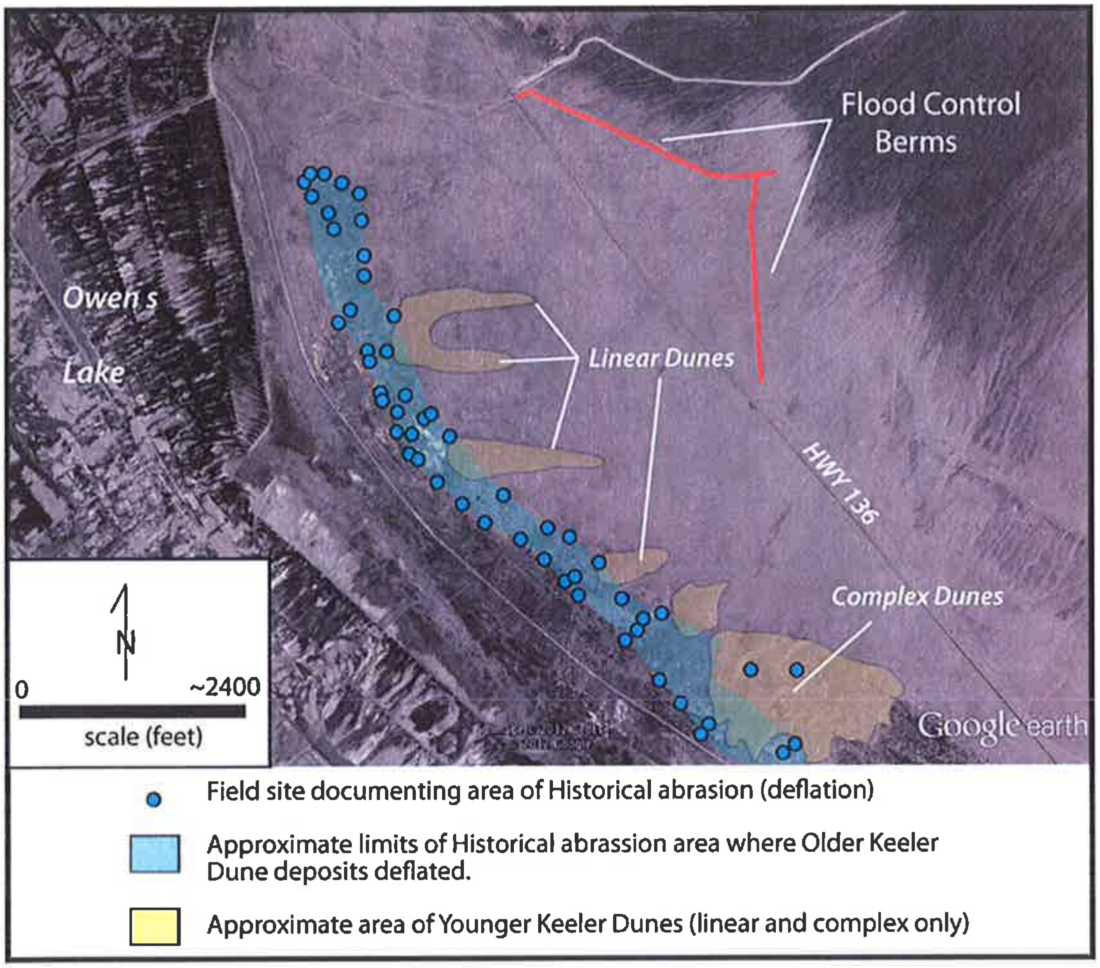
Figure 7: Approximate limits of the abrasion (erosion) area in the Keeler Dunes. The region of the abrasion closely matches the extent of the Older Keeler Dune mound system (Figures 3 and 4).



Based on observations, it is estimated that some of the ablation areas have eroded vertically between 5 to 15 feet, at a minimum. Ablation processes also eroded overlying Younger Keeler Dune sands deposited approximately between the 1890's to the late 1970's.

Ablation initiated in the northwestern Keeler Dunes and migrated toward the southeast during the past 30 years. As deflation continued, the locally derived eolian sands caused the Younger Keeler Dune sediments to grow in mass downwind. The linear dunes, complex dunes, and thickness of the sand sheets and coppice dunes upslope all increased in size and thickness during the past 30 years. In the southeastern ablation areas, the Older Keeler Dunes were destabilized by the large quantities of recent ablated sands. In these dunes, Younger Keeler Dune sands were deposited on top of Older Keeler Dune mounds, which evolved overtime into southeastward migrating dunes. The migration of these dunes assisted in erosion of the underlying Older Keller Dunes. Deep erosion of the Older Keeler Dunes also played a very important role in the geomorphic development of the Younger Keeler dune system, which for the most part, no longer exists in the northwestern part of the Keeler Dune system. It should be noted that the erosion and associated exposure of the interbedded distal flood deposits provide a local source of fine-grained material to the Younger Keeler Dunes sufficient to cause dust emissions in the area, which was personally observed during field mapping.

Figure 4: Ablation areas in the Keeler Dunes

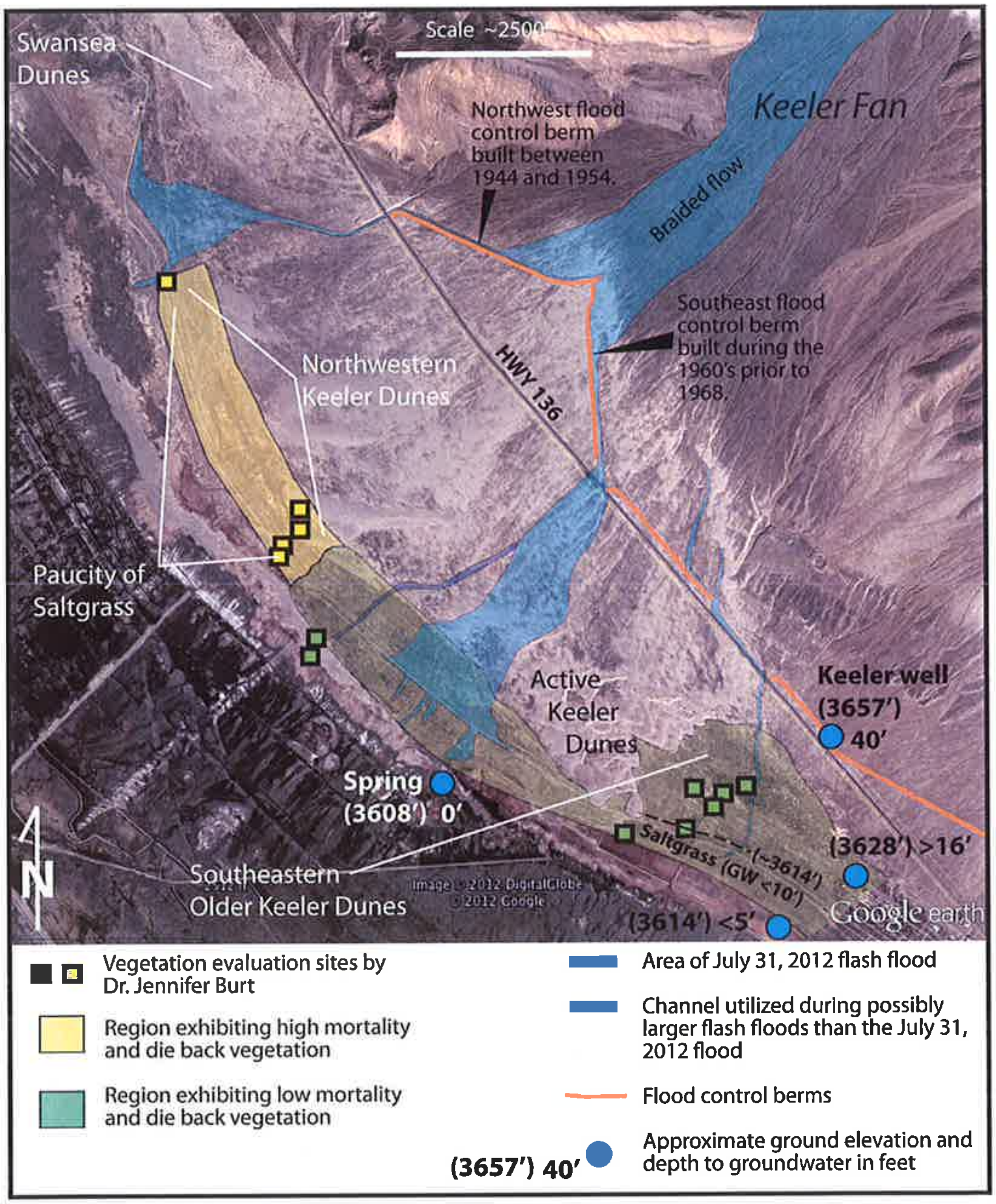


3.2.1 EVIDENCE FOR DEPTH OF GROUNDWATER

The research evaluated whether the deep erosion of the Older Keeler dune mound system was caused by a decrease in dune core moisture content associated with the depth of groundwater. Groundwater depths in the Keeler Fan and Dune areas are limited. Figure 8 shows some approximate groundwater depths in the southeastern Keeler Fan/Dune area indicating that groundwater exists near the surface at elevations of 3608 to 3614 feet, a depth greater than 16 feet at elevation 3628 feet, and approximately 40 feet deep at an elevation of 3657 feet. No or only very weak springs (seeps?) occur on Owens Lake outboard of the central and northwestern Keeler Dunes suggesting that groundwater depths in this region are likely deeper than in the southeastern Keeler Dune region. Saltgrass is generally prevalent in areas with an apparently shallow water table and is often indicative of relatively shallow water tables of less than approximately 10 feet (Dr. J. Burt, personal communication). Saltgrass exists at elevations equal to and less than 3614 feet in the southeastern Keeler Dune region (Figure 8); however it is much less prevalent below these elevations in the northwestern Keeler Dunes (Dr. Burt, personal communication). This suggests that groundwater depths are deeper in the northwestern Keeler Dunes compared to the southeastern

Keeler Dunes. Based on these data it is unlikely that fluctuating groundwater levels caused the moisture loss in the Keeler Dunes, but more research is warranted.

Figure 8: Depth to groundwater, vegetation sites evaluated on August 14, 2012 with Dr. Jennifer Burt, regions of relatively healthy vs. unhealthy vegetation, and region of flash flood flow on July 31, 2012 on the Keeler Fan and Dune area.



3.2.2 VEGETATION (COLLABORATION WITH DR. J. BURT)

Types of vegetation provide important information regarding near surface soil moisture conditions. Water availability is likely to be a highly limiting factor to vegetation cover (and thus potentially affecting sand transport and soil loss) within the Keeler Dunes. Where groundwater tables are at depths below utilization by surface vegetation, vegetation will have to be entirely precipitation- (or overland flow-) dependent. When groundwater is extremely shallow (<1m deep), it can cause stress to plants associated with anoxic rooting conditions or toxicity (as in portions of the Owens Lake playa), but shallow groundwater availability at greater depths (~2-8 meters; ~6.5 to 26 feet) can generally increase growth and vigor of plants that are able to access it.

Vegetation at the Keeler Dunes sites visited on August 14, 2012 (Figure 8) could potentially be benefiting from shallow groundwater at some or all locations, but current and historic depth to groundwater in this region is not well understood. Shallower depths to groundwater or increased precipitation-derived available water would support increased growth and vegetative cover by saltgrass, greasewood, and other groundwater utilizing species. However, this is also the area where the flood waters are redirected by the flood control berms. The redirected flood waters provide a source of surface water.

Currently, portions of the Keeler Dunes (ablation areas) have less vegetative cover and essentially no cover by saltgrass. Prior to approximately 3 years ago, very few plants were growing within the ablation areas of the Keeler dunes (Figure 3, Zone A, Figure 7). However, during the past 3 years, a few plants have begun to grow in many of the ablations areas suggesting that ablation rates are decreasing. The areas that have the lowest vegetative cover and the most apparent shrub mortality are in the northwestern region of the Keeler Dunes (Zone A of Figure 3 and at lower elevations) which is located immediately downslope of the flood control berms. In addition, salt grass is much less plentiful in the lower elevations in this region. In contrast, plant health and density is markedly higher in the southeastern region of the Keeler Dunes and shoreline areas (Figure 3, Zone C) which receive the redirected flood waters. Salt grass is abundant in the lower elevations in this zone.

3.3 KEELER FAN FLOODS AND DUNE STABILITY

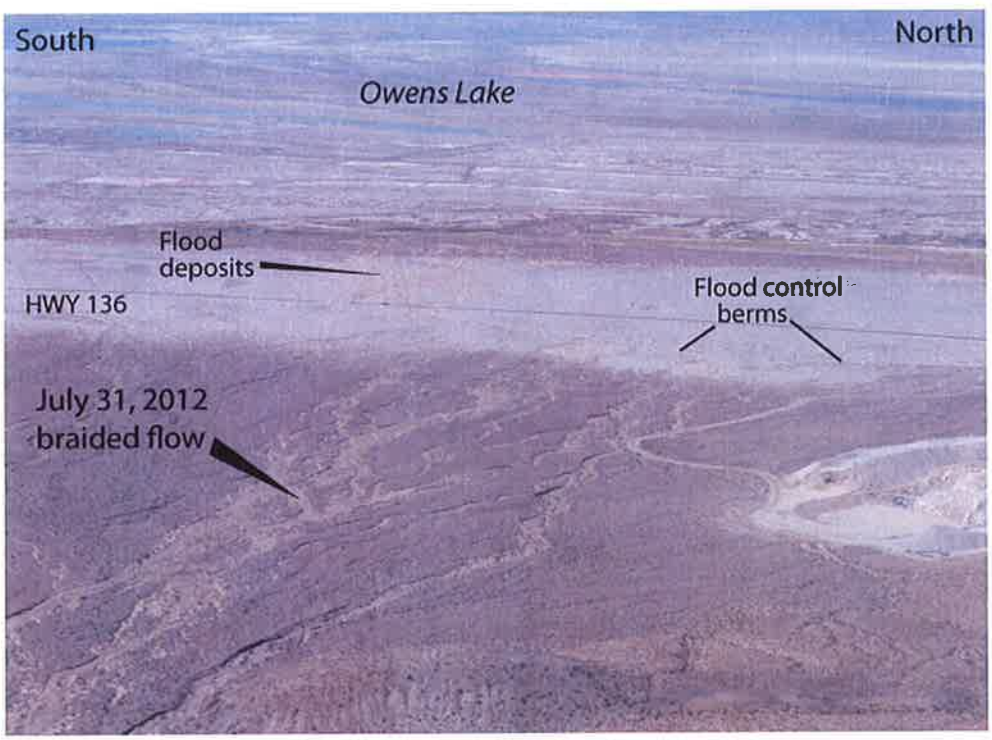
The Keeler Dune system has existed during at least the past 2000 years where they received new pulses of sand (grew) when Owens Lake was naturally low and subsequently stabilized during periods of high lake stand. The Older Keeler Dune system therefore continued to get larger during its history and appears to have never internally eroded as observed to have occurred during the past 30 years. Thus, each time the lake elevation lowered it would be expected that the Keeler Dunes system would grow and not undergo ablation. Thus, many natural processes that interact with the dune system are likely important to their long term growth and stability. Some of these natural parameters include changes in Owens Lake levels, abundance of sand, possibly the water table remaining at a particular depth, and flood waters from Slate Canyon across the Keeler Fan. Moisture is a critical parameter for the stability of the Keeler Dune system, and possibly the only parameter that has significantly changed. Dune moisture increases stability in two ways. Moisture assists plant growth, health and density, and wind abrasion rates dramatically decrease in moist sediments. Thus, it is reasonable that the Keeler Dunes became less stable due to a decrease in core moisture content. Hence, flash flood waters that reached the Keeler Dunes were a critical factor associated with the dunes stability.

It is evident from multiple lines of evidence that flash flood waters would naturally reach the Keeler Dunes during their development. Numerous fine grained flood deposit members are identified within the Older Keeler Dune deposits and two flash floods reached the Keeler dunes during this year (July 31, and September 12). Flash floods with sufficient strength to reach the Keeler Dunes likely occur every 3 to 5 years (Dr. J. Humphries, personal communication).

During deposition of the Older Keeler Dunes over the last 2,000 years, flash floods naturally would pond behind the dune mound system, and slowly meander through the dunes. (Figure 12) This type of flooding still occurs in the Southeast Keeler Dunes (Figure 3, Zone C) and observed soon after the July 31, 2012 flood event. In addition, this style of flooding is still observed to occur in both the Swansea and Southeast Keeler Dunes. For example, a flood occurring between May 27and August 25 of 2011 reached the northeastern side of the Southeast Keeler Dunes where the flood waters crossed Highway 136 and ponded along the northeastern side of the dune system (Figure 5). The fine grained flood deposits were protected from the wind by the height of the dune mounds, and the flood waters were able to infiltrate into the underlaying sediments.

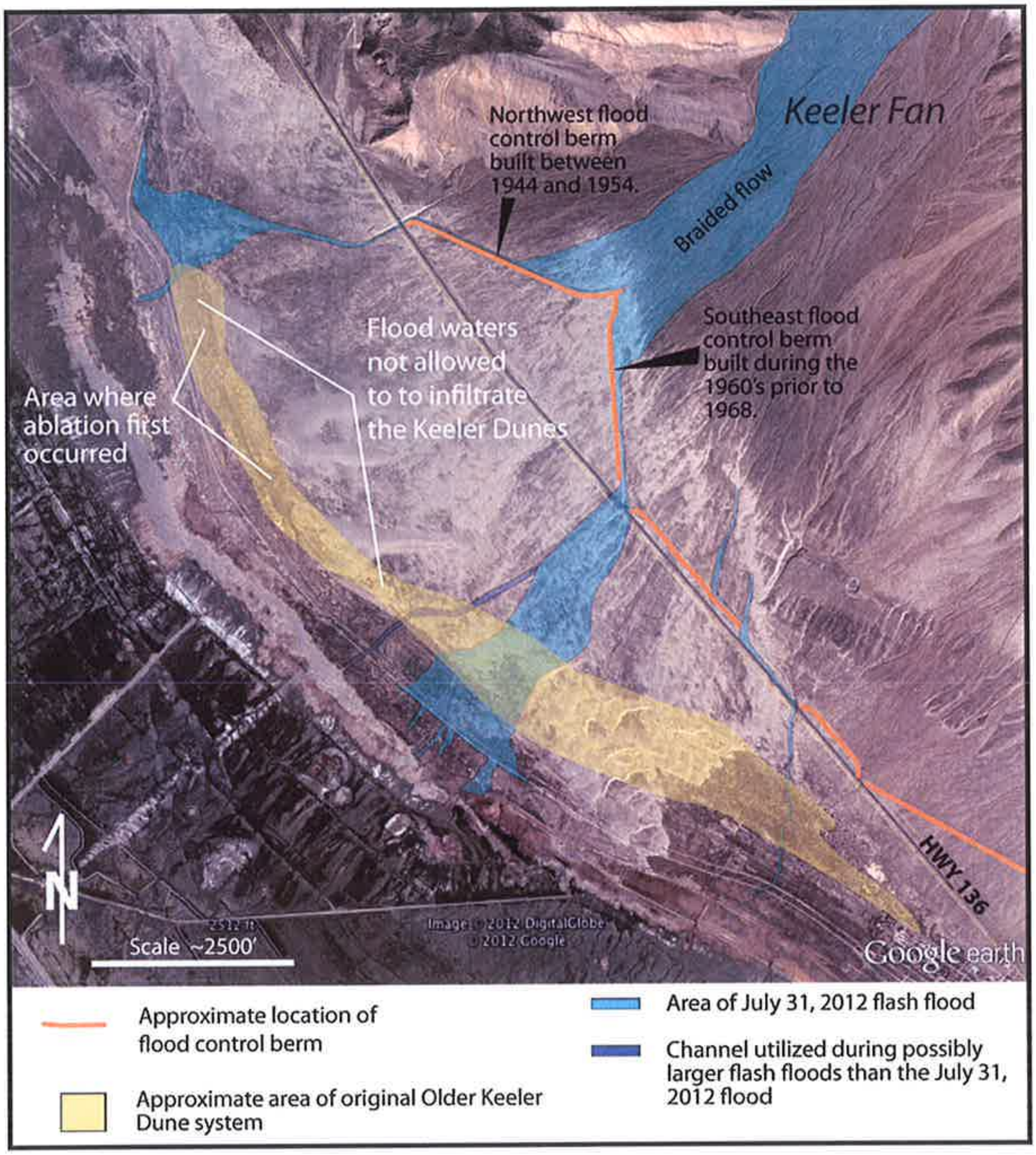
Personally observed during this study were the immediate effects of a flash flood occurring on the night of July 31, 2012. These flood waters flowed down the Slate Canyon/Keeler Fan and reached the Keeler Dunes area (Figure 9). However, the flood waters were diverted by two flood control berms located immediately northeast of Highway 136 which did not allow for the flood waters to reach the northwestern Keeler Dunes (Figures 10, 13).

Figure 9: Aerial photographs of July 31, 2012 flash flood on the Keeler Fan.



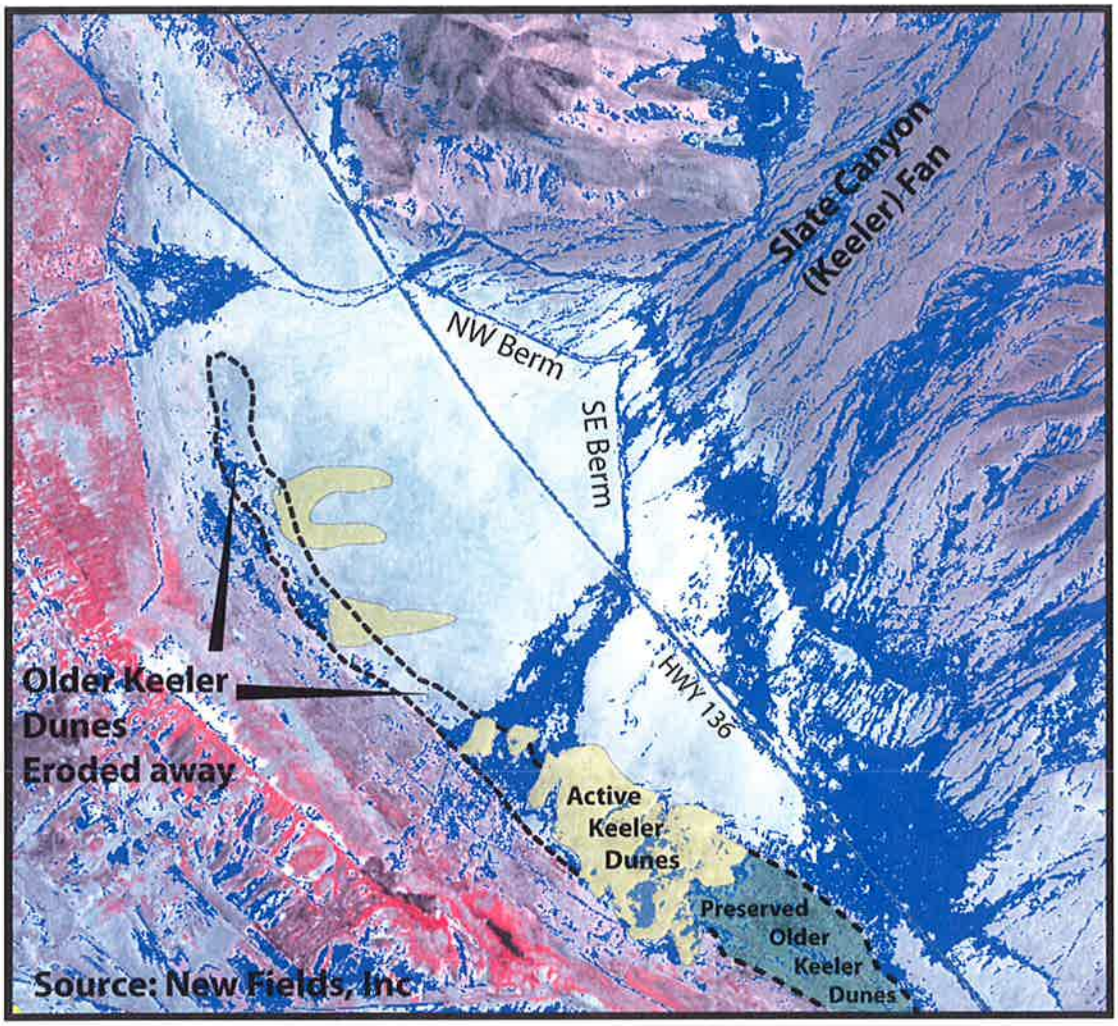

North
Slate Canyon
South
Flood control
berms
HWY 136
July, 31, 2012
flood deposits
(fine-grained)

Figure 10: Diversion of flash flood waters by flood control berms associated with the July 31, 2012 flood and location of the flood control berms.



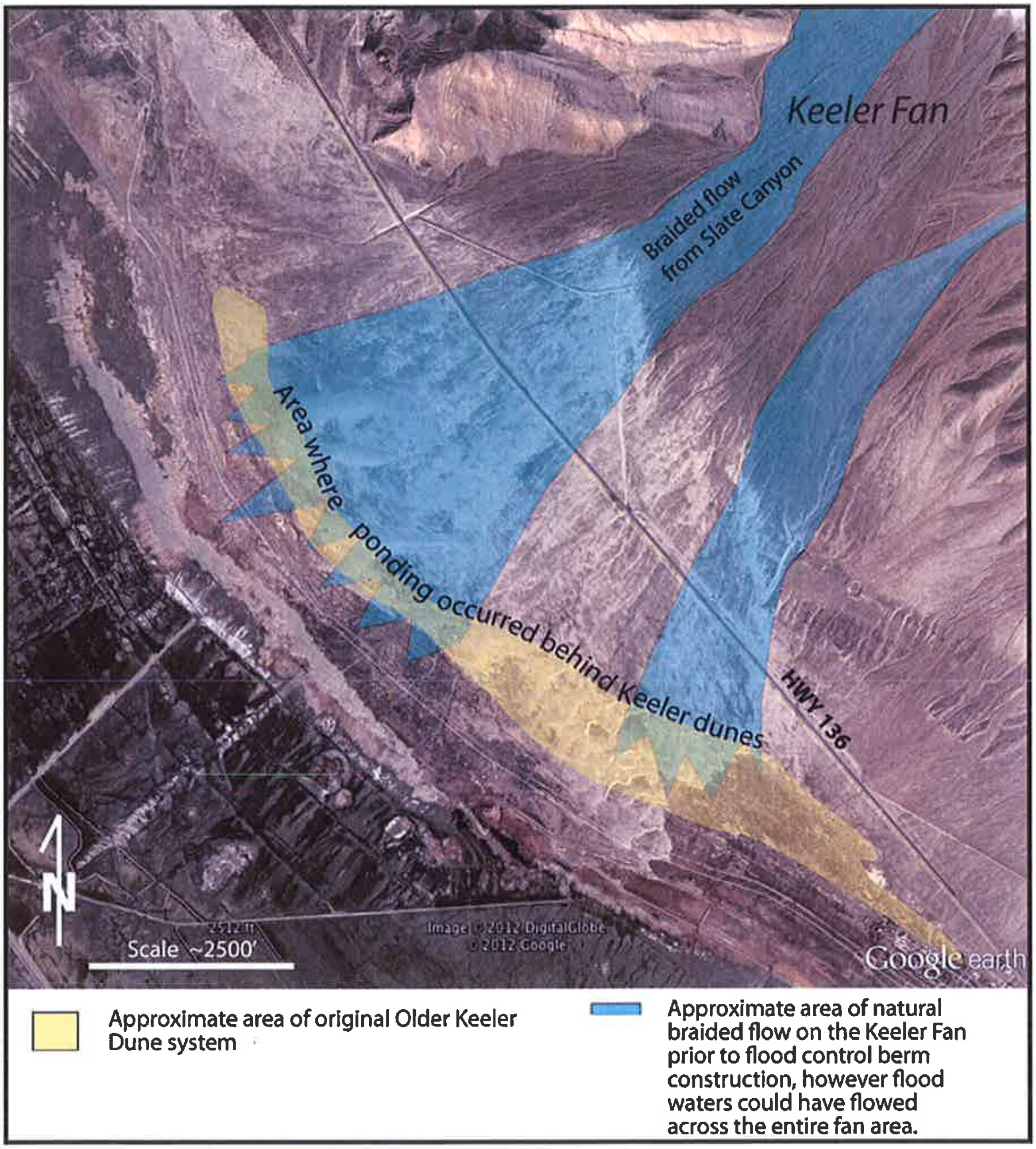
Flood waters exhibited braided flow across the Keeler Fan until they encountered the flood control berms where the flow was concentrated until it again fanned outwards to exhibit braided flow through the Keeler Dunes and lake plain areas. The flows transported and thus deposited very fine to fine sand silty clay sediments (light tan areas). Large quantities of Younger Keeler Dune sands were entrained within the flow once the flood waters reached these deposits just north of the flood control berms. Mapping of the flood limits indicates that essentially 100% of the flow emanating down the Keeler Fan was diverted by the flood control berms to the north of the Keeler Dunes and to within the southeastern Keeler Dunes (Figures 10 and 11).

Figure 11: Approximate areas exhibiting moisture after the July 31, 2012 flood (Base map provided by New Fields, 2012). The yellow areas represent the Younger Keeler Dunes.



Prior to the construction of the flood control berms, flood waters on the Keeler Fan routinely reached the northeastern edge Keeler Dune mound system where the waters would pond and in places slowly meander through the dunes (Figure 12; Figure 3, blue dashed lines). This process was directly observed for the July 31, 2012 flood in the Southeast Keeler Dunes (Figure 3, Zone C). In this area flood flow ponded and entered the dune system allowing for infiltration. The fine grained flood deposits are protected in this area as well by the dunes and local vegetation. It is not surprising that in this area the Older Keeler Dunes remained preserved and stabilized.

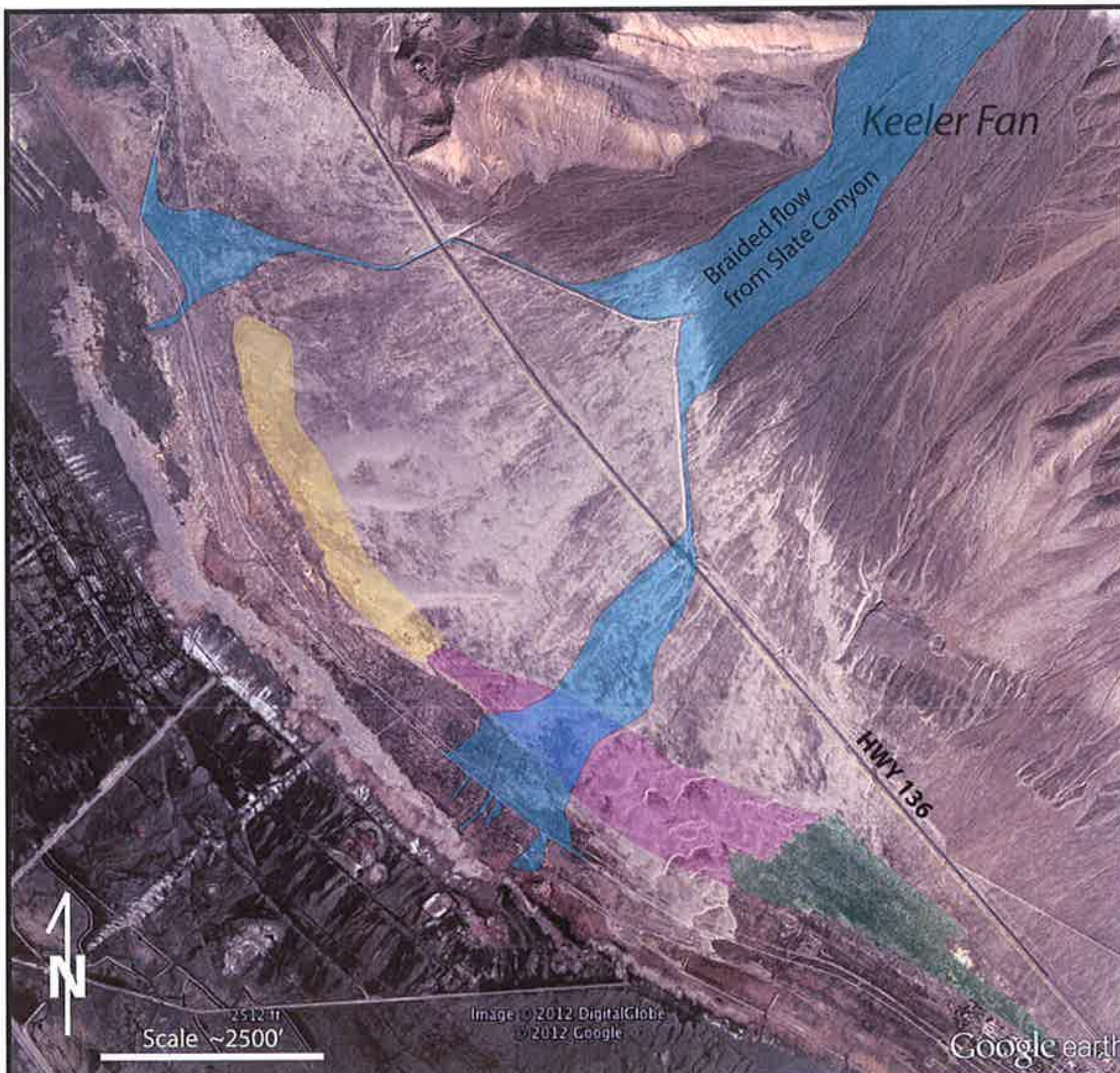
Figure 12: Approximate area of natural flood flow on the Keeler Fan prior to construction of the flood control berms.



3.3.1 GEOMORPHIC RAMIFICATIONS OF THE FLOOD CONTROL BERMS

The geomorphic ramifications of the flood control berms on the recent ablation of the Keeler Dunes are profound. The northwestern flood control berm was built in 1953 and near the period of time of the construction of Highway 136 (Figure 11). Flood waters flowing along this berm flow through culverts under the highway and force the waters northwest of the Keeler Dunes. The southeast berm was constructed in 1967 and diverts flood waters away from the northwestern Keeler Dunes and into the central Keeler Dunes. Flash floods occur in this area every 3 to 5 years, and on that time scale, the dunes could reasonably experience a decrease in dune moisture in the timescale of a decade. Internal abrasion (erosion) initiated within the northwestern region of the Keeler Dunes in the early 1980s, which is 27 years after construction of the northwest berm, and 13 years after construction of the southeast berm. Abrasion initiated in the same region most strongly affected by the water diversions (yellow region on Figure 13), which closely parallels the region exhibiting less dense and healthy vegetation in addition to less salt grass requiring a shallow water table (Figure 8).

Figure 13: Region of recent ablation and area that typically receives new eolian sand during aggredational events (yellow), area of Older Keeler Dune complex mound system overrun by Younger Keeler complex mounds (purple) and region of preserved Older Keeler shoreline dunes (green).



Approximate region of the Older Keeler Dunes where ablation due to decrease in infiltration flood waters occurred. Also the area where Keeler Dunes recieved sand input during aggredational events when Owens Lake was low similar to Historic times.

Limits of July 31, 2012 flash flood

Approximate region where destruction (erosion) of the Older Keeler Dunes was primarily associated with migration of Younger Keeler Dunes. Original Older Keeler Dunes in this area were primarily complex and not shoreline type.

Approximate region of preserved Older Keeler Shoreline dune mounds still preserved today.

4 CONCLUSION

The construction of flood control berms has had a large impact on the recent geomorphic development of the Keeler Dunes. If the berms had never been built, it is likely that the Keeler Dunes would have behaved similar to the Swansea and Southeast Keeler Dunes which remain "stable". Younger Keeler Dune sands would have continued to deposit over the Older Keeler Dune mound system and the dunes would likely have simply grew in size and extent in a similar style as they had during other depositional events of the past 2000 years. Instead, the Keeler Dunes were starved of critical moisture by the diversion of flood waters which began a cascade of geomorphic events to occur. The first was deep erosion within the northwestern Keeler Dunes that was sufficient to essentially destroy the 2000 year old dune mound system beginning sometime in the late 1970s to early 1980s. The eroded sands from the erosion areas were then transported to the southeast which provided sufficient sand to the Younger Keeler Dune system for the development of the transverse dunes in this area. The migrating transverse dunes assisted in the erosion of the underlying Older Keeler Dune deposits. This resulted in the development of two geomorphic domains within the Keeler Dunes. A northern domain exhibiting almost complete removal of the Older Keeler Dune mound topography, abrasion hallows, thin sand sheets, coppice dunes, and some active linear dunes, and a southeastern domain exhibiting actively transverse dunes, interdunes, sand sheets, coppice dunes and mounds. Flood flows from the southeast berm flow and deposit fine grained sediments in the region between these two Geomorphic dune terrains. Just northwest of the preserved Older Keeler shoreline dunes, the Younger Keeler dune sediments deposited over Older Keeler Dune mounds as well. Hence, nearly all the dune sediments, including the Younger and Older Keeler Dunes, have been eroded away in the northwestern Keeler Dunes. These sands have been blown toward the north, northeast and southeast by prevailing winds.

5 REFERENCES

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APPENDIX A

Glossary of Terms

eolian—Refers to that which is blown by the wind; windblown. Aeolus was ruler of the winds in Greek mythology.

eolian deposits—Sediments transported and subsequently deposited by moving air.

aggradation—An increase in land elevation resulting from the deposition of sediment. Aggradation occurs in areas in which the supply of sediment is greater than the amount of material that the system is able to transport. For example, sand dunes will undergo aggradation if the supply of eolian sand is greater than the flux of sand out of the system.

alluvial deposit—Sediments deposited by flowing water.

alluvial fan—A fan-shaped alluvial deposit formed where a fast-flowing stream flattens, slows, and spreads, typically at the mouth of a mountain valley or a canyon, onto a flatter plain.

alluvial plain—A level, gently sloping, or slightly undulating land surface produced by extensive deposition of alluvium, usually adjacent to a river that periodically overflows its banks. The alluvial plain may be situated on a flood plain, a delta, or an alluvial fan.

bajada—An alluvial plain formed along the flanks of a mountain by the coalescing of a number of alluvial fan deposits.

coppice dunes—Vegetated sand mounds commonly scattered throughout sand sheets in semi-arid regions where shrubs and blowing sand are abundant. Any shrub protruding into the airborne stream of sand impedes the flow, and the resulting loss of turbulence and speed cause sand grains to settle out on the downwind side of the shrub and around its base. Coppice dunes range from 0.5–3.0 meters in height and from 1.0 to 15.0 meters in breadth. Within any given field of coppice dunes, however, the dune size tends to be uniform. Under certain conditions, when individual dunes or clusters of dunes grow large and are called vegetation mounds. Because the sand accumulates in piles around the plants and is swept from the surfaces between the plants, a hummocky, rough topography develops that is very different from the smooth, flat, and locally gentle undulatory surfaces of sand plains that are devoid of vegetation and are frequently barren, typically have firm, trough like, scoured surfaces of hard-packed soil, with thin patches of rippled sand or granules (Desert Processes Working Group).

Most active coppice dunes in the Chuckwalla Valley region exhibit "coppice tails" on the leeward side (downwind side) of the coppice mound at the base of the plant. The tails are triangular in shape and with the wide end attached to the plant sand mound and points (narrows) downwind from the plant. The coppice tails are generally 3-inches to 3 feet long and provide excellent wind vector data for approximately graded time (past 1 to 10 years). In addition, a lack of active coppice tails and degraded and/or vegetated coppice mounds at the base of plants is an excellent indicator that sand is not currently migrating within that area.

corridor system (eolian)—Pertains to eolian sand pathways that extend for tens of miles and involve numerous subbasins within the Mojave Desert. Regarding the site, a number of studies have identified the Dale Lake to Mule Mountains sand corridor system that allows windblown sand to travel approximately 70 miles toward the east via topographic valleys and playa lake basins (Palen and Ford Dry Lakes). Our study has identified that the simple single sand corridor is from Dale Lake to the north end of the Mule Mountains is also fed by considerable sand from north to south valleys as well (Palen Valley to Palen Dry Lake and the Palen-McCoy Valley which feeds the eastern end of Ford Dry Lake).

cyclic temporal and spatial scale—Cyclic scale includes a temporal scale, involving periods of 10^3 to 10^5 years, and a spatial scale, corresponding to that of large dune-field areas (Lancaster 1995). For this study, cyclic scale involved the formation of the most of the larger dunes within the Chuckwalla eolian system that took thousands of years during major aggradational events of the latest Pleistocene and mid Holocene.

Graded Temporal and Spatial Scale—Graded scale time is a temporal scale involving periods of 1 to 10^2 years and particularly concerns the dynamics and morphology of dunes, which tend towards an actual or partial equilibrium with respect to rates and directions of sand movements generated by surface winds (Lancaster, N., 1995). Eolian structures or deposits that may have formed or existed between 1 to less than approximately 1000 years is considered to have formed during graded time. For example within this study, graded time structures include small active dunes and medium to relatively larger size active coppice dunes and their respective tails. In addition, graded special scale involves eolian processes as the migration of individual dunes within a dune system.

Holocene epoch—A geological epoch that began approximately 11,700 years ago. According to traditional geological thinking, the Holocene continues to the present.

instantaneous temporal and spatial scale—Instantaneous temporal and spatial scale involves very short to instantaneous periods of time and small areas. Some examples of eolian structures that form within instantaneous scale involve the formation of sand ripples that can develop in a few minutes and very small coppice dune tails behind shrubs.

interdune—Areas of a desert floor occurring between individual dunes in fields. Closed interdune areas may be poorly drained, contain playas, and are typically flat. Where dry and floored by sandy sediment, they have many of the same characteristics as sand sheets. If near-surface moisture is present, interdune areas may contain grasses, shrubs, trees, or even settlements. Interdune areas range in size from a couple to tens of square miles. In any given locality, the sizes and shapes of the interdune areas are similar, as are those of the intervening dunes

linear dunes—A common dune type, generally straight to irregularly sinuous and elongated, with sand ridges of loose, well-sorted, very fine to medium sand. The lengths of individual dunes, which are much greater than the widths, and can range from a few meters to many kilometers.

playa lake—An ephemeral lake found in a round hollow in the ground, typically in the Southern High Plains of the United States. Playa lakes can be filled by rain (usually in the spring) or by underlying aquifers, in which case the water carries salt to the surface and then leaves the salt behind when it evaporates.

Pleistocene epoch—The epoch from 2.588 million to approximately 12,000 years before present (BP) and covering the world's recent period of repeated glaciations. In this report, the term Latest Pleistocene is considered to be the last 50 to 60 years of the epoch.

sand sheets—Sand sheets (or plains) are flat or gently undulating broad floors of tabular, windblown sand deposits derived from accumulating sand ripple migration. The tabular deposits generally range in thickness from a few centimeters to a few meters. Some sand sheets, as in the southwestern United States, are local deposits that extend only a few square kilometers in and around dune fields, where they are exposed on interdune floors and form the aprons or trailing margins of dune fields and/or sand migration corridors.

stabilized dunes—Sand dunes that are unable to migrate, owing to vegetation growth on the dune itself. This type of dune is also referred to as a vegetated dune. Stabilized dunes often develop when the input of eolian sand is insufficient to allow for growth and migration.

ventifacts—Rocks that have been abraded, pitted, etched, grooved, or polished by wind-driven sand. Ventifacts typically occur on gravel-size rocks exposed to sand-bearing wind on the ground surface, where there is little vegetation to interfere with eolian sand transport.