HydroBio
Advanced Remote Sensing

Preliminary Assessment of Dune Movement, and Factors Influencing Air Quality and Potential Mitigation Near Keeler, California

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Abstract

Dune movement in the northeast corner of the Owens Lake shoreline has given rise to a fugitive dust problem and concern for future encroachment on the town of Keeler. The release of fugitive dust is expected to decrease over time as fine particles are separated from the dune sand, however, the rate of this decrease is not yet known. The dunes have undergone significant changes in the period following the 2002 establishment of shallow-flooding dust control measures that effectively ended wind deposition of additional lakebed material. Since then, the dunes have changed shape, coalesced and begun moving. The direction of dune movement is toward the east in the northern portion and toward the southeast in the southern one third of the dune field. Preliminary results from these analyses suggest that the southern one third of the dune field should have a more intensive focus for study and mitigation planning since dunes are moving much faster in this location and are closer to the community of Keeler.

1. Summary

Sand dunes and sand deposit to the northwest of the community of Keeler, California (est. population 90) are actively moving in the direction of the community. As the sand is moved by the wind, fine particles are lofted resulting in violations of state and federal air quality standards (GBUAPCD 2008) in Keeler. To gain an understanding of this phenomenon preparatory to intervention and remediation, these dunes are under study in five tasks: (1) determine a sand budget to understand where the sand is moving, (2) evaluate wind data to assess how wind has influenced dune movement, (3) determine the direction and rate of dune movement through the Keeler dune field, (4) determine the rate of movement and winnowing of the dune material to determine whether fine particulate releases are a temporary or long-term problem, and (5) determine how to mitigate this problem.

As part of the first task, the dunes were visited with staff from the Great Basin Unified Air Pollution Control District (District) during October 2008 and a series of transects were established in order to provide a benchmark for assessing sand budgets. This work is in progress and so only the experimental design and initial observations are discussed. One strong relationship noted was that large amounts of sand had apparently moved to the east onto the fan above State Route 136 that passes around the eastern margin of Owens Lake. This sand apparently moved from the deposits at the north of the Keeler field since sand deposits in that location contain strong evidence of deflation and have a trend for easterly movement. These trends were not observed in the most southerly portions of the dune field, those more proximal to Keeler. Here, the dunes apparently have grown taller and more discrete and are actively moving to the southeast.

The second task consisted of an examination of wind data from two anemometers in the region of Keeler, one located at the north end of the community and the other at the District's A-tower meteorological site, on the playa. Winds with sufficient velocity to move sand predominantly blow from the south and the northwest. Though directly related to the winds at the A-Tower on the playa, winds in Keeler were significantly reduced (though this may be influenced, in part, by the obstructions surrounding the Keeler meteorologic station). Such a drop in velocity would be an important factor for accumulation of the sand deposits in the region of the Keeler field that occurred prior to dust control. Since 2002, the Keeler field has been protected from further deposition by the operation of shallow flood dust control cells to the west and northwest and associated stabilization of the soil surface on the playa. With the cutoff of the supply of particles has come wind reworking of the sand deposits and lofting of the fine particle fraction that was originally deposited before shallow flood dust control measures were implemented. The reworking has also reshaped and moved the dunes.

The third task used photogrammetry to determine the rates of movement of the dunes throughout the Keeler field. Because this analysis required historical perspective, a temporal sequence of Quickbird (QB) satellite imagery was assembled spanning from 2002 to 2008. The imagery was highly geocorrected using image-to-image registration and invariant features visible on each image. Nine Dunes were chosen for analysis and the edges of these examples were mapped on each image. Through observation of the trends of these boundaries, dune movement was inferred.

Dunes located in the northern portion of the dune field appeared to move only slightly to the east, with one completely reversing movement to its initial start position. The generally easterly trend confirms the trend observed in the field for deflation and overall movement of sand to the east in this area. In contrast, dunes in the southern one-third of the field showed consistent southeastern movement toward Keeler.

The fourth task, establishing an understanding of the content of loftable fine particles in the dune material is planned for 2009 field work. Over time, reworking of the dune material will remove the fine particles and the dunes should naturally lose their emissivity. Combined with the resurveying to establish a sand budget, this sampling is expected to define why a remediation program is necessary: the natural process may take an unacceptably long time and will not meet the timing required for control of the dust emissions from the area. Knowing where fine particles may continue to be released is expected to help define the areas where remediation should occur and where it is not needed.

The last task, how to mitigate dune movement and associated release of particulates, is approached by describing objectives that include low impact, minimal entry, and minimal infrastructure. Results reported here, especially indications that only the southern one-third of the Keeler field constitutes the majority of the air quality and dune impacts are expected to have an important influence for meeting these objectives.

2. Introduction

Sand dunes are formed through two factors, (1) a supply of sand, and (2) consistent strong winds (McKee 1979). Depending on the size of the grain of sand, which can range from 0.0625mm to 2mm in diameter (Wentworth scale), wind speeds needed to move sand can range from ten to twenty miles per hour (Bagnold 1941 and Ahlbrandt 1979). These velocities bracket the wind speed that has been determined to generally initiate surface erosion from Owens Lake bed: 17mph (GBUAPCD 2008). Once a sand grain is set in motion, it proceeds along in the direction of the wind through creep and saltation. In the saltating fraction that is is too heavy to be suspended by the wind, the sand falls back to the ground to bounce and knock other sand particles loose to join the saltating throng of sand already energized by the wind (Mangimeli 2009). This process continues until the sand reaches a location protected by vegetation and/or other obstacles, such as the front slip face of the dune where the lowered wind speed lacks sufficient force to maintain the process. Here the sand particles accumulate in a process that moves the dunal sand mass slowly along in the direction of the wind.

Just to the northwest of the rural community of Keeler, California lays a dune field and sand deposit that are the subject of this report. This dune field and deposit are the result of deposition of particles eroded from the Owens Lake bed (GBUAPCD 2008). The dunes are of concern because they are moving towards the community of Keeler and give rise to significant dust pollution as they are reworked by the wind. This report evaluates dune movement through survey data, observation and photogrammetry.

Figure 1 provides a synoptic view of Owens Lake, the Keeler dunes and the surrounding terrain. The highest winds are driven by frontal passage, first from the south as the front approaches, then from the north after frontal passage. The highest winds are from the west-through-northwest with general trend of the jet stream. The terrain of the of the Owens Valley represents significant forcing of the wind direction as can be seen by the arrows interpreted on Figure 1. One aspect of siting for the Keeler station is apparent in observation of Figure 1. When winds are from north through about 30^{o} west of north, the Keeler station is partially protected by the mass of the Inyo Mountains projecting into the Owens Valley in the region of Dolomite (region directly north of the A Tower in Figure 1.)

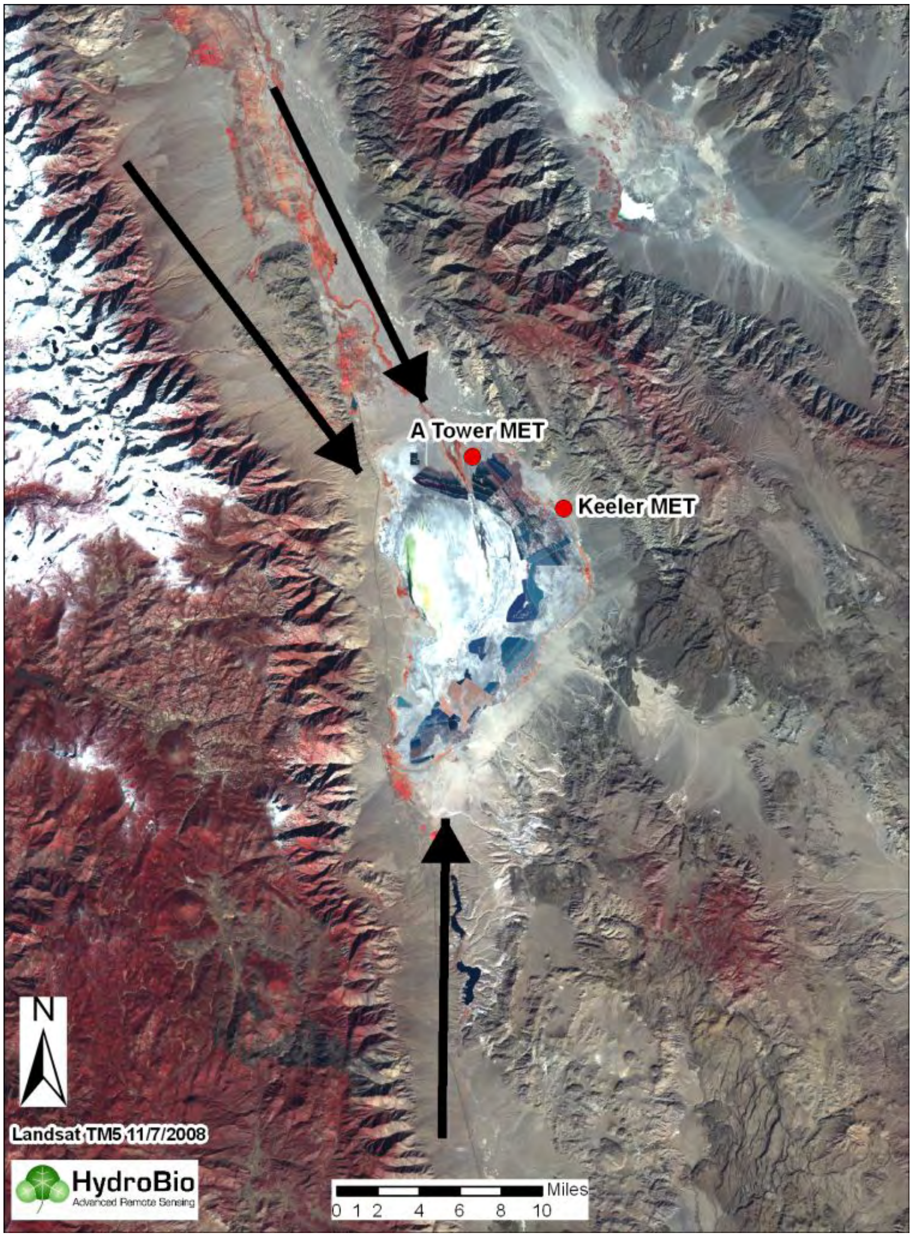


Figure 1. The Keeler dunes can be seen just northwest of the Keeler MET weather station depicted on the map. Most high winds at Owens Lake are driven by frontal passage that almost exclusively occurs during the winter and spring. During approach of a frontal system, the winds blow from the south. After frontal passage, winds blow almost exclusively from the northwest. These directions are depicted by arrows and show the influence of the surrounding mountains for channeling this flow. The highest velocity, longest duration and most erosive winds are from the northwest.

2.1 Keeler Dunes Before and After Shallow Flooding Cells

It is instructive to look at why dunes are found in the region northwest of Keeler. As will be seen in the evaluation of wind speed data, high winds from the south and northwest, cross the expanse of the Owens Lake bed and diminish significantly as they reach the Keeler area (though as noted earlier, this apparent drop in wind velocity, in part, may also be due to obstructions around the meteorological tower) . The drop in wind speed along this transition from across-surface to upward-trending air flow creates a depositional zone along the fan base for particles eroded and suspended by the high velocity winds across the lake. The deposited material from the high rates of lake erosion originally contained both coarse particles (sand) and fine particles (silt and smaller fraction).

In recent years, the dune forms within the Keeler field have changed significantly and the mass of dunes and related sand deposits have migrated east and southeast, depending on location within the field. As they move, the dunes emit fine particles that were deposited within the matrix of sand. The reworking causes the fine particles to be suspended while the coarse particles creep and saltate and remain within the area but extending the mass downwind. The process of winnowing of fine particles from the dunes will naturally continue until all of the dune material is reworked by the wind. A portion of the emitted dust is the result of erosion of aggregated fines in sand-sized particles and these give rise to dust emissions through particle-to-particle collisions.

The dunes logically can be expected to eventually become non-emissive after all fine particles that can be lofted by the wind energy have been removed. The timing of this gradual process is not known, however, it will be determined as part of the analysis of the Keeler dune problem.

Given the rate of the reworking of these dunes, this process may require many years, thus requiring that the dunes be stabilized by human intervention to prevent further dust releases in the short term. Such remediation may be costly and difficult and so, it is best to evaluate the dune problem thoroughly before planning. A major intent of these studies is to determine what parts of the dune field need to be addressed and what portions may be left alone to the natural processes. Thus, this investigation is designed to provide the practical considerations necessary to formulate a remediation program that is focused, lower cost and defensible.

Figure 2 presents images of the same dune taken in 1993 (Digital Orthophoto Quad, DOQ, photography) and again in 2004 (QB pan). Comparison of these two images is highly instructive. The dune slip face observable on the 1993 image indicates that the lack of other features on this dune at that time is not due to the limitations of the photography—the dune simply lacked observable features such as slip faces and it's shape was low lying and flattened. In the 2004 image, the dune has grown starker in outline with observable features indicating consolidation of the dune—it has grown more discrete. This dune consolidation has resulted in (1) a smaller footprint visible in 2004 than 2002 and (2) deflation of the adjacent areas, both features visible on Figure 2.

Why is there such a stark contrast for the morphology and the erosion and deposition processes of the dune from early (1993) versus late (2004)? Insufficient data exists to say definitively, however, one working hypothesis is that during 1993 the massive amounts of sand and finer particles were eroded from the lake bed and transported to this location. In this process when the wind speed dropped in the transition to the fan, the material tended to settle out. The year 1993 was a period of active particle transport from the lake bed and deposition within the dune area. The concentration of PM_{10}-sized particles declined at the Keeler monitoring site (24-hour TEOM particle sample records in Keeler) recorded an average of 45 $\mu g/m^3$ PM_{10} particles from 1993 - 2000, and at the same site from 2002 - 2006 an average of 34 $\mu g/m^3$ was recorded; GBUAPCD 2008). With high burdens of entrained dust and saltating particles during the period of active lake bed erosion, perhaps less energy was available for resorting particles deposited in the Keeler field to form dunes. After the establishment of highly effective shallow flood dust control to the west of the dune region in 2001 (Figure 3), the wind no longer carried heavy burdens of particles and so, the wind energy became available to re-sort the deposited material and create and move discrete dunes. Following this line of reasoning, the greatest portion of the particulate burden in Keeler during 2002-2006 (described parenthetically above) may have been re-entrained from the dunes.

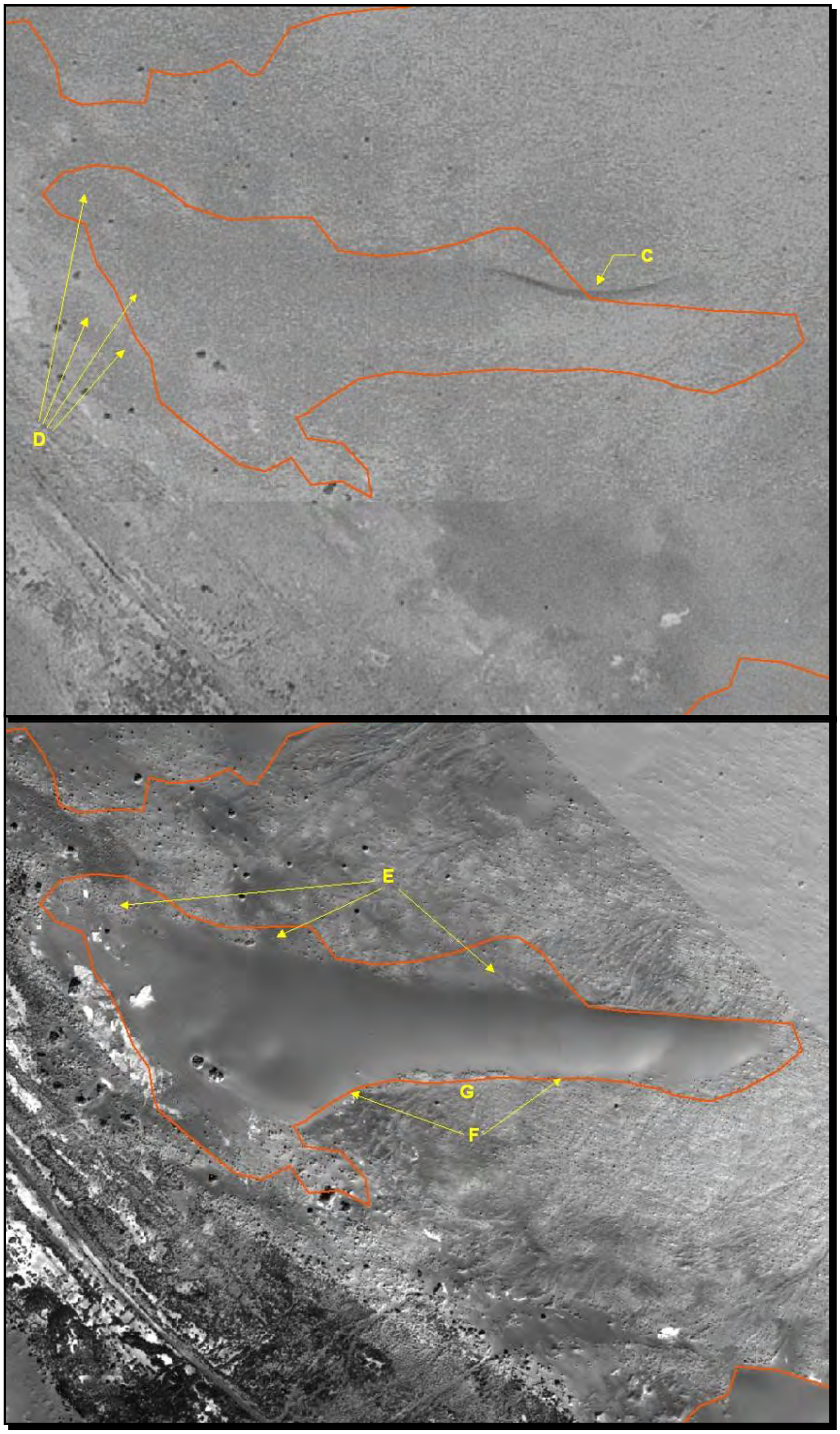


Figure 2. Images of a dune in the Keeler dune field shown at the same scale; is also presented and discussed later in this report, it received topographic surveying (Transects C) and is evaluated through time on QB images (as Dune 2). The orange outline is a GPS line mapped by Great Basin Unified APCD (GBUAPCD) outlining the dune in 2002.

Upper image: this relatively low resolution (DOQ, 9-23-93), features "C", a dune slip face indicating primary movement for the dune from south winds and "D", locations that are obviously deflated on the lower image. Note that the dune features are more pronounced and the dune is better formed in 2004 than in 1993.

Lower image: (QB, 1-03-04) provides a striking contrast to the 1993 photograph above, including deflation of areas to the west and building of the dune shape to the east. Featured are "E" areas that have deflated between the 2002 GBUAPCD mapping to become discrete dune edges, "F" areas of sand buildup on the leading face of the dune and "G" the dune edge in the same position as mapped by GBUAPCD—these areas are in the same position in 2002 and 2004.

2.2 Phases of Establishment and Operation of Shallow Flood Cells

The phasing of the shallow flooding cells was examined relative to the dune movement within the Keeler field. As can be seen in the images of Figure 3, the first phase of the mitigation, beginning operation in 2002, effectively blanketed the source region for the Keeler dune field, the lake bed to the northwest through south.

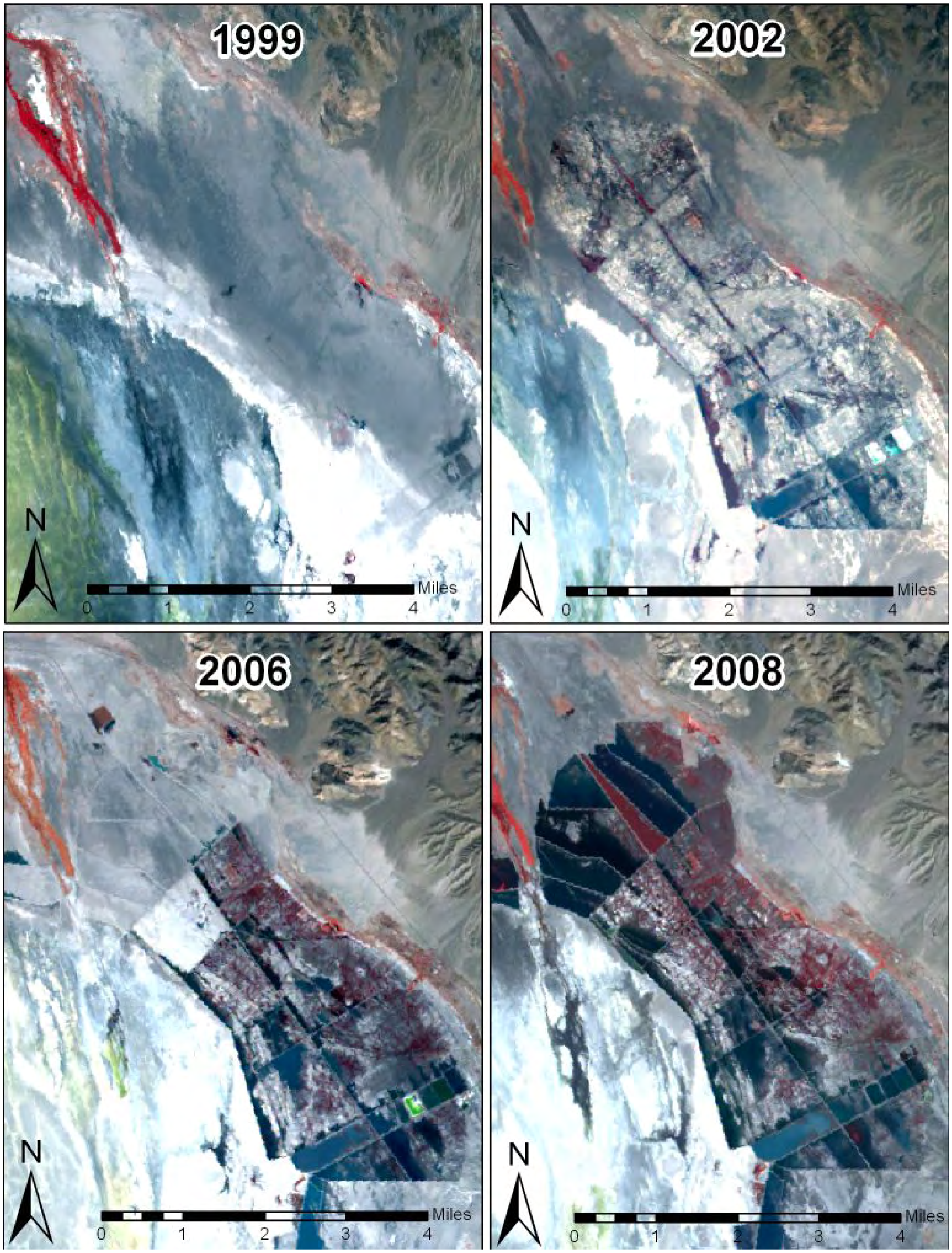


Figure 3. Views of the northeast portion of the Owens Lake bed that illustrate the establishment and development of the shallow flood dust control measures. Clockwise from Left to right the images dates are 6/24/1999, 8/3/2002, 10/17/2006 and 10/6/2008.

3. Surveying to Develop a Sand Budget

The development of sand budget requires the use of careful repeated measurements. This was approached by surveying to determine the change (movement, aggradations or deflation) in the amount of sand at the same location over time. For example, if the overall trend is deflation, then the elevation of the majority of the elevation surveyed points will decrease. If the trend is for a change in dune form (i.e. deflation on the west and aggradation on the east) this will be visible as well. Because the end points of each transect are monumented, an evaluation of such changes over time is possible. There were five discrete areas of transects established for evaluating the Keeler field (Figure 4). These were labeled “Transects A” through “Transects E”.

The Transects A region east of State Route136 was approached in a different manner than the other transects. Transects A, described below, was surveyed by measuring the depth of the aeolian sand deposit. Transects B through E were surveyed using a laser level to achieve a mathematical representation of the topographic surface. This surveying followed a scheme of linear transects with measured distances between elevation points. The starting point for each linear transect was located well off of the main portion of the dune. A shrub was chosen as the starting point of each linear transect into which a 2-foot piece of rebar was driven into the ground. The shrub locations were selected in order to minimize the potential for ATV or motorcycles to impact or be impacted by the re-bar stake. The horizontal component of the transect was determined with a 100-m tape (or multiple 100-m tapes) connected to the end point stake. Pin flags were placed at 5-m intervals along the tape starting from the zero position of the stake. The terminal measurement position of the transect was also monumented with a 2-foot piece of rebar. A laser base station was then set up in one or more appropriate locations to enable measuring the surface of the dunes along each transect to an accuracy of ±0.01 foot using a stadia rod outfitted with a receiver.

The measurement technique adopted for Transects B through E represents a rapid survey measurement technique that will permit comparison to data collected during resurvey in 2009 and into the future. These measurements are important because they provide an estimate of the mass of sand that is found in the dunes and the rate that it is aggrading or deflating. This information will be compared to measurements of the content of fines in the original dune material when they were originally deposited that should remain intact at depth within certain areas of the dunes that have not yet been reworked. This combination of data can then provide the basis for projection of the time frame necessary to naturally reduce these dunes' PM_{10} emissions to a level that no longer violates standards. Such a determination will admittedly be crude but sufficiently accurate to determine whether dune emission of PM_{10} is a problem that will take 1, 10, 100, or more years to resolve naturally. Hence, this activity is expected to set the logical basis for intervention to mitigate this problem. It will also separate out areas that may need no remediation (for example, potentially the northern portion of the dune field. Another approach, looking at the emission rates from within the area and the overall fine particle content to calculate the length of time needed to "clean" the dunes is also desirable, but must have the stochastic effect due to variable wind events removed (some years are windy, some are not).

3.1 Separate Sand Budgets for Dividing the Keeler Field

During the October 2008 field work it was evident HydroBio field observations indicated that areas of the Keeler field were responding in different manners, some apparently moving to the southeast at a relatively rapid rate, some staying in the same locations while deflating, and some experiencing intermediate conditions. The visual cues used were: (1) indicators of deflation, including exposed lakebed substrate, formation of desert pavement of coarse sand, and shrubs isolated on wind-eroded pedicels, and (2) indicators of moving dune fronts, including partially buried shrubs with stems indicating relatively newly buried conditions (buds that developed partially under the top layers of sand). To capture the variability indicated by field observation, five different areas of transects were established. This division will enable the determination of sand budgets for each of these areas.

In this section, Transects A are illustrated on the 10/6/08 Landsat TM5 image and Transects B-E are illustrated on various views of the 12/2/2007 QB image. This QB image was chosen because it is relatively recent, offers a pan-sharpened multispectral view and was taken with a relatively lower solar angle that enhances topographic features such as dunes, shrubs and fan drainages. The arrows shown on these examples indicate the direction in which the survey data were collected. The relationship of the five sets of Transects is illustrated on Figure 4.

The reason that separate dunes were observed and measured is because (1) individual dunes in the Keeler field appear to be moving in different manners, (2) understanding the dune movement directions and magnitudes is central to designing effective low cost mitigation, (3) such an understanding may enable eliminating certain areas of the Keeler Dune field from further concern, and (4) once the movements of individual dunes is understood the pieces can be reassembled into a holistic understanding of the entire dune field.

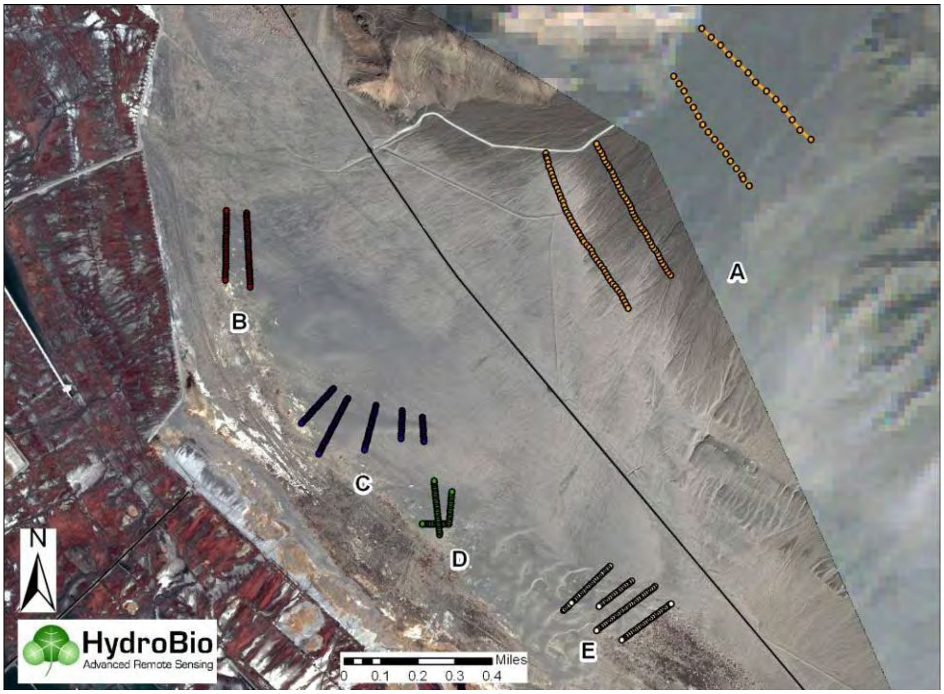
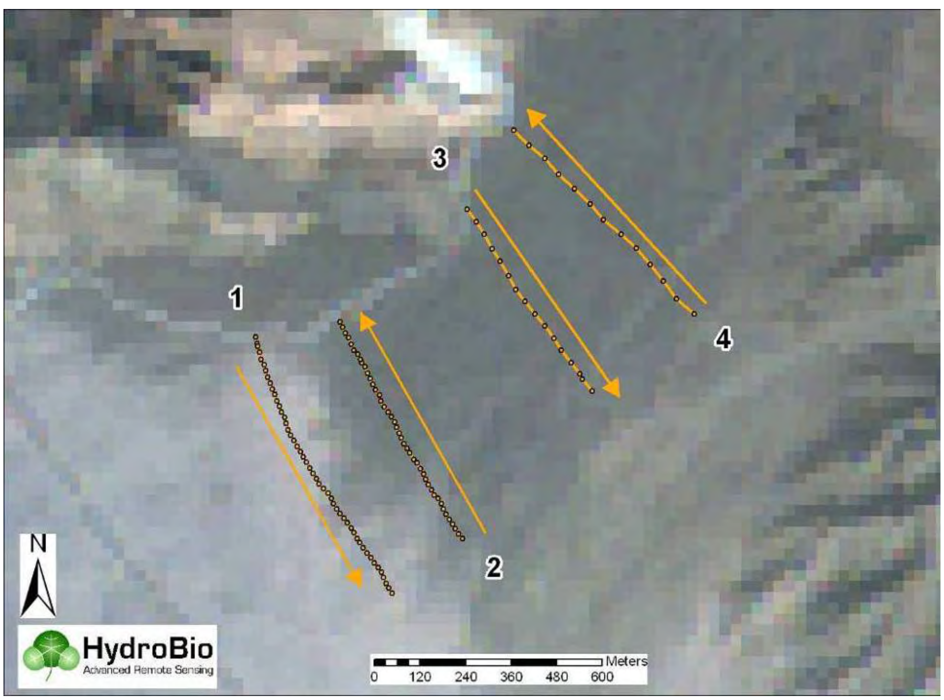


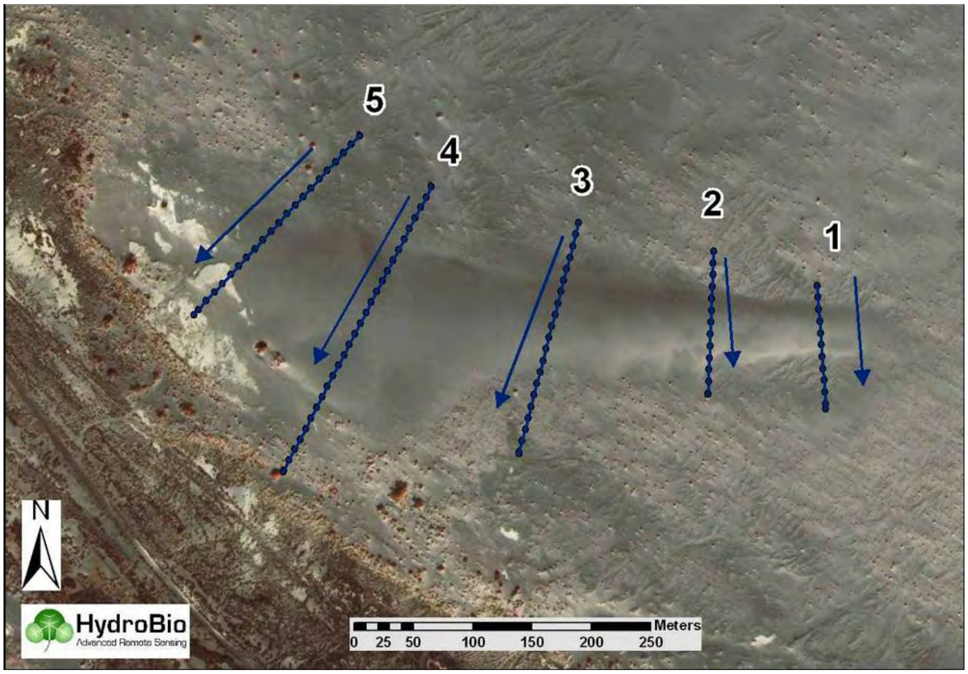
Figure 4. Dune Transects for September 29, 2008 displayed on Quickbird 3/19/2008 image. Landsat TM 5 10/6/2008 image was supplemented to show the upper area (on the right) of the alluvial fan not covered by the Quickbird imagery.



Transects A.

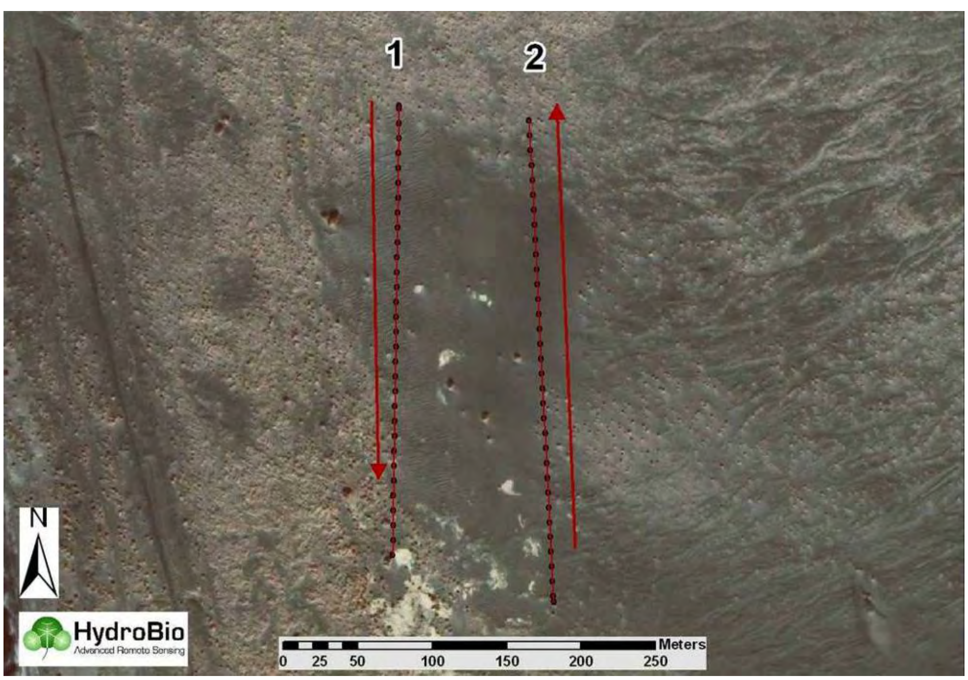
This field of transects is a thin sand sheet deposition area located on the alluvial fan above State Route 136. The physical environment makes this a difficult location for surveying because of the often very thin and patchy veneer of Aeolian sand that is present (i.e., relatively small vertical variability compared to the variability of the terrain) and combined complexity of the drainage channels that cut perpendicular to the survey transects. Rather than measure the surface height as in the other transects, geopositional data were obtained to sub-meter accuracy using handheld GPS of points spaced across the fan by pacing. This activity was deemed a "rapid survey" method and so the spacing of the estimation points was made variable depending upon the transect. Farther up the fan, the depth of the sand veneer diminishes, hence, requiring less points for sampling. For this reason, Transects

A consisted of four individual transects with the spacing on the lowest at approximately 20m between points, 40m between points on the middle two, and on the uppermost transect, approximately 60m. The intention was to get an estimate of the depth of the Aeolian sand deposit for future comparison to sand budgets under development. The majority of points on Transects A contained at least a small layer of sand, often when very thin, worked into the undisturbed natural alluvial fan surface. The sand varied from "zero" thickness to over half a meter deep. Where the sand was over a half meter, the total depth was not measured.



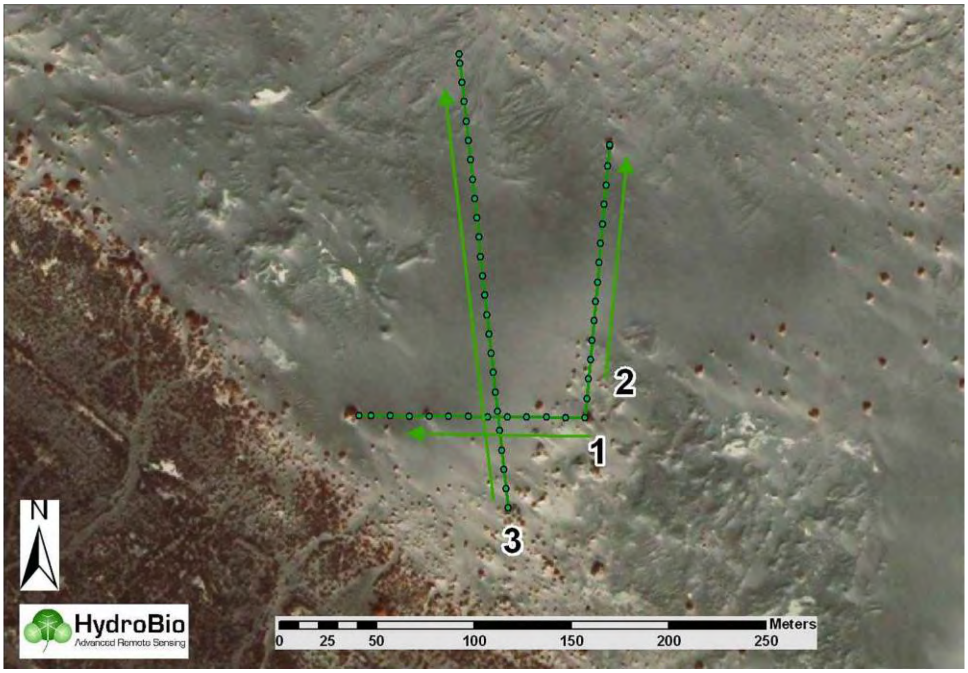
Transects B.

Transects B were located in a dune that showed numerous signs of deflation that included shrubs on erosion pedicels, exposure of old mud-cracked flash flood deposits, and flattened shape of the dune (rather than showing signs of deposition and movement in contrast to the other dunes). This dune was surveyed to confirm whether the deflation process is active. Another indicator of deflation shown in the area of Transects B was the presence of a layer of coarse particles (coarse sands to small gravel-sized, >2mm) at the surface unlike the finer sands found within more southern dunes in this field. Coarser particles are thought to be erosion remnants that will tend to armor the remaining soil, in effect a "lag deposit". Thus the dune evaluated by Transects B appears to be in the stages of deflation since it is nearly flat, resistant to further erosion and consisting of coarser particles that form only a very small percentage of the dune material observed in the Keeler dunes.



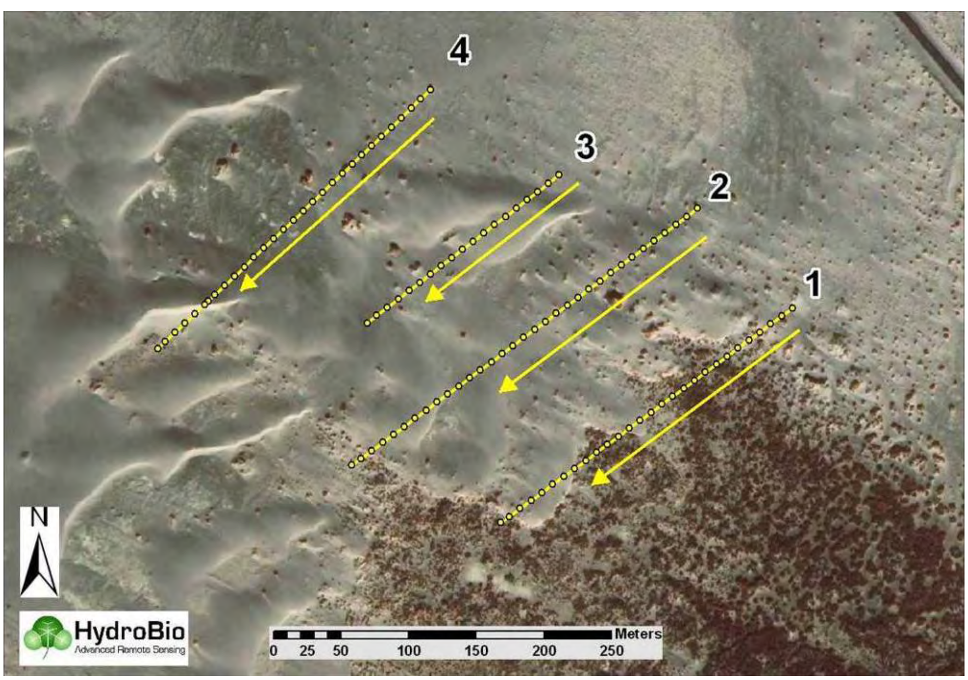
Transects C.

Transects C cross a prominent eastward-trending dune located near the center of the dune field. From field observations, this dune appears to be deflating on the western edge and moving and aggrading toward the east. Transects C are configured to test for this hypothetical trend. One aspect that is not yet understood is why the western edge, the source area for the eastern portion of the dune is so much broader than the eastern edge that represents the farthest projection up the fan. This is an important question to answer because the highly mobile dunes located in the portions farthest to the southeast show this same elongated trend. Being isolated from other sand sources, the dune covered by Transects C is expected to provide a test relationship. Understanding the mass balance of this dune is a critical part of this analysis as it can be hypothesized that the material projecting outward toward the east may represent sand that has been winnowed of its original content of fines; hence, no longer emissive. The region both north and south of this dune contains a large sand sheet that ranges in thickness from a few centimeters to about one half meter.



Transects D.

The dune of Transects D shows marked appearance of deflation toward the western edge in the form of pedicel coppice mound shrubs. Unlike the dune captured by Transects C, however, the shape of the dune does not indicate marked eastward movement nor pronounced aggrading. For this reason, a pattern of transects was laid across this area that is different from the other locations. This pattern is intended to capture changes in the north-to-south and east-to-west directions. The presence of this area of deflation and lack of discrete dune forms contrasts with the discrete dune covered by Transects C just to the north. A hypothesis that will be tested for possible incorporation into mitigation planning is that the area covered by Transects D lacks discrete dune form because the energy of the wind is sufficiently reduced by the surface roughness from the thick shrub growth to the west through northwest. This hypothesis can be confirmed using data from Great Basin’s anemometer field now in place on the Keeler dune field.



Transects E.

This set of transects is more extensive than the remainder of the transect fields established to measure elevation. It was apparent during the field work that the dunes in this area are the most active; they are well formed and are closest to the community of Keeler. The shape of the dunes traversed by Transects E contrast with the dune in

Transects D. These dunes are prograding into an area of vigorous greasewood to the southeast. Note that although the dunes extend in a southwest-northeast orientation, the pattern of the advancing front of sand indicates that the movement is perpendicular to the dune faces (and at an approximately right angle to the transects.) Typical of a barchans dune form.

3.2 Synopsis of Survey Transects

The series of transects A-E are intended to provide sufficient data to establish a sand budget within the dune field. Observations made during this task are that the northern portions of the dune field has much different characteristics than that found in the southerly portions. A series of hypotheses have been formulated that will be tested after the transects are resurveyed. These include:

- The dunes in the northern portion of the field are deflating and have been transported onto the alluvial fan to the east.
  Importance: this portion of the field may not need remediation.
- As the dunes deflate, the coarser particles are left behind leaving a "lag deposit" that is resistant to erosion.
  Importance: use of coarse sand/small gravel (available in the region of the Owens River delta) may be a useful and practical mitigation, alone or in combination with other methods.
- The formation of dunes is inhibited by the upwind location of thick greasewood growth.
  Importance: fostering greasewood growth may be a potential low-impact mitigation method.
- Dunes are formed through reworking by the wind, and in this process the fine particles giving rise to air pollution concerns.
  Importance: there may be large portions of the dunes that have already been reworked and "winnowed" that do not need remediation. This aspect will be addressed with the collection of samples from the dunes during 2009 to address the concentration of available fine particles.

The foregoing hypotheses combined with additional measurements, will be partly addressed through periodic resurveying of the dune field to establish a sand budget. It is expected that these activities will provide the basis for designing a focused remediation achieved at the lowest cost and impact.

4. Assess the Role of Wind Movement

Meteorological stations have been operated by GBUAPCD at Owens Lake to record surface wind, direction and velocity. Two stations from this monitoring network were used in this analysis, A-Tower and Keeler (Figure 5). A-Tower is located on the lake bed and the Keeler station is located within the community of Keeler. Both stations provide records that pre-date the creation of the Owens Lake mitigation program. The Keeler record runs from 1985 to present and the A-Tower from 1990 to present. The analyses presented in this section represent the first step for understanding historic winds through the Keeler dune field.

4.1 Analyses

Wind roses from data collected at A-Tower and Keeler meteorological stations were displayed with the wind origin direction indicated and the total hours for winds in excess of 17 mph, the velocity considered to be the lake bed threshold velocity. The wind roses were calculated for water years 1991 through 2008. The water year is a recognized unit of time (October 1st until the following September 30th) that coincides with the seasonal high winds associated with frontal passage at Owens Lake. Since strong fronts typically only occur during the winter and early spring, the water year format was chosen to provide the best means for characterizing winds during each influencing winter period. As a

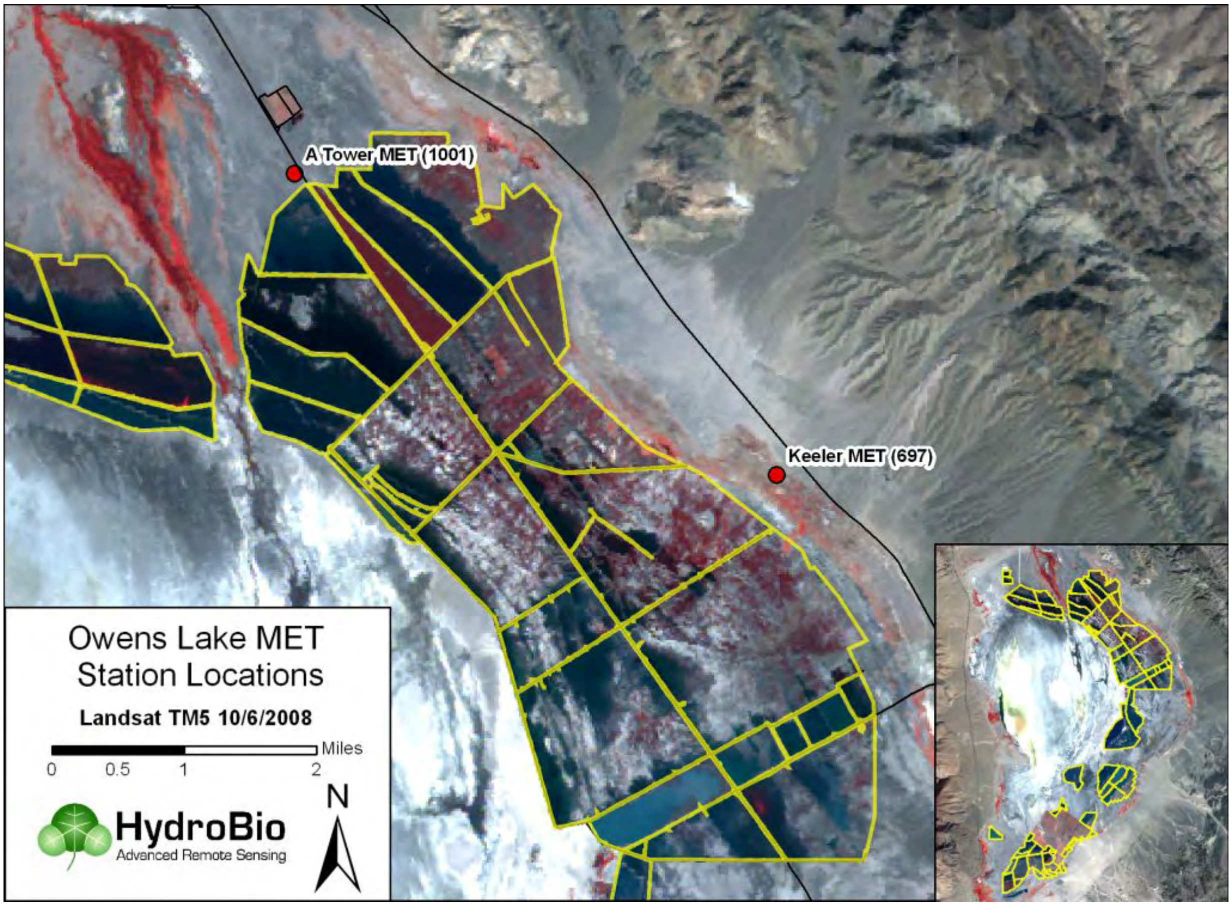


Figure 5. Location Map of MET stations

convention, water years are named for the year with the greatest time representation, for example WY1991 contains October-December of 1990 as well as January-September, 1991. All wind roses are displayed at the same scale to permit ready comparison among years.

Wind roses allow ready interpretation of the annual patterns of velocity and direction for winds capable of inducing sand movement. Consistent trends of winds from the northwest and south were seen throughout the entire dataset as shown in Figure 1. The A-Tower station, located on Owens Lakebed consistently showed much stronger wind when compared to Keeler to the southeast of the dune field (Figures 6 and 7). This trend follows the conceptual model for hypothesized meso-scale air movement noted in the introduction in which the Keeler dune field was a region of deposition during the period of active erosion of the Owens Lakebed to the west. Although the Keeler station showed a lower percentage of high wind events, they were consistently in the same direction as the A-Tower. The difference in wind speed between the two sites is remarkable. Since they are plotted with the same scaling, it is readily apparent that often when winds are quite high on the Owens Lakebed, they are well below the 17 mph threshold in Keeler. This interpretation, though, must be accompanied by the caveat that the Keeler wind data may be highly influenced by nearby obstructions.

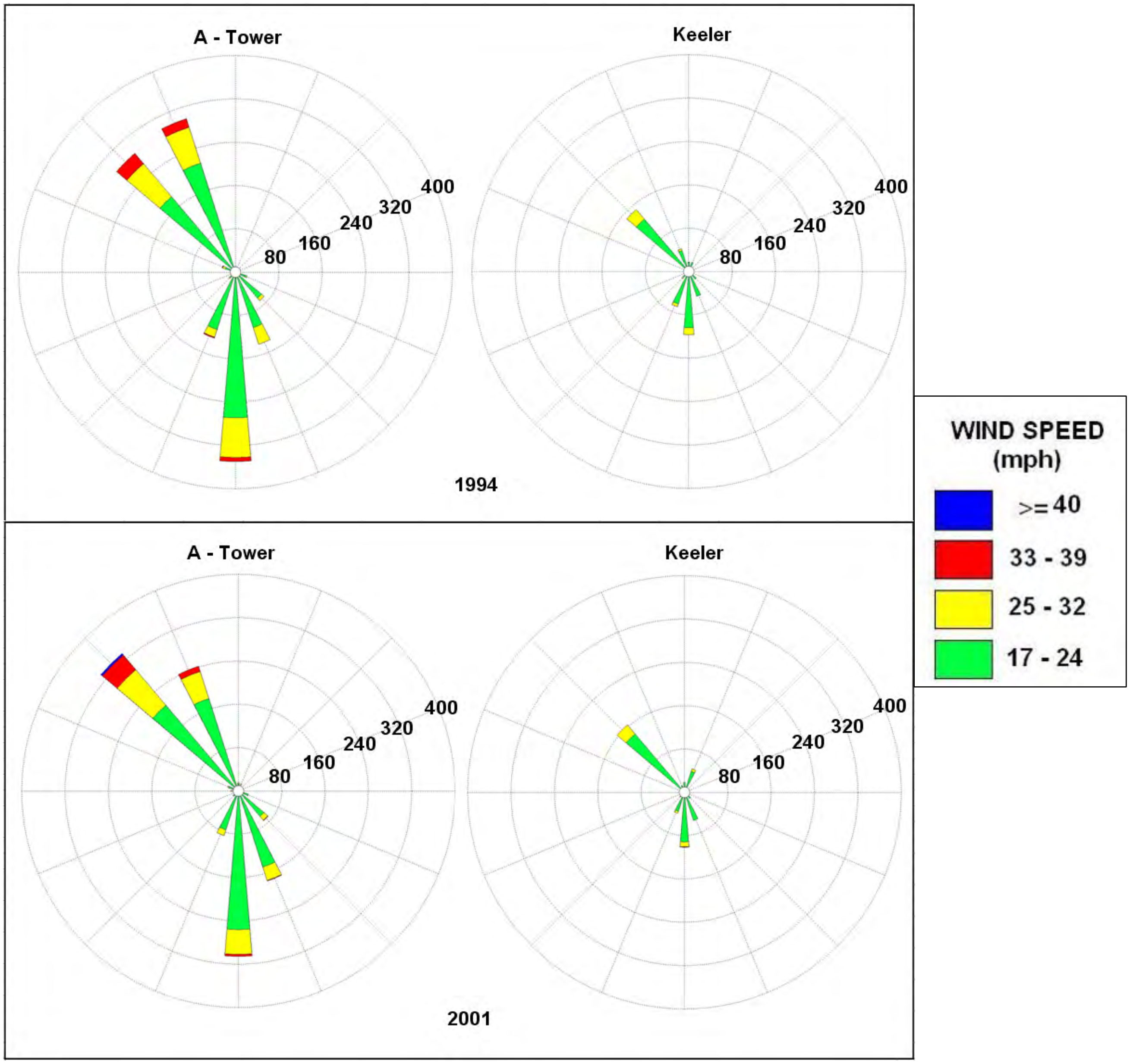
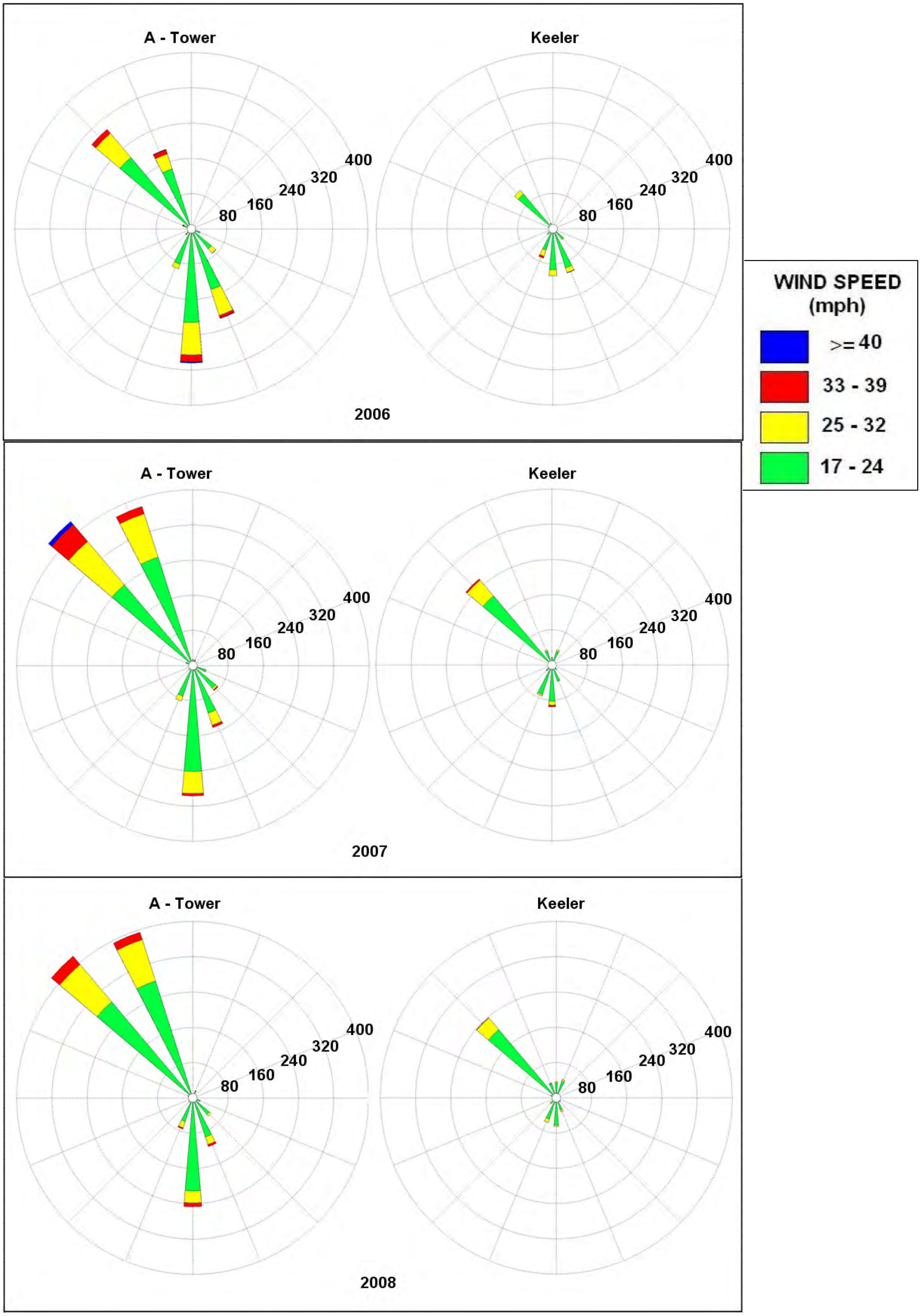


Figure 6. Example of A-Tower and Keeler wind data for WY1994 (top) and WY2001 (bottom), roughly indicative for the period prior to construction of the shallow flooding cells west of the dune field area. Total hours >17 mph are displayed. Note the markedly lower wind velocity for Keeler. Note here that the northern limb of the predominant wind directions at the A-tower is lacking at the Keeler station. This may arise due to topographic protection from the Inyo Mountains (see Figure 1 for this topographic influence).

Figure 7. Cumulative wind velocity >17mph in total hours, WY2006 – WY2008.

Keeler wind speeds for 2006 were atypically low in comparison to 2007 and 2008, while Keeler winds in 2007 and 2008 were higher than other recorded years.



4.2 Initial Results of Wind Analysis

As captured in Figure 7 the wind movement recorded during 2007 and 2008 was significantly higher in Keeler than in earlier years (compare entire suite of wind roses in Appendix A). It is not known whether these recent two years of significantly greater winds in Keeler are exemplary of new conditions due to the operation of the shallow flooding cells, however, as data are collected they should be evaluated to check for a trend. Arguing against this interpretation, 2006 experienced much lower wind activity than most years in the data base (Figure 7 and Appendix A). A better understanding of the regional wind patterns should be sought through evaluation of wind data from around the lack, not just the A-Tower and Keeler stations.

The effects of dune restructuring are visible as early as 2002 in QB images about the time that the first stages of the shallow flooding dust mitigation were brought on line (and as shown in Figure 3). Looking through the entire wind rose record in Appendix A (and disregarding anomalously greater wind activity in 2007 and 2008) overall wind velocities in Keeler appear to have remained steady.

4.3 Additional Work

As evident in the plotted wind roses, high annual winds recorded for the A-Tower are accompanied by commensurately high winds at Keeler. Thus, this relationship can be used to establish an index to determine how winds are changing over time in the region. Given that the A-Tower site located on the open Owens Lake bed is an indicator of regional wind conditions, this normalization would provide a more sensitive indicator to confirm whether a trend for higher wind velocity (apparent for 2007 and 2008) is occurring. This analysis would take into account the lumped effects of topographic position of the two locations and the differing surface roughness for both locations.

5. Assessment of Dune Movement Using Photogrammetry

QuickBird (QB) is an earth observation satellite launched in 2001 by DigitalGlobe that provides panchromatic (pan) data at 61cm (2 ft) spatial resolution and multispectral data at 2.4 meter (8 ft) resolution (DigitalGlobe 2009). QB images were used as a photogrammetric base for plotting cumulative dune movement. The high spatial resolution allows for detailed analysis of the dune fields since individual shrubs are visible.

Twelve QB images were used to track the movement of the sand dunes in this study. Nine of the twelve images were pan and three were pan-sharpened multispectral. The pan-sharpened images provide equivalent spatial resolution due to DigitalGlobe's process for merging panchromatic imagery to multispectral images. The 12 images range from 2002 until 2008 (Table 1) capturing the period of shallow flood-cell operation for Owens Lake dust control adjacent to the Keeler Dunes. Due to the very high resolution of the QB imagery, it was necessary to geocorrect each image using invariant features with an image-to-image protocol. Shrubs present in and around the dune field were matched in each image. These images were all geocorrected to the "Gold Standard" QB geocorrection image from June 19, 2007 (HydroBio 2007).

Scene	PAN	PAN-SHARPENED
10/16/2002	X	
6/7/2003	X	
1/4/2004	X	
5/4/2004	X	
12/19/2004	X	
5/25/2005	X	
3/9/2006	X	
10/6/2006	X	
7/16/2007	X	
12/2/2007		X
3/19/2008		X
9/18/2008		X

Table 1. Quickbird Imagery used in the photogrametric analysis. Pan imagery is black and white while the pan sharpened multispectral imagery show color.

It should be noted that the positioning of the QB data in large part determines the detail of interpretation that can be gained from the analysis of dune movement. For example, were late summer and late spring images available for all years (as in 2008) this would enable determining whether a seasonal trend of dune movement exists. The seasonal movement of each dune is described for 2008.

5.1 Photogrammetry

This analysis built upon field observations from the surveying work described above that observed the western portions of the dunes tend to be deflating, while the east through southeast fronts of the dunes had moved. Thus, for this analysis, only the dune fronts to the east through southeast were mapped. The dune fronts selected for analysis are shown on Figure 8.

The geocorrected QB data were displayed in ArcMap and the dune fronts mapped at each time step. Once mapped, all of the resulting shapefiles, one each per time step, were displayed together for individual measurements. The overall vector for the direction of movement of each dune was determined by reference to features on the first (2002) and last (2008) images. Scaling tools in the ArcMap software were used to measure the incremental distances of travel represented by the dune fronts at each time step along this vector.

Analysis of individual dune movement was performed because it is the only way to understand the wind and dune movement across the entire Keeler dune field. Each dune, in essence, becomes a surrogate for the historic air movement that has created and shaped it. This reductive approach was used because we know of no way to approach the dune field to understand it in an holistic sense. Only by dividing the field into its component dunes can an understanding be gained for how winds are playing across the area of interest and whether some areas are affected more than others. This reductive analysis can then enable assembly of a mitigation program that focuses effort where it is needed.

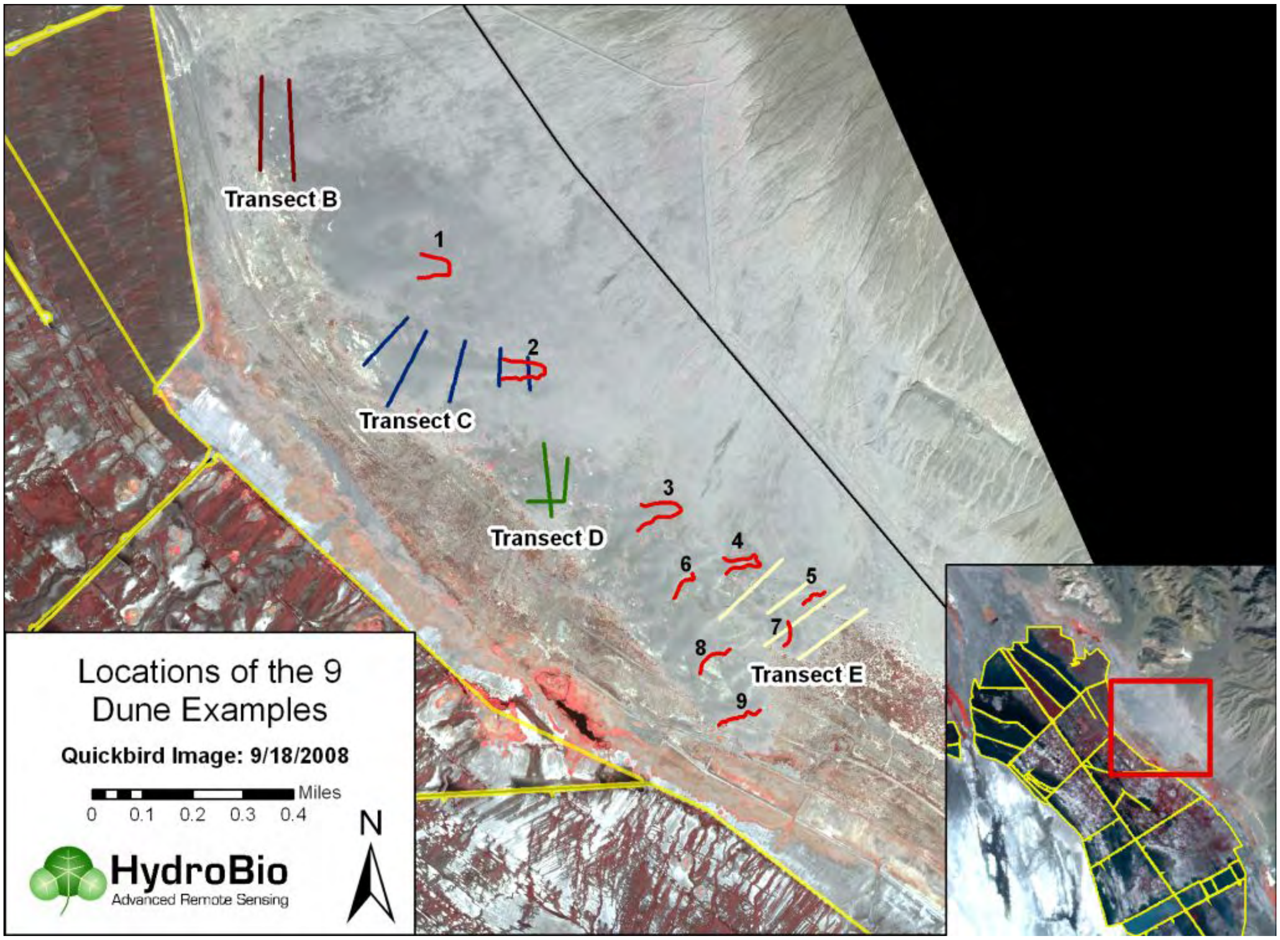
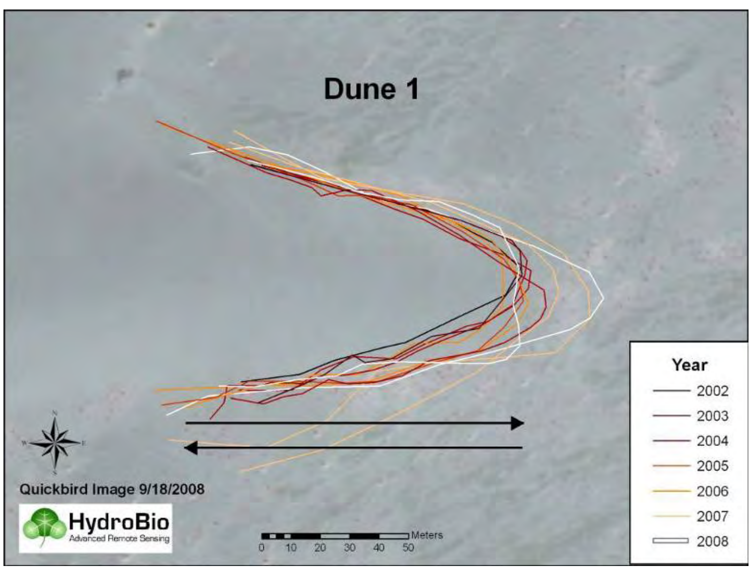
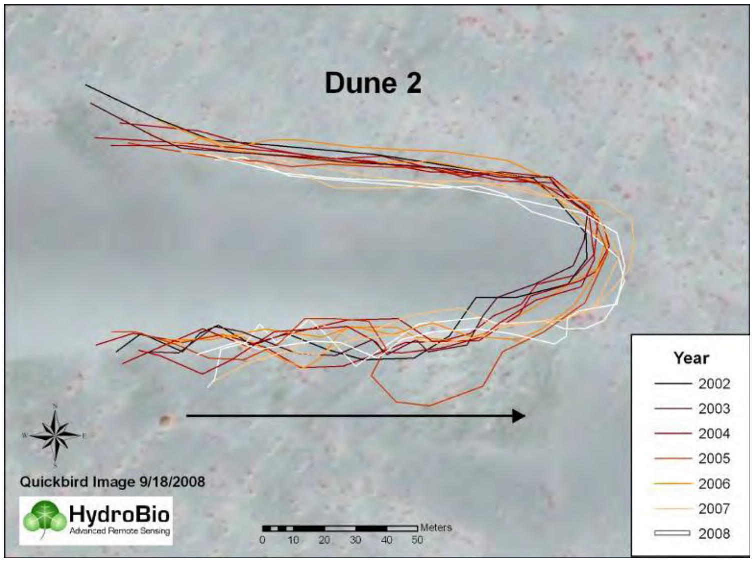


Figure 8. Dune fronts chosen for analysis of movement through time. These locations were scattered through the dune field.



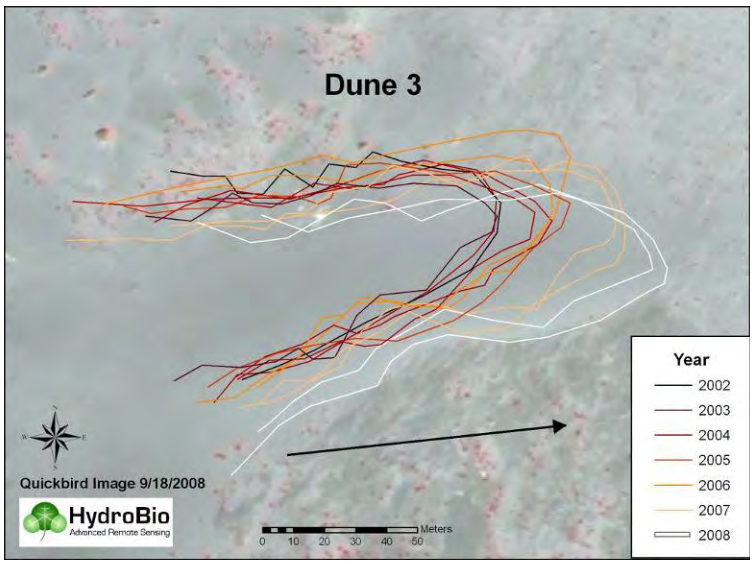
Dune 1

Dune 1 is located farthest north of the mapped examples. Dune 1 showed a pattern of occasional eastward and westward movement with a cumulative movement of 0 meters. The reversal in direction of Dune 1 throughout the study period reflects the variability in wind velocity and direction at this location. Once sand has coalesced into a dune, the overall direction and shape of the dune is determined by the direction and force of the wind. For example, in 2006 the dune made a dramatic shift westward and then a large shift eastward in 2007. As seen in the MET data this was the result of wind from the south and southeast pushing the dune back. In 2007 the predominant force was from the northwest with lower wind velocity from the south, causing the dune to move eastward about 26 meters. Early in 2008 this eastward expansion continued until wind velocity from the south reduced eastward movement. Deflation of Dune 1 may be a factor in the reversal of sand movement in summer 2008 that caused the total cumulative movement to equal zero. Note that there is nothing in this nearly featureless portion of the alluvial fan that could be controlling the edge of Dune 1 other than wind and the supply of sand it receives. Because the influence could only be wind, the sloshing back and forth of Dune 1 is the result of both complex winds within the field and significant seasonal variation. Note that 2008 is represented by the two white lines with the second line retreating to the west after the summer season.



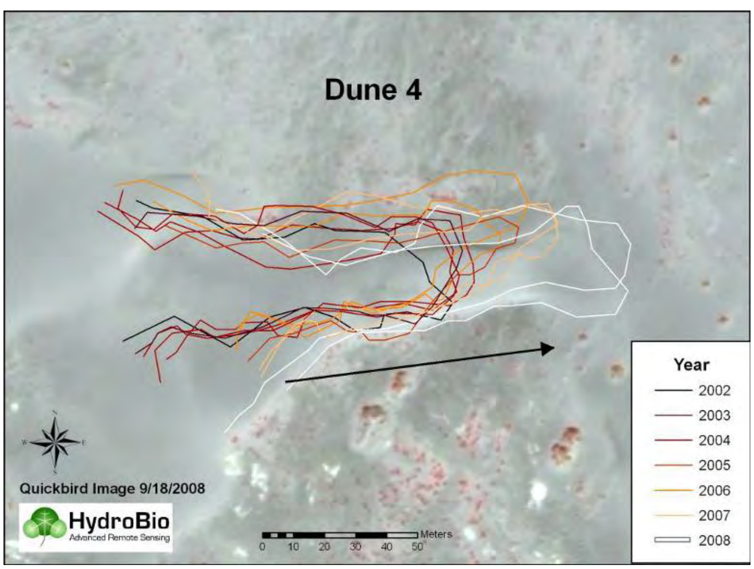
Dune 2

Located just south of Dune 1, Dune 2 also shows an eastward trend, however, Dune 2 showed cumulative movement of 17 meters. It is hypothesized that the more southern location of Dune 2 has an effect on the dune movement, where changes in wind velocity and direction are factors in forcing the dune to cover more distance than Dune 1. Dune 2 is located within Transects C. 2008 is represented by two white lines with the second one (September) located mostly left (west) of the one measured in March.



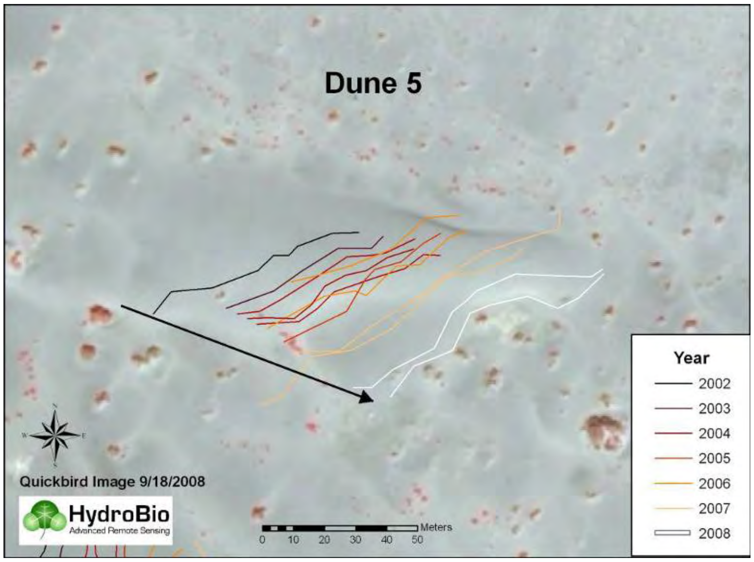
Dune 3

Dune 3 is located to the southeast of Dune 2. It shares the eastward expansion with Dunes 1 and 2, but it is moving to the northeast. With a cumulative movement of 56 meters, Dune 3 is moving faster than Dunes 1 and 2, to the north. Wind variability also has affected this example. Dune 3 back tracked (moved west) from 2002 until early 2004, where the dune shifted back in the eastward direction. High winds of 2008 moved the dune eastward from a general east-northeast long term track. The two lines for 2008 (white) moved east between March and September.

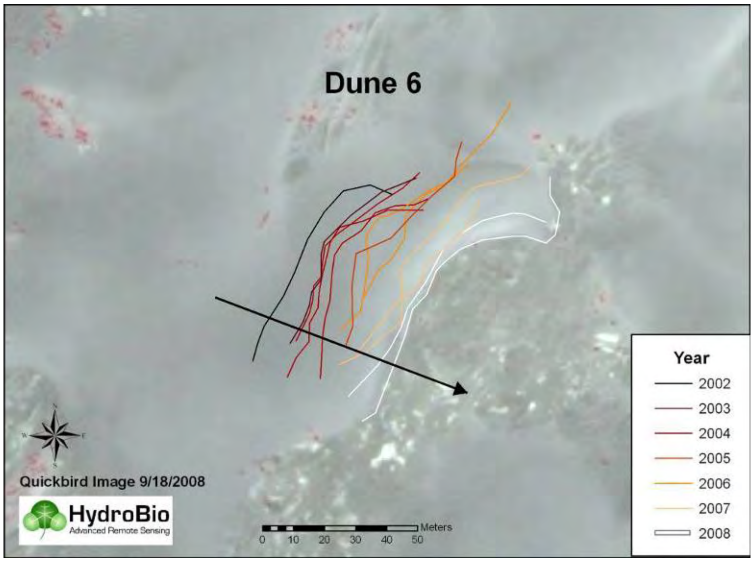


Dune 4

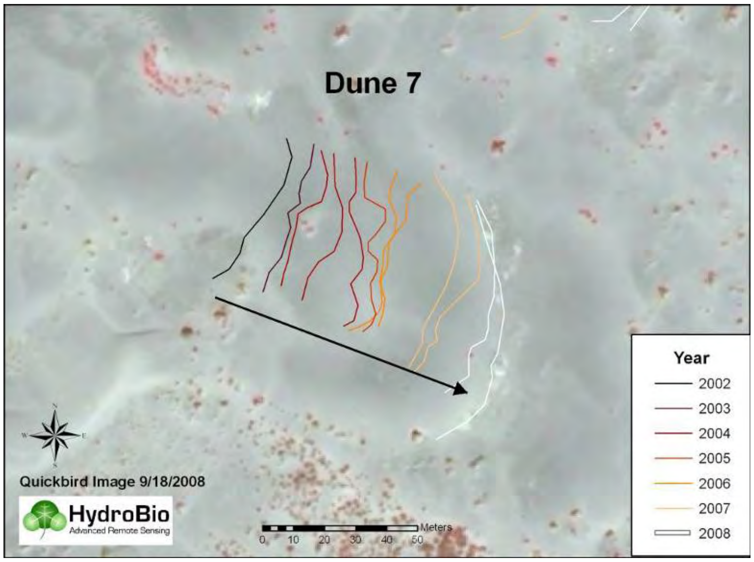
Just southeast of Dune 3, Dune 4 also shows a slight northeastern movement with a cumulative movement of 6 meters. The same reversal of movement exists in Dune 4 as all of the eastward moving sand dunes. The most significant movement of sand material was in 2007 where the movement pattern returned to the eastward direction. Dune 3 moved 19 meters from 2006 to 2007. The two lines for 2008 (white) show that leading edge deformed to the southeast between March and September.



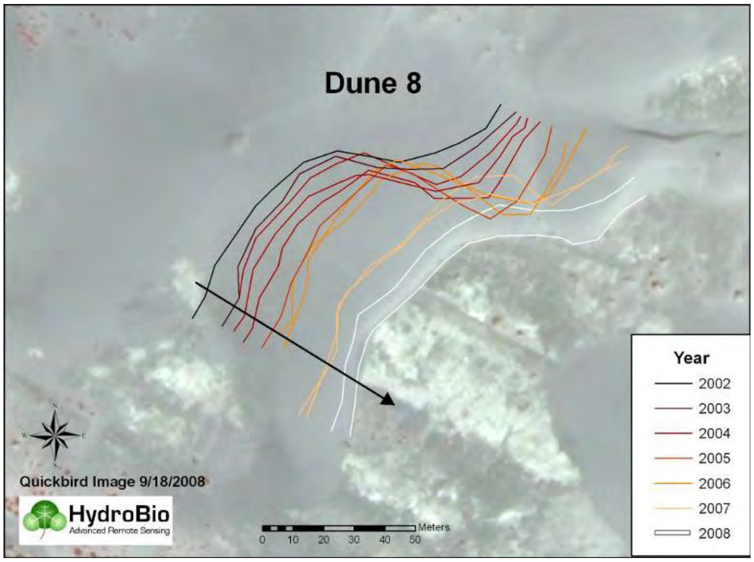
Dune 5
Located to the northeast of Dune 9, Dune 5 is located within Transect E. Dune 5 shows a consistent southeastern movement as well. With a total movement of 86 meters between 2002 – 2008, Dune 5 had an average distance of 10 m/yr. Dune 5 also showed variation in movement with the second largest distance covered out of the nine dune examples. The two lines for 2008 (white) moved southeast between March and September.



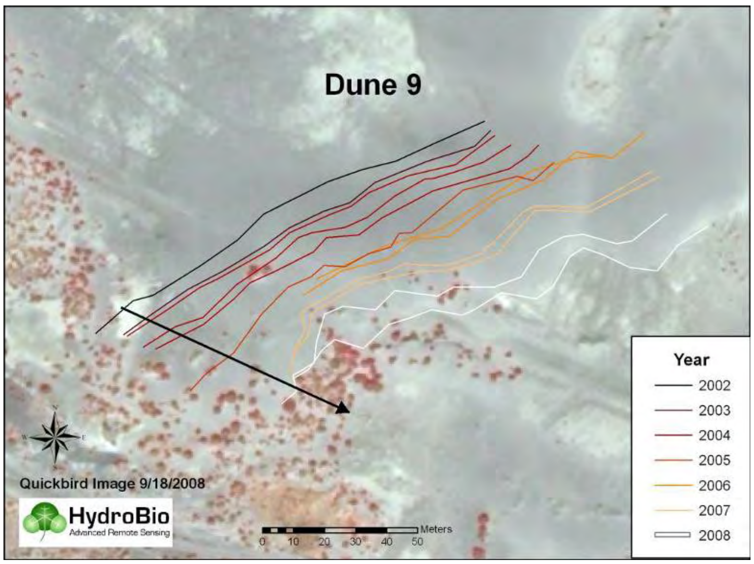
Dune 6
Located to the west of Dune 4, Dune 6 shows a consistent southeastern movement similar to Dunes 8 and 9. Dune 6 moved a total of 40 meters from 2002 to 2008. Although the dune had a consistent movement southeast, there was a slight reversal in movement between 2006 and 2007. The two lines for 2008 (white) moved southeast between March and September.



Dune 7
Dune 7 is located to the southwest of Dune 5 within Transect E. This dune has a consistent southeastern movement, where the total movement, 92 meters, was the greatest out of the nine dune examples. The two lines for 2008 (white) moved southeast between March and September.



Dune 8
Located in the southern portion of the Keeler Dune field, dune 8 had consistent southeastern movement toward Keeler. Using the QB imagery from 2002 until 2008, Dune 8 showed a total movement of 58 meters. During the five year study period the average distance that dune 8 moved was over 5 m/yr. The two lines for 2008 (white) moved southeast between March and September.



Dune 9
Just south of Dune 8, Dune 9 also has a consistent southeastern movement. Dune 9 is the located farthest to the south out of all nine examples. It had a total movement of 69 meters from 2002 until 2008. The average distance moved was over 6 m/yr, an increase in movement when compared to Dune 8. The two lines for 2008 (white) moved southeast between March and September.

5.2 Synopsis of Dune Movement

From observations of the graphics presented in the descriptions of the individual dunes, it is apparent that, from north to south through the dune field, vectors change direction from east to southeast. Dunes 1 through 4 show an eastward movement, while dunes 5 through 9 show a southeastern movement. Located farthest to the north are Dunes 1 and 2 that are apparently not moving and appear to be deflating (to be confirmed with transects).

These dunes may need no intervention due to the deflation process where the sand will disperse to the east and the dunes will eventually become relatively flat sand sheets. From this observation the primary area of focus for study should be the southern portion of the dune field. Further work in the north of the field is expected to yield confirmation of easterly trend for dune movement and deflation.

Dunes 5, 7 and 9 showed the greatest cumulative movement for all of the dunes that received measurements. These dunes are located at the farthest southeast portion around the leading edge of the Keeler field. Graphs of dune movement are presented in Figure 9.

Comparison of the mapped dune fronts with the wind roses provides support for the contention that greater movement of the dunes occurs during years with greater wind energy. Both 2007 and 2008 experienced significantly higher winds than earlier years and this corresponds with the mapped position of the dune front as is shown on the graphs and in the graphs that achieved generally greater slopes in these years.

What is somewhat surprising in this analysis was the trend for reversed movement that was noted. This result is not reflected in the wind roses and indicates that wind movement in the dune field may be particularly complex. A quick look at the graphs in Figure 9 suggests that reversal of movement may be related to seasonal influences. In particular, a trend for reversal in movement occurred over summer 2008 for Dune 1 and occurred slightly for Dune 2. All other dunes moved southeastward during the summer period of March 2008. Thus, dune movement in the Keeler field is apparently complex, influenced by the wind energy in any one year, has a seasonal component and is probably also influenced by the up-wind terrain.

Conclusively, like the field observations of deflation and dune movement that noted differences between north and south parts of the dune field, the photogrammetric examination of the individual dunes above, shows that the far northern part of the Keeler field is affected very differently than the southern part. Since wind energy is the only source for moving these dunes, this difference reflects very different winds at the northern and southern ends of the field.

6. The Rate of Re-sorting of Dune Particles

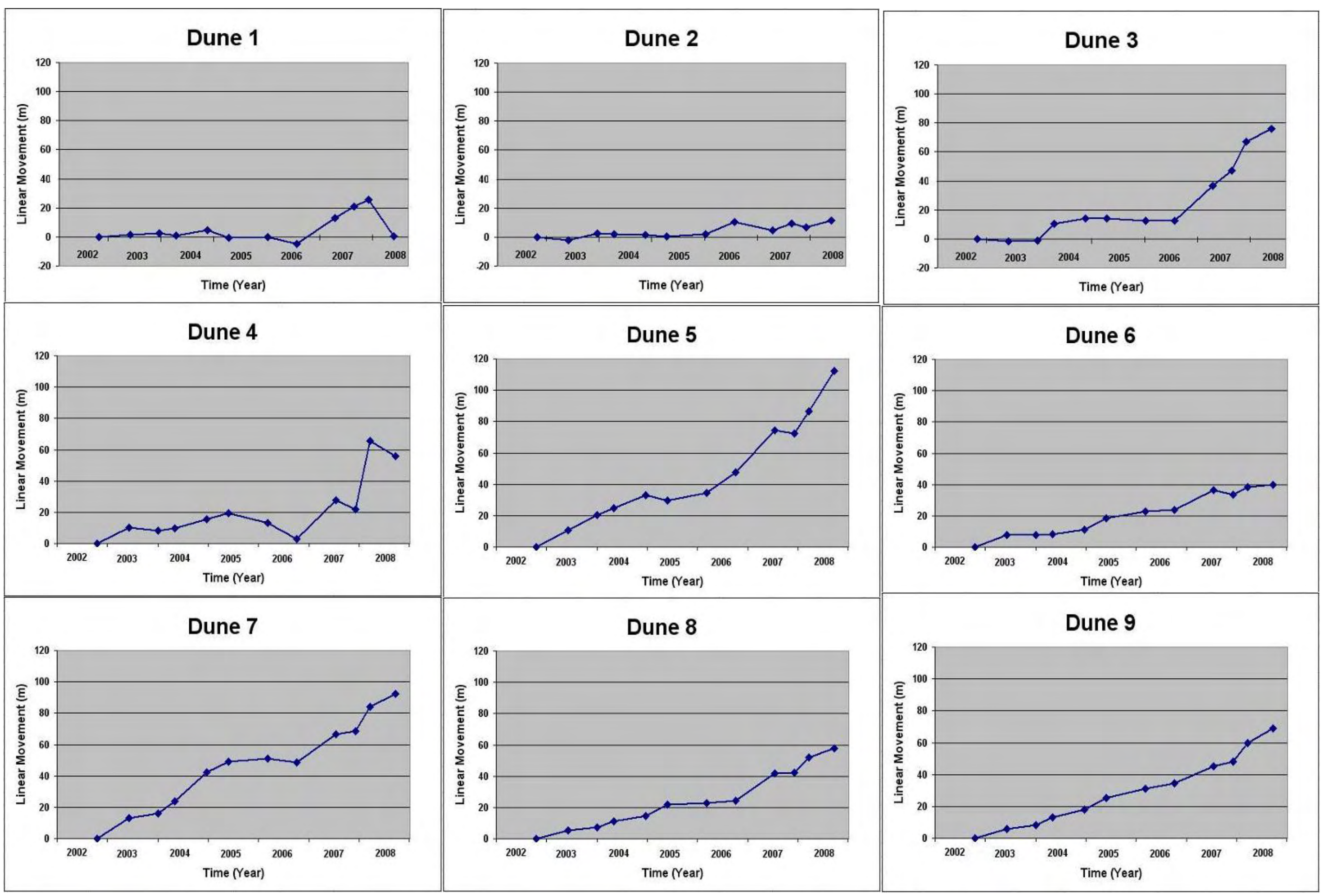
Sampling of the original dune material within the outer portions of the dunes that have yet been reworked by the wind is a planned activity for fall of 2009. Locations of essentially pristine dune material (containing fines as deposited) will be identified, samples taken of this material and particle size determinations made. These samples will be compared to sand that has been extensively reworked by the wind to determine concentration of fine particles present. The experimental design for this analysis has not yet been prepared, however, it is known that the dunes will need to be excavated or cored to provide the samples for this determination.

7. How to Mitigate the Dune Problem

From analysis of dune movement, it is apparent that the main focus for future intensive study should be the southern one third of the dune field represented in Figure 10 as the area south of the blue dotted line. Repeated transects are expected to provide confirmation that the dunes in the north are deflating and that the sand they contain is moving eastward in a large sand sheet toward and across State Route 136. This trend is expected to be ongoing. If protecting vehicle travel is of interest, an evaluation may need to be made to determine if this moving sand poses a problem for motor travel. Then, if warranted, this sand sheet can then be included in future mitigation planning.

Figure 9. Cumulative linear dune movement measured in the predominant direction of movement.


Year
2002
2003
2004
2005
2006
2007
2008
1
2
3
4
5
6
7
8
9
N
Miles
0 0.08 0.16 0.24 0.32
HydroBio


Dune 1
Dune 2
Dune 3
Dune 4
Dune 5
Dune 6
Dune 7
Dune 8
Dune 9
Linear Movement (m)
Time (Year)
2002
2003
2004
2005
2006
2007
2008

One attractive remedy for the most active southeastern portions of the Keeler dunes is enhancement of surface roughness by fostering shrub growth. The apparent area of concern is sufficiently small to restrict the potential water required here to about several hundred acre feet. The method of application will need to be determined, however, several aspects of this location may enable low cost and low impact mitigation: the ground surface slopes toward the lake, the water table is relatively close to the surface, water can be expected to move readily through the bases of the dunes (known as "dune plinths"). Thus, a low cost, relatively low water application method of releasing water on the uphill side of the dunes, followed by widespread planting of seedling greasewood in the spaces between the dunes may work to slow and eventually stabilize the dunes. The entire area of concern may be about 0.5 x 0.7 miles in extent (visible on Figure 10), constituting about 224 acres in total. The consumptive use of water can be estimated roughly at about 224 acre feet/year (224 acres x 0.5 fraction of affected area between dunes x 2 feet/year).

Toward planning mitigation, determining the slope of the natural ground surface (that exists below dune deposits), and the slope of the regional water table are research goals for the 2009 effort.

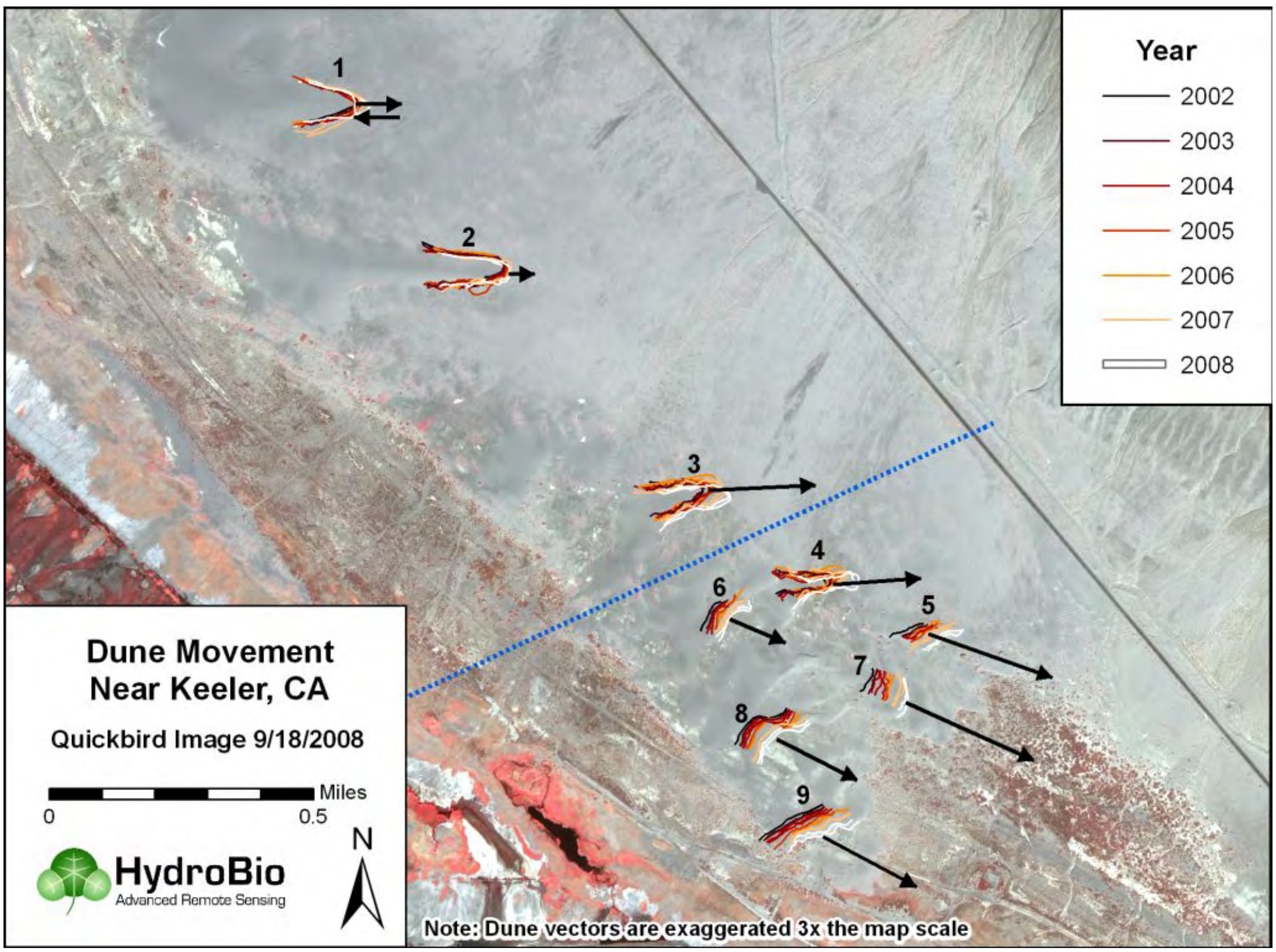


Figure 10. Map of total movement of dunes. The area south of the dotted blue line is an area for greater concentration of research effort since this is the area of most active dune movement and is closest to the community of Keeler.

8. References

Ahlbrandt, Thomas S. 1979. Textural parameters in eolian deposits. In *A Study of Global Sand Seas*. E. McKee, ed., pp. 21-52. Washington, U.S. Geological Survey Paper 1052.

Bagnold, R. A. 1941. *The Physics of Blown Sand and Desert Dunes.* Chapman and Hall, London.

GBUAPCD 2008. FINAL 2008 Owens Valley PM_{10}Planning Area Demonstration of Attainment State Implementation Plan. http://www.gbuapcd.org. retrieved February 16, 2009.

HydroBio 2007. HydroBio Quickbird Image Geocorrection. Owens Lake Project, October.

McKee, Edwin. 1979. An introduction to the study of global sand seas. In *A Study of Global Sand Seas*, E. McKee, ed., pp. 1- 20. Washington, U. S. Geological Survey Paper 1052.

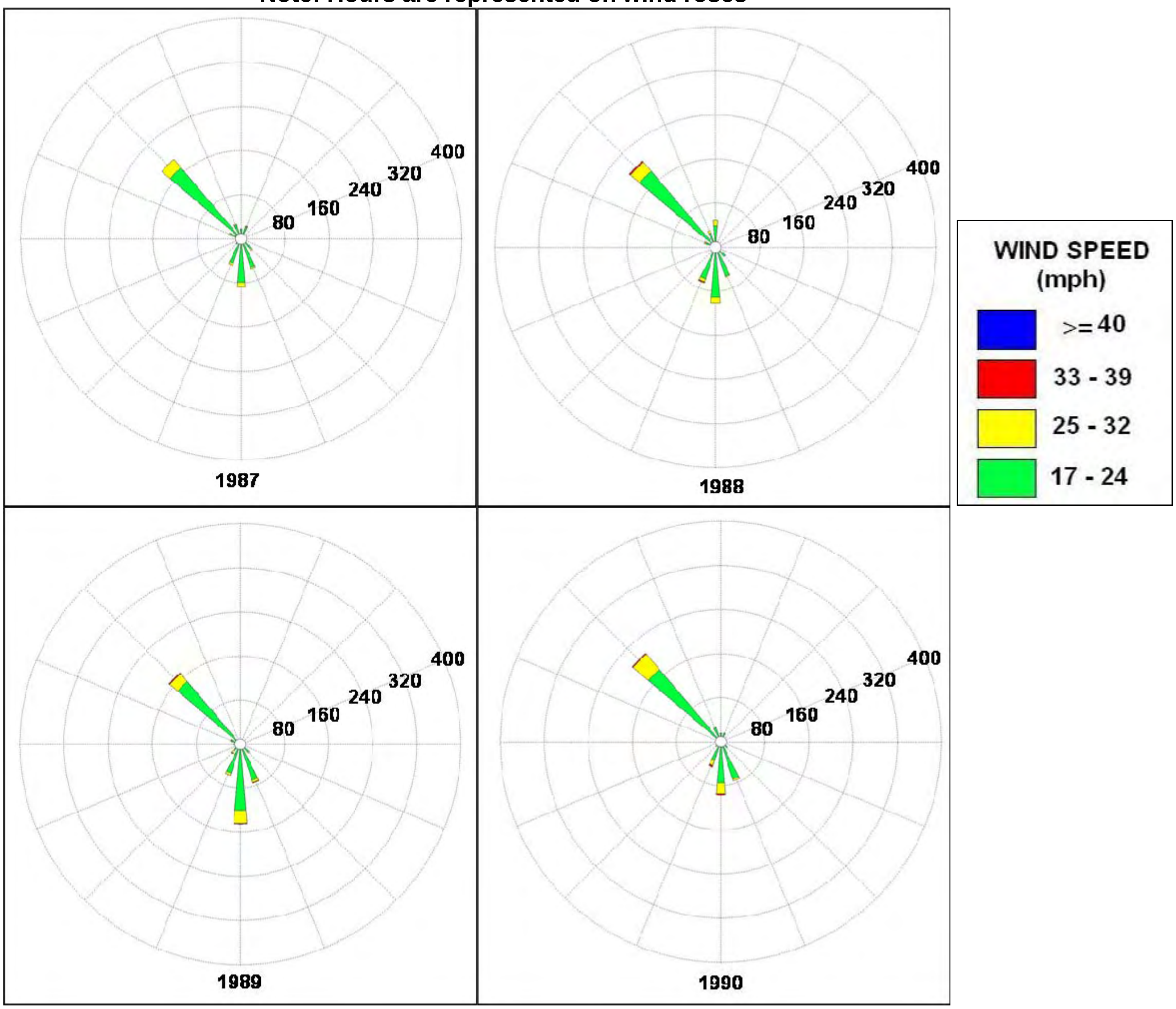
Mangimeli, John (2009). Geology of Sand Dunes. http://www.nps.gov/archive/whsa/Sand%20Dune%20Geology.htm. retrieved February 17, 2009.

APPENDIX A

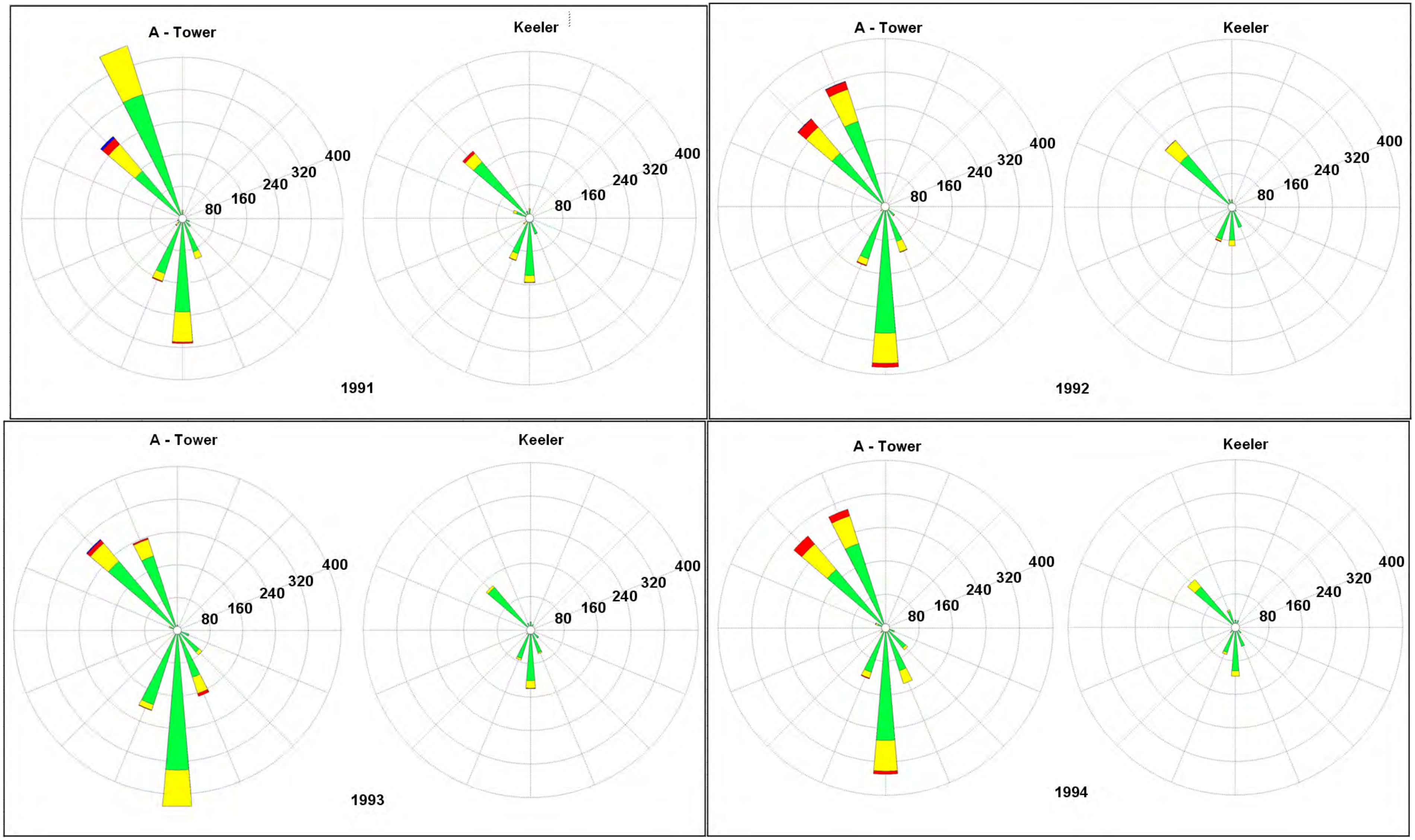
MET Data Before Shallow Flooding Cell Construction/Operation

These data provide documentation for the results claimed within the document. The data on this page are for Keeler data only since the A-Tower was not yet established.

Note: Hours are represented on wind roses



MET Data Before Shallow Flooding Cell Construction/Operation



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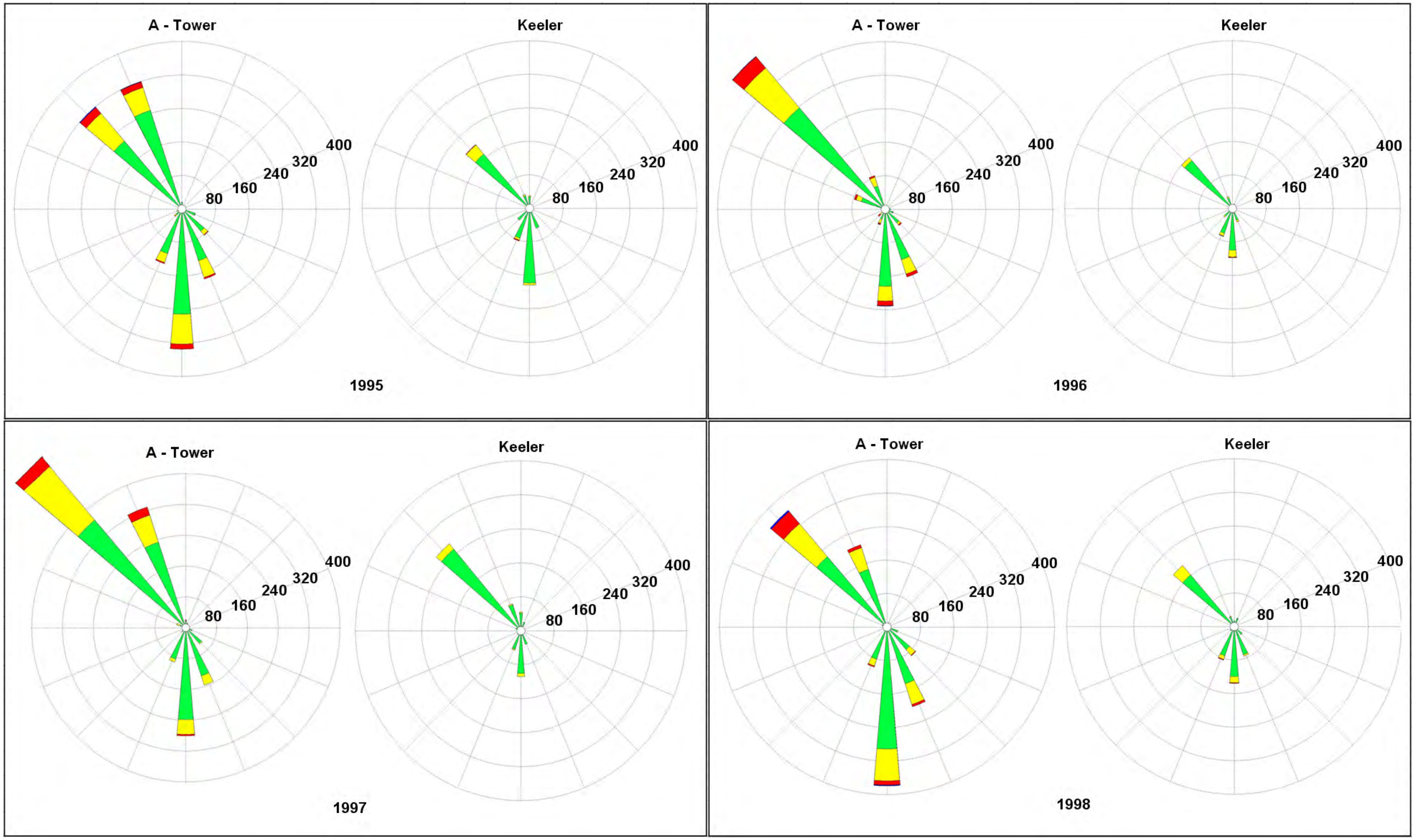
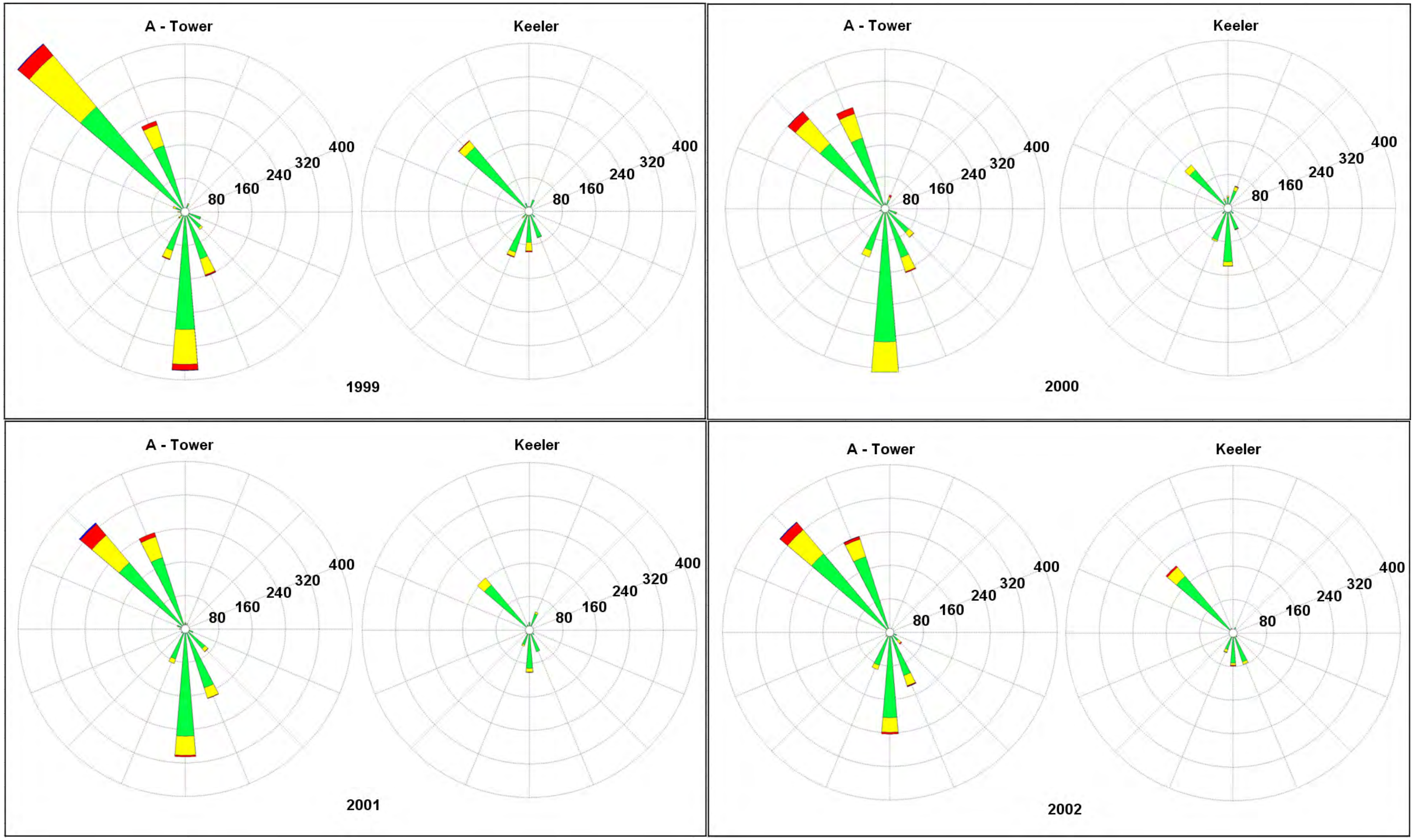
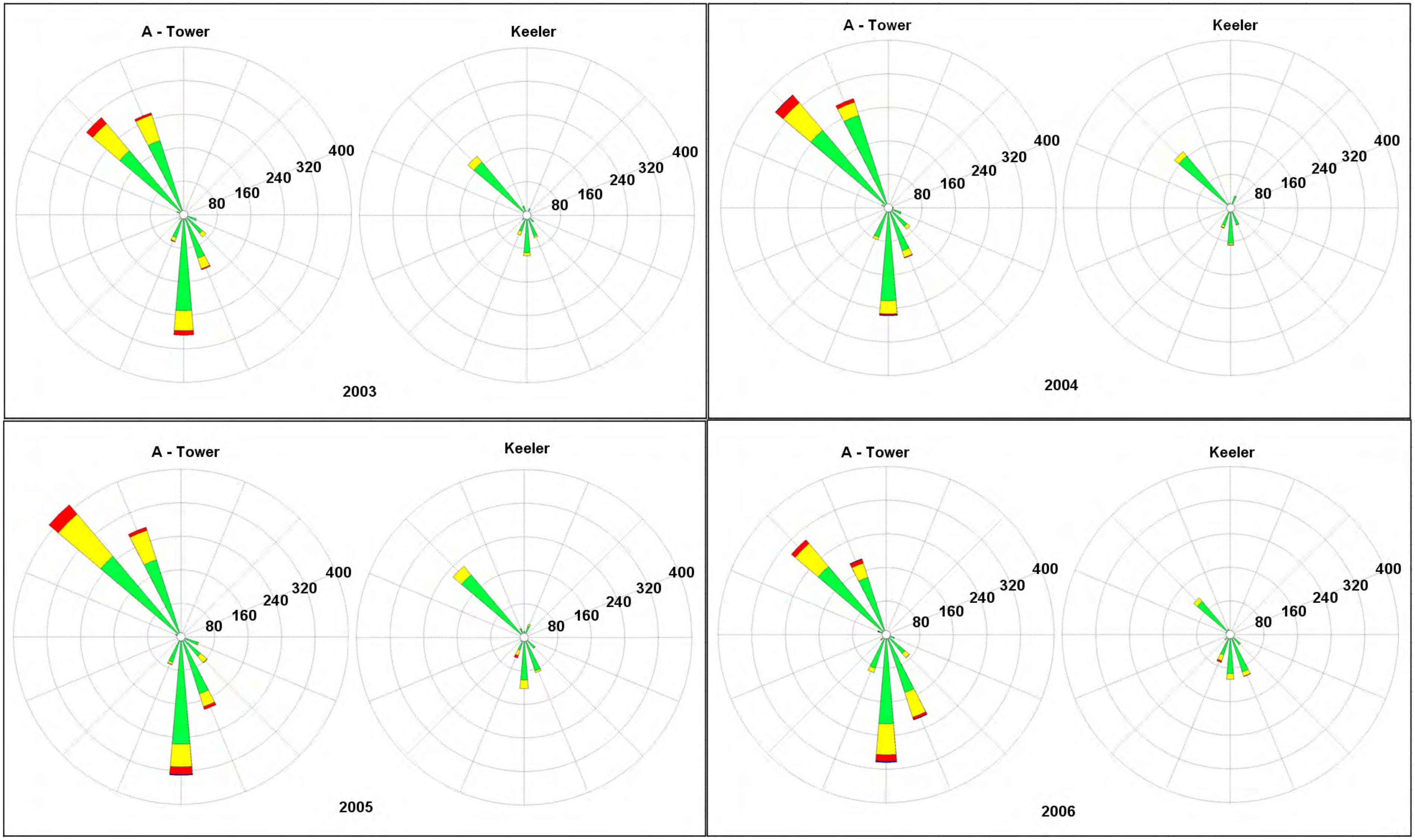


MET Data Before and at Inception of Shallow Flooding Cell Construction/Operation



MET Data After Shallow Flooding Cell Construction/Operation



MET Data After Shallow Flooding Cell Construction/Operation